Macroalgal Open-Ocean Mariculture and Sinking: At a Glance

Macroalgae, or seaweeds, are large, plantlike organisms that grow naturally in the ocean and, like land plants, take up and store carbon via photosynthesis. These organisms, which include kelp and rockweed, can transform dissolved CO_2 into biomass at some of highest rates on earth.[22] There are three proposed CDR methods based on cultivation of seaweeds: the deliberate sinking of biomass grown in open-ocean seaweed farms into the deep sea, natural sinking and sequestration, and the deliberate use of seaweed biomass to reduce emissions through technologies or methods other than deliberate sinking.[23] The first pathway, sometimes termed ocean afforestation or macroalgal open-ocean mariculture and sinking, has received the most attention as a CDR method and is the subject of this fact sheet.

Potential Scale of Carbon Storage: Under the most ideal growing conditions, sequestering 0.3 gigatonnes of carbon per year ($GtC\ yr^{-1}$) via sinking macroalgal biomass—equivalent to about 22 percent of U.S. CO_2 emissions in 2021—would require new seaweed farms covering an ocean area about the size of Kentucky, roughly 40 times as much area as is currently devoted globally to seaweed farming for all other uses.[24] This would require unprecedented logistics. Any biomass that is sunk to the bottom of the ocean via this method cannot be harvested for other beneficial uses.

Cost: One group of scientists recently estimated that sequestration via sinking of macroalgal biomass could be achieved today for approximately $2,050 per ton C.[25] This is considerably more than the U.S. Department of Energy's long-term cost goal for this CDR pathway of $275 per ton C.[26]

Duration of Carbon Storage: The length of time for which the sunken macroalgal biomass could be sequestered from the atmosphere depends heavily on where in the ocean the sinking takes place. Biomass could be sequestered for more than 500 years if sunk below 1,000 meters in many parts of the ocean, but the timescale would be considerably less if the biomass were sunk in shallower waters.[27]

Technical Readiness: Knowledge borrowed from the existing seaweed farming industry could help advance the technical readiness of macroalgal CDR methods. However, much of the current seaweed farming industry has experience only in inshore and coastal environments; the space in inshore and coastal waters is often already devoted to other marine uses, and these environments are removed from the deep waters where one would need to sink biomass to sequester it for long periods. Farming in the offshore environment has been demonstrated in pilot projects but would be costly and logistically difficult to scale up.[28] Importantly, the sinking of biomass into the deep sea at scales required to achieve gigatonne levels of sequestration has not been demonstrated and remains surrounded by questions of safety, durability, and legality.

Potential Risks and Benefits (Social and Environmental): The effectiveness, scalability, ecological safety, and co-benefits of seaweed-based CDR approaches will depend on many factors, including where the seaweeds are grown and the end use for the plant biomass.[29] Sinking harvested biomass into the deep ocean could lock large amounts of carbon away from the atmosphere for long periods yet rob fragile, slow-growing deep-sea ecosystems of oxygen and increase deep ocean acidity.[30] Cultivated macroalgae canopies could cover large spatial areas and shade local natural primary producers or compete with them for nutrients.[31] Large offshore seaweed farms could also increase the incidence of marine mammal entanglement and compete with other marine spatial uses such as fishing.[32] However, macroalgal aquaculture could create jobs, provide opportunities for co-location with other new, sustainable ocean uses (e.g., renewable energy installations), and create new habitat for a diversity of macroalgae-associated water column species. Some scientists have also argued that seaweed aquaculture could be used to remediate ocean "dead zones," such as in the Gulf of Mexico, by removing excess nutrients that cause these harmful phenomena.[33]

Outstanding Questions: Several aspects of proposed seaweed-based CDR methods are not well understood, including their sequestration potential, the durability of the carbon storage, and how much additional carbon could be stored above the baseline.[34] Verifying the capture and sequestration of CO_2 by macroalgae against the background of natural processes in the ocean remains extraordinarily challenging, from both a technical and a methodological standpoint. For example, due to ocean physics and chemistry, tracking the movement of carbon dioxide from the atmosphere into the ocean and then into the biomass grown in a specific seaweed farm is extremely difficult. Fundamental research is needed in this area to improve carbon accounting. Finally, life-cycle analyses are needed to compare the net CDR benefit of sinking macroalgal biomass against other potential macroalgal CDR pathways such as incorporation into animal feeds or as a substitute for GHG-intensive products such as plastics or fertilizers.[35]

22 Francois Fernand et al., "Offshore Macroalgae Biomass for Bioenergy Production: Environmental Aspects, Technological Achievements and Challenges," *Renewable and Sustainable Energy Reviews* 75 (August 2017): 35–45, https://www.sciencedirect.com/science/article/abs/pii/S1364032116307018.

23 See Rodney M. Fujita et al., "Carbon Sequestration by Seaweed: Background Paper for the Bezos Earth Fund—EDF Workshop on Seaweed Carbon Sequestration," Environmental Defense Fund, 2022, https://www.edf.org/sites/default/files/2022-10/Carbon%20Sequestration%20by%20Seaweed.pdf. Natural sequestration is the least certain of these pathways; as seaweeds grow, they shed fronds and release some long-lived dissolved carbon into the deep sea, but these natural losses account for only a fraction of the overall carbon they take up and are hard to measure. If not deliberately sunk to the deep sea, seaweeds can serve as the basis for CDR by being converted into products that could reduce greenhouse gas emissions, either directly (e.g., by addition to feed for cows and other ruminants, which may reduce the production of methane, another highly potent greenhouse gas) or indirectly (e.g., by replacing GHG-intensive products such as fossil fuel–based plastics or fertilizers). Seaweed biomass can also be used as an input for other land-based CDR methods such as bioenergy with carbon capture and storage.

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25 DeAngelo et al., "Economic and Biophysical Limits to Seaweed-Based Climate Solutions."

26 National Academies of Sciences, Engineering, and Medicine (hereinafter NASEM), *A Research Strategy for Ocean-Based Carbon Dioxide Removal and Sequestration* (Washington, D.C.: National Academies Press, 2022), https://doi.org/10.17226/26278.

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28 Urd G. Bak, Agnes Mols-Mortensen, and Olavur Gregersen, "Production Method and Cost of Commercial-Scale Offshore Cultivation of Kelp in the Faroe Islands Using Multiple Partial Harvesting," *Algal Research* 33 (July 2018): 36–47, https://doi.org/10.1016/j.algal.2018.05.001.

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31 Wu, Keller, and Oschlies, "Carbon Dioxide Removal via Macroalgae Open-Ocean Mariculture and Sinking."

32 NASEM, *A Research Strategy*.

33 Phoebe Racine et al., "A Case for Seaweed Aquaculture Inclusion in U.S. Nutrient Pollution Management," *Marine Policy* 129 (July 2021), https://doi.org/10.1016/j.marpol.2021.104506.

34 Ibid.

35 Ibid.