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Commentary

Deep-ocean seaweed dumping for carbon sequestration: Questionable, risky, and not the best use of valuable biomass

Thierry Chopin,[1,2,3,*] Barry A. Costa-Pierce,[4,5] Max Troell,[6,7] Catriona L. Hurd,[8] Mark John Costello,[4] Steven Backman,[9,3] Alejandro H. Buschmann,[10] Russell Cuhel,[11] Carlos M. Duarte,[12] Fredrik Gröndahl,[13] Kevin Heasman,[14] Ricardo J. Haroun,[15] Johan Johansen,[16] Alexander Jueterbock,[4] Mitchell Lench,[17] Scott Lindell,[18] Henrik Pavia,[19] Aurora M. Ricart,[20,21] Kristina S. Sundell,[22] and Charles Yarish[18,23]

[1]Seaweed and Integrated Multi-Trophic Aquaculture Research Laboratory, University of New Brunswick, 100 Tucker Park Street, Saint John, New Brunswick E2L 4L5, Canada
[2]Chopin Coastal Health Solutions Inc., Quispamsis, New Brunswick E2E 1W4, Canada
[3]Turquoise Revolution Inc., Quispamsis, New Brunswick E2E 1W4, Canada
[4]Faculty of Biosciences & Aquaculture, Nord University, Postboks 1490, Bodø 8049, Norway
[5]Ecological Aquaculture, LLC, 8 Coastal Lane, Biddeford, ME 04005, USA
[6]The Beijer Institute, Royal Swedish Academy of Sciences, Box 5000, Lilla Frescativägen 4, 104 05 Stockholm, Sweden
[7]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
[8]Institute for Marine and Antarctic Studies, University of Tasmania, 20 Castray Esplanade, Hobart, TAS 7004, Australia
[9]Magellan Aqua Farms Inc., 130 King Street, St. Stephen, New Brunswick E3L 2C8, Canada
[10]Centro i-mar & CeBiB Nucleo, Milenio MASH, Universidad de Los Lagos, Puerto Montt 1080000, Chile
[11]Great Lakes WATER Institute, University of Wisconsin-Milwaukee, 600 E. Greenfield Avenue, Milwaukee, WI 53204, USA
[12]Red Sea Research Center and Computational Bioscience Research Center, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
[13]Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Teknikringen 10b, 114 28 Stockholm, Sweden
[14]Blue Technology Group, Cawthron Institute, 98 Halifax St., Nelson 7010, New Zealand
[15]Research Institute ECOAQUA, Scientific & Technological Marine Park, Universidad de Las Palmas de Gran Canaria, Crta. Taliarte s/n, 35214 Telde, Spain
[16]Norwegian Institute of Bioeconomy Research, Kudalsveien 6, Bodø 8927, Norway
[17]Ocean's Balance, 10 West Point Ln. #105, Biddeford, ME 04005, USA
[18]Applied Ocean Physics & Engineering, Woods Hole Oceanographic Institution, 266 Woods Hole Road, MS #24, Woods Hole, MA 02543, USA
[19]Tjärnö Marine Laboratory, Department of Marine Sciences, University of Gothenburg, Laboratorievägen 10, 452 96 Strömstad, Sweden
[20]Institut de Ciències del Mar (ICM-CSIC), Passeig Marítim de la Barceloneta, 37-49, 08003 Barcelona, Spain
[21]Bigelow Laboratory for Ocean Sciences, 60 Bigelow Dr., East Boothbay, ME 04544, USA
[22]Swedish Mariculture Research Centre (SWEMARC) and Department of Biological and Environmental Sciences, University of Gothenburg, P.O. Box 463, 405 30 Göteborg, Sweden
[23]Department of Ecology & Evolutionary Biology, University of Connecticut, 1 University Place, Stamford, CT 06901-2315, USA
*Correspondence: tchopin@unbsj.ca
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Deep-ocean seaweed dumping is not an ecological, economical, or ethical answer to climate-change mitigation via carbon "sequestration." Without sound science and sufficient knowledge on impacts to these fragile ecosystems, it distracts from more rational and effective blue-carbon interventions. We call for a moratorium on sinking seaweeds to deep-ocean ecosystems until its efficacy is established, and there is robust, evidence-based assessment of its environmental, economic, and societal sustainability.

The cruciality of the climate crisis has attracted attention on the potential use of the ocean to help mitigate climate change. Coastal ocean "blue" carbon options have focused on mangrove forests, intertidal saltmarshes, and seagrass beds, where carbon is captured by living organisms and stored in biomass and sediments. As the solution for climate change mitigation will consist of a portfolio of practices, other "blue" carbon options, such as seaweed bed restoration and afforestation, and the expansion of seaweed aquaculture, including into the open ocean, are being proposed.[1] Climate change "nature-based solutions" must, however, benefit both climate change mitigation and biodiversity. Here, we argue that sinking seaweeds in the deep ocean does neither.

We are witnessing a surge in projects attracting significant investments by groups who want to grow seaweeds in very large aquaculture systems, establish new, open-ocean seaweed floating belts, or fish them from existing belts and bale them after ocean harvesting, to then sink them to the deep ocean based on the notion that those actions represent "carbon sequestration."[2] Despite the urgent need for solutions to reduce atmospheric greenhouse gases, these proposals and projects are not supported by available scientific or engineering knowledge, and they present unacceptable risks to deep-ocean ecosystems.[3–5] They are also fraught with national and international legal issues. The focus here is on seaweeds farmed for sinking in the deep ocean; however, the same arguments and uncertainties also hold true for sinking naturally occurring seaweed biomass.

The misguided notion of carbon sequestration

Seaweed aquaculture accounts for 51.3% of global mariculture production and grew at 5.7% yr^{-1} from 2010 to 2020.[6] It provides a source of food, feed, and natural products across a range of industries and delivers a broad range of ecosystem services.

Seaweed aquaculture for carbon sequestration and offsets has captured the attention of investors worldwide.[7] One industry report identified more than $375 million in equity investments in seaweed projects over the past three years.[8] These figures likely underestimate total investments, as complete information was not available on many companies listed. The report mentioned one company earning $15 million for carbon credits investment for seaweed dumping.

Radical suggestions to expand seaweed farming into the ocean to occupy about 48 million km^2[2] underestimate the nutrient requirements necessary to avoid biomass growth limitations as well as societal acceptability for such expansions. It is estimated[9] that harvesting 1 GT yr^{-1} of seaweed carbon would require farming over 1 million km^2 of the most productive exclusive economic zones (EEZ) located in the equatorial Pacific region.

The likelihood that dumping seaweeds into the deep ocean will provide meaningful, large-scale permanent carbon sequestration at sufficient time scales is highly questionable. It is also likely to cause negative environmental impacts[10] except possibly in small areas of the ocean where sinking seaweeds could be permanently sequestered, if the technology was available to sink deep enough into the areas of permanent hypoxia. The uncertainties related to efficiency and environmental sustainability are many. This includes insufficient knowledge of the fate of seaweed biomass during different phases of sinking, its ecological impacts, and understanding net-carbon sequestration from a life-cycle perspective. This is also true for deep-ocean areas with permanent hypoxia.

To make any significant contribution toward net zero emission targets, vast new ocean areas would have to be allocated to seaweed aquaculture, which could be in direct conflict with existing ocean users and have adverse impacts on biodiversity.[9]

Large scale, well-funded projects developing seaweed aquaculture to sink millions to billions of tons of seaweeds are underway.[11] To expand seaweed aquaculture into the ocean requires both extensive science and new technologies, especially new mechanical and ocean engineering protocols and devices. Bioengineering and logistical efficiencies for sinking mostly buoyant seaweeds to deep-ocean ecosystems do not exist.

The risk to deep-ocean ecosystems

Scientific review of marine CO_2 removal (mCDR) proposals state that ocean-based climate interventions could potentially smother seafloor life, alter water and sediment chemistry, promote deoxygenation and anoxia, and release additional hydrogen sulfide and methane.[12] Sinking could change pelagic, mesopelagic, and benthic food webs, causing unpredictable ecosystem changes, unnatural animal clustering, alterations to population interactions (e.g., "nutrient robbing" reallocation between macro- and micro-algal populations), and acceleration of mortalities (Figure 1). The potential release of CO_2 from calcification and possible heating effects from the removal of seaweeds changing albedo (e.g., in the context of the Great Atlantic Sargassum Belt) have also been mentioned and challenged.[13]

Seaweeds not making it to the ocean floor would decay to detrital organic particles and eventually inorganic matter, not providing sequestration, but undergoing elemental recycling and transformation. The fate of seaweed biomass accumulating on the deep-ocean floor is uncertain. Ultimately, organic forms of carbon, nitrogen, phosphorus, and trace minerals will return to their inorganic forms and will be available again.[5] Time scales for decomposition and remineralization are uncertain, but sinking may constitute only transient carbon "sequestration," not sequestration on a climate-relevant timescale.[14]

Sinking seaweeds will require passage through kilometers of little understood, multi-layered pelagic ecosystems. Currents from different origins, directions, and intensities could transport seaweeds (including reproductive materials) considerable distances across ocean basins. Depending on where and what species of seaweeds are dumped, this may contribute to dispersal, colonization, and possible invasion and genetic pollution.[15] For example, one seaweed cultivation for carbon credits enterprise is planning to use a highly invasive seaweed (Undaria; https://bluecarbon.co.nz). Long-range transportation of seaweed biomass may increase their decomposition rate but not necessarily provide sequestration.

Going beyond carbon: Other nutrients are also key

In coastal environments, nutrient pollution, due to wastewater and runoffs containing large quantities of nitrogen and phosphorus, is significant and should be addressed urgently. Accelerated nutrient loading in coastal waters is also contributing to the carbon/acidification crisis and has been called "the other CO_2 problem."[16] Coastal acidification could be mitigated by nutrient uptake by seaweed farms and restored wild beds.

Nutrient biomitigation is a key ecosystem service provided by seaweeds. Total nitrogen, phosphorus, and carbon biomitigation for the worldwide seaweed aquaculture production (35.1 million tons fresh weight in 2020) can be valued at between $2.6 billion and $5.1 billion, i.e., as much as 31% of its present commercial value ($16.5 billion; updated numbers from Chopin and Tacon[6]).

While much emphasis has been placed on carbon trading credits (CTCs), there is a need to consider trade-offs and potential co-benefits of a more integrated approach. Interestingly, there is more money to be made with nutrient trading credits (NTCs) than with CTCs with seaweeds: between $2.5 and 4.9 billion for nitrogen and $140.4 million for phosphorus, compared to only $51.0 million for carbon (updated numbers from Chopin and Tacon[6]). This is due to the fact that treatment costs for nitrogen and phosphorus are generally expressed per kilogram, whereas those for carbon are per ton, a factor of 10^3 often missed in calculations.

Species receiving most investments for large-scale farming and carbon "sequestration" (e.g., kelps[7,8]) are often

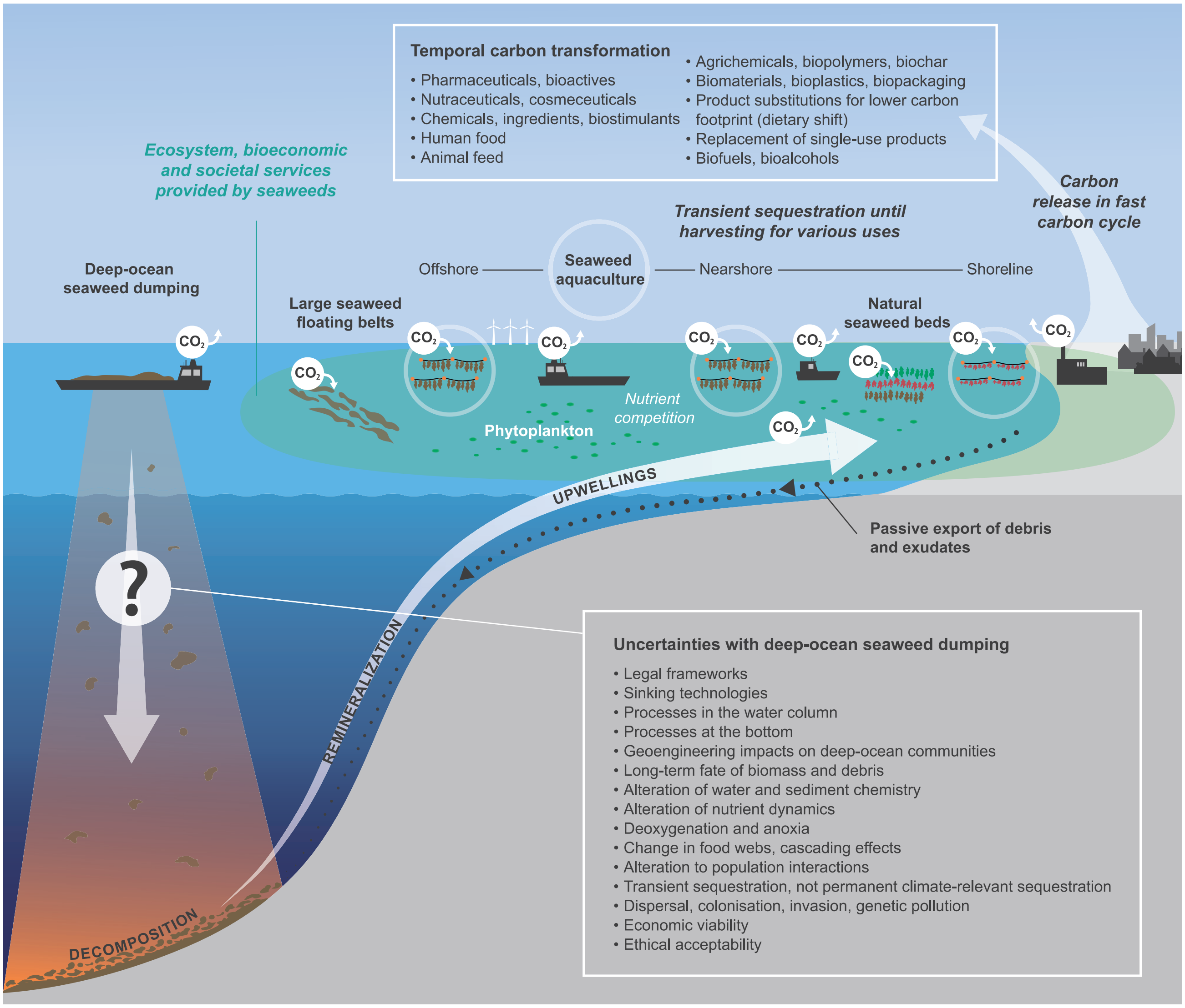

Figure 1. Deep-ocean seaweed dumping, and its associated uncertainties, may not be the tool for carbon sequestration at geological time scales

Seaweed aquaculture (at the shoreline, nearshore, or offshore) and the harvesting of natural beds and large floating belts participate in transient sequestration until harvesting for various uses when carbon is released in the fast carbon cycle for temporal transformation and substitution. Seaweeds also provide ecosystem, bioeconomic and societal services.

proposed to be located offshore. However, the open ocean is generally poor in nutrients,[9] which could limit the potential for large-scale seaweed aquaculture and afforestation.[17] The productivity of 30% of the global ocean is iron limited and preventing healthy microalgal growth and that of seaweeds.[17] Paradoxically, discussions have re-emerged regarding fertilizing seaweed farms, which would impact marine food webs by altering trophic interactions and ecosystem balances and further complicate legal issues. Strategies will have to be chosen; one cannot claim wanting to develop "regenerative" aquaculture to reduce nutrient inputs and at the same time advocate adding nutrients in the ocean. Moreover, the way "regenerative" has recently been associated with aquaculture contradicts the original meaning associated with agriculture, wherein retaining nutrients is key.

Legal challenges to deep-ocean dumping

Sinking seaweeds into the deep ocean would be subject to international legislations, long-standing anti-dumping conventions, and litigations.[18] Disposal would be subject to the United Nations Convention on the Law of the Sea for the High Seas, the Convention on Biological Diversity, the 1972 "London" Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, and constrained by nation states if disposal is within their EEZ.

The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) decided in June 2023 to broaden the conservation scope of the North Atlantic Current and Evlanov Sea Basin marine protected area (the largest in the North Atlantic international

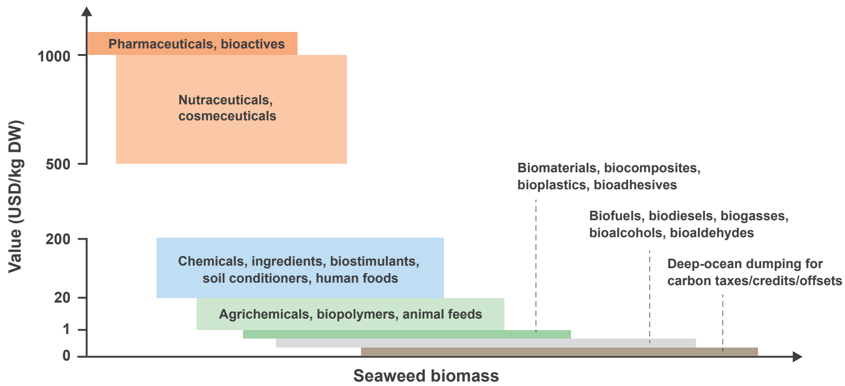

Figure 2. Variability of the price of seaweeds according to their applications, markets, and the added value of seaweed products (without any additional value for the ecosystem services they provide)

Note that not all applications start with the same minimal seaweed biomass, as a minimal tonnage is necessary to enter and carve a niche in a market or to displace an existing, more carbon-intensive usage. There could be supply bottlenecks for the upscaling of some new applications, as the current seaweed biomass is fully allocated/subscribed and the seaweed aquaculture sector may not increase at a speed matching the demand. Growing seaweeds to dump them in the deep ocean for potential carbon credits, when there are no competitive financial incentives, means that the biomass/volume will have to be significant to start with and significant to make some/any money.

high seas) to strengthen the protection of the seabed and a number of species and habitats. This contributes to the Global Biodiversity Framework agreement committing to protect at least 30% of the global ocean by 2030 and supports the recently adopted (June 2023) and signed (September 2023) High Seas Agreement on protecting biodiversity beyond national jurisdiction (BBNJ).

FINDING REAL SOLUTIONS BEYOND THE PRESENT HYPE

There are significant barriers to address before seaweeds can be included in robust climate change mitigation schemes, including scalability; durability; conflicts with existing ocean users; risk management; standards, policies, and legal frameworks; economic frameworks; lack of robustly calculated credits, offsets, and incentives; adequacy of approaches to account for carbon sequestration and transformation in these highly dynamic and naturally variable ecosystems; and societal and ethical issues.[3,5,19] There is a need to develop new forensic carbon accounting methods for quantifying, monitoring, reporting, and verifying legitimate carbon schemes with integrity.[19]

It should also be made abundantly clear that when seaweeds are harvested and developed into different products, the carbon and other nutrients (e.g., nitrogen and phosphorus) that were transiently incorporated into seaweed tissues do not disappear. They are transformed and enter the composition of other products, hence entering the fast carbon cycle and other fast nutrient cycles. This is not permanent sequestration at geological time scales.[5,20] Financial and auditing institutions are becoming more aware of this potential for double dipping/accounting, ''blue washing,'' and subterfuge.

There are presently no logical incentives to grow seaweeds for sinking them to the deep-ocean ecosystems for carbon sequestration.[6] The price of any carbon tax (or credit) is insignificant (for example, in Canada, equivalent to $0.0145/kg dry weight [DW] of seaweeds) compared to the market price of seaweeds, which can vary from a few dollars to more than $1,000/kg DW, depending on applications (Figure 2). Dumping seaweeds seems to be an economically inefficient method to develop blue bioeconomies for seaweeds. Market forces are driving seaweed utilization toward more lucrative applications.

Financial and regulatory tools being proposed as incentives to sink seaweeds are, at present, poorly designed, not competitive, and inadequate for meaningful climate impacts. During the United Nations Climate Change COP 28 event, carbon taxes were reported to vary between $0.01 and $154/ton, with an average of less than $20/ton, which put the Canadian carbon tax/credit within the bracket and above the average. Even Stripe Climate's purchasing offer of CO_2 removal at $250 a ton[11] (equivalent to $0.075/kg DW of seaweeds) and seaweed carbon credits for restoration reportedly sold for $500 a ton in Japan ($0.15/kg DW of seaweeds) remain unattractive to have an impact or act as an incentive to orient climate change biomitigation solutions on the right path(s).

Seaweeds are valuable, not low commodity products to dump. Many profitable applications have been developed by the seaweed industry for centuries or have emerged as innovations supporting circular approaches to develop a greener blue (turquoise) economy.[6]

Depending on the fate of the production, seaweeds can contribute to emission reduction by being transformed into useful products that might substitute products with a higher CO_2 footprint or replace single-use products, thereby avoiding emissions (rather than directly contributing to sequestration) in the production of food, feed, fertilizers, ingredients, nutraceuticals, bioplastics, biochar, and other nonfood applications (Figure 2).

Transformation, and possibly some sequestration, could happen via passive export of seaweed debris and exudates during the farming process before harvesting. The amount of passive export could also reflect the efficiency of farmers and possibly be reduced with improved practices. Upscaling seaweed farming would have to be commensurate with market developments for the produced biomass to be absorbed and these markets to flourish without supply bottlenecks.

Instead of promoting seaweeds to sink them for profit from trading carbon credits, we recommend taking advantage of the ecosystem, bioeconomic and societal services they provide (Table 1) and their multiple roles in transforming value chains, decarbonization and mitigation of excess nutrients, and coastal acidification through both established and yet-to-be-developed profitable, beneficial, and ethical applications, all complying with global sustainable development goals.[5] True environmental gains from seaweeds can more likely be achieved by shifting the use (replacement/supplementation) of terrestrial sources of biomasses, dietary shifts in food and feeds, and replacing materials with higher carbon footprints.

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Table 1. Ecosystem, bioeconomic, and societal services provided by seaweeds (note that seaweeds often render services across the subcategories below)

Ecosystem services	● Nitrogen, phosphorus, carbon, etc. transient sequestration and transformation after harvesting and processing ● Biomitigation of excess nutrients ● Improvement of water quality ● Reduction of harmful micro- and macro-algal biomass ● No need of freshwater irrigation (but need seawater of appropriate quality) ● No need of fertilization (but need nutrient-rich seawater) ● No need of land deforestation, cleared land ● No need of new arable land ● Production of oxygen and consumption of carbon dioxide ● Reduction of coastal hypoxia ● Underwater afforestation and restoration of natural seaweed beds ● Habitat restoration benefiting wild populations of other species ● Sheltering and fostering biodiversity ● Provision of nursery grounds for other species ● Participation in the reduction of coastal acidification ● Improvement of shellfish and coral early calcification (reduction in mortalities)
Bioeconomic services	● Implementation of nutrient trading credits (NTCs) and carbon trading credits (CTCs) ● Displacement of chemical fertilizers with natural fertilizers ● Protection against coastal erosion and destruction of coastal infrastructures ● Participation in the adaptation to, and reduction of, impacts of climate change ● Production of biofuels and bioalcohols ● Participation in decarbonization ● Participation in the reduction of methane emissions from terrestrial livestock
Societal services	● Participation in the dietary shift toward food production systems with a lower carbon footprint than terrestrial ones ● Product substitution for lower carbon footprint and replacement of single-use products (biomaterials, bioplastics, biopackaging, biochar) ● Fostering multi-crop diversification of sustainable coastal communities ● Risk mitigation, job creation, revitalization, and increased resilience of coastal communities ● Increasing gender equity and woman empowerment in the aquaculture sector ● Improvement of diets and general welfare and well-being in humans and animals ● Enhancement of immune system and gut health ● Treatment of neurodegenerative diseases ● Mitigation of nutritious food insecurity ● Seafood entry point for vegetarians, vegetalians, and vegans ● Increasing acceptability of aquaculture in general through the development of Integrated Multi-Trophic Aquaculture (IMTA) systems ● Key component in the development of aquaculture eco-tourism experiential traveling, especially with urban visitors disconnected from the mechanics of production systems bringing food to their tables (better understanding of the turquoise economy mutual benefits) ● Footprint reduction and increased acceptability of combined offshore activities (e.g., with wind or hydro-turbine farms) ● Contribution to not only Sustainable Development Goal 14 (SDG14; Life Below Water), but to at least 10 others of the SDGs of the United Nations

Seaweeds are remarkable organisms, but let's reduce the hype. While it is causing an amazing surge in interest for seaweeds, we also need to ensure that this "seaweed moment" is translated into a more sustainable momentum for the seaweed sector.

The hype over seaweeds as a carbon sequestration solution, as implied in some mCDR proposals, represents a dangerous fallacy and amounts to "blue washing." We are concerned that investments, based on a limited number of poorly designed, conducted, and reviewed third-party scientific assessments, marketing large-scale seaweed farming as a "quick fix" climate solution, risk jeopardizing the future growth of the seaweed industry. Failing to deliver the promised climate mitigation may distract from more impactful climate actions that could be taken and instill distrust as to what can be done with seaweeds, similar to what happened in the 1980 and 1990s with inflated claims regarding seaweed biogas and biofuels.

A call to action for a global rethinking of priorities

We argue that claims of carbon sequestration by sinking cultured and fished seaweeds risk "blue washing" investors and are distracting from research on seaweed aquaculture and natural bed harvesting, and that funds should be directed toward food security and other transformative seaweed-product value chains.

In light of remaining uncertainties, we call for an immediate moratorium on the sinking of seaweed biomass—from expanded farms, wild beds, or large floating accumulations—for disposal in the deep ocean, and urge suspending commercial permits until legal, environmental, and ethical consequences and economic viability are investigated and better understood and appropriate regulations are developed.

Sinking seaweeds to deep-ocean ecosystems is not an answer to climate change mitigation biologically, environmentally, economically, societally, or ethically. It is presently not based on sound science. Sufficient knowledge on the functionality of deep-ocean ecosystems, their biodiversity, the ecosystem services they provide, and the geoengineering impacts on those is lacking and distracts from other more rational and effective actions.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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