DEEP-OCEAN STEWARDSHIP INITIATIVE

POLICYBRIEF
Deep Ocean Climate Intervention Impacts
DECEMBER 2021

Deep Ocean Climate Intervention Impacts

Macroalgal and Crop-Waste Deposition into Deep Water

The Concept:

Algae and plants, including the brown algae called kelp (Fig. 1), remove carbon dioxide (CO_2) from the atmosphere through photosynthesis and convert it into organic matter. Cultivation of macroalgae such as kelp (inshore and offshore) (Fig. 2) and sinking it into the deep ocean below 1000 m has been proposed for CO_2 sequestration (Ocean Visions, 2021). Similarly, sequestration of ballast bales of crop residues (corn, soya, etc.) have been proposed for burial in the deep ocean (>1000-1500m depth) (Strand and Benford, 2009; Keil et al., 2010; GESAMP, 2019). A related proposal is to dispose of bales off the deltas of major rivers carrying substantial sediment loads, where the crop residues would be rapidly buried by newly deposited sediments (Strand and Benford, 2009; GESAMP, 2019).

Key Points

- Very large areas would be required to be used to produce significant amounts of macroalgae for CO_2 sequestration in the deep ocean that would be sequestered for several hundred years to a maximum of ~1500 years unless incorporated in deep-sea sediments when it could be sequestered for geological timescales.

- There is potential for massive nutrient depletion by macroalgae to cause local declines in phytoplankton production, leading to carbon sequestration tradeoffs, alteration of the biological pump and removal of large amounts of nutrients to the deep ocean, potentially perturbing global oceanic nutrient cycles.

- Free floating rafts of macroalgae could facilitate the introduction of non-native species into new areas of the ocean and may interfere with marine mammal or turtle migrations, and other anthropogenic ocean uses such as shipping and fishing.

- Introducing large amounts of macroalgae/crop waste to the deep-sea floor would temporarily create "reefs" and substrate in the deep sea, altering the physical dynamics of the benthic boundary layer; increase the supply of organic matter in a typically food-poor environment, very likely altering ecological interactions and equilibria; and bury or smother benthic fauna in areas of consolidated waste disposal.

Fig. 1 Macrocystis pyrifera kelp forest at San Clemente Island, southern California, USA. This is a rapidly growing species that is often naturally exported into deep waters off the narrow California shelf. Photograph courtesy of Eric Hanauer.

- The physical and biogeochemical changes in benthic habitats are expected to decrease biodiversity, and alter biomass, species composition and density.

- Carbon will be initially released by decomposition of sinking algae or via resuspended seafloor sediments and later by microbial decay of deposited organic matter. Ensuing oxygen consumption by bacteria and archaea will yield sub-oxic or anaerobic conditions, with release of CO_2, methane, sulfide, nitrous oxide, reduced sediment pH, affecting seafloor functioning and bentho-pelagic communities.

- Deposition of algae or crop waste seems likely to be covered by the existing provisions of the London Convention/London Protocol, allowing disposal of such material at sea to be permitted subject to satisfactory assessments.

Scaling and Effectiveness

A significant amount of macroalgae naturally enters the deep sea as drift material, with estimates of 61–268 TgC/yr (Krause-Jensen and Duarte, 2016) and a range of invertebrates are capable of consuming the algae or the invertebrates that eat it (Fig. 3). Active macroalgal culture and sinking can potentially greatly magnify this quantity. It has been proposed that removal of 1GT/yr of carbon by macroalgae would require ocean culture of an area of about 667,000 km^2 (based on Carlos Duarte's figure of 1500 t/ km^2/yr in his NASEM presentation: (**https://www.nationalacademies.org/event/02-02-2021/a-research-strategy-for-ocean-carbon-dioxide-removal-and-sequestration-workshop-series-part-3**).

Carbon could be sequestered for hundreds to thousands of years, or even longer if buried in deep sediments (Ocean Visions, 2021). However, if macroalgal material is not buried but consumed by macro or micro biota, then the turnover time of the ocean varying from several hundred years to a maximum of ~1500 years for the deep Pacific Ocean would return the carbon to the surface eventually. Notably, it is less in other parts of the deep ocean and can be much less if the organic material is placed at shallower depths (see Khatiwala et al., 2012; DeVries and Primeau, 2011; Robinson et al., 2014; and Siegel et al., 2021). Questions arise regarding the cost per carbon removed. Even the lowest estimates ($200/ton) make macroalgal culture removal twice as expensive as carbon removal factories (Temple, 2021).

Deep ocean crop residue sequestration could reduce annual global CO_2 accumulation by up to 15%, possibly for millennia (Strand and Benford, 2009). Coverage could be 260 km^2/yr to deposit 30% of US crop residue in an annual layer 4 m deep – removing 0.15 Gt or 1000 km^2 to remove 30% of global annual crop residues (0.6 GtC).

Fig. 2 Representative macroalgal farm
https://steemitimages.com/DQmWe8YouYDHu6w74ui6CVEFZo6pbimQJeiW3m1ZVa97Lme/image.png

Physical, Biogeochemical, and Ecological Impacts

This massive cultivation of macroalgae, which consumes nitrogen and phosphorus from the surrounding waters, would almost certainly reduce phytoplankton production in the vicinity, and cancel some macroalgal carbon removal by increased growth of hosted calcified organisms (Bach et al., 2021). This could affect the planktonic larvae of deep benthic species that develop in near surface waters. Also, very large-scale macroalgae farms could perturb global oceanic nutrient cycles by moving large amounts of organic matter into the deep ocean. 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). While the pumping up of deep ocean water could supply nutrients for macroalgae farms, the effects of this on the global nutrient cycles would need to be researched. The presence of massive amounts of macroalgae at the sea surface will reduce the ocean albedo leading to less reflectance of sunlight and greater heat uptake of surface waters (Bach et al., 2021).

Macroalgae are known to release bromoform and other halomethanes (Carpenter et al., 2009 and Mehlmann et al., 2020) and thus, large-scale macroalgae cultivation seems likely to increase the release of these substances. This needs additional research as the natural marine sources of these gases are currently estimated to be responsible for around 9% of stratospheric ozone loss, including depletion due to anthropogenic causes (Tegtmeier et al., 2015) and they contribute to global warming. The scale of this effect compared to the potential benefits of carbon sequestration need to be researched.

We do not know how fast the macroalgae will sink and consequently how much degradation might occur in the water column. If a significant amount of degradation occurs in the water column, it will add nutrients to those water masses and reduce oxygen levels. Algae and plants may act as transport of pollutants, and other noxious compounds, from the ocean surface/land to the deep sea when sunk.

The process of organic bundle deposition on the deep seabed could resuspend sediments and cause disruption of the seafloor. Bathymetry and current directions will influence both the fate of released macroalgae and crop waste and of resuspended sediments. At the same time, large amounts of bundled macroalgae and crop waste would temporarily create reefs and substrate in the deep sea, altering the physical dynamics of the benthic boundary layer. The interface between sediment and water column is a region of increased carbon processing and disturbing and smothering this environment may result in reduced capacity for natural sedimentation and hence carbon sequestration.

Burial and smothering of benthic fauna will be almost total in areas of consolidated waste disposal. Macroalgal material seems likely to be more rapidly degradable than crop wastes but probably less degradable than material from the natural background flux of phyto/zooplankton. Introducing large amounts of organic matter in a typically food-poor environment will very likely alter ecological interactions and equilibria. 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; Lampitt et al., 2008; Wolff et al., 2011; Nomaki et al., 2021, Harbour et al., 2021).

Carbon will be initially released by suspended sediments and later by microbial decay of deposited organic matter. Ensuing oxygen consumption by bacteria and archaea may yield sub-oxic or anaerobic conditions, with release of CO_2, methane, sulfide, nitrous oxide, reduced sediment pH, affecting seafloor and bentho-pelagic communities. It is unclear whether the resulting greenhouse gases will remain at depth, if or how soon they would return to surface waters and the atmosphere, and thus create negative climate feedbacks, impacting the Carbon Dioxide Removal.

Ecosystem Impacts and Services

Free floating rafts of macroalgae will facilitate the introduction of non-native species into new areas of the ocean. Large areas of algal rafts may also interfere with marine mammal or turtle migrations, or preclude other anthropogenic ocean uses such as shipping and fishing. There is potential for massive nutrient depletion by macroalgae to cause local declines in phytoplankton production, leading to carbon sequestration tradeoffs and alteration of the biological pump. The alteration of the phytoplankton community may negatively affect benthic communities and species depending on certain phytodetritus composition (Smith et al., 2008; Nomaki et al., 2021). The physical and biogeochemical changes in benthic habitats are expected to decrease biodiversity, alter biomass, species composition and density. Infauna will be killed completely in the deposition area by the waste burial process, smothering or chemical changes unless the deposited material is spread widely. Some animals at depth readily find and consume macroalgal detritus (e.g., pink urchins on the California margin; Sato et al., 2017). The appearance of fast-growing species and opportunists that feed on the organic matter may raise biomass and alter food webs (Harbour et al., 2021). Chemosynthetic communities (dependent on methane and hydrogen sulfide) are likely to develop in macroalgae/crop waste (Bernardino et al., 2010). Duration of effects may persist longer for crop waste than macroalgae, which is more degradable but probably less degradable than material from phyto/zooplankton.

If deposition takes place on the continental margin (e.g., at river mouths) or near seamounts, this could affect bottom fisheries through the loss of habitat, nursery grounds, or food supply for demersal species. Other lost services could include disruption of natural carbon sinks and burial processes, or elimination of genetic resources; but added organic matter to the deep sea could provide food for some benthic and demersal species.

Given that processes taking place at, and impacts derived from, macroalgae cultivation will be at large scales, there are several key physical, biogeochemical and biological impacts that would require small/medium-scale field experiments and modelling to scale-up their implications at regional/basin scale.

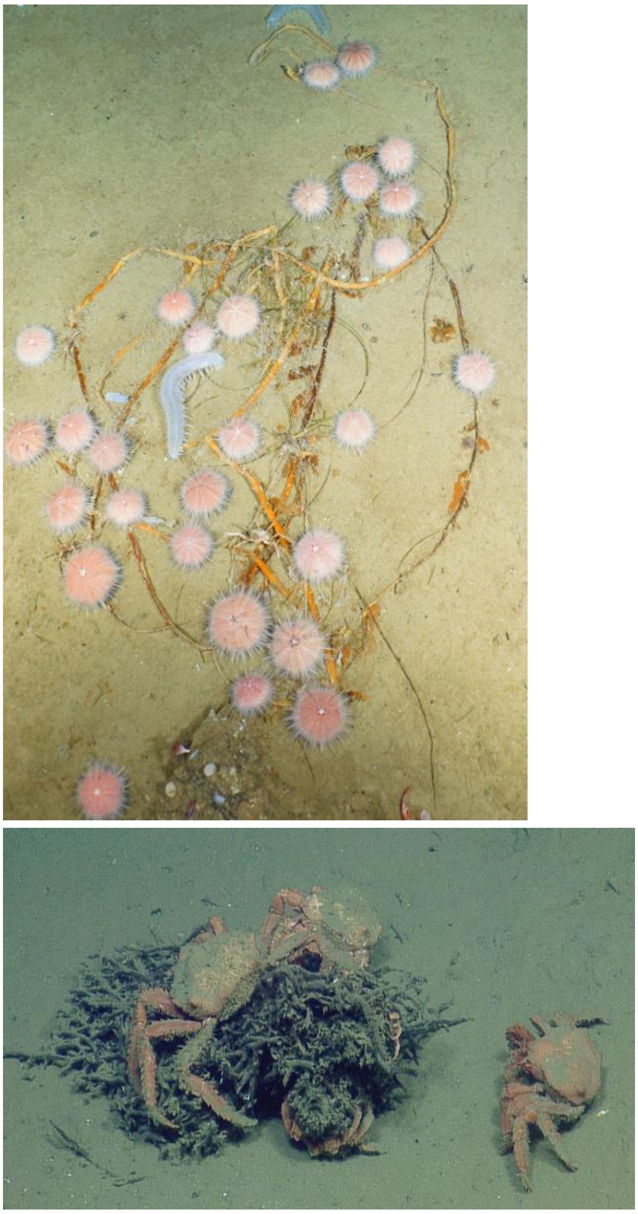

Fig. 3. Examples of kelp and its consumers occurring naturally on the deep-sea floor off southern California. A. Crabs on a Macrocystis holdfast at Palos Verdes margin, Aug. 2015, approx. 783 m; B. Pink urchins consuming Macrocystis at Patton Ridge ~700 m. Images taken Oct. 2020 from Nautilus 124, Dive H1844; L Levin Chief Scientist, courtesy of Ocean Exploration Trust and NOAA Office of Ocean Exploration and Research.

Governance

Macroalgae cultivation and the deposition of algae or crop wastes 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 the activity is carried out. While macroalgae and crop waste depositions are often likely to occur within the territorial sea or exclusive economic zones of states where they will be subject to domestic as well as international regulation, some proponents of macroalgal sequestration are proposing these activities take place on the high seas. As both cultivation and deposition have the potential to adversely affect the marine environment, both methods are potentially subject to customary and treaty laws addressing marine pollution. Note that some proponents of macroalgal sequestration are proposing to pump up sea water from the deep water to supply nutrients to fertilize the macroalgae and this then would seem likely to be considered an ocean fertilization activity.

The key international instruments are:

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

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

Exploratory Practitioners and Research

A number of emerging entrepreneurs are exploring different business models to scale seaweed production and demand for products (carbon credits, high value bio-products, bioenergy) (e.g., C-Combinator, Running Tide Technologies, Ocean Rainforest, The Climate Foundation, Catalina Sea Ranch, Seakura, GreenWave, KelpBlue, SeaFarm, Fearless Fund). Also, https://pulltorefresh.team/, South Pacific Marine Park https://southpacificmarinepark.com/ and Marine BioEnergy https://arpa-e.energy.gov/mariner-annual-review-2021/marine-bioenergy (Ocean Tides Road Map). Additional proposals are to store lumber wastes in deep Norwegian fjords (Zimmerman and Cornelissen, 2018) – and to sequester pellets of biocoal on the ocean floor (Miller and Orton, 2021).

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.

This policy brief was prepared by:
Dr Lisa A. Levin, Scripps Institution of Oceanography, UC San Diego, USA
Dr Chris Vivian, Co-chair GESAMP Working Group 41
Dr Henk-Jan Hoving, GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
Dr Joan M. Alfaro-Lucas, Senckenberg Research Institute and Natural History Museum, Frankfurt am Main, Germany
Dr Neil Craik, School of Environment, Enterprise and Development, University of Waterloo, Canada
John Davis, Open Communications for The Ocean (OCTO)

Contact: dosi@soton.ac.uk

How to cite:

DOSI (2021). "Impacts of Macroalgal and Crop-Waste Deposition into Deep Water." Deep Ocean Stewardship Initiative Policy Brief. https://www.dosi-project.org/wp-content/uploads/Macroalgae-Crop-Deposition-Policy-Brief.pdf

DOSI
DEEP-OCEAN STEWARDSHIP INITIATIVE

References to support this policy brief

Bach, L.T., Tamsitt, V., Gower, J., Hurd, C.L., Raven, J.A. and Boyd, P.W. (2021). Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. *Nature Communications* 12: 2556. doi: **https://doi.org/10.1038/s41467-021-22837-2.**

Bernardino, A.F., Smith, C.R., Altamira, I., Baco-Taylor, A.R. and Sumida. P. (2010). Macrofaunal succession in sediments around kelp and wood falls in the deep NE Pacific and community overlap with other reducing habitats. *Deep-Sea Research I: Oceanographic Research Papers* 57: 708–723. doi: **https://doi.org/10.1016/j.dsr.2010.03.004.**

Carpenter, L.J., Jones, C.E., Dunk, R.M., Hornsby, K.E. and Woeltjen, J. (2009). Air-sea fluxes of biogenic bromine from the tropical and North Atlantic Ocean. *Atmospheric Chemistry and Physics* 9: 1805–1816. doi: **https://doi.org/10.5194/acp-9-1805-2009.**

DeVries, T. and Primeau, F. (2011). Dynamically and Observationally Constrained Estimates of Water-Mass Distributions and Ages in the Global Ocean. *Journal of Physical Oceanography* 41: 2381–2401. doi: **https://doi.org/10.1175/JPO-D-10-05011.1.**

GESAMP (2019). High level review of a wide range of proposed marine geoengineering techniques. (Boyd, P.W. and Vivian, C.M.G., eds.). (IMO/FAO/UNESCO- IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). *GESAMP Reports and Studies* 98: 144 p. **http://www.gesamp.org/site/assets/files/1996/rs98e-1.pdf**

Ginzky, H. and Frost, R. (2014). Marine Geo-Engineering: Legally Binding Regulation under the London Protocol. *Carbon & Climate Law Review* 8: 82–96. **http://www.jstor.org/stable/24323921.**

Ginzky, H. (2018). Marine Geo-Engineering. In: Salomon M. and Markus, T. (Eds.) Handbook on Marine Environment Protection: Science, Impacts and Sustainable Management. Springer, Cham. Pp. 997–1011. doi: **https://doi.org/10.1007/978-3-319-60156-4_53.**

Harbour R.P., Smith, C.R., Simon-Nutbrown, Cecchetto, C.M., Young, E., Coral, C. and Sweetman, A.K. (2021). Biodiversity, community structure and ecosystem function on kelp and wood falls in the Norwegian deep sea. *Marine Ecology Progress Series* 657: 73–91. doi: **https://doi.org/10.3354/meps13541.**

Keil, R.G., Nuwer, J.M., and Strand, S.E. (2010). Burial of agricultural byproducts in the deep sea as a form of carbon sequestration: A preliminary experiment. *Marine Chemistry* 122: 91–95. doi: **https://doi.org/10.1016/j.marchem.2010.07.007**

Khataiwala, S., Primeau, F. and Holzer, M. (2012). Ventilation of the deep ocean constrained with tracer observations and implications for radiocarbon estimates of ideal mean age. *Earth and Planetary Science Letters* 325/326: 116–125. doi: **https://doi.org/10.1016/j.epsl.2012.01.038.**

Krause-Jensen, D., and Duarte, C.M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience* 9: 737–742. **https://doi.org/10.1038/ngeo2790.**

Lampitt, R.S., Achterberg, E.P., Anderson, T.R., Hughes, J.A., Iglesias-Rodriguez, M.D., Kelly-Gerreyn, B.A., Lucas, M., Popova, E.E., Sanders, R., Shepherd, J.G., Smythe-Wright, D. and Yool, A. (2008). Ocean fertilization: a potential means of geoengineering? *Philosophical Transactions of the Royal Society A* 366: 3663919–3945. doi: **https://doi.org/10.1098/rsta.2008.0139.**

Mehlmann, M., Quack, B., Atlas, E., Hepacha, H. and Tegtmeier, S. (2020). Natural and anthropogenic sources of bromoform and dibromomethane in the oceanographic and biogeochemical regime of the subtropical North East Atlantic. *Environmental Science: Processes and Impacts* 22: 679–707. doi: **https://doi.org/10.1039/C9EM00599D.**

Miller, L.A. and Orton, P.M. (2021). Achieving negative emissions through oceanic sequestration of vegetation carbon as pellets. *Climatic Change* 167: 29. doi: **https://doi.org/10.1007/s10584-021-03170-5**

Nomaki, H., Rastelli, E., Ogawa, N.O., Matsui, Y., Tsuchiya, M., Manea, E., Corinaldesi, C., Hirai, M., Ohkouchi, N., Danovaro, R., Nunoura, T., and Amaro, T. (2021). In situ experimental evidences for responses of abyssal benthic biota to shifts in phytodetritus compositions linked to global climate change. *Global Change Biology* 00: 1–17. doi: **https://doi.org/10.1111/gcb.15882.**

Ocean Visions (2021). Ocean-Based Carbon Dioxide Removal: Road Maps 'Macroalgae Cultivation and Carbon Sequestration' **https://oceanvisions.org/roadmaps/macroalgae-cultivation-carbon-sequestration/**

Robinson, J., Popova, E.E., Yool, A., Srokosz, M., Lampitt, R. S. and Blundell, J. R. (2014). How deep is deep enough? Ocean iron fertilization and carbon sequestration in the Southern Ocean. *Geophysical Research Letters* 41: 2489–2495. doi: **https://doi.org/10.1002/2013GL058799.**

Sato, K.N., Powell, J., Rudie, D. and Levin, L.A. (2017). Evaluating the promise and pitfalls of a potential climate change–tolerant sea urchin fishery in southern California. *ICES Journal of Marine Science* 75: 1029–1041. doi: **https://doi.org/10.1093/icesjms/fsx225.**

Siegel, D.A., DeVries, T., Doney, S.C. and Bell, T. (2021). Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. *Environmental Research Letters* 16: 104003. doi: **https://doi.org/10.1088/1748-9326/ac0be0.**

Silverman-Roati, K., Webb, R.M., and Gerrard, M.B. (2021). Removing Carbon Dioxide Through Seaweed Cultivation: Legal Challenges and Opportunities. *Sabin Center for Climate Change Law,* September 2021 **https://climate.law.columbia.edu/sites/default/files/content/Webb%20et%20al%20-%20Removing%20CO2%20Through%20Ocean%20Alkalinity%20Enhancement%20and%20Seaweed%20Cultivation%20-%20Feb.%202021.pdf**

Smith, C.R., De Leo, F.C., Bernardino, A.F., Sweetman, A.K., and Martinez Arbizu, P. (2008). Abyssal food limitation, ecosystem structure and climate change. *Trends in Ecology and Evolution* 23: 518–28. doi: **https://doi.org/10.1016/j.tree.2008.05.002.**

Strand, S.E. and Benford, G. (2009). Ocean sequestration of crop residue carbon: recycling fossil fuel carbon back to deep sediments. *Environmental Science and Technology* 43: 1000–1007. doi: **https://doi.org/10.1021/es8015556.**

Tegtmeier, S., Ziska, F., Pisso, I., Quack, B., Velders, G. J. M., Yang, X. and Krüger, K. (2015). Oceanic bromoform emissions weighted by their ozone depletion potential. *Atmospheric Chemistry and Physics* 15: 13647–13663. doi: **https://doi.org/10.5194/acp-15-13647-2015**

Temple, J. (2021). MIT Technology Review. Companies hoping to grow carbon-sucking kelp may be rushing ahead of the science. **https://www.technologyreview.com/2021/09/19/1035889/kelp-carbon-removal-seaweed-sinking-climate-change/.**

Wolff, G.A., Billett, D.S.M., Bett, B.J., Holtvoeth, J., FitzGeorge-Balfour, T., Fisher, E.H., Cross, I., Shannon, R., Salter, I., Boorman, B., King, N.J., Jamieson, A. and Chaillan, F. (2011) The Effects of Natural Iron Fertilisation on Deep-Sea Ecology: The Crozet Plateau, Southern Indian Ocean. *PLoS ONE 6*: e20697. doi: **https://doi.org/10.1371/journal.pone.0020697.**

Zimmerman, A.R. and Cornelisseen, G. (2018). Consider fjord-assisted carbon storage. *Environmental science and Technology* 52: 10911–10913. doi: **https://doi.org/10.1021/acs.est.8b04854**