INSIGHTS

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MARINE SCIENCE

Deep-sea impacts of climate interventions

Ocean manipulation to mitigate climate change may harm deep-sea ecosystems

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Scientists, industry, and policy-makers have turned increasing attention toward the ocean as a source of climate change mitigation solutions. Efforts to develop ocean-based climate interventions (OBCIs) to remove and sequester carbon dioxide (CO_2), manage solar radiation, or produce renewable energy have accelerated. Questions have been raised about OBCI costs, governance, impacts, and effectiveness at scale, but limited attention has been given to ocean biogeochemistry and ecosystems (*1*) and particularly to impacts on deep-sea ecosystems (>200-m water depth), an ocean region that is understudied but fundamental for Earth's healthy function. The deep sea, with low energy supply; typically cold, stable conditions; and a low density of organisms with reduced metabolism, requires specific attention. Here we discuss OBCIs that could affect deep-ocean ecosystems and their services, identify governance challenges, and highlight the need for an integrated research framework to help centralize consideration of deep-sea impacts in mitigation planning.

Science and governance gaps have featured broadly in past discussions of ocean vulnerabilities to anthropogenic pressures including overfishing, biodiversity loss, plastic pollution, climate change, acidification, and deoxygenation. Threats to the deep sea have emerged from oil spills, destructive bottom fisheries, and seabed mining. Many of these stand to be compounded or exacerbated by OBCIs. In addition, the massive deposition or transfer of particles, organic matter (OM), and CO_2 into the deep ocean from OBCIs present new biogeochemical and ecosystem threats

Squat lobsters are on a *Leiopathes* sp. black coral on a seamount off the Pacific Coast of Costa Rica.

and governance challenges, particularly in international waters.

MITIGATION ACTIVITIES

Although some ocean-based climate mitigation activities, such as the expansion of coastal blue carbon ecosystems, have been put into practice, most remain conceptual, model-based, or at the pilot study stage (*2*).

Carbon sequestration

The ocean contains 50 times as much carbon as the atmosphere and acts as a biotic and abiotic thermostat, absorbing and releasing CO_2 and heat. The potential to modify these processes underpins the different OBCI methods under consideration. Natural removal of photosynthetically fixed carbon to depths below 1000 m for varied amounts of time (through mixing, sinking, aggregation, and vertically migrating animals) is considered sequestration. Ocean fertilization (OF) and macroalgal culture and sinking [afforestation (AF)] seek to enhance natural processes of marine photosynthetic uptake of carbon and removal to depth. OF adds limiting nutrients to stimulate carbon capture by phytoplankton that will sink, sequestering carbon to the deep sea (*2*). AF acts by culturing massive amounts of seaweed and sinking them to deep waters (*1*). Deep-sea disposal of terrestrial crop waste is under consideration, and expansion of coastal blue carbon as wetlands or macroalgae will also introduce OM to the deep sea.

Natural weathering of rocks from Earth's surface removes carbon on geological time scales, whereas ocean alkalinity enhancement (OAE) is intended to speed the process of removing CO_2 from the atmosphere by adding alkaline material. Through addition of calcium carbonate or calcium silicate to seawater, OAE can also act to reduce ocean acidification locally (*2*). OAE can also be achieved by electrochemically splitting surface seawater into acid and base, then pumping the weakly acidic waste stream downward to >2000-m depth, leaving the alkaline waste stream to be put back into surface waters to increase alkalinity and pH (*3*). Enormous amounts of carbon are stored in the deep sea, but the rates of carbon deposition are limited by the rate of carbon uptake at the surface. Direct injection of liquid CO_2 in deep water or below the seafloor attempts to speed up the processes of CO_2 sequestration and buffering (*4*).

Emission reduction

Several ocean-based technologies seek to reduce carbon demand and emissions by generating renewable energy from offshore wind and wave energy, or by harnessing geothermal energy from deep-sea hydrothermal systems. Ocean thermal energy conversion (OTEC), through artificial upwelling, harnesses the temperature difference between cold deep and warm surface water to power a turbine to produce electricity, whereas heat pipe OTEC uses a fluid other than seawater to transfer heat. These methods can also produce desalinated water (*4*).

Cooling techniques

There are proposed methods to reduce the heat in the atmosphere by transferring it to the deep ocean or raising ocean albedo and reflecting more heat. Thermodynamic geoengineering directly or indirectly transfers heat from surface waters to depth, allowing the surface ocean to absorb additional heat from the atmosphere. Cloud brightening and cloud seeding can be achieved by adding aerosols to layers of the atmosphere above the ocean where clouds form or using salt extracted from the ocean as nuclei for cloud formation. "Bubble dispersion" is a proposed technique for increasing the formation or the lifetime of bubbles at the ocean surface in an effort to increase ocean albedo and the amount of light reflected (*5*). Alternatively, added chemicals can induce or stabilize foam on the surface of the water, increasing light reflection.

DEEP-SEA IMPACTS

Strong connectivity between the surface and deep ocean will transfer impacts through the water column and to the seafloor (see the figure). When applied at full scale, several methods would alter albedo and reflectance over large areas of the ocean surface. The introduction of very fine inorganic particles (e.g., carbonates or silicates) into ocean waters (or ice) to enhance alkalinity, modify albedo, or inject CO_2 would alter turbidity and light fields. Artificial upwelling, OF, and AF will change surface ocean color and albedo (*6*). Cooling techniques will alter ocean stratification and the distribution of heat, which will alter midwater processes including particle flux, vertical migrations, metabolic rates, larval distributions, oxygenation, and remineralization rates, with effects cascading to the seabed.

Resulting changes in the distribution and productivity of plankton will affect ecosystem connectivity and food supply to other organisms. Smaller inorganic and organic particles are unlikely to reach the deep seafloor as detectable deposits but may be ingested or entrained in aggregations of sinking particles (marine snow) and transported to the deep ocean. OF, artificial up-

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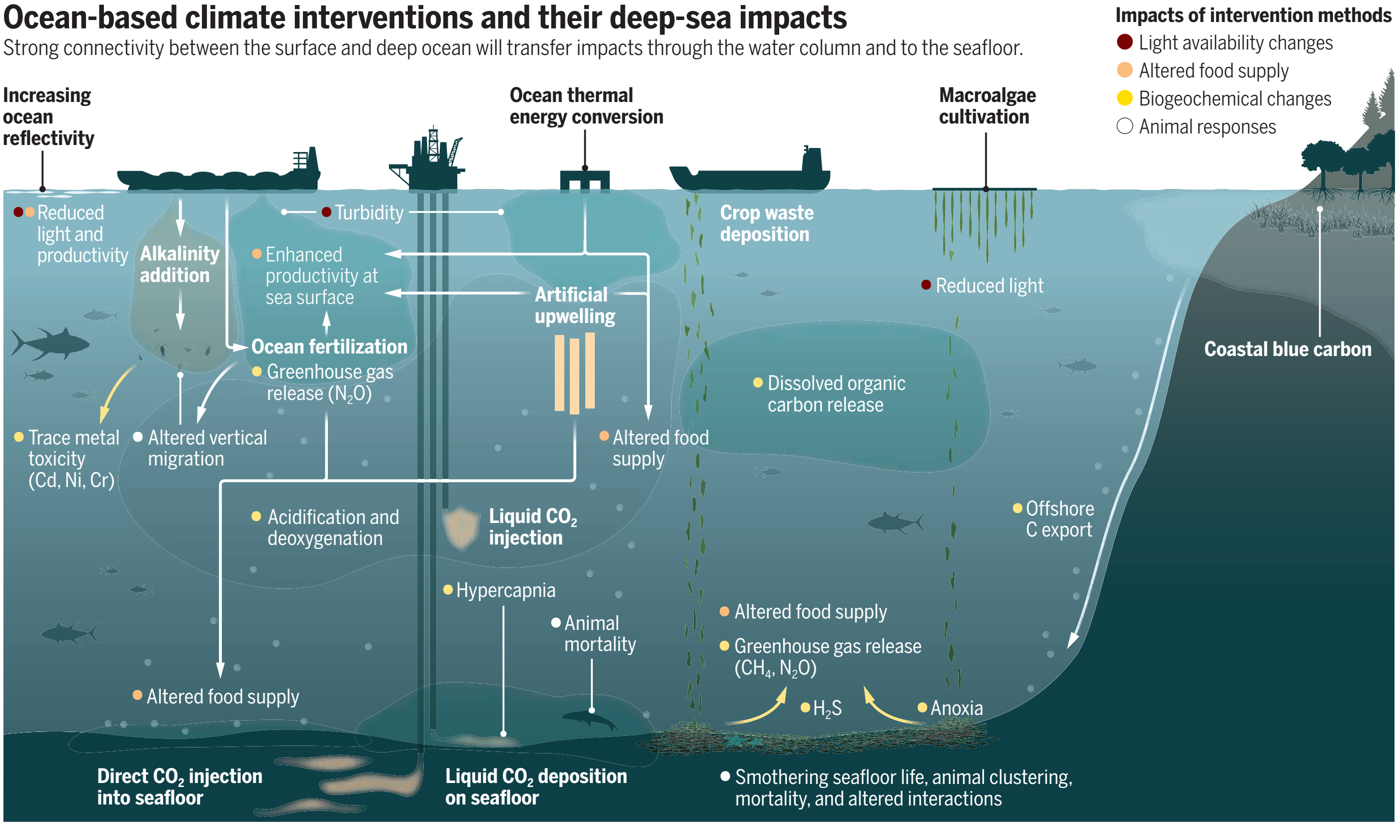

Ocean-based climate interventions and their deep-sea impacts

Strong connectivity between the surface and deep ocean will transfer impacts through the water column and to the seafloor.

GRAPHIC: A. MASTIN/SCIENCE BASED ON LEVIN ET AL.

welling, and OTEC are likely to enhance phytoplankton growth, which may increase local particulate organic carbon flux to the seabed. Extensive nitrogen and phosphorus uptake by macroalgal culture could exacerbate open-ocean nutrient limitation and lower rates of nitrogen and phosphorus recycling, which could affect nutrient stoichiometry and phytoplankton composition or productivity (*1*, *6*). These changes would alter the supply, composition, and lability of OM to the deep sea, leading to changes in food webs, communities, biodiversity, and ultimately in carbon sequestration. Macroalgae and crop waste could release particulate or dissolved OM on descent, altering microbial production, oxygen consumption, and food supply in the mesopelagic realm and beyond. Algae and crop waste may create physical resuspension and disturbance upon reaching the seabed, introduce unnatural amounts of food into a typically oligotrophic system, and smother the sediment biota. The resulting increased food supply will attract large numbers of opportunist detritivores and predators and alter species interactions. These changes could harm commercially harvested fish and invertebrates.

Hypercapnia (excessive CO_2) and deoxygenation are serious concerns. Liquid CO_2 injected just above the seabed will form a blanket that initially might suffocate biota; dilution will eventually cause differential effects on deep-sea biota (*7*). Artificial upwelling and OF-enhanced phytoplankton production will intensify oxygen consumption and increase CO_2 production in midwater, with possible negative effects on the behavior, growth, and survival of mesopelagic organisms. Decay of phytodetritus, macroalgae, or crop waste at the seafloor will deplete oxygen. At very low oxygen concentrations, biodiversity of megafauna and macrofauna is reduced and anoxia is lethal to nearly all multicellular animals. Other effects of severe oxygen depletion can include smaller body size, reduced abundance of large taxa, loss of carnivory, reduced bioturbation, and faunal emergence or avoidance (*8*). Intense organic enrichment by phytodetritus or seaweed could produce hydrogen sulfide, which is toxic to most biota, and/or methane, a potent greenhouse gas. Their release would drastically alter the species composition of the communities below these OBCI sites.

Other indirect effects on deep-ocean ecosystems may occur. If silicate materials are used for OAE, they may release associated trace elements (e.g., cadmium, nickel, or chromium) (*9*) into deeper waters and affect deep-sea biota. Additionally, proposals to use artificial upwelling from deep water as a source of nutrients for macroalgae would also exacerbate ocean acidification. Macroalgal rafts associated with AF might serve as vectors introducing coastal contaminants, microbes, parasites, and other associated species to the open ocean and potentially the deep sea.

Taken together, the changes described above may have unforeseen or unwanted consequences for critical ecosystem services provided by the deep ocean, including carbon and nutrient cycling, remineralization, pelagic and demersal fisheries production, or the support of threatened or endangered species. These indirect effects on carbon flux, transport, transformation, and burial need to be factored into assessment of scaling and effectiveness and incorporated into carbon measurement, verification, and reporting.

GOVERNANCE CHALLENGES

Given the interconnectivity of the ocean, a key governance challenge is establishing decision-making processes and standards of assessment for OBCI. Currently, OBCI-related inorganic inputs to the deep ocean (e.g., silicate, carbonate for alkalinity, iron for fertilization, or foam for albedo) occurring within national marine jurisdictions are governed by policies of individual states and by international treaties, such as the United Nations Convention on the Law of the Sea (UNCLOS), the London Convention (LC), and London Protocol (LP) (regulating dumping at sea).

Material deposited in international ocean waters will be covered by the LC and LP, with crop waste and macroalgae potentially falling under the existing categories of wastes "Organic material of natural origin" and "Uncontaminated organic material of natural origin" in Annex I of each convention, respectively (*10*), i.e., as a dumping activity. However, the LP Parties could add crop waste, macroalgae, and inorganic inputs to the new Annex 4 of the 2013 LP amendments that could then permit their regulation, as was done for inputs of iron or macronutrients associated with ocean fertilization activities (*4*). The central regulatory mechanism employed under the amendment is to require a detailed environmental assessment. However, the amendments to the Protocol have yet to enter into force. Direct CO_2 injection into the deep ocean is currently not allowed by the LP or the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) (*4*). Currently, the LC status of direct CO_2 injection from vessels or platforms is unclear. It is even less clear who would govern transfer of seawater (as in OTEC and artificial upwelling) or the culture and sinking or transport of seaweed to international waters or seabed.

These techniques may create secondary effects in other regions of the world, by interacting with one another or other deep-sea activities. The key consideration is establishing an integrated governance framework that incorporates tools such as strategic and environmental assessment, integrated ocean management techniques, and marine spatial planning (*11*). There is potential for this role to be fulfilled by institutions created under the international agreement on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ), which is currently under negotiation, and through state integrated coastal management processes. However, the proposed BBNJ treaty is not intended to override existing institutions' powers (e.g., LC or LP), and endowing international bodies with oversight powers under the treaty remains controversial.

FUTURE PERSPECTIVES

The development of a climate mitigation industry is at the core of the ecological transition that the planet needs. Research on the effectiveness and impacts of different OBCI technologies is in its infancy but is needed urgently. Owing to the unprecedented spatial scale of actions, trade-offs between avoiding dangerous impacts of climate change and OBCI-induced risk to deep-sea biodiversity and ecosystems must be carefully and transparently evaluated (*12*). For instance, experiments with OF have provided contrasting results (*13*), and there is substantial uncertainty about side effects such as oxygen decline, and production of toxic substances associated with the artificial blooms. Moreover, OBCIs should not be considered a substitute for measures to reduce CO_2 emissions (*12*).

Strategic and environmental assessment processes of OBCI activities should explicitly require examination of impacts on deep-ocean ecosystems and ocean chemistry. Baseline data should be collected and shared in standardized formats to facilitate data comparisons. Clearing-house mechanisms, such as proposed under the BBNJ Agreement, and data repositories associated with the Global Ocean Observing System and Deep Ocean Observing Strategy, can support OBCI-specific data sharing and research transparency. The Intergovernmental Panel on Climate Change could focus on assessing evidence for OBCI effectiveness.

Activities can be coordinated through ocean governance and epistemic institutions, such as LC and LP meetings of the Contracting Parties and the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), already familiar with OBCI technologies. A concerted effort is required to explore avenues of cooperation with other existing and emerging ocean governance institutions, including those contemplated under regional seas commissions, regional fisheries management organizations, and the BBNJ Agreement.

Funding to examine trade-offs and interactions between OBCIs and the risks they impose on marine ecosystems has been called for with urgency (*2*), as has the need for cross-scale governance mechanisms to achieve political consistency and efficiency. Comparative study of OBCI technologies, and development, deployment, experimentation, and scaling of such technologies, can guide prioritization, managerial, and research governance actions. Calls for a research code of conduct for OBCI highlight the principle "do no significant harm" for marine biodiversity and ecosystems (*14*).

The urgency of the climate crisis demands an accelerated, focused research effort on the effects of OBCI techniques on deep-ocean physical and chemical properties and on deep-sea ecosystems and their services. This will require partnering of academic deep-sea scientists and engineers, nascent or existing industries promoting the technologies, regulators, and funders. This effort, grounded on the ocean-focused Sustainable Development Goal 14 (SDG 14), should ensure that OBCI activities do not work against SDG 14 targets that address pollution (14.1), adverse impacts to ecosystems (14.2), and acidification (14.3). The UN Decade for Ocean Science Collaborative Center for Ocean-Climate Solutions has started to identify research needs related to OBCI, but with each technology treated in isolation.

We call for a holistic approach to consider deep-sea consequences of all OBCI together. A transdisciplinary, international, and transparent framework is needed, similar to recommendations made for solar geoengineering research (*15*). The requirement for rapidly generated, quantitative, interoperable data across technologies leads us to recommend an integrated, coordinated approach to observation, experimentation, and modeling that includes the early integration of ecological, social, economic, and legal considerations and engages local communities and traditional knowledge holders (*2*). Together these actions will allow for the design of climate solutions able to "do no significant harm" and provide evidence-based support to policy-makers. ■

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