Seeking natural analogs to fast-forward the assessment of marine CO_2 removal

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Mitigating global climate change will require gigaton-scale carbon dioxide removal (CDR) as a supplement to rapid emissions reduction. The oceans cover 71% of the Earth surface and have the potential to provide much of the required CDR. However, none of the proposed marine CDR (mCDR) methods is sufficiently well understood to determine their real-world efficiency and environmental side effects. Here, we argue that using natural mCDR analogs should become the third interconnecting pillar in the mCDR assessment as they bridge the gap between numerical simulations (i.e., large scale/reduced complexity) and experimental studies (i.e., small scale/high complexity). Natural mCDR analogs occur at no cost, can provide a wealth of data to inform mCDR, and do not require legal permission or social license for their study. We propose four simple criteria to identify particularly useful analogs: 1) large scale, 2) abruptness of perturbation, 3) availability of unperturbed control sites, and 4) reoccurrence. Based on these criteria, we highlight four examples: 1) equatorial upwelling as a natural analog for artificial upwelling, 2) downstream of Kerguelen Island for ocean iron fertilization, 3) the Black and Caspian Seas for ocean alkalinity enhancement, and 4) the Great Atlantic *Sargassum* Belt for ocean afforestation. These natural analogs provide a reality check for experimental assessments and numerical modeling of mCDR. Ultimately, projections of mCDR efficacy and sustainability supported by observations from natural analogs will provide the real-world context for the public debate and will facilitate political decisions on mCDR implementation. We anticipate that a rigorous investigation of natural analogs will fast-forward the urgently needed assessment of mCDR.

negative emissions | artificial upwelling | ocean iron fertilization | ocean alkalinity enhancement | ocean afforestation

The Value of Natural Analogs for Research on Marine CO_2 Removal

It is becoming increasingly evident that atmospheric CO_2 removal (CDR) will be needed to keep global warming well below 2 °C (1). Integrated assessment modeling suggests that CDR must be initiated in the 2020s and quickly be accelerated to remove ~100 to 1,000 gigatons CO_2 until 2100 (2). These astronomical CDR requirements are unlikely to be met by a single "silver bullet," but more likely to be achieved with a portfolio of terrestrial and marine methods (3). However, uncertainties around CDR feasibility, costs, and acceptability are often too large to decide whether their deployment is both effective and safe (4). Uncertainties are particularly pronounced for marine CDR (mCDR) methods, as evidenced by a recent report on marine geoengineering, which concluded that none of the proposed mCDR methods can be scientifically assessed due to major knowledge gaps (5). Thus, one emerging priority for marine research in the 2020s is to provide this missing knowledge and narrow down uncertainties to the extent that qualified policy decisions regarding the implementation of mCDR become possible.

A range of mCDR methods have been proposed to date (5). Some of them build upon chemical and biological processes to draw CO_2 out of the atmosphere, while concurrently using the oceans as a long-term carbon depository (e.g., ocean iron fertilization). Others may only exploit one of these two functions (e.g., terrestrial biomass dumping in the oceans). Key questions in the assessment of mCDR are: 1) Can proposed methods effectively counteract climate change? 2) Are they associated with positive and/or negative side effects for the Earth System? Essential tools to address these questions are laboratory- and field-based experiments, as well as

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numerical model simulations. Experiments provide detailed insights into complex processes and provide direct comparison with control environments not perturbed by the mCDR treatment (6–8). However, experiments are short term (mostly days to weeks) and conducted mainly in the laboratory, occasionally under enclosed field conditions, and very rarely in the open ocean at the mesoscale (Fig. 1). Thus, they fall far short of the spatiotemporal scales envisioned for the eventual deployment of climate relevant mCDR (Fig. 1). Models enable simulations at such deployment scales but they are simplifications of reality and can miss important feedbacks in the Earth System (9).

A potent way to interlink advantages provided by both experiments and modeling is the in-depth investigation of suitable large-scale Earth System phenomena that represent natural analogs for mCDR methods (Fig. 2). These natural analogs provide the complexity of the real world at a scale that is relevant for the future deployment of mCDR. While no natural analog can completely represent a proposed mCDR method, key components of the analog resembling those of the mCDR method can be utilized to inform and validate numerical models (Fig. 2). Likewise, natural analogs can be employed to investigate whether observations made during smaller-scale experiments reoccur on the larger scale, which adds robustness and relevance to upscaling such findings (Fig. 2). Thus, comprehensive integration of natural analogs into the assessment of mCDR methods can enhance both numerical and experimental approaches (Fig. 2).

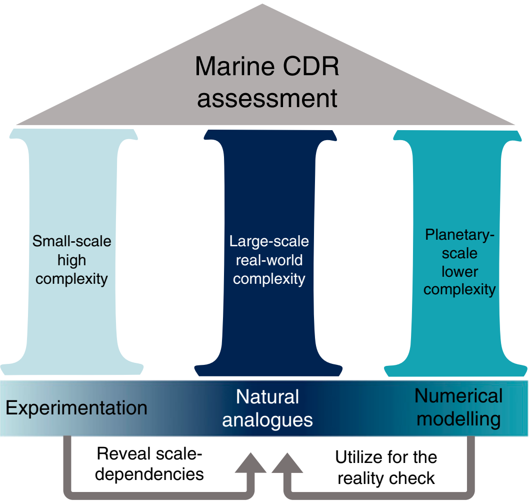

Fig. 2. **The proposed three pillars, and their interplay, for the scientific assessment of mCDR. Real-world experimentation and numerical modeling are currently the most important and widely considered approaches. We argue that the application of natural analogs for envisioned mCDR approaches should become the central, interconnecting pillar that can help to reveal scale dependencies of experimental findings and can provide reality checks for modeling. The figure illustrates the three scientific approaches for the mCDR assessment as equally large pillars but we note that the suitability of each approach may vary among different mCDR methods.**

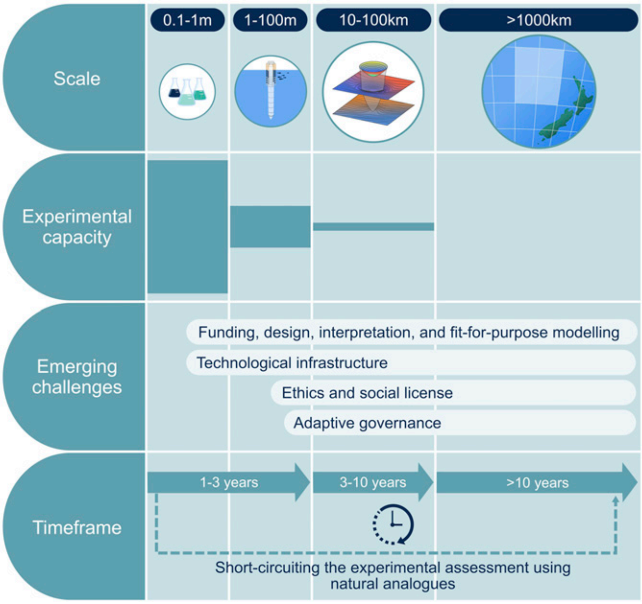

Fig. 1. **Temporal and spatial scales of the experimental mCDR assessment. The top panel shows the progression of the relevant scales of the experimental assessment. The second panel indicates the available experimental capacity at each scale, with the majority at laboratory scale, some at enclosed field scale, very little to none at mesoscale field trials, and no capacity at the scale envisioned for the deployment of mCDR. The third panel indicates some key challenges that emerge with the need for upscaling. The bottom panel illustrates estimates of the approximate time frame, at which experimentation at each scale may be achievable. The 3 to 10 y to transition from laboratory and field enclosed, to mesoscale unenclosed studies is based on that observed for OIF research (see main text for details), but may vary across the diverse range of mCDR methods, many of which are still in their infancy (5). This caveat will also apply to the >10-y estimate for upscaling pilot studies toward deployment. Natural analogs provide a potential short-circuit to studying mCDR methods at deployment scale.**

Next to augmenting the scientific toolbox, natural analogs also provide a range of practical and logistical benefits. They are comparatively cheap to study using widely employed observational infrastructure (e.g., satellites, drones, robotic profiling floats). In many cases, these diverse observational datasets are already available and can be readily repurposed for the mCDR assessment (10, 11). Furthermore, using natural analogs to assess mCDR will rarely require legal or social approval. Thus, the application of natural analogs offers major advantages over large-scale field trials, which would be unlikely to receive necessary approval and funding without prior supporting evidence of the effectiveness and sustainability of the tested mCDR approach (12).

Assembling all necessary requirements before initiating large-scale field trials will likely take at least 3 to 10 y (Fig. 1). Such assembly requires numerical simulations, laboratory-based sensitivity studies, enclosed and then unenclosed field experiments, technological developments, as well as ongoing legal and public consultation (Fig. 1). One example showcasing this time frame is the research trajectory into the fundamental role of iron in limiting both oceanic primary production and carbon sequestration. Small-scale experiments and technological developments commenced in the 1980s and carried on until enough knowledge was assembled to initiate the first of 13 mesoscale iron fertilization experiments from 1993 to 2009 (13, 14). These mesoscale experiments were fundamental science on iron limitation and, at least in the 1990s, were not planned or executed under the controversies around the topic, which evolved later (15). Presently, mCDR is becoming increasingly controversial so that assembling the necessary requirements for large-scale field studies may take even longer (16). In this contentious setting, natural analogs can provide the ability to short-circuit the pathway toward the large-scale field assessment (Fig. 1).

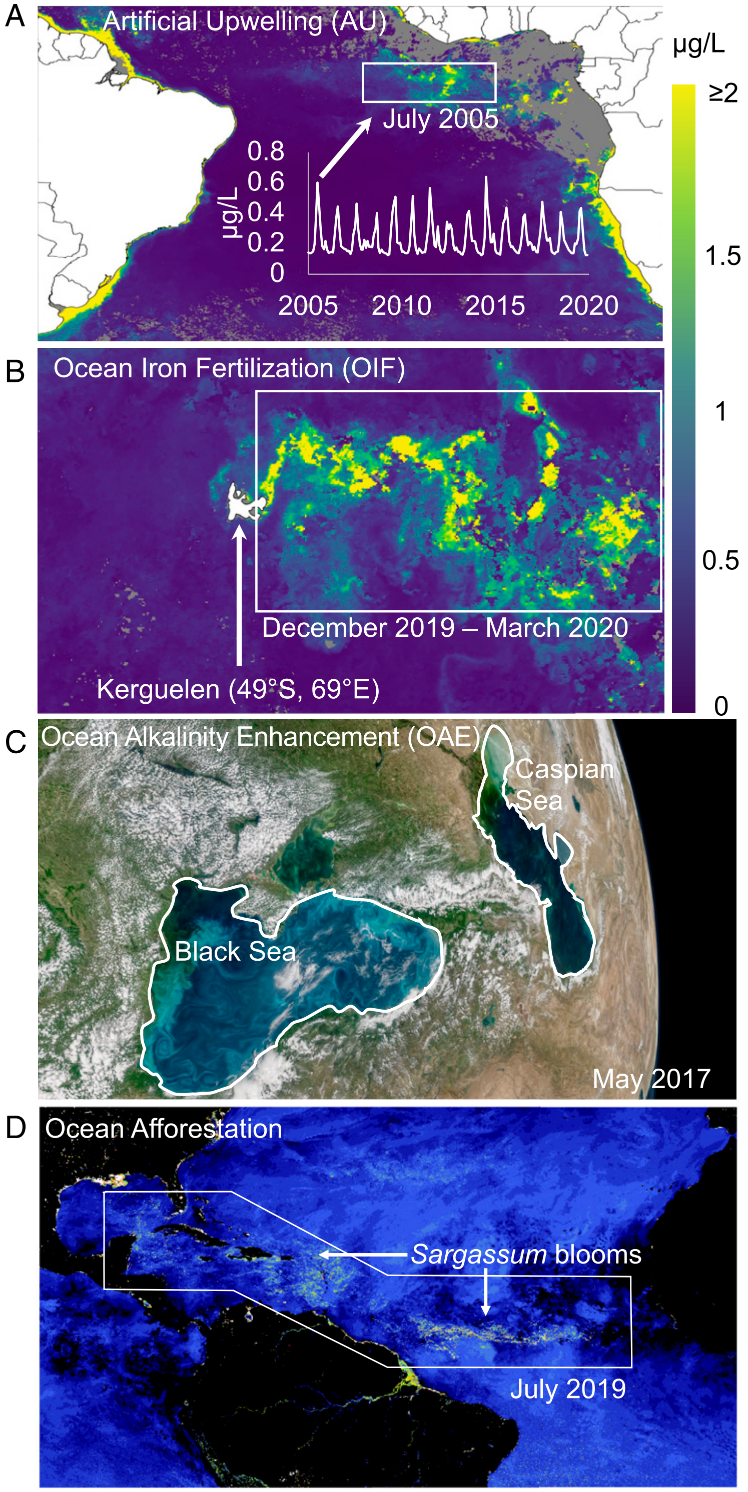

Fig. 3. Examples of natural mCDR analogs on Earth. (*A*) Equatorial upwelling in the Atlantic (marked with the white box) occurs periodically in boreal summer and perturbs the oligotrophic surface ocean with nutrients from below. Shown here are satellite-derived chlorophyll a concentrations for July 2005. The *Inset* shows chlorophyll a averages over the area marked with the white box (72). (*B*) Natural iron fertilization downstream of Kerguelen in the Indian sector of the Southern Ocean. Abrupt OIF occurs when eastward flowing water passes the island, entraining iron and stimulating blooms that spin off downstream. Satellite chlorophyll a averaged from December 1, 2019 to March 1, 2020 (73). Please note that *A* and *B* share the same color scale. The 4-km resolution chlorophyll a data were captured by using the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite and downloaded from the Giovanni online data system, developed, and maintained by the NASA GES DISC. (*C*) The Black and Caspian Seas in Eurasia have 1.4- and 1.7-fold higher alkalinity than the average surface ocean, making them useful end members for a highly alkalinity perturbed future ocean. The data for this satellite image was captured by MODIS-Aqua. Image credit: NASA/Norman Kuring. (*D*) Satellite image of floating seaweeds of the genus *Sargassum* bloom in (sub)tropical Atlantic in July 2019, recorded with the Ocean and Land Color Imager on the Sentinel-3A satellite of the European Space Agency (74). Blooms occur in the open ocean, making them useful natural analogs for ocean afforestation. Image credit: European Space Agency/Jim Gower.

Support for advocating mCDR analogs comes from research on solar radiation management (SRM) with stratospheric aerosol injection. The understanding of the benefits and challenges of SRM has made rapid progress by studying the 1991 Mt. Pinatubo volcanic eruption (17, 18). This analog revealed that aerosol SRM can transiently cool the global climate but at the cost of major side effects, such as shifts in the global hydrological cycle, leading to drought (19, 20). As a consequence, knowledge and confidence in both the SRM effectiveness along with the co-occurrence of major environmental side effects appears to be relatively high (20), even though the Pinatubo analog is not identical to aerosol SRM approaches (18).

In this Perspective, we argue that such rapid knowledge and confidence gains through rigorous investigation of a natural analog could also be achieved for research into multiple mCDR methods. We determine four criteria to define particularly useful natural analogs, provide examples, and discuss their value beyond the scientific assessment.

Four Criteria to Identify Valuable Natural Analogs

Large Scale. Natural analogs of any size can be useful to gain insights on certain aspects of mCDR functioning. Hence, their particular value is defined primarily by the individual research question being addressed. However, the uniqueness of natural analogs, which distinguishes them from experimental approaches, is their potential to extend >>100,000 km^2. It is unlikely that an mCDR experiment at such a scale will be conducted before political decisions on their deployment are made, because such an experiment would already constitute a deployment (9). This is a dilemma, since real-world data for climate-relevant deployment of mCDR methods will be needed ultimately to fully evaluate them. If no such data become available, then there is a risk of missing nonlinear relationships that exist between the scale of mCDR deployments and their CO_2 sequestration efficiency or environmental side effects, as reported for mesoscale ocean iron fertilization (21–23). The utilization of large-scale natural analogs circumvents this dilemma. Indeed, natural analogs are probably our only opportunity to study mCDR methods under large-scale, real-world conditions before deciding on their suitability for future implementation.

Abruptness of Perturbation. The goal of mCDR is to alter ocean systems, such that they absorb and store more atmospheric CO_2. The urgency for CDR means that such goals must be met early within this century. Thus, a natural mCDR analog that mimics an "abrupt perturbation" of the ocean system on the timescale of a few decades or shorter would be particularly informative. Another case (and still useful) is when natural analogs represent a new steady state, which resembles the altered final stage of an ocean system established after sustained implementation of a mCDR method. This "steady-state–type" analog can provide an initial assessment on whether a proposed mCDR method will ultimately have sequestered carbon or result in unacceptable changes in the ocean system. There are also natural analogs reflecting slow perturbations over the timescale of centuries to millennia, for example those that drive changes in atmospheric CO_2 between glacial and interglacial periods as evidenced in the paleorecord. These paleo-analogs are undoubtedly important to constrain the longer-term potential (i.e., full-scale deployment over decades) of mCDR methods. However, as for the steady-state–type analog, paleo-analogs will often not capture the aspect of abruptness due to the generally slower rate of perturbations of the Earth System prior the Anthropocene (24, 25). Thus, paleo-analogs are potentially less representative and informative for the necessarily rapid (decades) gigaton-scale mCDR implementation.

Availability of a Control Site. The strength of well-designed experiments is that treatments can be compared to controls where everything except for the simulated perturbation is identical. Such stringent control and comparability is unlikely to be found in natural analogs and could be seen as a weakness of their scientific value (26). However, some options remain to establish comparability. The obvious one would be a similar but unperturbed ocean region in the vicinity of the perturbed system. Alternatively, the perturbed system could be compared with its prior unperturbed state. Either way, the usefulness of natural mCDR analogs clearly increases when comparability to unperturbed control systems exists because a well-documented baseline is needed to evaluate the many impacts of the perturbation.

Reoccurrence. Regularly reoccurring natural analogs have several advantages over those that are sporadic and unpredictable. First, they are logistically easier to study because research campaigns can be planned and prepared in advance and improved over time. Second, reoccurring analogs provide opportunities to study the confounding influence of changing internal or external forcing, for example if the CO_2 sequestration associated with a natural analog is different during El Niño than for La Niña years or changes due to ongoing climate change. This information is important because it reveals how sensitive the outcome of a large-scale mCDR deployment would be to natural and anthropogenic changes in the climate system. Third, reoccurring analogs provide opportunities to assess how reproducible CO_2 sequestration or associated environmental impacts are. For example, a similar magnitude of CO_2 sequestration observed for reoccurring events increases the confidence that the mCDR method corresponding to the investigated analog is not subject to unpredictable variability. Importantly, "reoccurrence" may not only refer to temporal but also for spatial scales. A natural analog that occurs at multiple locations globally provides opportunities to study differences due to geographic location and underlying climatic or environmental conditions.

Examples of Natural Analogs for Marine CDR Methods

The evaluation of mCDR methods can range from being heavily reliant on natural analogs to not assessable with natural analogs. A conspicuous example of the integration of natural mCDR analogs into the research trajectory is blue carbon–CDR via restoration of coastal macrophyte assemblages. Blue carbon research is largely built upon studying numerous natural analogs such as saltmarshes, mangrove forests, or sea grass meadows (27). An example where natural analogs may not be available is the engineered CO_2 extraction from seawater with subsequent deep-sea disposal and storage. In this section, we focus on identifying natural analogs for four predominant mCDR methods that lie in between these two extremes: that is, mCDR methods where natural analogs exist but have not been fully utilized. These are artificial upwelling (AU), ocean iron fertilization (OIF), ocean alkalinity enhancement (OAE), and ocean afforestation (Fig. 3 and Table 1). The highlighted analogs for these mCDR methods are not exclusive and others are likely to be identified for the various aspects of mCDR research. The knowledge base available for each method and the corresponding natural analog is wide ranging so that they must each be discussed below with different levels of detail.

Artificial Upwelling. AU aims to transport nutrient and CO_2-rich deep water into the oligotrophic surface ocean to enhance

Table 1. Highlighted natural analogs for four predominant mCDR approaches and approximate scales at which they occur

mCDR approach	Analog	Scale (km^2)	Perturbation	Control	Reoccurrence
Artificial upwelling (AU)	Equatorial upwelling (Atlantic)	1.7×10^{6}[*]	Abrupt	Nonupwelling season	Annually in boreal summer
Ocean Iron Fertilization (OIF)	Downstream Kerguelen	0.7×10^{6}[†]	Abrupt	upstream Kerguelen	Fertilized patches spinning off downstream of Kerguelen
Ocean Alkalinity Enhancement (OAE)	Black Sea	0.44×10^{6}[‡]	Steady state	Baltic Sea	Consistently present
	Caspian Sea	0.38×10^{6}[‡]	Steady state	Baltic Sea	Consistently present
Ocean Afforestation	Great Atlantic *Sargassum* Belt (GASB)	12×10^{6}[§]6×10^{3}[¶]	Abrupt	Slightly north of the GASB	Annually since 2011 except for 2013

The column on "Perturbation" indicates whether the natural analogs are perturbing the oceans on a similar timescale as is anticipated for their mCDR implementation (i.e., abrupt) or if they represent steady-state end members. Potential control sites as well as the reoccurrence patterns are also identified.

[*] Area denoted by the white box in Fig. 3*A*.

[†] Area denoted by the white box in Fig. 3*B*.

[‡] Areas denoted by the white outlines in Fig. 3*C*.

[§] The main GASB area as marked in Fig. 3*D*.

[¶] The maximum Sargassum surface coverage within the area bounded by 25° N – 5°S and 89°W to 15°E for June 2018 as calculated by Wang et al. (62).

photosynthetic carbon fixation by phytoplankton and ultimately generate a net uptake of atmospheric CO$_2$ (28–30). Natural upwelling is common in the ocean and fuels a large proportion of marine primary production (31). It can be driven, for example, by winter mixing, mesoscale circulation (eddies), or large-scale current systems, such as the Southern Ocean divergence, eastern boundary upwelling systems, or equatorial upwelling (32). Much can be learned from each of these analogs on how plankton communities and associated biogeochemical fluxes are modified by cool and nutrient-rich water, and there are significant oceanographic research efforts focusing on upwelling and associated ocean productivity (32). Perhaps the natural analog with most relevance for current AU ideas is equatorial upwelling, as it occurs in the open ocean and in low latitudes for which AU proposals are generally targeted (29).

Equatorial upwelling extends several million square kilometers in tropical regions (e.g., eastern tropical Atlantic) (Fig. 3*A*), reoccurs annually, and leads to abrupt increases in surface chlorophyll a concentration (Fig. 3 *A*, *Inset*). It is driven by a combination of remote processes and easterly trade winds causing thermocline shallowing and seasonal nutrient entrainment into the mixed layer from relatively shallow depths (32, 33). Although these physical processes are not identical to the engineered upwelling envisioned for AU (28), equatorial upwelling causes the same desired biogeochemical responses. It supplies nutrients to surface waters with higher light intensities, thereby causing an increase in phytoplankton abundance and productivity, as well as increased downward carbon export, although the latter is difficult to study due to strong lateral displacements of vertical fluxes (33–35). The regular reoccurrence of the phenomenon not only provides advantages of repeated studies but also facilitates the identification of suitable control systems, either by investigating the same area when it returns to baseline oligotrophy during the absence of upwelling. Alternatively, because the relatively mild latitudinal gradient in the equatorial regions may justify the comparison with nearby oligotrophic gyres (34). Utilizing equatorial upwelling for AU research has the potential to answer important open questions. For example, comparing upwelling fluxes of respired CO$_2$ against the sinking fluxes of photosynthetically fixed CO$_2$ driven by fertilization could help to answer if AU has a net positive effect on CO$_2$ sequestration at large scale (36).

Ocean Iron Fertilization. OIF aims to stimulate marine primary production and associated CO$_2$ sequestration by the addition of iron fertilizer to iron-limited surface waters (37). Through research efforts to understand glacial–interglacial cycles of atmospheric CO$_2$, OIF has become the most thoroughly investigated open-ocean CDR approach and the only one where several mesoscale experiments have previously been conducted (14). However, in situ experiments have been perceived as posing a threat to marine life (15) and new governance rules set regulatory hurdles for future studies (38). Iron can be added naturally to the surface ocean, for example through upwelling, dust, rivers, hydrothermal vents, ice, or sediment resuspension (39). Among these options, iron inputs from ocean islands located in iron-limited regions (e.g., Kerguelen or Galapagos) have been proven to be particularly useful locations to study OIF (40, 41). If we consider, for example, the Kerguelen archipelago located in the Southern Ocean: the iron-fertilized blooms downstream of Kerguelen extend over several hundred thousand square kilometers (Fig. 3*B* and Table 1), and therefore much beyond the scale achieved with experimental OIF studies (~up to several thousand square kilometers) (41). The OIF perturbation is abrupt since unperturbed upstream water east of Kerguelen only becomes enriched while passing the island within the Antarctic Circumpolar Current (Fig. 3*B*). The blooms developing downstream reoccur with a distinct seasonality and can be investigated in a lagrangian manner (i.e., observation while drifting within the target water body) and compared to the unperturbed upstream system, which provides an ideal control (41–43). Studies on downward carbon export in the fertilized regions downstream of Kerguelen have already provided key insights on how efficiently an abruptly iron-fertilized water mass could sequester CO$_2$ under different modes of iron supply (40, 42). Kerguelen (and other ocean island) natural OIF analogs can be utilized more systematically for mCDR-related research by making use of comprehensive biogeochemical datasets that exist (40), and are continuously generated (44) for these areas.

Ocean Alkalinity Enhancement. OAE aims to increase CO$_2$ storage capacity by increasing seawater pH and alkalinity through the acceleration of rock weathering (45). In essence, OAE utilizes CO$_2$-absorbing chemical reactions that occur during the weathering of certain rocks. Naturally, rock weathering is slow, taking thousands of years (46). OAE aims to accelerate weathering by pulverizing and distributing rock powder over large surfaces (47), or by increasing the rates of weathering in electrochemical reactors (48), thereby transforming a slow process into one that is relevant on the timescales of climate change (decades). Large-scale natural OAE analogs that mimic such an abrupt perturbation may not exist due to the inertia of the natural geological cycles and weathering processes. The above-mentioned aspect of "abruptness" may therefore not be covered by mCDR research on natural OAE analogs. Furthermore, the OAE perturbation itself is currently unclear because the desired alkalinity enhancement through accelerated rock weathering can be accompanied with the release of various other dissolution products, depending on the applied source minerals and weathering methods (45, 47). Thus, it is also uncertain how an ideal OAE analog should look with respect to the unintentional side effects that accompany the intentional alkalinity perturbation.

Despite these unresolved questions on the perturbation itself, the Black and Caspian Seas (Fig. 3*C*) may represent two distinctive and informative natural OAE analogs when focusing primarily on the alkalinity perturbation (49). The Black Sea covers 0.44 million km^2 and a surface alkalinity that is 1.4 times higher than surface ocean average (i.e., $\sim$3,300 µmol kg^{-1} relative to 2,308 µmol kg^{-1}) (31, 50). Its surface pH is between 8.3 and 8.4 (51), compared to the surface ocean average of around 8.1 on the total pH scale (31). The Caspian Sea covers $\sim$0.38 million km^2 and an $\sim$1.7 times higher surface alkalinity (i.e., $\sim$3,800 µmol kg^{-1}) (52). The surface pH is likely even higher than in the Black Sea (i.e., $\geq$8.4) (52) (but note that refs. 51 and 52 did not report the pH scale). These elevated surface ocean alkalinities and pH values are probably beyond what is achievable through OAE in the 21st century (53) [but note that such elevated alkalinity and pH can readily be reached at OAE perturbation sites (54)]. Thus, both the Black and the Caspian Seas constitute steady-state end members for highly alkalinity-perturbed "far-future" oceans and their ecosystems. The Baltic Sea may serve as lower-alkalinity control site for the Black and Caspian Sea analogs (55). All three are semienclosed marginal seas that have similarly low salinities, although the Baltic Sea is further north. One fundamental question that may be assessed by referring to the Black and Caspian Seas is whether high alkalinity could be detrimental to marine life. The answer to this question may be obvious, considering that the Black Sea has harbored thriving ecosystems, especially before it became increasingly polluted since the 1970s (56, 57). However, these insights will become essential to provide real-world constraints on experimental observations. Additionally, this information may prove to be useful to understand how high alkalinity could evolve in the Black and Caspian Seas while maintaining healthy ecosystems, thereby providing insights on how OAE could be conducted in a sustainable way. Finally, these analogs can be utilized to test various more nuanced aspects of OAE, such as the anticipated proliferation of marine calcifiers under high alkalinity and high pH conditions (49, 58).

Ocean Afforestation. Ocean afforestation aims to grow benthic seaweeds on free-drifting platforms in the open ocean to exploit their capacity to photosynthetically capture CO$_2$ in macroscopic biomass (59). Seaweeds occur sporadically in the open ocean due to offshore drift (60), but usually do not grow there. A prominent exception is floating seaweed of the genus *Sargassum*, which occurs in rafts on the surface or slightly below (61). *Sargassum* has a holopelagic life cycle and was historically found in the Sargasso Sea, but since 2011 has extended its occurrence to form a trans-basin belt throughout the Atlantic from West Africa to the Gulf of Mexico (62, 63). This "Great Atlantic *Sargassum* Belt" (GASB) (62), combines some features that represent a useful ocean afforestation analog (11). The new area where *Sargassum* occurs straddles $\sim$12 million km^2 (Fig. 3*D* and Table 1). At its maximum extent, all *Sargassum* rafts in the GASB combined can cover up to 6,000 km^2 (62). Thus, the *Sargassum* analog resembles a scenario where small free-drifting seaweed farms are dispersed by ocean currents over the (sub)tropical North Atlantic. The sudden expansion of *Sargassum* blooms in the GASB since 2011 constitutes an abrupt and reoccurring perturbation, similar to the establishment of seaweed farms in regions where these species do not naturally occur. Regions affected by *Sargassum* can also readily be compared to conditions before 2011, or to years where *Sargassum* did not bloom significantly, such as in 2013 (62). Alternatively, the new *Sargassum*-affected areas can be compared to unaffected ones slightly north or south of the GASB. The GASB can be utilized to test the real-world CDR potential of ocean afforestation by repurposing a wide range of datasets from satellite observations to the elemental composition of individual seaweed thalli (11). This analog also holds significant potential to understand environmental impacts of the expansion of seaweeds into areas where they had not previously occurred (64).

Value Beyond the Scientific Assessment

Scientific and public debates often classify mCDR approaches as "natural" (e.g., ocean afforestation) or "unnatural" (e.g., OAE) depending upon the dominant CO$_2$-absorption process each method is based upon and also cultural perceptions (65, 66). However, such classification has recently been challenged as it lacks a scientific basis and may bias political decisions on CDR implementation (66, 67). Our ability to identify useful natural analogs even for mCDR methods currently considered unnatural (Fig. 3) provides additional support that such classification should be rethought.

Including natural analogs more rigorously into mCDR assessments could moderate the wide-ranging public discourse around their potential future implementation. Consider, for example, the case of OIF: Stakeholders promoting OIF are generally positive about its carbon sequestration efficiency, use positive terms to underscore its environmental benefits (e.g., "ocean pasture restoration"), while omitting reference to the associated risks of OIF (68). Stakeholders advocating against OIF use negative terms (e.g., "harmful toxin-producing algal blooms") to emphasize almost exclusively its potentially detrimental side effects (69). The arguments on both sides are based on selective referencing of individual published studies and thus lack balance. A rigorous examination of the diverse datasets available for the Kerguelen OIF analog could help to moderate such one-sided narratives, simply because it is difficult to deny and ignore what can be seen in reality, and particularly at large scale, already today. For example, investigating planktonic food webs downstream of Kerguelen could provide important insights into whether widespread harmful algal blooms are of considerable concern in the naturally fertilized blooms (70). For more recently emerging mCDR methods, such as OAE, a tight alignment of research to Black or Caspian Sea natural analogs from the beginning may help to prevent such unbalanced reporting from evolving. That is because cross-validation of outcomes from experimental studies or numerical modeling with natural analogs reassures nonexperts that findings are reproducible in real-world systems. Thus, we anticipate that rigorous reference to natural mCDR analogs could provide great value by constraining the public debate as they ground-truth the arguments and impede a drift into overly positive or negative framing.

In addition to moderating the public discourse, natural analogs could also help to identify and evaluate geopolitical risks associated with regional upscaling of mCDR methods (71). For example, seaweed inundations due to the emergence of the GASB cause severe economic damage along affected coastlines in the Atlantic and intra-America seas (62). Such damage, when linked to ocean afforestation, could lead to conflict between political entities (e.g., states or federations) and those operating the free-drifting seaweed farms even though the farms, when initially deployed, may be remote and fall under different jurisdiction. Not only can natural analogs help to anticipate such transboundary risks, but they can provide the rich archives of data needed to establish adaptive governance and compensation schemes long before mCDR methods are being implemented.

The outcomes of mCDR research have potentially large implications for the Earth's future as they build the foundations for upcoming decisions on whether humankind will aim to deliberately modify the ocean system to counteract climate change. Hence, we constantly must remind ourselves of the responsibility that comes with this research. The goal of the mCDR assessment is to determine mCDR potentials and risks and to evaluate them against risks of climate change. However, some uncertainty will always remain. In that context, natural mCDR analogs may provide an insurance for the research process as they allow robust testing, at deployment scale, of the findings from experiments and modeling. Thus, the utilization of natural analogs may ultimately lead to the necessary confidence into the scientific assessment, which is needed to decide whether mCDR should move from research to implementation.

Data Availability. Previously published data were used for this work [satellite chlorophyll a data were downloaded from the Giovanni online data system (https://giovanni.gsfc.nasa.gov/giovanni/) (72, 73); developed and maintained by the NASA GES DISC].

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