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PERSPECTIVE

Illuminating deep-sea considerations and experimental approaches for mCDR proposals

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1. Introduction

As society recognizes the urgency of reducing atmospheric CO_2 levels, industries and nations are increasingly considering marine carbon dioxide removal (mCDR) in their climate mitigation portfolios. The deep sea (defined as depths below 200 m) is the storage site for removed carbon for most mCDR technologies [1, 2] because, here, carbon is out of contact with the atmosphere on societally relevant timescales (>100 years). However, the deep sea is often treated as a 'black box' without sufficient consideration given to deep-sea ecological processes and ecosystem services that may be impacted by mCDR activities (e.g. [2, 3]).

The often held 'out of sight, out of mind' relationship with the deep sea has previously been used to justify disposal of radioactive, military, and chemical waste in the deep sea [4]. These activities were assumed harmless due to the large and sparsely inhabited nature of the deep sea, and expectations that waste would be permanently removed and that negative impacts would remain in the deep sea and not impact coastal areas or socioeconomic activities.

The deep sea is the largest habitable volume on Earth [4]. It harbors many different ecosystems supporting diverse life forms [4], carries out key ecosystem functions and services, including fisheries and climate regulation [5], and houses non-living and genetic resources. Rather than a disconnected empty space, as it often appears in diagrams of mCDR activities, it harbours numerous complex and intricately linked ecosystems and is connected to the shallow ocean and coast through biological, chemical and physical processes (figure 1).

Climate change negatively impacts deep-sea ecosystems [6]. Scalable mCDR activities may limit climate change severity, but such interventions will also directly impact deep-sea ecosystems [1]. Thus, an appropriate representation of the deep sea in cost-benefit evaluations and environmental impact assessments of mCDR proposals is urgently needed. Deep-sea impacts will differ among mCDR methods, forms of carbon removed [i.e. particulate organic carbon (POC), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate inorganic carbon (PIC)], and recipient deep-sea habitats.

This manuscript provides key deep-sea considerations for research on the environmental impacts of mCDR with a focus on ocean fertilization (OF), organic matter sinking, ocean alkalinity enhancement (OAE), and direct ocean capture. We also consider carbon capture and storage (CCS) because installation, operation, and potential leakage is relevant for deep-sea impacts, though the carbon may come from non-marine sources. Methods are defined in table 1 and method-specific deep-sea considerations are provided in table 1 and figure 1.

2. Unique deep-sea features and relevant processes for assessing mCDR impacts

The deep sea contains a mosaic of ecosystems, encompassing sedimented slopes, biogenic reefs, chemosynthetic ecosystems, oxygen minimum zones, knolls, seamounts, ridges, canyons, basins, fjords, deep pelagic zones, abyssal plains, and trenches. These ecosystems are connected vertically and horizontally via diffusion, advection, circulation, carbon exchange, fluid emission and animal migrations (figure 1). Benthic and pelagic environments interact constantly through the exchange of matter, energy, nutrients, gases and organisms [7]. In each habitat, species have different potential vulnerabilities and thresholds to changes in light, turbidity, and physical and chemical properties that could be induced by mCDR technologies. As such, mCDR proposals should be clear about the specific deep-sea ecosystem(s) and processes that may be affected.

Deep-sea ecosystems rely on organic matter sinking from upper ocean layers, making them particularly sensitive to changes in surface productivity and midwater processes [8]. The flux of food from the upper ocean is mediated biologically by diel vertically migrating organisms, and bentho-pelagic coupling, which links the seafloor and water column through food, carbon and waste exchange [9]. Food availability in the deep sea is generally low and the phenology of organisms can be linked to seasonal and sporadic variations in food supply. mCDR activities that increase organic matter flux and deposition, like OF and organic matter sinking, could affect multiple deep-sea water column and/or seafloor habitats. For example, fragile coral or sponge grounds and xenophyophore or sea pen fields and microbial communities may be highly vulnerable to smothering from excess organic matter or mineral deposition from OAE. Similarly, the delicate body structures of midwater organisms such as gelatinous taxa (e.g. cnidarians, ctenophores, tunicates), crustaceans and fishes may be damaged, and communication through bioluminescence altered.

The biological degradation of organic matter introduced by organic matter sinking and enhanced by OF can potentially lead to deoxygenation, hypoxia, acidification and other chemical changes in the deep sea [10]. Because of the heterogeneity of deep-sea water masses and sequestration timescales [11], impacts can vary significantly across geographic regions (e.g. low-oxygen upwelling areas versus well-oxygenated downwelling areas). OF intended to enhance carbon sequestration may lead to unintended changes in bioturbation on the seafloor, affecting infaunal and epifaunal benthic organisms and processes [12].

Many species in the deep sea remain unknown, with new species frequently being discovered [4]. Many deep-sea organisms have great longevity, slow growth rates, long maturation times, and low fecundity [13] making them particularly vulnerable to disturbances and sensitive to change. Rarity is also a feature of deep-sea taxa that may make species loss from disturbance more likely, but also difficult to detect. High volumes of water intake, which are needed for electrochemical OAE and direct ocean capture, may also impact deep-sea species by entraining diel vertical migrating species, which are present in shallow waters at night, or deep-sea larvae that disperse long distances using surface currents [14].

3. Potential effects of mCDR in the deep sea

For all mCDR methods, duration, volume, frequency of deployment, scale, timing, and seasonality are

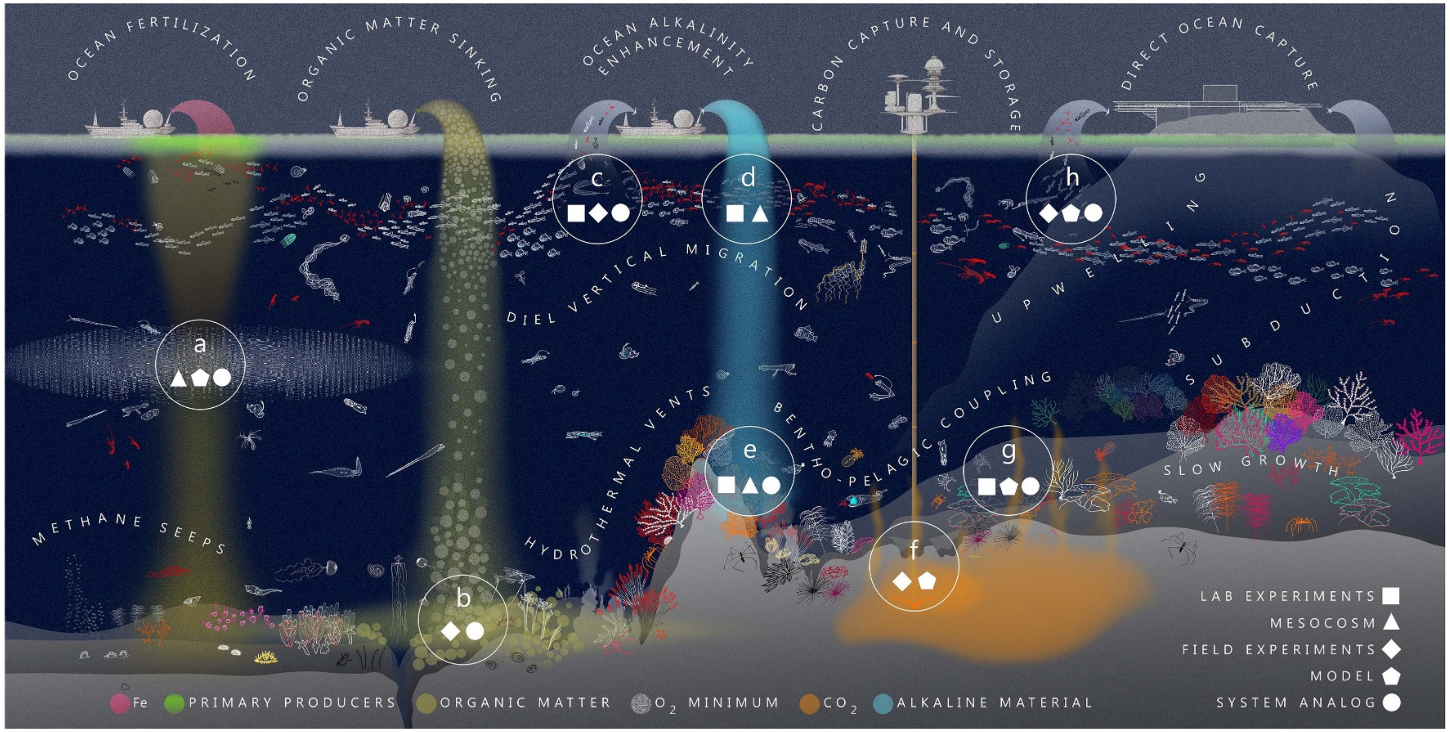

Figure 1. Key processes, impacts, and experimental approaches for five mCDR methods with regard to the deep sea. The deep sea represents a variety of interconnected habitats; impacts of mCDR will differ by method as well as the recipient ecosystem. Impacts are shown as circles and from left to right are: (a) oxygen loss, acidification, and increased food flux from ocean fertilization, (b) benthic smothering from organic matter sinking, (c) water intake for electrochemical ocean alkalinity enhancement (OAE) and associated deep-sea organism entrainment and mortality, (d) clogging of respiratory and filtration structures from mineral-based OAE for pelagic organisms, as well as (e) benthic organisms in addition to trace-metal leaching, (f) seafloor habitat disruption during installation of carbon capture and storage infrastructure and (g) possible leaching of stored CO_2 and (h) water intake for direct ocean capture and associated deep-sea organism entrainment and mortality. Shapes (legend, bottom right) indicate which experimental approaches may be most instructive for filling knowledge gaps for each key impact category, while shaded colors (legend, bottom) indicate certain features or materials. Reproduced with permission from Alejandro Carretero.

Table 1. Five mCDR technologies and relevant deep-sea considerations and impact analogs. Impact analogs refer to natural or artificial events or processes that present certain similarities of impact to the mCDR method and may therefore be informative.

	Method description	Relevant deep-sea considerations	Impact analogs
Ocean fertilization (OF)	OF aims to stimulate phytoplankton production and consequently export more particulate organic carbon into the deep sea, by introducing limiting nutrients to the surface ocean. Methods include iron fertilization and artificial upwelling.	If particulate organic carbon flux to the deep sea increases following OF, oxygen demand can increase, leading to oxygen loss and acidification. Small particles sink slowly, so OF can have more impacts on deep pelagic (i.e. water column) organisms, in addition to benthic organisms. Out-of-season sinking of organic matter to the seabed can disrupt reproductive cycles and lead to changes in life-history phenology. OF done at scale could cause benthic smothering. In oligotrophic areas, limited OF may have a positive effect by introducing more food to the deep sea. Nutrient robbing and redistribution of organic matter flux to the deep sea is also a concern of OF.	Analogs include the sinking of phytodetritus following large algal blooms, and coastal eutrophication near deep-sea sites.
Organic matter sinking	Organic matter sinking refers to the purposeful sinking of marine algae, agricultural crop waste, or wood waste into the deep sea. Marine organic materials, such as seaweeds, remove carbon from the seawater, while terrestrial materials remove carbon from air. Sinking of terrestrial materials is thus not considered a form of mCDR but deep-sea impacts may be similar.	Amount, timing, location, underlying oxygen conditions, and source and processing of organic material are important considerations for deep-sea impacts. Key potential impacts include smothering, anoxia, and seafloor habitat modification from high-volume organic matter addition, additional bacterial respiration leading to localized oxygen loss and acidification, and pesticide exposure from agricultural material. Nutrient robbing and redistribution of organic matter flux to the deep sea is also a concern of organic matter sinking.	Analogs include storm-driven fluxes of terrestrial matter, such as wood falls, to the deep sea, and the sinking of *Sargassum* biomass, and vertebrate carcasses.

(Continued.)

Table 1. (Continued.)

	Method description	Relevant deep-sea considerations	Impact analogs
Ocean alkalinity enhancement (OAE)	OAE is the process of increasing ocean alkalinity either through the addition of alkaline minerals or solutions to seawater or through electrochemical methods, so the seawater can uptake additional anthropogenic CO_2 at the air-sea interface.	Deep-sea considerations will differ by OAE method. Concerns for mineral addition are: clogging of respiratory and filtration structures of deep-sea organisms by small particles, seafloor sedimentation of precipitates, leaching of trace metals (e.g. Ni, Mg, Fe), and secondary food-web impacts of shading. Possible electrochemical OAE impacts include entrainment from water intake, discharge of water with altered chemistry affecting ecosystems, and flux of carbonate minerals from secondary precipitation.	Analogs include sediment plumes and mineral deposits from trawling and mining, NaOH use in desalination plants, and liming to remove sea urchins from kelp forests.
Carbon capture and storage (CCS)	CCS involves the capturing of CO_2 from CO_2-generating industrial activities, directly from the atmosphere, or from seawater, and storing the captured CO_2 in geologic reservoirs such as the seabed.	Installation of CO_2 injection infrastructure may disrupt seafloor habitats, resulting in habitat loss and fragmentation, and impaired ecosystem services such as nutrient cycling and carbon sequestration. CO_2 leakage from storage reservoirs and subsequent organismal exposure to low pH conditions is also a concern.	Analogs include seabed disturbance from oil and wind installations, and ocean acidification research for CO_2 leakage effects.
Direct ocean capture	Direct ocean capture removes dissolved inorganic carbon (DIC) from seawater and returns the DIC-depleted water back to the ocean where it can uptake additional anthropogenic CO_2 at the air-sea interface. The captured and removed CO_2 is stored.	Depth, timing, and volume of water intake are important for assessing mortality due to entrainment of diel vertical migrators and planktonic larval stages of deep-sea organisms. The precipitation of carbonate minerals in returned seawater and their flux into the deep sea may have a positive buffering effect at depths with carbonate undersaturated waters.	Analogs include impingement and entrainment mortality from intake waters of desalination and power plants.

important considerations (table 1). Certain similarities of impacts emerge for biotic methods, such as smothering or biological degradation of excess organic matter for OF and organic matter sinking, and geochemical methods, such as deep-sea plankton entrainment and mortality due to high-volume water intake for direct ocean capture and electrochemical OAE. Future mCDR applications may also incorporate multiple methods (e.g. sinking terrestrial wood pucks with macroalgal spores and limestone powder), with mixed impacts.

Individual impacts of mCDR may be additive, synergistic, or antagonistic with impacts from climate change, ongoing human activities such as oil and gas extraction, fisheries, tourism, waste disposal, cable laying, and bioprospecting [4], as well as potential activities such as deep-sea mining. Cumulative impacts may weaken the resilience of communities compared to individual stressors. Physical disturbance and habitat alteration from infrastructure installation and increased sedimentation can lead to habitat loss and fragmentation. Biogeochemical alterations, such as acidification and oxygen loss from organic matter degradation can have additive or synergistic effects with ongoing climate change-associated acidification and deoxygenation. Consequently, interactive effects should be considered when evaluating mCDR proposals to support sustainable management of the affected ecosystems.

4. Experimental approaches and considerations for evaluating mCDR impacts in the deep sea

4.1. Laboratory experiments

Laboratory experiments allow for detailed examination of organismal responses to aspects of an mCDR intervention under highly controlled conditions. Lessons learned from laboratory experiments on the effects of ocean acidification on organismal survival, growth, calcification, and other metrics, including in multi-stressor treatments [15], may be informative to the mCDR community. Laboratory experiments using deep-sea organisms are mainly feasible for shallower dwelling taxa (<1 km) tolerant of surface pressures or small taxa that can be kept in pressure chambers. There are representatives of important deep-sea taxa that can be amenable to laboratory experiments, such as diel vertical migrating organisms (krill and copepods), gelatinous organisms (jellyfish, salps), benthic filter-feeders (sponges, deep-sea corals), hydrothermal vent organisms (mussels and shrimps), and slope-associated fishes (flatfish, rockfish). A best practice guide for OAE laboratory experimentation includes guidance for achieving optimal experimental design, including on how to ensure reproducibility and select appropriate response variables (e.g, physiological, biogeochemical, ecological), but recommendations largely apply to pelagic systems and there is no explicit focus on deep-sea organisms [16].

4.2. Mesocosms

Mesocosms allow controlled manipulation of certain variables, but in a semi-natural enclosed environment and generally contain multiple species and trophic levels, offering an integrative approach to study ecosystem function. Deep-sea mesocosm experiments share some similar challenges with laboratory experiments, including depressurization artifacts, working with deep-sea species, and challenges replicating natural temperature dynamics. There are few examples of deep-sea mesocosm experiments in the literature, but some exist [17, 18]. Mesocosm experiments can be used to address the impacts of mCDR on marine chemistry, oxygen dynamics, and toxicity, the reciprocal interactions at the water-sediment interface, the impact of blooms on benthic foraminifera and bacteria [17], and the impact of multiple stressors on deep-sea corals and sponges [18]. Free-ocean CO_2 enrichment (FOCE) systems were developed for ocean acidification research and are a series of benthic enclosures that allow for precise control of CO_2 enrichment and examination of marine community responses [19]. They have been successfully used in a variety of marine habitats, including in the deep sea, allow for longer-term experiments (months to years) [19], and may be useful tools for mCDR research, but are non-trivial to deploy.

4.3. Field experiments

Field experiments are conducted directly in the marine environment to study ecosystem responses and thus offer less controlled conditions than laboratory or mesocosm studies. Many deep-sea field research tools exist that can be used for examining ecosystem responses to mCDR field experiments. These include observing technologies such as the Environmental Sample Processor for environmental DNA collection, Underwater Vision Profilers for monitoring plankton and large particulate matter, autonomous underwater vehicles and drop cameras for monitoring organismal responses, as well as deep-sea observatories [20]. Deep-sea landers, remotely operated vehicles, submersibles, and benthic flux chambers can also support *in situ* experimentation and/or serve as observational tools depending on how they are used [20]. Many mCDR technologies are yet to be tested *in situ* in the deep sea, due to the challenge of upscaling approaches, tracking exported carbon at relevant spatial and temporal scales, and permitting. *In situ* scientific studies are available for OF [21], but carbon export and deep-sea impacts were not directly examined because the studies did not include the deep pelagic and seafloor sampling. Kelp and wood fall experiments at 1670 m in the Santa Cruz Basin indicate that kelp-derived organic material is rapidly utilized by microbes and metazoans and not retained in the sediments [22]. Manipulative field experiments that simulate elevated CO_2 levels can inform potential ecological impacts of mCDR [23], such as reductions in biodiversity and shifts in community composition. Future field experiments should focus on how much carbon is drawn down, sequestration permanence, and how shallow and deep-sea ecosystems respond.

4.4. Modeling approaches

Models can be powerful tools to evaluate mCDR impacts on deep-sea ecosystems. Conceptual models can be based on expert opinion and be used to describe the structure of ecosystems, flows of energy, materials and organisms, and trophic interactions, and to identify knowledge gaps. Mathematical models use quantitative and qualitative data to identify the relative importance of different physical and biogeochemical drivers to ecosystem properties and functions and associated uncertainty. They can be used to project impacts at different scales or resolutions and are used to evaluate different aspects of mCDR [24]. For example, a coupled hydrodynamic and biogeochemical ocean model was used to simulate OAE efficiency by calcite dissolution in one of the deepest basins of the Baltic Sea, but ecological responses were not modeled [25]. Due to data-limitation, deep-sea ecosystem modeling has specific challenges, but modeling capabilities are growing [26] and advances in machine learning are already improving modeling capabilities. However, our understanding of underlying deep-sea processes, scalability, data availability at relevant resolutions, and model evaluation remain key challenges for the use of models to study mCDR impacts.

4.5. System analogs

Natural analogs that resemble aspects of an mCDR application can provide inferences on ecosystem-level effects [27, 28] and offer advantages in that they allow large-scale, real-world examination of aspects of mCDR applications. For example, natural iron fertilization via iron originating from the Crozet Islands (Southern Ocean) led to high plankton productivity in an otherwise high-nutrient, low-chlorophyll ocean and elevated POC flux to the deep sea [29]. Other opportunities to gain insight from natural analogs for deep-sea mCDR research include the Great Atlantic Sargassum Belt [27] and natural wood and kelp falls [22] for organic matter sinking, shallow to deep-sea CO_2 vents for CCS, naturally alkaline sites like alkaline fjords and the Black Sea for OAE [28], and equatorial upwelling for OF by artificial upwelling [27]. Certain anthropogenic activities may also offer useful analogs for mCDR impacts (table 1). These include organismal entrainment in desalination plant water intake for direct ocean capture and OAE, sediment plume effects from deep sea mining [18] for mineral-based OAE, community responses to liming (used to control sea urchin populations in kelp beds and biofouling in mussel farms) for OAE, benthic disturbance from offshore wind turbine installation and oil and gas drilling for CCS, and coastal eutrophication for OF (table 1).

5. Social, governance and equity implications of mCDR in the deep sea

The challenges related to costs and access in deep-sea research [30] introduce further social, governance, and equity issues for mCDR proposals. Deep-sea research faces significant financial and technical challenges [20], thus affecting who can explore mCDR as a potential climate solution and monitor deep-sea impacts. Currently, most mCDR research is led by industrialized nations and excludes low- and middle-income countries—a neocolonial approach that raises equity issues [30, 31]. Lack of inclusivity is an increasing concern as commercial interests in blue carbon credits expand, primarily benefiting companies in developed nations while offering uncertain environmental gains.

Before commercializing mCDR technologies, more research is needed to address risks and establish equitable governance frameworks. This should allow for a fair distribution of benefits and address concerns over inequitable profit distribution and insufficient or unintended climate impacts. A robust system for monitoring, reporting, and verification, including all aspects of environmental impacts, is vital to ensure transparent and effective management of mCDR projects (as discussed, along with legal considerations, in [3]).

6. Conclusion

Deep-sea ecosystems have been poorly considered in mCDR initiatives and many uncertainties remain about the efficacy, scale, and degree of impacts, which will vary by technology type and if implementation is continuous or intermittent. Before mCDR technologies are employed, the risks, costs and benefits must be understood. For effective impact monitoring, there is the need to identify the deep-sea processes impacted and potential indicator species. Holistic research programs are needed to provide robust baseline data and examine impacts through the use of shallow-to-deep-sea lab and field experiments, supplemented by modeling and system analog studies. Understanding of the timescales of carbon sequestration and permanency among mCDR/CCS methods and deep-sea areas is needed, as well as monitoring of deep-sea POC, DOC, DIC, and PIC that would make induced changes conspicuous. At every stage of this research process, transparent and inclusive international governance frameworks that address equity and guarantee that mCDR strategies serve the greater public interest are essential to a comprehensive approach.

Data availability statement

No new data was created or analyzed in the study.

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Ethics

This manuscript involved no experimentation on either humans or animals.

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