DEEP-OCEAN STEWARDSHIP INITIATIVE

POLICYBRIEF

Deep Ocean Climate Intervention Impacts

DECEMBER 2021

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Ocean Fertilization

The Concept:

Ocean fertilization is an attempt to stimulate primary production in the surface ocean to take advantage of the natural process that moves carbon from the atmosphere to the deep sea. Phytoplankton remove atmospheric carbon dioxide (CO_2) through photosynthesis and convert it into biomass. Their dead bodies that are not remineralized in the surface mixed layer are exported into the deep ocean and ultimately to the deep seafloor as marine snow (particulate organic carbon flux) via the ocean biological pump (McClain, 2010; Fig. 1). Phytoplankton need key elements (e.g., iron, nitrogen, or phosphorus), and the addition of those in areas where they are depleted has been proposed to stimulate phytoplankton growth, enhancing CO_2 uptake and, in consequence, the carbon export to the deep sea as a method to actively remove atmospheric CO_2 (Yoon et al., 2018). Ocean iron fertilization (OIF) is the best studied approach (Wallace et al., 2010) but the addition of nitrate and phosphate has been also proposed and seems technically plausible yet immature (Jones and Young, 1997; Harrison, 2017).

Key Points

- Ocean fertilization stimulates phytoplankton growth, potentially enhancing atmospheric CO_2 removal and subsequent sequestration in the deep sea.
- Fertilization of very large areas (e.g., the entire Southern Ocean) during multiple years/decades would be required for significant amounts of carbon sequestration.
- The potential excess of organic matter in the water column and in deep seafloor environments can induce deoxygenation.
- Under most circumstances a very limited amount (~2%) of carbon will reach the deep-sea floor and ~0.2% will be preserved in the sediment.
- Carbon produced through ocean fertilization and decayed in the water column will eventually go back to the atmosphere. This will take anywhere from decades to a millennium depending on the location of the fertilization activity, but half will be retained for less than 150 years in most places.
- Because particulate organic carbon flux supplies food to the deep sea, it is considered a main factor controlling various aspects of deep-sea ecosystems. Thus, ocean fertilization can alter biogeochemical cycling, change deep-sea ecosystem structure fundamentally, and may cause homogenization (reduced regional differences) or loss of ecosystem services.

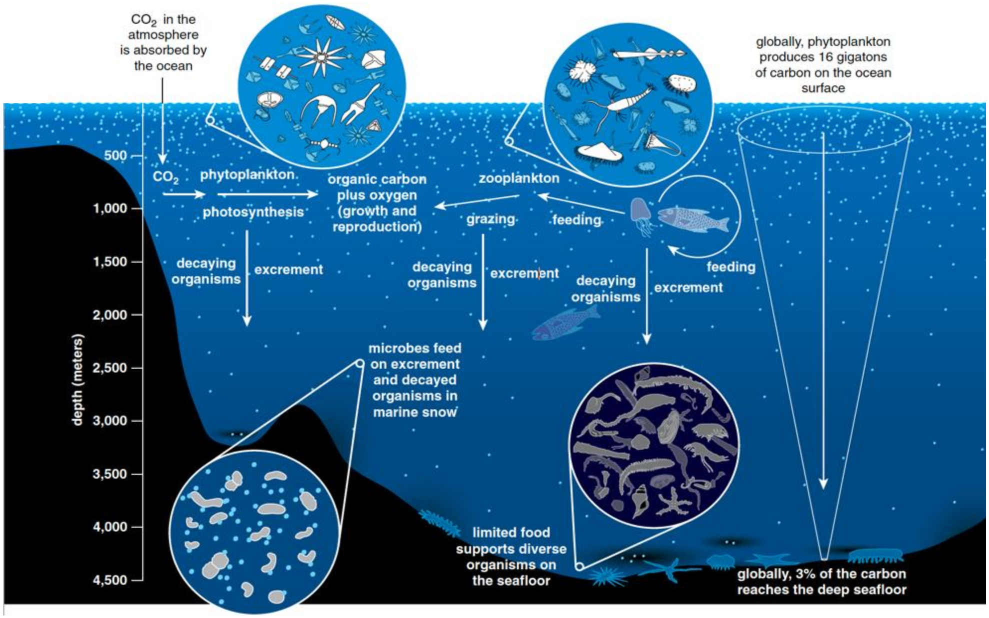

Fig. 1 Elements of the biological pump (Fig. 1 From McClain (2010) American Scientist)

Scaling and Effectiveness

The subarctic Northern Pacific, Eastern Equatorial Pacific and Southern Ocean are high-nutrient, low-chlorophyll regions where iron scarcity limits phytoplankton growth, and thus have been proposed for OIF (Yoon et al., 2018, GESAMP, 2019). An area as large as the entire Southern Ocean would be required to be fertilized during multiple years/decades for significant carbon removal (Sarmiento and Orr, 1991; Oschlies et al., 2010; GESAMP, 2019).

Experiments suggest that OIF may create phytoplankton blooms (Fig. 2) and increase carbon export but reported estimates vary dramatically between experiments (~15 to 200-300% increases). The most critical factor for OIF effectiveness is that carbon has to be exported below the winter mixed layer depth for long-term sequestration (~1000 years). Only the EIFEX experiment reported significant carbon export at enough depth (>3000 m) for long-term sequestration (Smetacek et al., 2012; Yoon et al., 2018). Other factors compromised deep-sea carbon export effectiveness in OIF experiments, such as low silica concentrations (limiting phytoplankton growth factor), and high rates of zooplankton predation on phytoplankton (Yoon et al., 2018). Modeling of carbon remineralization and export via the biological pump suggests that the influence of OIF on atmospheric CO_2 levels will be short term, with median carbon sequestration times for most of the ocean being less than 100 or 150 years (Seigel et al., 2021; Fig. 3).

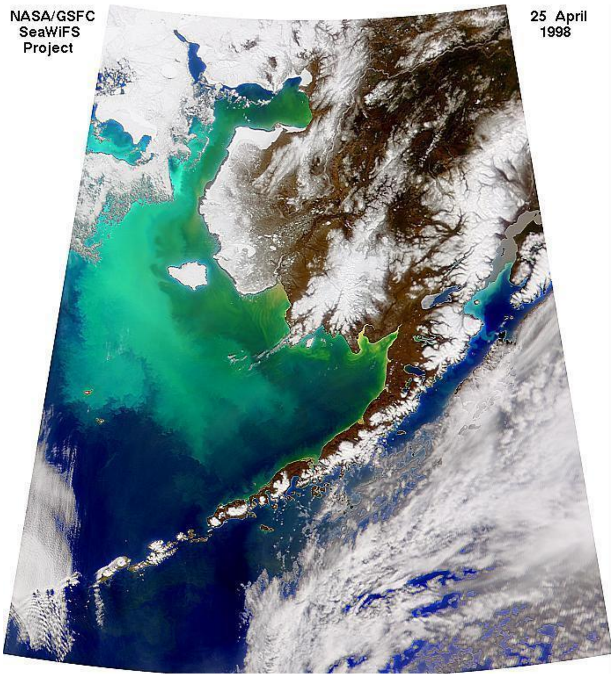

Fig. 2 An aerial image of a plankton bloom, such as would be stimulated by ocean fertilization. (Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE) https://commons.wikimedia.org/wiki/File:Coccolithophore_bloom.jpg

Carbon-removal effectiveness may also be offset by the production of nitrous oxide (N_2O) and methane (CH_4) due to bacterial remineralization; these have ~300 and ~20 times greater warming potential than CO_2, respectively (Yoon et al., 2018). The production of CH_4 may offset ~1% OIF carbon removal, however, OIF N_2O production may offset from 5 to >40% OIF carbon removal. Oxygen depletion in the water column following OIF may also diminish carbon removal effectiveness. The production of dimethyl sulfide, a cloud-formation compound, as a OIF byproduct would have positive effects for the purpose of decreasing global warming although it is considered an unresolved topic (Yoon et al., 2018).

Physical, Biogeochemical, and Ecological Impacts

Ocean fertilization will increase seafloor sedimentation of particulate organic carbon and inorganic compounds derived from phytoplankton and zooplankton dead bodies. The increased particulate organic carbon flux may increase bacterial remineralization leading to deoxygenation in the water column, especially in the oxygen minimum zone and in benthic environments (Breitburg et al., 2018; Yoon et al., 2018; Yasuhara et al., 2019). Increased carbon levels in deep-ocean waters may enhance the productivity of ecosystems in other remote regions where these waters are eventually returned to the surface ocean by upwelling or mixing (Siegel et al., 2021). The alteration of natural phytoplankton communities may result in changes in the seasonality of particulate organic carbon flux to the deep-sea floor (benthic-pelagic coupling) and in compositions of phytoplankton species in the marine snow, potentially impacting deep-sea benthic communities that rely on food from the ocean surface (Billet et al., 1983; Gooday, 1988; Graf, 1989; Ruhl and Smith, 2004; Nomaki et al., 2021). It is likely that enhanced carbon flux to the seafloor may change deep-sea benthic biomass, species composition and community structure (Smith et al., 2008; Lampit et al., 2008; Wolff et al., 2011; Nomaki et al., 2021).

Ecosystem Impacts and Services

Large-scale fertilization could have unintended and difficult-to-predict impacts not only locally, but also at great distances in space and time. Halogenated volatile compound production, well known for ozone layer destruction capacity, has been measured, though not consistently, during some OIF experiments (Yoon et al., 2018). Fertilization may lead to harmful algal blooms (Silver et al., 2010; Trick et al., 2010; Yoon et al, 2018) negatively impacting pelagic fisheries, marine mammals and turtles, and pelagic taxa in general. The larvae of benthic species that develop in surface waters could be affected.

The enhanced carbon flux to the seafloor could increase seafloor biomass and biodiversity as long as oxygen is not depleted in oligotrophic regions and/or very deep basins where little organic carbon flux arrives (Wei et al., 2011; Williamson et al., 2012). However, it can negatively affect biodiversity in regions with naturally high organic carbon flux (Yasuhara et al., 2009; Jöst et al., 2019; Tittensor et al., 2011).

Deep-sea canyons and trenches, where organic matter accumulation is high (Itoh et al., 2011; Liao et al., 2020), may have unpredicted responses to ocean fertilization. Enhanced marine snow flux may also change benthic communities functionally (Kuhnz et al., 2020), likely altering ecosystem functioning and perhaps services such as efficiency of biogeochemical cycling.

Governance

Ocean fertilization will be governed by both international and domestic law as well as customary international law, with the applicability of rules being dependent to some degree on both the effect of the activity and how and where the activity is carried out. While ocean fertilization activities could occur within the territorial sea or exclusive economic zones of states where they will be subject to domestic as well as international regulation, most of these activities seem likely to take place on the high seas.
The key international instruments are:

- UN Convention on the Law of the Sea (UNCLOS).
- Convention on Biological Diversity (CBD).
- London Convention 1972 (LC) and the London Protocol 1996 (LP).

A separate Policy Brief will address the requirements of these international instruments that apply to the climate intervention techniques covered in the Policy Briefs. There is no attempt to cover domestic legislation since that would be a huge and challenging task on a global scale.

Uniquely amongst the techniques covered in this series of Policy Briefs, ocean fertilization is covered by specific non-binding resolutions and amendments addressing ocean fertilization from the London Convention/London Protocol (LC/LP) and the Convention on Biodiversity (CBD). These resolutions and amendments are covered in detail in the Governance Policy Brief but an outline of them is given below.

The LC/LP Parties have adopted non-binding resolutions specifically addressing ocean fertilization. They adopted a non-binding resolution on ocean fertilization in November 2008 (Resolution LC-LP.1, 2008) that stated, *"Given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed"*. In October 2010 the LC/LP Parties adopted the Ocean Fertilization Assessment Framework for assessing field research experiments (Resolution LC-LP.2, 2010). The non-binding resolutions, in addition to supporting the interpretation of the treaties, set clear political expectations that only ocean fertilization that is characterized as legitimate scientific research is allowable, and that legitimacy at a minimum requires adherence to the Ocean Fertilization Assessment Framework.

In October 2013, the LP Parties adopted a legally binding decision on marine geoengineering (Resolution LP.4 (8) that amends the Protocol by prohibiting listed forms of marine geoengineering unless they are authorized in accordance with the requirements of the LP. Ocean fertilization is identified as a prohibited form of marine geoengineering. However, the amendment states that *"An ocean fertilization activity may only be considered for a permit if it is assessed as constituting legitimate scientific research taking into account any specific placement assessment framework."* The amendment further specifies the requirements for prior assessment. These amendments have yet to enter into force.

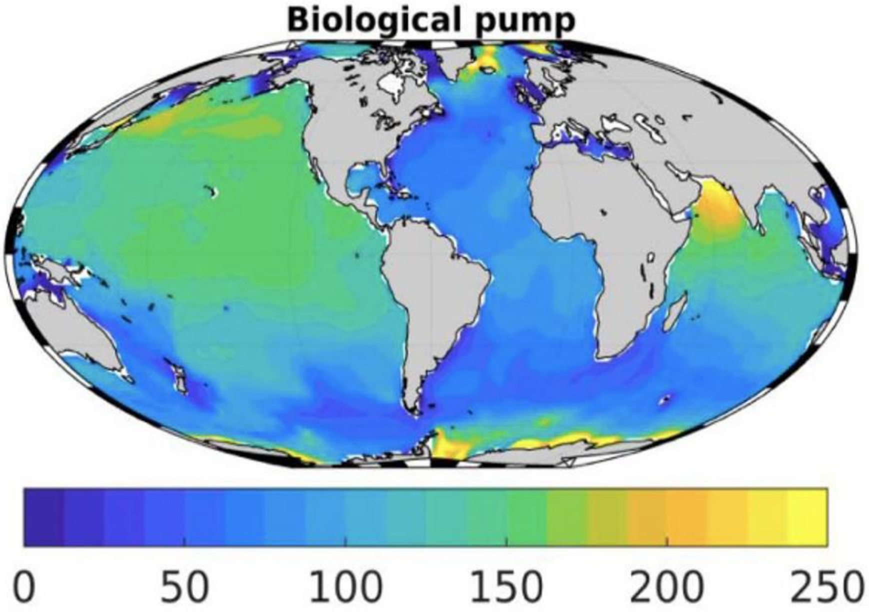

Fig. 3 Variation in sequestration time for carbon fixed through photosynthesis near the surface prior to returning to the atmosphere. Projections of export and remineralization to depth follow the Martin curve. Modified from Fig 3 in Siegel et al. (2021).

In 2008, the CBD adopted Decision IX/16 C to *"…ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities; with the exception of small-scale scientific research studies within coastal waters…"*. This decision is not legally binding. The CBD also adopted non-legally binding Decision X/33(8)(w) in 2012 that covered all climate-related geoengineering activities.

Exploratory Practitioners and Research

A legal framework was put in place in 2013 to prevent venture capitalists from deploying large-scale ocean iron fertilization in any marine waters covered by the London Protocol due to the unknowns involved and the potential threat of commercialization and large-scale damage inflicted on the environment (see LP Resolution LP.4(8) referred to in the Governance section above). This legal framework also applied to large-scale experimentation. In 2002, the Patent number: 6440367 was Assigned to GreenSea Venture, Inc. as a Method of sequestering carbon dioxide with a fertilizer comprising chelated iron (**https://patents.justia.com/assignee/greensea-venture-inc** visited 31 October, 2021). In 2007, a few commercial companies (e.g., Climos, **http://www.climos.com**, last access: 31 October 2021) were searching for funds to promote large-scale commercial ocean iron fertilization as a climate mitigation strategy and as a means to gain carbon credits (Freestone and Rayfuse, 2008). OIF remains controversial with various OIF actions or technologies within EEZs having been attempted (Buck et al., 2018, proposed and denied (Tollefson, 2018; **https://www.geoengineeringmonitor.org/2018/07/pirates-of-the-pacific/** access 31 October 2021) or being developed (**https://www.oceaneos.org/company/**).

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How to cite:

DOSI (2021). "Impacts of Ocean Fertilization." Deep Ocean Stewardship Initiative Policy Brief. **https://www.dosi-project.org/wp-content/uploads/Ocean-Fertilization-Policy-Brief.pdf**

DEEP-OCEAN STEWARDSHIP INITIATIVE

ABOUT DOSI

The Deep-Ocean Stewardship Initiative seeks to integrate science, technology, policy, law and economics to advise on ecosystem-based management of resource use in the deep ocean and strategies to maintain the integrity of deep-ocean ecosystems within and beyond national jurisdiction.

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