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# Grappling with a sea change: Tensions in expert imaginaries of marine carbon dioxide removal

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A B S T R A C T

While research on marine carbon dioxide removal (mCDR) expands apace, significant unknowns persist regarding the risks and benefits of individual mCDR options. This paper analyses the assumptions and expectations that animate expert understandings of mCDR, with a focus on issues that are central to the responsible governance of this emerging field of climate action. Drawing upon interviews with experts involved in mCDR research projects both academic and entrepreneurial, we highlight four thematic tensions that orient their thinking but are often unstated or left implicit in scientific and technical assessments: (1) the relevance of 'naturalness' as a criterion of evaluation for mCDR approaches; (2) the perceived need to accelerate research and development activities via alternative paradigms of evidence-building; (3) a framing of mCDR as a form of waste management that will, in turn, generate new (and currently poorly understood) forms of environmental pollutants; and (4) a commitment to inclusive governance mixed with difficulty in identifying specific stakeholders or constituencies in mCDR interventions. Although expert consensus on these four issues is unlikely, we suggest ways of ensuring that consideration of these themes enriches debate on the responsible development of novel mCDR capabilities.

## 1. Introduction

The prospect of deploying new technologies for carbon dioxide removal (CDR) has gained considerable attention, as reductions in greenhouse gas emissions fail to keep pace with climate stabilization targets (Intergovernmental Panel on Climate Change, 2023). Among the different ways of drawing carbon from the atmosphere, approaches that involve alterations in marine environments are seeing a surge in interest and funding, partly due to the geophysical potential of the oceans as an sink for atmospheric $CO_2$ (National Academies of Sciences Engineering and Medicine, 2021). Proposed methods of ocean-based or marine CDR (henceforth "mCDR") include those such as ocean alkalinity enhancement, ocean iron fertilization, macroalgae cultivation and sinking, direct removal of $CO_2$ from seawater, blue carbon (restoration of vegetated coastal ecosystems), and direct air capture with carbon storage (DACCS) in offshore locations. While many of these approaches are currently being assessed in mathematical models or small-scale experiments, others remain at the concept stage, and the specific configurations that they will adopt in deployment scenarios remain, for the most part, highly speculative (Gattuso et al., 2021). Broad societal assessments of the technical, environmental, regulatory, and economic considerations of different mCDR options are just beginning (Boettcher et al., 2023; Cooley et al., 2022).

The current state of play thus combines a plethora of research, development, and demonstration initiatives with a high degree of indeterminacy as to the actual contours of any mCDR option at scale. Fundamental issues remain unanswered about the direct and indirect environmental impacts of different interventions, their cost and safety, the additionality and durability of carbon sequestration, or the methods that would be used for the measurement, reporting and verification (MRV) of any purported removals (Mace et al., 2018). These indeterminacies constrain the design of appropriate governance mechanisms. While a handful of codes of conduct and best practice guidelines are now available to orient further research and development efforts (Boettcher et al., 2023; Satterfield et al., 2023; The Aspen Institute, 2021), these are yet to be trialled or tested, and the work of adapting national and international regulatory schemes to the specific risks and requirements of mCDR interventions is still to be done.

Acknowledging the range of relevant questions awaiting clarification, funding agencies, scientific bodies and advocacy groups are emphasizing the importance of conducting mCDR research and innovation 'responsibly' (Ocean Visions, 2023a). Academic and policy literatures on 'responsible research and innovation' (RRI) highlight the need to make R&D processes accountable to societal needs and expectations through dialogue with relevant publics and constituencies. Oft-cited tenets of RRI are the principles of anticipation, inclusivity,

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reflexivity and responsiveness (Burget et al., 2017; Macnaghten, 2016; Owen et al., 2013). Yet what such values and principles might mean in practice for mCDR is not immediately obvious (Low and Buck, 2020). Translating principles into specific guidance or institutional arrangements for mCDR governance is challenging, as CDR at climate-relevant scales still remains an 'abstract notion' to policymakers and researchers alike (Honegger et al., 2022).

In this evolving context, expert understandings of the current state and future configuration of the field play a central role in shaping scientific and policy outcomes. Experts often hold a near monopoly of discursive resources for framing technologies at an early stage of development, and they define the parameters of emerging governance architectures, informing the views of policy-makers and influencing how public views are elicited and interpreted (Smallman, 2020, 2018). The values and expectations that orient these expert understandings can be characterized as expressing a particular 'sociotechnical imaginary,' a set of 'collectively held and stabilized visions of desirable futures' associated to the advancement of a suite of new technologies (Jasanoff and Kim, 2009). In a field like CDR, where technologies remain speculative or are limited to small and/or experimental formats of deployment, such imaginaries offer "relatively coherent ideas and visions about the future informed by expectations about certain technoscientific practices, which in turn influence present-day governance of those practices" (Christiansen and Carton, 2021).

Expert imaginaries of mCDR centre on the prospect of enrolling the Earth's largest carbon sink in the fight against climate change. "Because the ocean is so vast," Zak and Ack write in a recent call to accelerate research on mCDR, "any proven safe and effective approaches could ultimately operate at the massive scale necessary to reduce atmospheric carbon levels meaningfully" (Zak and Ack, 2023). The possibility of devising 'climate-relevant' interventions through gigaton-level removals of $CO_2$ is what attracts many practitioners to this field, and it often nudges them to develop a sort of 'planetary social thought,' a mode of reasoning where specific scientific and technical issues are directly related to far-reaching questions about "how to inhabit a planet in transition to a new and unfamiliar operating state" (Clark and Szerszynski, 2020). Like other expert communities investigating phenomena 'on the brink' of environmental catastrophe (Braverman, 2018), or who contemplate, with 'troubled hope,' radical measures of climate stabilization (Shewry, 2015), the reflections mCDR researchers and entrepreneurs offer on the current state and future trajectory of their field reveal deeply set values and moral judgments, combining scientific, ethical and political considerations. In this context, a 'socio-technical imaginary' is less a stable set of assumptions underpinning expert consensus, and more a series of tacit, often under-articulated preoccupations over fundamental aspects of the issue at hand. These preoccupations are in a continuing state of evolution, as the very contours of the field remain fluid.

In this paper, we identify four such tensions: (1) the role of 'naturalness' as a criterion for the evaluation for mCDR options; (2) a perceived need to accelerate research and development efforts, with varying perspectives on how acceleration relates to conventional understandings of precaution; (3) a view of mCDR as a planetary waste management tool, combined with an emerging awareness of the forms of contamination and pollution that it will generate; and (4) a commitment to engage stakeholders in governance processes, without a clear sense yet of who constitutes a relevant public for mCDR interventions. We outline our research methods in Section 2, before turning to the exploration of these four themes in Section 3. In the second half of the article, we offer a discussion of each of the four themes with a view to enriching public debate on mCDR.

## 2. Methods

To explore expert imaginaries of mCDR, we conducted semi-structured interviews with experts involved in mCDR research projects, from academic to non-governmental to private sector, that explore the feasibility and early-stage piloting of different mCDR approaches. Interviews were conducted between January and December of 2022.

Our guiding definition of mCDR was broad and drew on the inventories of technologies or approaches used by the U.S. National Academies of Sciences, Engineering and Medicine; the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP); the advocacy group Ocean Visions; and other bodies that have mapped, or are currently mapping, research and governance needs in this domain. Our definition of mCDR includes ocean alkalinity enhancement/alkalinization, nutrient fertilization, artificial upwelling and downwelling, electrochemical removal of $CO_2$ from seawater, seaweed cultivation, coastal macroalgae cultivation, and the recovery of marine and coastal ecosystems ('blue carbon'). To this list we added DACCS projects in marine environments, as such projects raise overlapping ocean-related themes.

Our definition of 'expert' included active participants in projects engaged in research on and/or development of mCDR or ocean-based negative emissions technologies (as they are also known). Although most of our interviewees were experts in different fields of the natural sciences and engineering, our sample also included individuals with a background in business, external relations, and law and social sciences (see Table 1). Participants were largely from North America and Europe. The diversity of this group is certainly limited. This is partly due to our sampling approach, but is also representative of the current state of the field, which is largely dominated by global North actors and institutions, and is grounded in the expertise of natural scientists and engineers. It is worth noting that we did not include experts from the broader carbon removal ecosystem, such as funders, regulators, or policymakers. These actors are highly influential in shaping the field and would have contributed additional dimensions to the imaginaries driving the development of mCDR options. They would be worth studying in the future.

To identify these experts for interviews, we used a mix of purposive and convenience sampling, in order to achieve breadth of technologies covered as well as depth on specific mCDR approaches (Boyd and Vivian, 2019; National Academies of Sciences Engineering and Medicine, 2021; "Ocean Visions | Catalyzing Solutions For Ocean Health," n.d.). Purposive sampling involved identifying mCDR projects. We drew upon CarbonPlan's CDR database (CarbonPlan, 2022), which includes publicly available materials on applications to Stripe and Microsoft's carbon removal purchase agreements, as well as GESAMP's list of

**Table 1**
Summary of expert sample.

| Primary employment/affiliation | |
|---|---|
| Academic institution | 27 |
| Business (e.g., start-up) | 13 |
| Those with dual academic and business affiliations | 6 |
| | |
| Discipline | |
| Natural science and engineering | 29 |
| Business/external relations | 5 |
| Other academic (social, legal) | 2 |
| | |
| Geographic location | |
| Europe | 9 |
| North America | 22 |
| Elsewhere | 4 |
| | |
| Total interviewees | 35 |

*Note that sums do not add up to the total in 'primary employment/affiliation' and 'discipline' sections, as some participants fall into more than one category. For example, a number of academics also have founded and/or are employed at mCDR start-ups.

proposals on ocean climate intervention. We selected these registers as sources of potential interviewees, given the relatively advanced nature of the projects included in these databases. Convenience sampling involved identifying interviewees through two academic research projects in which the authors are participating, OceanNETs and Solid Carbon. This convenience sample helped us source additional detail regarding two ocean-based NETs of interest: (1) ocean alkalinity enhancement (OAE), and (2) offshore DACCS. Our convenience sampling also included snowball sampling, by asking interviewees for recommendations on others to interview. This approach made use of the connections present in the still relatively small mCDR community to increase the number of interviews conducted.

We conducted 35 interviews, each of which lasted between 40 and 90 minutes. Interviews were transcribed and coded using an open-ended approach, allowing themes to emerge from transcripts (Saldaña, 2016). Following an initial coding round, we returned to the codes to explore groupings of codes and describe the themes, narratives and patterns that emerged from these groupings. At this point, we coalesced codes into several primary categories, revealing the four main themes discussed here. The topics that came up were wide-ranging—from economic issues such as cost, to issues of durability, MRV, the role of government, to questions of moral hazard, safety, and uncertainty. Many of these were only referenced once or twice; many others did not represent value-laden issues with diverse viewpoints in ways that we could meaningfully analyse as social scientists. The themes that we discuss here represent some of the most frequently discussed topics, but they were not selected based on a simple frequency analysis. Rather, they were selected on the basis of a) their apparent function as organising ideas or concerns in expert appraisals; b) variability in the range of views expressed across the dataset; and c) their salience to current governance challenges. The results of this thematic analysis are presented in the following section.

## 3. Key themes in expert imaginaries of ocean-based CDR

We identify four salient themes, or tensions, in expert discourse on mCDR: (1) the role that 'naturalness' should play as a rubric for characterizing mCDR options; (2) the need to accelerate research and development activities in response to the climate crisis (and the implications of this acceleration for risk governance); (3) the significance of 'waste,' 'contamination' and 'pollution' as lenses to interpret mCDR and the trade-offs it imposes; and (4) a commitment to inclusive governance with an imprecise delineation of the publics, rightsholders and stakeholders whose views and interests should be considered in that process. We first illustrate each of these themes with material from the interviews, before discussing them in Section 4.

### *3.1. Nature as baseline and rhetorical resource*

Notions of 'naturalness' are a seemingly unavoidable reference point in discussions of mCDR options, with different approaches often described as 'enhancing' or 'accelerating' natural carbon cycles ("Ocean Visions | Catalyzing Solutions For Ocean Health," n.d.). The role of the oceans as the largest sink for atmospheric $CO_2$ provides the discursive starting point for many assessments of mCDR methods. GESAMP, for example, describes ocean-based CDR as interventions that "involve the enhancement of natural sinks" (pg. 17, Boyd and Vivian, 2019). The 2021 report of the U.S. National Academies on mCDR grounded its assessments in the role the oceans play as "a large natural reservoir for $CO_2$," where "natural ocean processes" already remove large amounts of anthropogenic $CO_2$ emissions, and includes numerous references to 'natural' carbon cycles as the relevant context of interpretation for new technological options (National Academies of Sciences Engineering and Medicine, 2021). In many proposed governance frameworks, individual mCDR approaches are classified on the basis of how well they mimic, hack, or capitalize on natural processes, leading to taxonomies where different options are placed along a linear spectrum, from the most 'natural' to the most 'technological' or 'engineered' (e.g., Lebling et al., 2022).

Our interviewees (ID#2, 3, 5, 11, 13, 14, 15, 16, 21, 23, 30, 32, 34, 35), echoed this framing repeatedly, but the criteria they used to determine where to place a particular mCDR option along the spectrum of naturalness were diverse, and often implicit. In general, interviewees were keen to emphasize similarities or affinities between processes already unfolding in nature and the mCDR approach they were investigating or invested in. Thus ocean alkalinization, for instance, was described by one interviewee (ID#2) as "mimicking nature," as it replicates a process (rock weathering) that nature "does all the time" (ID#34). This form of reasoning could be extended by analogy to essentially all proposed forms of mCDR. When discussing an ocean afforestation approach that involved artificial upwelling, for example, an interviewee (ID#12) commented that the approach could be considered "natural," since the mechanical process of pumping nutrient-rich seawater to the ocean surface mirrored the work that tree roots do to bring nutrients to its upper branches. Discussions of 'blue carbon' offered multiple examples of this interpretive flexibility. Often considered the most self-evidently 'natural' form of mCDR, the category has imprecise boundaries and can expand to encompass a wide variety of interventions. A recent McKinsey report, for example, includes within this category highly engineered operations, such as bailing and sinking seaweed to the ocean floor or improving the management of fisheries (Blue carbon: The potential of coastal and oceanic climate action, 2022). Indeed, as one of our interviewees (ID#11) put it, "blue carbon is in the eye of the beholder."

Underlying many attributions of naturalness was a shared perception that those options deemed to be most akin to natural processes would enjoy the greatest level of public and political support. Referring to ocean liming (a variety of ocean alkalinity enhancement), one interviewee (ID#35) commented that limestone originally comes from coral reefs and other forms of marine life, so "it comes from the ocean… maybe if you explain this then people will better understand [that] this is not something dangerous." Some interviewees commented on the perceived public preference for 'natural solutions' with a tinge of deprecation, nothing that everybody is "feel-good" (ID#25) or "warm and fuzzy" (#24) about approaches they can plausibly interpret as nature-based.

Although actions such as coastal ecosystem restoration were seen by many as a "no brainer" (ID#11), several of our interviewees raised objections to them on two fronts. First, some challenged the degree of naturalness of specific interventions, even when they closely mimick traditional conservation practices. Referring to the restoration of coastal ecosystems and to blue carbon more generally, one of our interviewees (ID#32) noted that these forms of mCDR will "always lead to changes in the system," and that, as a result, inevitably "induce winners and losers." Second, several respondents were eager to question whether the approaches considered most natural would be able to deliver the scale of removals required for climate stabilization, noting that the public tends to have a "misplaced faith" (ID#31) in them. A partial explanation for such misplaced faith, this same interviewee hypothesized, is the common conflation of carbon stocks and carbon removal potential, a misunderstanding that leads to exaggerating the role that 'natural' forms of removal can play in relation to global climate targets. Another interviewee (ID#34) claimed that "people default to preferring the natural option but then they don't necessarily consider things like: 'is that natural option scalable?'."

The implication running through these comments is that, even if the intervention in question closely tracks a naturally occurring process, the scale and/or rate of deployment necessary for climate stabilization will render virtually any approach deeply 'unnatural'. Ocean alkalinity enhancement was a common object of discussion in this context. Even if it is considered "broadly inspired by Earth's modulation of alkalinity on geological timescales," as the report of the U.S. National Academies put it (National Academies of Sciences Engineering and Medicine, 2021: 181), its use as a climate stabilization intervention means "that we [would be] escalating a process so many orders of magnitude beyond its natural occurrence" (ID#13) that our ability to anticipate its impacts would be severely limited. In discussing biomass (macroalgae) cultivation and sinking, another interviewee (ID#3) noted that any deployment of this mCDR option at scale would be radically different from anything occurring in nature. The sort of aquacultural intensification necessary to maximize $CO_2$ removal, they noted, has little to do with "working with nature," since it would involve species selection and management practices that do not resemble anything nature would be doing on its own.

The intrinsic flexibility of the category of 'natural' is compounded by the radical changes that oceans are undergoing as a result of human action. Many of our interviewees emphasized that climate change is creating deeply 'unnatural' oceans, and that this should influence our criteria of evaluation. One interviewee (ID#13) commented, for example, that concerns about mCDR modifying the ocean were "ironic," since ocean chemistry is already being heavily "manipulated" by the high concentration of greenhouse gases in the atmosphere and other forms of anthropogenic pollution. Ocean alkalinity enhancement, another interviewee (ID#3) noted, is essentially an attempt to "get the ocean back more towards its proper pH" (ID#3). From this perspective, all mCDR interventions, no matter the degree of human engineering involved, would represent actions that brings the oceans closer, in some key measure, to a state of pre-industrial 'naturalness.'

### *3.2. Climate urgency and research acceleration*

The urgency of the climate crisis and the need to accelerate research practices emerged as a second dominant theme in our interviews. Most of our interlocutors placed mCDR in the context of a rapidly changing climate and the pressing need to reduce accumulations of greenhouse gasses in the atmosphere. This scenario invests mCDR research with a clear sense of urgency, but interviewees responded to this urgency in different ways, and with varying implications for the organisation of research efforts.

Many interviewees who operate primarily in academic contexts (ID#1, 24, 27, 28, 30, 32, 33, 35), as well as those who combine roles in both academic and start-up ventures (ID#3, 4, 12, 14), commented critically on the pace of academic research, and on the limited scale at which academic researchers tend to think about key issues. As one (ID#12) commented, "Scientists tend to think in small scales, maybe except modelers, but… the issue of climate change and the approach that we need to implement to solve it… it is just so huge that it just escapes our comprehension." Academic research, several interviewees noted (ID#4, 30), operates according to the timelines of grant funding, and tends to proceed on decade-long horizons that are inadequate to the climate emergency. This contributes to what one interviewee (ID#35) described, pejoratively, as a culture of "responsive" research, by which they meant that scientists "never have to make hard decisions… They have to say yes or no to very specific types of research, but never in consideration of how that will affect our opportunities to mitigate climate change." Another interviewee (ID#28) contrasted what they perceived as the relaxed procedures of academic science—the tendency of academic scientists, as they put it, to "potter on and slowly produce something"—with the pace at which global warming is unfolding, which they described as akin to "being attached to the front of this huge rocket and being fired up." Interviewees involved in start-up companies also remarked repeatedly on the inadequacy of academic research modes, noting for example (ID#12) that the ability to fast-track research and produce evidence on shorter timelines was a pre-condition for attracting private investment.

The prospect of accelerating conventional research practices generated concern, however, among several interviewees, particularly those whose affiliation was with academic institutions—even despite their frustration with the pace of academia. Unfettered haste, they cautioned, could in fact slow down scientific progress: "the big worry is that… badly designed projects are run, they get lots of money, they have adverse impacts, and this sets [back] the possibilities for doing any of this stuff at scale"(ID#28). Several respondents (ID#11, 32, 33) alluded to past experiments in ocean fertilization as a cautionary example of how rushed field studies can generate a backlash that sets whole areas of legitimate research back for decades. Frequent calls to speed up research efforts, one of our interviewees (ID#30) argued, was primarily motivated by the large amounts of private and philanthropic funding suddenly flowing into this field, rather than by any change in the severity of the climate crisis or a clearer understanding of scientific priorities and knowledge gaps. As an interviewee (ID#35) put it: "Things have changed, so we have now more money than ideas." Another interviewee (ID#21) noted a connection between calls to accelerate research and the desire of many scientists to "catch up" after a "lost decade" of virtually no field research, now that experimental work on some of the most controversial approaches had been somewhat de-stigmatized:

> *"For many years I myself have had these conversations with our funders. For many years they came back saying that this is dirty research… [they did not want to fund it] as long as this hasn't been taken up strongly [elsewhere]… It wasn't really still until the [2018 IPCC special report on 1.5°C global warming] where it came out very clearly that we need these forms of carbon dioxide removal in order to achieve the climate goals. It wasn't until then that our funding agencies really opened doors for providing funding to support this kind of science."*

Discussions of the pace of research efforts were often framed in relation to arguments over 'precaution' or the 'precautionary principle.' Interviewees who emphasized the rapidly dwindling time horizon created by the climate crisis noted repeatedly that 'precaution' did not equal 'slowness,' but rather acceleration, in the service of preventing even more profound impacts on the oceans and the planet. By the same token, they questioned the idea that 'fast' research was inherently reckless or irresponsible. One interviewee (ID#4), for example, questioned the idea that "if you haven't been studying something for 15 years, then we don't know enough about it," and argued that the assumption that "good research must take decades" is one reason that field is not progressing adequately.

Arguments against a *pre*-cautionary understanding of prudence went in some cases further. Several interviewees argued against the very notion that, as one of them (ID#12) put it, "it is the duty of scientists to be…safeguards of the pristine ocean environment… and [that] we should not touch the ocean unless we're 100% sure that what we're going to do does not have any environmental impacts." This line of argument led this interviewee to reflect critically on the dispositions of some of their colleagues, pointing out, for example, a tendency to assume the inevitability of negative effects: "They don't even go and see if there are any environmental impacts. They just assume there will be some environmental impacts" (ID#12).

What does research *acceleration* mean in practice? Views on this issue were varied. One key area of discussion was the extent to which the gathering of evidence should proceed along the traditional linear progression, from laboratory or computational work towards progressively more ambitious and less controlled/contained field experiments and studies. Multiple interviewees (ID#5, 12, 35) pointed out that such a linear model was not appropriate to the urgency of the moment, nor to the vast number of scientific unknowns.

> *I know that a lot of researchers will start with simple lab experiments, that's cheap. You get results very quickly. They're nicely interpretable. You get them published quickly… But, the question is, how meaningful are these results when you want to understand complex ecosystems?"* (ID#5)

This interviewee argued for an inversion of the conventional sequence of research stages, starting with field studies to identify interactions of interest in natural systems and better parametrize models, then moving to contained facilities to delve more deeply into their characterization:

*"I would rather… start with the more complex field or field contained experiments with natural ecosystems, see what responses actually work out in this more complex environment and then go into the lab and try to understand in dedicated lab experiments what could [identify] the underlying mechanisms of those responses. Not each mechanism that you can tease out in the lab actually matters in a natural community. So, I would start from the more complex and then try to understand the underlying mechanism based on dedicated lab experiments rather than doing this huge amount of lab studies that, in the end, turned out not to be particularly relevant for natural ecosystems."*

For other interviewees, acceleration was rather of matter of *diversification*, of expanding the number of studies and increasing variation among them, so that future international assessments would not rely on an exceedingly small set of largely homogeneous trials. Referring specifically to ocean alkalinity enhancement, one of the interviewees (ID#32) expressed concern over the fact "that too small a set of experiments might randomly decide which option we are going to take," and advocated for a different model, in which studies addressing different environmental contexts and embodying greater variability of experimental designs would be running in parallel:

*"I think that's absolutely needed, to scale this up in more than one direction, but in parallel. To have many parallel efforts to get a better sampling of the statistics in the environment, and also the experimental setting, which we don't understand why it works sometimes and why it doesn't other times."*

These reflections on the pace and internal diversity of the field often segued into recommendations for improving research governance, but these recommendations rarely included specific proposals for institutional design. Most of them centred enhancing openness and transparency, with suggestions for putting more effort into "public communication" (ID#21), or creating stronger incentives "to report failed experiments" (ID#32).

### 3.3. Complex Materialities of mCDR

Although they were not included in our interview guide, a close analysis of the data reveals a recurrent discussion of issues relating to waste, contamination, and pollution (ID#2, 14, 15, 16, 26). Several interviewees explicitly framed mCDR as a form of waste management or waste disposal at planetary scale, removing excess carbon from the atmosphere and placing it in a safer location for long-term storage. Two researchers (IDs#15 and 16), who were working together on a new approach for marine biomass sinking, described their project as a 'natural' climate solution for a more efficient management of waste flows, using one form of waste (biomass produced in agricultural operations) to dispose of another form of waste (carbon accumulated in the atmosphere):

*"Oil used to be organic matter buried underground or under water for millions of years. And then we took it out and burned it… we're going to take it back to where oil was, kind of, created."*

In their view, presenting this form of mCDR as a way of closing (or reversing) the carbon cycle should increase public support. "That story resonates better with people rather than just, 'hey, we're taking agricultural waste and we're throwing it in the sea'." There may also be specific applications of mCDR with a near-term dividend in terms of bioremediation – for example sinking seaweed from the Great Atlantic Sargassum belt. Cleaning up this belt, created in part by terrestrial runoff, might generate multiple benefits, in the form of increased economic income from tourism, protection of wildlife, and local health improvements.

Although the idea of putting carbon back in its rightful place was appealing to some of our interviewees, others (ID#2, 13, 14, 31) drew attention to mCDR as a potential source of new forms of contamination and pollution. Several discussions of ocean alkalinity enhancement, for example (ID#13), included a consideration of the waste and pollution associated with large increases in mineral extraction, and the grinding, transportation, or calcination of vast amounts of alkaline materials. Electrochemical approaches for alkalinity production might not require an expansion of mining activities, but they would involve the use of large quantities of chemicals and generate volumes of hazardous by-products, such as hydrochloric acid or chlorine gas, far in excess of existing global demand. These aspects are highlighted in several of our interviews, and increasingly in the fast-growing literature on OAE (Bach et al., 2019; Fakhraee et al., 2022; Guo et al., 2022; Nawaz et al., 2023; Renforth and Henderson, 2017). Other mCDR approaches present comparable challenges. Artificial upwelling and iron fertilization, for example, could generate harmful algal blooms that release toxicants harmful for benthic ecosystems and human communities (ID#s13, 17).

In this context, one interviewee (ID#2) emphasized the relevance of thinking systemically about the inputs and outputs of different CDR approaches, suggesting a sort of future circular economy of CDR that could become apparent once large demonstration projects came into operation. For example, acid by-products generated by electrochemical processes could be deployed to assist in enhanced rock weathering, or to improve injection of carbon dioxide into rock for geological storage. Or brines obtained in the course of geological carbon storage could be used to produce alkalinity for ocean alkalinisation projects. As this interviewee described, right now each company or project "is dealing usually with one aspect of [the carbonate silicate cycle]. And so they each have a co-product or a by-product… they will have to end up trading those products." This sort of systems thinking offered a fruitful space to imagine future synergies and complementarities between different forms of CDR, and indeed between CDR and other aspects of decarbonization.

### 3.4. Inclusive Governance and mCDR publics

A fourth theme that emerges from our interviews is the importance of obtaining public support and political buy-in for the development of mCDR approaches. This view underpinned expert discussions of emerging governance arrangements, expressed in the recognition of the need to engage a range of different groups in decisions on mCDR. Difficulties arose, however, when interviewees were pressed to identify the specific 'publics' who might be affected by their work and should therefore have a say in its governance. In the interviews, we asked our interlocutors who they felt responsible towards in the design or conduct of their research/work, or what sense of responsibility guided their work. Most interviewees identified future generations (ID#12, 20), or people affected by climate change (ID#14), but more granular characterizations of relevant publics or communities were rare.

A degree of vagueness over the identity of mCDR 'stakeholders' or 'rightsholders' is likely a function of the early-stage nature of the field, and of the central role that models with low regional resolution continue to play in the scientific assessments of technical options (Lezaun, 2021), not to mention the (minimal) degree of social science involved thus far in the space. In our interviews, when experts discussed 'governance' they often referred to national or international policy (e.g., the London Convention and Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter), rather than to specific constituencies to whom they imagine themselves as being accountable. One interviewee (ID#17) flagged the lack of a more fine-grained characterization of mCDR publics as problematic from an environmental justice perspective. The risks and benefits of these interventions will be unevenly distributed, they noted, and it is critical that vulnerable and disadvantaged groups are identified and involved early in the process so as to avoid entrenching existing inequities. As they explained:

*"If you have something and that goes wrong and you're risking a subsistence livelihood community downstream that could be at risk, that's very different to a downstream at- risk [facility] being like … an industrial port that you could just scrape the stuff out the way and keep going."*

Notably, interviewees with experience in place-based research were generally in a better position to articulate a notion of responsibility in relation to specific groups. One interviewee (ID#3) working on biomass sinking listed as a key stakeholder the residents of a coastal area affected by seaweed overgrowth due to ocean acidification or agricultural runoff. Another (ID#4) cited local communities they had identified in the region of a planned field trial in ocean alkalinization in a small and developing island-state. In these instances, interviewees identified constituencies that stood to benefit directly from a proposed intervention, over and above the general provision of a global public good in the form of a reduction in the level of greenhouse gases in the atmosphere.

A notable example (ID#23) illustrated further the impact of place-based research and on-the-ground activities on the ability to identify 'subjects of responsibility'. This interviewee was involved in an exploratory macroalgae cultivation project and had negotiated access to a particular coastal site with an Indigenous group that holds sovereign rights over those territories. They spoke at length about the importance of "working with communities and… incorporating their thoughts and opinions into the process and having some sort of a community giveback program," and offered a detailed consideration of governance arrangements (in relation, for example, to the ownership of the equipment used to grow and sink seaweed). Indigenous groups, this interviewee noted, are "rights-entitled holders to the water and they are the world's best partners if you want… to do good for the people that live on the coastline and ultimately… beyond."

## 4. Discussion

These four tensions orient expert understandings of mCDR but are rarely articulated explicitly in technical appraisals. They reflect a set of values and judgements—on the relevance of natural processes of carbon removal and sequestration, the appropriate pace and sequencing of research and development, the distribution of the material by-products of carbon dioxide removal, or the role of specific actors in governance processes—that often remain implicit in the design of research projects or in discussions of their outcomes. They provide key entry points, however, for defining the parameters of responsible mCDR, and represent themes where expert and lay understandings are mutually informed. In this section, we reflect further on these four tensions, with a view towards articulating them for broader public debate and governance.

### *4.1. The need for more reflexive discussion of 'naturalness' in mCDR research*

A public preference for climate interventions that can be plausibly characterized as 'natural' is well documented (Bertram and Merk, 2020; Corner and Pidgeon, 2015). As we saw, 'nature' is also a common rhetorical resource in expert assessments, but the meaning of the term is seldom specified, leaving ample room for fluid taxonomies and contested attributions (Nawaz and Satterfield, 2022; Rayner and Heyward, 2013). As Osaka and Bellamy point out, describing some climate 'solutions' as more natural than others serves primarily to draw a distinction between the environmental and the social dimensions of the intervention in question, impoverishing the assessment of what are, in fact, complex socio-technical arrangements (Bellamy and Osaka, 2019). Highly divergent visions of CDR coexist in relation to those approaches most commonly described as 'nature-based'. Low et al (2022), for example, distinguish between a *Big Nature* pathway, characterized by large biomass monocultures, and a *Small Nature* pathway that prioritizes the preservation of a diverse set of carbon stocks and the achievement of co-benefits for local development.

Given the salience of this vocabulary, and since notions of naturalness are highly contingent on culturally specific assumptions, it is essential that expert discussions of mCDR articulate the scientific, aesthetic, or political criteria that underpin attributions of naturalness, so that the classification of one approach as more or less natural than others can be subject to reasoned debate, both amongst experts and the broader public.

Furthermore, our interviews reveal a rich set of reflections within the mCDR community on the value of 'naturalness' in a world irrevocably transformed by climate change. Even when they peppered their discourse with references to natural carbon cycles or processes that nature 'does all the time,' interviewees were generally clear-eyed about the descriptive limitations of this lexicon (particularly when they discussed mCDR options other than the ones they were pursuing). Their use of terms like 'natural' or 'nature-based' was often strategic, moreover, driven by the perception that the public is more likely to support interventions deemed to replicate or restore natural processes.

In their use of these terms, then, mCDR experts appear to be responding to what they perceive to be an entrenched nature/society dichotomy in public perception, rather than following a consistent set of principles of their own. All mCDR approaches imply profound human-driven alterations in marine ecosystems, undertaken for the purpose of mitigating anthropogenic risks. Although this is often couched in terms of protecting the oceans or the planet, there is no obvious way of characterizing any of the proposed interventions as a means of reverting to a state of 'pristine' or 'pre-industrial' oceanic nature.

If a return to a previous historical baseline is no longer a viable option, which values or qualities should be prioritized in the creation of the oceans of the future? How might experts and policymakers justify their choices? Scholarship on other Anthopocenic practices, such as novel conservation approaches, highlight the dynamic and non-linear aspects of ecosystems and landscapes, and the increasing unfeasibility of targeting historical precedents in a changing climate (Clement and Standish, 2018; Higgs et al., 2014; Hobbs et al., 2009). A recent survey of biodiversity experts found that roughly a third viewed historical baselines as less relevant, and roughly half viewed them as likely to be less relevant in the future (Clement et al., 2023). The field of mCDR may benefit from considering what other goals might be prioritized if returning the industrial to pre-industrial or even contemporary baselines is no longer an option.

This is not to say that letting go of ideas of pristine nature or historical precedent will be easy. Recent studies of scientists' relationship to a changing ocean suggest that, no matter how flexibility they are applied, conceptions of 'naturalness' anchor moral imaginaries of responsibility. In her interviews with scientists working on coral death and restoration, Braverman (2018) identifies a "pendulum" or "bipolar oscillation" between the extremes of hope and despair, and notes that this polarity "maps onto the coral scientists' internal debates over the naturalness and pristineness of coral reefs and about the appropriate levels of intervention in their ecosystems."

Public debate on mCDR capabilities is thus ripe for a more reflexive consideration of the meaning of 'natural' and 'naturalness,' in the sense or reflexivity originally proposed by Wynne (1993): a more systematic exploration of the prior commitments that motivate use or attribution of these categories. When they remain implicit or unexamined, these terms bias assessment and obscure the inevitable trade-offs that will arise with the deployment of mCDR at scale. When, instead, experts help clarify the different criteria that can be used to give these keywords meaning, a set of difficult but useful questions arise (Thomas et al., 2018).

### *4.2. Paradoxes of cautious acceleration*

The climate crisis provides a hegemonic frame to interpret the pace of mCDR research. In our interviews, it facilitated frequent lamentations about 'lost' time, and motivated calls to radically accelerate research efforts. These calls do not originate exclusively in expert communities or policy institutions. The ocean fertilisation activities carried out off the islands of Haida Gwaii in 2012, for example, mentioned by some of our interviewees as an example of "rushed" or ill-conceived research, were supported by some Indigenous institutions that saw in them a way of addressing environmental degradation (depletion of salmon stocks), in a context of political exclusion from the management of local natural resources (Buck, 2018; Gannon and Hulme, 2018).

'Acceleration' is an ambiguous term, however. As our interviews suggest, it can mean a rapid expansion of research efforts under conventional forms of science organisation (e.g., a larger and more diverse set of studies running in parallel along a linear model of innovation). But it can also imply a radical departure from the traditional sequences of evidence-building (e.g., moving up field experiments, or even potentially small-scale deployments, to fast-track in situ evaluation of efficacy and impacts).

Each of these two approaches carries a different set of implications for risk and science governance. Our interviewees rarely explored these implications in detail, but many did reflect on the compatibility of acceleration with traditional notions of 'precaution.' They often echoed challenges to the precautionary principle, and to the assumption that 'cautious' is an inherently more responsible approach in matters of risk management (Clarke, 2010; Dana, 2002; Engelhardt and Jotterand, 2004; Origgi, 2014; Steel, 2013). Morrow et al. (2020) for example, argue that "[r]obust, flexible, precautionary climate policy requires recognizing that, despite our best-laid plans, future generations might benefit from large-scale CDR in the second half of this century." One would be far more 'cautious,' the argument goes, by acknowledging the medium-term need for large-scale CDR and planning accordingly, ensuring that the evidence needed to prove or disprove different technologies is available as soon as possible. Jebari et al. (2021) have offered a related argument, suggesting that in a context where all options are understood as having risks it is necessary to fully explore each trajectory—rather than assume that the default of 'no action' is by definition the safest course.

Rethinking the idea of prudence that is built into the precautionary principle does not imply *carte blanche* for indiscriminate technological development, however. Guardrails might be put in place to ensure that the risks taken are proportionate to the harm and uncertainty expected (Steel, 2013). Others have noted that cognitive biases also affect the implementation of alternatives to the precautionary principle, and that these biases need to be reconciled via alternative decision-making approaches (Clarke, 2010; Dana, 2002). Many of these arguments seek to push past the concerns over 'moral hazard' that dominated earlier discussions on geoengineering, or they invert the argument altogether by suggesting that a misplaced hope in decarbonisation efforts is slowing down the development of much-needed CDR capabilities (Global Ocean Health, n.d.).

And yet, calls to 'accelerate' scientific efforts often assume that the direction of travel of the endeavour in question is well understood and can be maintained throughout the process of inquiry; that acceleration is simply a matter of 'compressing' a given timeline, so that the evidence needed to reach a well-informed decision is produced earlier. In practice, however, accelerating research means speeding up the generation of unexpected findings and ambiguous data, or bringing forward the realization that certain study designs and experimental set-ups were not up to the task. Science rarely travels on a straight road, and when you accelerate it can become increasingly unclear where you are actually going. Some forms of acceleration inhibit the ability of the research community to correct course in time to prevent negative outcomes, but the relationship between the pace of research activities and the ability to remain flexible and responsive to surprising observations is not linear. Plenty of 'slow' science proceeds rigidly on a straight path, with little room to accommodate or even recognize the anomalies it encounters along the way. Ensuring that moments of pause and reflection are built into research pathways requires appropriate governance architectures, particularly when we adopt unconventional models of evidence-building (Buck and Nicholson 2023).

The challenge is compounded here by the need to design interdisciplinary research programs to assess the wide range of issues at stake (Nawaz et al., 2023a). Different disciplines relate differently to calls to 'speed up' their own research practices. Furthermore, when, as with many mCDR field experiments, scientific investigations are embedded in complex processes of public outreach and consultation, pursuing a compressed research timeline can undermine efforts to establish broad public legitimacy for the intervention. From the perspective of the publics that take an interest in mCDR research and development, an 'accelerated' project might appear as simply hurried, particularly in a field is still contending with fundamental uncertainties regarding key aspects of the approaches under consideration.

Finally, and more generally, participants in mCDR projects need to be wary of the justice implications of any research conducted under the banner of a 'crisis' or 'emergency' (Nawaz and Satterfield, 2024). Declarations of 'emergency' have often been used to justify harms to disadvantaged groups, and arguments for expedited research need to be attentive to the real possibility that the burden of risk may once again be shifted onto marginalized communities or territories (Carton and Edstedt, 2021; Whyte, 2020).

### 4.3. Matter out of place

It is not surprising that several of our interviewees were drawn to the idea of mCDR as a form of planetary waste disposal. The language of 'cleaning' or 'scrubbing' the skies has a long pedigree in discussions of CDR, and the oceans have been increasingly valorised as a 'sink' essential to any prospects of 'cleaning up carbon pollution' in the atmosphere (Ocean Visions, 2023b). Conceptualizations of CDR as waste management fit neatly with new 'carbon management' strategies in the petrochemical sector, and other emerging visions of a circular (fossil) carbon economy (Buck, 2020; Palm et al., 2024). And there might be ways in which mCDR could be (at least in the short term) part of bioremediation and waste management efforts, as in the case of the Great Atlantic Sargassum belt mentioned earlier.

Yet the language of waste disposal obscures the fact that mCDR will also generate a set of contaminants, residues and material by-products that complicate any ideal of circularity or safe relocation. Even if we imagine excess concentrations of greenhouse gases in the atmosphere as 'matter out of place'—to riff on Mary Douglas' classic definition of 'dirt'—mCDR may will never put it *back* in its rightful place. Rather (and in the best scenario) it will reconfigure and displace carbon matter to locations where its contribution to global warming will be diminished. mCDR might be understood as an industrial effort that, in order to offset the effects of past industrial activities, introduces a new range of pollution risks and waste management challenges.

These issues will come increasingly into focus as mCDR moves from a research or demonstration stage to the building of new industrial infrastructures. Life-cycle analysis of different mCDR options illuminates a range of material inputs and outputs, complicating any straightforward understanding of mCDR as a matter of carbon disposal. For example, mineral-based forms of ocean alkalinization will likely be associated with a significant expansion of mining activities (and mine tailings), the potential introduction of trace elements in marine ecosystems, or an increase in the volume of hazardous by-products (including the greenhouse gases generated in the sourcing, processing, and dissemination of alkaline materials). In the case of biomass sinking, relevant constituencies might construe a wide range of material inputs and outputs might as a form of waste or pollution, from the contaminants present in aquaculture nutrients to the alterations that sunk seaweed might provoke in deep-sea biodiversity, or the gases released through biomass decomposition. The concept of a 'negative emissions technology' focuses on a net reduction of carbon dioxide in the atmosphere, but the processes set in motion to achieve this goal redistribute a much later set of material entities, and create multiple axes of potential contamination.

This aspect of mCDR is not a fatal flaw, but it does need to be recognized, managed, and planned for. Not least, much more attention is needed to ensure that the material inputs and outputs of mCDR operations do not become a pressing environmental justice concern, given the scale of removals anticipated in most climate stabilization scenarios. Historically, marginalized groups have borne the brunt of the negative impacts of waste disposal, be they via waste incinerators, landfills, hazardous waste sites, or otherwise (e.g., Lejano and Iseki, 2001; Martuzzi et al., 2010; Mohai et al., 2009; Yandle and Burton, 1996). The experience of other climate transitions, notably the development of large-scale renewal energy infrastructures, indicates the importance of informing policy decisions with an appreciation of the full life cycle of the relevant materials, and the new and often unexpected hazards they introduce (Mulvaney, 2020). We must ensure that policy decisions fully attend to these materialities, initially through a rigorous life-cycle analysis of proposed mCDR interventions (Grubert, 2021). Additionally, it will be essential to carefully consider how future waste management might be structured, including the implications of these possible management regimes for the most vulnerable communities.

### *4.4. Research as a public-generating intervention*

Our interviews suggest a desire on the part of experts to identify and engage relevant stakeholders as part of the 'responsible' conduct of mCDR research. This is often a requirement of research funding bodies, and is leading to the design of public consultation exercises run in anticipation or alongside field activities. Our interviews also showcased, however, the difficulty of moving beyond generic framings of the relevant audiences or constituencies. The difficulty emerges partly from the fact that, until recently, expert imaginaries of mCDR have often been planetary in scope, and reliant on simulations that offer little insight into potential participants in governance processes (Lezaun, 2021).

This trend reinforces the tendency in many quarters to conceive of marine or oceanic spaces as vast and empty, a sort of *terra nullius* unburdened by the kind of contestation that accompanies radical changes in land use (Steinberg, 2001). Too often marine environments have been assumed to be devoid of social actors and relations and, as such, 'easier' to manage from the perspective of obtaining a 'social license' to operate: Industrial infrastructures are offshored in the hope of less 'NIMBY' opposition (Mabon et al., 2014; van der Zwaan and Gerlagh, 2016), and the assumption of marine spaces as socially empty continues to frame planning decisions on the siting of activities such as wind energy generation, carbon capture and storage, or deep-sea mining (Childs, 2020). The resulting histories of erasure—including of marginalized groups such as Indigenous communities and actors in the global South—offer a cautionary tale for the mCDR community if it hopes to avoid the cycles of exploitation and resistance that often accompany offshore extractive activities. Even when due attention is paid to coastal communities, Indigenous groups, or island-dwelling nations, there is still a tendency amongst some expert groups to overlook the full spectrum of impacts to those who rely on marine environments for their livelihood and cultural reproduction (Alaimo, 2020; Ingersoll, 2016; Taitingfong, 2020).

Our interviews, as well as our own experience carrying out public engagement activities alongside outdoor experiments in ocean alkalinization, suggest some initial practical ways forward. As the field expands beyond modelling and laboratory studies to include a variety of field research practices, the site-specific nature of these activities creates opportunities to identify and engage a diverse array of local constituencies. Discussions with actors that are geographically, economically, or emotionally close to sites of experimentation quickly exceed the narrow framing of most mCDR imaginaries, even moving beyond climate change as the primary concern, to encompass broader questions of social and environmental justice tied to longer histories of resource exploitation, environmental degradation, and political conflict. The cases discussed earlier of Indigenous sovereignty and ownership in a seaweed cultivation project, or the distinct implications of siting an experiment in ocean alkalinization in a developing island-state, exemplify how experimental mCDR research might help broaden our definition of relevant publics and enrich our understandings of the experiences that bear on the social appraisal of mCDR.

This broadening is not an inevitability, however. It requires harnessing place-based small-scale and experimental natural science research to leverage interdisciplinary collaborations, including with social scientists who can understand the communities potentially affected by mCDR (Nawaz et al., 2023a). Carton et al. (2020) have noted how the marginalization and exclusion of social science from CDR research can exacerbate policy failures, not least by ignoring long histories of carbon sequestration that could teach many important lessons about so-called 'novel' or 'emerging' technologies. Will mCDR enrich local economies, or will it destabilize them? Will they incur trade-offs with local food production or create territorial dispossession, rights abuses, conflict, and violence in the same way that interventions to manage land-based carbon sinks have done? Do local communities stand to benefit directly from removals, or will windfalls cycle back to actors and institutions in the global North? Will mCDR disincentivize working towards other non-carbon goals, such as human development or biodiversity-related outcomes? And, last but not least, who should be considered 'affected' by interventions that unfold in the high seas or in the deep ocean? These and other questions are essential to determine whether and how mCDR might deliver a climatic public good in harmony with other human and non-human development goals.

## 5. Conclusions

This paper has discussed four key themes of expert imaginaries on mCDR, highlighting tensions that merit greater reflexivity and more explicit articulation in public debate and governance initiatives. Our examination of these tensions leaves us with a number of outstanding questions. (1) If we acknowledge that mCDR cannot return oceans to a pristine or natural state, and that it inevitably introduces significant changes in marine environments, how much change to the oceans is 'too much'? (2) If we must urgently develop an appropriate knowledge base to decide on mCDR deployment, how do we ensure that research acceleration does not occur to the detriment of understanding the full range of impacts and involving affected groups? (3) Even if we conceive of mCDR as a form of planetary waste management, how do we ensure adequate attention to understanding and mapping the material impacts and byproducts that it will generate, and what mechanisms could prevent burdening vulnerable communities with these new environmental harms? (4) Finally, who should 'count' as a relevant public for mCDR projects, and what should be the manner of their involvement in governance processes?

None of these questions can be 'resolved' simply by expanding empirical research efforts, but they can be formulated with greater precision, and in ways that allow a fruitful dialogue among experts, and between them and the larger public. Consensus on any of these four issues is unlikely, given that positions are rooted in deeply set value judgments on matters that exceed scientific logic; our study suggests a significant heterogeneity of views among experts, and this heterogeneity will only increase as a greater number (and a more diverse set) of experts, stakeholders and rightsholders participate in mCDR research and development efforts. Yet exploring mCDR options in full, and in public, makes untenable the sort of 'trade-off denialism' (Gerrard, 2022) that currently characterizes many arguments on the subject, and on climate transitions more generally. When mCDR is brought 'down to earth' (Clery et al., 2021), and the complex choices it entails come into view, a more realistic grappling with the consequences of this sea change become possible.

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## CRediT authorship contribution statement

**Sara Nawaz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Javier Lezaun:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2024.102806.

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