FARMING SEAGRASSES AND SEAWEEDS:

Responsible Restoration & Revenue Generation

A Report Generated by the Bigelow Laboratory for Ocean Sciences for the Interagency Working Group for the Farming of Seagrasses and Seaweeds

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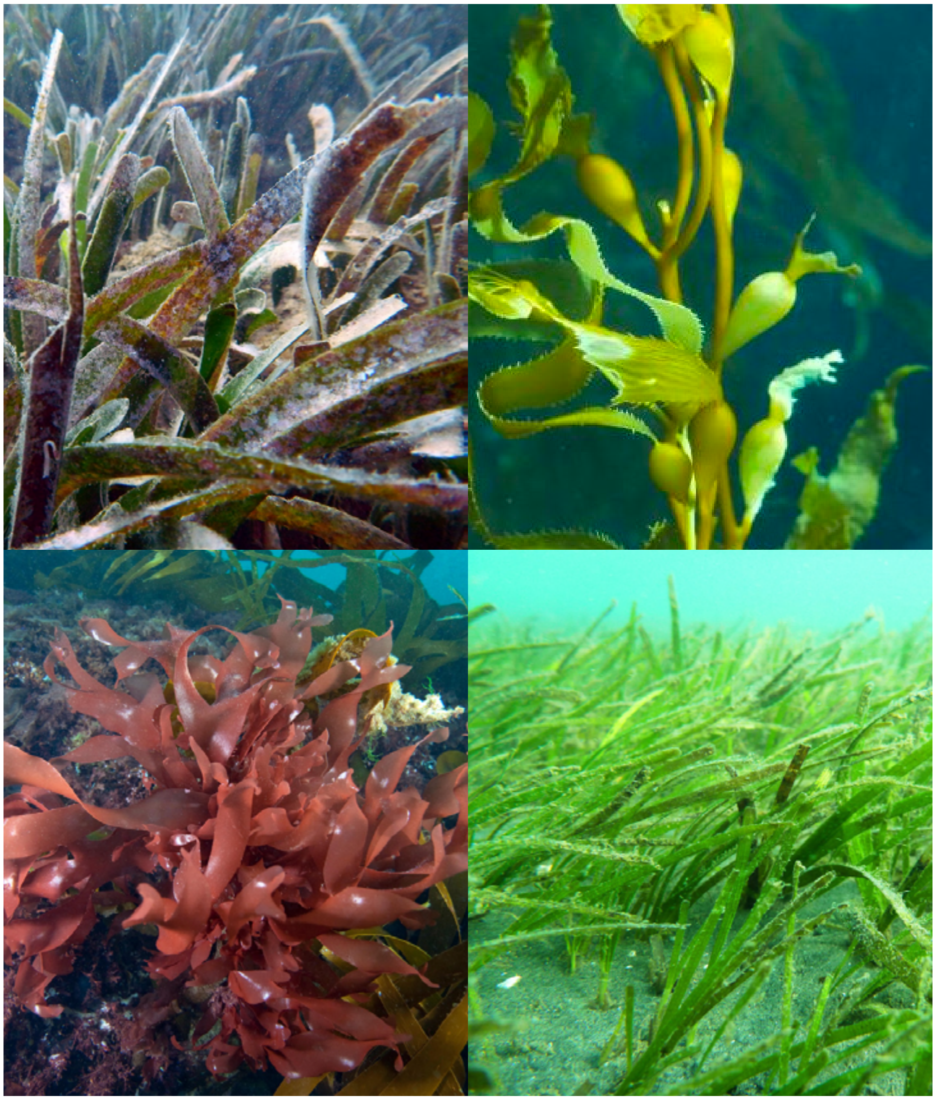
Bigelow Laboratory dedicates this report to Dr. Durham M. Robinson (Rob) Swift, a professor of Mechanical and Ocean Engineering at the University of New Hampshire (UNH) who was dedicated to the development of offshore seaweed ranching and cultivation systems.



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[1] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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EXECUTIVE SUMMARY

In 2019, the United States Congress charged the Secretary of Agriculture, in coordination with the Administrator of the National Oceanic and Atmospheric Administration, to establish a working group to conduct a comprehensive evaluation of U.S. seaweeds and seagrass farming, describing its current state, its potential to drive economic growth through production of livestock feeds and other commercial applications, and improve ocean health through deacidification. USDA partnered with Bigelow Laboratory for Ocean Sciences (BLOS), a global research institution located in East Boothbay, Maine, for assistance in collecting public input, providing subject matter expertise, and drafting a report to fulfill the Congressional mandate.

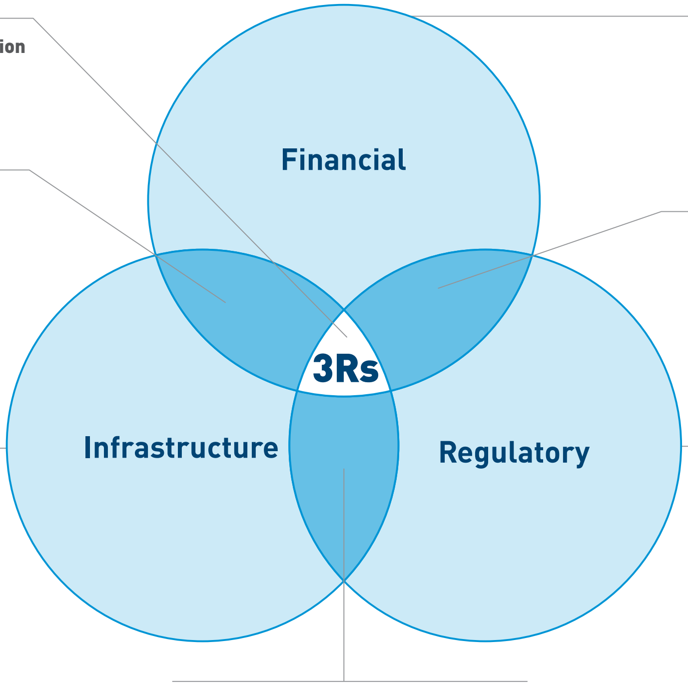
Bigelow Laboratory and the 46-member U.S. Government Interagency Working Group (IWG) for the Farming of Seaweeds and Seagrasses gained valuable insight from more than one thousand stakeholders representing communities across the United States and its territories. Through a series of inclusive listening sessions and workshops, purposeful research pilot projects, and one-on-one meetings, the IWG gained much information about the state of the science and the industry from individuals, organizations, and governments.

The report is shaped by thoughtful stakeholder insight, science, and facts and includes valuable perspectives from the nation's Indigenous peoples. It is built to satisfy Congress' expectations and provide the public and policymakers with sound information and a precise set of recommendations that, if taken, hold great potential to ignite growth of an emerging high powered and environmentally beneficial economic sector.

Scientific research, government funding, environmental implications, and commercial activity related to U.S. seaweed farming and seagrass restoration have spiked since the turn of the century, largely driven by their nutritional and climate positive applications. The report will show significant growth in scientific understanding and the commercialization of beneficial everyday food, animal feed, health, fuel, ecosystem services, carbon markets, and bio-based products from seaweeds in particular. A small but mighty industry is forming along the nation's coastlines, transforming working waterfronts and giving a boost of energy into already emerging life science and blue economy clusters from Maine to Alaska and beyond.

The science is motivating demonstrable growth in the sector. Commercial interests are accelerating marketplace activity because consumers are demanding new products. The future of the sector could be bright if it can be positioned to thrive into the future. The set of comprehensive recommendations in this report were created with much input from across the country and with the goal of helping this nascent sector to flourish and become an ecological and economic driver for good. A snapshot of the highest priority recommendations is set forth in the graphic on next page.

Responsible Restoration & Revenue Generation from Farming US Seagrasses and Seaweeds



- **Seaweed-specific Trade Association**
- **Global industry collaboration**
- **Nation to Nation tech transfer**

- Funding instruments
- Economic impact analyses
- Subsidies & insurance

- Workforce development
- Expanded R&D funding
- Biomass monitoring

- Fully-staffed permitting bodies
- Online databases
- Ecosystem services task force(s)

- Reinforced wharves, docks, etc.
- Processing & storage facilities
- Remote sensing tools
- Species inventories
- Research & nursery facilities

- Best practices guidance
- Standardized reporting
- Product safety protocols
- Export, import, and domestic movement
- Harmonizing across all regulatory agencies

- Certified testing materials & facilities
- Best practices for farm design, efficacy and safety

I. INTRODUCTION

A. Purpose, Goals and Approach

In accordance with the fiscal year (FY) 2019 U.S. congressional appropriations bill, section 770, this document reports on (1) how kelp and seagrasses could help deacidify the oceans; (2) how emerging ocean farming practices could use seaweeds and seagrasses to provide a feedstock for agriculture and other commercial and industrial inputs; and (3) the results of six pilot-scale research projects on farming seaweeds and seagrasses that study (A) ocean deacidification; (B) the production of a feedstock for agriculture; and (C) how to develop scalable commercial applications to support a blue economy. **Figure 1** depicts the timeline of preparing this report.

The Interagency Working Group (IWG) for Farming Seaweeds and Seagrasses, formed September 2021, has 46 members representing 8 Departments/Agencies from 25 Offices/Divisions. The working group Steering Committee (USDA Chair and collaborators from Bigelow Laboratory) hosted two IWG virtual sessions, and eight public stakeholder listening sessions over the course of two years. The roughly three-hour long listening sessions engaged >1,000 stakeholder registrants from almost every coastal U.S. territory. Each registrant was granted access to the report at its current stage of development, and asked to comment on content, either in the live session, or via email and surveys. The IWG announced the development of the report and listening sessions as broadly as possible across virtual networks. The IWG Steering Committee also recognized the absence of perspectives from those who do not frequent those platforms and sought their feedback via direct phone contact during the final development stages of the report.

To maintain the spirit of the FY 2019 congressional appropriations bill's language, the IWG Steering Committee elected to interpret the term "kelp" in section 770 as all commercialized seaweeds, including red, green, and other brown species. In addition, while seagrasses are rarely farmed, there have been extensive restoration efforts over the past several decades to replace degraded beds in both tropical and temperate U.S. coastal zones (see Section C.4). Finally, while "deacidification" is not frequently used in the peer-reviewed scientific literature, we interpret this term as referring to the slowing or reversal—in a localized area—of coastal and ocean acidification (OA), driven by rising carbon dioxide (CO2) levels in the atmosphere. The IWG Steering Committee also elected to expand interpretation of "deacidification" to include other ecosystem services, such as oxygenation and nutrient bioremediation, performed by farmed seaweeds and seagrasses. The term "farmed" in an ocean setting can also be interpreted broadly; the IWG Steering Committee erred on the side of inclusivity in this term, which can reference gardening and rotational harvesting, aquaculture, or mariculture. The IWG Steering Committee described these considerations in full at each stakeholder listening session.

The first series of four stakeholder listening sessions, held on March 8, 2022; March 22, 2022; March 29, 2022 and April 5, 2022, took place virtually and had 178 attendees. The preliminary workshops conducted in spring 2022 focused on aquaculture needs and efforts in four U.S. regions: the Gulf of Mexico and the southern Atlantic coast, the U.S. island territories, the Pacific coast, and the north Atlantic coast. The workshops were well attended and fostered dialogue on a proposed outline and suggested content for the report to Congress. The purpose of these sessions was to elicit commentary on the content of the report and identify region-specific issues. The USDA Agricultural Research Service (ARS) and Bigelow Laboratory also announced a request for pilot research proposals during the first series of sessions.

A request for proposals (RFP) was open from April 22, 2022 June 1, 2022 to conduct 18 months-long pilot projects, with the funding administered by Bigelow Laboratory for Ocean Sciences. There were dozens of applicants from across the U.S. territories, and six awards made at $100,000 each. Successful applicants were identified by a panel of ten peers based upon relevance to RFP, intellectual merit, and alignment with language in the FY 2019 U.S. congressional appropriations bill, section 770. The pilot studies were all completed by May 30, 2024 and preliminary data from these pilot studies is reported in Section III.

The second series of four stakeholder listening sessions took place on October 23, 2023; October 30, 2023; November 6, 2023 and November 13, 2023 and was, like the first series, virtual and well attended (518 attendees). These events showcased a written draft of the congressional report and enabled interested parties to provide extensive feedback on recent research developments, including early results of funded pilot projects, as well as the content of the draft report, which was the primary focus of discussion. The IWG Steering Committee collected feedback and recommendations through verbal comments, Zoom chat box comments, live polls, and Google Forms. These information gathering tools enabled the IWG Steering Committee to seek consensus on knowledge gaps and resource needs, as well as identify, topics, graphics and other features to incorporate into the report draft.

At each of the stakeholder listening sessions, the IWG Steering Committee also invited subject matter experts (SMEs) to engage more deeply in the report preparation process in an effort to ensure that each topic was addressed with the most recent and cutting-edge information available. These SMEs are acknowledged as contributing authors in each of the sections to which they contributed in the main body of the report, and in the appendices. Their full titles and affiliations are also provided in Appendix A.

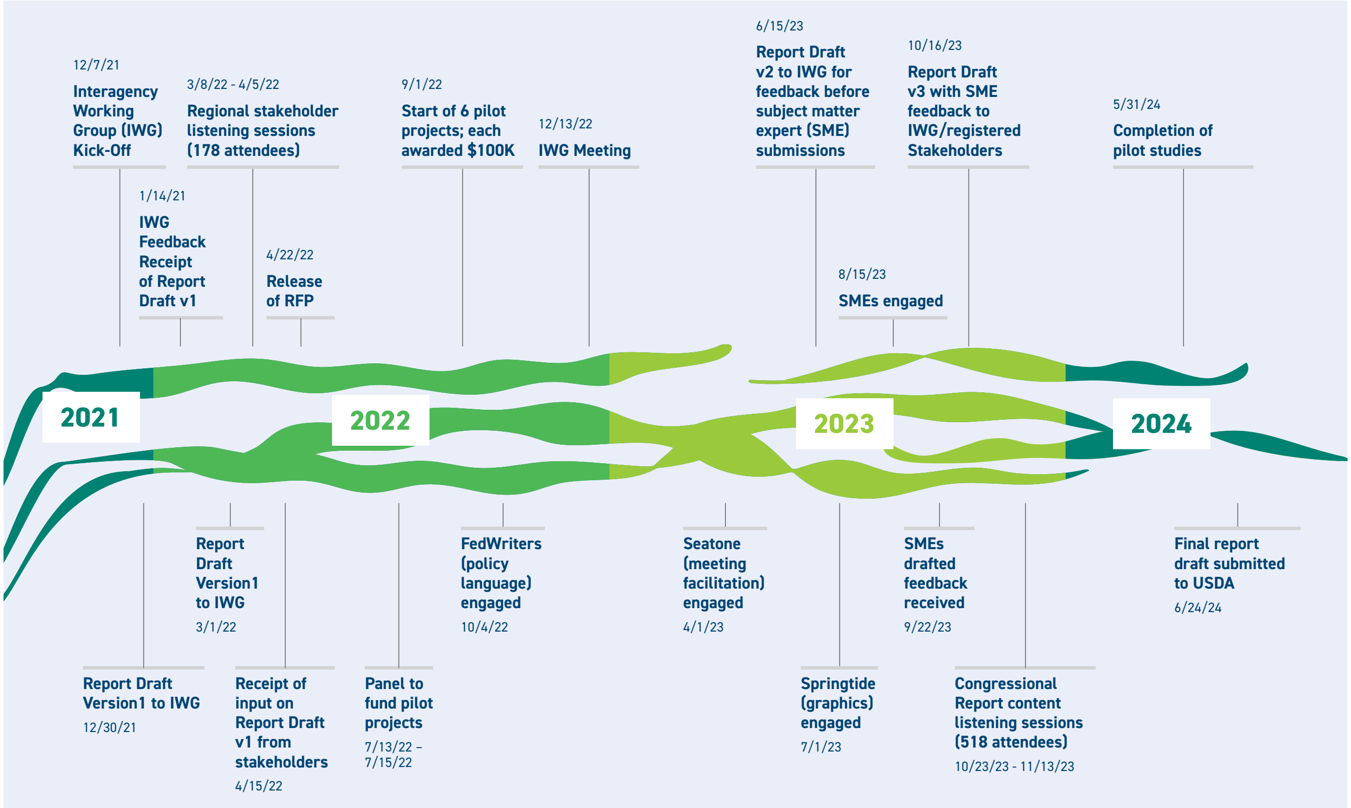


Figure 1. Timeline of pilot studies and report preparation, including instances where/when stakeholders and the IWG were engaged and how many stakeholders contributed.

B. History of Indigenous Use, Research and Commercial Development

Contributing Authors: Jay Brandeis, Maile Branson, Victorino "Mayo" Floro, Gene Kim, Richard Langton, Briana Murphy, Elena Shippey, and Jeremy Wierenga

In the US, people have used seagrasses and seaweeds as a natural resource for fiber, food, and feed for thousands of years.[2] For a deeper chronicling of Indigenous knowledge and use, and 'natural history' descriptions of seagrasses and seaweeds, see **Appendix 1**.

Figure 2 presents U.S. Indigenous and settler people harvesting seaweeds in Alaska and Maine, respectively in the past two centuries. In the US, however, widespread use and application and presence of seaweeds in mainstream media and modern lexicon has only really developed momentum in the recent decade.

Figure 2. Historical harvesting practices of seaweeds. Left: Peter, a native with a boat load of kelp at Potato Patch Beach. The kelp is put on the potato patches as fertilizer. Based on other photos in the series this photo was most likely taken on Kodiak Island, Alaska. Photo taken during National Geographic Society expedition on the way to Katmai area, 1919. Source: Alaska State Library Archive Right: Gathering kelp, Long Sands, York, Maine, ca. 1882. This is a farmer loading his cart with kelp..

1. Indigenous uses of seagrasses and seaweeds

Indigenous peoples across North America have managed and cultivated seagrass as a source of food, roofing, fodder for smoking meat, medicine as well as mulch and fertilizer for growing crops[3]. The approach of managing seagrass beds is often called gardening or tending and encompasses the intentional growth, cultivation and propagation of seagrass beds for generations. Although typically valued for the fish and sea birds that thriving seagrass beds support, Zostera marina (eelgrass) rhizomes were also harvested in spring and served as an

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[2] O'Connor, K. (2017). Seaweed: a global history. Reaktion Books; Buchholz, C.M., Krause, G., Buck, B.H. (2012). Seaweed and Man. In: Wiencke, C., Bischof, K. (eds) Seaweed Biology. Ecological Studies, vol 219. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-28451-9_22; Wyllie-Echeverria, S., & Cox, P. A. (1999). The seagrass (Zostera marina [Zosteraceae]) industry of Nova Scotia (1907-1960). Economic Botany, 419-426.

[3] Kikuchi, K., Kawasaki Sato, Y.S., 2001. Effect of seasonal changes on the carbohydrate levels of eelgrass Zostera marina at Odawa Bay. Fish. Sci. 67 (no. 4), 755–757.

important source of sugar (sucrose) which accounts for approximately half of their dry weight. Full of vitamins and minerals, this energy-rich resource was a small but important source of sustenance to coastal communities.[4]

Seaweeds have long been utilized by Indigenous peoples as a source of food, medicine, textiles, insulation, and handicrafts, from the tropics to artic regions. Although Tribal members use many species, kelp, a group brown subtidal macroalgae with large blades, often represents a significant component of local Indigenous foods in many temperate coastal regions. Kelp harvesting in the Pacific northwest and northern Atlantic regions is often intertwined with the harvesting of other marine resources, such as fish and shellfish. In addition to kelp itself, many Tribes along the southern coast of Alaska deeply value herring roe that is laid on kelp. This delicacy is central to native kelp harvest practices and is often regarded as a major component of kelp garden site selection and harvest timing. Herring typically spawn in April, and this event has anecdotally been utilized to mark the start of the summer season. South central Alaskan Tribes also use this event to denote the beginning of seasonally warmer seawater temperatures and the threshold at which species of harmful algae may begin to bloom. Thus, herring roe on kelp is also used as an indicator that it is no longer safe to harvest and consume shellfish that season. These relationships highlight only a few instances of the vast cultural importance of seaweeds to Indigenous communities across the U.S. and its territories.

2. Research history of seagrasses and seaweeds

Contemporary interest in seagrasses and seaweeds has grown, which is particularly apparent based on its recent coverage in popular media; this attention may be partially explained by a recent wave of research and development on these macrophytes (seaweeds and true marine plants), and their commercial and climate change applications. Google Scholar, which is a dynamic search engine, offers a mechanism to assess such changes in scientific interest. It allows users to search peer-reviewed articles, theses, books, technical reports, abstracts and reprints from academic publishers and universities. Google Scholar can be used to track emerging fields of scientific interest based on changes in the number of topical publications over time. **Figure 3A** and **Figure 3B** show how a series of key words, related to different aspects of seaweed and seagrass research, document shifts in research activity in five-year blocks beginning in 1970. The number of seaweed- and seagrass-related publications clearly increased over time.

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[4] Cullis-Suzuki, S., Wyllie-Echeverria, S., Dick, K.A., Sewid-Smith, M.D., Recalma-Clutesi, O.K. and Turner, N.J., 2015. Tending the meadows of the sea: a disturbance experiment based on traditional indigenous harvesting of Zostera marina L. (Zosteraceae) the southern region of Canada's west coast. Aquatic Botany, 127, pp.26-34.; Cullis-Suzuki, S., 2007. Tending the meadows of the sea: Traditional Kwakwaka'wakw harvesting of Ts' áts' ayem (Zostera marina L.; Zosteraceae) (Doctoral dissertation).; Vichkovitten, T., Holmer, M. and Frederiksen, M.S., 2007. Spatial and temporal changes in non-structural carbohydrate reserves in eelgrass (Zostera marina L.) in Danish coastal waters.; Kikuchi, K., Kawasaki, Y. and Sato, S., 2001. Effect of seasonal changes on the carbohydrate levels of eelgrass Zostera marina at Odawa Bay. Fisheries science, 67(4), pp.755-757.

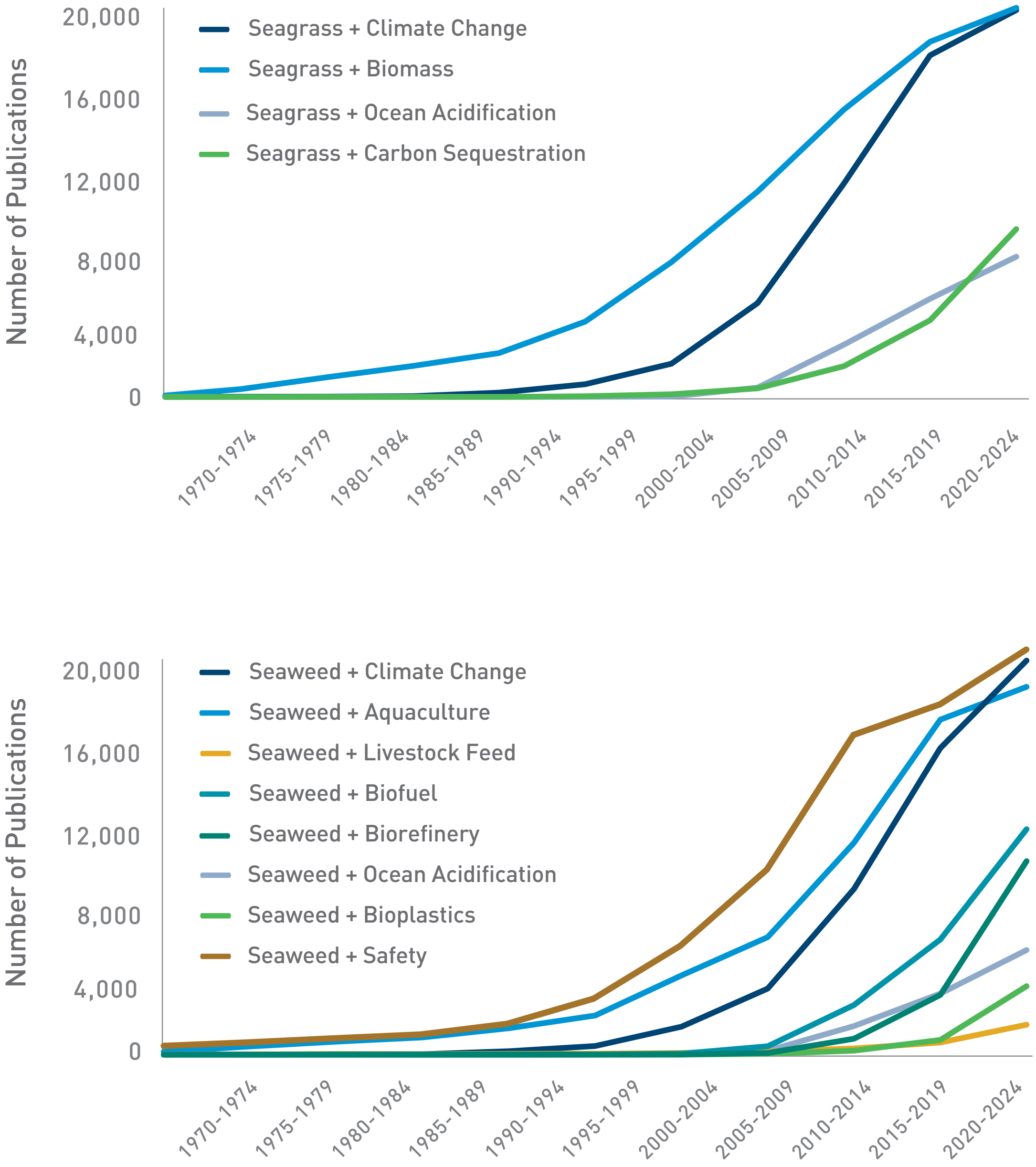


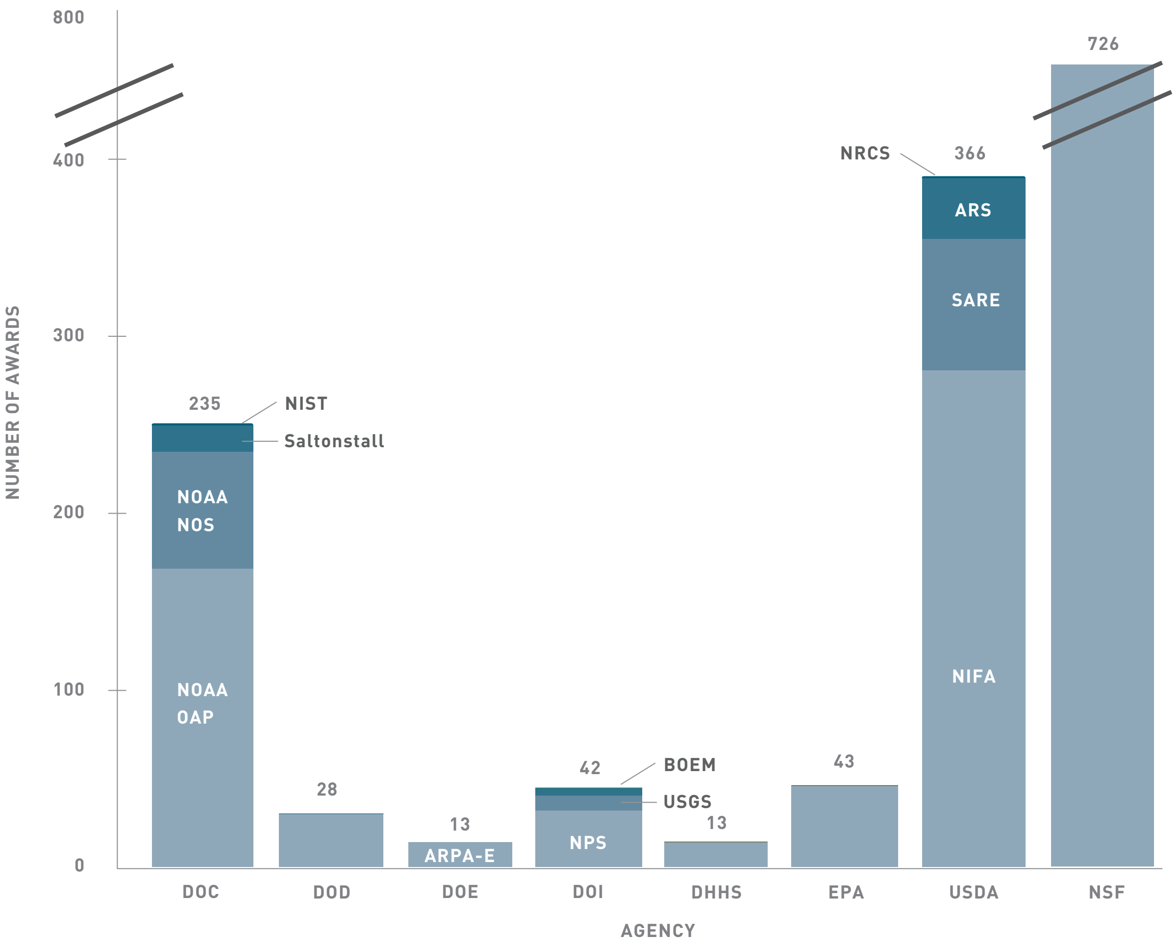
Figure 3. Trends in scholarly literature since the 1970s for (A) seagrasses and (B) seaweeds.

The general search term "seaweed" or "seagrass" was paired with more specific search terms, such as aquaculture, OA, biofuels or bioplastic. In all instances, the number of publications substantially increased, generally beginning in the late 1990s or early 2000s. In the case of seaweed-derived bioplastics, which is one of the newest areas of seaweed research, the uptick did not occur until c.a. 2015. In addition, the concept of biorefineries to generate more than one product from a single crop of seaweed started to generate more interest and publications in the last decade.

3. Federal research funding trends to date

Federal investment in seagrass and seaweed research has increased along with increases in popular media attention and academic interest. Federal government-wide databases on spending, such as USAspending.gov, provide data on the grant funds allocated by all agencies, while some agencies and offices host agency-specific databases on research funding. Though these sources offer varying levels of detail and little information is publicly available online about research funding prior to 2000, the data overall show an increase in funding for research and development related to farmed seagrasses and seaweeds. **Figure 4** shows how the keywords "seaweed" and "seagrass," along with related terms (e.g., "kelp" and "turtle grass") demonstrate increased federal research funding for farmed seagrass and seaweed in the 2010s and 2020s. This increase in research funding mirrors recent national priorities and goals, including increasing resilience to climate impacts,[5] strengthening domestic supply chains[6] and improving domestic aquaculture.[7] The funded research spans a wide range of topics and investigates various uses for seaweeds and seagrasses, including as livestock feed, as a method for reducing greenhouse gas (GHG) emissions and other climate impacts (e.g., harmful algal blooms) and as a way of supporting local food systems via aquaculture. The National Science Foundation has invested the most funding support in seagrasses and seaweeds to date (**Figure 4B**).

A



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[5] "The Biden-Harris Administration Immediate Priorities," The White House, n.d., https://www.whitehouse.gov/priorities/.

[6] "Trump Administration Accomplishments," Trump White House National Archives, January 2021, https://trumpwhitehouse.archives.gov/trump-administration-accomplishments/.

[7] The White House, *Fact Sheet: Leading at Home and Internationally to Protect Our Ocean and Coasts* (Washington, DC: White House Office of the Press Secretary, June 17, 2014), https://obamawhitehouse.archives.gov/the-press-office/2014/06/17/fact-sheet-leading-home-and-internationally-protect-our-ocean-and-coasts.

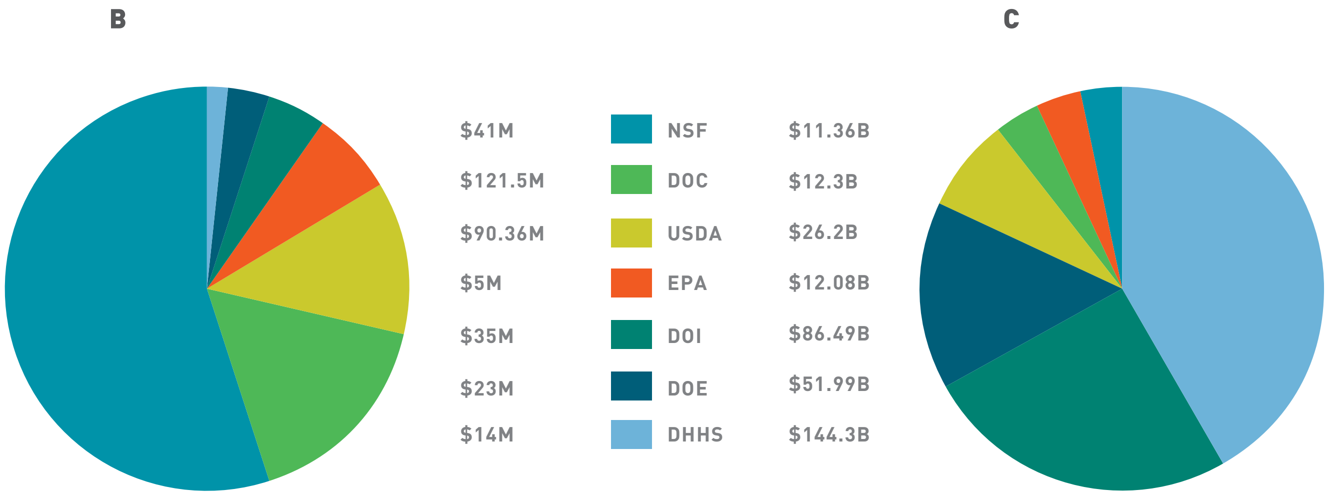

Figure 4. U.S. federal funding patterns. (A) U.S. federal agency number of awards made for research and development in farmed seagrass and seaweed since 2014. (B, *left*) Funding in USD allocated to research on seaweeds or seagrasses, categorized by federal agency, since 2014. (C, *right*) Total discretionary operating budget in billions USD in 2024 by agency

4. Current state of the seagrass and seaweed industries: production, processing, distribution across the U.S.

Seagrass restoration efforts have been occurring since the 1930s, and tend to have a regional distribution, with efforts currently focused on the mid-Atlantic region (**Figure 5A**). Not-for-profit, nongovernmental organizations, state agencies, academic institutions, and grassroots organizations largely orchestrate U.S. seagrass restoration efforts. There are very few for-profit entities involved in growing or harvesting seagrasses, but a few do exist. These companies are exploring seagrass genes that could build saline resistance in land-based crops (*Alora*), co-culturing oysters to filter turbidity and allow better light penetration to restored seagrass beds (Oyster Haven) or developing autonomous robotics to inject seeds and optimize plant spacing and vastly expand areal coverage for restoration efforts (Reefgen).[8]

A small but growing number of companies (almost 200) comprise the seaweed aquaculture industry in the United States, which is the fastest-growing sector of U.S. aquaculture.[9] The U.S. seaweed industry dates back to at least the early 1910s, when the USDA funded research on methods for processing kelp into potash for use in agriculture on the West Coast.[10] In the 1970s, researchers launched experimental farms off the coast of California to explore seaweed as an alternative fuel source to fossil fuels.[11] In the 1980s and 90s, farming of *Kappaphycus spp*. and *Eucheuma denticulatum (spinosum)*, non-native tropical red seaweeds, were introduced in Hawaii for carrageenan production[12]. Ultimately, efforts with these two particular species were each abandoned in the U.S. (but expanded elsewhere) because the former non-natives caused destruction to natal U.S. coral reefs[13]. However,

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[8] M. L. Gräfnings et al. "Optimizing Seed Injection as a Seagrass Restoration Method," *Restoration Ecology* 31, no. 3 (2023): e13851.

[9] "Seaweed: It's Not Just for Sushi Anymore," U.S. Department of Agriculture, n.d., https://tellus.ars.usda.gov/stories/articles/seaweed-it-s-not-just-for-sushi-anymore.

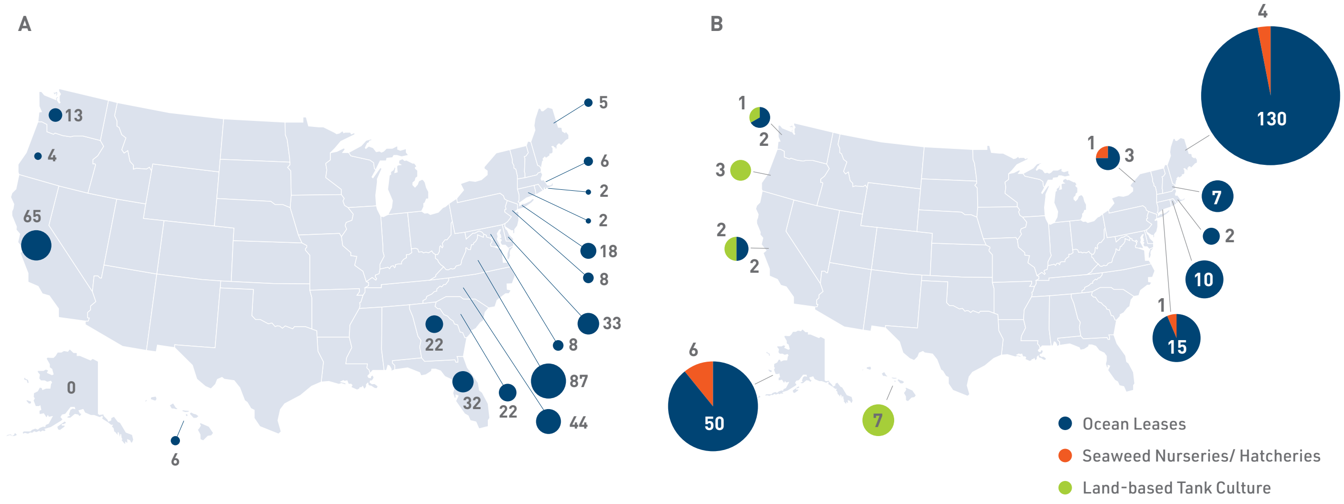
[10] "Giant Kelp and Bull Kelp Enhanced Status Report," California Marine Species Portal, 2021, https://marinespecies.wildlife.ca.gov/kelp/the-fishery/.

[11] "Seaweed Aquaculture," Sea Grant California, n.d., https://caseagrant.ucsd.edu/our-work/discover-california-seafood/seaweed-aquaculture.

[12] Bindu, M.S. and Levine, I.A., 2011. The commercial red seaweed *Kappaphycus alvarezii*—an overview on farming and environment. Journal of Applied Phycology, 23, pp.789-796; Glenn, E.P. and Doty, M.S., 1990. Growth of the seaweeds *Kappaphycus alvarezii, K. striatum* and *Eucheuma denticulatum* as affected by environment in Hawaii. *Aquaculture*, 84(3-4), pp.245-255.

[13] Smith, J.E., Hunter, C.L. and Smith, C.M., 2002. Distribution and reproductive characteristics of nonindigenous and invasive marine algae in the Hawaiian Islands. *Pacific science*, 56(3), pp.299-315.

farming of the native temperature red *Chondrus crispus* seaweed species was explored in Maine to extract similar gel products[14], but ran into permitting for ocean leases and labor costs roadblocks. Ocean farming seaweed companies and requisite nurseries or hatcheries in the U.S. are currently primarily located in New England, the Pacific Northwest and Alaska, with a limited number of land-based cultivation systems for red species located in California and Hawaii (**Figure 5B**). As measured by landings in wet pounds and in wet metric tons, Maine is the leading state on the East Coast for seaweed farming, and Alaska is the leading state on the West Coast (**Figure 5C**); both farm primarily various kelp species, namely *Saccharina latissima* (sugar kelp), *Saccharina latissima* forma *angustissima* (skinny kelp), and *Alaria esculenta* (winged kelp), with growing interest in bull kelp and giant kelp in the Pacific. Data suggests U.S. companies are significantly increasing their offerings of seaweed-based products, with Alaska seeing a 200 percent increase in its commercial kelp harvest from 2017 to 2019[15] and Maine reporting landings increases by a factor of 22 from 2017 to 2022.[16] Nationwide, seaweed production has increased from 18 tons in 2017 to 440 tons in 2021.[17]



C

REGION	EAST COAST						WEST COAST				
STATE	ME	NH	MA	RI	CT	NY	AK	WA	OR	CA	HI
2022 Landings in wet pounds (wet MT)	1,000,000+ (454+)	N/A (N/A)	9,500 (4.3)	14,500 (6.6)	3,800 (1.7)	N/A (N/A)	871,000+ (395+)	10,000 (4.5)	N/A (N/A)	N/A (N/A)	250,000+ (113+)

Figure 5. Maps depicting current U.S. state estimates in (A) distribution of cumulative seagrass restoration efforts since 1930s,[18] (B) seaweed aquaculture or mariculture permit types and total numbers from 2022,[19] and (C) total seaweed landings in pounds (lbs), wet, by state (size of pie chart) as reported in 2022.[20]

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[14] Zertuche-González, J.A., García-Lepe, G., Pacheco-Ruiz, I., Chee, A., Gendrop, V. and Guzmán, J.M., 2001. Open water *Chondrus crispus* Stackhouse cultivation. *Journal of applied phycology*, 13, pp.247-251.

[15] "Seaweed Aquaculture," National Oceanic and Atmospheric Administration Fisheries, updated February 28, 2024, https://www.fisheries.noaa.gov/national/aquaculture/seaweed-aquaculture.

[16] Brayden, Christian, and Struan Coleman. "Maine seaweed benchmarking: Economically assessing the growth of an emerging sector." *Aquaculture Economics & Management* (2024): 1-24.

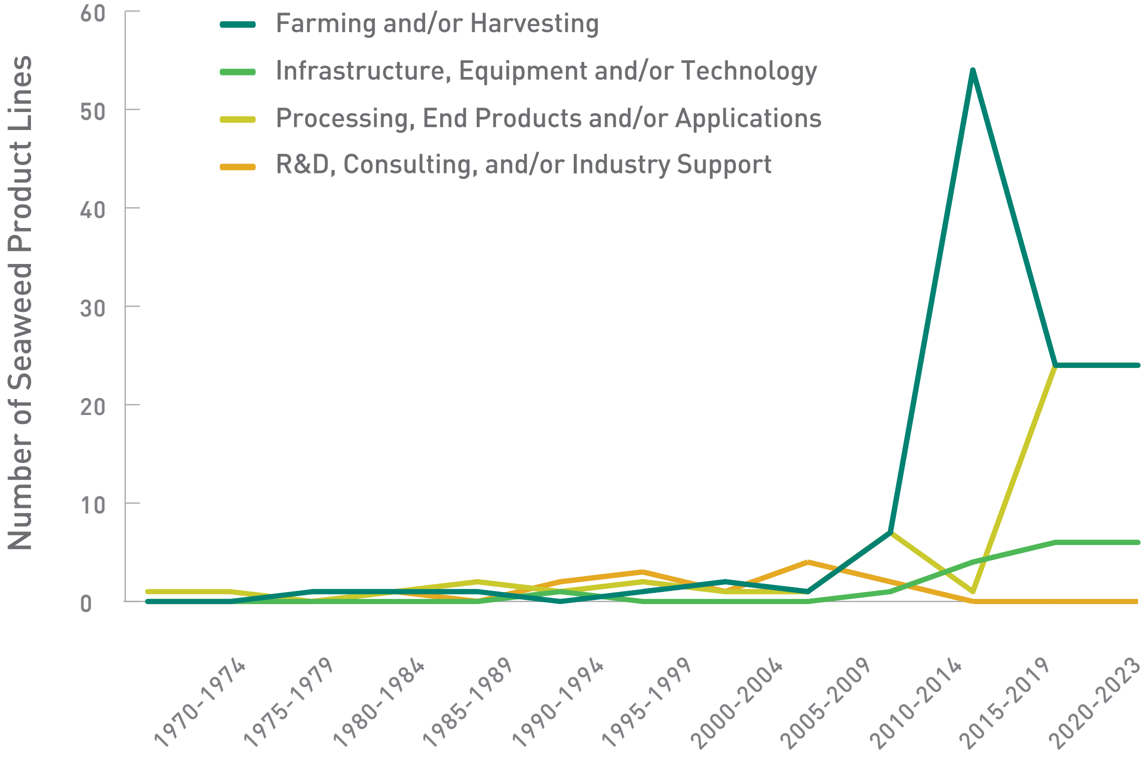
[17] "Not Just for Sushi."

[18] Compiled via google search with terms "seagrass restoration"+ [State Name] and reviewed the first ~5 search hits for credible primary or secondary (media) sources that list or quantify seagrass restoration efforts and totaled those tallies per coastal US state. Note that these tallies include efforts across time, and do not distinguish between successful attempted restoration efforts.

[19] Data pulled from: Jaclyn Robidoux and Melissa Good, "State of the States: Status of U.S. Seaweed Aquaculture" (presentation, National Seaweed Symposium, Portland, ME, December 2023), https://seaweedhub.extension.uconn.edu/wp-content/uploads/sites/3646/2023/04/2023-State-of-the-States_For-Posting_Dec2023.pdf

[20] Same as above

Today, most U.S. seaweed companies cultivate a limited number of kelp species as food products, but also farm seaweed for use as an ingredient in products such as cosmetics, animal feed and fertilizer. Subsequent to the increased funding support for seaweed research and development (**Figure 4**), and rapid increase in scholarly literature being released (**Figure 3B**), there has been a rapid expansion in the number of companies offering seaweed services (**Figure 6A**). The distribution of seaweed companies across the U.S. has vastly expanded to even include interior states (**Figure 6B**), where processing equipment for the harvested crop is manufactured. The farmed seaweed sector, today, represents an ever-growing diversity in the types of products it offers.



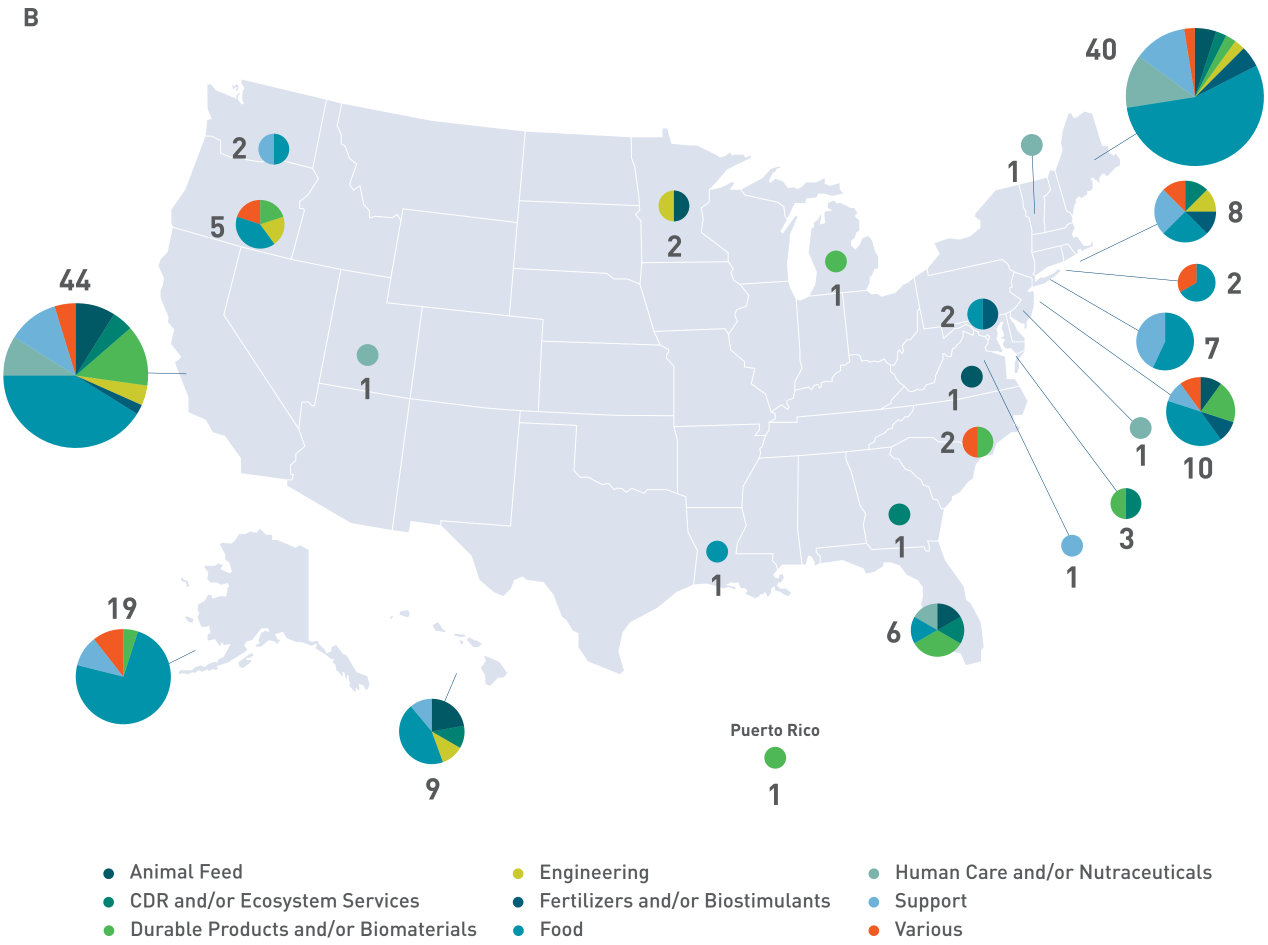


Figure 6. Temporal rends and spatial distribution of the U.S. seaweed sector. (A) trends in U.S. companies offering seaweed-based products over time and (B) map of the distribution of U.S. seaweed companies (number of companies portrayed above pie charts, and size of pies corresponds to the number of companies) and commodities and services offered.

5. Current state of global trade in seagrass and seaweed products

The National Aquaculture Act of 1980 stated that "Congress declares that aquaculture has the potential for reducing the United States trade deficit in fisheries products, for augmenting existing commercial and recreational fisheries, and for producing other renewable resources, thereby assisting the United States in meeting its future food needs and contributing to the solution of world resource problems."

Global markets for seaweed and seaweed products are expanding rapidly as this emerging natural resource gains greater awareness from governments and consumers. In 2023, the World Bank's "Global Seaweed New and Emerging Markets Report 2023" forecast global seaweed and farmed seaweed production to reach approximately $11.8 billion dollars in value by 2030 in ten emerging seaweed applications.[21] Emerging global seaweed applications include the following: nutraceuticals ($3.9 billion), biostimulants ($1.9 billion), construction ($1.4 billion), animal feed as additives ($1.1 billion), pet food ($1 billion), fabrics ($862 million), bioplastics ($733 million), alternative proteins ($448 million), methane additives ($306 million), and pharmaceuticals (undefined) (**Table 1**).[22]

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[21] "World Bank. 2023. Global Seaweed: New and Emerging Markets Report, 2023. http://hdl.handle.net/10986/40187 License: CC BY-NC 3.0 IGO."

[22] Seaweed is an emerging export category with a wide swath of HS codes, complicating trade estimates. The exact value of global seaweed trade is difficult to calculate due to the classification of seaweeds and derivates under the harmonized system (HS codes). Nonetheless, the global market for seaweed is expected to continue to grow due to emerging applications for seaweed beyond its current and primary uses.

Table 1. Summary of global market value (in millions U.S. dollars) and share of seaweed-based products and anticipated growth rates of each sector.

EMERGING SEAWEED APPLICATION	ESTIMATED MARKET VALUE (IN MILLIONS U.S. DOLLARS)		ESTIMATED COMPOUND ANNUAL GROWTH RATE (CAGR) 2022-2030
	TOTAL GLOBAL MARKET VALUE, ALL PRODUCTS 2022	SEAWEED-BASED MARKET 2030 FORECAST	
Nutraceuticals	450,000	3,954	7.5%
Biostimulants (seaweed-based)	1,000	1,876	10.0%
Construction (green materials)	312,500	1,396	10.0%
Animal feed additives	38,860	1,122	3.9%
Pet food	115,500	1,078	5.1%
Fabrics (biosynthetic textiles)	17,180	862	10.0%
Bioplastics	11,500	733	20.0%
Alternative proteins	10,200	448	36.0%
Methane-reducing feed supplements	47	306	57.0%
Pharmaceuticals (marine-derived)	2,560	Undefined	5.0-10.0%

Note: Global market values reflect values of the entire industry, including seaweed and seaweed derivatives. Data Source: World Bank. 2023. Global Seaweed: New and Emerging Markets Report, 2023.

According to Trade Data Monitor (TDM), in 2023, global exports of seaweed, seaweed products, agar-agar, and prepared/processed products totaled $6.9 billion (**Table 2, Fig. 7**).

Table 2. Global exports by Harmonized System (HS) code (in millions U.S. dollars); code references are presented in the legend of **Fig. 7**

HS Code	2019	2020	2021	2022	2023	%Δ 2023/2019
121221	639	570.4	626.1	810.2	765	11%
121229	212.7	198.8	240.8	354.5	302	4%
130231	217.9	207	218.1	232.8	224.8	3%
130239	1,150.30	1,099.10	1,354.70	1,943.90	1,563.30	23%
200899	2,973.30	3,144.90	3,685.80	3,834.40	4,049.10	59%
Total	**5,193.2**	**5,220.2**	**6,125.5**	**7,175.8**	**6,904.2**	**33%**

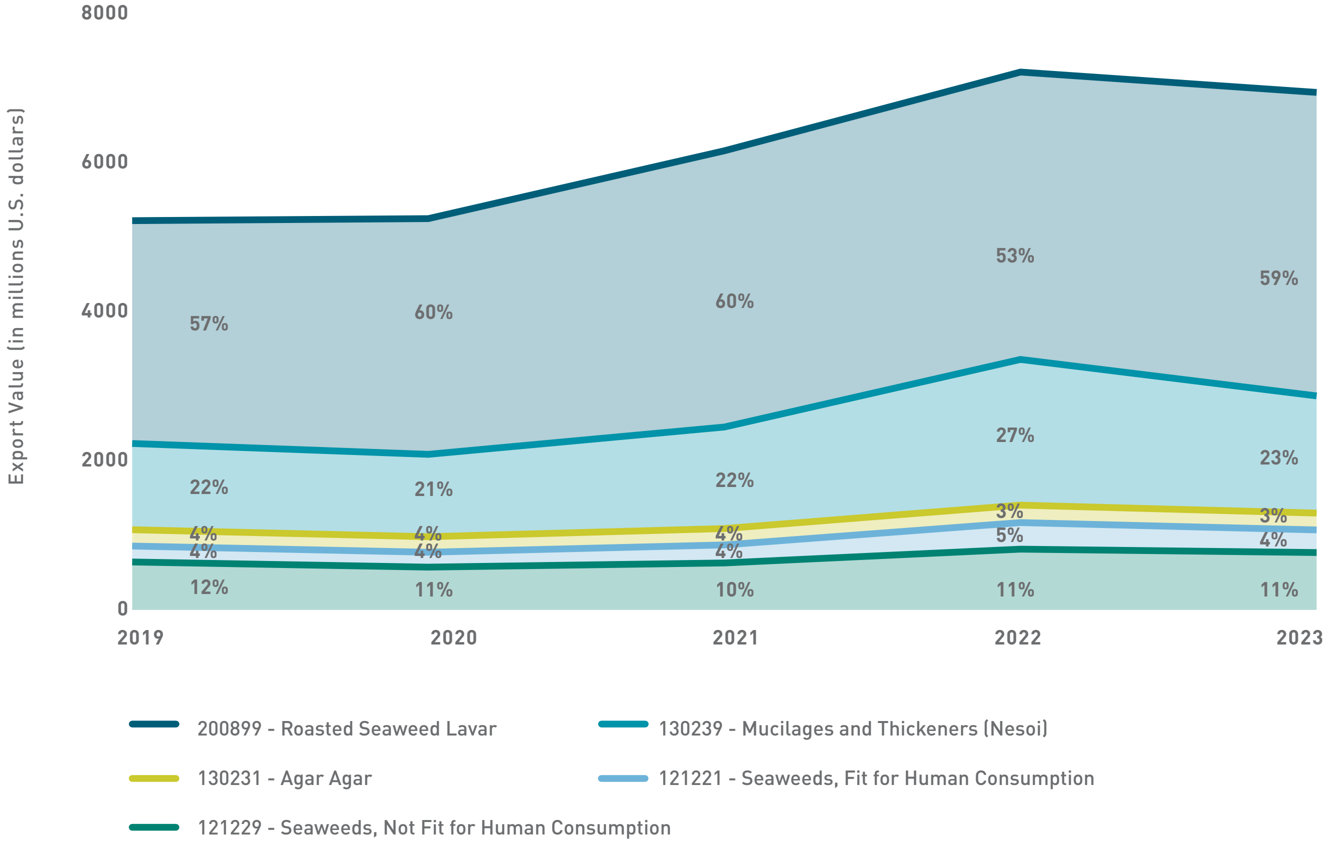

Figure 7. Global exports by Harmonized System (HS) code (in millions U.S. dollars).

Considering strictly seaweed specific Harmonized System codes (HS 121221, 121229, 130231, and 130239), in 2023, China was the largest exporter of seaweed and seaweed products ($704.8 million), followed by Indonesia ($442.3 million), and South Korea ($400.2 million). When these export numbers are broken down by bulk seaweed (Table 3), the top exporters in 2023 were South Korea ($355.6 million), Indonesia ($284.9 million), and Chile ($157.4 million). Considering agar-agar exports, China was the largest exporter in 2023 (85.1 million), followed by the European Union ($36.2 million), and then Morocco ($28.8 million). Since carrageenan is categorized with other mucilages and thickeners, total exports are difficult to measure, but the global carrageenan market is estimated to be around $800 million.[23]

Table 3. Global exports (in millions U.S. dollars) by exporting country[24]

Country	2019	2020	2021	2022	2023	%Δ 2023/2019
China	1428.0	1338.1	1636.0	1948.2	1674.1	17%
South Korea	470.7	746.1	852.1	813.1	947.4	101%
EU 27 External Trade (Brexit)	435.0	426.3	482.4	547.9	548.1	26%
Indonesia	350.9	297.2	367.2	631.2	465.5	33%
Philippines	360.8	334.4	383.5	481.4	416.7	16%
Mexico	286.1	263.4	343.2	399.2	370.7	30%
Chile	194.7	196.7	221.8	312.7	319.1	64%
Thailand	291.5	276.7	265.1	278.1	311.0	7%
Canada	156.0	172.4	206.3	247.3	264.1	69%
United States Consumption	276.1	229.5	239.5	260.6	222.7	-19%
Rest of World	943.4	939.5	1128.3	1256.1	1365.3	45%
Total	**5193.2**	**5,220.3**	**6125.5**	**7175.8**	**6904.6**	**33%**

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[23] Zhang, Jing, et al. "The Global Carrageenan Industry." Globalisation and Livelihood Transformations in the Indonesian Seaweed Industry, Routledge, London, 2024, www.taylorfrancis.com/chapters/oa-edit/10.4324/9781003183860-3/global-carrageenan-industry-jing-zhang-zannie-langford-scott-waldron; Sultana, Fahmida, Md Abdul Wahab, Md Nahiduzzaman, Md Mohiuddin, Mohammad Zafar Iqbal, Abrar Shakil, Abdullah-Al Mamun, Md Sadequr Rahman Khan, LiLian Wong, and Md Asaduzzaman. "Seaweed farming for food and nutritional security, climate change mitigation and adaptation, and women empowerment: A review." Aquaculture and Fisheries 8, no. 5 (2023): 463-480.

[24] HS codes 121221/121229/130231/130239/200899, Seaweeds and other algae, fit for human consumption/seaweeds and other algae, not fit for human consumption/agar-agar/mucilages and thickeners, whether or not modified, derived from vegetable products, nesoi/fruit and other edible parts of plants, nesoi, prepared or preserved, whether or not containing added sweetening or spirit, nesoi

C. Abundance, Distribution and Range Shifts of Standing Stock Biomass

Contributing Authors: Tom Bell, Aurora Ricart, Katherine DuBois, Nate L'Esperance, Christopher Oakes, Madeline Pomicter, Robert J. Orth, Jonathan Lefcheck, Kelly Darnell and Bradley Furman

1. Native U.S. seaweed and seagrass species abundance and distribution

Seagrasses are distributed along most of the coast of the contiguous United States, as well as the coasts of Alaska, Hawaii and U.S. territories. They form lush meadows that are typically fully submersed, even at low tide. Detailed distribution maps are available through the United Nations Environment Programme World Conservation Monitoring Centre[25], and general global distribution is provided in **Figure 8A**.

Along the northeast Pacific coast (California, Oregon, Washington and the Alaska panhandle), common species are eelgrass (*Zostera marina*), wigeongrass (*Ruppia maritima*) and surfgrass (*Phyllospadix serrulatus, P. scouleri* and *P. torreyi*), with eelgrass being the most common.[26] The Pacific northwest also hosts *Zostera japonica*, a nonnative/invasive species that originated from Japan and has been documented from California to British Colombia with recent but unconfirmed populations sighted in Southern Alaska.[27] With the exception of surfgrass, which is found in high-energy environments, seagrasses along the West Coast are limited to low-energy estuaries and embayments. Particularly in California, seagrass habitats are limited, and seagrass meadows provide critical, rare migration stopovers. Eelgrass and wigeongrass are also found in the temperate Atlantic along protected coastlines and in protected estuaries.

Along the Atlantic seaboard, seagrasses are divided into biogeographic zones: the Temperate North Atlantic zone, which spans from Maine to North Carolina; and the Tropical Atlantic zone, which spans from northern Florida to Texas and outlying territories.[28] The Temperate North Atlantic zone is dominated by eelgrass (*Zostera marina*) and, to a lesser extent, by widgeongrass (*Ruppia maritima*). At the southern edge of this zone, eelgrass and widgeongrass mix with shoalgrass (*Halodule wrightii*). Due to high tidal range, freshwater input, and low light availability, seagrasses are not present in South Carolina or Georgia. In the Tropical Atlantic zone, seagrasses are once again observed just north of the Indian River Lagoon on the east coast of Florida and along the rest of the Atlantic coast into the Gulf of Mexico and throughout Caribbean Sea. The meadows in South Florida and the Florida Keys constitute one of the largest in the world at nearly 5,900 square miles. Shoalgrass and turtlegrass (*Thalassia testudinum*) are the dominant species in this zone, accompanied by widgeongrass, manatee grass (*Syringodium filiforme*), and three species in the genus Halophila: stargrass (*H. engelmannii*, on the Gulf Coast and in the Caribbean), Caribbean seagrass or paddlegrass (*H. decipiens*), and what was formerly known as Johnson's seagrass (*H. johnsonii*)—previously listed as a federally threatened species and delisted in 2022 as it is now understood to be a subspecies of the more widespread H. ovalis.[29] Clovergrass (*H. baillonii*) is observed in Puerto Rico). *H. stipulacea* is a nonnative seagrass that was accidentally introduced to the Caribbean and has been reported in Puerto

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[25] United Nations Environment Program World Conservation Monitoring Center, Global Distribution of Seagrasses (Version 7.1). *Seventh Update to the Data Layer Used in Green and Short* (2003) (Cambridge, UK: UN Environment World Conservation Monitoring Center, 2021).

[26] S. Wyllie-Echeverria and J.D. Ackerman, "The Seagrasses of the Pacific Coast of North America," in *World Atlas of Seagrasses*, eds. E.P. Greene and F.T. Short (Berkeley, CA: University of California Press, 2003): 199–206.

[27] Mach, M.E., Wyllie-Echeverria, S. and Chan, K.M., 2014. Ecological effect of a nonnative seagrass spreading in the Northeast Pacific: a review of *Zostera japonica*. Ocean & coastal management, 102, pp.375-382.

[28] Short, F., et al. "Global seagrass distribution and diversity: a bioregional model." Journal of experimental marine biology and ecology 350.1-2 (2007): 3-20.

[29] Waycott, Michelle, et al. "Genomics-Based Phylogenetic and Population Genetic Analysis of Global Samples Confirms *Halophila johnsonii* Eiseman as Halophila ovalis (R. Br.) Hook. f." Frontiers in Marine Science 8 (2021): 740958.

Rico and the U.S. Virgin Islands as of 2017.[30] This species may have unintended impacts on local diversity, but may also provide ecosystem services that have disappeared along with the loss of native species.[31]

Seagrasses are also found in the tropical Pacific territories, including tape seagrass (*Enhalus aceroides*), narrowleaf seagrass (*Halodule uninervis*) and *Halophila gaudichaudii* in the Northern Mariana Islands and Guam, where populations are declining, and paddleweed (*H. ovalis*) and noodlegrass (*S. isoetifolium*) in American Samoa.[32]

Seaweeds are found in shallow, well-lit coastal habitats in all the world's oceans, from the poles to the tropics, and contribute significantly to marine biodiversity. There are hundreds of species of seaweeds that inhabit diverse environments across numerous ecosystems including the rocky intertidal zone, coastal wetlands, temperate rocky reefs, tropical coral reefs and sandy seagrass beds. While most seaweeds are classified as "benthic" or attached to the bottom, some, such as Sargassum, drift on the surface of the ocean, creating floating rafts in the Sargasso Sea, and more recently in the Caribbean and along the coast of Florida. While seaweeds need light to survive, some species can exist with less than 0.0005% of surface sunlight, including the deepest seaweed ever collected from a seamount at a depth of 268 meters.[33]

Kelp forests are made of a subset of fast-growing brown, subtidal, canopy-forming seaweeds, and are distributed largely in temperate and subtropical regions worldwide (Figure 8B). Detailed national distribution maps of seaweed species other than kelp (e.g., intertidal seaweeds or understory red and green species) are near impossible to obtain, in part because the specialized labor required to identify, quantify, and document relative abundances while SCUBA (Self Contained Underwater Breathing Apparatus) diving. Remote sensing technology is changing the way natural resource managers can monitor and document changes in distributions of seaweeds and seagrasses.

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[30] Winters, Gidon, et al. "The tropical seagrass *Halophila stipulacea*: reviewing what we know from its native and invasive habitats, alongside identifying knowledge gaps." Frontiers in Marine Science 7 (2020): 300.

[31] Viana, Inés G., Rapti Siriwardane-de Zoysa, Demian A. Willette, and Lucy G. Gillis. "Exploring how non-native seagrass species could provide essential ecosystems services: a perspective on the highly invasive seagrass *Halophila stipulacea* in the Caribbean Sea." *Biological Invasions* 21, no. 5 (2019): 1461-1472.

[32] L.J. McKenzie et al., "Seagrass Ecosystems of the Pacific Island Countries and Territories: A Global Bright Spot," *Marine Pollution Bulletin* 167 (2021).

[33] M.M. Littler et al., "Deepest Known Plant Life Discovered on an Uncharted Seamount," *Science 227*, no. 4682 (1985): 57–59.

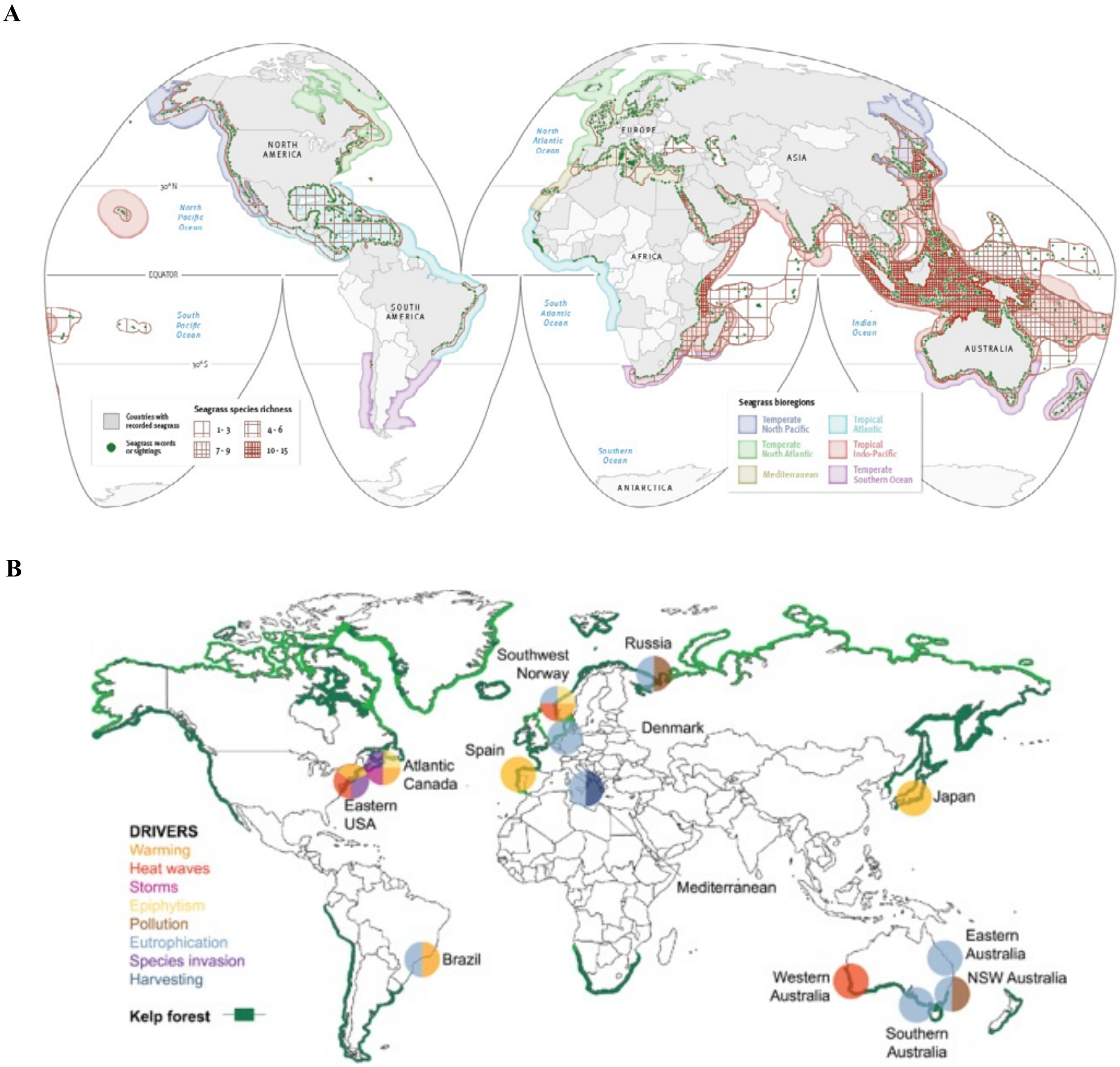

Figure 8. Global distributions reprinted from scholarly literature of (A) seagrasses[34] and (B) wild subtidal kelp and drivers of loss.[35] This map shows the locations of shifts from habitat-forming macroalgae to turfs (circles) overlaid on the approximate distribution of global kelp forests (green; light green unknown but inferred from habitat requirements); the slice colors of circles indicate different drivers implicated in the shift.

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[34] Reprinted from https://www.grida.no/resources/13590.

[35] Filbee-Dexter, K., & Wernberg, T. (2018). Rise of turfs: a new battlefront for globally declining kelp forests. Bioscience, 68(2), 64-76.

2. Advances in remote sensing technology for biomass monitoring

Remote sensing is a process for obtaining information about objects or areas from a distance, often from submersible craft or satellites for marine systems. Remote sensing tools use sensors that measure reflected energy from physical characteristics and collect images. Remote sensing has various applications, including monitoring ocean conditions and measuring the extent of and trends in seaweed and seagrass populations. Remotely sensed images provide data about the physical characteristics of seaweeds and seagrasses, enabling researchers to understand the status of seaweed and seagrass populations and informing decisions about seaweed and seagrass management and restoration. Recent advances in imaging capabilities, vehicle platforms and access to these technologies and data products have led to rapid progress in measuring standing stocks of seaweeds and seagrasses (see **Appendix 2** for history of development). **Table 4** summarizes the range of new remote sensing technologies emerging for this particular application. Emerging sectors such as offshore seaweed aquaculture and marine carbon dioxide removal are furthering the science of remote and precise seaweed stock evaluation. In combination with aerial technologies, remotely sensed acoustics has vastly advanced the capacity to estimate standing stock canopy biomass.

Table 4. Summary of remote sensing tools to detect submerged aquatic vegetation biomass.

REMOTE SENSING TOOL	USE / APPLICATION
Aerial and satellite imagery	Has been used for several decades to detect the presence of surface canopy-forming seaweeds (e.g., kelp).
Centimeter-resolution multispectral drone	An advanced tool for seaweed aquaculture farms that provides estimates of kelp canopy biomass, including edges and sparse canopies.[36]
Landsat satellite	Has been used for decades to acquire images of land on Earth. Provide data on seaweeds, such as estimates of kelp canopy biomass. Satellite remote sensing has also been used extensively for seagrass mapping.
Aerial hyperspectral imagery	Has shown the most promise for mapping standing stocks, primarily through quantifying leaf area index (LAI) using models and the study of water bodies' floors.[37] A global hyperspectral satellite mission, Surface Biology and Geology, will launch in the late 2020s.[38]
Acoustic Remote Sensing Technology	A remote sensing technique that obtains information about biomass distribution via sound waves as they are reflected.
Subsurface acoustic technology	Acoustic surveys have been used to identify the presence and relative abundance of seaweeds for the past few decades.[39] Applying this technology to aquaculture has reinvigorated algorithm development for standing stock estimates.
Multibeam sonar	Multibeam sonar systems use multiple, simultaneous sonar beams, or sound pulses, to map the seafloor and detect objects in the sea. The Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) MARINER program has used multibeam sonar to map subsurface kelp biomass and determine the effects of farm lines on acoustic properties.[40]

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[36] Tom W. Bell et al., "The Utility of Satellites and Autonomous Remote Sensing Platforms for Monitoring Offshore Aquaculture Farms: A Case Study for Canopy Forming Kelps," *Frontiers in Marine Science 7* (2020).

[37] Heidi M. Dierssen et al., "Ocean Color Remote Sensing of Seagrass and Bathymetry in the Bahamas Banks by High-Resolution Airborne Imagery," *Limnology and Oceanography* 48, no. 1 (2003): 444–55; John Hedley et al., "A Physics-Based Method for the Remote Sensing of Seagrasses," *Remote Sensing of Environment* 174 (2016): 134–47; and John D. Hedley et al., "Remote Sensing of Seagrass Leaf Area Index and Species: The Capability of a Model Inversion Method Assessed by Sensitivity Analysis and Hyperspectral Data of Florida Bay," *Frontiers in Marine Science* 4 (2017).

[38] E. Natasha Stavros et al., "Designing an Observing System to Study the Surface Biology and Geology (SBG) of the Earth in the 2020s," *Journal of Geophysical Research: Biogeosciences* 128, no. 1 (2023).

[39] Karel Zabloudil et al., "Sonar Mapping of Giant Kelp Density and Distribution, Coastal Zone '91," in *Coastal Zone 1991: Proceedings of the 7th Symposium on Coastal and Ocean Management*, ed. Orville T. Magoon (Long Beach: American Society of Civil Engineers, 1991); and P. Edward Parnell, "The Effects of Seascape Pattern on Algal Patch Structure, Sea Urchin Barrens, and Ecological Processes," *Journal of Experimental Marine Biology and Ecology* 465 (2015): 64–76.

[40] Erin Fischell et al., "Monitoring of Macroalgae (Kelp) Farms with Autonomous Underwater Vehicle-Based Split-Beam Sonar," Journal of the Acoustical Society of America 144, no. 3 (2018): 1806; and Miad Al Mursaline et al., "Acoustic Scattering by Smooth Elastic Cylinders Insonified by Directional Transceivers: Monostatic Theory and Experiments," Journal of the Acoustical Society of America 154, no. 1 (2023): 307–22.

REMOTE SENSING TOOL	USE / APPLICATION
Sidescan sonar	Sidescan sonar systems are active systems that use multiple physical sensors to send and receive acoustic pulses to detect and image objects in the sea. Combined with empirical kelp allometric relationships, show promise in rapidly mapping subsurface biomass using surface or underwater autonomous vehicles.[41] Along with multibeam sonar, has been an effective method for mapping seagrass cover in turbid waters.[42]

3. Evidence of range shifts

Seagrasses have declined worldwide due to anthropogenic activities.[43] Historical seagrass extent has declined by 29% globally, and seagrass meadows have disappeared at a rate of 110 square kilometers per year since 1980.[44] There have been well-documented declines since the beginning of the 20th century,[45] and palaeoceanographic work has also detected human impacts beginning centuries ago.[46] Average global declines of seagrasses are estimated to be between 1% and 2% annually.[47] However, declines vary by bioregion; for example, 1000-fold losses are estimated to have occurred between the 1950s and the 1970s in the temperate north Pacific, but have slowed down more recently.[48] In contrast, declines as high as 7% have been occurring since 2000 along the temperate Atlantic Coast of the United States.[49] Restoration efforts and improvements in water quality have effectively slowed and reversed these trends in some locations, most notably within the Chesapeake Bay.[50] Range contractions are expected to occur in most seagrass species as a result of climate change, except for the non-native seagrasses *Z. japonica* and *H. stipulacea*, which both appear to be expanding. Habitat suitability models suggest these species could increase dramatically.

Global warming threatens seagrass meadows by causing physiological stress but some species of seagrass occur over a wide range of temperatures. Many subtropical and tropical seagrasses thrive at high ocean temperatures, while widespread seagrasses such as eelgrass range from 25 degrees Celsius in the southern United States to arctic conditions.[51] Two primary mechanisms underlie the physiological stress seagrasses experience at high temperatures. First, acute warming can impair photosynthesis.[52] Second, increased plant metabolism drains stored sugar reserves within plant tissues, which plants need to survive low-light conditions, causing delayed diebacks months after warming exposure.[53]

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[41] Bell et al., "Utility of Satellites."

[42] Teruhisa Komatsu et al., "Use of Multi-Beam Sonar to Map Seagrass Beds in Otsuchi Bay on the Sanriku Coast of Japan," *Aquatic Living Resources* 16, no. 3 (2003): 223–30; Austin Greene et al., "Side Scan Sonar: A Cost-Efficient Alternative Method for Measuring Seagrass Cover in Shallow Environments," *Estuarine, Coastal and Shelf Science* 207 (2018): 250–58; A. Lefebvre et al., "Use of a High-Resolution Profiling Sonar and a Towed Video Camera to Map a *Zostera Marina* Bed, Solent, UK," *Estuarine, Coastal and Shelf Science* 82, no. 2 (2009): 323–34; and M. Hamana and T. Komatsu, "Real-Time Classification of Seagrass Meadows on Flat Bottom with Bathymetric Data Measured by a Narrow Multibeam Sonar System," *Remote Sensing* 8, no. 2 (2016): 96.

[43] Frederick T. Short and Sandy Wyllie-Echeverria, "Natural and Human-Induced Disturbance of Seagrasses," Environmental Conservation 23, no. 1 (1996): 17–27; Robert J. Orth et al., "A Global Crisis for Seagrass Ecosystems," Bioscience 56, no. 12 (2006): 987–96; and Michelle Waycott et al., "Accelerating Loss of Seagrasses Across the Globe Threatens Coastal Ecosystems," Proceedings of the National Academy of Sciences 106, no. 30 (2009): 12377–81.

[44] Waycott et al., "Accelerating Loss of Seagrasses."

[45] Short and Wyllie-Echeverria, "Natural and Human-Induced Disturbance"; and Dorte Krause-Jensen et al., "Century-Long Records Reveal Shifting Challenges to Seagrass Recovery," *Global Change Biology* 27, no. 3 (2021): 563–75.

[46] Oscar Serrano et al., "Seagrass Sediments Reveal the Long-Term Deterioration of an Estuarine Ecosystem," *Global Change Biology* 22, no. 4 (2016): 1523–31.

[47] J.C. Dunic et al., "Long–Term Declines and Recovery of Meadow Area across the World's Seagrass Bioregions," *Global Change Biology* 27, no. 17 (2021): 4096–109.

[48] Dunic et al., "Long-Term Declines."

[49] Dunic et al., "Long-Term Declines."

[50] J.S. Lefcheck et al., "Long-Term Nutrient Reductions Lead to the Unprecedented Recovery of a Temperate Coastal Region," *Proceedings of the National Academy of Sciences* 115, no. 14 (2018): 3658–62.

[51] K.S. Lee, S.R. Park, and Y.K. Kim, "Effects of Irradiance, Temperature, and Nutrients on Growth Dynamics of Seagrasses: A Review," *Journal of Experimental Marine Biology and Ecology* 350, no. 1–2 (2007): 144–75.

[52] T. Repolho et al., "Seagrass Ecophysioogical Performance under Ocean Warming and Acidification," *Scientific Reports* 7 (2017).

[53] G. Hernan et al., "Future Warmer Seas: Increased Stress and Susceptibility to Grazing in Seedlings of a Marine Habitat-Forming Species," *Global Change Biology* 23, no. 11: 4530–43.

While worldwide seagrass declines in previous decades were primarily driven by poor water quality, marine heat waves are emerging as a primary threat to seagrasses. Marine heat waves are high-temperature events in the 90th percentile, with the long-term average lasting for more than five days.[54] Examples of massive seagrass diebacks that coincide with marine heat waves have occurred in Australia,[55] the Mediterranean,[56] and in the eastern U.S.[57] At the interface between temperate and tropical seagrass species, the increasing frequency of high temperature anomalies is expected to cause a range extension of tropical seagrasses.[58]

Another consequence of climate change is sea level rise which exacerbates the effects of ocean warming. Deeper waters decrease light penetration, impacting suitable seagrass habitats, while warming increases the light requirements for survival.[59] The consequences of sea level rise (SLR) for eelgrass persistence will depend on coastal habitats' ability to migrate inland. For example, researchers anticipate a 14-18% expansion of suitable seagrass habitat in certain locations,[60] while others project a total loss of suitable seagrass habitat.[61]

Stakeholders are currently debating proactive management strategies related to assisted gene flow from warming-adapted populations.[62] To be successful, management strategies aimed at mitigating the effects of warming on seagrasses must also protect genetic diversity and incorporate the impacts of sea level rise.[63] (see **Appendix 3**, Seagrasses Genetic Connectivity). Maintaining several adjacent populations (including locations for potential populations) as opposed to single populations is critical to facilitating adaptation and protecting source populations in the context of rapidly changing environmental conditions. Hot spots for future seagrass populations have been forecasted to fall outside marine protected areas.[64]

Seaweeds distributions are experiencing similar losses and shifts as seagrasses, but the process is less well documented for this far more diverse and widely dispersed set of macrophytes. Particularly in the U.S. in California, Alaska, and the north Atlantic, losses of kelp forest coverage have been well documented[65] and are often attributed to gradual warming and marine heat waves. The extent to which SLR will also impact the intertidal seaweed species is less studied than the impact on seagrasses. Spatially explicit modeling efforts using various SLR scenarios predict loss of suitable habitat in rocky intertidal zones, driving reductions in areal extent of intertidal seaweeds.[66]

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[54] A.J. Hobday et al., "A Hierarchical Approach to Defining Marine Heatwaves," *Progress in Oceanography* 141 (2016): 227–38.

[55] S.K. Strydom et al., "Too Hot to Handle: Unprecedented Seagrass Death Driven by Marine Heatwave in a World Heritage Area," *Global Change Biology* 26, no. 6 (2020): 3525–38.

[56] N. Marba and C. M. Duarte, "Mediterranean Warming Triggers Seagrass (*Posidonia oceanica*) Shoot Mortality," *Global Change Biology* 16, no. 8 (2010): 2366–75.

[57] L. Aoki et al., "Depth Affects Seagrass Restoration Success and Resilience to Marine Heatwave Disturbance," *Estuaries and Coasts* 43 (2020): 316–28.

[58] A. Bartenfelder et al., "The Abundance and Persistence of Temperate and Tropical Seagrasses at Their Edge-of-Range in the Western Atlantic Ocean," *Frontiers in Marine Science* 9 (2022).

[59] Aoki et al., "Depth Affects Seagrass Restoration."

[60] M. Valle et al., "Projecting Future Distribution of the *Seagrass Zostera noltii* under Global Warming and Sea Level Rise," *Biological Conservation* 170 (2014): 74–85.

[61] C.R. Scalpone et al., "Simulated Estuary-Wide Response of Seagrass (Zostera marina) to Future Scenarios of Temperature and Sea Level," *Frontiers in Marine Science* 7 (2020).

[62] C.P. Nadeau et al., "Incorporating Experiments into Management to Facilitate Rapid Learning about Climate Change Adaptation," *Biological Conservation* 289 (2024).

[63] Valle et al., "Projecting Future Distribution"; and Scalpone et al., "Simulated Estuary-Wide Response."

[64] B.H. Daru and B.M. Rock, "Reorganization of Seagrass Communities in a Changing Climate," *Nature Plants* 9, no. 7 (2023): 1–10.

[65] Wernberg, T., Krumhansl, K., Filbee-Dexter, K., & Pedersen, M. F. (2019). Chapter 3. Status and trends for the world's kelp forests. In 'World Seas: an Environmental Evaluation', 2nd edn.(Ed. C Sheppard.) pp. 57–78.

[66] Kaplanis, N. J., Edwards, C. B., Eynaud, Y., & Smith, J. E. (2020). Future sea-level rise drives rocky intertidal habitat loss and benthic community change. *PeerJ,* 8, e9186; Schaefer, N., Mayer-Pinto, M., Griffin, K. J., Johnston, E. L., Glamore, W., & Dafforn, K. A. (2020). Predicting the impact of sea-level rise on intertidal rocky shores with remote sensing. *Journal of environmental management*, 261, 110203; Martínez, B., Viejo, R. M., Carreño, F., & Aranda, S. C. (2012). Habitat distribution models for intertidal seaweeds: responses to climatic and non–climatic drivers. *Journal of biogeography*, 39(10), 1877-1890.

Another notable example of an acute human-driven reduction in seaweed populations occurred along 1,400 miles of Alaska's southern coastline following the March 1989 Exxon Valdez Oil Spill. Seaweed populations were greatly affected by the initial spill and by cleanup activities over the following two years. By 1991, many organisms in the lower and middle intertidal zones had recovered significantly, however, several important traditional subsistence seaweed species were wholly eliminated by cleaning efforts in some areas resulting in critical resource and habitat loss. The eradication of seaweed from certain areas has caused a disruption in the ecological balance, and instability in marine populations, as recolonized seaweed populations are more susceptible to die-offs. The Exxon Valdez Oil Spill Trustee Council lists intertidal communities as "Recovering" on their website, though little mapping of these communities has been conducted since 1997, so it's difficult to say with precision to what degree these communities have returned. This example highlights the long-term and multi-faceted impacts associated with large-scale seaweed loss events.

4. Seagrass and seaweed restoration practices

Overall seagrass loss in the U.S. in particular is poorly documented, but regional studies report significant rates of decline reaching historical lows.[67] To counter and mitigate the rate of loss, seagrass restoration efforts have been implemented and have improved significantly over time. Restoration (i.e., returning an ecosystem to its original state) can be done passively and actively. Passive restoration, better understood as rehabilitation, reduces anthropogenic stressors to facilitate natural regeneration e.g., by improving water quality from agricultural run-off, to tackle eutrophication, or nutrient loading[68]. Other examples include the modification (e.g., placement of fill, sediment tubes or breakwaters) or creation of new habitat (e.g., lagoon creation or spoil island scrape-down) to promote natural unaided recruitment. Active restoration also requires reducing anthropogenic stressors and is recommended when a seagrass or seaweed ecosystem has been altered to such an extent that it can no longer self-recover.

Active restoration for seagrasses is based on three main approaches: transplanting local seagrass shoots to a new location, recollecting and dispersing local seeds in a new location and modifying the new location's habitat to facilitate seagrass growth. Many active restoration techniques have been developed, but none of them are universally applicable.[69] Success depends on the seagrass species; the characteristics of the site to be restored (sediment grain size, currents or turbidity, etc.); and the human expertise involved in each project.[70] (**Appendix 4**). Consequently, this historically active area of research on seagrass restoration techniques for the past four decades has been expanding recently and will continue to be very active in the future.

The number of restoration attempts has increased dramatically in the last two decades, with mixed outcomes. Generally, the success of seagrass restorations is improved when the causes of loss are understood and when passive and active efforts are coupled. Many urbanized estuaries have documented large passive gains in

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[67] Max Chesnes, "Tampa Bay Lost 12% of Its Seagrass in 2 Years; Some Areas at Historic Low, Study Shows," Tampa Bay Times, February 13, 2023, https://www.tampabay.com/news/environment/2023/02/13/tampa-bay-lost-12-its-seagrass-2-years-some-areas-historic-low-study-shows/; Robby Lewis-Nash, "'Staggering' Loss of Eelgrass Habitat in Casco Bay," Friends of Casco Bay, April 21, 2023, https://www.cascobay.org/staggering-loss-of-eelgrass-habitat-in-casco-bay/; R.K. Walter et al., "Large-Scale Erosion Driven by Intertidal Eelgrass Loss in an Estuarine Environment," *Estuarine, Coastal and Shelf Science* 243 (2020); C.T. Costello and W.J. Kenworthy, "Twelve-Year Mapping and Change Analysis of Eelgrass (Zostera Marina) Areal Abundance in Massachusetts (USA) Identifies Statewide Declines," Estuaries and Coasts 34, no. 2 (2011): 232–42; and New York State Seagrass Taskforce, *Final Report of the New York State Seagrass Task Force: Recommendations to the New York State Governor and Legislature* (New York State Seagrass Taskforce, December 2009).

[68] Yi Mei Tan et al., "Seagrass Restoration Is Possible: Insights and Lessons from Australia and New Zealand," *Frontiers in Marine Science* 7 (2020).

[69] Fonseca, "Addy Revisited," 73–81; and Marieke M. van Katwijk et al., "Global Analysis of Seagrass Restoration: The Importance of Large-Scale Planting," *Journal of Applied Ecology* 53, no. 2 (2016): 567–78.

[70] Melissa Ward and Kathryn Beheshti, "Lessons Learned from Over Thirty Years of Eelgrass Restoration on the U.S. West Coast," *Ecosphere* 14, no. 8 (2023).

underwater grasses stemming from watershed and infrastructure modification (i.e., advanced wastewater treatment, stormwater upgrades, TMDL setting, fertilizer regulation), such as in Tampa and Chesapeake Bays.[71]

From North Carolina to Maine, most restoration programs in each state have focused on eelgrass, generally on small scales (< 1 acre) and testing potential methods that could help facilitate the success (e.g., proper site selection, appropriate planting technique for a specific site, use of seeds vs. whole plants). Although dozens of seagrass planting projects are attempted every year along the eastern coast of the U.S., including Florida, areas in the northern Gulf of Mexico have little active restoration, despite substantial losses in seagrass coverage in several states, including Mississippi and Louisiana.[72] Barrier island restoration efforts in these two states, however, have been undertaken (Mississippi) and are planned (Louisiana) with a goal of increasing seagrass coverage.[73] Some emerging restoration approaches involve coupling seagrass and bivalves such as clams to enhance restoration success, and incorporating plant genetic structure into restoration design. Long-term monitoring to assess performance of seagrass restoration efforts is essential for developing best practices. Many of these projects have involved cooperative efforts between scientific research organizations and non-government civic volunteer groups.

Historically, for active seagrass restoration, divers would manually insert seagrass “planting units” into the seabed, which was laborious and costly.[74] The development of innovative techniques such as Buoy Deployed Seeding (BuDS),[75] Bags of Seagrass Seeds Line (BoSSLine),[76] and Transplanting Eelgrass Remotely with Frames (TERFs)[77] has greatly improved the speed and cost of restoration although the labor required for site preparation and to ensure overall success still varies.[78] Today, the focus is trending toward seed-based methods, which are less damaging to harvested donor beds, and toward using machinery to plant both shoots and seeds.[79] The mechanization of seagrass planting started with a boat designed to insert planting units into the seabed, which led to low shoot survival rates.[80] The Virginia Institute of Marine Science later developed a planting sled, which planted seeds in a gel matrix, helping them stay in place while deterring predation and improving seedling establishment rates.[81] Recent advancements, such as Dispenser Injection Seeding (DIS), have shown promise for increasing the density of restored seagrass meadows.[82] Complex marine environments, which demand more sophisticated navigation and object avoidance techniques, complicate the design and deployment of mechanized out-planting systems.

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[71] Greening, Holly, et al. “Ecosystem responses to long-term nutrient management in an urban estuary: Tampa Bay, Florida, USA.” Estuarine, Coastal and Shelf Science 151 (2014): A1-A16; Lefcheck, Jonathan S., et al. “Long-term nutrient reductions lead to the unprecedented recovery of a temperate coastal region.” Proceedings of the National Academy of Sciences 115.14 (2018): 3658-3662.

[72] Handley, L. and Lockwood, C. 2020. Seagrass Status and Trends Update for the Northern Gulf of Mexico: 2002-2017. Final Report to the Gulf of Mexico Alliance for Contract No.: 121701-00. Ocean Springs, Mississippi.

[73] Enwright NM, KMD Darnell, GA Carter. 2022. Lacunarity as a tool for assessing landscape configuration over time and informing long-term monitoring: an example using seagrass. Landscape Ecology 37: 2689-2705; Chandeleur Island Restoration Project. 2024. https://coastal.la.gov/chandeleur-island-restoration-project/. Accessed July 25, 2024.

[74] Mark S. Fonseca, *A Low-Cost Transplanting Technique for Shoalgrass (Halodule wrightii) and Manatee Grass (Syringodium filiforme)* (Vicksburg, MS: Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, September 1984).

[75] Christopher Pickerell, Steve Schott, and Sandy Wyllie-Echeverria, Buoy-Deployed Seeding: *A New Low-Cost Technique for Restoration of Submerged Aquatic Vegetation from Seed* (Vicksburg, MS: U.S. Army Engineer Research and Development Center, 2006).

[76] R.K. Unsworth et al., “Sowing the Seeds of Seagrass Recovery Using Hessian Bags,” *Frontiers in Ecology and Evolution* 7 (2019).

[77] F.T. Short et al., “Seagrass Ecology and Estuarine Mitigation: A Low-Cost Method for Eelgrass Restoration,” *Fisheries Science* 68, no. 2 (2002): 1759–62.

[78] S.R. Marion and R.J. Orth, “Innovative Techniques for Large-Scale Seagrass Restoration Using Zostera marina (Eelgrass) Seeds,” *Restoration Ecology* 18, no. 4 (2008): 514–26; and J. Park and K. Lee, “Site-Specific Success of Three Transplanting Methods and the Effect of Planting Time on the Establishment of Zostera marina Transplants,” *Marine Pollution Bulletin* 54, no. 8 (2007): 1238–48.

[79] Y.M. Tan et al., “Developing Seed– and Shoot–Based Restoration Approaches for the Seagrass, Zostera muelleri,” *Restoration Ecology* 31, no. 5 (2023); and K.E. Busch et al., “Large-Scale Zostera marina (Eelgrass) Restoration in Chesapeake Bay, Maryland, USA. Part I: A Comparison of Techniques and Associated Costs,” *Restoration Ecology* 18, no. 4 (2008): 490–500.

[80] J.R. Fishman et al., “A Comparative Test of Mechanized and Manual Transplanting of Eelgrass, Zostera marina, in Chesapeake Bay,” *Restoration Ecology* 12, no. 2 (2004): 214–19.

[81] R.J. Orth et al., “Evaluation of a Mechanical Seed Planter for Transplanting Zostera marina (Eelgrass) Seeds,” *Aquatic Botany* 90, no. 2 (2009): 204–8.

[82] M.L. Gräfnings et al., “Optimizing Seed Injection as a Seagrass Restoration Method,” *Restoration Ecology* 31, no. 3 (2022).

Seagrass restoration project developers are moving toward automation, using Remote Operated Vehicles (ROVs) that can plant many seagrass shoots and seeds efficiently. For example, the National Science Foundation-funded startup, Reefgen, is deploying seed-planting robots to reduce costs, reduce the need for manual labor, and potentially create a future in which unmanned vehicles can handle large-scale restoration efforts (see **Appendix 4**).[83] Currently, the largest manual seagrass restoration project, based in the Chesapeake Bay, restores less than 55 acres per year.[84] Scaled mechanization will enable hundred-fold increases in areal restoration capability. As such, seagrass has strong potential to become an important aquaculture product in the United States, especially since seagrass is a known, but potentially undervalued, climate-resilient commodity crop.[85] Public and private sector investment in seagrass production and planting technology lowers barriers to scaled seagrass aquaculture practices.

Active seaweed bed restoration as a technique is still in its infancy, but new efforts use simple techniques to seed small rocks or line with kelp propagules, rearing them in the lab and then out-planting them into the field. This restoration technique essentially follows that of kelp farming, but uses very low-tech practices to reduce dependence on vessels or SCUBA diving and gear maintenance. Seaweed farming techniques, definitions, and advances therein are covered in detail in **C. Blue Economy 2. Farm tech innovation to optimize yield**, and are also summarized here in **Figure 9** for quick reference. Depending on the stakeholder group conducting the farming practice, different approaches may be taken – but nearly all require a 'nursery' stage before the seaweeds are out planted at the farm site for subsequent grow out. The types of seaweed species that are farmed continues to expand, but the most popular seaweed species (and seagrasses used in restoration efforts) are provided in **Table 5**.

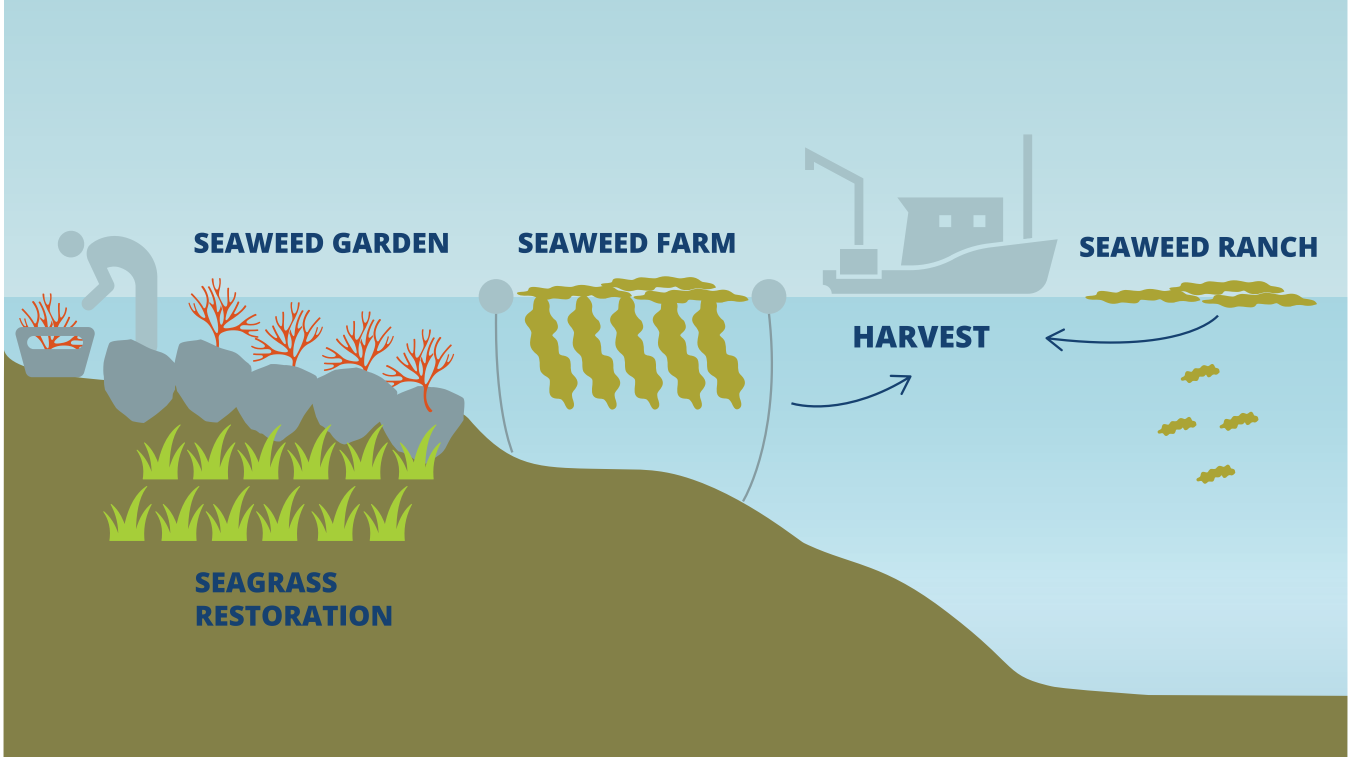

Figure 9. Conceptual diagram of typical seaweed farm and seagrass restoration effort processes (including imagery of what a seaweed farm looks like from surface and subsurface).

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[83] Elen Davies and Antonia Matthews, "Climate Change: Robots Help Seagrass Restoration," *BBC News*, June 29, 2023, https://www.bbc.com/news/uk-wales-66050848.

[84] "Sav Monitoring & Restoration," Virginia Institute of Marine Science, accessed January 12, 2024, https://www.vims.edu/research/units/programs/sav1/restoration/index.php.

[85] Ana Fernandez Abad, "'*Zostera marina*,' a Michelin-Starred Sea Grain That Could Point to the Future of Hydroponic Crops," El Pais News, May 11, 2023, https://english.elpais.com/science-tech/2023-05-11/zostera-marina-a-michelin-starred-sea-grain-that-could-point-to-the-future-of-hydroponic-crops.html.

Table 5. List of most common seagrass species currently in restoration efforts and seaweed species currently farmed (top five by landings). A more complete list of Latin names and common names of seagrass and seaweed species is presented in **Appendix C**

RESTORED SEAGRASSES	FARMED SEAWEEDS
Zostera marina (eel grass)	*Saccharina latissima* (brown kelp)
Thalassia testudinum (turtle grass)	*Saccharina angustissima* (brown kelp)
Halodule wrightii (shoal grass or shoalweed)	*Alaria esculenta* (brown kelp)
	Alaria marginata (brown kelp)
	Laminaria digitata (brown kelp)
	Nereocystis luetkeana (brown kelp)
	Palmaria palmata (red alga)

II. STATE OF THE SCIENCE

This section shares the results of the Federal Interagency Working Group and Regional Stakeholder working groups' research and fact-finding, and also reflects considerable contributions from the subject matter experts recruited to expand the representation of the report.

A. Ecosystem Services

Contributing Authors: Suzanne Arnold, Simona Augyte, Damian Brady, Carrie Byron, Kelly Darnell, Katherine DuBois, Rod Fujita, Bradley Furman, Maya Groner, Jonathan Lefcheck, Elizabeth Lewis, Robert J. Orth, Aurora Ricart, and Shane Rogers

Ocean or coastal sea farms and seagrass beds offer valuable ecosystem services (which are both direct and indirect benefits ecosystems provide to humans), such as habitat provisioning for coastal organisms, nutrient bioremediation, water quality improvement, seawater oxygenation, reduced local OA and potential climate mitigation.[86] Seaweed farming focused explicitly on kelp species is an emerging maritime sector in the United States that holds promise for generating substantial economic returns. Both seaweed farming and seagrass restoration offer ecosystem services and community opportunities that align with the UN Sustainable Development Goals (**Table 6**).[87]

Table 6. UN Sustainable Development Goals and which SDGs seagrass restoration efforts and seaweed farming ventures align with most closely.

SUSTAINABLE DEVELOPMENT GOAL	SEAGRASS RESTORATION	SEAWEED FARMING
No Poverty		X
Zero Hunger		X
Good Health and Well-Being		X
Quality Education		
Gender Equality		X
Clean Water and Sanitation	X	X
Affordable and Clean Energy		X
Decent Work and Economic Growth		X
Industry, Innovation and Infrastructure		X
Reduced Inequalities		X
Sustainable Cities and Communities	X	X
Responsible Consumption and Production		X

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[86] João Cotas et al., "Ecosystem Services Provided by Seaweeds," *Hydrobiology* 2, no. 1 (2023): 75–96; Ricard Langton et al., *An Ecosystem Approach to the Culture of Seaweed*, NOAA Technical Memorandum NMFS-F/SPO-195 (Washington, DC: National Marine Fisheries Service, 2019), 24; S.J. Theuerkauf et al., "Habitat Value of Bivalve Shellfish and Seaweed Aquaculture for Fish and Invertebrates: Pathways, Synthesis and Next Steps," *Reviews in Aquaculture* 14, no. 1 (2022): 54–72; Charles Yarish et al., "Developing an Environmentally and Economically Sustainable Sugar Kelp Aquaculture Industry in Southern New England: from Seed to Market," *Department of Ecology and Evolutionary Biology Articles* (2017); and Spillias, S., Kelly, R., Cottrell, R. S., O'Brien, K. R., Im, R. Y., Kim, J. Y., ... & McDonald-Madden, E. (2023). The empirical evidence for the social-ecological impacts of seaweed farming. *PLOS Sustainability and Transformation*, 2(2), e0000042

[87] "The 17 Goals," UN Department of Economic and Social Affairs, n.d., accessed on May 16, 2024, https://sdgs.un.org/goals.

SUSTAINABLE DEVELOPMENT GOAL	SEAGRASS RESTORATION	SEAWEED FARMING
Climate Action	X	X
Life Below Water	X	X
Life on Land	X	
Peace, Justice, and Strong Institutions		
Partnerships for the Goals	X	X

This report reviews each of the ecosystem services that seagrass meadows and farmed seaweeds can provide, with a particular focus on the biogeochemical feedback loops most relevant to ocean deacidification and decarbonization (**Figure 10**), as was requested in the original FY19 appropriations bill.

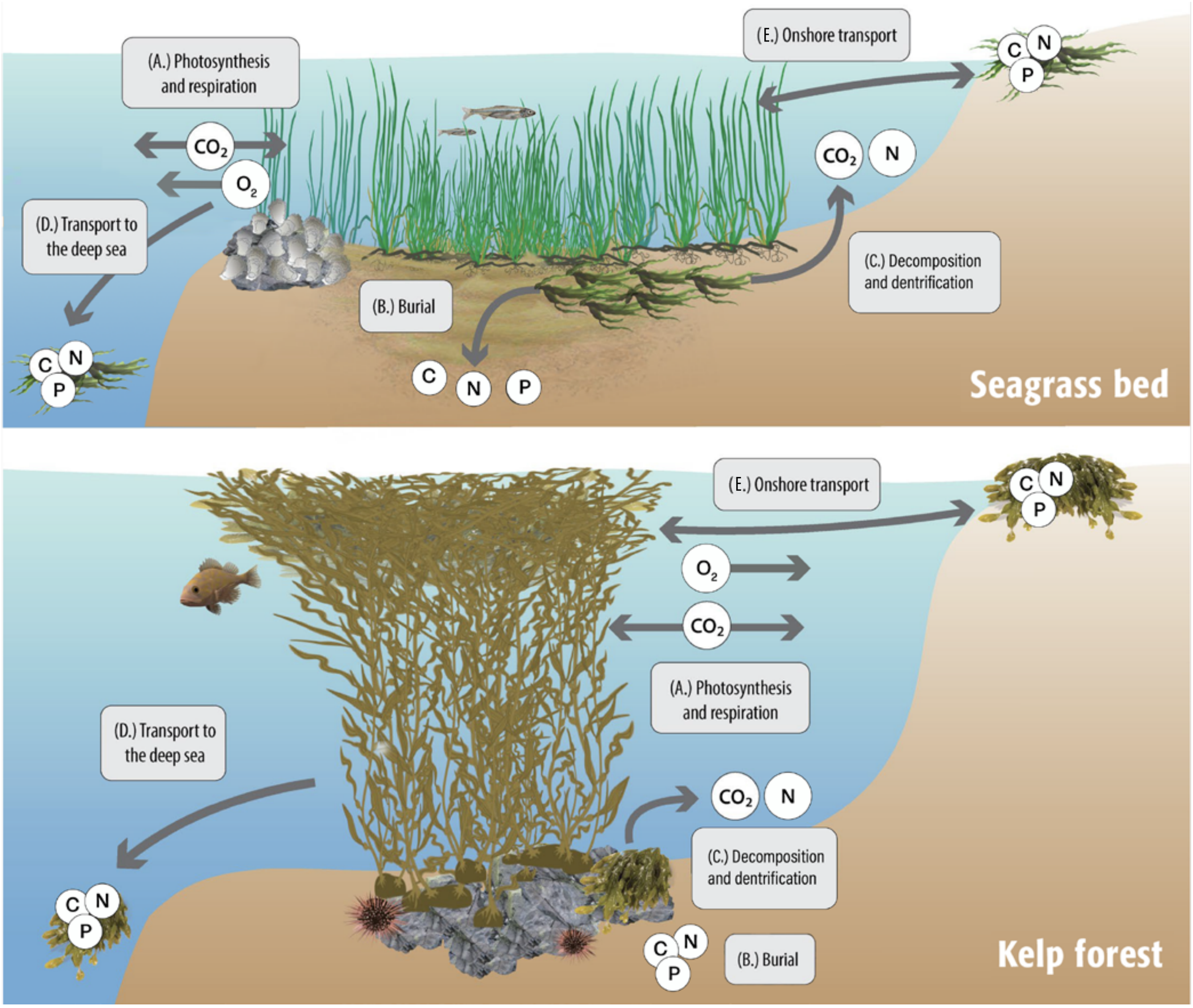

Figure 10. Conceptual diagram of biogeochemical feedback loops (reprinted from Neilson et al 2018[88]).

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[88] Nielsen, K. J., Stachowicz, J. J., Carter, H., Boyer, K., Bracken, M., Chan, F., ... & Wheeler, S. (2018). Emerging understanding of seagrass and kelp as an ocean acidification management tool in California.

1. Habitat provisioning and coastal protection

Seagrass meadows are diverse, productive habitats that provide numerous ecosystem services. These hot spots of biodiversity provide shelter, feeding grounds, nursery grounds, migration stop-overs and spawning habitat for numerous species, including several with large commercial value (e.g., juvenile blue crab, American lobster and various salmon species), and others with endangered or threatened statuses (e.g., Florida manatee, green sea turtles, sharks and seahorses).[89]

One highly valuable ecosystem service seagrass provides against climate change impacts is coastal protection. The ability of seagrasses to enhance coastal protection is highly dependent on energy flux, plant density, biomass and stiffness.[90] In general, seagrasses are not effective in directly reducing storm energy, but seagrasses indirectly dissipate storm energy by reducing current velocities and enhancing sedimentation rates.[91] Similarly, the impacts of severe storms on seagrass meadow persistence are highly variable.[92] One study found that seagrasses are typically resilient to hurricanes, but when seagrass decline does occur, it is because storm-derived sedimentation reduces water quality and buries plants.[93] One extreme example of seagrass decline occurred in the Mediterranean in 2018, when a severe storm buried local seagrass meadows in 10 centimeters of sediment, resulting in 50% meadow loss in one day.[94] While the potential for severe storms to cause catastrophic meadow loss is concerning, the resilience of most seagrass meadows to storm damage highlights their value for coastal protection via sediment stabilization, and requires further research.[95]

In tropical settings, large seaweed farms situated over otherwise barren sandflats can locally enhance biodiversity of invertebrate and finfish species.[96] Temperate kelp farms similarly provide shelter to juvenile lumpfish and structure for myriad small (<5mm) invertebrates in the Gulf of Maine. But there is a mismatch in timing of kelp farming activity with the presence of other finfish, lobsters and most other organisms and the seasonality in their preferred nursery habitat needs. Kelp farms in the Gulf of Maine are harvested, and most of the gear (anchors, lines) removed in the spring as the water begins to warm, immediately before the arrival of finfish and crustaceans. Biodiversity and abundance of wild organisms in this cooler ecosystem can be linked to seasonal timing, and not the presence of these small-scale (<10 acres), near-shore (<2 km) temperate kelp farms;[97] however, larger, older kelp farms greatly enhance finfish species richness and number during the periods when kelp is grown.[98] Generally, mobile finfish and invertebrates stand to gain more habitat provisioning from seaweed farming, but the exact impacts are highly variable and will depend on the species of seaweed farmed.[99] Part of the challenge of identifying whether or not seaweed farms can provide sufficient habitat to enhance local biodiversity in any ecosystem is the lack of a systematic sampling program to quantify consistently across systems and trophic level, though guidance has recently been proposed.[100]

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[89] Duffy, "Biodiversity and the Functioning."

[90] Ondiviela et al., "Role of Seagrasses."

[91] Ondiviela et al., "Role of Seagrasses."

[92] K.M. Correia and D.L. Smee, "A Meta-Analysis of Tropical Cyclone Effects on Seagrass Meadows," *Coastal Wetlands* 42, no. 108 (2022).

[93] Correia and Smee, "Meta-Analysis."

[94] A. Gera et al., "The Effect of a Centenary Storm on the Long-Lived Seagrass *Posidonia Oceanica," Limnology and Oceanography* 59, no. 6 (2014): 1910–18.

[95] R.K. James et al., "Tropical Biogeomorphic Seagrass Landscapes for Coastal Protection: Persistence and Wave Attenuation during Major Storms Events," *Ecosystems* 24 (2021): 301–18.

[96] Radulovich, R., Umanzor, S., Cabrera, R., & Mata, R. (2015). Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. *Aquaculture*, 436, 40-46.

[97] Schutt, E., Francolini, R., Price, N., Olson, Z., & Byron, C. J. (2023). Supporting ecosystem services of habitat and biodiversity in temperate seaweed (*Saccharina* spp.) farms. *Marine Environmental Research*, 191, 106162.

[98] Corrigan, S., Smale, D. A., Tyler, C. R., & Brown, A. R. (2024). Quantification of finfish assemblages associated with mussel and seaweed farms in southwest UK provides evidence of potential benefits to fisheries. *Aquaculture Environment Interactions*, 16, 145-162.

[99] Spillias, S., Kelly, R., Cottrell, R. S., O'Brien, K. R., Im, R. Y., Kim, J. Y., ... & McDonald-Madden, E. (2023). The empirical evidence for the social-ecological impacts of seaweed farming. *PLOS Sustainability and Transformation*, 2(2), e0000042.

[100] Corrigan, S., Brown, A. R., Ashton, I. G., Smale, D. A., & Tyler, C. R. (2022). Quantifying habitat provisioning at macroalgal cultivation sites. *Reviews in Aquaculture*, 14(3), 1671-1694.

It has been hypothesized that seaweed farms can provide coastal protection services, much like seagrasses. The limited empirical evidence that wild kelp "curtains" can dampen wave energy and lessen dune erosion comes from natural seaweed systems, not cultivated ones.[101] Even in these wild kelp beds, a recent study found that giant kelp (*Macrosystis pyrifera*) had only a modest impact on damping (7 ± 1.2%, mean and standard error).[102] Expectations that farmed kelp, when oriented and situated to maximize impact, could contribute meaningful reductions to coastal erosion are still under exploration.

2. Nutrient remediation

Human activities that result in nutrient pollution in coastal systems have profound repercussions on marine ecosystems and human well-being.[103] The impacts of this phenomenon, known as eutrophication, are many and encompass diminished water clarity, harmful algal blooms, heightened bacterial activity and oxygen depletion. The synergistic effects of eutrophication are habitat deterioration and economic losses.[104] To address these impacts, the United States has instituted the Clean Water Act (CWA), which mandates that each state establish a program for monitoring and reporting on water quality.[105] Various methodologies, including point sampling and satellite imaging, are employed to meet monitoring objectives.

Seagrasses support healthy ecosystems via physical and biological processes, each of which can influence nutrient loading. Physical processes that purify water include the filtration of sediments (via wave attenuation), and the removal of excess nitrogen via uptake and burial.[106] Biological processes include the removal of nitrogen, phosphorus and metal toxins via adsorption and uptake into tissues,[107] and by harboring algicidal bacteria that can limit the duration of harmful algal blooms.[108]

Seaweeds rely primarily on inorganic carbon, nitrogen and phosphorus for photosynthesis and growth.[109] Therefore, cultivating seaweeds, particularly in eutrophic marine environments, may alleviate excess nutrient concentrations locally and even regionally through bioextraction. A burgeoning body of evidence highlights the potential of seaweeds, particularly kelp, to counterbalance and eliminate excessive nutrients and metals stemming from sources like coastal finfish aquaculture, urban and industrial runoff and agricultural activities.[110] Multiple

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[101] Spillias, S., Kelly, R., Cottrell, R. S., O'Brien, K. R., Im, R. Y., Kim, J. Y., ... & McDonald-Madden, E. (2023). The empirical evidence for the social-ecological impacts of seaweed farming. *PLOS Sustainability and Transformation*, 2(2), e0000042.

[102] Elsmore, Kristen, Kerry J. Nickols, Luke P. Miller, Tom Ford, Mark W. Denny, and Brian Gaylord. "Wave damping by giant kelp, *Macrocystis pyrifera." Annals of Botany* 133, no. 1 (2024): 29-40.

[103] Dubravko Justić et al., "Changes in Nutrient Structure of River-Dominated Coastal Waters: Stoichiometric Nutrient Balance and Its Consequences," *Estuarine, Coastal and Shelf Science* 40, no. 3 (1995): 339–56; and Hans W. Paerl, "Assessing and Managing Nutrient-Enhanced Eutrophication in Estuarine and Coastal Waters: Interactive Effects of Human and Climatic Perturbations," *Ecological Engineering* 26, no. 1 (2006): 40–54.

[104] Susana M. Coelho, Jan W. Rijstenbil, and Murray T. Brown, "Impacts of Anthropogenic Stresses on the Early Development Stages of Seaweeds," *Journal of Aquatic Ecosystem Stress and Recovery* 7, no. 4 (2000): 317–33; P. Hoagland et al., "The Economic Effects of Harmful Algal Blooms in the United States: Estimates, Assessment Issues, and Information Needs," Estuaries 25 (2002): 819–37; Val H. Smith, "Eutrophication of Freshwater and Coastal Marine Ecosystems a Global Problem," *Environmental Science and Pollution Research* 10, no. 2 (2003): 126–39; Boris Worm and Heike K. Lotze, "Effects of Eutrophication, Grazing, and Algal Blooms on Rocky Shores," *Limnology and Oceanography* 51, no. 1 (2006): 569–79; and N.N. Rabalais et al., "Global Change and Eutrophication of Coastal Waters," *ICES Journal of Marine Science* 66, no. 7 (2009): 1528–37.

[105] C. Copeland, *Clean Water Act: A Summary of the Law*, Congressional Research Service Report RL30030 (Washington, DC: Congressional Research Service, 2016).

[106] L.R. Aoki, K.J. McGlathery, and M.P. Oreska, "Seagrass Restoration Reestablishes the Coastal Nitrogen Filter through Enhanced Burial," *Limnology and Oceanography* 65, no. 1 (2020): 1–12.

[107] Y. Li et al., "A Review of Metal Contamination in Seagrasses with an Emphasis on Metal Kinetics and Detoxification," *Journal of Hazardous Materials* 454 (2023).

[108] N. Inaba et al., "Algicidal and Growth-Inhibiting Bacteria Associated with Seagrass and Macroalgae Beds in Puget Sound, WA, USA," *Harmful Algae* 62 (2017): 136–47.

[109] Roleda and Hurd, "Seaweed Nutrient Physiology," 552–62.

[110] G.S. Grebe et al., "The Nitrogen Bioextraction Potential of Nearshore *Saccharina latissima* Cultivation and Harvest in the Western Gulf of Maine," *Journal of Applied Phycology* 33 (2021): 1741–57; J.S. Park et al., "Evaluation of Nutrient Bioextraction by Seaweed and Shellfish Aquaculture in Korea," *Journal of the World Aquaculture Society* 52, no. 5 (2021): 1118–34; and I.K. Chung et al., "Application of Seaweed Cultivation to the Bioremediation of Nutrient-Rich Effluent," Algae 17, no. 3 (2002): 187–94.

studies have reported the nutrient bioextraction potential of seaweed aquaculture, including the possibility of using seaweed aquaculture to trade nutrient discharge from wastewater resource recovery facilities (WRRF) for nutrient management in coastal areas.[111] In an extensive life cycle assessment (LCA) of seaweed aquaculture strategies, platforms and end-use products,[112] the environmental service of marine eutrophication mitigation was reported for a variety of scenarios; this ecosystem service was directly proportional to the production of macroalgae biomass.

Changing the cultivation platform from a traditional longline with a single annual grow-out to a dual-layer cultivation strip, and using a rotational cultivation strategy, increased the total annual biomass yield by as much as 4.4 times, decreasing net economic and environmental costs (see **C. Blue Economy 2. Farm tech innovation to optimize yield** for further description of farming systems). Van Oirschot et al. (2017)[113] also reported the influence of platform choice on the environmental impacts of macroalgae cultivation, indicating that the aquaculture system can be more environmentally friendly with the reduced use of steel chains and ropes for infrastructure and with increased productivity density.[114]

Further, farmed kelp's expected success in removing excess nutrients is modulated by the kelp species, with an interplay between the species and their environment.[115] For example, Umanzor and Stephen suggest that *Alaria marginata* (winged kelp) is a more effective species for removing nitrogen than *Saccharina latissima* (sugar kelp). For a more thorough review of the trade-offs between cultivation strategies and species to achieve nutrient bioremediation, see **Appendix 5**.

Nutrients are rarely a limiting resource in coastal marine waters that tend to suffer from eutrophication, but offshore seaweed cultivation potential is expected to be limited by nitrogen and phosphorus availability in these oligotrophic ocean conditions. Technologies to pump nutrient rich seawater from the deep ocean to the surface where offshore seaweed farms would be installed, or to hydraulically lower farms at night, promise to alleviate 'starvation' on farms, but are still in development. Meanwhile, some are expressing concerns that nutrient scavenging by vast offshore seaweed farms could impede phytoplankton (microalgae) abundance. Empirical evidence to date is equivocal: the impact of farmed seaweed on plankton communities is highly dependent on the location and species of seaweed under cultivation.[116]

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[111] J.K. Kim, G.P. Kraemer, and C. Yarish, "Field Scale Evaluation of Seaweed Aquaculture as a Nutrient Bioextraction Strategy in Long Island Sound and the Bronx River Estuary," *Aquaculture* 433 (2014): 148–56; M. Seghetta et al., "Bioextraction Potential of Seaweed in Denmark – An Instrument for Circular Nutrient Management," *Science of the Total Environment* 563–564 (2016): 513–29; X. Zhang et al., "Blue Growth and Bioextraction Potentials of Danish *Saccharina latissima* Aquaculture — a Model of Eco-Industrial Production Systems Mitigating Marine Eutrophication and Climate Change," *Algal Research* 64 (2022); M. Seghetta et al., "Life Cycle Assessment of Macroalgal Biorefinery for the Production of Ethanol, Proteins and Fertilizers – A Step towards a Regenerative Bioeconomy," *Journal of Cleaner Production* 137 (2016): 1158–69; Grebe et al., "Nitrogen Bioextraction Potential"; and J. Wu et al., "Bioextractive Aquaculture as an Alternative Nutrient Management Strategy for Water Resource Recovery Facilities," *Water Research* 212 (2022).

[112] J. Wu et al., "Comparison of Multiple Macroalgae Cultivation Systems and End-Use Strategies of *Saccharina latissima* and *Gracilaria tikvahiae* Based on Techno-Economic Analysis and Life Cycle Assessment," *Sustainability* 15, no. 15 (2023).

[113] Roel van Oirschot et al., "Explorative Environmental Life Cycle Assessment for System Design of Seaweed Cultivation and Drying," *Algal Research* 27 (2017): 43–54.

[114] Van Oirschot et al., "Explorative Environmental Life Cycle," 43–54.

[115] S. Umanzor and T. Stephens, "Nitrogen and Carbon Removal Capacity by Farmed Kelp *Alaria marginata and Saccharina latissima* Varies by Species," *Aquaculture Journal* 3, no. 1 (2023): 1–6.

[116] Spillias, Scott, Rachel Kelly, Richard S. Cottrell, Katherine R. O'Brien, Ran-Young Im, Ji Yoon Kim, Chuan Lei et al. "The empirical evidence for the social-ecological impacts of seaweed farming." *PLOS Sustainability and Transformation* 2, no. 2 (2023): e0000042.

3. Seawater decontamination

Seagrass canopies promote cleaner, clearer waters and improve human health by removing harmful pathogens.[117] But the contribution of macrophytes to seawater decontamination is better studied with respect to phytoremediation.

Phytoremediation is an incredibly efficient and cost-effective ecosystem restoration tool to bioadsorb heavy metals,[118] organic compounds (e.g., polycyclic aromatic hydrocarbons [PAHs], polychlorinated biphenyls [PCBs]),[119] and potentially microplastics,[120] thereby decontaminating and restoring coastal marine systems. Both seagrasses and seaweeds are capable of phytoremediation, but seaweeds are more so due to their faster growth rates. In fact, seaweeds are such effective 'sponges' that they may provide a unique biotechnology opportunity for recovering highly valuable rare earth elements from marine systems.[121] Seaweeds can provide this service dead or alive, although the latter may allow for greater bioaccumulation.[122]

For farmed seaweeds, the ultimate use of the crop merely as a green technology, or also as a food or feed product will depend on the bioavailability of any of these contaminants to the consumer. Rarely are these contaminants reported at concentrations in seaweeds at a level sufficient to surpass human or animal health guidelines. Further, careful lease site selection and monitoring, harvest washing, and biomass processing techniques can be applied to prevent contamination or bioaccumulation for consumable products. However, therein lies the challenge: standard operating procedures (SOPs) and protocols for measuring basic, abundant macronutrients and elements in seaweeds do not yet exist for the U.S., never mind for the aforementioned contaminants.

The National Institute of Standards and Technology (NIST), in collaboration with the World Wildlife Fund, recently hosted a Dietary Supplement Quality Assurance Program (DSQAP) exercise to support the standardization of seaweed measurements.[123] The goal of the exercise was to offer the opportunity for laboratories to assess their in-house techniques on a variety of measurements. Analytes were select toxic and nutritional elements, vitamins, contaminants and proximates in kelp, polyphenol content in kelp and green tea, water-soluble vitamins in meal replacement drink formulations and botanical marker compounds in dietary supplement ingredient materials and finished products. Overall, 39-53 U.S. laboratories that participated in the toxic and nutritional element portion of the exercise performed well, but frequently either collectively under- or overestimated the concentrations of a given element, as compared to the target value (**Table 7**). Only magnesium and zinc were consistently measured on target, and targets have not yet been developed for sulfur and iodine. Some of these between-laboratory discrepancies can be attributed to variable sample preparation protocols that can lead to incomplete extraction of the target analyte from the tough, cellulosic seaweed tissues.

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[117] Lamb, Joleah B., et al. "Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates." Science 355.6326 (2017): 731-733.

[118] Foday Jr, E. H., Bo, B., & Xu, X. (2021). Removal of toxic heavy metals from contaminated aqueous solutions using seaweeds: A review. *Sustainability,* 13(21), 12311.

[119] Michalak, I. (2020). The application of seaweeds in environmental biotechnology. In *Advances in botanical research* (Vol. 95, pp. 85-111). Academic Press.

[120] Rozman, U., Kokalj, A. J., Dolar, A., Drobne, D., & Kalčíková, G. (2022). Long-term interactions between microplastics and floating macrophyte Lemna minor: The potential for phytoremediation of microplastics in the aquatic environment. *Science of the Total Environment*, 831, 154866.

[121] Giese, E. C. (2020). Biosorption as green technology for the recovery and separation of rare earth elements. *World Journal of Microbiology and Biotechnology*, 36(4), 52.

[122] Pinto, J., Henriques, B., Soares, J., Costa, M., Dias, M., Fabre, E., ... & Pereira, E. (2020). A green method based on living macroalgae for the removal of rare-earth elements from contaminated waters. *Journal of environmental management*, 263, 110376.

[123] Burdette, C., Hayes, H., Klingsick, J., Sallee, C. E. B., Barber, C., ... & Yu, L. L. (2023). *Dietary Supplement Laboratory Quality Assurance Program: Exercise 1 Final Report*. U.S. Department of Commerce, National Institute of Standards and Technology.

For the nascent U.S. seaweed industry, it will be integral to develop SOPs, best practice guidelines, and (certified) reference materials for seaweed tissues and all the beneficial macronutrients and contaminants mentioned on previous page.

These tools will need to be implemented both to evaluate efficacy of seawater decontamination efforts, and to confirm safety standards for edible products.

Table 7. Description of the consensus confidence interval in relation to the NIST target range for elements in kelp, reprinted from the NIST Internal Report 8494. Kelp A: *Saccharina latissima f. angustissima* (skinny or strap kelp) from the coast of Maine, U.S.; Kelp B: Ascophyllum nodosum (rockweed) from the Northern Atlantic Ocean; SRM 3232 Kelp Powder: *Thallus laminariae* (mixed laminarid tissues)

Analyte	Consensus Confidence Interval in relation to NIST Target Range		
	Kelp A	**Kelp B**	**SRM 3232**
Total Arsenic (tAs)	Overlapping Above (mean at top of range)	Within (mean above target)	Within (mean = target)
Inorganic Arsenic (iAs)	Overlapping (mean = target)	Within (mean below target)	Overlapping Above (mean at top of range)
Cadmium (Cd)	Overlapping Below (mean below range)	Below (mean below range)	Overlapping Below (mean below range)
Calcium (Ca)	Overlapping Above (mean above target)	Above (mean below range)	Overlapping Above (mean above target)
Chromium (Cr)	Overlapping Below (mean below range)	Overlapping Below (mean within range)	Within (mean below target)
Copper (Cu)	Within (mean = target)	Overlapping (mean at top of range)	Overlapping Below (mean at bottom of range
Iodine (I)	(no target)	(no target)	Within (mean below target)
Lead (Pb)	Overlapping Below (mean below target)	Overlapping (mean = target)	Overlapping Below (mean below range)
Magnesium (Mg)	Within (mean above target)	Within (mean above target)	Within (mean = target)
Mercury (Hg)	Below (mean above range)	Above (mean above range)	Overlapping Below (mean below range)
Potassium (K)	Above (mean above range)	Within (mean below target)	Overlapping Below (mean below range)
Selenium (Se)	Above (mean above range)	Above (mean above range)	Above (mean above range)
Sodium (Na)	Overlapping (mean within range)	Overlapping Below (mean at bottom of range)	Overlapping Below (mean below target)
Sulfer (S)	(no target)	(no target)	(no target)
Zinc (Zn)	Within (mean below target)	Within (mean = target)	Within (mean = target)

4. Oxygenation

Seagrass beds vary in oxygen flux rates on a diurnal cycle: they respire at night and generate oxygen during daylight hours.[124] The overall impact of seagrasses to dissolved oxygen concentrations in the shallow environment also depends on tidal influences, turbidity and light intensity. Respiration at night in extremely dense seagrass beds can lead to cumulative low oxygen conditions that are not counterbalanced by daytime photosynthesis,[125] so restoration efforts established specifically to address hypoxia issues or generate habitat for juvenile fish species should consider planting densities carefully.

Increasing dissolved oxygen concentrations in the vicinity of a farm is a well-established environmental impact of coastal seaweed cultivation,[126] and is often employed in proposed integrated multitrophic aquaculture (IMTA) systems to counterbalance respiration rates from finfish and shellfish species. Net primary productivity of any seaweed farm will depend on the species used and the surrounding water clarity and light level conditions.

The ability for either seaweed farms or restored seagrass beds to either reverse or lessen hypoxic conditions driven by harmful algal blooms is less well studied.

5. Decarbonization and deacidification of seawater (carbon uptake)

The term ocean acidification (OA) describes the consequences of the ongoing influx of CO_2 into seawater, which induces changes in the seawater carbonate system, including reductions in pH and carbonate ion (CO_3^{-2}) concentration (**Fig. 11**).[127] OA is predicted to significantly impact species and the ecology of marine communities.[128] In particular, OA is a major threat to calcifying taxa that precipitate calcium carbonate ($CaCO_3$) shells or skeletons, as the decrease in CO_3^{-2} concentrations drives an accompanying decline in $CaCO_3$ saturation state, with associated negative effects on the growth, performance and survival of many species.[129]

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[124] Hume, A. C., Berg, P., & McGlathery, K. J. (2011). Dissolved oxygen fluxes and ecosystem metabolism in an eelgrass (*Zostera marina*) meadow measured with the eddy correlation technique. *Limnology and Oceanography*, 56(1), 86-96.

[125] Shoji, J., & Tomiyama, T. (2023). Influence of Vegetation Coverage on Dissolved Oxygen Concentration in Seagrass Bed in the Seto Inland Sea: Possible Effects on Fish Nursery Function. *Estuaries and Coasts*, 46(4), 1098-1109.

[126] Spillias, S., Kelly, R., Cottrell, R. S., O'Brien, K. R., Im, R. Y., Kim, J. Y., ... & McDonald-Madden, E. (2023). The empirical evidence for the social-ecological impacts of seaweed farming. *PLOS Sustainability and Transformation*, 2(2), e0000042.

[127] Ken Caldeira and Michael E. Wickett, "Anthropogenic Carbon and Ocean pH," *Nature* 425 (2003): 365.

[128] Brian Gaylord et al., "Ocean Acidification through the Lens of Ecological Theory," *Ecology* 96, no. 1 (2015): 3–15; Ivan Nagelkerken and Sean D. Connell, "Global Alteration of Ocean Ecosystem Functioning Due to Increasing Human CO2 Emissions," *Proceedings of the National Academy of Sciences* 112, no. 43 (2015): 13272–77; and Brittany M. Jellison and Brian Gaylord, "Shifts in Seawater Chemistry Disrupt Trophic Links within a Simple Shoreline Food Web," *Oecologia* 190, no. 4 (2019): 955–67.

[129] Kristy J. Kroeker et al., "Impacts of Ocean Acidification on Marine Organisms: Quantifying Sensitivities and Interaction with Warming," *Global Change Biology* 19, no. 6 (2013): 1884–96.

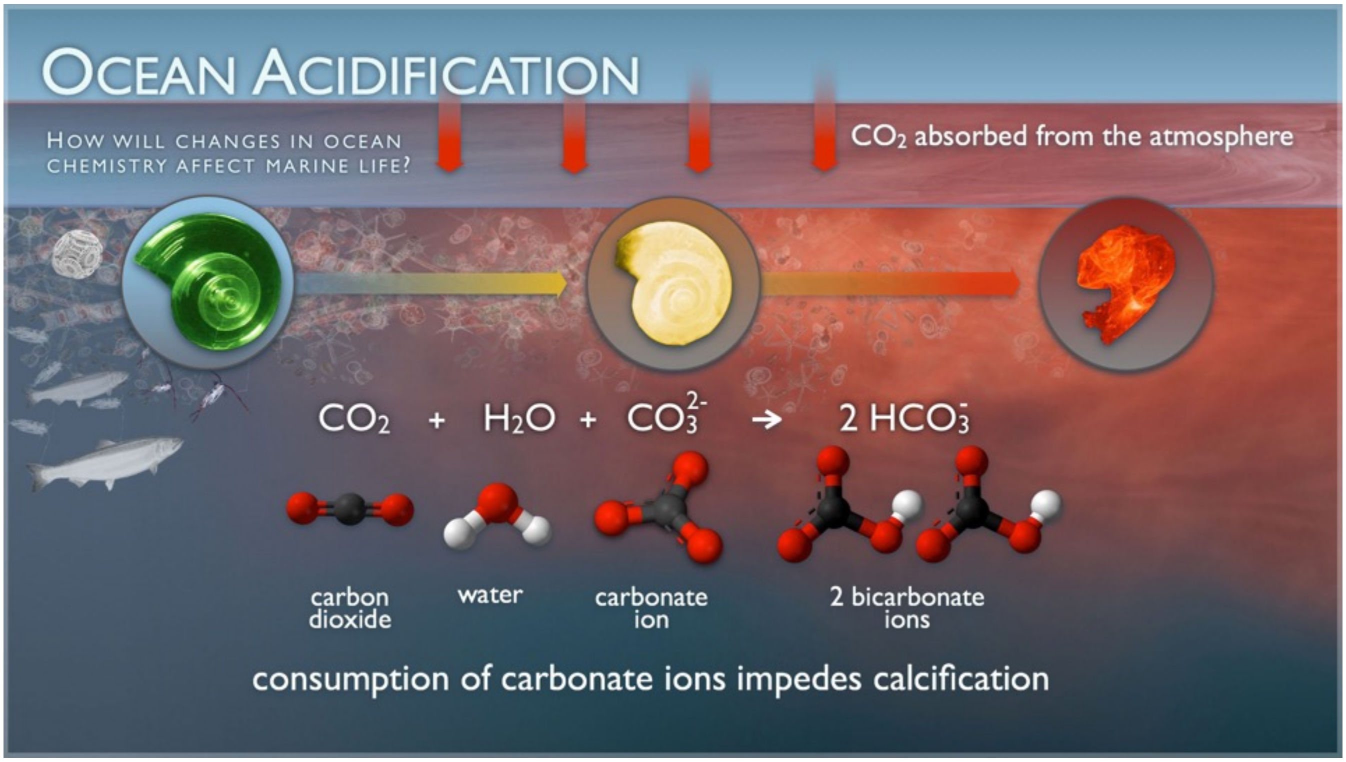

Figure 11. The process of ocean acidification (OA) and impacts: A pteropod shell is shown dissolving over time in seawater with a lower pH. When carbon dioxide is absorbed by the ocean from the atmosphere, the chemistry of the seawater is changed. (Image credit: NOAA)

Marine macrophytes (i.e., seagrasses and seaweeds), remove dissolved inorganic carbon (DIC), especially CO_2 but also HCO3−, through their metabolic activity, which shifts the equilibrium of inorganic carbon constituents and increases local pH and CO_3^{-2} concentration when photosynthesis dominates over respiration.[130] Besides this biological feedback, seagrass meadows and kelp forests may also generate favorable chemical habitats through modulating water motion.[131]

At local levels and on shorter time scales, the practical question emerges: can seagrasses or seaweeds ameliorate acidification via uptake of CO2 and other forms of dissolved inorganic carbon (DIC) during photosynthesis? This question is particularly relevant to the numerous co-occurring species that are highly sensitive to small changes in oceanic pH.[132] Varied experimental results suggest that complex environmental and biotic processes occurring along coastlines can influence the net effects,[133] though sustained increases in pH at biologically relevant spatial and temporal scales have been documented.[134] While most seagrasses are expected to increase productivity as seawater carbon dioxide partial pressure (pCO2) increases,[135] more research is required to understand the mediating effects

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[130] Sware Semesi, Sven Beer, and Mats Björk, "Seagrass Photosynthesis Controls Rates of Calcification and Photosynthesis of Calcareous Macroalgae in a Tropical Seagrass Meadow," *Marine Ecology Progress Series* 382 (2009): 41–48; Iris E. Hendriks et al., "Photosynthetic Activity Buffers Ocean Acidification in Seagrass Meadows," *Biogeosciences* 11, no. 2 (2014): 333–46; Jianzhong Su et al., "Chesapeake Bay Acidification Buffered by Spatially Decoupled Carbonate Mineral Cycling," *Nature Geoscience* 13 (2020); and Ricart et al., "Coast-Wide Evidence."

[131] Fanny Noisette et al., "Role of Hydrodynamics in Shaping Chemical Habitats and Modulating the Responses of Coastal Benthic Systems to Ocean Global Change," *Global Change Biology* 28, no. 12 (2022): 3812–29.

[132] S.C. Doney et al., "The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities," *Annual Review of Environment and Resources* 45 (2020): 83–112.

[133] Pacella, Stephen R., Cheryl A. Brown, Rochelle G. Labiosa, Burke Hales, T. Chris Mochon Collura, Wiley Evans, and George G. Waldbusser. "Feedbacks between estuarine metabolism and anthropogenic CO2 accelerate local rates of ocean acidification and hasten threshold exceedances." Journal of Geophysical Research: Oceans 129, no. 3 (2024): e2023JC020313.

[134] Aurora M. Ricart et al., "Coast-Wide Evidence of Low pH Amelioration by Seagrass Ecosystems," *Global Change Biology* 27, no. 11 (2021): 2580–91.

[135] Doney et al., "Impacts of Ocean Acidification."

of changing seawater temperature and turbidity on seagrasses.[136] Studies are just beginning to emerge for seaweed species, and kelp may be more effective in a future 'high CO2' world than any other macrophyte[137].

Seagrass meadows have been proposed as OA refugia in which environmental stress is reduced and organisms' performance is enhanced,[138] as well as potential management tools to ameliorate low pH in coastal areas.[139] Coastal areas, however, are typically characterized by variable environmental conditions driven by complex interactions between physical and biological processes.[140] These processes alter the coastal seawater carbonate system and induce appreciable fluctuations in pH and other carbonate system parameters.[141] Because of the variability of environmental conditions, the role of seagrasses in ameliorating exposure to low pH, in terms of timing, magnitude, extent and relevance for organisms, remains uncertain.[142] The results reported to date vary enormously, calling for more research on the generality of potential benefits. Nevertheless, of the available studies in seagrass ecosystems, most report amelioration of low pH,[143] and in some cases, sufficient amelioration to create conditions more conducive to shellfish growth.

The ability for farmed kelp to likewise ameliorate, or remediate, OA in the vicinity of a farm, and while the kelp is growing, is an active area of research. A detailed case study from coastal Maine is reviewed in detail in **Appendix 6**, and early results three pilot projects initiated for this report are shared in **III Results of Pilot Studies A-C**.

6. Climate mitigation: Legacy Carbon Dioxide Removal and Greenhouse Gas Emission Reductions

In 2021, the Intergovernmental Panel on Climate Change released its 6th Assessment Report, which highlighted the importance of negative emission scenarios that incorporate legacy CO2 removal to prevent global temperatures from rising by more than 1.5 and 2 degrees Celsius. Later that same year, the National Academy of Sciences described the state of the science and provided a research roadmap for marine carbon dioxide removal (mCDR).[144] The primary considerations included "blue carbon" removal in coastal marine sediments by mangroves, saltmarshes, and seagrasses and the potential for macroalgal ocean sinking to contribute to long-term mCDR to deep ocean waters. Accounting in geopolitical carbon budgets, in policy-driven markets, and to access the voluntary carbon offset markets all require baseline data on historical removal rates, changes to those rates after restoration efforts or other interventions, estimations of longevity of carbon rich deposits (e.g., true removal from the global carbon cycle for decades to centuries), and a robust estimation of the likelihood of a reversal (see **Appendix 7**). As a scientific body, we are just beginning to generate the measurement, monitoring, reporting and

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[136] Doney et al., "Impacts of Ocean Acidification."

[137] Ricart, A. M., Honisch, B., Fachon, E., Hunt, C. W., Salisbury, J., Arnold, S. N., & Price, N. N. (2023). Optimizing marine macrophyte capacity to locally ameliorate ocean acidification under variable light and flow regimes: Insights from an experimental approach. Plos one, 18(10), e0288548.

[138] Aurora M. Ricart et al., "Seagrass-Driven Changes in Carbonate Chemistry Enhance Oyster Shell Growth," *Oecologia* 196, no. 2 (2021): 565–76.

[139] Karina J. Nielsen et al., *Emerging Understanding of Seagrass and Kelp as an Ocean Acidification Management Tool in California* (Oakland, CA: California Ocean Science Trust, 2018).

[140] George G. Waldbusser and Joseph E. Salisbury, "Ocean Acidification in the Coastal Zone from an Organism's Perspective: Multiple System Parameters, Frequency Domains, and Habitats," *Annual Review of Marine Science* 6 (2014): 221–47.

[141] Pacella et al., "Feedbacks between estuarine metabolism…"

[142] Aurora M. Ricart et al., "Commentary: Overstated Potential for Seagrass Meadows to Mitigate Coastal Ocean Acidification," *Frontiers in Marine Science* 9 (2022): 1–4.

[143] Richard K.F. Unsworth et al., "Tropical Seagrass Meadows Modify Seawater Carbon Chemistry: Implications for Coral Reefs Impacted by Ocean Acidification," *Environmental Research Letters* 7, no. 2 (2012); Pimchanok Buapet, Martin Gullström, and Mats Björk, "Photosynthetic Activity of Seagrasses and Macroalgae in Temperate Shallow Waters Can Alter Seawater pH and Total Inorganic Carbon Content at the Scale of a Coastal Embayment," *Marine and Freshwater Research* 64, no. 11 (2013): 1040–48; Hendriks et al., "Photosynthetic Activity Buffers"; T. Cyronak et al., "Short-Term Spatial and Temporal Carbonate Chemistry Variability in Two Contrasting Seagrass Meadows: Implications for pH Buffering Capacities," *Estuaries and Coasts* 41 (2018): 1282–96; E. Scanes, P. R. Scanes, and P. M. Ross, "Climate Change Rapidly Warms and Acidifies Australian Estuaries," *Nature Communications* 11, no. 1803 (2020): 1–11; Su et al., "Chesapeake Bay Acidification"; Ricart et al., "Coast-Wide Evidence"; and Beheshti et al., "Rapid Enhancement."

[144] National Academies of Sciences, Engineering, and Medicine. (2021). *A research strategy for ocean-based carbon dioxide removal and sequestration*.

verification (MMRV) protocols and protocols required for comprehensive carbon budgeting of seagrass meadows and seaweed farms, as called for by the Whitehouse's joint policy statement and numerous scientific groups.[145] The following section summarizes the myriad data challenges and opportunities for mCDR and emissions reductions strategies via seagrass restoration and farming seaweeds only, not wild populations of macroalgae.[146] This section also does not review other ocean-based negative emissions technologies with macrophytes that include capture of industrially exhausted carbon dioxide emitted directly from point sources and subsequent storage underground or in the deep sea (carbon capture and storage, CCS), as macrophyte CCS is less developed.

Marine Carbon Dioxide Removal and Macrophytes

The potential capacity of seagrass meadows to act as carbon sinks and trap organic carbon in the sediments is an active area of research, and this capacity may be enhanced through the aforementioned seagrass restoration efforts.[147] These studies demonstrate that mCDR functions of seagrasses can be recovered fairly rapidly (a few years to two decades) after restoration. Seagrass meadows are one of the most efficient carbon sinks in the world, removing carbon directly from the atmosphere during photosynthesis and storing large amounts of belowground carbon by burying rhizomes and organic matter from other (non-seagrass) sources.[148] Further, seagrass canopies also filter particles from the water column[149], including seaweed fragments,[150] which contain organic carbon that would otherwise be remineralized and released back into the atmosphere as greenhouse gases. Rates of mCDR vary across seagrass meadows and depend upon numerous environmental and biotic factors including sediment composition and density, salinity, water depth, seagrass species and meadow connectivity.[151]

Seagrasses constitute a carbon sink that exceeds many marine and terrestrial ecosystems, including temperate forests.[152] For example, a recent EPA report estimates approximately 932,400 metric tons of carbon currently exist in in the top 30 cm of seagrass meadows from New York to Maine,[153] which is equivalent to the annual energy use of 446,653 homes.[154] The most recent Greenhouse Gas Inventory for the state of North Carolina estimated approximately 56.5 kilotons of CO2 equivalent were removed by seagrasses as of 2020,[155] analogous to removing 13,455 vehicles from the road for one year. Both reports followed IPCC guidelines for Tier 2 assessment, which incorporates regional- and species-specific estimates of carbon in the top layer of marine sediments (rather than a global average for seagrasses) to account for the aforementioned variability in rates. These examples demonstrate that seagrasses can be important contributors to the global carbon cycle and key allies in reversing the impacts of climate change.

Conversely, loss of seagrass can result in erosion of stored carbon and release of methane, a more potent GHG. Seagrasses are highly adapted to specific light and temperature conditions, and their growth is intricately tied

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[145] https://www.whitehouse.gov/wp-content/uploads/2024/05/VCM-Joint-Policy-Statement-and-Principles.pdf

[146] For a recent review of considerations specifying wild seaweed beds, see Pessarrodona, Albert, Rita M. Franco-Santos, Luka Seamus Wright, Mathew A. Vanderklift, Jennifer Howard, Emily Pidgeon, Thomas Wernberg, and Karen Filbee-Dexter. "Carbon sequestration and climate change mitigation using macroalgae: a state of knowledge review." *Biological Reviews* 98, no. 6 (2023): 1945-1971.

[147] J.T. Greiner et al., "Seagrass Restoration Enhances 'Blue Carbon' Sequestration in Coastal Waters," *PLoS* One 8, no. 8 (2013); and Marbà et al., "Impact of Seagrass Loss."

[148] C.M. Duarte et al., "The Role of Coastal Plant Communities for Climate Change Mitigation and Adaptation," *Nature Climate Change* 3 (2013): 961–68.

[149] Lamb, Joleah B., et al. "Seagrass ecosystems reduce exposure…"

[150] Ortega, Alejandra, Nathan R. Geraldi, and Carlos M. Duarte. "Environmental DNA identifies marine macrophyte contributions to Blue Carbon sediments." *Limnology and Oceanography* 65, no. 12 (2020): 3139-3149.

[151] M.E. Röhr et al., "Blue Carbon Storage Capacity of Temperate Eelgrass (Zostera Marina) Meadows," *Global Biogeochemical Cycles* 32, no. 10 (2018): 1457–75; and S.C. Johannessen, "How Can Blue Carbon Burial in Seagrass Meadows Increase Long-Term, Net Sequestration of Carbon? A Critical Review," *Environmental Research Letters* 17, no. 9 (2022).

[152] Fourqurean, James W., et al. "Seagrass ecosystems as a globally significant carbon stock." Nature geoscience 5.7 (2012): 505-509.

[153] Colarusso, Phil, et al. "The blue carbon reservoirs from Maine to Long Island, NY. EPA Region 1 Report." (2023).

[154] https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

[155] https://www.deq.nc.gov/energy-climate/climate-change/greenhouse-gas-inventory

to water levels.[156] As sea levels rise, seagrasses face submersion, reduced light penetration and increased sedimentation, which can hinder their growth and survival. Seagrass mortality is closely linked to the release of methane.[157] When seagrasses die off, they release stored carbon and organic matter, creating conditions conducive to anaerobic microorganisms producing methane in waterlogged sediments. This methane release can further exacerbate climate change, as methane is roughly 30 times more effective at trapping heat than CO2. Thus, understanding and addressing the intricate relationship between seagrasses, sea level rise and methane emissions is imperative for coastal ecosystem conservation and climate change mitigation. However, revegetation can remedy seagrass loss and methane release.[158] Within the U.S., estimates of current and potential carbon mCDR rates of seagrasses are lacking[159] but will increasingly be affected by emerging conditions such as sea level rise and heat domes.[160]

While recent emphasis has been placed on seagrass blue carbon to meet state and federal climate goals, a new economic valuation of 3,400 hectares of seagrass restored to Virginia's Eastern Shore reported that mCDR accounted for less than half of the total economic value of the ecosystem.[161] Further, a lack of full accounting of carbon emissions from seagrass meadows, such as those occurring from the process of calcification which releases carbon dioxide, may cancel out any perceived mCDR value.[162] Thus, it is important to recognize the suite of ecosystem services provided by seagrasses described earlier in this report, alongside any carbon capture benefits.

Interest in the potential role of farmed seaweeds in mCDR has grown rapidly,[163] due, in part, to the relatively high rate at which seaweed can convert difficult-to-extract dissolved inorganic carbon (DIC) in seawater into sinkable particulate organic carbon while not competing with arable, land-based vegetative systems. However, the fate of carbon in either wild or aquaculture seaweed systems is complex. This ecosystem service that seaweed farms provide has seldom been accounted for due to a lack of empirical data quantifying the service.

Quantification is difficult in part because the pathway of carbon dioxide removal from seaweeds is less direct than for seagrasses, as seaweeds uptake carbon from seawater and do not transport this captured carbon to roots and rhizomes. Instead, seaweeds release carbon as detritus and particles or as dissolved organic carbon (DOC). Only a portion of that fixed carbon dioxide is then transported and stored in marine sediments or in the deep ocean; much of the organic carbon is in a labile form and rapidly remineralized (**Figures 10 and 12**). Thus, seaweed's potential for climate mitigation and atmospheric CO_2 drawdown and long-term removal depends on various context-specific, complex biochemical processes, such as exudation, grazing, microbial activity, carbon transport, gas release and the balance between heterotrophic and autotrophic processes within seaweed systems. For example, Gallagher et al. (2022) recently determined that some **wild** kelp beds are net heterotrophic (i.e., producers of carbon) when accounting for external sources of carbon processed within the beds.[164] Filbee-Dexter et al. (2023) pushed back on this contention by pointing out that the choice of seaweed ecosystems explored in Gallagher et

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[156] Duarte, "Seagrass Depth Limits," 363–77.

[157] S. Schorn et al., "Diverse Methylotrophic Methanogenic Archaea Cause High Methane Emissions from Seagrass Meadows," *Proceedings of the National Academy of Sciences* 119, no. 9 (2022).

[158] N. Marbà et al., "Impact of Seagrass Loss and Subsequent Revegetation on Carbon Sequestration and Stocks," *Journal of Ecology* 103, no. 2 (2015): 296–302.

[159] A.B. Novak et al., "Factors Influencing Carbon Stocks and Accumulation Rates in Eelgrass Meadows across New England, USA," *Estuaries and Coasts* 43, no. 8 (2020): 2076–91.

[160] Johannessen, "How Can Blue Carbon."

[161] Camacho, M., et al. "Economic valuation of restored seagrass the Virginia Coast Reserve." Internal report, The Nature Conservancy (2024).

[162] Van Dam, Bryce R., et al. "Calcification-driven CO2 emissions exceed "Blue Carbon" sequestration in a carbonate seagrass meadow." Science Advances 7.51 (2021): eabj1372.

[163] C.M. Duarte et al., "Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation?," *Frontiers in Marine Science* 4 (2017): 100.

[164] J.B. Gallagher, V. Shelamoff, and C. Layton, "Seaweed Ecosystems May Not Mitigate CO2 Emissions," *ICES Journal of Marine Science* 79, no. 3 (2022): 585–92.

al. (2022) was not representative of global seaweed ecosystem carbon dynamics. They argued that ultimately, net mCDR is based on the difference between carbon uptake in the original and replacement ecosystems.[165] But even Fillbee-Dexter et al. (2023) admit that there are substantial uncertainties in estimates of the rates of carbon drawdown and net deposition.[166] Therefore, alternative, scalable and more reliable carbon removal applications, including cultivating seaweeds that are harvested at peak productivity and prior to biofouling, are being explored globally. There are many potential carbon removal pathways associated with seaweed aquaculture that have not yet been thoroughly explored, including local burial,[167] the production of highly recalcitrant dissolved organic matter,[168] and export to the deep ocean.[169]

While the global spatial extent of seaweed farming remains uncertain, using Duarte et al.'s (2022) estimate of 4,200 square kilometers and the Duarte et al. (2023) estimate of the carbon export rate from these farms suggests that seaweed farms may be depositing, on average, 210,000 tons of CO2-equivalents (CO2e) each year,[170] but this number is small relative to other well-described mCDR pathways, such as conservation and restoration of tropical forests and mangroves.[171] The fact that the CO2 drawdown from the atmosphere by seaweeds depends not only on carbon export but also on many factors affecting the CO2 flux from the atmosphere to the ocean supports the conclusion that seaweed farming's current impact on climate mitigation is small relative to anthropogenic GHG emissions and to other proposed CO2 drawdown and sequestration pathways. A recent analysis of 20 seaweed farms from around the globe suggests that these farms exported about 0.5 tons of CO2e/ha to marine sediments directly beneath the farm, as a consequence of fragments lost during normal farming activities.[172] Carbon exports from seaweed farms are, however, highly variable[173], and likely relate to farm size, yield, the species grown, and local oceanic circulation.

Unlike many other drawdown and sequestration pathways, seaweed farming can be scaled up and can be profitable, even without carbon financing. This is because, while most seaweed farming is conducted in nearshore waters, seaweeds can be grown profitably anywhere in the ocean where there is sufficient light and nutrients, and where maintenance, transport and other costs are not prohibitive (see **II.C. Blue Economy**). A recent study estimates that about 1 million square kilometers — 240 times the current area occupied by seaweed farms — meet these criteria.[174]

There are some who are considering growing seaweed for sole purpose of sinking the entire harvested biomass crop as an active means of facilitating mCDR, as opposed to the passive forms of natural fragmentation and deposition of senescent tissues described thus far. The unintended ecological consequences of sinking large

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[165] K. Filbee-Dexter et al., "Seaweed Forests Are Carbon Sinks That May Help Mitigate CO2 Emissions: A Comment on Gallagher et al. (2022)," *ICES Journal of Marine Science* 80, no. 6 (2023): 1814–19.

[166] Filbee-Dexter et al., "Seaweed Forests," 1814–19.

[167] Duarte et al., "Carbon Burial."

[168] Y.S. Li et al., "Skinny Kelp (*Saccharina angustissima*) Provides Valuable Genetics for the Biomass Improvement of Farmed Sugar Kelp (*Saccharina latissima*)," *Journal of Applied Phycology* 34, no. 5 (2022): 2551–63.

[169] D.A. Smale et al., "Threats and Knowledge Gaps for Ecosystem Services Provided by Kelp Forests: A Northeast Atlantic Perspective," *Ecology and Evolution* 3, no. 11 (2013): 4016-38; and K. Filbee-Dexter et al., "Kelp Carbon Sink Potential Decreases with Warming Due to Accelerating Decomposition," *PLoS Biology* 20, no. 8 (2022).

[170] C.M. Duarte et al., "A Seaweed Aquaculture Imperative to Meet Global Sustainability Targets," *Nature Sustainability* 5 (2022): 183–93; and Duarte et al., "Carbon Burial."

[171] C.E. Lovelock and R. Reef, "Variable Impacts of Climate Change on Blue Carbon," *One Earth* 3, no. 2 (2020): 195–211; and Maria del Rosario Uribe et al., "Net Loss of Biomass Predicted for Tropical Biomes in a Changing Climate," *Nature Climate Change* 13, no. 3 (2023): 274–81.

[172] C.M. Duarte et al., "Carbon Burial in Sediments below Seaweed Farms" (preprint, submitted in 2023), https://doi.org/10.1101/2023.01.02.522332.

[173] R. Fujita et al., "Seaweed Blue Carbon: Ready? Or Not?," *Marine Policy* 155 (2023).

[174] J. DeAngelo et al., "Economic and Biophysical Limits to Seaweed Farming for Climate Change Mitigation," *Nature Plants* 9, no. 1 (2023): 45–57.

masses of seaweeds in the deep ocean are challenging to predict but could be considerable.[175] Further, the scale at which these operations would need to operate to rival the potential of other carbon dioxide removal strategies calls into question the true financial and mCDR benefits in question, as operating expenses and fuel consumption to move and ballast the biomass could be considerable.[176] Yet to be determined is whether otherwise unsellable culled biomass (frayed and fouled fronds or holdfasts that have no demonstrable market value), a smaller fraction of the total harvest yield, could be purposefully sunk in shallow coastal waters where ecosystem impacts and mCDR rates and ecosystem impacts can be carefully monitored.

The critical element of true carbon sequestration, whether manifested by seaweeds or seagrasses, is the long-term removal of carbon from the global cycle, typically defined as 100 years or longer. In order to evaluate the feasibility, efficacy, and ecosystem impacts of any pathway for blue carbon sinking, burial, and long-term deposition in the deep ocean (e.g., approximately >1,000 m depth) or in coastal or deep marine sediments, several federal agencies have allocated funds to stakeholder engagement sessions and research projects (**Table 8)**. Further, in 2023, the White House Office of Science and Technology Policy (OSTP) formulated a Fast-Track Action Committee on Marine Carbon Dioxide Removal to evaluate different types of marine carbon dioxide removal strategies, and to shape relevant policy and research on safe and effective marine CO2 removal and potential carbon sequestration.[177] Specifically, the OSTP-FTAC is developing recommendations and guidelines for policy, permitting, and regulatory standards for mCDR research and implementation. Within the EEZ and territorial seas, several regulatory bodies oversee aquaculture related research.[178] Specific state-by-state variations in regulatory oversight of the territorial seas are covered in greater detail in II. C.Blue Economy 4. Further, high-integrity voluntary carbon credit market "brokers" (**Appendix 7**) are in the process of considering new methodologies for seaweeds, and are revising those that exist for seagrasses as new research emerges.

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[175] Chopin, Thierry, Barry A. Costa-Pierce, Max Troell, Catriona L. Hurd, Mark John Costello, Steven Backman, Alejandro H. Buschmann et al. "Deep-ocean seaweed dumping for carbon sequestration: Questionable, risky, and not the best use of valuable biomass." *One Earth* 7, no. 3 (2024): 359-364.

[176] Coleman, S., Dewhurst, T., Fredriksson, D. W., St. Gelais, A. T., Cole, K. L., MacNicoll, M., ... & Brady, D. C. (2022). "Quantifying baseline costs and cataloging potential optimization strategies for kelp aquaculture carbon dioxide removal." *Frontiers in Marine Science*, 9, 966304.

[177] *Charter of the Marine Carbon Dioxide Removal Fast Track Action Committee of the Subcommittee on Ocean Science and Technology National Science and Technology Council* (Washington, DC: Executive Office of the President of the United States, 2023). Available at https://www.noaa.gov/sites/default/files/2023-10/mCDR_FTAC_charter_2023_09_19_approved.pdf

[178] NOAA Fisheries, *Guide to Permitting Marine Aquaculture in the United States* (2022) (Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 2022). Available at https://www.fisheries.noaa.gov/s3//2022-07/Guide-Permitting-Marine-Aquaculture-United-States-June2022.pdf

Table 8. Various recent federal and philanthropic marine carbon dioxide removal and blue carbon funded projects with respect to seaweeds and seagrasses.

FUNDING SOURCE	COGNIZANT AGENCY	TITLE	LEAD PI	AFFILIATION	AWARD (M USD)
Department of Energy Office of Fossil Energy and Carbon Management	NOAA OAP, NOPP	Assessing the effects and risks of ocean alkalinity enhancement on the physiology, functionality, calcification, and mineralogy of corals and crustose coralline algae in the Pacific	Melissa Melendez	University of Hawaii	1.99
NOAA	NOAA OAP, NOPP	Developing a coupled benthic-pelagic biogeochemical model to evaluate the effectiveness of mCDR interventions	Cristina Schultz	Northeastern University	1.26
NOAA	NOAA OAP, NOPP	Carbon capture and ocean acidification mitigation potential by seaweed farms in tropical and subtropical coastal environments	Andreas Andersson	Scripps Institution of Oceanography	1.45
Office of Naval Research, ClimateWorks Foundation	NOAA OAP, NOPP	Engaging U.S. commercial fishing community to develop recommendations for fishery-sensitive mCDR governance, collaborative research and monitoring, and outreach to fishing communities	Fiona Hogan	Responsible Offshore Development Alliance	0.99
Builders Initiative Foundation	Catalyzing Restorative Aquaculture	Farmed kelp blue carbon: Developing MRV tools and techniques	Nichole Price	Bigelow Laboratory for Ocean Sciences	0.80
World Wildlife Fund	Seaweed and Shellfish Farming	Global Review of Seaweed Farms' "Halo Effect": variations in legacy carbon dioxide uptake rates around the world	Nichole Price	Bigelow Laboratory for Ocean Sciences	0.30

Greenhouse Gas Emissions Reductions and Macrophytes

While seaweed farms' carbon drawdown and removal will remain variable and small relative to global GHG emissions and legacy atmospheric CO2 concentrations, expanding the markets for seaweed products that can trap carbon long-term (e.g., durable construction materials), avoid GHG emissions (e.g., bioplastics) or suppress GHG emissions (e.g., ruminant feed supplements) could greatly increase the climate change mitigation effects of seaweed farming.[179] Indeed, modeling studies suggest that a more promising avenue for seaweed's contribution to climate mitigation lies in replacing products with large carbon emission profiles with farmed seaweed.[180] Once harvested, farmed seaweeds can also be used as an alternative, less carbon-intensive, feedstock to create bio-based products and replace petroleum-derived ones, particularly for production pathways that generate more potent gases GHGs like nitrous oxide and methane. Seaweeds can support circular marine bioeconomies by recycling waste products and producing various valuable items, such as food, feed, hydrocolloids, biofuels, fertilizers, construction materials, bioplastics and soil amendments. However, quantifying food and animal feed disadoption, which refers to permanently reducing or ceasing consumption of the high-emitting product, is complex and will require approaches like LCA and techno-economic analyses (TEAs) to fully characterize the trade-offs.

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[179] Fujita et al., "Seaweed Blue Carbon."

[180] I.B. Arzeno-Soltero et al., "Large Global Variations in the Carbon Dioxide Removal Potential of Seaweed Farming Due to Biophysical Constraints," *Communications Earth & Environment* 4, no. 1 (2023): 185; S. Spillias et al., "Reducing Global Land-Use Pressures with Seaweed Farming," *Nature Sustainability* 6, no. 4 (2023): 380–90; and A.M. Ricart et al., "Sinking Seaweed in the Deep Ocean for Carbon Neutrality Is Ahead of Science and Beyond the Ethics," *Environmental Research Letters* 17, no. 8 (2022).

Recent work highlights some opportunities to reduce CO2-eq emissions in supply chains.[181] Two studies explored four seaweed product alternatives, including dried food, feed, fertilizer and bioenergy feedstock via anaerobic digestion, with stabilized byproducts used to offset chemical fertilizers for land-based crops. Considering the processing steps, energy-intensive seaweed drying (for food or fertilizer) had significant global warming impacts for both studies. The life cycle inventory of these studies assumed the use of electricity and natural gas for seaweed drying. Alternative and more sustainable drying schemes could significantly reduce impacts. Thomas et al. (2020) conducted an LCA and compared the environmental impacts of alternative seaweed preservation methods; these authors reported that use of outdoor hanging methods dramatically improved the environmental performance of seaweed drying, and seaweed freezing led to the highest impacts.[182] Efforts to recycle heat from other sources to dry seaweed also present a more climate friendly approach to seaweed processing. Use of seaweed as a bioenergy feedstock has low global warming impacts, owing to trade-off with fossil fuel sources of energy.

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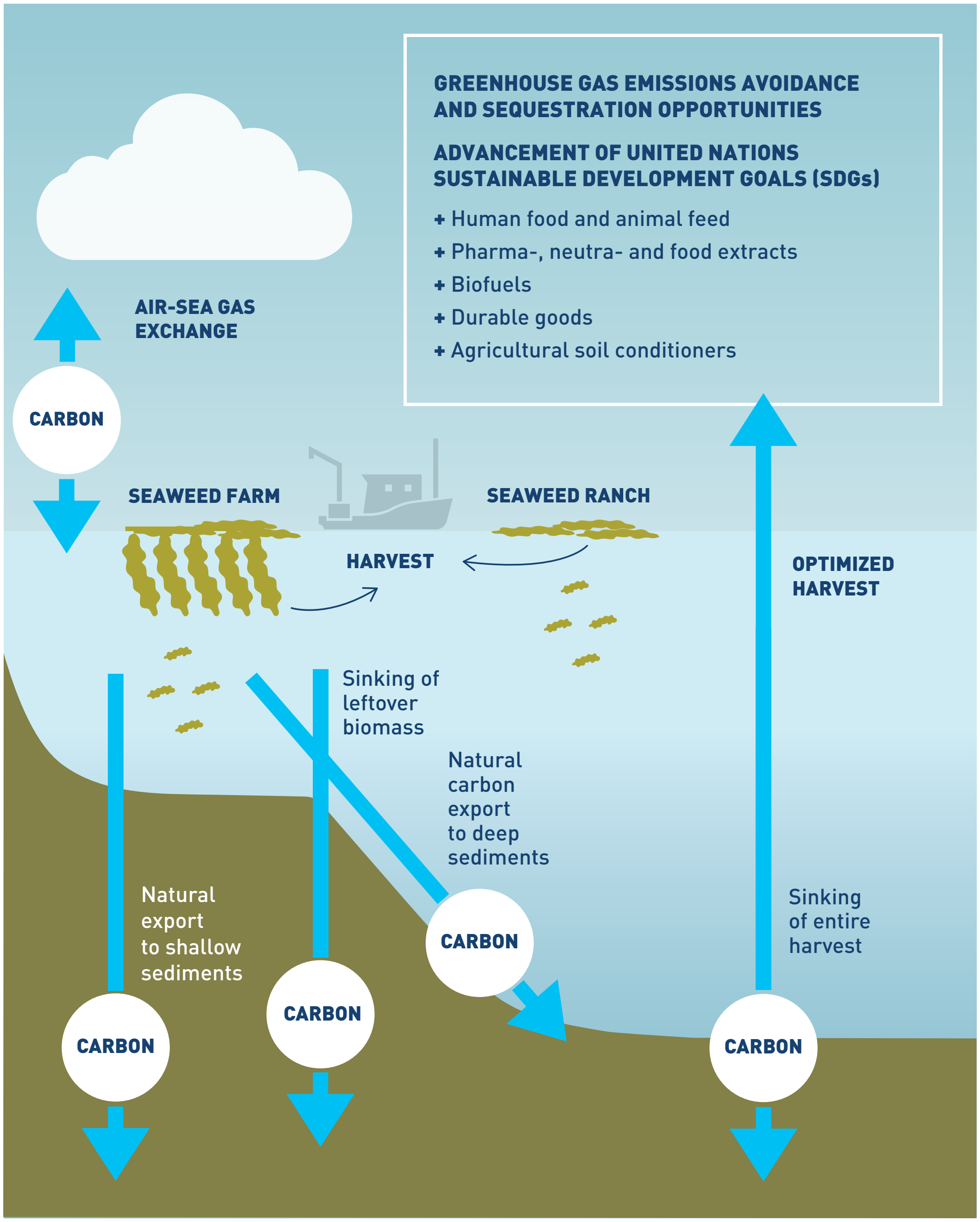
[181] Wu et al., "Bioextractive Aquaculture"; and Wu et al., "Comparison of Multiple Macroalgae." 12072.

[182] J. Thomas et al., "A Comparative Environmental Life Cycle Assessment of Hatchery, Cultivation, and Preservation of the Kelp *Saccharina Latissima," ICES Journal of Marine Science* 78, no. 1 (2020): 451–67.



All options need life cycle assessment to account for total greenhouse gasses.

Figure 12. Conceptual diagram of climate mitigation strategies with farmed seaweed (redrawn from Ricart et al.)183 Regardless of the carbon climate mitigation strategy for farmed seaweeds (e.g., replacement of high carbon emission food and animal feeds, intentional sinking and natural long-term capture through recalcitrant DOC production or particle dispersion), perhaps one of the most important lessons learned in this burgeoning field is that seaweed cultivation as currently practiced in North America and Europe is too costly to scale effectively solely for climate mitigation.184 Future research on the potential for seaweed aquaculture in carbon markets will universally be served by reducing cultivation costs and addressing monitoring, measuring, reporting and verification challenges to find robust and durable pathways to mCDR or reduced GHG emissions climate solutions.

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183 A.M. Ricart et al., "Sinking Seaweed in the Deep Ocean for Carbon Neutrality Is Ahead of Science and Beyond the Ethics," *Environmental Research Letters* 17, no. 8 (2022).

184 DeAngelo et al., "Economic and Biophysical Limits," 45–57.

B. Seagrass and Seaweed as Agricultural Feedstock

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Our society currently faces challenges to food, energy and water security and will continue to do so in the coming decades.[185] These challenges are associated with rapid global human population growth and a corresponding increase in resource demand.[186] According to a recent United Nations report, the world's population is expected to reach 8.5 billion by 2030 and 9.7 billion by 2050.[187] To meet this rising food and energy demand, land-based agriculture is projected to increase, with associated demands for nutrients, clean water and energy resources, but our limited terrestrial resources are already overburdened. Agricultural runoff is considered the primary contributor of nutrients to rivers, streams and estuaries in the United States, which leads to eutrophication. Inorganic agricultural fertilizer use has risen drastically in the past 50 years and is projected to rise as much as 30% in the coming decade. Producing inorganic chemical fertilizer, through methods such as the Haber-Bosch process for nitrogen-based fertilizers and mining rock phosphorus, result in significant environmental impacts. The carbon footprint of these activities is likewise large. Managing the nitrogen cycle and developing methods of sequestering carbon are two of 14 Grand Challenges presented by the National Academy of Engineering.

This section of the report will be highly focused on seaweeds, as seagrasses have very few instances of being used or farmed as an agricultural feedstock. Seaweed farming may produce feedstocks for many applications, including food, feeds, fertilizers, biostimulants and biofuels (**Figure 13**). Seaweeds have advantages over the production of land-based biomass in that they require very little freshwater (for rinsing or during the nursery phase) and external nutrient input, and no allocation of arable land. Sea-based biomass alternatives, such as macroalgae aquaculture, provide a promising approach to improve our ability to meet future demands for food, feed, fertilizers and biofeedstock for a variety of products.[188]

Most of the farming and consumption of seaweeds has been in Asian countries, primarily China, Indonesia, the Philippines, Korea and Japan. According to the Food and Agriculture Organization (FAO), aquaculture production globally in 2018 was 30 million metric tons wet weight with over 99% of this production occurring in Asia, and 97% of Asian production being derived from open ocean cultivation.[189] However, seaweed cultivation in the United States has slowly expanded for use in food products or directly as a food.[190] In 2018, the ARPA-E MARINER program began providing $22 million in funding to lower seaweed production costs and increase

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[185] World Economic Forum, *Water Security: The Water- Food-Energy-Climate Nexus* (Washington, DC: Island Press, 2011); M. Bazilian et al., "Energy Access Scenarios to 2030 for the Power Sector in Sub-Saharan Africa," *Utilities Policy* 20, no. 1 (2012): 1–16; and V. Smil, "Feeding the World: How Much More Rice Do We Need?," in *Rice is Life: Scientific Perspectives for the 21st Century*, eds. K. Toriyama, K.L. Heong, and B. Hardy (Los Baños, PH: International Rice Research Institute, 2005), 21–23; and H. Hoff, *Understanding the Nexus: Background Paper for the Bonn2011* Nexus Conference (Stockholm: Stockholm Environment Institute, November 11, 2011).

[186] Bazilian et al., "Energy Access Scenarios"; G.M. Thirlwell, C.A. Madramootoo, and I.W. Heathcote, "Energy-Water Nexus: Energy Use in the Municipal, Industrial, and Agricultural Water Sectors," in *Canada – U.S. Water Conference* (Washington, D.C.: Policy Research Initiative of Canada and the Woodrow Wilson Institute, 2007), 1–16; and D.P. Van Vuuren et al., "A Proposal for a New Scenario Framework to Support Research and Assessment in Different Climate Research Communities," *Global Environmental Change* 22, no. 1 (2012): 21–35.

[187] "World Population Prospects: 2015 Revision," United Nations Department of Economic and Social Affairs, July 29, 2015, https://www.un.org/en/development/desa/publications/world-population-prospects-2015-revision.html.

[188] Damiano Spagnuolo et al., "Screening on the Presence of Plant Growth Regulators in High Biomass Forming Seaweeds from the Ionian Sea (Mediterranean Sea)," *Sustainability* 14, no. 7 (2022): 3914; Nida Khan, K. Sudhakar, and R. Mamat, "Thermogravimetric Analysis of Marine Macroalgae Waste Biomass as Bio-Renewable Fuel," *Journal of Chemistry* 2022 (2022); C. Filote et al., "Biorefinery of Marine Macroalgae into High-Tech Bioproducts: A Review," *Environmental Chemistry Letters* 19, no. 2 (2020): 969–1000; and M.D.H. da Rosa et al., "Macroalgae and Microalgae Biomass as Feedstock for Products Applied to Bioenergy and Food Industry: A Brief Review," *Energies* 16, no. 4 (2023): 1820.

[189] "Global World Aquaculture Production Food and Agriculture Organization of the United Nations," Food and Agriculture Organization, accessed on June 1, 2018, http://www.fao.org/fishery/en.

[190] J. Robidoux and M. Good, "State of the States: Status of U.S. Seaweed Aquaculture" (presentation, 2023 National Seaweed Symposium, Portland, ME, December 2023), https://seaweedhub.extension.uconn.edu/wp-content/uploads/sites/3646/2023/04/2023-State-of-the-States_For-Posting_Dec2023.pdf.

its potential for use as a biofuel feedstock. This program acknowledged that, by accessing the U.S. Exclusive Economic Zone (EEZ, the largest in the world at over 11,350,000 km2),[191] producing seaweed on a massive scale in the open ocean could be feasible in the United States.[192] By accessing expansive areas for production, some historical limitations could be avoided, such as user conflicts (e.g., recreational and fishing activities) and permitting issues.[193] The project's goal was to lower production costs to under $80/dry weight ton and supply sufficient biofuel to power the equivalent roughly 10% of the transportation energy demand in the United States.[194] The research funded by the MARINER program is ongoing.[195]

Seaweeds are newly appreciated in the United States as a valuable feedstock and as a resource to enhance the production of other feedstocks with a lower nutrient and freshwater resource demand. The Department of Energy's Bioenergy Technologies Office (BETO) recently funded the first comprehensive analysis of seaweed biomass potential across the U.S. EEZ.[196] This analysis was included in their Billion-Ton Report, which is an assessment of renewable carbon resources across the U.S (BETO: Billion-Ton 2023 | Department of Energy). Utilizing a cost threshold of ≤$1,000 per metric ton of dry weight (t-DW) and a multicriteria marine spatial area screening, a total of 293,000 km2 in the Alaska, Pacific, and Atlantic coastal regions were identified as having the capacity to generate approximately 0.38 Gt of macroalgae biomass per year with an estimated average farm gate cost of $739/t-DW.[197] This EEZ is necessarily smaller than identified in the MARINER program, as it has numerous screening criteria that remove some regions from consideration. Ecological carrying capacity of all U.S. coastal territories for farming seaweeds has not been reached, but the social license for seaweed farmers to operate in densely populated riparian areas with a public unused to this practice is often more limiting than ecological considerations.[198]

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[191] "What Is the EEZ?," National Oceanic and Atmospheric Administration, 2018, https://oceanservice.noaa.gov/facts/eez.html.

[192] "MARINER," Department of Energy, December 16, 2016, https://arpa-e.energy.gov/?q=arpa-e-programs/mariner.

[193] J. A. Duff, T. S. Getchis, and P. Hoagland, *A Review of Legal and Policy Constraints to Aquaculture in the U.S. Northeast, NRAC Publication* No. 03-005 (College Park, MD: University of Maryland, 2003); T. L. Getchis and C. M. Rose, "Balancing Economic Development and Conservation of Living Marine Resources and Habitats: The Role of Resource Managers," in *Shellfish Aquaculture and the Environment*, ed. S. E. Shumway (Oxford, UK: Wiley-Blackwell, 2011), 425–46; and R. Langan et al., "The United States," in *Aquaculture and Ecosystems: An Integrated Coastal and Ocean Management Approach*, ed. J. P. McVey, C. S. Lee, and P. J. O'Bryen (Portland, ME: World Aquaculture Society, 2006), 109–139.

[194] S. Lindell et al., *New Tools for Selectively Improving Strains of Sugar Kelp for Food and Fuel, Abstracts of the 38th Annual Milford Aquaculture Seminar* (Milford, CT: NOAA Fisheries, 2018), 23.

[195] "MARINER"

[196] Coleman, A., K. Davis, J. DeAngelo, T. Saltiel, B. Saenz, L. Miller, K. Champion, E. Harrison, and A. Otwell. 2024. "Chapter 7.2: Macroalgae." In 2023 Billion–Ton Report. M. H. Langholtz (Lead). Oak Ridge, TN: Oak Ridge National Laboratory. doi: 10.23720/BT2023/2316176

[197] Coleman, A., K. et al. "Billion Ton Report"

[198] Whitmore, E., Davis, C., & Safford, T. Working the Ground Game: How Maine Shellfish and Seaweed Farmers are Building Social License to Operate. *Available at SSRN 4783738.*

Figure 13. Diversity of seaweed (and limited seagrass) products.

1. Seaweed as food

Seaweed has long been consumed as a sea vegetable in Asian countries and in some Latin American countries, and the market for edible seaweed in the United States and European countries is expanding.[199] Red seaweeds, including Gracilaria, are also the main source of gelling agents and hydrocolloids, like commercial agar extraction.[200] Seaweeds are a good source of nutrients including proteins, vitamins, minerals, dietary fiber and antioxidants[201], but also can provide elements like iodine at levels that exceed daily recommended doses.[202] However, nearly 40% of the U.S. population is experiencing iodine deficiencies that can lead to poor thyroid performance;[203] seaweeds are among the only remaining natural resources for dietary iodine. It is also a very unique sea 'vegetable' that does not require land, freshwater or chemicals to produce. Seaweeds may increasingly

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199 Peter Piconi, Rob Veidenheimer, and Bob Chase, "Edible Seaweed Market Analysis Published by Island Institute," The Island Institute, March 3, 2020, https://www.islandinstitute.org/2020/03/03/edible-seaweed-market-analysis/; J. Fleurence, "Seaweeds as Food," in *Seaweed in Health and Disease Prevention*, eds. Joël Fleurence and Ira Levine (Amsterdam: Elsevier, 2016): 149–67; and E.J. Cottier-Cook et al., *Safeguarding the Future of the Global Seaweed Aquaculture Industry,* United Nations University and Scottish Association for Marine Science Policy Brief (Hamilton, CA: United Nations University and Scottish Association for Marine Science, 2016), 12.

200 C.M. Rocha et al., "Characterization of Agar from *Gracilaria tikvahiae* Cultivated for Nutrient Bioextraction in Open Water Farms," *Food Hydrocolloids* 89 (2019): 260–71.

201 R. Peñalver et al., "Seaweeds as a Functional Ingredient for a Healthy Diet," *Marine Drugs* 18, no. 6 (2020): 301.

202 P. Cherry et al., "Risks and Benefits of Consuming Edible Seaweeds," *Nutrition Reviews* 77, no. 5 (2019): 307–29.

203 A. Hatch-McChesney and H.R. Lieberman, "Iodine and Iodine Deficiency: A Comprehensive Review of a Re-Emerging Issue," *Nutrients* 14, no. 17 (2022): 3474.

contribute to food security in low-income and middle-income countries, by improving export potential and household purchasing power in addition to providing inputs to diets.[204]

Most U.S. seaweed production supply chains have repurposed manufacturing equipment originally developed for land-based agricultural produce to freeze, rinse, blanch, puree, dry, mill and distribute food-safe edible seaweed products. Much of this equipment has been imported from other countries with longer histories of farming seaweeds. Further, in 2019, the U.S. imported about $95 million worth of seaweed products from other countries, and it only exported about $18 million worth of seaweed products to other countries. The opportunity for the U.S. to more meaningfully enter the global seafood market – specifically for seaweed – is large, and uncapitalized.

2. Seaweed as fertilizer, soil amendment and biostimulant

Seaweed is also commonly used as a fertilizer or biostimulant for plants and soil health.[205] In contrast to land-based fertilized agriculture, macroalgae extracts existing inorganic nutrients, such as nitrogen and phosphorus, from the ocean during growth, including nutrients from agricultural land runoff (**Appendix 5**).[206] Thus, one way in which seaweeds can affect land nutrient recycling is through substituting seaweed for land-based vegetables, livestock feed or biofeedstocks for industrial processes or biofuel production. Reducing the amount of cultivated land also reduces the need for inorganic fertilizer to support crop production, which is in addition to the benefits of nutrient bioextraction that occurs during seaweed growth or as a result of the use of seaweed as an organic fertilizer.

Another way in which seaweeds can improve land nutrient recycling is through the direct use of harvested seaweed, culls from seaweed production, and other byproducts of seaweed biomass. These various sources of primary or secondary seaweed biomasses can be refined as high-quality, seaweed-based organic fertilizers and biostimulants. While fertilizer and biostimulant production will not reduce the use of cultivated land (and associated nutrient requirements), these products can directly offset the need and production of inorganic chemical fertilizer. However, the additional environmental benefits of cultivating seaweeds for the solitary disposition as fertilizers or biostimulants may be negated if the seaweeds are heat dried, for example, rather than air (hung) dried.[207] Another potential issue with the use of seaweed as fertilizer is the presence of excess elements, which can build up in soils over long periods and influence crop production or quality; some are even regulated as limiting factors for biosolids applications (e.g., arsenic). Thus, designing bioprocessing appropriately is important to avoiding increasing unintended environmental harms.

The number of peer-reviewed literature articles that summarize the utility of seaweeds as a biostimulant has rapidly increased in just the past 5-10 years. Most articles explore the impact of seaweed biostimulants on only one crop at a time, and no comprehensive review currently exists. Presented in **Appendix 8** is a comprehensive literature review

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[204] P. Webb, N.K. Somers, and S.H. Thilsted, “Seaweed’s Contribution to Food Security in Low-and Middle-Income Countries: Benefits from Production, Processing and Trade,” *Global Food Security*, 37 (2023): 100686.

[205] Cottier-Cook et al., *Safeguarding the Future*, 12; N. Palmieri and M.B. Forleo, “The Potential of Edible Seaweed within the Western Diet. A Segmentation of Italian Consumers,” *International Journal of Gastronomy and Food Science* 20 (2020); C. Engle et al., *Potential Supply Chains for Seaweed Produced for Food in the Northeastern United States*, final report for USDA FSMIP Award No. 16FSMIPR10004 (Providence, RI: University of Rhode Island, 2018); A.H.L. Wan et al., “Macroalgae as a Sustainable Aquafeed Ingredient,” *Reviews in Aquaculture* 11, no. 3 (2019): 458–92; and X. Qiu et al., “Evaluation of Green Seaweed Ulva Sp. as a Replacement of Fish Meal in Plant-Based Practical Diets for Pacific White Shrimp, *Litopenaeus vannamei,” Journal of Applied Phycology* 30 (2018): 1305–16.

[206] S. García-Poza et al., “The Evolution Road of Seaweed Aquaculture: Cultivation Technologies and the Industry 4.0,” *International Journal of Environmental Research and Public Health* 17, no. 18 (2020): 1–42; A. Leandro, L. Pereira, and A.M.M. Gonçalves, “Diverse Applications of Marine Macroalgae,” *Marine Drugs* 18, no. 1 (2020): 17; and Wu et al., “Comparison of Multiple Macroalgae.”

[207] Wu et al., “Comparison of Multiple Macroalgae”; van Oirschot et al., “Explorative Environmental Life Cycle,” 43–54; X. Zhang and M. Thomsen, “Techno-Economic and Environmental Assessment of Novel Biorefinery Designs for Sequential Extraction of High-Value Biomolecules from Brown Macroalgae Laminaria digitata, Fucus vesiculosus, and *Saccharina latissima," Algal Research* 60 (2021); A.E. Nilsson et al., “Life Cycle Assessment of a Seaweed-Based Biorefinery Concept for Production of Food, Materials, and Energy,” *Algal Research* 65 (2022); and Thomas et al., “Comparative Environmental Life Cycle,” 451–67.

of all reported crop types and positive responses to seaweed biostimulants, including improved yield/quality, greater germination/growth efficiency, increased a/biotic stress resistance and enhanced soil quality.

3. Seaweed as livestock feed

Extensive research has demonstrated the nutritional value of seaweed in the diets of pigs, cows, sheep and poultry. Even small additions of seaweed, or its components, consistently improve feed quality and animal performance. For instance, seaweed inclusion enhances gut microbial populations and boosts immune responses in pigs.[208] Supplemented diets also improve rumen fermentation and digestion in cattle,[209] and lower cholesterol levels in eggs.[210] Some species, like *Ascophyllum nodosum, Saccharina latissima* and *Ulva spp.*, contain protein levels ranging from 11% to 16%,[211] making seaweed protein a potentially cost-effective substitute while improving feed quality and reducing costs in finfish aquaculture.[212] However, seaweeds' higher ash and fiber content might, in some cases, limit their suitability due to nutrient dilution, reduced digestibility and potential toxicity. Nevertheless, seaweeds offer vital microminerals and functional polysaccharides, which suggests incorporating seaweed extracts into feed formulations is a viable option. Commercial seaweed-based supplements provide micromineral supplementation primarily for cattle, pigs and small ruminants. While seaweed has vast untapped potential as a livestock supplement, its' sustainable use requires addressing safety concerns as mentioned above.[213] Considerable funding is required to ascertain the types, appropriate levels and optimal diets for incorporating seaweed into livestock feed.

There is a growing body of evidence that seaweed feed can provide health benefits for finfish and shellfish. Fermented *Ulva lactuca* can increase feed conversion efficiencies and digestibility for freshwater prawns when included as 20-30% of the diet.[214] Seaweed feeds can help reduce oxidative stress in finfish,[215] improve protein efficiencies, growth, survival, gut health, innate immunity, and provide other value-add components like pigmentation.[216]

Seaweeds possess a varied chemical composition influenced by factors like species, collection timing and growth conditions; this composition can further be manipulated through biorefinery and processing techniques to enhance suitability for livestock feed, or to achieve value-added feed supplement capacity.[217] A comprehensive assessment of nutritional requirements is available for most land-based livestock (e.g., dairy cattle[218]), but not

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[208] J.V. O'Doherty et al., "The Effects of Lactose Inclusion and Seaweed Extract Derived from *Laminaria* spp. on Performance, Digestibility of Diet Components and Microbial Populations in Newly Weaned Pigs," *Animal Feed Science and Technology* 157, no. 3–4 (2010): 173–80.

[209] M.M. Bendary et al., "Effect of Premix and Seaweed Additives on Productive Performance of Lactating Friesian Cows," *International Research Journal of Agricultural Science and Soil Science* 3, no. 5 (2013): 174–81.

[210] S. Carrillo et al., "Potential Use of Seaweeds in the Laying Hen Ration to Improve the Quality of n-3 Fatty Acid Enriched Eggs," *Developments in Applied Phycology* 2 (2009): 271–78.

[211] M.B. Samarasinghe et al., "A Descriptive Chemical Analysis of Seaweeds, *Ulva sp., Saccharina latissima and Ascophyllum nodosum* Harvested from Danish and Icelandic Waters," *Animal Feed Science and Technology* 278 (2021).

[212] V. Kumar and P. Kaladharan, "Amino Acids in the Seaweeds as an Alternate Source of Protein for Animal Feed," *Journal of the Marine Biological Association of India* 49, no. 1 (2007): 35–40.

[213] Gaurav Rajauria, "Seaweeds: A Sustainable Feed Source for Livestock and Aquaculture," in *Seaweed Sustainability,* eds. Brijesh K. Tiwari and Declan Troy (Amsterdam: Elsevier, 2015), 389–420.

[214] Felix, N., & Brindo, R. A. (2014). Evaluation of raw and fermented seaweed, *Ulva lactuca* as feed ingredient in giant freshwater prawn *Macrobrachium rosenbergii. Int J Fish Aquat Stud*, 1(3), 199-204.

[215] Morais, T., Inácio, A., Coutinho, T., Ministro, M., Cotas, J., Pereira, L., & Bahcevandziev, K. (2020). Seaweed potential in the animal feed: A review. *Journal of Marine Science and Engineering*, 8(8), 559.

[216] Thepot, V., Campbell, A. H., Rimmer, M. A., & Paul, N. A. (2021). Meta–analysis of the use of seaweeds and their extracts as immunostimulants for fish: a systematic review. *Reviews in Aquaculture*, 13(2), 907-933.

[217] Sandra Vijn et al., "Key Considerations for the Use of Seaweed to Reduce Enteric Methane Emissions from Cattle," *Frontiers in Veterinary Science* 7 (2020): 1135.

[218] National Academies of Sciences, Engineering, and Medicine. *Nutrient requirements of dairy cattle*. 2021.

all aquatic (e.g., mollusks and finfish). The National Science and Technology Subcommittee on Aquaculture has called for additional research efforts to understand what role macroalgae can play as livestock feed in marine farming systems, as well as terrestrial systems.[219] The same Subcommittee envisages sector growth potential as for seaweeds as livestock feed ingredients, in part due to recent revelations on the role that seaweed additives can play in the fight against climate change.

Some seaweeds contain bioactive elements that inhibit methanogenesis, including halogenated compounds prevalent in red seaweeds like *Asparagopsis taxiformis* and *A. armata*. Various substances in seaweeds, such as polysaccharides, proteins, peptides and lipids, reduce methane production by suppressing archaea and protozoa. Studies on livestock like sheep,[220] steers[221] and dairy cows[222] demonstrated that supplementing Asparagopsis in livestock diets can reduce methane emissions by up to 98%, with effects varying by diet. Effectiveness depends on bromoform concentration, ranging from 3.0 to 51.0 milligrams per kilogram of dry matter intake. While some studies show decreased feed intake,[223] this decrease generally does not impact efficiency, meat quality or taste. Some cases even report improved feed efficiency.[224] Concerns about long-term efficacy and animal health exist, but dietary levels (<0.5% of seaweed/feed intake) show no detectable residues in milk or meat.[225] Additional research is necessary to evaluate the anti-methanogenic effectiveness of different seaweeds across diverse conditions and optimized bioactive compound concentrations, as well as seaweeds' safety for humans, animals and the environment. There are several funding agencies (USDA, FFAR, DOE, NSF) supporting such research, but rapid adoption of these additives depends on regulatory approval pathways not yet available in the U.S. (**Table 9**).

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[219] https://www.ars.usda.gov/sca/Documents/2022%20NSTC%20Subcomittee%20on%20Aquaculture%20Research%20Plan_Final%20508%20compliant.pdf

[220] X. Li et al., "Asparagopsis taxiformis Decreases Enteric Methane Production from Sheep," *Animal Production Science* 58, no. 4 (2016): 681–88.

[221] Roque et al., "Red Seaweed (*Asparagopsis taxiformis*)"; and R.D. Kinley et al., "Mitigating the Carbon Footprint and Improving Productivity of Ruminant Livestock Agriculture Using a Red Seaweed," *Journal of Cleaner Production* 259 (2020).

[222] B.M. Roque et al., "Inclusion of *Asparagopsis armata* in Lactating Dairy Cows' Diet Reduces Enteric Methane Emission by Over 50 Percent," *Journal of Cleaner Production* 234 (2019): 132–38; H.A. Stefenoni et al., "Effects of the Macroalga *Asparagopsis taxiformis* and Oregano Leaves on Methane Emission, Rumen Fermentation, and Lactational Performance of Dairy Cows," *Journal of Dairy Science* 104, no. 4 (2021):4157–73; and P.S. Alvarez-Hess et al., "Twice Daily Feeding of Canola Oil Steeped with *Asparagopsis armata* Reduced Methane Emissions of Lactating Dairy Cows," *Animal Feed Science and Technology* 297, no. 3 (2023).

[223] Roque et al., "Inclusion of *Asparagopsis armata.*"

[224] Kinley et al., "Mitigating the Carbon Footprint."

[225] F. Cowley et al., *Efficacy and Safety of Asparagopsis Extract in a Canola Oil Carrier for Feedlot Cattle* (Sydney: Meat and Livestock Australia, 2023); and C.T. Eason and P. Fennessy, "Methane Reduction, Health and Regulatory Considerations Regarding Asparagopsis and Bromoform for Ruminants," *New Zealand Journal of Agricultural Research* (2023): 1–30.

Table 9. Countries, respective regulatory bodies and procedures for approving ‘zootechnical’ additives that claim to modify livestock gut microbiome to reduce greenhouse gas emissions.

COUNTRY/ NATIONS	CERTIFYING BODY	PROCEDURE
European Union	European Food and Safety Authority (EFSA)	https://www.efsa.europa.eu/en/applications/feedadditives
United Kingdom	Food Standards Agency (FSA)	https://www.food.gov.uk/business-guidance/animal-feed-additives
Canada	Canadian Food Inspection Agency (CFIA)	https://inspection.canada.ca/en/animal-health/livestock-feeds/novel-feeds
Japan	Japan Ministry of Agriculture, Forestry and Fisheries (JMAFF)	https://www.maff.go.jp/e/policies/animalwelfare/animalwelfare.html
New Zealand	New Zealand’s Ministry of Primary Industries (NZ MPI)	https://www.mpi.govt.nz/animals/pet-food-animal-feed-nutritional-supplements/defining-pet-food-animal-feed-and-supplements/
Australia	Australian Pesticides and Veterinary Medicines Authority (APVMA)	https://www.apvma.gov.au/registrations-and-permits/chemical-product-registration/animal-feed-products#:~:text=The%20APVMA%20regulates%20feed%20additives,’non%2Dactive%20constituents
Brazil	Agência Nacional de Vigilância Sanitária (Anvisa)	https://www.gov.br/anvisa/pt-br/english/regulation-of-products/food

Note: U.S. does not currently have a comparable pathway as of August 2024, and thus these additives default to a lengthy and cost-prohibitive drug pathway certification.

Based upon prior work,[226] the added global warming potential of cultivating seaweed to support the appropriate inclusion rate in dietary rations is dwarfed by the methane mitigation potential of feeding bioactive seaweed ingredients to cows, without even considering any passive carbon removal through existing farming techniques. A more complete LCA, including the production chain for the feed supplement, is needed to understand the overall trade-offs of this strategy.

4. Seaweed as biofuel and renewable energy

Biofuels are produced from renewable, organic material, whereas fossil fuels are harvested from the planet and were formed over millions of years by decaying organisms, making them a finite resource. Interest in biofuels is increasing as our ability to produce them may be infinite over time (not space), and are more sustainable than fossil fuels. Biofuels should produce far fewer GHG emissions than fossil fuels when burned for energy.[227] Biofuels have been categorized as first generation (derived from chemical conversion of oils or fermentation of starches and sugars sourced from edible materials such as corn), second generation (derived from biochemical or thermochemical conversion of cellulosic biomass such as grasses), third generation (derived from microbiological processes of yeast, fungi, or algae; chemical treatment of bio-oil extracts of algae; or pyrolysis of micro or macroalgae biomass),

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[226] Wu et al., Comparison of Multiple Macroalgae.”

[227] T. Hertel et al., “Effects of U.S. Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses,” *BioScience* 60 (2010): 223–31; and H. Huang et al., “Stacking Low Carbon Policies on the Renewable Fuels Standard: Economic and Greenhouse Gas Implications,” *Energy Policy* 56 (May 2013): 5–15.

and fourth generation (derived from hydroprocessing, oxy-fuel combustion or thermochemical processing of genetically optimized biofeedstocks). First-generation biofuels require land-use and have been criticized for potential negative impacts on food prices and GHG emissions, but other researchers have reported as much as 48% to 52% reduction over the burning of gasoline for fuel.[228] Second-generation biofuels use non-food biomass sources that may reduce impacts to food prices relative to first-generation biofuels but still require land, water and other resources. Third-generation biofuels, sourced largely from microalgae produced on land and seaweed cultivated in the U.S. EEZ, can potentially avoid land-use issues associated with producing first- and second-generation biofuels.[229] Biodiesel, bioethanol, biogases, and jet fuel can be derived from algae sources. Fourth-generation biofuels are predominantly developmental at this time. They focus on high optimization of biofuels processes such as genetic engineering approaches to increase desired traits of organisms used in biofuels production. Their increased efficiency contemplates potential as carbon capture rather than carbon neutral technology. Combined use of different biofeedstocks and biofuel production technologies will likely be required to meet our renewable energy goals and reduce GHG emissions by 2050.

As described in this report, there are many advantages to using seaweeds as a biomass source to produce fuels over land-based plants, including their ability to be farmed in the ocean without the addition of fertilizers or freshwater. Seaweeds contain a variety of unique sugars and polysaccharides, meaning there is potential for seaweed biomass to be utilized for a variety of fuels and co-products. Furthermore, seaweeds contain little to no cellulose and lignin, which can impede the deconstruction of terrestrial biomass. The unique nature of seaweeds compared to terrestrial biomass offers distinct opportunities but also presents challenges that need to be specifically addressed through targeted research and development efforts. For instance, the high moisture, salt, and mineral content of seaweeds can be problematic for existing thermochemical and biological conversion technologies, and new effective approaches need to be developed. Furthermore, seaweed composition is species-dependent and can vary substantially with growth phase, season, and geography for the same species. Therefore, seaweed processing technologies need to be flexible within a certain degree of composition variability.

Various conversion pathways hold promise for converting seaweeds into biofuels and bioproducts, including thermochemical, biological, and biochemical approaches, which have been summarized in recent reviews.[230] Seaweeds have been investigated as bioenergy feedstocks to produce biogas, considering the rapid growth rate,

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[228] J. Hill et al., “Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels,” *Proceedings of the National Academy of Sciences* 103, no. 30 (2006); P. Cavelius et al., (2023) “The potential of biofuels from first to fourth generation,” *PLoS Biology* 21, no. 3 (2023):e3002063; A Mohr and S. Raman, “Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels,” *Energy Policy* 63 (2013): 114–122; A. M. N. Renzaho, J. K. Kamara, and M. Toole, “Biofuel production and its impact on food security in low and middle income countries: Implications for the post-2015 sustainable development goals,” *Renewable and Sustainable Energy Reviews* 78 (2017): 503–516; A. Kendall and B, Chang, “Estimating life cycle greenhouse gas emissions from corn–ethanol: a critical review of current U.S. practices,” *Journal of Cleaner Production* 17, no.13 (2009): 1175–1182; M. Wang, M Wu, and H. Hou, “Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types,” *Environmental Research Letters* 2 (2007): 024001; and A. J. Liska et al., “Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn-Ethanol,” *Journal of Industrial Ecology* 13, no. 1 (2009): 58–74.

[229] Preetha Ganguly, Rwiddhi Sarkhel, and Papita Das, “The Second- and Third-Generation Biofuel Technologies: Comparative Perspectives,” in *Sustainable Fuel Technologies Handbook*, ed. Suman Dutta and Chaudhery Mustansar Hussain (Cambridge, MA: Academic Press, 2021), 29–50.

[230] Laurens, L. M. L., & Nelson, R. S. (2020). Sustainable technologies for seaweed conversion to biofuels and bioproducts. In M. D. Torres, S. Kraan, & H. Dominguez (Eds.), Sustainable seaweed technologies (pp. 643–661). Elsevier Inc. https://doi.org/10.1016/b978-0-12-817943-7.00022-6; Soares Dias, A.P.; Rijo, B.; Santos, F.; Galhano dos Santos, R.; Frade, T. (2023). Overview on biofuels production in a seaweed biorefinery. Sci. Total Environ. 884, 163714; Raikova, S., Allen, M.J., Chuck, C.J. (2019). Hydrothermal liquefaction of macroalgae for the production of renewable biofuels. Biofuels Bioprod. Bioref. 13, 1483–1504; and Sasaki, Y., and Yoshikuni, Y. (2022). Metabolic engineering for valorization of macroalgae biomass. Metab. Eng. 71, 42–61. doi: 10.1016/j.ymben. 2022.01.005.

high biomass yield and noncompetitive nature of macroalgae for arable land with terrestrial crops.[231] The use of seaweed to produce biofuel by anaerobic digestion has been previously investigated and reported to be feasible.[232] For example, fermentation of sugars to bioethanol, hydrothermal liquefaction to bio-oils, and anaerobic digestion to biogas are all active areas of research in seaweed conversion to fuels and products. In all cases, research advancements are necessary to optimize the pre-treatment and conversion technologies for the unique characteristics of different seaweeds in order to minimize environmental impacts and costs. Breakeven electricity selling prices have been estimated at $0.16 to $0.24 per kilowatt-hour, about 23.1% to 84.6% higher than the average U.S. electricity price in 2020. However, it is worthwhile to note that estimated macroalgae cultivation costs were more than two orders of magnitude lower in these studies (e.g., $0.05 per kilogram dry weight)[233] than other estimates recently reported.[234] Significant technological advancement is needed to reduce production costs before using seaweeds to produce biofuel will be economically viable.

As interest in seaweed as a biomass resource for fuels and products grows in the United States, the federal government is increasing investments in research and development to convert seaweeds into low-carbon fuels and products. For example, the Department of Energy's (DOE's) Bioenergy Technologies Office (BETO) partnered with DOE's Office of Fossil Energy and Carbon Management on an opportunity announced in the spring of 2024 called MACRO: Mixed Algae Conversion Research Opportunity (EERE eXCHANGE: Funding Opportunity (energy.gov)). This opportunity will award up to $18.8 million to address research and development challenges in converting algae, such as seaweeds and other wet waste feedstocks, to biofuels and bioproducts that can decarbonize domestic transportation, industry, and communities. The topic area being run by BETO focuses specifically on converting seaweeds into low-carbon fuels and bioproducts. This type of work has the potential to fill in the research gaps needed in the space of conversion pathways to create a market pull for seaweed biomass to be integrated into biofuel and bioproduct industries.

Seaweed-based biofuels are not currently being produced in the United States or anywhere in the world as of yet. However, U.S. interest in using seaweeds to produce biofuels dates back to the 1970s.[235] In the early 1970s in California, the Marine Biomass Program began researching the production of seaweed to convert biomass to methane.[236] In 1980, this research expanded to New York and Connecticut. These programs were discontinued in 1986 because the cost of biomass production was much greater than the cost of fossil fuels, estimates showed

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[231] F. Fernand et al., "Offshore Macroalgae Biomass for Bioenergy Production: Environmental Aspects, Technological Achievements and Challenges," *Renewable and Sustainable Energy Reviews* 75 (2017): 35–45; J. Langlois et al., "Life Cycle Assessment of Biomethane from Offshore-Cultivated Seaweed," *Biofuels, Bioproducts and Biorefining* 6, no. 4 (2012): 387–404; M. Alvarado-Morales et al., "Life Cycle Assessment of Biofuel Production from Brown Seaweed in Nordic Conditions," *Bioresource Technology* 129 (2013): 92–99; M. Ghadiryanfar, "A Review of Macroalgae Production, with Potential Applications in Biofuels and Bioenergy," *Renewable and Sustainable Energy Review*s 54 (2016): 473–81; V. Vivekanand, V.G.H. Eijsink, and S.J. Horn, "Biogas Production from the Brown Seaweed *Saccharina latissima*: Thermal Pretreatment and Codigestion with Wheat Straw," *Journal of Applied Phycology* 24, no. 5 (2012): 1295–301; M. Seghetta et al., "Seaweed as Innovative Feedstock for Energy and Feed – Evaluating the Impacts through a Life Cycle Assessment," *Journal of Cleaner Production* 150 (2017): 1–15; D. Aitken et al., "Life Cycle Assessment of Macroalgae Cultivation and Processing for Biofuel Production," *Journal of Cleaner Production* 75 (2014): 45–56; P.D. Kerrison et al., "The Cultivation of European Kelp for Bioenergy: Site and Species Selection," *Biomass and Bioenergy* 80 (2015): 229–42; and M. Soleymani and K.A. Rosentrater, "Techno-Economic Analysis of Biofuel Production from Macroalgae (Seaweed)," *Bioengineering* 4, no. 4 (2017): 92.

[232] A. Dave et al., "Techno-Economic Assessment of Biofuel Development by Anaerobic Digestion of European Marine Cold-Water Seaweeds," *Bioresource Technology* 135 (2013): 120–27; and Soleymani and Rosentrater, "Techno-Economic Analysis."

[233] Dave et al., "Techno-Economic Assessment," 120–27

[234] Neushel, *Marine Farming*

[235] J. Kim, M. Stekoll, and C. Yarish, "Opportunities, Challenges and Future Directions of Open-Water Seaweed Aquaculture in the United States," *Phycologia* 58, no. 5 (2019): 446–461.

[236] A. B. Flowers and K. Bird, "Marine Biomass: A Long-Term Methane Supply Option," *Hydrobiologia* 116 (1984): 272–275; M. Neushul, *Approaches to Yield Studies and an Assessment of Foreign Macroalgal Farming Technology. Proceedings of Bio-Energy: '80 World Congress and Exposition* (Atlanta: Bio-Energy Council, 1980), 59–75; M. Neushul, *Marine Farming: Macroalgal Production and Genetics. Final Technical Report* (Chicago: Gas Research Institute, 1986); W. J. North, V. Gerard, and J. Kuwabara "Farming Macrocystis at Coastal and Oceanic Sites," in *Synthetic and Degradative Processes in Marine Macrophytes,* ed. L. M. Srivastava (Berlin: deGruyter, 1982), 247–62; and A. Tompkins, *Gas Research Institute Marine Biomass Program Annual Report* (Chicago: Gas Research Institute, 1982).

fossil fuel reserves were sufficient for the foreseeable future and research shifted toward microalgae for biofuels.[237] In 2010, research on producing seaweed began again, but focused more on food products and acknowledged that, due to costs, higher-value products were necessary to support biomass production for biofuels.[238]

5. Seaweed applications in biopharma

Recent decades have seen a surge in the use of natural products in the biopharmaceutical space and macroalgae hold a very prominent place. Macroalgae produce a dizzying array of biochemicals which have many functional attributes. Some of the more important compounds are lipopolysaccharides, sulfated polysaccharides, halogenated terpenes and polyphenols. These compounds display antimicrobial, antifungal and antiviral activities against a wide range of human-related bacteria. These compounds, along with pigmented molecules (e.g., fucoxanthin and phycobilin), also have strong antioxidant and anti-inflammatory functions, the latter of which relates to many human ailments such as cancers. Macroalgae produce terpenes, flavonoids and uronic acids that have analgesic, antipyretic, anticoagulant, antidiabetic and hypertensive properties. This amazing diversity of biopharmaceutical functions has resulted in the rapid growth of this research sector.

Beyond their direct biopharmaceutical role, researchers have also explored macroalgae as potential drug delivery systems. Fucoidans, carrageenans and ulvans produced by brown, red and green macroalgae, respectively, are all highly branched, large compounds that stabilize conjugated compounds as part of drug delivery systems. These drug delivery systems have been explored in tablet, film, bead and hydrogel forms. Researchers have vigorously explored hydrogels, as their biophysical attributes (i.e., flexible, biodegradable and injectable) make them readily conducive to diverse applications. Beyond the traditional means of delivering drugs orally, the ulvans have been used for wound dressing and tissue and bone regeneration due to their strong cell adhesion properties.

Genetic engineering in macroalgae is in its infancy relative to higher plants and microalgae but has already shown significant promise as a novel source of biopharmaceutical compounds. Macroalgae have already been engineered to produce recombinant enzymes and therapeutic drugs, with some initial success as a novel vaccine production system. Using macroalgae as a vaccine production system is attractive because they grow rapidly, require much lower production costs compared to bacteria, yeast and animals; and are generally considered safer, as they are not susceptible to cell-animal pathogens.[239]

6. Seaweed for alternative plastics and other durable goods

Since the 1950s, 8.3 billion metric tons of plastic have been produced, with 6.3 billion metric tons ending up as waste.[240] Despite the potential for recycling plastic into various products like bottles, swimsuits, or backpacks, the reality is bleak: less than 10% of all plastics are recycled.[241] As a result, the vast majority of plastic waste accumulates in landfills or as litter in the natural environment. While land-based bioplastics are becoming mainstream, these feedstocks require carbon-intensive inputs, take up enormous amounts of arable land, and depend on industrial agriculture systems, oftentimes competing with food crops. Seaweed bioplastics are a new

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[237] Neushul, Marine Farming.

[238] Kim, Stekoll, and Yarish, “Opportunities, Challenges.”

[239] S. Adarshan et al., “Understanding Macroalgae: A Comprehensive Exploration of Nutraceutical, Pharmaceutical, and Omics Dimensions,” *Plants* 13 (2024): 113; M. M. Ismail, B. S. Alotaibi, and M. M. El-Sheekh, “Therapeutic Uses of Red Macroalgae,” *Molecules* 25 (2020): 4411; B. S. Negreanu-Pirjol et al., “Marine Bioactive Compounds Derived from Macroalgae as New Potential Players in Drug Delivery Systems: A Review,” *Pharmaceutics* 14 (2022): 1781; and E. Trujillo et al., “Macroalgae: Marine Players in Vaccinology,” *Algal Research* 78 (2024): 103392.

[240] Geyer, R., Jambeck, J.R., and Law, K.L. 2017 Production, use, and fate of all plastics ever made. Science Advances, 3(7), DOI: 10.1126/sciadv.1700782.

[241] “From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution,” United Nations environment programme 5, 1972-2022, https://www.unep.org/interactives/beat-plastic-pollution/?lang=EN.

and emerging category of material that solves the problems of plastic and challenges of currently commercialized alternatives. Dozens of startups and academic researchers are exploring the use of seaweed polymers (agar, alginate and carrageenan) as a feedstock for plastic replacements, attracted to seaweed's inherent gelling properties. An example start-up based in California is Sway who is using seaweed polymers to create scalable flexible packaging. Their patented products match the vital performance attributes of conventional plastics and are designed to mesh seamlessly with existing infrastructure, enabling scale and massive impact. Unlike plastic, however, their materials decompose into healthy soil after use via home and industrial composting.

Seaweeds can also be used in other durable goods, such as biopolymers in composite construction materials.[242] One such example is using alginate in unfired clay bricks to improve mechanical strength, and offer an environmentally friendly alternative to conventional masonry materials.[243] Buy-in from stakeholders across the value chain – from farmers to manufacturers to customers – will help accelerate adoption of seaweed biomaterials. Policy frameworks and subsidies can also help incentivize raw material producers and businesses to participate in the production and scaling of biomaterials.

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[242] Dove, C. (2017). Exploring the use of seaweed biopolymers in composite construction products.

[243] Dove, C. A., Bradley, F. F., & Patwardhan, S. V. (2016). Seaweed biopolymers as additives for unfired clay bricks. *Materials and Structures*, 49, 4463-4482.

C. Blue Economy

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The commercial development of farming seaweed and seagrasses is a foundational element to build a Blue Economy. Seaweed and seagrasses offer ecosystem services which complement other forms of aquaculture production, and potentially contribute productive value to adjacent emerging maritime sectors like wind power generation. Commercial seaweed and seagrass farming also offer coastal communities alternative or supplementary income sources as traditional fisheries experience increased pressures from the impacts of climate change. Furthermore, international trade in seaweed and seagrasses offer market opportunities globally.

In Western countries, the cultivated seaweed market and production technology are expanding rapidly,[244] yet studies that compare the trade-offs of different seaweed production platforms, processing, and end-use products are limited in scope. National priorities in the United States include food and nutrition security and reducing GHG emissions; however, the United States currently imports up to 85% of its seafood with about 50% of the imported seafood being farmed. Additionally, the United States cannot fulfill its own critical mineral needs and must source minerals from other countries. Terrestrial mining can cause environmental impacts and involves a complex permitting process, but farmed seaweeds can offer another viable mineral source and additional biostimulant capacity (see **A. Ecosystem Services 3. Water decontamination**). Aquaculture ventures that include extracting critical minerals from seawater can significantly contribute to the U.S. demand along with meeting other critical needs for sea-based protein and higher productivity of land-based agriculture, all with relatively low GHG and sustainable products with very small environmental impacts.[245] More information is needed to support seaweed growers in balancing environmental sustainability, marketing their products and optimizing revenue streams while reducing capital and operational costs. Nutrient and carbon trading markets, improved production platforms, alternative practices such as rotational growing and efficiencies in hatcheries and product innovation all hold promise for improving the economic outlook of seaweed aquaculture. But U.S. domestic seaweed aquaculture remains largely reliant on pre-existing working waterfront and fisheries infrastructure and our ability to enhance the blue economy will depend, in part, on investment in improving farming techniques.

1. Fisheries diversification, workforce development, and infrastructure needs

The general call for improving engineering for farmed seaweeds is a concept echoed by the National Science Technology Council Subcommittee on Aquaculture.[246] Specifically, that Subcommittee seeks to enhance farmed seaweed production system performance by incorporating technology from other sectors, facilitating knowledge transfer and training an informed workforce through extension. Here we described the steps the state of Maine has taken to achieve similar goals.

Maine has the fastest growing commercialized kelp farming sector in the U.S. since 2009, and has an economy the leans heavily on fisheries and the surrounding working waterfront. Thus, Maine is the ideal testbed for understanding potential economic impacts to rural regions. Maine is currently dependent on a single species wild capture fishery (lobster), and seaweed farming offers an off-season, complimentary, and promising new source of income for which fishers can use exist capital resources (e.g., vessels, line, etc.) and apply generations of maritime knowledge and skills.

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[244] Food and Agriculture Organization of the United Nations, *The State of World Fisheries and Aquaculture: Meeting the Sustainable Development Goals* (Rome: United Nations, 2018); and Piconi, Veidenheimer, and Chase, “Edible Seaweed Market Analysis.”

[245] Haji and Slocum, “An Offshore Solution.”

[246] https://www.ars.usda.gov/sca/Documents/2022%20NSTC%20Subcomittee%20on%20Aquaculture%20Research%20Plan_Final%20508%20compliant.pdf

The Maine Economic Development Strategy 2020-2029[247] suggests pursuing opportunities for sustainable fishing, such as aquaculture, to complement traditional fishing and meet the growing demand for a traceable, safe and climate-responsible food supply. Similar to the global trend, the Maine plan anticipates growth in the aquaculture sector. With growth comes a need for expanded workforce training, including diversity, equity and inclusion in vocational training and apprenticeship programs. Maine also recently released a Maine Aquaculture Roadmap 2022-2032[248] within which hundreds of stakeholders provided input on the future of Maine's aquaculture sector. Several relevant themes emerged around the workforce, including that traditional commercial-fishing constituents view aquaculture as an attractive alternative or complement to commercial fishing and as a way to continue their maritime heritage. The Maine roadmap presents a robust and skilled workforce for transitioning into seaweed farming, because the kelp season complements the busy lobster fishing season in Maine. Interest and attendees have steadily increased for both the ongoing Aquaculture in Shared Waters Program[249] led by Maine Sea Grant and other partners, and the Aquaculture Business Development[250] program run by the Island Institute from 2016-2020. Together, these programs have reached over 300 students, many from the fishing industry, who are interested in the seaweed sector.

Despite the on-the-water skills that transfer easily from commercial fishing to farming, other aspects of farming seaweed require training. Critical to the growth of seaweed farming is the public's acceptance of the shift from wild fisheries to leased farms in shared coastal waters. Thus, part of any workforce training program should include guidance on how to conduct your sea farming business while also being a good neighbor. Several guides exist to help farmers learn how to communicate with coastal landowners and integrate within the community.

Another area on which farmers should focus when transitioning from a wild fishery to farming is risk management training, including crop insurance, biosecurity practices and lease application guidance. In addition to training farmers on engaging with the public, Maine's roadmap includes the broader goal of increasing integration and understanding of aquaculture in coastal communities. Numerous programs exist to improve municipal awareness of seaweed aquaculture, including videos, farm tours for local decision-makers, educational curriculum for K-12 schools, seaweed festivals and more. However, public acceptance remains a significant barrier to expanding the aquaculture industry.

Recurring topics of interest across the focus groups from the Maine Aquaculture Roadmap process included working waterfront infrastructure and supply chain needs. There are some linkages and overlaps between the support services (supply and distribution) of fisheries and aquaculture and other sectors of highly perishable products. However, even in a marine-resource dependent state like Maine, there are significant gaps in support services. Gaps also exist in waterfront access and infrastructure. The roadmap and a recent report from SeaMaine[251] each include concerns about limited local infrastructure for working waterfront operations, including cold storage, adequate transportation services, and trained drivers. The state of Maine administers the Working Waterfront Access Protection Program, which is a model for preserving critical working waterfront properties. Through a competitive application process, the program provides matching funds to assist commercial fisheries and aquaculture businesses, cooperatives, municipalities and other interested parties in securing strategically significant working waterfront properties. Between 2010 and 2020, $2.2 million was expended via the Working Waterfront Program across a total of 19 properties. Other mechanisms for preserving working waterfronts include

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[247] Maine, D. E. C. D. (2019). Maine Economic Development Strategy 2020–2029: A Focus on Talent and Innovation. Augusta: Maine DECD.

[248] Sadusky, H., Brayden, C., Zydlewski, G., & Belle, S. (2022). Maine Aquaculture Roadmap 2022-2032.

[249] https://aquacultureinsharedwaters.org/

[250] https://www.islandinstitute.org/ii-solution/aquaculture-business-development-program/

[251] https://www.seamaine.org/wp-content/uploads/2023/04/SeaMaine-Transportation-Report.FINAL_.pdf

incorporating working waterfront considerations in towns' comprehensive plans. Creating cooperatives is also a tool for maintaining the working waterfront. Lobster fishing cooperatives are common along the coast of Maine, and several regional aquaculture coops are using similar models.

2. Farm tech innovation to optimize yield

The term 'seaweed farming' actually encompasses a broad array of cultivation approaches, tools, designs and resource needs which vary by region, species, and the cultural history behind farm development. Each approach represents the farmers' strategy to optimize yields and crop quality while reducing labor and equipment expenses. A summary of the diverse seaweed farming innovations is provided here. Many of these farming practices are not mutually exclusive; rather, they are often linked and used for various stages throughout the seaweeds' life history. There are numerous open-sourced published resources (i.e., manuals) for cultivating seaweeds that coastal farmers in the territorial seas reference for hatchery/nursery development, ocean farming techniques, and harvesting protocols (**Table 10**).

Coastal Farming

U.S. macroalgae aquaculture largely employs longline and longline-based platforms (cultivation strips) in the territorial seas, which often limits technoeconomic analyses to this farming style.[252] Future investigations of macroalgae aquaculture can be expanded to other infrastructure platforms that may yield increased economic and environmental benefits, such as net cultivation, floating raft cultivation, ring cultivation and the repurposing of existing infrastructure (see several examples below).[253] Comparing economic costs and environmental impacts highlights benefits that can be achieved using rotational grow-out on shared aquaculture infrastructure.[254] This approach, reminiscent of crop rotation in traditional agriculture, holds promise for the future development of the phyconomy — an emerging field that integrates economic growth, environmental sustainability and the production of valuable biomass from macroalgae.

Table 10. Open-sourced reference manuals for coastal seaweed farming.

SEAWEEDS	TITLE	AUTHORS	YEAR PUBLISHED
Gracilaria tikvahiae, Chondrus spp., Ulva lactuca, Sargassum natans, Sargassum fluitans	Cultivation of Macroscopic Marine Algae	J.H. Ryther	1982
Gracilaria tikvahiae	Cultivation biology of *Gracilaria tikvahiae* in the United States	M.D. Hanisak, J.H. Ryther	1984
Alaria esculenta	Phase II: Strain hybridisation field experiments and genetic fingerprinting of the edible brown seaweed *Alaria esculenta*	S. Kraan, M.D. Guiry	2000

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[252] García-Poza et al., "Evolution Road," 1–42; van Oirschot et al., "Explorative Environmental Life Cycle," 43–54; Langlois et al., "Life Cycle Assessment," 387–404; Seghetta et al., "Seaweed as Innovative Feedstock," 1–15; Seghetta et al., "Bioextraction Potential of Seaweed," 513–29; Van Dijk et al., *Economic Model for Offshore*; S.E. Taelman et al., "Comparative Environmental Life Cycle Assessment of Two Seaweed Cultivation Systems in North West Europe with a Focus on Quantifying Sea Surface Occupation," *Algal Research* 11, no. 4 (2015): 173–83; and Seghetta et al., "Life Cycle Assessment," 1158–69.

[253] García-Poza et al., "Evolution Road," 1–42; and Javier Alexis Vincent Diaz, "Opportunities for Offshore Large-Scale Macro-Algae Production in the Dutch North Sea" (Master's thesis, University of Gronigen, 2021).

[254] Wu, J.; Rogers, S.W.; Schaummann, R.; Price, N.N. "A Comparison of Multiple Macroalgae Cultivation Systems and End-Use Strategies of *Saccharina latissima* and *Gracilaria tikvahiae* Based on Techno-Economic Analysis and Life Cycle Assessment." Sustainability 2023, 15, 12072. https://doi.org/10.3390/su151512072

SEAWEEDS	TITLE	AUTHORS	YEAR PUBLISHED
Laminaria digitata	Aquaculture Explained: Cultivating *Laminaria digitata*	M. Edwards, L. Watson	2011
Palmaria palmata	Aquaculture Explained: Cultivating *Palmaria palmata*	A. Werner, QUB, M. Dring, QUB	2011
Laminaria digitata, Palmaria palmata	Part II: Business Plan for the Establishment of a Seaweed Hatchery and Grow-out Farm	L. Watson, BIM, M. Dring, QUB	unknown*
Saccharina latissima	Sori disinfection in cultivation of *Saccharina latissima*	K.K. Rød	2012
Palmaria palmata, Laminaria digitata, Saccharina latissima, spp.	Development and Demonstration of Viable Hatchery and Ongoing Methodologies for Seaweed Species with Identified Commercial Potential	M. Dring, M. Edwards, L. Watson	2013
Saccharina latissima, Laminaria digitata, Alaria esculenta	Kelp Farming Manual: A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters	K. Flavin, N. Flavin, B. Flahive	2013
Alaria esculenta, Laminaria digitata, Laminaria hyperborea, Saccharina latissima, Palmaria spp., Porphyra spp., Ulva lactuca	A new Norwegian bioeconomy based on cultivation and processing of seaweeds: Opportunities and R&D needs	J. Skjermo, I.M. Aasen, J. Arff, O.J. Broch, A. Carvajal, H. Christie, A. Forbord, Y. Olsen, K.I. Reitan, T. Rustad, et al.	2014
Alaria esculenta, Laminaria digitata, Saccharina latissima, Gracilaria tikvahiae, Chondrus crispus, Porphyra spp., Pyropia spp.	New England Seaweed Culture Handbook – Nursery Systems	S. Redmond, L. Green, C. Yarish, J. Kim, C. Neefus	2014
Saccharina latissima, Gracilaria tikvahiae	Northeastern U.S. Aquaculture Management Guide: A manual for the identification and management of aquaculture production hazards	D. Bouchard, D. Bushek, J. Buttner, R. Carnegie, M. Chambers, A. Concepcion, J. Ewart, A. Faulds, T.L. Getchis, G. Flimlin, et al.	2014
Alaria esculenta	Optimization of seedling production of using vegetative gametophytes of Alaria esculenta	A. Duarte	2017
Alaria esculenta, Laminaria digitata, Saccharina latissima	Seaweed Cultivation Manual	C. Rolin, R. Inkster, J. Liang, J. Hedges, L. McEvoy	unknown*
Saccharina latissima	Kelp sporulation protocol	unknown	unknown
Alaria esculenta, Palmaria palmata, Laminaria digitata, Saccharina latissima, Porphyra umbilicalis	A perspective on the Irish seaweed industry	L. Watson	2019
Alaria esculenta, Saccharina latissima	Seaweed cultivation in the Faroe Islands: An investigation of the biochemical composition of selected macroalgal species, optimised seeding tecnics, and open-ocean cultivation methods from a commercial perspective	U. Grandorf Bak	2019

Offshore Farming

While large-scale, open-ocean seaweed farming shows promise, with rapid advances in infrastructure development, these offshore farm operations present challenges, including requirements for nutrient subsidies in otherwise low nutrient conditions, safety for operators, and fuel consumption considerations when shipping the harvest long distances; depending on whether the off-shore cultivation site falls within or beyond the exclusive economic zone (EEZ), there may be either significant or little regulatory oversight, respectively. But these open-water systems can yield large quantities of feedstock for various applications, making the systems essential contributors to the American Blue Economy.[255] The United States' exclusive economic zone (EEZ) in the open ocean presents ample opportunities to expand seaweed aquaculture, as its' size exceeds the nation's entire landmass and presents fewer user conflicts.[256] The 2023 BETO Billion Ton Report[257] dedicates an entire chapter to the offshore production potential of seaweeds in the U.S. EEZ, with the aforementioned limitations in mind. This report estimates that "of the total U.S. EEZ, 58.5% (7.1 million km2, or 2.8 million mi2) is potentially available for macroalgae cultivation after accounting for existing conflicting uses of marine spatial areas through a multi-criteria screening process."

Land-based Farming

There are several land-based tank cultivation systems, that may have flow-through seawater or have a recirculating aquaculture system (RAS) built in to conserve seawater. Flow-through seawater systems can require less energy to maintain temperature, but create the added problem of necessitating water treatment at influx and outflow for biosecurity purposes. In a land-based RAS, water is continuously purified and reused within a closed circuit, with waste either removed or converted into nontoxic products. Land-based seaweed cultivation systems allow for precise control of various abiotic factors like temperature, nutrient supply and light, and they provide a more uniform biomass quality with a continuous production cycle.[258] Additionally, biotic parameters can be monitored and potentially mitigated including fouling, epiphytes, pests and diseases if caught at early stages. However, RASs demand a large land footprint, may require artificial inputs and may be costly to install and maintain.

Currently, coastal and open-ocean sea farming systems depend on several weeks of limited land-based farming to establish seed in a nursery or hatchery phase. For instance, kelp farming involves collecting reproductive sporophytes from the wild, which carry meiospores. These meiospores then settle onto spooled twine in an RAS hatchery, and are later deployed on ocean farms.[259]

Opportunistic Farming

Shellfish culture operations generate a lot of macroalgae that grows on crops and gear. This represents a potential biomass resource to harvest, as long as the seaweed species are also listed as permitted aquaculture organisms. While biomass yields and crops can be unreliable with the opportunistic approach, these sources of seaweeds can provide another revenue stream that helps defray the costs of labor to remove 'biofouling' from shellfish operations.

Indigenous Farming/Gardening

Owning to the importance of seaweeds to Indigenous cultures throughout North America, the practice of tending to these bountiful systems can be passed down for generations within a single family, a group of families or an entire community. Often located in rocky near-coastal regions that can be accessed at low spring tides, seaweed gardens are often established in naturally productive areas fed by cool, clear marine waters[260]. It is not only the location that matters but the knowledge and techniques of what species to harvest, when to harvest them

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[255] H.L. Kite-Powell et al., "Estimating Production Cost for Large-Scale Seaweed Farms," *Applied Phycology* 3, no. 1 (2022): 435–45.

[256] J.K. Kim, M. Stekoll, and C. Yarish, "Opportunities, Challenges and Future Directions of Open-Water Seaweed Aquaculture in the United States," *Phycologia* 58, no. 5 (2019): 446–61.

[257] Coleman, A., K. Davis, J. DeAngelo, T. Saltiel, B. Saenz, L. Miller, K. Champion, E. Harrison, and A. Otwell. 2024. "Chapter 7.2: Macroalgae." In 2023 Billion–Ton Report. M. H. Langholtz (Lead). Oak Ridge, TN: Oak Ridge National Laboratory. doi: 10.23720/BT2023/2316176.

[258] Zertuche-González et al., "Seasonal and Interannual Production."

[259] R. Pereira and C. Yarish, "Mass Production of Marine Macroalgae," in *Encyclopedia of Ecology*, eds. S.E. Jørgensen and B.D. Fath (Amsterdam: Elsevier, 2008): 2236–47; and S. Redmond et al., "New England Seaweed Culture Handbook," in Seaweed Cultivation (Storrs, CT: University of Connecticut, 2014).

[260] Turner, N.J. (2016) "We give them seaweed": Social economic exchange and resilience in Northwest America. Indian Journal of Traditional Knowledge. 15(1) 5-15.

(seasonality), and how much to harvest from a given area. Through their careful stewardship, they have avoided diminishing their resources despite obtaining plentiful harvests that can rival modern commercial practices. The "when" and "how much to harvest" is an ongoing struggle for many Tribes in heavily colonized areas like the Kashia Band of Pomo Indians whose traditional waters exist along the coast of California. Restrictions on coastal access means that both Tribal and non-tribal harvesters are sharing the same traditional garden areas but do not necessarily have access to the same traditional ecological knowledge of how or desire to maintain seaweed bed/garden productivity for future generations. Some of the traditional Tribal techniques are almost exactly the same as those used around the world, and in U.S. colonial cultures (**Table 10, Figure 14**), but 'gardening' can also sometimes include rearrangement of rocks and benthic substrates to encourage recruitment of the next generation and crop of seaweeds.

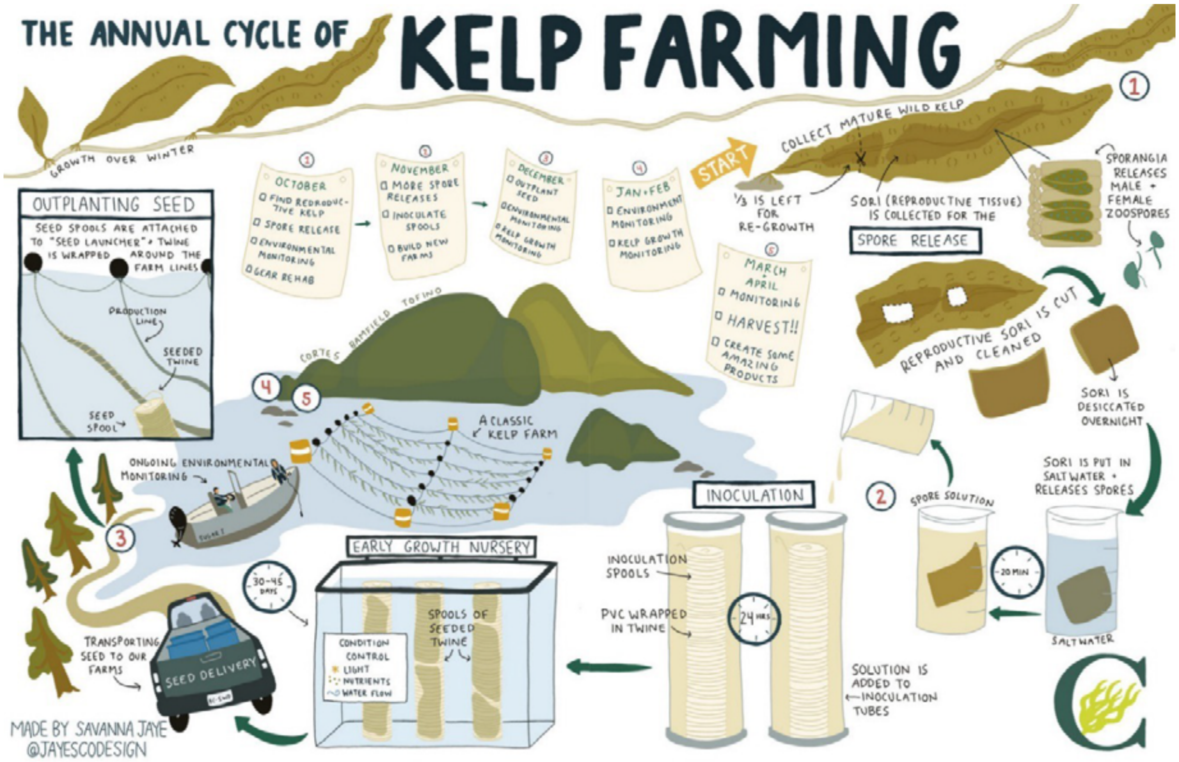

Figure 14. A new partnership between SȾÁUTW̱ First Nation and Cascadia Seaweed, and their annual cycle of kelp farming practice, figure generated for IndigiNews.

Integrated Multitrophic Aquaculture

Inorganic extractive species like seaweeds can be integrated into co-culture with other organisms to integrate fed species, such as finfish, and organic extractive species, such as suspension feeders, where the wastes of a resource become a fertilizer or food for others.[261] In this way, nutrient-assimilating seaweeds use solar energy to turn effluent into profitable resources.[262] IMTA systems can be established in RAS, coastal, or offshore settings, but the largest challenge in any circumstance is coordinating harvest timing and crop size for each species to achieve a balanced and profitable operation. There are few examples of IMTA to date, but the number of coastal aquaculture sites that co-cultivate seaweeds and shellfish is growing in the US.

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[261] T. Chopin et al., "Integrating Seaweeds into Marine Aquaculture Systems: A Key toward Sustainability," *Journal of Phycology* 37, no. 6 (2001): 975–86.

[262] A. Neori et al., "Integrated Aquaculture: Rationale, Evolution and State of the Art Emphasizing Seaweed Biofiltration in Modern Mariculture," *Aquaculture* 231, no. 1–4 (2004): 361–91.

Co-location with Existing Infrastructure

Due to the inherent complexity of working in offshore environments, many researchers, and some commercial operations, have considered co-locating aquaculture with existing offshore structures such as oil platforms[263] and wind installations.[264] The reuse or repurposing of offshore oil and gas platforms is not well understood; however, the Bureau of Ocean Energy Management has recognized the potential of repurposing these structures and has had regulations in place since 2012.[265] For example, the DOE recently identified the need to understand potential synergies between offshore wind development and offshore aquaculture (as in Holland), including the need to understand how co-located aquaculture and offshore wind could provide benefits to affected communities.[266] Fixed-gear activities, like seaweed aquaculture, may be more adaptable to operate within areas that would otherwise exclude mobile fishing gear activities. Additional potential benefits of co-location with a wider variety of ocean renewable energies or platforms include on-site power from micro-wind turbines or shared mooring systems and protection from waves if deployed in the lee of large platforms.[267] The possibility of fisheries enhancement, ecosystem restoration, and eco-tourism paired with the opportunity for marine carbon dioxide removal (mCDR) and GHG emissions reductions makes the concept of co-location of offshore aquaculture with these platforms enticing.

However, the oft-stated challenges to these approaches are also numerous, and are related to permitting these activities without significant incentives for both parties (the offshore energy and aquaculture sectors) to collaborate. Further, there are regulatory challenges and limitations in creating a framework where agencies can interact during the permitting processes associated with offshore aquaculture and wind. Co-located infrastructure could exacerbate potential for wildlife interaction, such as marine animal entanglements and avian attraction, thus amplifying insurance costs. Feasibility studies can include economics, scalability, environmental impacts, co-use interactions (e.g. with fisheries), workforce requirements, and social acceptance. Many partners could be involved in this type of transdisciplinary research: aquaculture companies, offshore wind energy developers, government agencies, academia, key local communities (fishery sector, indigenous groups, other community groups), insurance and legal entities and technology developers. Federal interagency coordination and clear articulation of lead agency authorities in this space is critical.

Aquaculture sites co-located on offshore platforms have the advantage of structurally and electrically supporting environmental monitoring with uncrewed systems. One example of successful co-location is an open-ocean IMTA site co-located with a retired Gulf of Mexico offshore platform site developed for wave and wind energy. The research on this IMTA site has focused on repurposing an offshore oil and gas platform and using it as a logistical hub and energy source.[268] The platform will serve as the offshore field office, will provide renewable energy to operate the facility and will be automated to the extent possible. The desired outcome is a multitrophic farm that is scalable, has minimal environmental impacts and addresses national goals related to climate change. Currently, there are 1,547 offshore oil and gas platforms in the Gulf of Mexico, with 349 end-of-life platforms.[269] These 349 platforms are at an important crossroad, as the federal government is required by law to see that these platforms are removed unless they can be repurposed. Seaweed can potentially be grown year-round in the Gulf

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[263] M.J. Kaiser, Y. Yu, and B. Snyder, "Economic Feasibility of Using Offshore Oil and Gas Structures in the Gulf of Mexico for Platform-Based Aquaculture," *Marine Policy* 34, no. 3 (2010): 699–707.

[264] Buck et al., "State of the Art."

[265] 43 U.S.C. § 1337.

[266] "DOE Requests Information on Offshore Wind Workforce Development Hubs and Co-Location of Aquaculture with Ocean Renewable Energy" Department of Energy Office of Energy Efficiency and Renewable Energy, February 13, 2023, https://www.energy.gov/eere/wind/articles/doe-requests-information-offshore-wind-workforce-development-hubs-and-co.

[267] M.C. Freeman et al., *Offshore Aquaculture: A Market for Ocean Renewable Energy* (Lisbon: Ocean Energy Systems, 2022).

[268] "Creating Alternate Uses for Offshore Oil & Gas Platforms," Gulf Offshore Research Institute, n.d., www.gulfoffshoreresearch.com.

[269] "Bureau of Safety and Environmental Enforcement," U.S. Department of the Interior, n.d., www.bsee.gov.

of Mexico, highlighting the benefits of developing co-located IMTA sites for harvesting in this region. To test the possibility of co-location, dynamic modeling has been used to simulate the effect of cultivation design parameters and environmental factors on macroalgal growth. Dynamic modeling is designed to provide essential guidance to optimize farm design and operations.[270] Research indicates that IMTA[271] and extraction of critical minerals[272] are two of the best uses for some of the 349 end-of-life platforms.

3. Nation to Nation tech transfer

Seaweed farming has been underway in other countries across the globe for centuries, and many have far surpassed the U.S. in terms of developing nursery and planting efficiencies. U.S. farmers can learn from these examples, but also have a lot to offer in terms of product innovation. Regardless of the direction of information exchange, there are only about two dozen species of seaweeds that are actively farmed at a meaningful scale, and hundreds more species that remain to be explored. See **I.B.5 Current state of global trade in seagrass and seaweed products** for a review of which countries are major seaweed producers.

Certification Instruments

In countries that have been farming seaweeds for decades or centuries, the necessary infrastructure has been developed to support the sector, like federally, state, or municipally funded hatcheries and testing facilities. In comparison, the U.S. lacks certified seaweed testing facilities: e.g., SOPs or best practices for analyzing seaweed tissues offered by NIST with requisite reference materials are not yet in place to ensure product quality and safety standards. Likewise, federally-based product safety and efficacy, and environmental impact assessments specific to seaweeds have yet to be well-established in the U.S. either. Currently, the U.S. has no regulatory pathways for certifying algae-based feed additives that modify the gut microbiome of livestock, either as a pre- or probiotic, or as a method of reducing enteric methane emissions. Without such a pathway, the U.S. will remain at a competitive disadvantage to numerous other countries (**Table 10**).

Manufacturing Equipment Improvements

In the U.S., there are very few – if any – pieces of manufacturing equipment engineered exclusively for use in the seaweed farming sector. Most mooring systems, harvesting tools, and stainless-steel processing equipment has been adopted from other working waterfront or agriculture industries, and is often sourced from outside of the U.S. For example, drying and milling, washing, blanching, pressing, chopping/pureeing, and packing equipment installed in seaweed processing facilities were originally developed for leafy greens and other land-based agriculture feedstocks. Even amongst those, the seaweed industry has not yet tapped into new technology used in the feed industry, e.g. in-line near infrared reflectance spectrometry to evaluate forage quality on-farm, or during

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[270] C. Frieder et al., "A Macroalgal Cultivation Modeling System (MACMODS): Evaluating the Role of Physical-Biological Coupling on Nutrients and Farm Yield," *Frontiers in Marine Science* 9 (2022); and S. Hadley et al., "Modeling Macroalgae Growth and Nutrient Dynamics for Integrated Multi-Trophic Aquaculture," *Journal of Applied Phycology* 27, no. 2 (2014): 901–16.

[271] K. Satterlee, S. Watson, and E. Danenberger, "New Opportunities for Offshore Oil and Gas Platforms–Efficient, Effective, and Adaptable Facilities for Offshore Research, Monitoring, and Technology Testing" (paper presented at the OCEANS 2018 Conference & Exposition, Charleston, SC, October 22–25, 2018), 1–5; B.H. Buck et al., "State of the Art and Challenges for Offshore Integrated Multi-Trophic Aquaculture (IMTA)," *Frontiers in Marine Science* 5 (2018): 1–21; K. Satterlee et al., MMEERSET Phase One: *Developing Platform-Based Offshore Aquaculture Using a Multi-Use Approach at Station Padre* (Ocean Springs, MS: Gulf States Marine Fisheries Commission, 2020); K. Satterlee et al., *Advancing the Viability of Oil Rig Associated Aquaculture*, Subgrant No.: ACQ-210-039-2020-GORI (Ocean Springs, MS: Gulf States Marine Fisheries Commission, 2022); J. Kaiser and M. Chambers, "Offshore Platforms and Mariculture in the US," in *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*, eds., B.H. Buck and R. Langan (Cham, CH: Springer Nature, 2017); and R. Robinson, K. Satterlee, and G. Englemann, "Repurposing Gulf of Mexico Oil and Gas Facilities for the Blue Economy" (paper presented at the Offshore Technology Conference, Houston, TX, May 2022).

[272] M.N. Haji and A.H. Slocum, "An Offshore Solution to Cobalt Shortages via Adsorption-Based Harvesting from Seawater," *Renewable and Sustainable Energy Reviews* 105 (2019): 301–9.

processing and packaging.[273] Those pieces of equipment marketed explicitly for seaweed processing have been developed outside of the U.S. Biorefinery processes are still in their infancy but will likely require customized combinations of pieces of equipment to optimize extraction efficiencies.

Advanced Hatchery Techniques

The preponderance of seaweed farming in the United States is currently focused on open-ocean cultivation of the brown, forest-forming (and fast growing) subtidal macroalgae referred to as kelp. The development of nursery/hatchery culture for kelp farm seeding prompted the significant advance of this farmed species.[274] All U.S. kelp hatcheries and farming operations currently rely upon the annual collection of wild spores to produce kelp seedlings (juvenile kelp blades for planting on the farm).[275] While this low-tech approach has proven effective on the smaller scale, it poses challenges to expanding kelp farming on a larger scale. The method is labor intensive and relies heavily on sourcing seeds from natural populations. Thus, the current method is unlikely to meet the expansion and reliability needs of a maturing industry and may stress the wild stocks of kelp. The natural seasonal availability of reproductive spores from the wild is short and is further constrained under warming ocean conditions. This limited availability restricts the timing of kelp seedling propagation and results in less time to grow, plant and meet the expanding demand for kelp seedlings. The cost of conventional spore-derived seedlings is high and constitutes up to 40% of farming costs.[276] Seedling costs and inconsistencies in their performance are major reasons why kelp is currently 10 times more expensive to grow than typical land crops. Harvest yields (kg biomass/meter of long line) of different kelp strains vary by 50%,[277] and methods to increase efficiencies are actively sought elsewhere in the world, largely through strain selection and improved husbandry techniques. In the United States, concerns about introducing nonnatives, or certain strains, via escapes currently limits selective breeding opportunities, as some states implement a 'do no harm' approach to permitting out-planting of natal broodstock (collected with 50 kilometers of farm lease site) only.

Controlled husbandry, like that performed in South Korea and Norway, offers enticing efficiencies that address many of the challenges when relying on wild kelp stocks to supply seed for aquaculture ventures (**Figure 15**). Hatcheries and repositories can maintain multi-annual gametophyte cultures in special light and temperature conditions for decades, relieving harvest pressure and conserving natural kelp populations.[278] Further, gametophytes cultures can be induced to start and prolong the hatchery season whenever it suits farmers, or on demand to recoup losses from storm damage. An earlier hatchery phase originating from gametophytes will allow multiple hatchery production cycles with the same capital resources.[279] Multi-annual gametophyte cultures can be grown efficiently in compact photobioreactors to produce on-demand seedlings, thereby reducing the time, resources and expenses (< 50%) required for typical spore-derived hatchery seedlings, doubling efficiency and lowering seedling costs. Finally, consistencies in product quality can only be replicated with cultured gametophytes because of the natural variability in wild-collected spores. Reliable, predictable and improved

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[273] Feng, Xiaoyu, Jerry H. Cherney, Debbie JR Cherney, and Matthew F. Digman. "Practical considerations for using the NeoSpectra-scanner handheld near-infrared reflectance spectrometer to predict the nutritive value of undried ensiled forage." *Sensors* 23, no. 4 (2023): 1750.

[274] T. Walker, "Selective Breeding: The Next Step for Kelp Culture," *Hatchery International*, May/June 2018, http://magazine.hatcheryinternational.com/publication/?i=486811&p=16#

[275] Redmond et al., "New England Seaweed Culture."

[276] S. Coleman et al., "Quantifying Baseline Costs and Cataloging Potential Optimization Strategies for Kelp Aquaculture Carbon Dioxide Removal," *Frontiers in Marine Science* 9 (2022); and Kite-Powell et al., "Estimating Production Cost."

[277] S. Umanzor et al., "Comparative Analysis of Morphometric Traits of Farmed Sugar Kelt and Skinny Kelp, Saccharina spp., Strains from the Northwest Atlantic," *Journal of the World Aquaculture Society* 52, no. 5 (2021): 1059–68; and Li et al., "Skinny Kelp," 2551–63.

[278] R. Wade et al., "Macroalgal Germplasm Banking for Conservation, Food Security, and Industry," *PLoS Biology* 18, no. 2 (2020).

[279] S. Coleman et al., "Identifying Scaling Pathways and Research Priorities for Kelp Aquaculture Nurseries Using a Techno-Economic Modeling Approach," *Frontiers in Marine Science* 9 (2022).

harvest yields will become available because of multi-annual gametophyte culture use. If the resources above were marshalled to drop kelp seedling costs by half and double the harvestable yield, then farmed kelp could compete for new and larger markets ([Appendix 5]()).

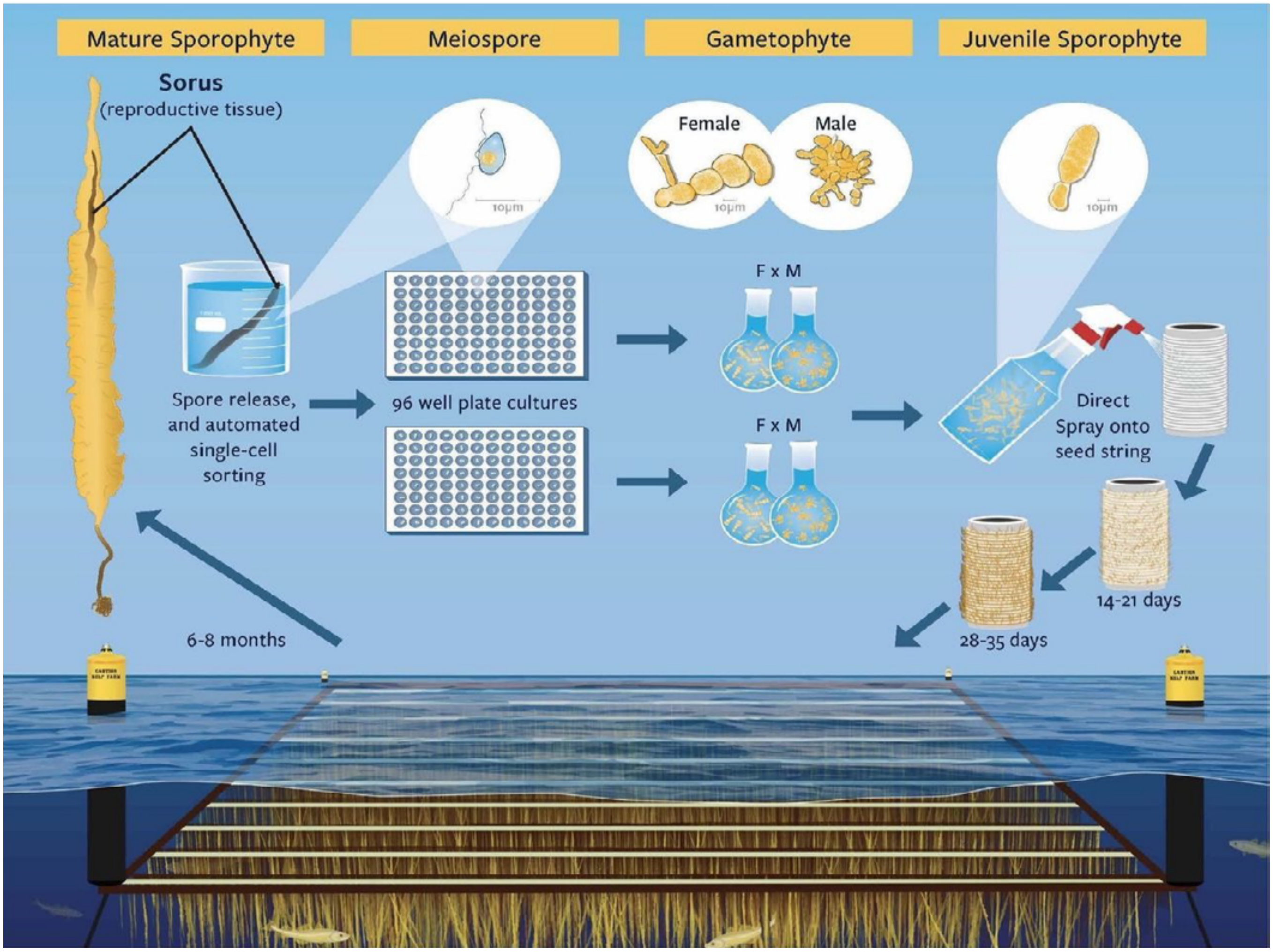

Figure 15. Biphasic life cycle and breeding pipeline of sugar kelp (*S. latissima*) in a research project.[280] Represented are meiospore release, flow cell sorting to 96-well plates, propagation to sufficient biomass for crossing, spraying of crossed sporophytes onto seed string, and outplanting to a farm-like common garden field experiment. Image credit: Scott Lindell © Wood Hole Oceanographic Institution, illustration by Natalie Renier, WHOI Creative.

The concern with these innovative husbandry approaches and selective breeding is that unintended "escapes" may contribute in unexpected ways to the natal kelp genetic diversity or outcompete the local, wild population. The risk of escapees may be managed by A) understanding native population genetic variance and distribution and working with genetic material from within this range, B) harvesting the farmed seaweed crops prior to reproductive maturity, and C) breeding infertile crops. Nonnatives may best be considered for RASs with sufficient biosecurity protocols to prevent escapees — and frameworks for this type of farming are already in place for shellfish species.

Other hatchery/nursery limitations revolve around proximity for farms. Alaska has some of the strictest

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[280] Huang, M., Robbins, K. R., Li, Y., Umanzor, S., Marty-Rivera, M., Bailey, D., ... & Jannink, J. L. (2021). Simulation of sugar kelp (*Saccharina latissima*) breeding guided by practices to prioritize accelerated research gains. *bioRxiv,* 2021-01.

regulations around propagating seed string in the nation; to comply with regulations imposed by the Alaska Department of Fish and Game, sorus tissue (seaweed's reproductive tissue) must be sourced from at least 50 different aquatic plants, to ensure genetic diversity, and must be collected from within 50 kilometers of where seed string will eventually be out-planted. Even with these limitations in place, Alaska has proven to be quite successful in securing hatcheries licenses for kelp; the number of licenses grew by 333 percent from 2020 to 2023. This success is driven in part by the Chugach Regional Resources Commission (CRRC)'s Alutiiq Pride Marine Institute (APMI) who is working with several novel species and techniques at the forefront of seaweed farming in Alaska. In collaboration with the Native Conservancy, CRRC has worked to create mobile hatchery units that can be permitted as standalone facilities. These units are established in shipping containers, and are intended to be shipped to rural communities, so that hatchery facilities can be located close to the communities they serve. This requires significant coordination between hatcheries and farmers on sorus collection and seed string shipment. The mobile hatchery units designed by CRRC and Native Conservancy were designed to be easily scalable and replicable, so that they could be established and operated in rural areas, allowing indigenous communities to control their own production of seed string for growing a commercial kelp industry. CRRC is also working to establish hatchery rearing models for novel and existing species of seaweeds. Species currently grown at APMI include sugar kelp, ribbon kelp, bull kelp, dulse, and 3-ribbed kelp.

The desire to use advanced hatchery techniques in seaweed aquaculture to improve nursery and farm yields, enhance the crop nutritional profile, elevate disease resistance, and develop thermal tolerance is in alignment with goals and actions outlined in the National Strategic Plan for Aquaculture Research (Action 2.1.2).[281] While import or export of germplasm as a possibility in the future, it will be well served by regulatory oversight.

4. Limits, threats and risks to sector growth

Growth in the U.S. farmed seaweed sector is not free from risk, limits and concerns. Experiences in the Gulf of Maine highlight a few of the social issues surrounding seaweed aquaculture. The struggle to engender the social license to operate (SLO) and concern for the safety of operators and any other unique hazards particular to offshore operations are valid. Equally troublesome are unfounded concerns about farm and processing waste and noise and odor impacts to riparian stakeholders that influence the permitting process, particularly in the Gulf of Maine. Finally, shoreline development and industrial or residential run-off (e.g., contaminants) can erode product safety and quality at lease sites that are downstream and difficult to re-locate. Perhaps even more difficult to manage than these social issues are the risks that the U.S. has not yet experienced, but have caused issues elsewhere in the world.

Though the U.S. industry has been fortunate thus far as no incidences of disease related to seaweed aquaculture have been reported, but the possibility of spreading seaweed-specific diseases, pests, predators and invasive species hitchhikers is ever present, and has impacted operations in other countries. To date, coastal states specify that farmed seaweeds must come from native populations; Alaska has adopted the further restrictive policy that natal populations for the nursery must be collected within 50 km of the intended seaweed farm (see above). Maine practitioners also use this guideline, despite the absence of the specific policy. Thus, the issue of non-native "hitchhikers" on imported germplasm is currently mitigated, but without specific policies or recommended procedures in place at the federal level to ensure this will remain true in the future. Further, the U.S. lacks a disease and pest reporting database or biological control program for seaweeds, as is available for land plants.

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[281] National Science and Technology Council Subcommittee on Aquaculture, *A National Strategic Plan for Aquaculture Research* (Washington, DC: National Science and Technology Council, February 2022), https://www.ars.usda.gov/sca/Documents/2022%20NSTC%20Subcomittee%20on%20Aquaculture%20Research%20Plan_Final%20508%20compliant.pdf.

While these aforementioned issues have yet to be documented in the U.S., there are others we are experiencing now. Here we highlight and focus on issues that **are currently documented to** limit growth in the United States.

Global Regulatory Development

U.S. legislation such as the National Aquaculture Act of 1980 and other mandates do not direct U.S. government agencies to address foreign trade barriers to facilitate expanded trade in U.S. aquaculture exports of seaweed and seagrasses in foreign markets. Regulatory oversight and export promotion are shared responsibilities between USDA and the U.S. Department of Commerce, National Oceanographic and Atmospheric Administration (NOAA). U.S. government regulatory leadership to establish global standards will enhance U.S. export competitiveness. For example, more clearly defined authorities divided between USDA and NOAA could further collaboration and help to build regulatory data bases to set international standards and avoid ceding initiative to U.S. export competitors. Moreover, seaweeds and seagrasses are not defined as either plants or animals according to taxonomic classification, further complicating regulatory authorities.

Foreign regulations and standards of identity of seaweed and seagrass are an emerging segment of food safety, consumer protection, and environmental health policies. Some seaweed- and seagrass-related requirements overlap with environmental regulations. Under U.S. law, state's retain legal jurisdiction over state territorial seas extending up to three nautical miles from their coastlines, including fisheries management, pollution control, and coastal development. Overall U.S. environmental and natural resource conservation efforts are assured through a robust framework of federal, state, and local regulations (**Table 11**), which have preserved one of the world's highest standards of clean water, abundant maritime resources, and ideal conditions for a high standard for safe, sustainable aquaculture development. While the patchwork regulatory approach—encompassing legislation, judicial rulings, and federal rulemaking—remains focused on conserving natural resources and environmental health, with remarkable success, it does not effectively promote global trade in aquaculture products derived from U.S. maritime territorial seas. State governments retain significant authority over monitoring, surveillance, and enforcement of maritime resources, which complicates efforts to centrally align U.S. standards for foreign export-oriented trade.

According to the World Trade Organization (WTO)'s ePing database, WTO members submitted 571 notifications to the WTO Committees on Sanitary and Phytosanitary Measures (SPS) and Technical Barriers to Trade (TBT). Japan is the global leader, submitting 435 notifications related to seaweed and seagrass products, accounting for more than 75 percent of all regulatory notification to the WTO. Other trading partners with regulations include Korea, the European Union, the East African Community, Vietnam, Thailand, Myanmar, Moldova, Brazil, Bolivia, Peru, Saudi Arabia, and India. There are no known requirements for feed additives, bio-based aquaculture products, or algal-based sustainable aviation fuels at this time. Most regulations to date focus on residue limits to ensure safety for human consumption and define limits for heavy metals, pesticides, toxins, and other contaminants.

Beleaguered State Permitting Process

Each State has its own set of applicable statutes and regulations for their developing farmed seaweed sector, with numerous and varying lease terms and review processes (Table 11). The lease permit application process is often described as restrictive, laborious, and difficult to navigate. Further, most states do not provide a clear permitting process that Tribal Nations can also access. For example, as a state, Alaska has not been historically receptive to aquaculture practices. This concept is a remnant of early opposition to salmon farming in many parts of the state. Indigenous communities maintain firm beliefs surrounding the concept of shared land and water usage and opposition to the idea of individual ownership. In many regions, Tribes have begun to voice concern surrounding seaweed farm leases in traditionally valued locations that were historically viewed as crucial to subsistence harvest. While communities are largely in support of new economic opportunities, the explosion of interest in Alaska's commercial kelp mariculture industry has left many Tribes feeling overwhelmed by the sudden interest in many of Alaska's remote coastal regions. In 2020, Alaska had only three hatcheries licensed to produce kelp seed string in the state; in 2023, that number had risen to 13. From 2016 to 2022, Alaska saw a veritable explosion in permitted mariculture acreage, which grew from 350 to just under 3,000. Alaska has some of the fastest turnaround time in the nation for approving aquatic farm permit applications, and generally applicants can be approved in approximately one year from the date of submission. Throughout the application process, the public is afforded only a 30-day public comment period, publicized through written notices hung in public areas in the aquatic farm location's closest community, and online. This public comment period offers the only time that Tribal members can comment on an aquatic farm application's location or operation. Tribal communities throughout Alaska have begun advocating for government-to-government consultation at some point during the aquatic farm application process, to ensure greater Tribal participation.

Permitting processes in the state of Alaska present a significant hurdle to rural and Indigenous farmers, as well as hatchery facilities. Current processes for farmers require navigation through several permitting entities. This can be challenging, costly, and time-consuming. The requirements necessary for permitted farms in Alaska mandate regular inspection of gear throughout winter months. This may also prove to be dangerous and costly for new farmers, particularly those in rural areas. The industry needs improved, cost-effective remote-sensing monitoring methods. Permitting for hatchery facilities also requires several steps, including establishing the farmer as a proxy of the hatchery for sorus collection. This often results in confusion between the permittees and can lead to permitting and transportation missteps that often occur at the cost of the hatchery.

Table 11. Domestic seaweed aquaculture industry inventory of applicable state statutes and regulations by state, as compiled by the National Sea Grant Law Center. The varied definitions and processes across states further complicate an already challenging permitting process for operation within the territorial seas.

State	Lead Agency	Definitions	State Permits	Leases	Licenses	Import, Transport, Harvest, Marketing or Sale	Stocking or Identification of Aquacultured Stock	Enforcement, Restrictions, Violations, or Penalties	Upland Owners
Alaska	Alaska Department of Natural Resources	Fish or fisheries products; aquatic farm; aquatic farm product; aquatic plants; stock; culture; aquatic farmsite lease; seafood	Aquatic farm and hatchery permits; criteria for issuance of permits; permit application, renewal, and transfer; aquatic stock acquisition permits; permits; aquatic farm and hatchery permit applications; review and determination, permit conditions; permit renewal or transfer; stock transport permits; permit classifications; application review; best interest finding	Aquatic farming and hatchery site leases; aquatic farmsite lease applications; issuance of aquatic farmsite lease; general lease provisions		Importation of aquatic plants of shellfish for stock; limitation on sale, transfer of stock, and products; retail seafood products		Prohibited conduct generally; restrictions	Upland owner preference right; upland owner access right
California	California Department of Fish and Wildlife			Leasing state water bottoms or water column; lease application; lease term; lease renewal; termination of lease; leasing of state water bottoms for aquaculture		Importation of plants or animals from diseased areas; sale or collection of aquatic plants and animals; importation by registers aquaculturist; importation application; importation of live aquatic plants and animals; sale and transportation of aquatic plants and animals	Placement of plants of animals in designated waters; stocking of aquaculture products; take of aquatic plants for aquaculture stocking		

State	Lead Agency	Definitions	State Permits	Leases	Licenses	Import, Transport, Harvest, Marketing or Sale	Stocking or Identification of Aquacultured Stock	Enforcement, Restrictions, Violations, or Penalties	Upland Owners
Connecticut	*Connecticut Department of Agriculture, Bureau of Aquaculture*	Aquaculture	Permits for aquaculture operations; permit application final determinations		Licensing of aquaculture operations; seaweed planting and cultivation license				
Maine	*Maine Department of Marine Resources*	Aquaculture; seaweed; culture or husbandry	Seaweed permit; primary buyer's permit	Research and aquaculture leases, lease option; nonpayment of aquaculture lease fees	Limited-purpose aquaculture license; harvester license exemption: aquaculture; special license; seaweed buyer's license; aquaculture license; limited-purpose aquaculture (LPA) license				
Massachusetts	*Massachusetts Division of Marine Fisheries*	Aquaculture; commercial aquaculture	Permits; application; site review						
New Hampshire	New Hampshire Fish & Game	Marine species; aquatic species; aquaculture; seaweeds			Nonresident and resident commercial salt water licenses; nonresident and resident wholesaler licenses, Penalties				
New Jersey	New Jersey Department of Agriculture	Aquaculture; aquatic organism; aquatic species			Aquatic Farmer License Requirements; Aquaculture Application		Sale or distribution; label requirements; food license		
New York	New York State Department of Environmental Conservation	Aquaculture; aquatic products; culture or cultivation; marine plant and animal life	Authority to issue permits; On-bottom and off-bottom culture permits			Marketing of agricultural products; sale of cultivation products; marketing and identification of cultivation products			

State	Lead Agency	Definitions	State Permits	Leases	Licenses	Import, Transport, Harvest, Marketing or Sale	Stocking or Identification of Aquacultured Stock	Enforcement, Restrictions, Violations, or Penalties	Upland Owners
Oregon	Oregon Department of State Lands	Aquaculture; biomass; lease; license; special use; submerged land						Criminal penalties; civil penalties; enforcement actions: civil penalties and other remedies	
Rhode Island	Rhode Island Coastal Resources Management Council	Farm products; aquaculture; aquaculture lease; cultured crops	Application for a permit to conduct aquaculture; procedures for approval; permits and licenses for the taking, possession, sale, importation, and transportation of species used in aquaculture; license or permit suspension or revocation					Penalties; arrest, seizure, and prosecution of violators; enforcement	
Washington	Joint Aquatic Resources Permit Application (JARPA) (Permits); Washington Department of Natural Resources (Leases)	Aquaculture; aquatic farmer; private sector cultured aquatic products; seaweed; marine aquatic plants; aquatic farm; marine plant; kelp				Sale of aquaculture products by leaseholder; commercial harvest and import restrictions; kelp importation		Infractions; seaweed harvest and possession violations; seaweed enforcement; facility inspection authority	

Aging and Vulnerable Working Waterfront Infrastructure

Working waterfront infrastructure that is easily accessible for refrigerated trucks and vessels at all tides, is well-maintained, and is closely located to requisite processing and distribution facilities is in very short supply for each coastal state hosting domestically ocean-cultivated seaweed businesses. In Maine, recent climate-related coastal zone damage last January 2024 resulted in $25 million worth of damage to municipally managed working waterfront property and demonstrates the nascent industry’s vulnerability (**Figure 16**).

Figure 16. A car sits in a flooded parking lot at Widgery Wharf on January 10, 2024, in Portland, Maine. Maine's government is making tens of millions of dollars available to rebuild the state's working waterfront communities after a series of devastating winter storms pummeled the state's docks, wharfs and coastal businesses. (AP Photo/Robert F. Bukaty). Portland Press Herald, May 13, 2024.

Marine Animal Entanglement

Permitting for offshore seaweed aquaculture structures deployed in the Gulf of Maine is, as an example of permitting challenges, very difficult to attain because the structures are perceived to pose a potential risk to the endangered North Atlantic Right Whale. Research and development are underway to design, model and deploy a marine mammal friendly, composite farm for the cultivation of sugar kelp by replacing synthetic fiber ropes with composite fiberglass rods that have a high tensile strength, are rigid and break at a minimum radius (**Appendix 9**). This reduces the chance of the rod wrapping around a whale appendage before it breaks. In addition to addressing wildlife entanglement risks, designs can optimize economic feasibility, maximize productivity per area and minimize seabed footprints and installation challenges.[282]

5. Unique opportunities in seaweed aquaculture

In the U.S., farmed seaweeds have a vastly untapped biological and ecological carrying capacity, and are rather more limited by social carrying capacity. A truly 'restorative aquaculture' venture, seaweed farming also has unrealized potential to restore degraded coastal ecosystems, provide targeted spill-over impacts to other fisheries, and potentially contribute to greenhouse gas emissions reductions and marine carbon dioxide removal. Listed here are some newer, additional perhaps less appreciated emergent opportunities in seaweed aquaculture.

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[282] Z. Moscicki et al., "Using Finite Element Analysis for the Design of a Modular Offshore Macroalgae Farm" (paper presented at the 9th Conference on Computational Methods in Marine Engineering, January 31, 2022).

Organic Certification for Up-sale

Organic certification is unique to seaweed farming and wild harvest — no other marine species is currently considered eligible for the organic certification pathway at USDA. This certification represents a value-add for farmers, but also a complicated process that is informed by land-based agriculture, and thus has some mismatched, unrealistic expectations. For seaweed farmers, each stage of the production process has to be certified separately: the nursery, the farm/harvest site, the processing facility, and the packaging facility. However, the certification makes U.S. seaweed products competitive on the international market and opens doors to the livestock feed sector and beyond.

Biorefinery Processes for Added Revenue

During the last decade, the concept of a biorefinery process for seaweed has emerged as a promising pathway to further develop the marine bioeconomy.[283] The concept is to fractionate the seaweed crop into a wide spectrum of valuable products using multistage cascade processes as a sustainable and cost-effective approach to extract bioactive ingredients, chemicals and biofuels.[284] Biorefineries for seaweeds promise to generate value-added products and create more than one revenue stream per harvest, but biorefineries require significant investment in infrastructure up front. There are scenarios for current seaweed processing; e.g., for carrageenans and alginates, that introduce too many chemicals and strip product to the point where the end result has limited utility.[285] Other proposed biorefinery processes — like extraction for biostimulants — that leave a pulp might find more purpose. A few examples of successful biorefinery approaches exist for red seaweeds,[286] and several are proposed for brown seaweeds.[287]

Socioeconomic Equity Potential

Many U.S. aquaculture and traditional capture-harvest fisheries producers face new environmental challenges as fisheries stocks decline, or high production costs. To mitigate losses, indigenous fishing communities are turning to seaweed aquaculture as a new stream of income based on a traditional, abundant, and natural resource.

Although many Tribal Nations have long histories of using and cultivating seaweeds, the systematic acquisition of Tribal territories has resulted in many nations having little to no access to coastal waters, leaving a notable gap in Indigenous-led farming entities in key states, like Maine. However, there are several established and expanding Indigenous-led businesses working to maintain their connections to coastal ecosystems while building thriving businesses.

For example, the Shinnecock Kelp Farmers are a multi-generational collective of Indigenous women from the Shinnecock Nation located in Southhampton on the coast of Long Island, New York. This non-profit organization is using sugar kelp to reduce the impacts of anthropogenic nutrient pollution coming from nearby developed lands, while building a skilled workforce and contributing to developing the blue economy in this region.

Indigenous-led aquaculture initiatives in Alaska include those led by Chugach Regional Resources Commission's Alutiiq Pride Marine Institute. CRRC was established in 1984 to represent the natural resource interests of Tribes in the Chugach region of southcentral Alaska; CRRC is a regional nonprofit and Tribal consortium run by a board

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[283] Baghel, R. S. (2023). "Developments in seaweed biorefinery research: A comprehensive review." *Chemical Engineering Journal*, 454, 140177.

[284] Torres, M. D., Kraan, S., & Domínguez, H. (2019). "Seaweed biorefinery." *Reviews in Environmental Science and Bio/Technology*, 18, 335-388.

[285] Yun, J. H., Archer, S. D., & Price, N. N. (2023). "Valorization of waste materials from seaweed industry: an industry survey based biorefinery approach." *Reviews in Aquaculture*, 15(3), 1020-1027.

[286] Álvarez-Viñas, M., Flórez-Fernández, N., Torres, M. D., & Domínguez, H. (2019). "Successful approaches for a red seaweed biorefinery." *Marine drugs*, 17(11), 620.

[287] Baghel, R. S. (2023). "Developments in seaweed biorefinery research: A comprehensive review." *Chemical Engineering Journal*, 454, 140177.

of directors with Tribal representatives selected from each of the seven communities CRRC represents. The APMI, based in Seward, Alaska, was established in the 1990s through criminal settlement funds from the Exxon Valdez Oil Spill. It was run first by the city of Seward and what was then the Marathon Native Tribe (now Qutekcak Native Tribe), before CRRC took over operation and management of the facility in 2004. APMI is Alaska's only tribally managed mariculture technical center.

With funding from the Economic Development Administration and continued support through the Exxon Valdez Oil Spill Trustees Council, CRRC, in partnership with Native Conservancy, has been operating several kelp "test sites" throughout Prince William Sound since 2020. These sites are monitored twice a month for collection of water quality samples and, in the spring, kelp tissue samples and harvest data are collected. The consistent growth data and water quality measurements collected over the course of several years provides CRRC with an expanding database of information on site suitability characteristics, to be used by Tribal members for development of native-owned aquatic farms. On these test sites, various farm designs, anchoring systems and hardware, and outplanting techniques are assessed and compared. These test sites were permitted in proximity to CRRC's Tribal communities and span throughout Eastern and Western Prince William Sound near the communities of Eyak (Cordova), Tatitlek, Chenega, and Qutekcak.

In rural Alaskan communities, the introduction of seaweed farming as a means of economic enhancement may present a unique opportunity for people experiencing loss of income due to declining commercial fishery opportunities. In southcentral Alaska, many of these people are lifelong fishermen, and are often members of the Indigenous community. Fishermen who are heavily invested in marine industry have experienced significant losses in income in recent years, and many are now unable to support their families with commercial fishing alone. As a wintertime activity, kelp farming does not interfere with salmon season as Alaska's largest fishery. This may help to complement existing fishery revenue.

Rural communities throughout coastal regions in Alaska typically experience higher unemployment rates than averages in other parts of the US. In 2022, nonresident workers made up 47% of the workforce in the Chugach Census Area.[288] Communities in that region experience drastic fluctuation in unemployment rates from season to season due to the fishing and tourism industries being the primary economic drivers in those areas. In 2023, unemployment rates from October-March averaged 7.4% in the Chugach Census Area.[289] These numbers underscore the importance of establishing a strong mariculture industry throughout the southcentral region, to provide an opportunity to diversify the economies of coastal and rural communities that depend heavily on the unpredictable and seasonal commercial fishing industry. CRRC's research sites have supported vital studies demonstrating the positive impacts a strong mariculture industry could exert on Alaska's waters. Preliminary research has shown that kelp farms can be a useful tool for combating localized eutrophication and ocean acidification, purifying the waters to support the health of Alaska's fisheries threatened by anthropogenic emissions. The Alaskan kelp farming industry, in addition to developing new product streams from kelp biomass and providing winter-time employment to coastal communities, can potentially mitigate water quality issues threatening Alaska's fishing industry, which contributed $5.7 billion to Alaska's statewide economy in 2019.[290]

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[288] Alaska Department of Labor and Workforce Development. (2024b, February). *Nonresidents working in Alaska.* Nonresidents Working in Alaska. https://live.laborstats.alaska.gov/reshire/nonres.pdf

[289] Alaska Department of Labor and Workforce Development. (n.d.). *Chugach Census Area Labor Force Data*. https://live.laborstats.alaska.gov/labforce/labdataall.html?a=0&s=8

[290] McDowell Group. "The Economic Value of Alaska's Seafood Industry." *Alaskaseafood.org,* Jan. 2020, https://stg.alaskaseafood.org/wp-content/uploads/McDowell-Group_ASMI-Economic-Impacts-Report-JAN-2020.pdf

Gender Equity Potential

Information on the role of gender in aquaculture and commercial fisheries in the United States is limited.[291] Researchers have called for aquaculture development that places human dimensions at the forefront[292] and have stated that future aquaculture policy should consider the social impacts of aquaculture development as well as environmental impacts.[293] Recent research has highlighted patterns of gender inequity in Maine's aquaculture industry[294] but scant other research exists. The IWG Steering Committee aimed to fill the existing data gaps by assessing current lease and license holder data in Maine and by assessing authorship in seaweed and aquaculture scientific literature.

An analysis of aquaculture and seaweed scientific literature in Scopus found that women and nonbinary people are the minority at every authorship level. (**Figure 17A**). Using the keywords "aquaculture" or "seaweed" from 1975 to 2023 reveals fluctuating levels of gender minority authorship, with a trend towards increased relative representation since the early 2000s. Gender minority authorship was highest from 2020-2023 in both aquaculture and seaweed literature, but remains unequally represented.

Maine's seaweed aquaculture industry is dynamic and expanding. In comparison to McClenachan and Moulton (2022)'s gender analysis of leases for seaweed cultivation[295], the number of seaweed limited purpose aquaculture (LPA) leaseholders in Maine has increased by 73%, and the number of seaweed standard or experimental leases has increased by 84% since 2020.[296] The number of gender minority (female and non-binary) lease and license holders has changed as well; while the percentage of gender minority LPA holders has declined (from 50.0% to 33.3%), the percentage of gender minority standard and experimental leaseholders has increased, from 21.1% to 28.57%.[297] Seaweed has been perceived as a maritime industry sector that allows women and gender minorities to thrive and has even been referred to as the only women-dominated ocean industry,[298] but data suggests this is not quite yet the case in Maine. However, the representation of gender minorities in the seaweed industry is vastly greater than in the shellfish aquaculture industry (**Figure 17B**).

Achieving gender equity is a universal non-negotiable component of achieving broader sustainability goals;[299] thus, the U.S. aquaculture industry has work to do before achieving either objective. Some of this work has already begun in Maine: The 2024 Women in Aquaculture Series, hosted by Aquaculture in Shared Waters in Maine and led by Maine Sea Grant and partners,[300] builds skills and centers community among active and aspiring aquaculturists in Maine who self-identify as women or nonbinary. The first course was oversubscribed with 76 applicants, but enrollment was limited to 42 students. All the instructors and support personnel for the course also identified as women or nonbinary, creating a supportive learning environment, whether administered in virtual or in-person settings. Hopefully, other states will likewise recognize the opportunity to support gender equity in aquaculture, and begin to offer similar workforce development courses across the U.S.

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[291] S. Harper et al., "Women and Fisheries: Contribution to Food Security and Local Economies," *Marine Policy* 39 (2013): 56–63; and M. Szymkowiak, "Genderizing Fisheries: Assessing Over Thirty Years of Women's Participation in Alaska Fisheries," *Marine Policy* 115 (2020).

[292] C. Brugere et al., "Humanizing Aquaculture Development: Putting Social and Human Concerns at the Center of Future Aquaculture Development," *Journal of the World Aquaculture Society* 54, no. 2 (2023): 482–526; and L. M. Campbell et al., "From Blue Economy to Blue Communities: Reorienting Aquaculture Expansion for Community Wellbeing," *Marine Policy* 124 (2021).

[293] G. Krause et al., "A Revolution without People? Closing the People–Policy Gap in Aquaculture Development," *Aquaculture* 447 (2015): 44–55.

[294] N. Lord, "A Rising Tide? The Role of Alternative Networks for Women Oyster Farmers in Maine and New Hampshire" (Master's thesis, University of New Hampshire, 2022), 1649; and L. McClenachan and A. Moulton, "Transitions from Wild-Caught Fisheries to Shellfish and Seaweed Aquaculture Increase Gender Equity in Maine," *Marine Policy* 146 (2022): 105312.

[295] McClenachan, L., & Moulton, A. (2022). Transitions from wild-caught fisheries to shellfish and seaweed aquaculture increase gender equity in Maine. *Marine Policy*, 146, 105312.

[296] "MaineDMR Aquaculture - AQ Leases," Maine Department of Marine Resources, updated March 21, 2019, https://dmr-maine.opendata.arcgis.com/datasets/mainedmr-aquaculture-aq-leases.

[297] "MaineDMR"; and McClenachan and Moulton, "Transitions from Wild-Caught."

[298] R. Fletcher, "Restorative Aquaculture: The Driving Force behind WWF's Adventures in the Seaweed Sector," The Fish Site, June 8, 2023, https://thefishsite.com/articles/the-driving-force-behind-wwfs-adventures-in-the-seaweed-sector-paul-dobbins-world-oceans-day.

[299] UN Women, *Turning Promises into Action: Gender Equality in the 2030 Agenda for Sustainable Development* (New York: UN Women, 2018).

[300] https://aquacultureinsharedwaters.org/2024-women-in-aquaculture

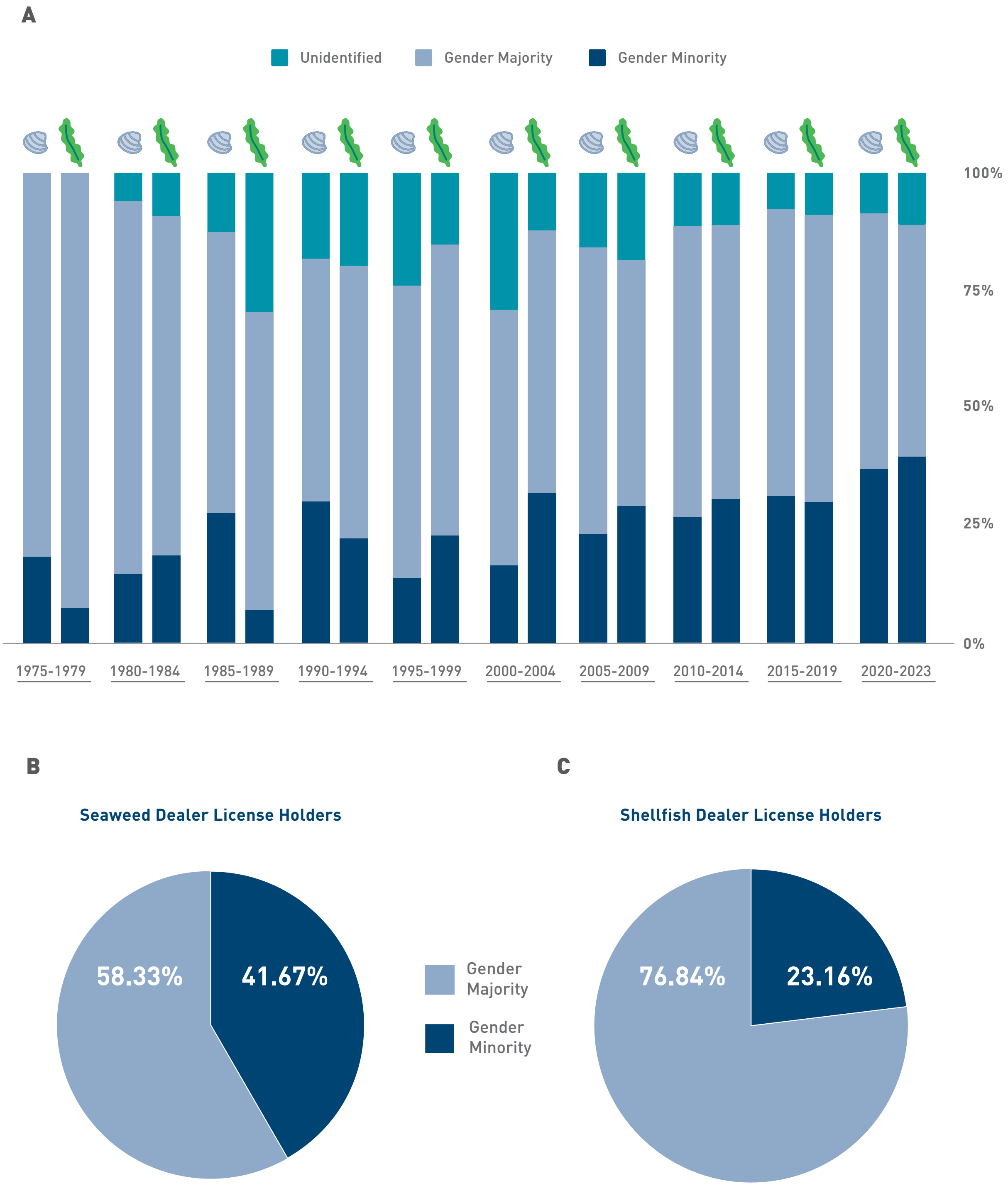

Figure 17. Gender equity considerations in seaweed aquaculture. (A) Gender minority led research on "seaweeds or macroalgae" (green icon) versus all "aquaculture" (shell) from Maine-based institutions: Summative, comparative percentages of gender identity for the first 10 listed authors in a given publication from a Scopus query result. From the "aquaculture" query results, 44 publications were excluded as no author names nor information were listed. "Gender minority" is defined as identifying as a woman, or non-binary. "Gender majority" is defined as identifying as a man. "Undefined" means that data were not sufficient to assign the author in either the minority of majority (e.g., full name was not listed, only initials; author search did not retrieve information on the individual, such as a profile from their affiliated institution which may include biographical information). (B) Percentage of aquaculture license holders in Maine as of 2023, categorized as gender majority (identifying as a man) or minority (identifying as a woman or non-binary).

III. RESULTS OF PILOT-SCALE RESEARCH

Pilot-scale research projects were conducted for approximately eighteen months, and were each funded at roughly $100,000 over that time period. Awards were made to institutions throughout the U.S. across both coasts and were fairly evenly dispersed across the three subject matters originally presented in the FY 19 Appropriations bill language (**Table 12**). Successful applicants were selected based on intellectual merit and fit to the programmatic topic areas. Nearly all of the funded pilot projects represent partnerships between academic and non-profit or commercial entities. The lead of each project provided a written summary and key graphics at the end of the study period for inclusion in this report, and those are presented in this section, with additional details provided in **Appendix 11**. None of the findings here have yet proceeded through the peer-review process for publication in primary literature. The results presented in this section are all *preliminary findings* from short studies and are included in this report to indicate the potential of farming seaweed as a mitigation strategy, as a feedstock, and as a major contributor to the blue economy. Every study concludes with the need for greater investment in research and development programs to optimize seaweed applications.

Table 12. Geographic, demographic and topical distribution of pilot-scale research funded for inclusion in this report.

TOPIC	TITLE	LEAD PI (GENDER)	LEAD INSTITUTION (STATE*)
“Deacidification”	Carbon capture and deacidification by marine seaweeds	Gregory Rorrer (gender majority)	Oregon State University (Oregon)
“Deacidification”	Use of seaweed to protect shellfish farming from ocean acidification	Loretta Roberson (gender minority)	Marine Biological Laboratory (Florida)
“Deacidification”	Evaluation of potential ocean acidification mitigation effects from sugar kelp growth in a Point Judith, RI kelp farm	Hongjie Wang (gender minority)	University of Rhode Island (Rhode Island)
“Feedstock”	Leveraging the sustainability of *Macrocystis pyrifera* as a feedstock to produce ingredients for food, animal and industrial applications	Juliana Leite Nobrega de Moura Bell (gender minority)	University of California, Davis (California)
“Scalable Blue Economy”	Offshore platform-based macroalgae production	Kent Satterlee (gender majority)	Gulf of Offshore Research (Louisiana)
“Scalable Blue Economy”	Bull kelp farm improvements to enable scaling of innovative food products	Julie Decker (gender minority)	Alaska Fisheries Development Foundation (Alaska)

*Note that the state listed is the physical location where the research was conducted, which may not be the same state where the lead institution is situated.

A. Carbon Capture and Deacidification by Marine Seaweeds

Contributing Authors: Gregory Rorrer

The capture of dissolved carbon in ocean waters by photosynthetic marine organisms plays a significant role in carbon cycling within the biosphere. Seaweeds have the potential to capture CO_2 and counteract OA in the immediate vicinity where seaweeds are farmed. Research out of Oregon State University, led by Gregory Rorrer, PhD, aimed to understand processes by seaweeds under controlled hydrodynamic and environmental conditions, so researchers can thoughtfully assess these processes' role in ocean-based carbon capture and deacidification. Clonal cultures of the red seaweed *Gracilaria vermiculophylla* were immobilized on vertical panels and placed in a flow stream within a recirculation system designed to measure CO_2 uptake, DOC release and pH plume downstream of the seaweed. This approach assessed the coupled rate processes of DIC uptake, DOC release and hydrogen ion consumption in real time to characterize pH gradient plume formation. Although these studies were performed in a laboratory mesocosm and not a field environment, they provided a simple testbed for evaluating seaweed-mediated deacidification strategies.

The project comprised three phases. In the first phase, the team developed a recirculating flow system to measure real-time CO_2 capture by seaweed, with the red seaweed *Gracilaria* serving as the model organism (detailed methods in **Appendix 11.1**). The seaweed filled the recirculation tank's channel with a contiguous bed and the team installed pH electrodes in and around the seaweed bed to capture the pH profile. In the project's second phase, the team characterized CO_2 capture under varying flow conditions (from 4 to 37 cm/s), including estimating rates of CO_2 uptake and capture. Notably, the team observed no DOC release to the seawater under active growth conditions. In the third phase of the project, the team characterized the seaweed bed's potential to deacidify seawater using mathematical simulation modeling approaches.

From these pilot testing results, the team calculated that a seaweed bed with 70 m^3 of bulk volume can process seawater flow of 6.0 m^3/h from an entrance pH of 8.1 to an exit pH of 8.8 with an 11-hour residence time. Seawater of pH 8.8 can then be mixed with seawater of pH 8.1 to titrate seawater up to pH 8.2 (**Figure 18**). Although the research outcomes are limited in scope, they are designed to be scalable, and so may garner the interest of potential stakeholders, including seaweed or multitrophic aquaculture operations needing to create options for onsite de-acidification of seawater. This work also represents the first step in evaluating carbon uptake for entering the voluntary carbon credit offset market, but additional research to determine carbon removal rates would need to first be verified and a full life cycle assessment of the process completed.

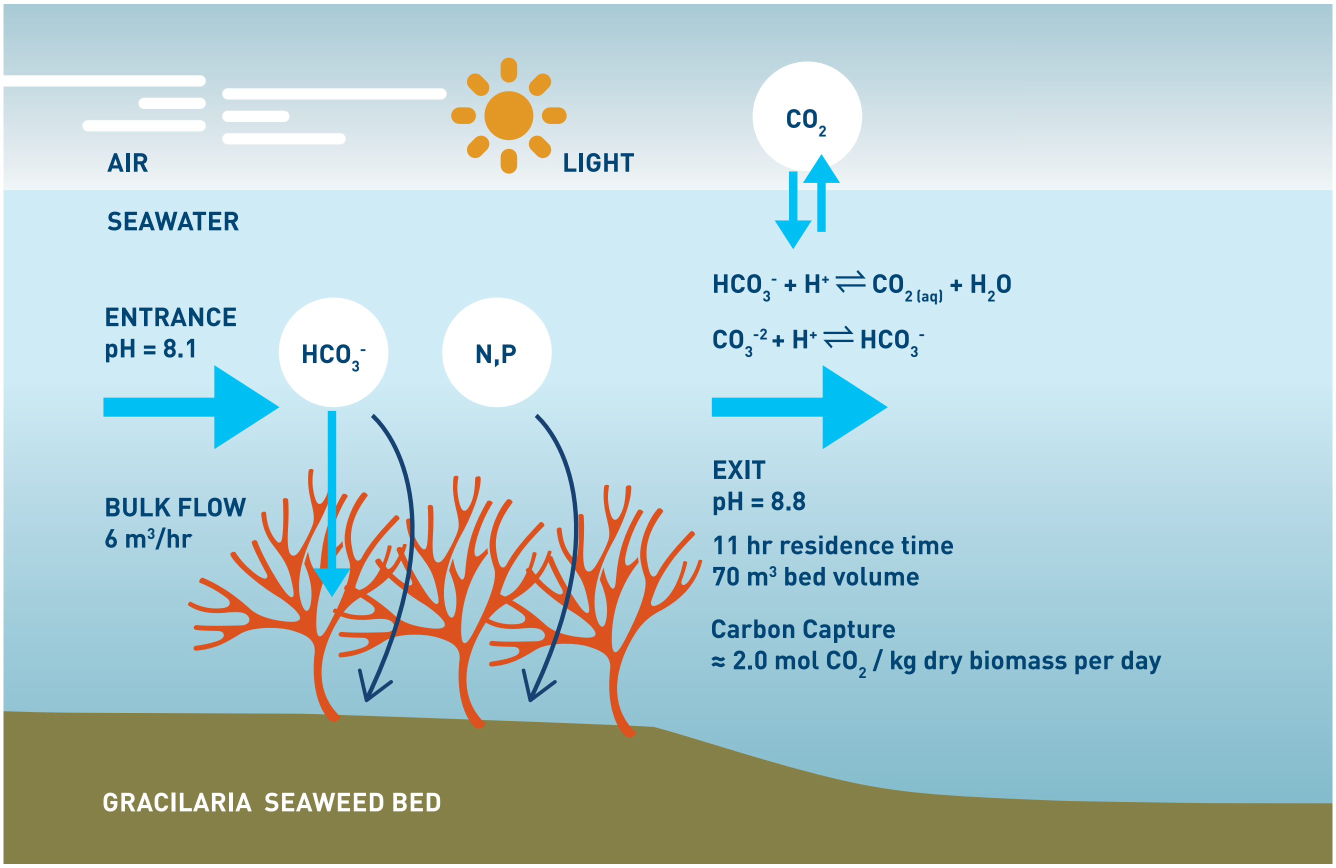

Figure 18. Carbon capture and deacidification processes and measured rates by an engineered *Gracilaria vermiculophylla* in a laboratory mesocosm.

B. Use of Seaweed to Protect Shellfish Farming from Ocean Acidification

Contributing Authors: Loretta Roberson, and Aaron Welch

At the Marine Biological Laboratory, Loretta Roberson teamed up with Aaron Welch of Two Docks Shellfish LLC to directly address how seaweed can enhance ocean alkalinity to support sustainable production of seafood in an underdeveloped region. This was the first commercial co-culture seafood operation in tropical U.S. waters. The study leveraged existing, already permitted technology to provide the ideal test bed (shellfish and seaweed farm in Tampa Bay) and microcosm (shellfish hatchery) to measure the seaweed's potential as a tool for ocean alkalinity enhancement. Our target species were tropical species endemic to Tampa Bay and tropical U.S. waters: the sunray venus clam, *Macrocallista nimbosa*, and the red seaweed, *Gracilaria mammillaris*. The team monitored shellfish growth rates and shell thickness in the hatchery and field, and conducted monthly readings of total alkalinity, DIC and pH in the presence and absence of macroalgae.

The co-cultivation systems we developed were effective at enhancing growth of clams in both the field and the nursery (**Figure 19**). The algae treatment had a significantly positive effect on the specific growth rate of the clams ($F_{(1, 17)} = 8.707$, $P = 0.0089$), with a higher specific growth rate ($F_{(1, 17)} = 7.212$, $P = 0.0156$) at the farm location than at the nursery. However, the co-cultivation systems are not currently cost-effective when scaling up for a commercial grow-out operation. It is also unclear if the mechanism underneath the seaweed's influence on clam growth was related to amelioration of acidification. Dissolved inorganic carbon and pH did not vary significantly between treatments, although this was confounded by seasonal differences and higher variability in the field versus the nursery (**Appendix 11.2**). For example, the average pH on the farm in winter in the algae treatments was 0.2 units higher (8.3) than the clams only (8.1), but observed values ranged from 8.1-8.4 compared to more steady measurements during spring and fall. Seaweed has the potential to enhance growth and survivorship of co-cultivated shellfish in tropical waters, but more sampling needs to be done to better understand the mechanisms of enhancement.

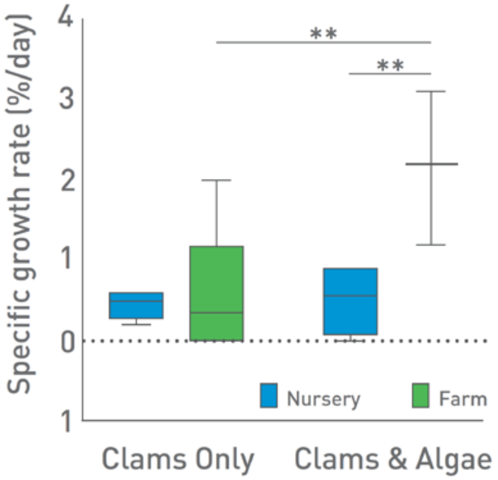

Figure 19. Use of seaweed to protect shellfish farming from ocean acidification. Specific growth rate of sunray venus clams by treatment and location.

C. Evaluation of Potential Ocean Acidification Mitigation Effects from Sugar Kelp Growth in a Point Judith, RI Kelp Farm

Contributing Authors: Hongjie Wang and Fiona Teevan-Kamhawi

Ocean acidification (OA), driven by the increasing level of anthropogenic atmospheric CO_2, is threatening the commercial fishery in Rhode Island because of its potential damage to food webs and economically important organisms such as shellfish (e.g., clams, quahogs and scallops) in Narragansett Bay. Macroalgae, through photosynthesis, plays a crucial role in CO_2 removal.[301] Sugar kelp, native to New England, has been identified as a natural means of mitigating OA because kelp can quickly convert DIC into organic biomass[302] and because of sugar kelp's rapid growth rate of up to 2 cm per day. As kelp cultivation increases in New England, understanding kelp's potential OA mitigation effects is urgent. However, despite previous studies indicating macroalgae aquaculture's effectiveness in local OA mitigation,[303] farming season-long observations of kelp's impact on OA are sparse. The working hypothesis is that the Point Judith Kelp Farm (roughly two acres), located in Rhode Island waters, can significantly decrease local surface pCO_2 and increase pH, but this impact wanes with the tidal exchange.

This project's major research activities were: 1) to deploy two monitoring packages to collect continuous surface pCO_2 and pH data inside and outside the kelp farm; 2) to collect discrete carbonate chemistry samples to understand the spatial extent of OA mitigation, if there were to be any. The data indicated trivial temperature and salinity disparities between these two sites. Temperatures climbed from 6°C in January to 14°C by May (**Appendix 11.3**), while salinity oscillated between 28.7 and 32.5 and was approximately 0.1 lower at the kelp farm. The kelp farm's pH varied depending on factors such as dissolved oxygen, and was about 0.01 higher before the final harvest on May 5, 2023. However, the pH in the kelp site quickly decreased after the final harvest. The pCO_2 change displayed a similar seasonal pattern as pH, and was only reduced – relative to control – on the farm during the kelp exponential growth period from February to March and immediately before final harvest in May, 2023 (**Figure 20**). On average, pCO_2 in the sugar kelp site was otherwise elevated throughout the 2022 to 2023 growth season.

In summary, the team only observed an OA mitigated impact for a small window at peak primary productivity on this extremely small sugar kelp farm. This result contradicts the expected consistent pCO_2 decrease throughout the farming period. The team hypothesizes that this negligible OA impact is due to the farm size and/or other indirect effects, which have not been adequately considered in prior studies. For example, we assumed that the phytoplankton-formed primary productivity was the same inside and outside the farm from March to April. Future research should delve deeper into how kelp cultivation might alter phytoplankton diversity, with more extended and comprehensive environmental observations.

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[302] Brady-campbell, A. M. M., Campbell, D. B., Harlin, M. M., Brady-campbell, M. M., Campbell, D. B., & Har, M. M. (1984). Productivity of kelp (Laminaria spp .) near southern limit in the Northwestern Atlantic Ocean, 18(1), 79–88; Ricart, A. M., Honisch, B., Fachon, E., Hunt, C. W., Salisbury, J., Arnold, S. N., & Price, N. N. (2023). Optimizing marine macrophyte capacity to locally ameliorate ocean acidification under variable light and flow regimes: Insights from an experimental approach. *Plos one*, *18*(10), e0288548.

[303] Young, C. S., Sylvers, L. H., Tomasetti, S. J., Lundstrom, A., Schenone, C., Doall, M. H., & Gobler, C. J. (2022). Kelp (*Saccharina latissima*) Mitigates Coastal Ocean Acidification and Increases the Growth of North Atlantic Bivalves in Lab Experiments and on an Oyster Farm. Frontiers in Marine Science, 9(April), 1–19. https://doi.org/10.3389/fmars.2022.881254; Xiao, X., Agustí, S., Yu, Y., Huang, Y., Chen, W., Hu, J., et al. (2021). Seaweed farms provide refugia from ocean acidification. Science of the Total Environment, 776. https://doi.org/10.1016/j.scitotenv.2021.145192;

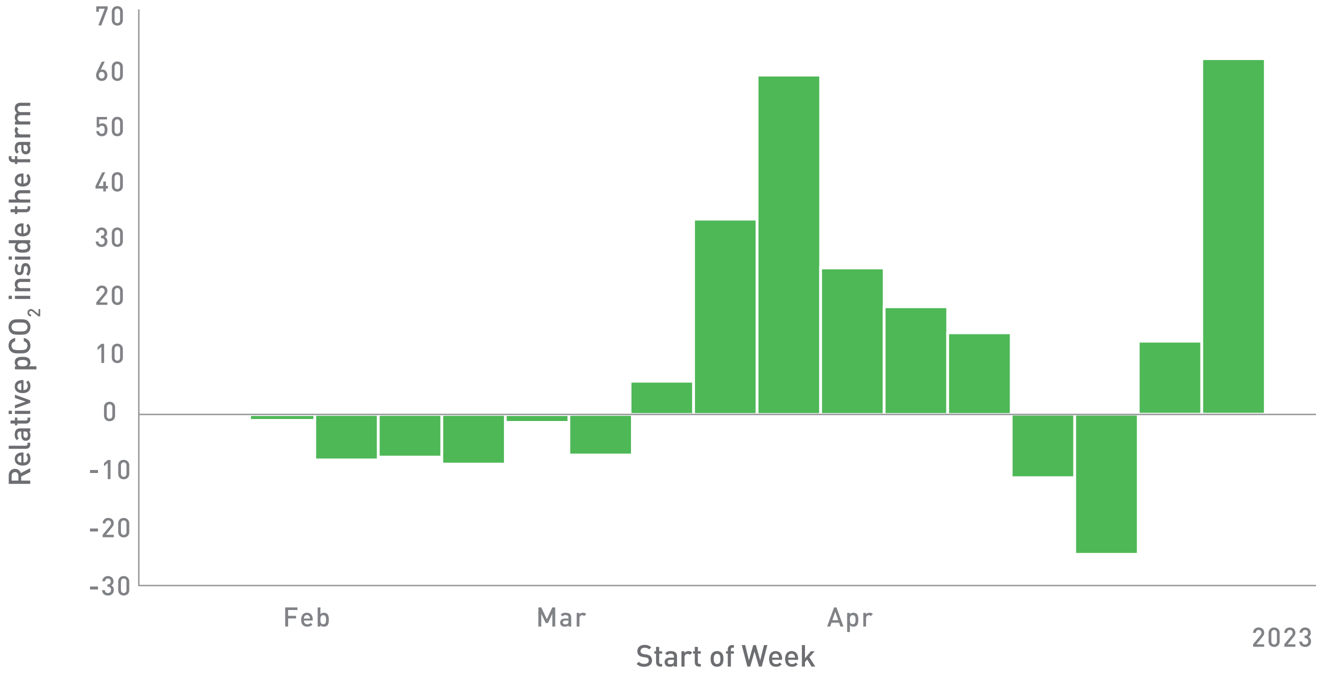


Figure 20. The weekly pCO_2 change of the farm site relative to the control site resulting from sugar kelp growth, calculated as $\Delta pCO_{2\ \text{nonthermal, kelp farm}} - \Delta pCO_{2\ \text{nonthermal, control}}$. Values below zero indicate that the sugar kelp has mitigated OA on the farm.

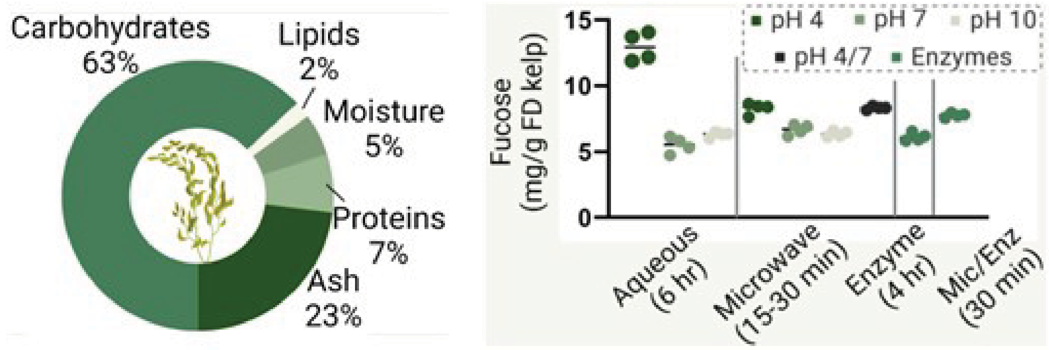
D. Leveraging the Sustainability of *Macrocystis pyrifera* as a Feedstock to Produce Ingredients for Food, Animal and Industrial Applications

Contributing Authors: Juliana Leite Nobrega de Moura Bell and Daniela Barile

The rising global human population, coupled with climate change-induced environmental stresses, is exerting extreme pressure on food production systems globally. This pressure is driving the quest for sustainable sources of macro- and micronutrients intended for industrial applications. Seaweeds are an untapped potential as a sustainable biomass resource with a wide range of potential food, feed, and industrial utilities, but lack detailed compositional analyses to explore alternative applications, like biopharma. The major goal of this research project was to uncover the effects of processing conditions (i.e., biomass-to-water (BWR) ratio, temperature, pH, time) and extraction methods (i.e., aqueous, enzymatic, and microwave-based extractions) on the extractability, structural composition and functional/biological properties of the major compounds of the giant kelp species *Macrocystis pyrifera*. The overarching aim was to develop sustainable extraction methods based on both structure and functionality to produce compounds with desired properties.

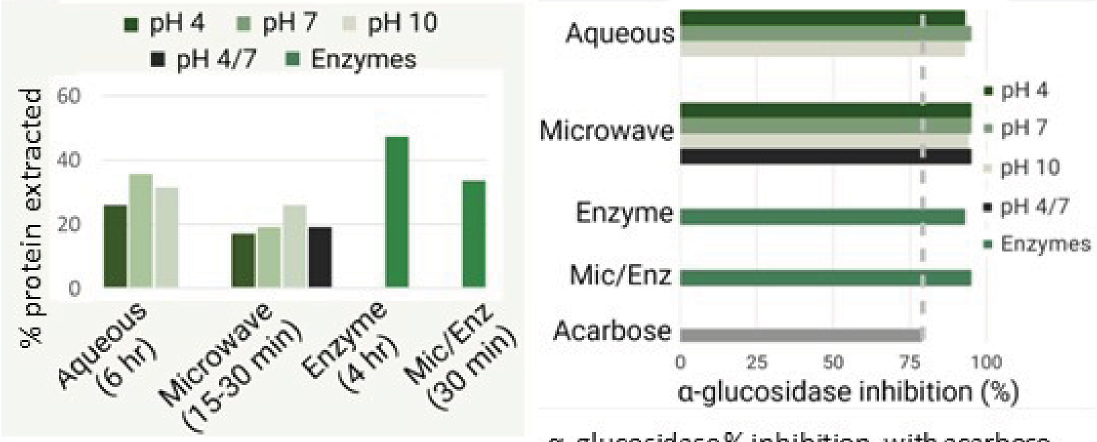
To understand how the parameters for extraction processes affect the extractability of key compounds and the biological properties of the extracts, this project evaluated the impacts of pH, BWR, reaction time and enzyme use. Details of extractions protocols, etc. provided in **Appendix 11.4**. Overall, acidic conditions led to a greater release of carbohydrates (**Figure 21**). Additionally, the use of higher temperatures led to enhanced extractability, likely due to decreased slurry viscosity. Diple-dipole interactions from microwaves enhanced compound extractability, allowing for faster extractions. Furthermore, the integration of enzymes and microwaves led to the release of more intracellular compounds (laminarin and peptides). Based on yields and resource utilization, microwave-assisted extraction (MAE) and microwave enzyme-assisted extraction (MEAE) conditions were selected for further characterization of their composition and biological activities. MEAE yielded extracts displaying high bioactivities.

Enzyme-assisted aqueous extractions generally yielded extracts of the highest bioactivity, with essential amino acids and antidiabetic properties 25 times better than market drugs. Microwave assisted extractions produced sodium alginate with the lowest M/G ratio – a difficult to achieve target for biopharma. Microwave enzyme assisted aqueous extraction released additional oligosaccharides, and generated higher bioactivity. These insights underscore the potential of sustainable and bio-guided downstream processing strategies to introduce this feedstock to industries worldwide.



Composition of *Macrocystis pyrifera* (giant kelp)

Fucose content of extracts (mg fucose/ g freeze dried kelp)



Total protein content (%) of all extracts

α-glucosidase % inhibition, with acarbose as control

Figure 21. Major findings from exploring sustainable extraction techniques and analytical approaches for giant kelp processing.

E. Offshore Platform-Based Macroalgae Production

Contributing Authors: Kent Satterlee, Kristen Davis, Brian Snyder, Ryan Bart Reid, Ivan Puckett, and Sara Hamann

Under the direction of Kent Satterlee, the Gulf Offshore Research Institute (GORI), with team members from UC Irvine, Louisiana State, Blue Silo Aquaculture and others, investigated and developed a preliminary design for an offshore platform-based macroalgae production system, including the planting and harvesting process, for the Gulf of Mexico. Our research focused on taking a retired/repurposed offshore oil platform in the Gulf of Mexico and using it as a logistical hub and energy source for seaweed farming with minimal environmental impacts. Retired offshore oil and gas platforms have several advantages that can scale up production of macroalgae, including an electrical supply, and are also designed and built to survive hurricane conditions. The team investigated ways of scaling the production, harvesting and refinement of seaweed through co-location with retired oil and gas platforms, and investigated the concept and scalability of platform-based macroalgae farming at two offshore platform sites located near the mouth of the Mississippi River.

The Gulf of Mexico is a promising location for seaweed aquaculture among U.S. and state waters given its high productivity, wide shelf, shallow depths, and the potential for ecosystem co-benefits. Specifically, the Gulf of Mexico suffers from high levels of macronutrients from agricultural and water treatment runoff, with harmful algal blooms and associated low-oxygen dead zones. Seaweed aquaculture requires abundant macronutrients and could reduce the impacts of such nutrient loads. Physical oceanographic observations were collected in fall 2023 and 16 years of simulations using the g-MACMODS model were used to create macroalga yield and nitrogen uptake maps across the Gulf of Mexico. Oceanographic conditions as measured in this study are conducive to seaweed growth.

To identify macroalgae species suitable for cultivation on platforms in the Gulf of Mexico, we studied species employed in commercial operations worldwide and concluded that the top five candidates were *Ulva Sp*., *Gracilaria Sp*., *Kappaphycus alvarezii, Caulerpa racemosa* and *Asparagopsis taxiformis*. We investigated the technoeconomic feasibility of platform-based seaweed culture by creating a set of net present value (NPV) models that simulates the costs of growing *Gracilaria* or *Sargassum*, with only one system modeled per species. Both systems modeled had a positive NPV and internal rate of return (IRR) between 16% and 19% (**Figure 22**).

Further details on modeling, site specific time series data, potential gear conflict issues, and crop production potential are provided in **Appendix 11.5**.

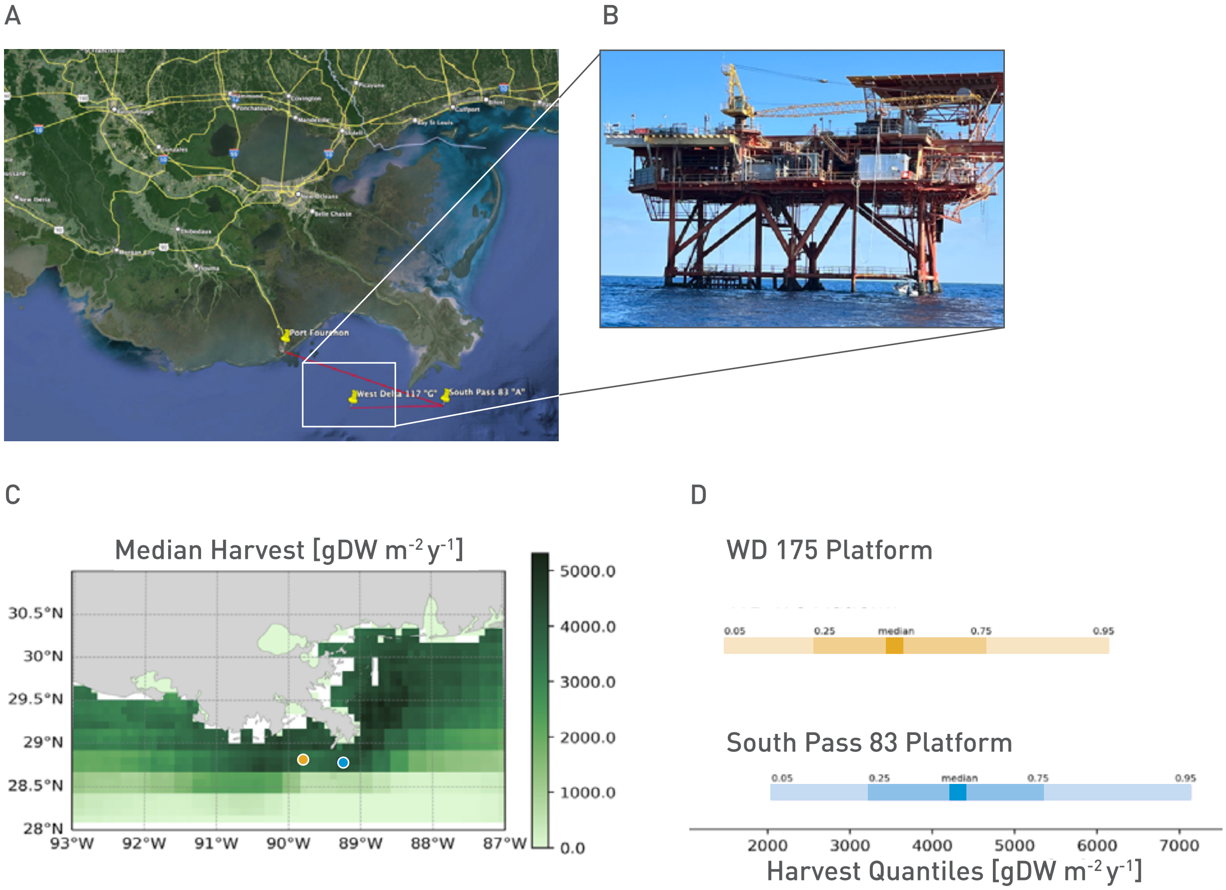


Figure 22. Offshore platform-based macroalgae production in the Gulf of Mexico. "(A) The project site is located in the Gulf of Mexico, approximately 53 nautical miles from Port Fourchon, LA (B) on the decommissioned platform-SP 83 (C) Model estimates of harvestable biomass in the area of the proposed oil platform location (D) Model estimates of harvestable biomass from specific oil platforms considered in this study.

F. Bull Kelp Farm Improvements to Enable Scaling of Innovative Food Products

Contributing Authors: Julie Decker, Schery Umanzor, Lia Heifetz, Angela Bowers, Tomi Marsh, Megan O'Neil, and Hannah Wilson

Alaska has a unique situation with bull kelp (Nereocystis luetkeana): local industry has used wild bull kelp to increase market demand, with the intent to scale by buying bull kelp from farmers. But the Alaska Department of Fish and Game strictly limits the amount of wild kelp harvested due to the lack of research documenting total biomass. Unlike sugar kelp, very few, if any funds, have been invested in research to farm bull kelp. A team of researchers—led by Julie Decker of the Alaska Fisheries Development Foundation, in partnership with University of Alaska investigators and industry members at Kelptastic and Level Island Kelp farms—provided input from researchers to farmers, enabling farm design innovations. The intent of the research is to enable farmers to provide raw resources to allow kelp manufacturers to meet market demand and continue to scale their food business.

The goal of this project was to design, evaluate and refine farming protocols that would optimize yields and production of bull kelp to meet a need identified by Alaska mariculture food manufacturers. The high demand for bull kelp in Alaska cannot be satisfied by current farming outputs. The seaweed farmers who have tried growing bull kelp to date have failed to get the stipe and fronds to grow to the same size found in the wild. To address this challenge, researchers attempted to determine site characteristics and cultivation methods that provide large, healthy stipes to meet market demand and allow food businesses to increase production.

Researchers collaborated with two kelp farmers tending three farm sites to preliminarily examine how depth, water flow and seeding density affected bull kelp stipes. Objectives were to determine if morphological differences occur between bull kelp farmed at various water flows, determine if seeding at a lower density contributes to increased stipe size and determine if the depth at which farming occurs contributes to producing larger bull kelp. Details on methods can be found in Appendix 11.6.

Researchers found that:

- Farming deeper, at lower density and at sites with adequate flow yielded longer, thicker sporophytes (**Figure 23**).
- Low sporophyte density can compensate for slow flow.
- Higher flow positively impacts stipe size.

The project team's outreach efforts encompass a diverse range of materials, and the team has formed a bull kelp working group with other researchers to synthesize current studies. Furthermore, a comprehensive summary of project results will be housed in the Alaska Fisheries Development Foundation Research Library and integrated into the Bull Kelp Growers Manual, titled "Farming Bull Kelp: Lessons Learned & Future Considerations," scheduled for republication in Spring 2024 (see **Table 11** for a list of similar manuals for other species). As a follow-up step to this project, the team has implemented cultivation technique adjustments based on insights from the 2022/23 harvest to enhance the overall cultivation process.

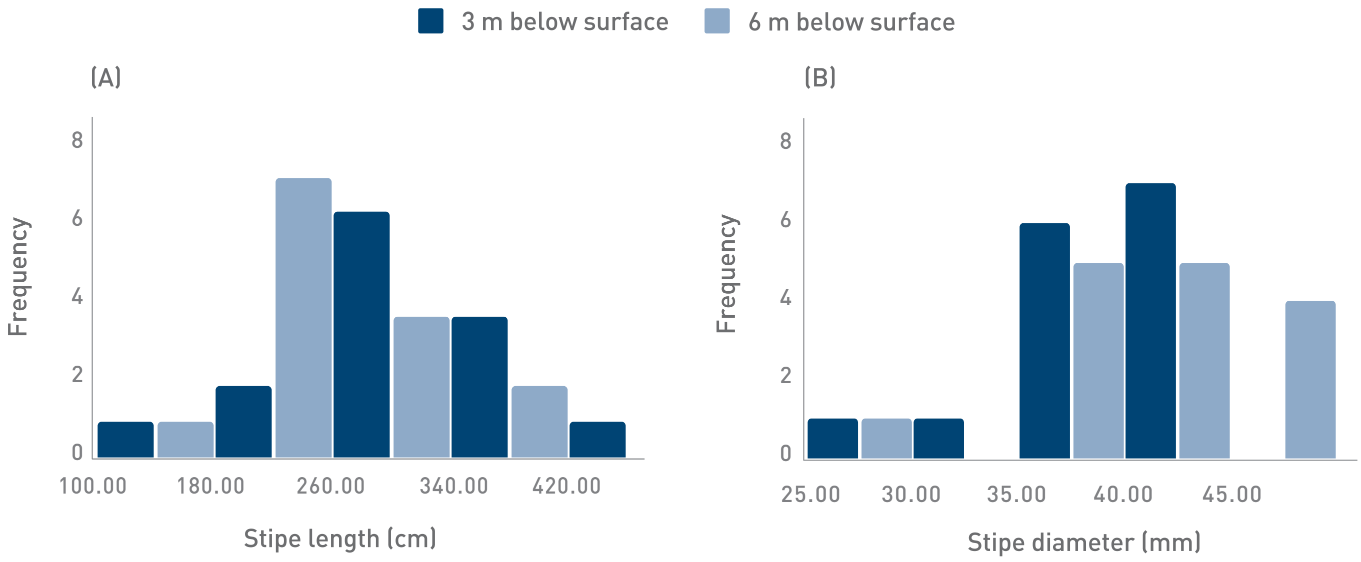


Figure 23. Frequency distribution of stipe qualities categorized by length (A) and diameter (B), dependent on depth of the long lines at the experimental bull kelp farm.

IV. RECOMMENDATIONS AND KNOWLEDGE GAPS BASED ON FINDINGS AND RESULTS

This section presents recommendations based on the collectively reviewed results of the IWG findings, the pilot-scale research studies, and feedback from the >1,000 stakeholders engaged over two years in virtual listening sessions. Almost all of the recommendations listed here garnered more than 70% support from attendees, with the exception of developing training materials and tools for entering carbon markets (> 63%), seaweed seed-banking (> 64%), and seeking alignment among state permitting processes (> 50%), which each also garnered the preponderance of support. **Table 14** summarizes and categorizes the knowledge gaps and recommendations mentioned throughout this report, and discussed at length during the listening sessions. It should be noted that almost all of these recommendations are focused on farmed seaweeds, and all are also in alignment with the series of reports released by the National Science and Technology Council Subcommittee on Aquaculture.

In summary, these recommendations ask that the U.S. invests in research and collaboration (from nation to nation, and within), sea farmers support systems, data collection and access, technological advancements, and infrastructure. Finally, and perhaps most importantly, this report also asks that the U.S. invests in regulatory modernization and policy opportunities to continue to support the nascent U.S. seaweed industry as a competitor in the global market. As an example of a specific recommendation, a national seaweed trade association (**Table 13 III.A.1**) could facilitate coordinating stakeholders, promoting SLO, standardizing industry best practices, and proactively confronting infrastructure, financial, and regulatory barriers. We have assigned a unique identifier to each recommendation to simplify references.

Table 13. Summary of the recommendations based on the collectively reviewed results of the IWG findings, the pilot-scale research studies, and feedback from more than one thousand stakeholders engaged over two years. Recommendations are categorized by topic area and arrayed across financial, infrastructure, or regulatory needs to support the growing U.S. seaweed farming sector.

RECOMMENDATION TYPE			
Topic Area	**I. Financial**	**II. Infrastructure**	**III. Regulatory**
A. Business Development	1. Fund instruments for new seaweed businesses 2. Provide federal subsidies for curricula development and tuition: job training; human resources; workforce development; voluntary carbon market entry 3. Bolster access to farm and crop insurance protections and subsidies for seaweed farmers 4. Convene manufacturers of land-based crop processing equipment within U.S. and support nation to nation tech transfer to convert equipment to meet seaweed hatchery/nursery, farming, and processing demands 5. Provide financial assistance to states to hire sufficient personnel with requisite expertise to review influx of farmed seaweed permitting applications 6. Conduct state-specific and US-wide economic impact analyses of seaweed farming	1. Produce LCA inventories, databases, and mathematical models for comparing mCDR and avoided GHG emissions scenarios using seaweed products 2. Conduct biomass standing stock surveys of wild populations of seaweeds and seagrasses (to understand natal broodstock availability and monitor for 'escapees' and species range shifts) 3. Develop ecosystem services valuation or monetization structures for seaweed farming and seagrass restoration 4. Relocate and rebuild failing and flood/climate-impacted municipal and state landing platforms proximal to sites most conducive to seaweed farming 5. Develop best practices for seaweed farm design to maximize yields and minimize gear interference (e.g., density, depth, etc.)	1. Establish a National Seaweed Trade Association 2. Develop regional level task forces or working groups (e.g., blue economy, mCDR, etc.) for farmed seaweeds 3. Standardize and coordinate farmed seaweed landing reporting procedures across states 4. Create a batch reporting process for nutritional profiles, which can be highly variable in seaweeds, for both food and feed 5. Revisit organic certification standards acknowledging unique nature of marine systems[304] 6. Speed FDA regulatory approvals for novel algal -based food, pharma, or animal feed ingredients (e.g., IFEED Act) 7. Develop data-driven selective breeding, genetically modified organism standards and guidelines for farmed seaweeds and restored seagrasses 8. Develop data-driven best practices and protocols for biosecurity measures for farmed seaweeds

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[304] A challenge is ensuring these certifications do not become counterproductive to nutrient remediation goals.

RECOMMENDATION TYPE			
Topic Area	**I. Financial**	**II. Infrastructure**	**III. Regulatory**
B. Marine Resource Planning	1. Invest in continued development of novel oceanographic, chemical and biological remote sensing for flux estimates during seaweed farm operations (e.g., for carbon and nitrogen and monitoring OA, eutrophication and deoxygenation) 2. Integrate remote sensing technologies and support development of open access databases of ocean conditions for sea farming	1. Produce online mapping tools with granularity and specificity to optimize farmed seaweed ecosystem services across seasons, natural climate solutions, spillover impacts to fisheries, and yield estimators 2. Produce oceanographic, biogeochemical and predictive modeling for seaweed farm siting (yield expectation), short-term warning (e.g., climate anomalies, HABs) and long-term adaptation 3. Develop databases and testing facilities for disease incidence reporting for farmed seaweeds (c.f., National Plant Diagnostic Network)	1. Generate policies to support permitting for successional seaweed planting in multi-use regions with potential for gear use conflict 2. Identify federal or state-specific realistic deacidification or decarbonization targets[305] 3. Identify consensus (and disparities) among state-permitting policies for seaweed farms 4. Develop and coordinate (inter) state permitting and federal importing policies for farmed seaweed
C. Research, Development and Engineering	1. Continue supporting voluntary comparisons of performance and adherence to best practices across U.S. seaweed testing facilities 2. Expand federal programs to support continued applied research in support of seaweed farming 3. Support discovery of novel farmable seaweed species 4. Research how to improve seaweed farming methods and configurations to maximize yields and minimize any negative ecosystem impacts 5. Identify practices that maximize marine carbon dioxide removal potential of farmed seaweeds 6. Develop standardized seaweed seed-banking protocols for marine repositories 7. Substantiate private-sector utility, safety, and efficacy claims of farmed seaweed through evidence-based research programs	1. Construct experimental seaweed hatcheries and farms, benchtop scale processing and production, proof of concept testing facilities, etc. 2. Conduct seaweed species inventories and create state and national seaweed species inventory lists (coordinated with WoRMS and Algaebase, and including DNA voucher and tissue archiving — working with culture collections and repositories) 3. Produce reference materials and lab testing facilities for various seaweed nutritional components 4. Further develop seaweed farming expertise through additional hires and training programs within federal agencies 5. Produce mCDR/Blue Carbon SOPs for experimentation with farmed seaweeds and seagrasses and measurement, reporting and verification standards for national carbon assessments	1. Establish data-driven HACCP specific for seaweed farming and processing: comprehensive review of what "kill-steps" and preservation or rinsing/chelation steps are available and relative efficacies[306] 2. Include "algae" and "seaweed" more explicitly in U.S. Farm Bill and in USDA APHIS regulations 3. Develop guidelines for environmental impact analyses of seaweed farms 4. Devise regulatory evaluations for the importation of live seaweed from other countries 5. Develop and provide trainings of federal staff and the public around seaweed as an agricultural commodity and the need for consistent inclusion in government programming and policy

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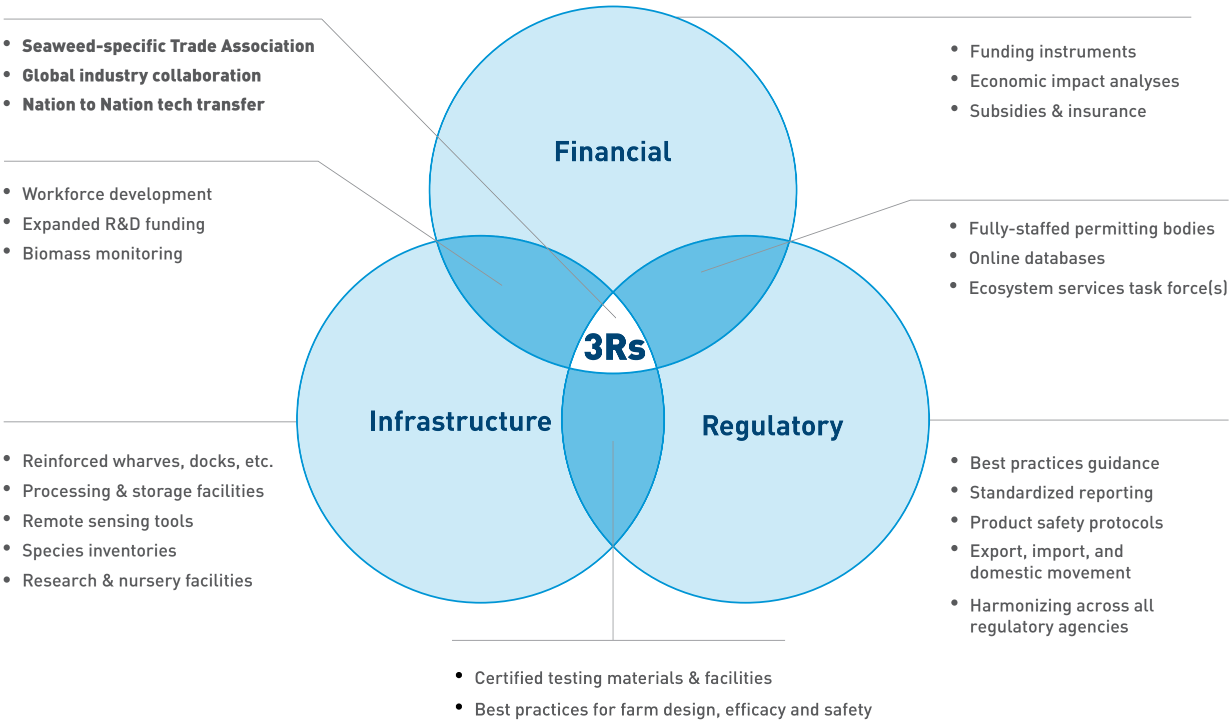
[305] Particular regions *may* want to deacidify mixed layer, others may have more modest goals for particular municipalities where the potential scale of seaweed farming best matches the scale of the water quality issue.

[306] A seafood HACCP exists, but some recommendations are not relevant to seaweeds. National Sea Grant Law Center, *Seaweed Food Safety: Comparing Compliance with Preventive Controls for Human Food with Seaweed HACCP* (Oxford, MS: National Sea Grant Law Center, September 2023); testing recommendations have been summarized in this report: Alaska Sea Grant, *Seaweed Hub Report for Seaweed Parameter Testing Resources* (Fairbanks, AK: Alaska Sea Grant, 2023)

V. CONCLUSION

Evidence continues to mount – including from pilot studies reported herein – that seagrass restoration and seaweed farming each offer numerous ecosystem services, including ocean deacidification and decarbonization. In addition, seaweed farming offers a valuable feedstock that will generate revenue and new jobs while restoring degraded coastal marine ecosystems. Aquaculture is rapidly becoming part of the fabric of the blue economy, with seaweed farming at the forefront of sector growth and providing unique socioeconomic opportunities for Tribal Nations and gender minorities. Resources like those summarized in **Figure 24** will need to be provided from U.S. federal agencies and programs, working closely with the growing number of seaweed-based for-profit companies, to grow the U.S. farmed seaweed (and seagrass restoration) industry responsibly.

Responsible Restoration & Revenue Generation from Farming US Seagrasses and Seaweeds



- **Seaweed-specific Trade Association**
- **Global industry collaboration**
- **Nation to Nation tech transfer**

- Workforce development
- Expanded R&D funding
- Biomass monitoring

- Reinforced wharves, docks, etc.
- Processing & storage facilities
- Remote sensing tools
- Species inventories
- Research & nursery facilities

- Funding instruments
- Economic impact analyses
- Subsidies & insurance

- Fully-staffed permitting bodies
- Online databases
- Ecosystem services task force(s)

- Best practices guidance
- Standardized reporting
- Product safety protocols
- Export, import, and domestic movement
- Harmonizing across all regulatory agencies

- Certified testing materials & facilities
- Best practices for farm design, efficacy and safety

Figure 24. Quick reference summary of knowledge gaps and resource needs for continued responsible sector growth of seaweed farming and seagrass restoration in the U.S.

VI. APPENDICES

A. Acronyms

ARPA-E	Advanced Research Projects Agency-Energy
AD	Anaerobic Digestor
AFDW	Ash Free Dry Weight
APMI	Alutiiq Pride Marine Institute
BoSSLine	Bags of Seagrass Seeds Line
BWR	Biomass to Water
BHSD	Boothbay Harbor Sewer District
BuDS	Buoy Deployed Seeding
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CO2	Carbon Dioxide
pCO2	Carbon Dioxide Partial Pressure
CRRC	Chugach Regional Resources Commission
CWA	Clean Water Act
DOE	Department of Energy
DIS	Dispenser Injection Seeding
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DSQAP	Dietary Supplement Quality Assurance Program
EEZ	Exclusive Economic Zone
FAO	Food and Agriculture Organization
FY	Fiscal Year
GHG	Greenhouse Gas
GOM	Gulf of Maine
GORI	Gulf Offshore Research Institute
HS code	Harmonized System Code
IMTA	Integrated Multitrophic Aquaculture
IWG	Interagency Working Group
IRR	Internal Rate of Return
LAI	Leaf Area Index
LCA	Life Cycle Assessment
LPA	Limited Purpose Aquaculture
mCDR	Marine Carbon Dioxide Removal
MRV	Measurement, Reporting and Verification
MEAE	Microwave Enzyme-Assisted Extraction
MAE	Microwave-Assisted Extraction
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NOP	National Organic Program
NPV	Net Present Value
OA	Ocean Acidification
PAH	Polycyclic Aromatic Hydrocarbons
PCB	Polychlorinated Biphenyls
QAP	Quality Assurance Program

RAS	Recirculating Aquaculture System
ROV	Remote Operated Vehicle
RFP	Request for Proposals
SPS	Sanitary and Phytosanitary
SAV	Submerged Aquatic Vegetation
SCUBA	Self-Contained Underwater Breathing Apparatus
SLO	Social License to Operate
SLR	Sea Level Rise
SME	Subject Matter Expert
SOP	Standard Operating Procedures
TBT	Technical Barriers to Trade
TDM	Trade Data Monitor
TEA	Techno-Economic Analysis
TERFs	Transplanting Eelgrass Remotely with Frames
UNDP	United Nations Development Programme
USDA	U.S. Department of Agriculture
USDA ARS	U.S. Department of Agriculture Agricultural Research Service
VCM	Voluntary Carbon Credit Market
WRRF	Wastewater Resource Recovery Facilities
WTO	World Trade Organization

B. Terminology

Agricultural feedstock: Any raw material, such as seaweed or seagrass, which can be used in an industrial agricultural process; e.g., a raw material that can be used as an animal feed, crop fertilizer, etc. A feedstock is any renewable, biological material that can be used directly as a fuel or converted to a fuel or energy product.

Aquaculture: Aquaculture is the production of aquatic organisms, including fish, shellfish and algae, in marine or freshwater environments. Aquaculture serves various purposes, such as to produce food and other commercial products, to restore habitats and wild stocks and to rebuild populations of aquatic species.

Biomass: Biomass refers to the weight or quantity of living organisms in a given animal or plant species or community. Biomass may also refer to the renewable energy from plant and animal products.

Blue carbon: The term for the legacy atmospheric carbon captured by the world's ocean and coastal ecosystems. Traditionally, this term had referred only to CO_2 removal to vegetation and marine sediments by saltmarshes, seagrasses, and mangroves. More recent definitions also include the contributions of seaweeds, phytoplankton, zooplankton, and macrofauna (e.g., whales) and other non-biologic processes.

Blue economy: The sustainable use of ocean resources for economic growth, improved livelihoods and jobs while preserving the health of the ocean ecosystem.

Carbon additionality: Carbon additionality refers to the positive effects produced by a carbon offset action (an action a company or other entity takes to reduce emissions or store carbon) relative to the baseline. When an activity is additional, it indicates the sale of carbon credits is leading to emissions reductions that would not have otherwise occurred.

Carbon capture and storage (CCS): A process that separates and captures industrially exhausted carbon dioxide emitted from point sources, like a smokestack or flue, such as in a coal-fired power plant or a cement factory, and then sequesters that carbon dioxide in deep underground geologic formations on land or in marine systems. Carbon storage can take place in both onshore and offshore settings, in a variety of geologic formations.

Carbon cycle: The carbon cycle is the process by which carbon moves between plants, animals and microbes; minerals, waterbodies, and the atmosphere.

Carbon dioxide equivalents (CO_2e): Carbon dioxide equivalents compare emissions from various greenhouse gases by calculating the number of metric tons of carbon dioxide emissions with a global warming potential that is equivalent to a metric ton of another greenhouse gas. This is a measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP) by conversion to an equivalent amount of carbon dioxide of the same global warming potential. The CO_2e for a gas is derived by multiplying the mass of the gas by the GWP of the gas.

Carbon dioxide removal (CDR): Refers to anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. Removals can 1) accelerate the reduction of net emissions (immediately), 2) counterbalance 'hard-to-abate' emissions (near-term), and 3) deliver net negative emissions (long-term). Carbon removals lead to the generation of "negative emissions", which are crucial in achieving climate goals. There are many pathways to achieve CDR, such as planting trees, “blue carbon”, and engineered direct air capture.

Carbon durability/longevity/permanence: Durability, longevity and permanence are terms that refer to the duration of carbon storage or sequestration and removal from the global carbon cycle. A durable or permanent method of storing or sequestering carbon suggests a meaningful removal or reduction of carbon emissions, and is often defined in terms of decades or centuries.

Carbon leakage: Carbon leakage occurs when a company moves its production activities from a country with strict climate policies to a country with more lenient emissions policies, leading to an increase in greenhouse gas emissions. It can also refer to the phenomena when policies that curtail emissions in one geopolitical region might increase emissions in another through the transfer of emission-intensive production across borders via international trade.

Carbon offsets and credits: Companies can purchase carbon offsets on the voluntary carbon market, which represent an amount of CO_2 removed from the atmosphere, to help them meet emissions targets. Carbon offsets go toward actions that reduce emissions or contribute to carbon storage or sequestration. Carbon credits are earned in the compliance market, where regulated entities obtain and surrender emissions permits (allowances) or offsets in order to meet predetermined regulatory targets.

Carbon sequestration: The process of capturing and then storing atmospheric CO_2 is known as carbon sequestration. Reducing the amount of CO_2 in the atmosphere can aid in reducing global climate change. Biological carbon sequestration occurs when carbon captured by biological organisms, such as seaweeds and seagrasses, is transferred to a pool that is not readily released back into the global carbon cycle; e.g., carbon is stored in deep-sea marine layers, in sediments, or in recalcitrant forms of carbon that do not re-enter the global cycle.

Carbon uptake/drawdown: Carbon uptake is the addition of carbon to a carbon pool or reservoir, which can be manmade (such as a cement-based product) or natural (such as the oceans or plants during photosynthesis). Carbon drawdown, also known as carbon removal, is the process of capturing CO_2 from the atmosphere and placing it in carbon storage.

Dipole-dipole forces/interactions: Attractive forces between the positive end of one polar molecule and the negative end of another, nearby polar molecule.

Ecological carrying capacity: The maximum population size of a biological species that can be sustained by that specific environment, given the food, habitat, water, and other resources available.

Eutrophication: Eutrophication occurs when bodies of water become overly enriched by nutrients such as nitrogen and phosphorus and other organic matter, increasing plant and algal growth. The results of eutrophication include harmful algal blooms, dead zones in which the environment lacks the requisite oxygen to sustain life and fish kills.

Exclusive economic zone (EEZ): An area of the ocean, generally extending 200 nautical miles (230 miles) beyond a nation's territorial sea, within which a coastal nation has jurisdiction over both living and nonliving resources. The EEZ starts at the edge of the territorial sea.

Harmonized system code: a universal economic language and code for goods, used as a tool for communicating in international trade

Heat dome: A hot mass of air that develops when high pressure prevents warm air below from rising, thus trapping the warm air in a dome. Heat domes can persist for days to weeks and extend across entire regions.

High-integrity voluntary carbon credit markets: In a voluntary carbon credit market (VCM), buyers and sellers exchange carbon offset credits that represent greenhouse gas removed from the atmosphere. High-integrity VCMs are VCMs that drive decarbonization, and in which the carbon credits represent real, verifiable emissions reductions beyond what would have otherwise occurred and include socioeconomic considerations and equity.

Hot spot: When used in the context of biodiversity, a hot spot is an area characterized by a significant number of native species and by high levels of habitat loss.

Hypoxia: In ocean and freshwater environments, the term "hypoxia" refers to low or depleted oxygen in a water body. Hypoxia is often associated with the overgrowth of certain species of algae, which can lead to oxygen depletion when they die, sink to the bottom, and decompose.

Kelp: Kelp are large brown algae (Phaeophyta) that live in cool, shallow, subtidal waters close to shore. They grow in dense groupings resembling forests on land and are found all over the world. There are about 30 species of kelp worldwide. Rockweeds are sometimes misnamed and marketed as kelp, but they are not in the order Laminariales, and are not considered 'true' kelp.

Labile carbon: Labile carbon comprises the portion of soil's, marine sediments, freshwater, or seawater's total organic carbon with the most rapid turnover and decomposition times. Through oxidation, labile carbon drives the transference of carbon dioxide between these media and the atmosphere. This is the highly reactive fraction of organic carbon with the most rapid turnover times (days to weeks). Its oxidation drives the flux of CO_2 between the atmosphere and soils, sediments, and the water column.

Life cycle assessment (LCA): Life cycle assessment is the process of evaluating the effects a product, material, process, or other measurable activity has on the environment over its entire life cycle, from 'cradle' to 'grave', or from product manufacturing through packing and distribution, use, and waste management.

Life cycle inventory (LCI): A phase of life cycle assessment that involves quantifying and documenting in a database the emissions and use of resources for each process in a given product, material, or activity.

Macroalgae: Seaweeds, or marine macroalgae, are large, macroscopic, generally multicellular photosynthetic organisms that live in the ocean. They include roughly 11,000 species[307] from three unique phyla, generally distinguished based upon color (a reflection of their unique photosynthetic pigments). The red (phylum Rhodophyta)

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[307] M.D. Guiry and G.M. Guiry, AlgaeBase: World-wide electronic publication, National University of Ireland, Galway, accessed January 19, 2024, https://www.algaebase.org.

and green (phylum Chlorophyta) seaweeds belong to the Kingdom, Plantae and are the most diverse groups, with roughly 7,000 and 2,500 taxa, respectively. The brown seaweeds (phylum Ochrophyta, class Phaeophyceae) belong to the Kingdom, Chromista and include around 2,000 currently recognized species. In addition to their unique color and pigmentation, these seaweed phyla have vastly different cellular components, biochemistry, reproductive characteristics, evolutionary origins and commercial applications. Collectively, the term "macroalgae" represents a broader swath of the tree of life than plants and animals combined.

Macrophyte: Macrophytes are large, photosynthetic organisms visible to the naked eye that grow in or near water. Macrophytes may be completely submerged, floating or include some upright portions above the water's surface. The term "macrophyte" encompasses a diverse range of organisms, including macroalgae and small angiosperms, and is a broader term than submerged aquatic vegetation.

Mariculture: Mariculture is the cultivation of aquatic organisms in marine and estuarine waters. Mariculture is distinct from aquaculture, which can also take place in freshwater environments.

Mesocosm: A simulated, controlled laboratory setting environmental scientists design to measure the effects of certain manipulations on an ecosystem. In the context of oceanography, mesocosms can range in size from 10s – 1000s liters.

Ocean deacidification: Atmospheric CO_2 reacts with surface water in the ocean to make carbonic acid, which releases H^+ ions and lowers the pH of the surface seawater, thus acidifying the ocean. The uptake of CO_2, by seaweeds and seagrasses, during the natural process of photosynthesis, reduces the accumulation of H^+ ions, locally and ephemerally increasing the pH of ocean water in a process called ocean deacidification.

Ocean/seaweed gardening: By creating new habitat, modifying existing habitat or transplanting species to new shallow coastal areas, indigenous peoples increased the availability of both plants—root crops and algae—and animals. Many traditional aquaculture practices include seaweed and shellfish gardening, which involves the maintenance of sites opportune for growth and harvest of key species near Indigenous communities.

Oligotrophic oceans: An area of the open ocean with a deficiency of nutrients, usually accompanied by an abundance of dissolved oxygen. The open ocean is called a "marine desert" because it has low biological productivity due to this nutrient scarcity and due to stratification, which reduces the supply of nutrients to surface waters, hence supporting fewer lifeforms than other areas.

Phytoremediation: A bioremediation strategy using algae or plants and associated soil microbes to reduce the concentrations or toxic effects of contaminants in the environment, including in marine systems. Phytoremediation is widely accepted as a cost-effective environmental restoration technology.

Recalcitrant carbon: The portion of organic matter in soils, marine sediments, freshwater, or seawater that is resistant to microbial decomposition and is not considered "labile". Pools of recalcitrant carbon can be considered as 'sequestered' if the longevity is sufficient to qualify as removal from the global carbon system; refractory carbon is synonymous with recalcitrant carbon

Remineralized carbon: Remineralized carbon is the result of organic carbon decomposing into smaller organic material, then further decomposing into dissolved inorganic carbon, much of which is labile and renters the global carbon cycle as other living micro-organisms can then reuse remineralized carbon for energy. This is also known as the dissolved inorganic carbon (DIC) that is a product of the decomposition (recycling) of organic carbon as dead cells or metabolites into smaller organics that are further degraded to mineral carbon.

Seagrasses: Seagrasses are a group of marine angiosperms (true flowering plants) that evolved from land plants and reestablished themselves in marine environments around 100 million years ago. Seagrasses are a type of submerged aquatic vegetation.

Seaweed farming: While regulations vary from state to state, seaweed farming generally involves collecting wild sorus (reproductive) tissue from a macroalga that is cultivated on land in a seaweed nursery. This “seed” is then applied to twine that is out-planted on long ropes at permitted aquaculture lease sites in accordance with each state’s department of marine resources, or equivalent, agency. Seaweed remains on the farm to grow to harvestable size and is then cut from the long lines and brought to shore. Other forms of seaweed farming include providing substrata to recruit wild “seed,” as in mussel and sea scallop farming. Some First Nations construct rocky reefs to encourage specific seaweed species to settle and grow (see Ocean gardening definition).

Seaweed wild harvesting: While regulations vary from state to state, and in accordance with treaties and agreements with some First Nations the wild harvest of seaweeds is when naturally occurring subtidal or intertidal macroalgal tissue is trimmed, usually leaving the meristematic tissue to allow for regrowth the next season. Most states require commercial harvesting licenses; there are restrictions on certain species and all harvesters must comply with area closures and random inspections by the regulating agency.

Social license to operate (SLO): The ongoing acceptance of a company or industry’s standard business practices and operating procedures by its employees, stakeholders, and the general public.

Standing stock: Standing stock is the total weight in biomass of a group of living organisms in a given area.

Submerged aquatic vegetation: Submerged aquatic vegetation (SAV) refers to rooted, vascular plants that grow completely underwater, except when briefly exposed to air at low tides. SAV includes seagrasses and attached epiphytic macroalgae, but is distinct from macroalgae or seaweed because it reproduces through pollination and has a vascular system that transports nutrients between the sediment, roots and leaves. SAV serves as a habitat and a source of food and energy for thousands of fish, invertebrates and other aquatic species.

Territorial sea: a belt of coastal waters that extends from the baseline to 12 nautical miles. It is a sovereign territory of the state. However, foreign ships, both civilian and military, are permitted ‘innocent passage’ through it. The sovereignty also includes the seabed below and the airspace above. The coastal state has the rights to: explore and exploit, conserve and manage the natural resources (living or non-living); produce energy from wind, currents and water; establish and use artificial islands, structures and installations; conduct marine scientific research, and protect and preserve the marine environment.

C. Seagrass and Seaweed Species and Common and Traditional Names

The list of species provided here (**Table 14**) is not exhaustive – it includes only the species mentioned in this report, and those at the ‘top’ of the U.S. seaweed farming list.

Table 14. Species of seagrasses and seaweeds mentioned in this report (may be from outside of the U.S.) and at the topmost restored or farmed in the U.S.

SEAGRASSES

Latin Name	Top Common and Traditional Names	Distribution	Native/Introduced/ Invasive to U.S.
Enhalus acoroides	Tape seagrass	Pacific Islands	Native
Halodule uninervis	Narrowleaf seagrass	Pacific Islands	Native
Halodule wrightii	Shoalgrass	Atlantic, Gulf of Mexico	Native
Halophila baillonii	Clovergrass	Caribbean Islands	Native
Halophila decipiens	Caribbean seagrass, paddlegrass	Atlantic, Gulf of Mexico	Native
Halophila engelmanni	Stargrass	Atlantic, Gulf of Mexico	Native
Halophila gaudichaudii		Pacific Islands	Native
Halophila johnsonii	Johnson’s seagrass	Atlantic	Introduced
Halophila ovalis	Paddleweed	Atlantic	Introduced
Halophila stipulacea	Broadleaf seagrass, halophia seagrass	Caribbean Islands	Invasive
Phyllospadix scouleri	Scouler’s surfgrass, surfgrass	Pacific	Native
Phyllospadix serrulatus	Toothed surfgrass, serrated surfgrass	Pacific	Native
Phyllospadix torreyi	Torrey’s surgrass	Pacific	Native
Ruppia maritima	Wigeongrass	Atlantic, Gulf of Mexico, Pacific	Native
Syringodium filiforme	Manatee grass	Atlantic, Gulf of Mexico	Native
Syringodium isoetifolium	Noodlegrass	Pacific Islands	Native
Thalassia testudinum	Turtlegrass	Atlantic, Gulf of Mexico	Native
Zostera japonica	Japanese eelgrass, dwarf eelgrass	Pacific	Invasive
Zostera marina	Eelgrass	Atlantic, Pacific	Native

BROWN MACROALGAE

Latin Name	Top Common and Traditional Names	Distribution	Native/Introduced/ Invasive to U.S.
Alaria esculenta	Winged kelp, “Alaria”	Atlantic, Pacific	Native
Alaria marginata	Ribbon kelp, Kapuustat, Nuya’it, Qahngut, “Alaria”e	Pacific	Native
Ascophyllum nodosum	Rockweed, “Asco”, Knotted wrack	Atlantic	Native
Laminaria digitata	Horsetail kelp, “Digitata”	Atlantic	Native
Laminaria hyperborea	Cuvie, Forest Kelp, Sea rods	Atlantic	Not in U.S.
Macrocystis pyrifera	Giant kelp	Pacific	Native
Nereocystis luetkeana	Bull kelp, Nasquluq, Qahhguq	Pacific	Native
Saccharina angustissima	Skinny or strap kelp	Atlantic	Native
Saccharina latissima	Sugar kelp, Kombu	Atlantic, Pacific	Native

BROWN MACROALGAE

Latin Name	Top Common and Traditional Names	Distribution	Native/Introduced/ Invasive to U.S.
Sargassum fluitans	Golden tide, “Fluitans”	Atlantic	Native
Sargassum natans	Golden tide, “Natans”	Atlantic	Native
Undaria pinnatifida	Wakame, “Undaria”	Pacific	Native

GREEN MACROALGAE

Latin Name	Top Common and Traditional Names	Distribution	
Caulerpa racemosa	“Caulerpa”	Atlantic	Native (other species are invasive in parts of the U.S.)
Ulva lactuca	Sea lettuce	Atlantic, Pacific	Native

RED MACROALGAE

Latin Name	Top Common and Traditional Names	Distribution	
Asparagopsis armata	Harpoon weed	Pacific	Introduced
Asparagopsis taxiformis	Kohu koko	Pacific	Native
Chondrus crispus	Irish moss	Atlantic	Native
Eucheuma denticulatum	Spinosum	Pacific	Introduced
Gracilaria mammillaris		Atlantic	Native
Gracilaria tikvahiae	Graceful redweed	Atlantic	Native
Gracilaria vermiculophylla		Atlantic, Pacific	Native
Kappaphycus alvarezii.		Pacific	Introduced
Palmaria palmata	Dulse	Atlantic	Native
Porphyra umbilicalis	Laver	Atlantic	Native

Appendix 1. Seagrasses and Seaweeds Natural History

Contributing Authors: Aurora Ricart, Jennifer E. Smith, and Charlotte Quigley,

1. Biology

Seagrasses and seaweeds are marine vegetative organisms that use photosynthesis to grow. As they grow, they serve as foundational species creating coastal habitats. They form the base of complex food webs and function as nursery areas for juvenile fish and crustaceans. Seagrasses and seaweeds both provide additional ecosystem services such as erosion prevention, nutrient bioremediation and ocean deacidification. There are, however, noteworthy botanical differences between these two groups of macrophytes. Seagrasses are considered submerged aquatic vegetation, which include various submerged monocot true plants (such as eelgrass, tape grass and turtle grass) that grow, often in dense meadows, in tropical to temperate shallow coastal waters. As true flowering plants, having evolved from their land-based ancestors around 100 million years ago, they are fully adapted to a saline environment. They have roots and rhizomes that anchor them to the seafloor and absorb nutrients as well as leaves that shoot up toward the surface (**Figure 25**). By comparison, seaweeds, also known as macroalgae, are an evolutionarily diverse group of marine multicellular organisms that can be found floating or attached to the seafloor. They have a simple anatomical structure that differs from the roots, stems, branches and leaves found on most land plants. The seaweed's entire structure is called the thallus, and the leaf-like portion is called the blade, which enables them to absorb nutrients, and some blades have a vein called the midrib. The stem-like portion of seaweed is called the stipe, and the root-like structure is the holdfast. A holdfast is notably different from a plant root in that it attaches the seaweed to the substrate but does not take up nutrients.

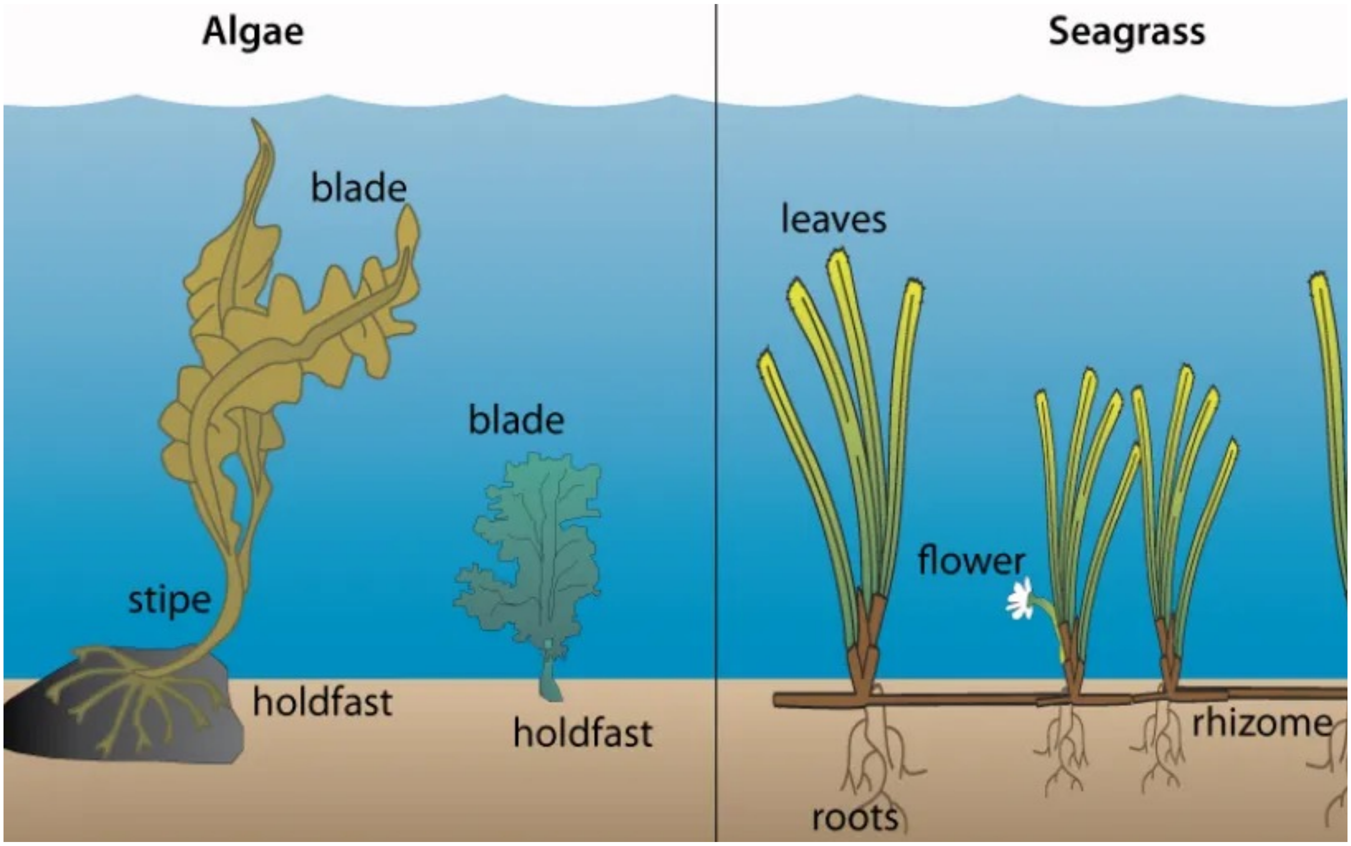

Figure 25. Reprinted from the Smithsonian Ocean *https://ocean.si.edu/holding-tank/images-hide/algae-vs-seagrass*.

Seagrasses have a very different life cycle than seaweeds. Seagrasses reproduce both sexually and asexually.[308] Sexual reproduction happens through the underwater pollination of seagrass flowers that then generate fruits and seeds which disperse and originate genetically different individuals.[309] Asexual reproduction happens via vegetative propagation, in which the rhizomes elongate and generate new seagrass shoots with the same genetic make-up. Because of their clonal growth, seagrasses are considered among the oldest living organisms on Earth, with some individuals documented to be up to 200,000 years old.[310]

Seaweeds differ from true plants—like seagrasses—in many fundamental ways. First, having evolved in an aquatic environment, they lack the constraints associated with gravity and, as such, have much more diverse growth forms than their land-based counterparts. Most seaweeds have a holdfast, or hair-like rhizoids, which attaches them to the benthos. Other, more complex, seaweeds have blades, fronds, stipes, pneumatocysts or air bladders that help them stay vertical or upright in the water column. Seaweeds generally lack true tissues and organs (e.g., leaves, roots and stems) and instead have highly variable body plans. The general thallus, or seaweed body, can be made of simple filaments; sheets; fern-like fronds; and lacy, flat, cylindrical or branched blades, while other seaweeds, such as giant kelp, have more complex body forms and tissue layers with features that resemble terrestrial plants. Seaweeds can absorb water and nutrients throughout their entire body and most cells can photosynthesize.[311] Reproduction also differs vastly between true plants and seaweeds. Reproduction in seaweeds does not involve flowers or seeds and is generally considered complex, involving multiple life stages (that look identical or completely different from one another) and the production of spores or gametes which are released into the seawater.

Many things separate seaweeds from their terrestrial counterparts, but both groups are immensely important for maintaining biodiversity by creating habitats and providing shelter for many species, as well as acting as a food source and playing a key role in carbon cycling and oxygen production. Interest in seaweeds, in particular, is increasing due to their enormous commercial potential as a source of human food, animal feed, biofuel, bioplastics, fertilizers, pharmaceuticals, methane mitigation when fed to livestock and potentially carbon storage in the deep sea and marine sediments. Seaweeds will certainly play an important role in helping global societies reach a carbon-neutral future.[312]

In essence, while seaweeds are akin to floating forests, seagrasses are the marine equivalent of terrestrial grasslands, and each enrich the ocean floor with their ecological significance and beauty.

2. Ecology

Seagrasses are habitat-forming species that grow as meadows and are among the most important coastal habitats for marine life, being equivalent to coral reefs, mangroves, salt marshes and macroalgal beds. Worldwide there are around 70 seagrass species that occur in depths ranging from 0 meters up to 70 meters[313] in tropical to subpolar areas, on soft and rocky bottoms, and in estuarine and open coast regions.[314] The depth limit of seagrasses is largely attributable to differences in light attenuation, as seagrasses have high light requirements to maintain the

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[308] Brigitta I. Van Tussenbroek et al., "Experimental Evidence of Pollination in Marine Flowers by Invertebrate Fauna," *Nature Communications* 7, no. 12980 (2016): 1–6.

[309] Paul A. Cox, "Hydrophilous Pollination," *Annual Review of Ecology and Systematics* 19 (1988): 261–79.

[310] S. Arnaud-Haond et al., "Assessing Genetic Diversity in Clonal Organisms: Low Diversity or Low Resolution? Combining Power and Cost Efficiency in Selecting Markers," *Journal of Heredity* 96, no. 4 (2005): 434–40.

[311] Linda E. Graham, James M. Graham, and Lee Warren Wilcox, *Algae* (San Francisco: Benjamin Cummings, 2009).

[312] Catriona L. Hurd et al., *Seaweed Ecology and Physiology* (Cambridge: Cambridge University Press, 2014).

[313] D.A. Jones, M. Ghamrawy, and M.I. Wahbeh, "Littoral and Shallow Subtidal Environments," in *Red Sea*, ed. A.J. Edwards and S.M. Head (Oxford: Pergamon Press, 1987), 169–93; and Carlos M. Duarte, "Seagrass Depth Limits," *Aquatic Botany* 40, no. 4 (1991): 363–77.

[314] Edmund P. Green and Frederick T. Short, eds., *World Atlas of Seagrasses* (Berkeley: University of California Press, 2003).

non-photosynthetic biomass (roots and rhizomes) in sediments. Some species of seagrasses are fast-growing colonizers, while others are slow-growing perennials.[315]

Seagrass meadows provide multiple ecosystem services,[316] and are hot spots of biodiversity offering crucial habitat and shelter for a multitude of organisms, and as nurseries for fish making them essential habitat supporting commercial fisheries, tourism and recreation.[317] As photosynthetic organisms, seagrasses sequester carbon and oxygenate the water,[318] and their primary productivity supports both herbivorous and detritivore organisms, contributing to coastal food webs and carbon transfer.[319] Additionally, seagrass root systems help stabilize sediments; protect the coast from erosion caused by wave action, storms and hurricanes.[320] Seagrasses help improve water quality by trapping sediments and absorbing nutrients, effectively acting as natural water filters that can also reduce pathogens.[321] Seagrasses are prolific carbon sinks, capturing and storing substantial amounts of carbon from the atmosphere in their tissues and burying it in the sediment.[322]

In summary, seagrasses are vital components of virtually every coastal ecosystem, providing ecological, economic and cultural benefits. Their unique biological characteristics and ecological functions make seagrasses crucial for the health and sustainability of coastal environments worldwide. Conservation and restoration efforts are essential for protecting the world's valuable underwater seagrass meadows.

Seaweeds generally grow much faster than terrestrial plants, with giant kelp growing up to 2 feet per day (0.0002 miles per hour). As such, seaweeds serve as the base of marine food webs, providing fixed carbon in the form of carbohydrates to numerous fish and invertebrate species. Seaweeds also create three-dimensional structures and provide a diversity of habitats in marine environments around the world. Some seaweeds produce calcium carbonate in or around their cell walls, which contributes to carbonate cycling. One green algal genus, *Halimeda*, is known for producing most of the sand in some tropical locations.[323] Other crustose coralline algae act as a glue, and are important reef-builders, which help to bind and stabilize loose reef fragments.[324] Some seaweeds are known for producing chemical compounds that induce settlement by larval marine invertebrates including corals,[325] urchins[326] and abalone,[327] and thus facilitate the growth and success of other marine species.

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[315] Larkum, Orth, and Duarte, *Seagrasses*, 1–691.

[316] L. Mtwana Nordlund et al., "Seagrass Ecosystem Services and Their Variability across Genera and Geographical Regions," *PLoS One* 11, no. 10 (2016).

[317] K.L. Heck Jr., G. Hays, and R.J. Orth, "Critical Evaluation of the Nursery Role Hypothesis for Seagrass Meadows," *Marine Ecology Progress Series* 253 (2003): 123–36; and Richard K.F. Unsworth, Lina Mtwana Nordlund, and Leanne C. Cullen-Unsworth, "Seagrass Meadows Support Global Fisheries Production," *Conservation Letters* 12, no. 1 (2019).

[318] Marten A. Hemminga and Carlos M. Duarte, *Seagrass Ecology* (Cambridge: Cambridge University Press, 2000).

[319] J. Emmett Duffy, "Biodiversity and the Functioning of Seagrass Ecosystems," *Marine Ecology Progress Series* 311 (2006): 233–50; and Glenn A. Hyndes et al., "Mechanisms and Ecological Role of Carbon Transfer within Coastal Seascapes," *Biological Reviews of the Cambridge Philosophical Society* 89, no. 1 (2014): 232–54.

[320] Barbara Ondiviela et al., "The Role of Seagrasses in Coastal Protection in a Changing Climate," *Coastal Engineering* 87 (2014): 158–68.

[321] Joleah B. Lamb et al., "Seagrass Ecosystems Reduce Exposure to Bacterial Pathogens of Humans, Fishes, and Invertebrates," *Science* 355, no. 6326 (2017): 731–33.

[322] Hilary Kennedy et al., "Seagrass Sediments as a Global Carbon Sink: Isotopic Constraints," *Global Biogeochemical Cycles* 24, no. 4 (2010): GB4026; and James W. Fourqurean et al., "Seagrass Ecosystems as a Globally Significant Carbon Stock," *Nature Geoscience* 5 (2012): 505–9.

[323] E.A. Drew, "*Halimeda* Biomass, Growth Rates and Sediment Generation on Reefs in the Central Great Barrier Reef Province," *Coral Reefs* 2 (1983): 101–110.

[324] C.E. Cornwall et al., "Crustose Coralline Algae Can Contribute More Than Corals to Coral Reef Carbonate Production," *Communications Earth & Environment* 4, no. 105 (2023).

[325] H. Jorissen et al., "Coral Larval Settlement Preferences Linked to Crustose Coralline Algae with Distinct Chemical and Microbial Signatures," *Scientific Reports* 11 (2021).

[326] B.A. Twist et al., "Kelp and Sea Urchin Settlement Mediated by Biotic Interactions with Benthic Coralline Algal Species," *Journal of Phycology* (2023).

[327] G.C. De Viçose et al., "Larval Settlement, Early Growth and Survival of Haliotis tuberculata coccinea Using Several Algal Cues," *Journal of Shellfish Research* 31, no. 4, (2013): 1189–98.

Seaweeds are highly nutritious and are known for producing up to 10 times more vitamins and minerals than leafy green vegetables while also providing a large amount of fiber and many proteins.[328] Humans have harvested seaweeds for thousands of years for food, medicine and ceremony.[329] In addition to their nutritional benefits, seaweeds have a remarkable capacity to take up and absorb toxins, heavy metals and other pollutants from seawater and have been used as a tool for bioremediation.[330] Seaweeds naturally, through the process of photosynthesis, take up CO_2, raise the pH of seawater during the day and produce vast amounts of oxygen.[331] As such, researchers are exploring seaweeds' potential to buffer against OA and sequester carbon (i.e., blue carbon potential). Some seaweeds have even shown promise as a methane-mitigating supplement in the highly carbon-intensive livestock industry by reducing methane emissions in cow burps by up to 95%.[332] Seaweeds can be used to make biofuel and bioplastics and are an important resource for drug discovery and biomedicine.[333] In sum, seaweeds are a critical component of natural marine ecosystems and are becoming increasingly valuable in human societies for their diversity of uses. Seaweeds will clearly play a role in a sustainable future.

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[328] P. MacArtain et al., "Nutritional Value of Edible Seaweeds," *Nutrition Reviews* 65, no. 12 (2007): 535–43.

[329] J.L. Pérez-Lloréns, "Seaweed Consumption in the Americas," *Gastronomica* 19, no. 4 (2019): 49–59.

[330] Michael Y. Roleda and Catriona L. Hurd, "Seaweed Nutrient Physiology: Application of Concepts to Aquaculture and Bioremediation," *Phycologia* 58, no. 5 (2019): 552–62.

[331] X. Xiao et al., "Seaweed Farms Provide Refugia from Ocean Acidification," *Science of the Total Environment* 776 (2021).

[332] B.M. Roque et al., "Red Seaweed (*Asparagopsis taxiformis*) Supplementation Reduces Enteric Methane by Over 80 Percent in Beef Steers," *PLoS One* 16 (2021).

[333] M. Farghali et al., "Seaweed for Climate Mitigation, Wastewater Treatment, Bioenergy, Bioplastic, Biochar, Food, Pharmaceuticals, and Cosmetics: a Review," *Environmental Chemistry Letters* 21, no. 1 (2023): 97–152.

Appendix 2. Remote Sensing Tools Summary

Contributing Author: Tom Bell

The first use of remotely sensed imagery to quantify harvestable seaweed canopy biomass was developed in the early-2000s using high resolution aerial multispectral imagery paired with diver surveys.[334] This was quickly followed by the development of a spectral unmixing method to estimate the biomass of kelp canopies from multispectral satellite imagery across a variety of seawater conditions,[335] made possible by a decade of diver-based biomass measurements by the Santa Barbara Coastal Long Term Ecological Research project[336] and the advent of the freely available catalog of multispectral Landsat imagery.[337] Hu (2009) developed the Floating Algal Index to detect the distribution of floating *Sargassum* in the western Atlantic.[338] This method utilizes low spatial, but high temporal, resolution imagery from a Moderate Resolution Imaging Spectroradiometer (and other ocean color satellite sensors) to track the large rafts of *Sargassum* that are carried by ocean currents and provide timely warnings to coastal communities threatened by the massive beach depositions of this seaweed that have increased over the past decade.[339] As new, daily high-resolution Cubesat[340] constellations are developed, there are increased opportunities to determine standing stocks of both canopy-forming kelps and floating *Sargassum* using novel classification techniques.[341]

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[334] M.S. Stekoll, L.E. Deysher, and M. Hess, "A Remote Sensing Approach to Estimating Harvestable Kelp Biomass," *Journal of Applied Phycology* 18 (2006): 323–34.

[335] K. Cavanaugh et al., "Environmental Controls of Giant-Kelp Biomass in the Santa Barbara Channel, California,*" Marine Ecology Progress Series* 429 (2011): 1–17.

[336] A. Rassweiler et al., "Improved Estimates of Net Primary Production, Growth, and Standing Crop of *Macrocystis pyrifera* in Southern California," *Ecology* 99, no. 9 (2018): 2132.

[337] C.E. Woodcock et al., "Free Access to Landsat Imagery," *Science* 320, no. 5879 (2008): 1011.

[338] C. Hu, "A Novel Ocean Color Index to Detect Floating Algae in the Global Oceans," *Remote Sensing of Environment* 113, no. 10 (2009): 2118–29.

[339] M. Wang et al., "The Great Atlantic *Sargassum* Belt," *Science* 365, no. 6448 (2019): 83–87.

[340] Katherine C. Cavanaugh et al., "CubeSats Show Persistence of Bull Kelp Refugia Amidst a Regional Collapse in California," *Remote Sensing of Environment* 290 (2023).

[341] M. Wang and C. Hu, "Satellite Remote Sensing of Pelagic *Sargassum* Macroalgae: The Power of High Resolution and Deep Learning," *Remote Sensing of Environment* 264 (2021); and Cavanaugh et al., "CubeSats Show Persistence."

Appendix 3. Seagrasses Genetic Connectivity

Contributing Authors: Katherine DuBois, Nate L'Esperance, Christopher Oakes, Madeline Pomicter, and Aurora Ricart,

Connectivity across populations of seagrass meadows—via seed dispersal and vegetative spread within meadows—determines how resilient meadows are to disturbance, rates of recolonization after meadow loss and the spatial scale needed to manage interconnected populations properly.[342] The study of population genetics, which examines the genetic variation within and among populations of an organism, provides valuable insights into evolutionary processes that both preserve genetic diversity and influence species' adaptive capacities. In seagrasses, the genetic variation within and among populations is determined by the dispersal of pollen and seeds across meadows as well as by the rate of clonal reproduction via vegetative branching.[343] The life histories of different seagrass species determine the potential dispersal distances and gene flow among meadows. Many temperate seagrasses (such as eelgrass) produce many dormant, negatively buoyant seeds that disperse only across a few meters.[344] Consequently, genetic differentiation across eelgrass meadows is estimated to be on the scale of <100 kilometers,[345] and local adaption of eelgrass meadows separated by <10 kilometers can determine the survival of transplants.[346] In contrast, many tropical seagrasses (such as turtlegrass) produce nondormant seeds in buoyant fruit that can disperse across 10s of kilometers, and genetic differentiation across such species is estimated to occur at distances of >350 kilometers.[347] These distances are averages and actual connectivity across seagrass populations is strongly influenced by coastal bathymetry and ocean currents.[348] In addition to sexually reproducing by seeds, seagrass individuals can spread vegetatively, producing clonal networks that are among the oldest living organisms on Earth and are up to 15 kilometers long.[349]

On local spatial scales, genome-wide associations with eelgrass traits linked to warming resilience reveal specific genes responsible for eelgrass's local adaptation to high temperatures.[350] Maintaining genetic diversity within eelgrass populations to preserve eelgrass's adaptive capacity is critical, as within-population genetic diversity is directly linked to a meadows' resilience to disturbance.[351] Fortunately, actively restoring eelgrass meadows by seeding can enhance the recovery rate of meadows' genetic diversity by almost twentyfold.[352]

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[342] Kendrick et al., "Demographic and Genetic Connectivity."

[343] G.A. Kendrick et al., "Demographic and Genetic Connectivity: The Role and Consequences of Reproduction, Dispersal and Recruitment in Seagrasses," *Biological Reviews* 92, no. 2 (2017): 921–38.

[344] M.H. Ruckelshaus, "Estimation of Genetic Neighborhood Parameters from Pollen and Seed Dispersal in the Marine Angiosperm Zostera Marina L," *Evolution* 50, no. 2 (1996): 856–64.

[345] J. L. Olsen et al., "North Atlantic Phytogeography and Large-Scale Population Differentiation of the Seagrass Zostera Marina L," *Molecular Ecology* 13, no. 7 (2004): 1923.

[346] K. DuBois et al., "Local Adaptation in a Marine Foundation Species: Implications for Resilience to Future Global Change," *Global Change Biology* 28, no. 8 (2022): 2586–610.

[347] K. van Dijk et al., "High Levels of Gene Flow and Low Population Genetic Structure Related to High Dispersal Potential of a Tropical Marine Angiosperm," *Marine Ecology Progress Series* 390 (2009): 67.

[348] U.E. Hernawan et al., "Historical Processes and Contemporary Ocean Currents Drive Genetic Structure in the Seagrass Thalassia Hemprichii in the Indo-Australian Archipelago," *Molecular Ecology* 26, no. 4 (2017): 1008–21.

[349] S. Arnaud-Haond et al., "Implications of Extreme Life Span in Clonal Organisms: Millenary Clones in Meadows of the Threatened Seagrass Posidonia Oceanica," *PLoS One* 7, no. 2 (2012).

[350] L.M. Schiebelhut et al., "Genomic Responses to Parallel Temperature Gradients in Eelgrass Zostera Marina in Adjacent Bays," *Molecular Ecology* 32 (2023): 2825–49.

[351] T.B.H. Reusch et al., "Ecosystem Recovery after Climatic Extremes Enhanced by Genotypic Diversity," *Proceedings of the National Academy of Sciences* 102, no. 8 (2005): 2826–31.

[352] L.K. Reynolds, M. Waycott, and K.J. McGlathery, "Restoration Recovers Population Structure and Landscape Genetic Connectivity in a Dispersal-Limited Ecosystem," *Journal of Ecology* 101, no. 5 (2013): 1288–97.

Appendix 4. Seagrass Restoration Techniques

Contributing Authors: Jonathan Lefcheck, Robert J. (J.J.) Orth, Aurora Ricart, and Rachel Sipler

The restoration of seagrass meadows not only rejuvenates critical marine habitats but also leaves behind a legacy of carbon removal and storage. By enhancing seagrass resilience and expanding seagrass coverage, we can meaningfully contribute to offsetting carbon emissions and mitigating the impacts of climate change on future generations. The process for successfully restoring seagrass relies on several stages (**Figure 26**), and can be subject to many failure points.

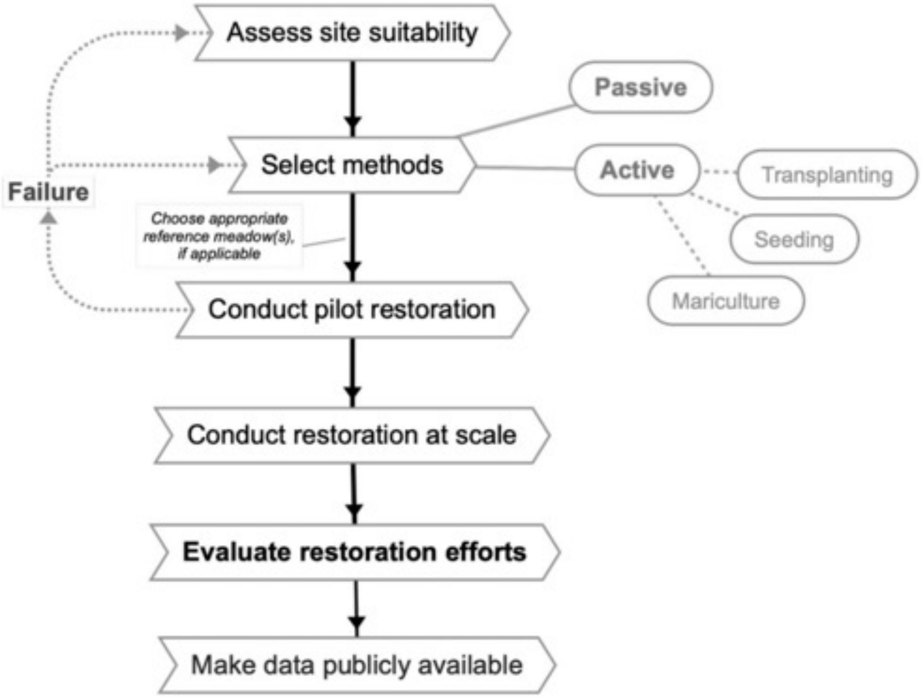

Figure 26. Restoration approach to minimize uncertainty and maximize the likelihood of meeting project goals. Figure modified from Ward and Behesti (2023)[353]:

Common reasons of failure of seagrass restoration efforts:

- No removal of anthropogenic stressors that caused the decline
- Inappropriate site selection
- The uprooting of transplants due to inadequate anchorage, bioturbation or strong flows, high wave energy or swell
- Sediment instability causing erosion or smothering and burial of seedlings
- Poor water quality (turbidity, eutrophication, low light)
- Algal blooms and/or excessive epiphyte growth
- Too shallow (desiccation) or too deep (insufficient light)
- (Over)grazing of transplants (e.g., by sea urchins or amphipods)
- Disease (e.g., fungal attack on seeds or seedlings)
- Too small scale (poor resilience, insufficient self-facilitation)
- Lack of donor material or seed stock (e.g., no flowering)

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[353] Ward, M., & Beheshti, K. (2023). Lessons learned from over thirty years of eelgrass restoration on the U.S. West Coast. *Ecosphere*, *14*(8), e4642.

- Damage from human activities, storms, floods or spills
- Large-scale application of unproven technology (insufficient testing)
- Unrealistic expectations (re: costs, scale, duration, chances of success)

It was recently estimated that the amount of funding allocated for the restoration of blue carbon ecosystems, including seagrasses, is about 2.5x less than necessary to meet biodiversity targets.[354] Thus, in addition to further investments, innovations in methodology (e.g., **see Fig. 27**) and design that will enable more efficient restorations will be necessary. Past advances include guidelines for seagrass restoration,[355] incorporating seeds rather than adult plants,[356] positive interactions in restoring seagrasses,[357] multiple plantings of different species,[358] or modifying planting designs by clumping plants to ameliorate physical stresses.[359] Future advances may include incorporating animals to enhance restoration outcomes,[360] and the development of land- or water-based nurseries and nursery networks to industrially scale seed and adult plant production to avoid lasting impacts to existing seagrass beds.

In 2024, the National Parks Service funded an initiative to restore eelgrass across five National Seashores ranging from North Carolina to Massachusetts, where successful restorations rates are the highest (**Fig. 28**), with the specific aim of building climate resilience into this cool-water species. The effort will identify heat-tolerant populations and transport and plant their seeds up the coast in a process known as "assisted gene flow," a method that has been successful in buffering corals, forests, and other systems against increasing temperatures. Key impediments to this effort include a lack of regulatory and permitting framework as well as facilities to hold and store seeds from multiple source populations. Generally, seagrass restoration will benefit from improved and coordinated monitoring and data sharing among practitioners and agencies.

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[354] Fu, Chuancheng, et al. "Achieving the Kunming–Montreal global biodiversity targets for blue carbon ecosystems." Nature Reviews Earth & Environment (2024): 1-15.

[355] Short, F.T., R.C. Davis, B.S. Kopp, C.A. Short, and D.M. Burdick. 2002. Site-selection model for optimal transplantation of eelgrass *Zostera marina* in the northeastern US. *Marine Ecology Progress Series* 227: 253–267.; van Katwijk, M.M., A.R. Bos, V.N. de Jonge, L.S.A.M. Hanssen, D.C.R. Hermus, and D.J. de Jong. 2009. Guidelines for seagrass restoration: Importance of habitat selection and donor population, spreading of risks, and ecosystem engineering effects. *Marine Pollution Bulletin* 58: 179–188.

[356] van Katwijk, M.M., B.I. van Tussenbroek, S.V. Hanssen, A.J. Hendriks, and L. Hanssen. 2020. Rewilding the sea with domesticated seagrass. *BioScience* 71: 1171–1178; Orth, R.J., M.C. Harwell, and G.J. Inglis. 2006b. Ecology of seagrass seeds and dispersal strategies. pp. 111–133. In *Seagrasses: Biology, ecology and conservation*, ed. A.W.D. Larkum, R.J. Orth, and C.M. Duarte, 691. The Netherlands: Springer.

[357] Valdez, S.R., Y.S. Zhang, T. van der Heide, M.A. Vanderklift, F. Tarquinio, R.J. Orth, and B.R. Silliman. 2020. Positive ecological interactions and the success of seagrass restoration. *Frontiers in Marine Science*. https:// doi. org/ 10. 3389/ fmars. 2020. 00091; Zhang, Y.S., R.K. Gittman, S.E. Donaher, S.N. Trackenberg, T. van der Heide and B.R. Silliman. 2021. Inclusion of intra- and interspecific facilitation expands the theoretical framework for seagrass restoration. *Frontiers in Marine Science* 8: 645673. https:// doi. org/ 10. 3389/ fmars. 2021. 645673.

[358] Williams, S.L., R. Ambo-Rappe, C. Sur, J.M. Abbott, and S.R. Limbong. 2017. Species richness accelerates marine ecosystem restoration in the Coral Triangle. *Proceedings of the National Academy of Sciences* 114: 11986–11991.

[359] Temmink, R.J.M., M.J.A. Christianen, G.S. Fivash, C. Angelini, C. Boström, K. Didderen, S.M. Engel, N. Esteban, J.L. Gaeckle, K. Gagnon, L.L. Govers, E. Infantes, M.M. van Katwijk, S. Kipson, L.P.M. Lamers, W. Lengkeek, B.R. Silliman, B.I. van Tussenbroek, R.K.F. Unsworth, S.M. Yaakub, T.J. Bouma, and T. van der Heide. 2020. Mimicry of emergent traits amplifies coastal restoration success. *Nature Communications* 11: 1–9.

[360] Sievers, M., C.J. Brown, C.A. Buelow, R. Hale, A. Ostrowski, M.I. Saunders, B.R. Silliman, S.E. Swearer, M.P. Turschwell, S.R. Valdez, and R.M. Connolly. 2022. Greater consideration of animals will enhance coastal restoration outcomes. *BioScience*. https:// doi. org/ 10. 1093/ biosci/ biac0 88.

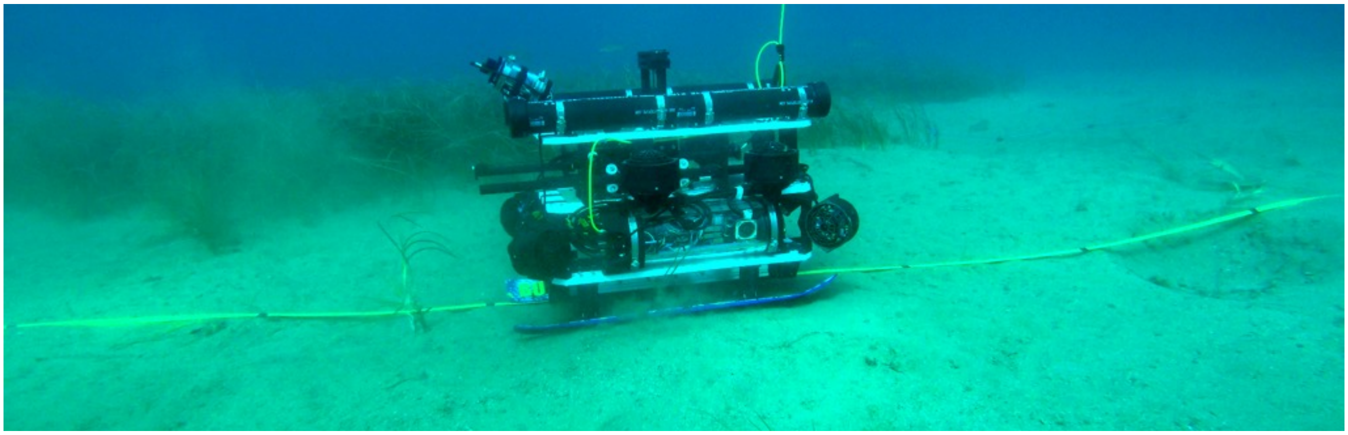

Figure 27. Reefgen's underwater remotely operated vehicle (ROV) plants a row of eelgrass off the coast of Catalina Island, California. Photo courtesy of Reefgen, Inc.

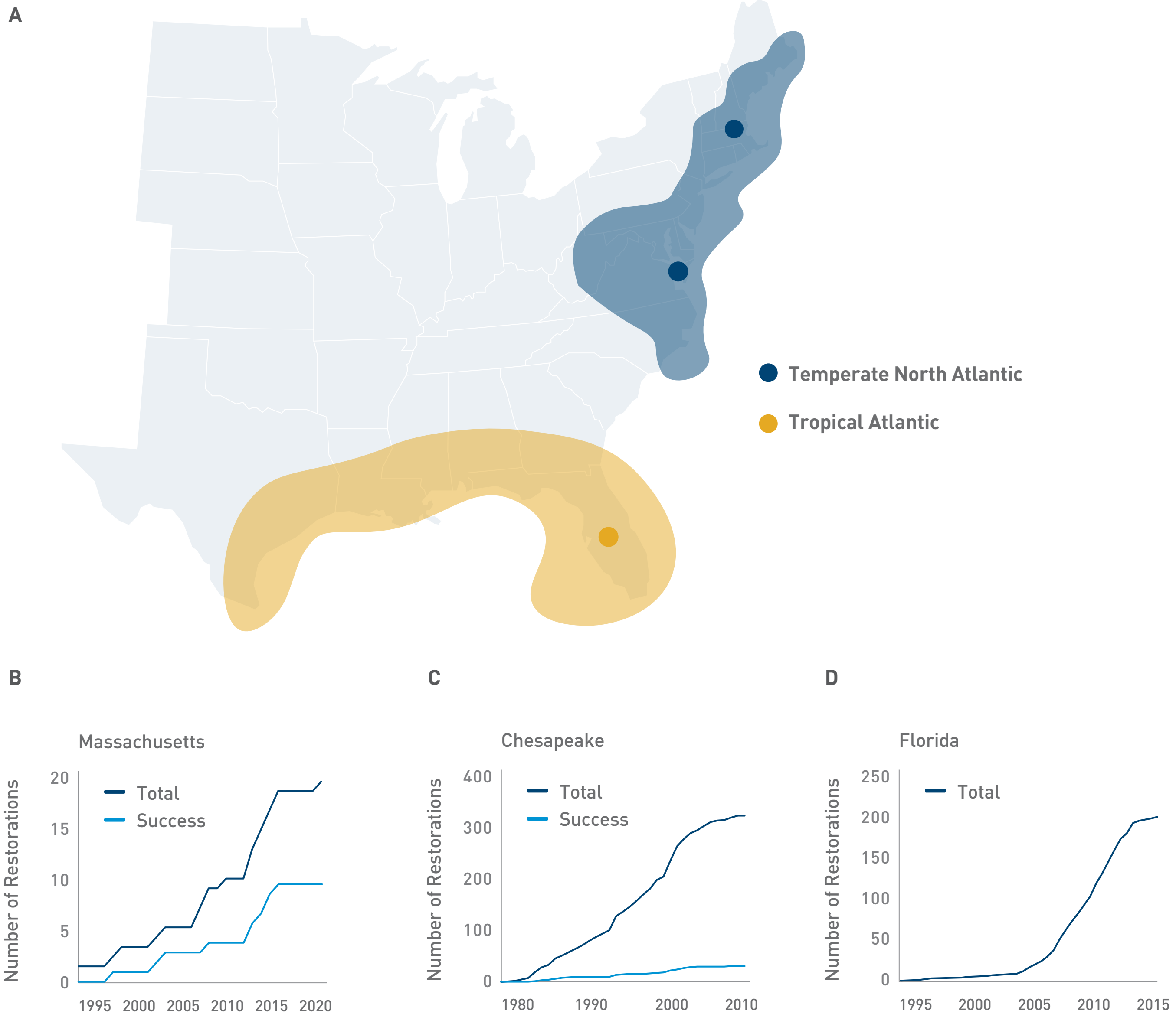

Figure 28. Ongoing restoration efforts are underway along the U.S. eastern seaboard. A) Regions where restoration efforts have received the most effort and attention. Restoration efforts over the past 25 years, and relative success, in B) Massachusetts, C) the Chesapeake, and D) Florida.

Appendix 5. Seaweed Feedstock Efficiencies Case Studies

Contributing Author: Shane Rogers

1. TEA and LCA of nutrient management cultivation

Case Study 1: Regarding land-nutrient recycling, we have recently investigated the use of seaweed aquaculture as an alternative or supplement to nutrient removal processes at wastewater treatment plants discharging to coastal areas via a case study with the Boothbay Harbor Sewer District (BHSD) in Boothbay Harbor, Maine.[361] Life cycle assessment (LCA) and techno-economic analysis (TEA) were used to compare options for nutrient management. In this study, potential end uses of seaweed biomass investigated included food, fish feed, biofeedstock as biofuel with byproducts used as organic fertilizer and commercial organic fertilizer production.

Nutrient bioextractive aquaculture can be scaled appropriately to manage nutrient discharges with favorable economic and environmental performance. Based on biomass production characteristics and tissue nitrogen contents in Boothbay Harbor, a longline platform-based aquaculture site of 5.4 hectares employing rotational grow-out of sugar kelp and *Gracilaria tikvahiae* would bioextract equivalent nitrogen mass as the wastewater treatment plant upgraded to meet level 2 nitrogen effluent goals of 3 mg-N/L. Further, bioextractive seaweed aquaculture with use of seaweed as a feedstock for anaerobic digestion resulted in improved environmental performance in all impact categories except for marine eutrophication (equivalent benefit) when compared to an upgraded wastewater treatment plant for the BHSD.

Importantly, this study estimated the nitrogen uptake of sugar kelp and *G. tikvahiae* based upon literature data of the harvested biomass tissue nitrogen content. However, the nitrogen concentrations and composition in coastal areas vary in space and time. For example, there can be seasonal changes in the flowrate, total nitrogen and nitrogen speciation (e.g., nitrate versus ammonium nitrogen) in treated wastewater discharged to coastal areas; in turn, these changes can impact nitrogen concentration and the composition of the resulting nutrient plume. Previous studies have demonstrated that environmental nitrogen can impact the physiological characteristics of seaweed grown in a given area, including the growth rate and the total nitrogen content.[362] However, data are still lacking to quantitatively model the impact of environmental nitrogen on seaweed growth and characteristics. Growth dynamics of seaweed biomass may also affect the rate and timing of nutrient bioextraction and may need to be considered in rotational cultivation design. Future work should leverage emerging information to maximize the placement of aquaculture platforms relative to nutrient sources and optimize harvest periods to advantage higher macroalgae nutrient contents and associated nutrient bioextraction from coastal areas.

Aside from an increase in fossil resource scarcity and a slight increase in global warming and human carcinogenic toxicity related to the drying process, the environmental trade-offs favored bioextractive seaweed aquaculture producing dried sea vegetables over the BHSD upgrade, provided displacement of land-based lettuce production. Bioextractive seaweed aquaculture, with the sale of dried seaweed commercial fertilizer, led to increased environmental impacts in all categories except for marine eutrophication when compared to upgrading the BHSD to manage nitrogen. More sustainable alternatives to seaweed drying would shift the balance of most negative

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[361] Wu et al., “Bioextractive Aquaculture.”

[362] O.J. Broch et al., “Modelling the Cultivation and Bioremediation Potential of the Kelp *Saccharina latissima* in Close Proximity to an Exposed Salmon Farm in Norway,” *Aquaculture Environment Interactions* 4 (2013): 187–206; and Y. Chen et al., “Physiological Impacts of Nitrogen Starvation and Subsequent Recovery on the Red Seaweed *Grateloupia turuturu* (Halymeniaceae, Rhodophyta),” *Sustainability* 15, no. 9 (2023): 7032.

impacts to favor sea vegetable and fertilizer production. Without drying seaweeds to prepare them for use as biofeedstock for anaerobic digestion, the environmental benefits of anaerobic digestion with use of products as fertilizers were excellent. Interestingly, an upgrade to the BHSD to achieve phosphorus removal requirements was not feasible owing to current site restrictions; however, phosphorus removal requirements could be achieved with bioextractive aquaculture.

Using a TEA, the cost of a WRRF upgrade was estimated to be \$0.31 m^{-3} wastewater treated. The cost of bioextractive seaweed aquaculture depended on beneficial use of seaweed. If dried and sold as sea vegetables, seaweed could generate a net revenue of \$0.72 m^{-3} wastewater treated. If dried and sold as commercial fertilizer, the net cost of nutrient removal would be \$0.26 m^{-3} wastewater treated, less than the WRRF upgrade. However, if anaerobically digested to produce biogas, the net cost of treatment was estimated to be \$0.499 m^{-3} wastewater treated. There has been keen interest in producing seaweed as a biofuel feedstock. Here, we demonstrate that using harvested macroalgae as anaerobic digestion feedstock to produce biogas, with land application of anaerobic digestor (AD) residuals to displace chemical fertilizer, largely decreases the economic value of cultivated macroalgae. Based upon the experience of industry, which prefers to sell seaweeds as food, this is not surprising.

An important finding of this work is that bioextractive seaweed aquaculture as an alternative to nutrient management upgrades at wastewater treatment plants could facilitate nutrient management at wastewater treatment plants with net positive revenue if harvested seaweeds are sold as sea vegetables (presuming they have been tested and are safe for consumption). If seaweed is sold as commercial fertilizer, the costs of nutrient management are also favorable over wastewater treatment plant upgrades, although the practice does not generate revenue. These results suggest that, under the correct conditions, nutrient trading schemes could be constructed for bioextractive aquaculture that would be economically and environmentally advantageous over wastewater treatment plant upgrades. These trading programs could supplement the emerging seaweed aquaculture industry in the United States, an industry that often operates with thin margins.

Case Study 2: In 2019, via its ARPA-E program, the DOE invested in a three-year initiative led by Dr. Schery Umanzor from the University of Alaska. The project focused on quantifying cultivated kelp's capability to remove carbon and nitrogen, spanning different species and geographical regions. This effort encompassed five farms across New England and an additional six farms in Alaska.

The project developed a user-friendly sampling kit for kelp farmers to facilitate straightforward sample collection. These samples were subsequently analyzed to determine carbon and nitrogen concentrations within kelp tissue. Outcomes were then used to calculate the overall nutrient removal in relation to kelp biomass yield at harvest. Notably, the study unveiled substantial variation in crop efficiencies across different farms and years. This variability was partly influenced by the COVID-19 lockdowns, which markedly reduced the influx of land-based nutrients into areas like the Long Island Sound. Consequently, kelp farms in Connecticut and New York encountered significant nutrient limitations, leading to reduced growth, reflected in poor yields and an overall 50-75% decrease in nutrient removal during harvest. These results underscore the significance of kelp farming as a pivotal strategy for addressing nutrient removal from the water column, particularly in urbanized coastal areas.

The work contemplates avenues of further investigation. For example, the USDA-NOP (National Organic Program) ruled that organic sea vegetables should be three miles away from sewage discharge; we used the lower (nonorganic) seaweed price as sea vegetables used in our study.[363] Nutrient trading schemes may offset differences in the value of organic and nonorganic sea vegetables, expanding profitable grow-out locations for aquaculture site licensing. To facilitate that possibility, further research is needed regarding safe setback distances from wastewater treatment plant outfalls for sea vegetable cultivation (for a land-based analog for lettuce production, see our prior work.[364] Willingness to buy should also be considered and may impact the macroalgae price.

2. Dual-layer versus strip cultivation

Recent work has demonstrated that substitution of land-based lettuce by sea vegetables (seaweed) can reduce marine and freshwater eutrophication; human noncarcinogenic toxicity; and freshwater, marine and terrestrial ecotoxicities, regardless of whether or not drying was used to preserve the seaweed for distribution and sale.[365] The breakpoints of substitution decreased when using dual-layer and strip cultivation platforms that yield higher production density than traditional longline systems. The use of seaweed biomass as biofeedstock to produce biogas for combined heat and power via anaerobic digestion resulted in even greater environmental performance. This suggests seaweed cultivation may contribute to sustainable food production and energy generation while mitigating environmental impacts. Using harvested biomass as fishmeal reduced marine eutrophication potential but did not yield similar net environmental benefits as using biomass for sea vegetables or using biofeedstock for methane production via anaerobic digestion.

3. TEA and LCA of cultivation scenarios (including rotation)

In recently published work, TEA and LCA were conducted to evaluate the economic and environmental trade-offs of 32 cultivation scenarios of sugar kelp and *G. tikvahiae* considering the macroalgae cultivation platform, cultivation strategy, processing steps and end-use products.[366] We focused on macroalgae cultivation platforms grounded in the common longline technology used globally, including a single longline platform, dual-layer longline platform and a "cultivation strip" platform. We evaluated both widely used and emerging end-use macroalgae products including sea vegetables, biofeedstock for combined heat and power production via anaerobic digestion, marketable seaweed fertilizer and animal feed.

Harvested biomass was most profitable when sold as sea vegetables, with net benefits between \$11.96 and \$16.89 kg^{-1} dry weight among the cultivation platforms and strategies. Indeed, the only processing and end-use strategies with the potential to be profitable were sea vegetables and fertilizer; the results were influenced heavily by aquaculture platform and cultivation strategy. When cultivated on rotation, the dual-layer strip cultivation platform reduced sugar kelp and *G. tikvahiae* cultivation costs by 50.7% and 49.1%, respectively, over traditional longline cultivation. Rotational grow-out of seaweeds reduced the amortized capital costs per kilogram of dry weight macroalgae by 19.2%. Seaweed drying was identified as the major contributor to both economic and environmental costs during the processing stage. Using macroalgae biomass as biofeedstock for anaerobic digestion or processing biomass into fishmeal was not economically beneficial, regardless of cultivation platforms or strategies. Using a rotational cultivation strategy, selection of a dual-layer strip cultivation platform at greater capital cost over a single longline system could reduce the payback period for sea vegetable production from two

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[363] Piconi, Veidenheimer, and Chase, "Edible Seaweed Market Analysis."

[364] M.A. Jahne et al., "Bioaerosol Deposition to Food Crops near Manure Application: Quantitative Microbial Risk Assessment," *Journal of Environmental Quality* 45, no. 2 (2016): 666–74.

[365] Wu et al., "Comparison of Multiple Macroalgae."

[366] Wu et al., "Comparison of Multiple Macroalgae."

years to one while also providing long-term increased revenue owing to greater biomass density. Considering fertilizer as an end-use product, the payback period could be reduced from 15 years to three years by choosing a dual-layer strip cultivation platform over a single-layer longline system. While harvested seaweed may be used as biofuel feedstock, fertilizer or fishmeal, when processed into dry human food, experience shows that harvested macroalgae would not be 100% utilized. We estimated that, even at 30% utilization of harvested biomass as sea vegetables when sugar kelp and *G. tikvahiae* were cultivated on rotation on a dual-layer strip platform, the operation would still be profitable, with a net benefit between \$3.30 to \$6.05 kg^{-1} dry weight, depending on the alternative disposition of remaining biomass (biofuel feedstock, seaweed fertilizer or fishmeal).

The results of this study highlight the potential of platform technology and rotational cultivation strategies to improve performance significantly. While these results focus on sugar kelp and *G. tikvahiae* on rotation, the results imply that other species could also share similar benefits when grown on rotation. Carefully considering factors such as demand, growing season and the biogeographic distribution pattern of seaweed species when designing macroalgae aquaculture platforms and grow-out strategies could lead to economic and environmental benefits at other locations. Overall, this research emphasizes the high market value of the selected macroalgae species and the utilization of shared infrastructure for cultivating multiple algae species.

Appendix 6. OA Remediation by Farmed Kelp Case Studies

Contributing Authors: Suzanne Arnold and Nichole N. Price

A partnership, which was established in 2015, between Bigelow Laboratory for Ocean Sciences, the Island Institute, the University of New Hampshire, Atlantic Sea Farms (a seaweed company), Bangs Island Mussels and other organizations, has been investigating the potential for farmed sugar kelp to remediate OA and improve growing conditions for nearby farmed shellfish. This research seeks to understand if fast-growing kelp can remove enough CO_2, the major cause of OA, from the seawater to improve water chemistry in and around the farm, thereby creating more favorable conditions for farmed mussels. Efforts include lab mesocosm experiments, field trials at two locations in Maine and monitoring at seaweed farms in Norway and Alaska.

Initial mesocosm experiments found sugar kelp removes DIC and alters saturation states (Ω) under increasing CO_2 conditions more substantially than three other macrophyte species.[367] Additionally, Ricart et al. shed light on the ideal light and flow rates under current and future climate scenarios to allow for projections at the ecosystem level. Field research at a kelp farm off Chebeague Island in Casco Bay, Maine took place over three seasons, using moored scientific instruments to measure water chemistry, which recorded a higher pH inside the kelp farm. Shipboard instruments mapped the water chemistry to determine the spatial extent of the remediated "halo" of water around the farm. Bangs Island Mussels out-planted mussels inside and outside the kelp farm, and the shellfish grown inside the farm for just two months had thicker shells. Based on these research findings, Bangs Island Mussels now grows kelp around their mussels at one site and intends to add kelp to all their mussel sites in the future.

The findings, that cultivated seaweed can raise seawater pH in the immediate vicinity of a sheltered coastal sea farm, were corroborated by field studies in Rhode Island as well as lab results from an experiment conducted at Bigelow Laboratory for Ocean Sciences to determine seaweed's capacity to increase pH in a warmer and more acidic ocean. In a tank experiment, blue mussels were grown with and without sugar kelp for 50 days. The shell thickness of mussels co-cultivated with kelp increased by 5.84% in both ambient and future climate scenarios and meat mass increased by 6.47% in future conditions. Given these promising findings, this research team is now working with kelp farms in Alaska (Seagrove Kelp) and Norway (Seaweed Solutions) to share the team's methodology for monitoring the parameters of OA, which is detailed in **Figure 29**.

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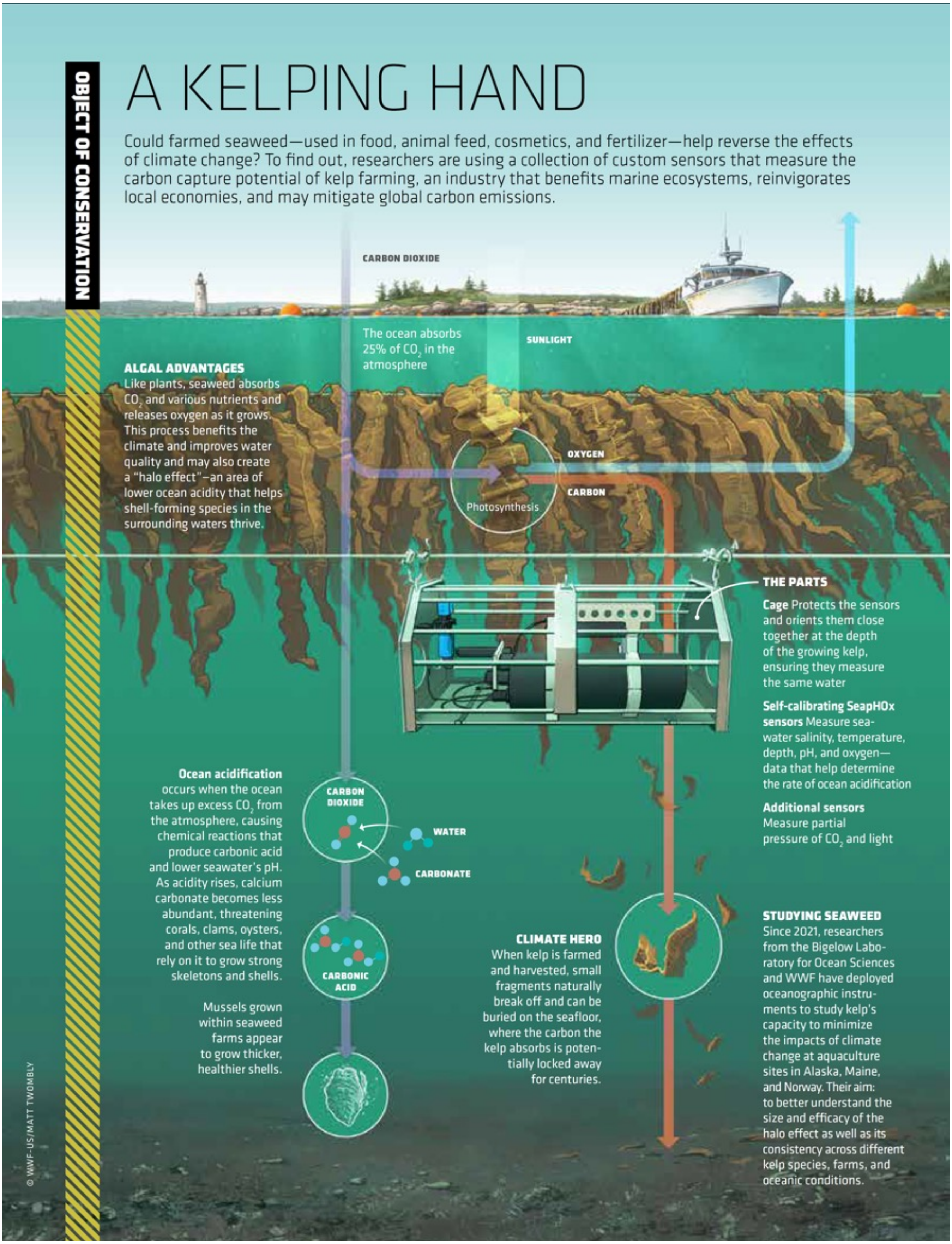
[367] Ricart, Aurora M., Brittney Honisch, Evangeline Fachon, Christopher W. Hunt, Joseph Salisbury, Suzanne N. Arnold, and Nichole N. Price. "Optimizing marine macrophyte capacity to locally ameliorate ocean acidification under variable light and flow regimes: Insights from an experimental approach." *Plos one* 18, no. 10 (2023): e0288548.



A KELPING HAND

Could farmed seaweed—used in food, animal feed, cosmetics, and fertilizer—help reverse the effects of climate change? To find out, researchers are using a collection of custom sensors that measure the carbon capture potential of kelp farming, an industry that benefits marine ecosystems, reinvigorates local economies, and may mitigate global carbon emissions.

The ocean absorbs 25% of CO_2 in the atmosphere

ALGAL ADVANTAGES
Like plants, seaweed absorbs CO_2 and various nutrients and releases oxygen as it grows. This process benefits the climate and improves water quality and may also create a "halo effect"—an area of lower ocean acidity that helps shell-forming species in the surrounding waters thrive.

THE PARTS

Cage Protects the sensors and orients them close together at the depth of the growing kelp, ensuring they measure the same water

Self-calibrating SeapHOx sensors Measure seawater salinity, temperature, depth, pH, and oxygen—data that help determine the rate of ocean acidification

Additional sensors Measure partial pressure of CO_2 and light

Ocean acidification occurs when the ocean takes up excess CO_2 from the atmosphere, causing chemical reactions that produce carbonic acid and lower seawater's pH. As acidity rises, calcium carbonate becomes less abundant, threatening corals, clams, oysters, and other sea life that rely on it to grow strong skeletons and shells.

Mussels grown within seaweed farms appear to grow thicker, healthier shells.

CLIMATE HERO
When kelp is farmed and harvested, small fragments naturally break off and can be buried on the seafloor, where the carbon the kelp absorbs is potentially locked away for centuries.

STUDYING SEAWEED
Since 2021, researchers from the Bigelow Laboratory for Ocean Sciences and WWF have deployed oceanographic instruments to study kelp's capacity to minimize the impacts of climate change at aquaculture sites in Alaska, Maine, and Norway. Their aim: to better understand the size and efficacy of the halo effect as well as its consistency across different kelp species, farms, and oceanic conditions.

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Figure 29 Measuring the 'halo' effect of farmed seaweeds on seawater quality and atmospheric carbon dioxide capture rates; graphic originally published in the August, 2024 issue of World Wildlife magazine.

Appendix 7. Requirements for High-Integrity Voluntary Carbon Offset Markets

Contributing Author: Nichole N. Price

There are two types of global carbon markets: Compliance (generally credits, and based on adherence to regulatory policies) and Voluntary (generally offsets to help meet emissions targets). Not all voluntary carbon markets (VCMs) are equal: they vary in quality. These VCMs are decentralized international markets where individuals or organizations buy credits to voluntarily offset their carbon footprint. These carbon credits are "voluntary" in the sense that the use of carbon credits for reducing emissions is not legally required or regulated. High-integrity VCMs attempt to set the standard for the confidence in the certainty of carbon emissions capture and removal (or reduced emissions).

Stakeholders seek guarantees that one credit truly represents one tonne of carbon dioxide (or its equivalent) reduced or removed from the atmosphere. The United Nations Development Programme (UNDP) created an initiative in 2023 to establish robust principles and guidelines that ensure high integrity across all types of carbon markets, including VCMs, with a larger vision to make carbon markets work for host countries and their nationally determined contributions.[368] Integrity is determined not only by environmental attributes of the offset practice and methodology, but also by its social impacts and pricing determination. The UNDP's High-Integrity Carbon Markets Initiative has proposed learning modules to assist with nations' (or companies') readiness to understand and responsibly participate in VCMs (**Table 15**).

For large purchasers of carbon seeking high-integrity VCMs, several purchase characteristics are crucial to evaluate, including durability (or longevity or permanence), physical footprint, cost, capacity, net negativity (using life cycle assessment), (carbon) additionality, verifiability and safety and legality. For example, legacy CO_2 removal must be additional; that is, the carbon must be new and not taking credit for carbon sequestration already occurring. Methodologies developed within the high-integrity VCMs aim to prevent dual counting and quantify carbon leakage. Critically, measurement, monitoring, reporting, and verification evaluations need to be conducted by a third party, with clear transparency of credited mitigation actions and transactions; this removes biases and circumvents fears about 'greenwashing'.

Currently, methodologies for seaweed-specific blue carbon are in development at Verra and Gold Standard (considered High-Fidelity VCMs), but do not yet exist. Additionally, there are numerous federally and philanthropically funded research projects (see **Table 8**) designed specifically to develop measurement, reporting, and verification protocols to evaluate longevity and net negativity, in particular. However, these projects are rarely in the position to predict risk of turnovers or reversals of permanently stored carbon, as research is still in early stages.

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[368] https://www.undp.org/publications/undps-high-integrity-carbon-markets-initiative

Table 15. High-integrity carbon market concepts [adapted from United Nations Development Programme's High-Integrity Carbon Markets Initiative (December 2023)].

INTRODUCTION TO CARBON MARKETS	HIGH INTEGRITY – CARBON ELEMENTS	HIGH INTEGRITY – SOCIAL ELEMENTS	ANALYSIS AND EMERGING LESSONS
Orientation to the carbon market ecosystem	**The latest thinking on environmental integrity and what it means for host countries**	**The latest thinking on social integrity and what it means for host countries**	**Making sense of the complexity**
• Historical and future trends • Compliance vs. voluntary markets • Pricing • Carbon market potential • Carbon market actors • Leading carbon standards • Demand-side claims • Roles government can play	• Robust quantification • Paris Agreement aligned • Contribution to the net-zero transition • No double counting (including double issuance, claiming & use) • Additionality, permanence, no leakage • Robust independent third-party validation and verification • Tracking of uniquely identified credits (registry) • Transparency of credited mitigation activities & transactions • Only jurisdictional or nested REDD+ projects	• Social and environmental safeguards • SDG Impact • Stakeholder engagement • Respect for Indigenous Peoples' rights • Gender equality and women's empowerment • Benefit sharing • Grievance mechanisms • Case study: Supporting 40 Jurisdictions to address Forest Carbon Market Safeguards Standard	• High level recommendations for host countries • Entry points for further engagement

Expected results:

- Informed and engaged on carbon market essentials.
- Clearer sense of opportunities and risks associated with the carbon market.
- Clarity on next steps required to engage further on carbon markets.
- Establish new relationships and partnerships to support their engagement in carbon markets.
- Know how to access additional resources to support their consideration of and engagement in carbon markets.
- Better placed to engage in strategic discussions related to their interest and role in carbon markets.

Appendix 8. Seaweeds as Biostimulants Review

Contributing Authors: Nichole N. Price, Charlotte Quigley, Elena Shippey

Below are seaweed-based biostimulant product application on agricultural crops and their learned benefits as presented in peer-reviewed literature (**Table 15**). Articles were retrieved from 2014-2024, a time frame that reflects a period of increased published research on the topic. Literature search results were retrieved from Scopus, using the following search terms: "("macroalg*" OR "seaweed") + "biostimulant" + "crop"".

With this terminology, 244 search results surfaced. For this purpose, publication document types that are not articles, including review papers, conference papers, book or book chapters, and editorials, were omitted (69 entries total), as well as one duplicate entry. Additionally, publications that did not test a specific seaweed-based product on a crop were removed (19 total). Notably, three search results tested seaweed-based biostimulant products on a crop, though results did not demonstrate a significant benefit, or in some cases, a slight negative impact on the crop. Thus, these three publications were omitted. Post-assessment for topical relevance, a final list of 152 search results were deemed appropriate for inclusion in this exercise.

Benefit categories/definitions:

- **improved yield/quality**: focus on harvest or post-harvest phase of the life cycle.
- **germination/growth efficiency**: focus on the pre-harvest phases of the life cycle.
- **abiotic stress resistance**: assessment of plant viability or immune response at the cellular level to heat, drought, salt, or nutrient level stress (notably nitrogen) e.g. through genomics.
- **biotic stress resistance**: assessment of plant viability or immune response, primarily by visual observation, to pests, mold, mildew, fungi, or other pathogens linked to disease in plants.
- **enhanced soil quality**: focus on microbial community present in plant soil
- **abiotic stress - manipulated**: often paired with another benefit category, a form of abiotic stress (heat, drought, salt, nitrogen level) serves as a manipulated variable in a factorial experimental setup. In this case, the assessment of abiotic stress resistance is observed by measure of the benefit it is paired with (e.g. plant growth) rather than measured directly at the cellular level.

Table 16. Evidence of categorial benefits of seaweed-based biostimulant application by crop type. Numbered literature cited provided in list immediately following table.

CROP NAME	LEARNED BENEFIT(S) OF SEAWEED-BASED BIOSTIMULANT APPLICATION					
	Germination / growth efficiency	Improved yield / quality	Abiotic stress resistance	Biotic stress resistance	Enhanced soil quality	Abiotic stress - manipulated
Apple		1				
Arugula	2,3	3				2,3
Avocado	4	4				
Barley	5	5				
Basil	6	6,7			7	6
Beet	8	8				
Cabbage	9		9			
Cannabis	10					
Canola	12					11,12
Carrot		13,14				
Collard Greens		15				
Cowpea	16	16				
Cucumber		17				
Eggplant	18	18-20				18
Fenugreek	21	21				21
Garden cress	22	22				
Gooseberry	23					23
Grape	28	24-27		27		28
Grass	29,30					
Green bean						31
Hydrangea						32
Kale	15,33					
Kiwifruit	34	34				
Lettuce	15,35-40	38,40,41				39
Maize	42,44	44-47	48,49	47		43,45,46
Marigold	50					
Milkweed	51-53					52,53
Millet	54	54				
Mint	55	56				56
Moth bean	57					
Mung Bean	58-60	59				
Mustard greens	15,61	61				61
Oats		62				
Oil palm	63					
Oilseed rape	64-66	67				
Okra	68-71	69,70				71

CROP NAME	**LEARNED BENEFIT(S) OF SEAWEED-BASED BIOSTIMULANT APPLICATION**					
	Germination / growth efficiency	**Improved yield / quality**	**Abiotic stress resistance**	**Biotic stress resistance**	**Enhanced soil quality**	**Abiotic stress - manipulated**
Olive		26				
Onion	72	72				
Pea	73					73
Pepper	74,76,77	76-79	75	76,77		
Pigweed	80,81					
Potato	82,83	83,84		82		
Radish	85					85
Rice	86	86		87		86
Rice bean	88	88				
Soybean	89,90,95	89-94	97	98		95,96
Spinach		99,100				
Strawberry	101,102	101-105		106		
Sugarcane	107,108	107-110				110
Sunflower	111					
Swiss chard	15					
Texas bluebell	112					
Thale cress	113,115,117	117	118	115,116		114,117
Tomato	37,76,77,119-125,141,142	77, 79, 123-134,142,143	140,144	76,77 145,146		122,131-139,141-143
Wheat	147-149	148-151				152

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Appendix 9. Farm Design Case Study

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A new farm design for offshore macroalgae farming will reduce marine mammal entanglement.

The University of New Hampshire, working together with Umaro Foods, Otherlab, Kelson Marine and Stationkeep LLC, developed a composite, subsurface grid for cultivating macroalgae in the open ocean. The project was part of a larger national effort funded by the DOE ARPA-E's MARINER program to develop technologies that enable large-scale macroalgae cultivation to generate material for sustainable food, feed and biofuel.

Offshore aquaculture structures deployed in the Gulf of Maine are perceived to pose potential risks to the endangered North Atlantic Right Whale, thereby making permits for such systems effectively unattainable. To overcome this challenge, the project designed, modeled and deployed a composite farm for cultivating sugar kelp intended to reduce entanglement risk. The farm was built by replacing synthetic fiber ropes with composite fiberglass rods. The composite rod has a high tensile strength, is rigid and breaks at a minimum radius. This reduces the chance of the rod wrapping around a whale appendage before it breaks. Imagine a piece of uncooked spaghetti as a composite rod: as you bend it, it will break in two. We believe that the chances of marine mammal entanglement can be reduced by replacing synthetic fiber ropes with composite rods (**Figure 30**).

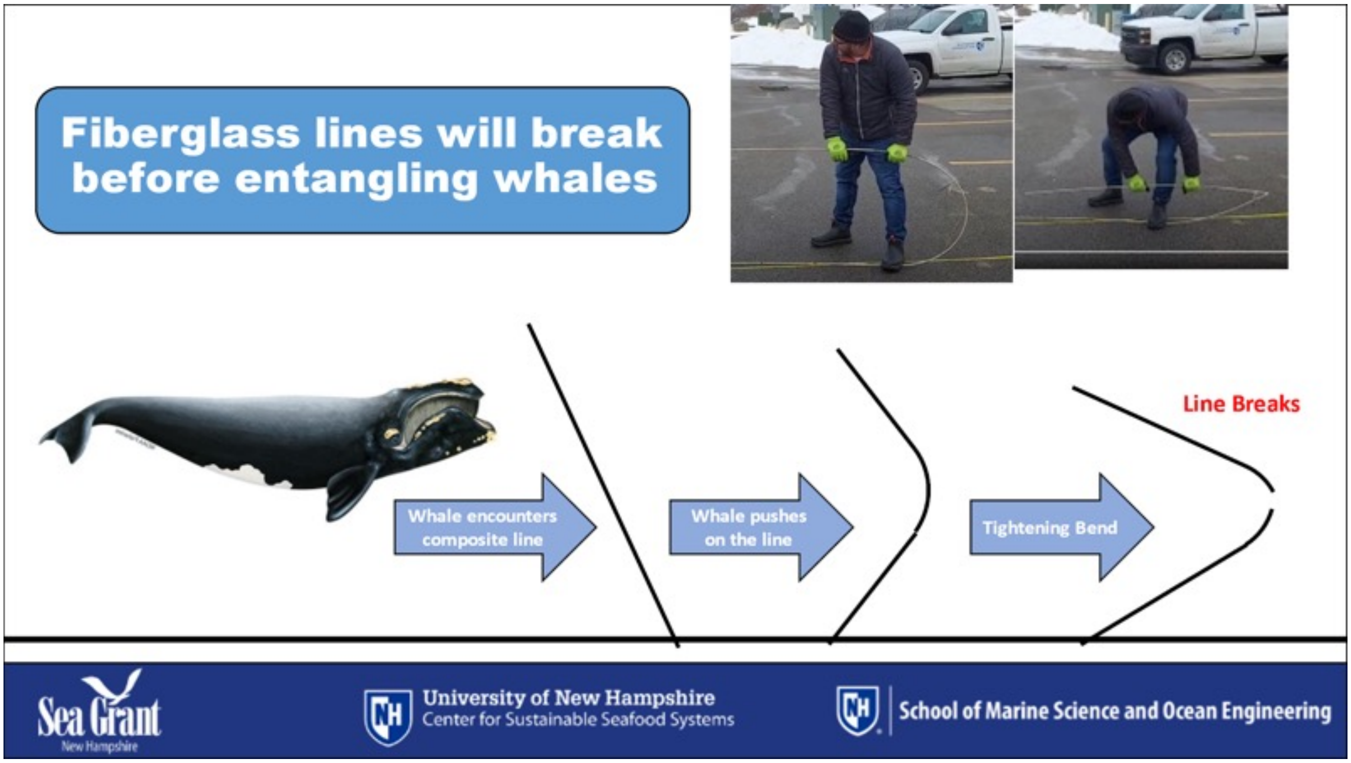

Figure 30. Illustration of a whale encountering a fiberglass rod and bending it until it breaks.

An experimental farm was deployed in the fall of 2021 at an exposed site near Ram Island, Maine. The permitted site was owned by the University of New England, which assisted in operations at the farm. The project demonstrated the composite rebar technology in the context of a multi-tile kelp cultivation array in a fully exposed site during harsh winter conditions characteristic of the Gulf of Maine.[369]

Composite Kelp Farm (AquaFields): The novel farming system (**Figure 31**) was designed with limited use of rope that can pose an entanglement risk to marine animals, particularly when slack. Instead, the mooring and kelp substrate components comprised tensioned semi-rigid fiberglass rods that resist bending. We hypothesized that this design would allow better shedding of the gear during a potential interaction event with marine mammals; however, quantifying what would occur in such an event requires further study. The fiberglass rods break at a specific bending radius, so wrapping or knotting around flukes, flippers, jaws, etc. would be minimized. We targeted a breaking radius greater than the typical whale appendage and we are actively designing custom composite rods for these desired characteristics. The grid system was held in place by 36, 7-meter-long, helical anchors. Tensioning floats were used to keep the grid taut between the surface and the helical anchors. **Figure 32** shows the system, combining an actual surface picture with a rendering of the submerged gear. The novel farming system was deployed, seeded and monitored at the site from November 2021 to May 2022. Though near shore, the site is exposed to the open ocean and sees annual maximum wave heights on the order of 6.1 meters (20 feet). Over 1,800 feet of kelp cultivation rods were planted over the farm.

In addition to addressing entanglement risks, the design was built to be cost effective. Therefore, to approach economic feasibility, our system integrated: (1) minimized scope to reduce required seabed footprint, (2) using single novel multi-shaft helical anchors to support multiple mooring attachments, (3) an overlapping modular design to maximize horizontal growing area per farm area and provide flexibility for piecemeal farm expansion, (4) minimized mooring equipment scales and infrastructure through distribution of hydrodynamic loads to localized mooring points and (5) optional wave-powered upwellers to enhance nutrient availability and maximize growth rates.

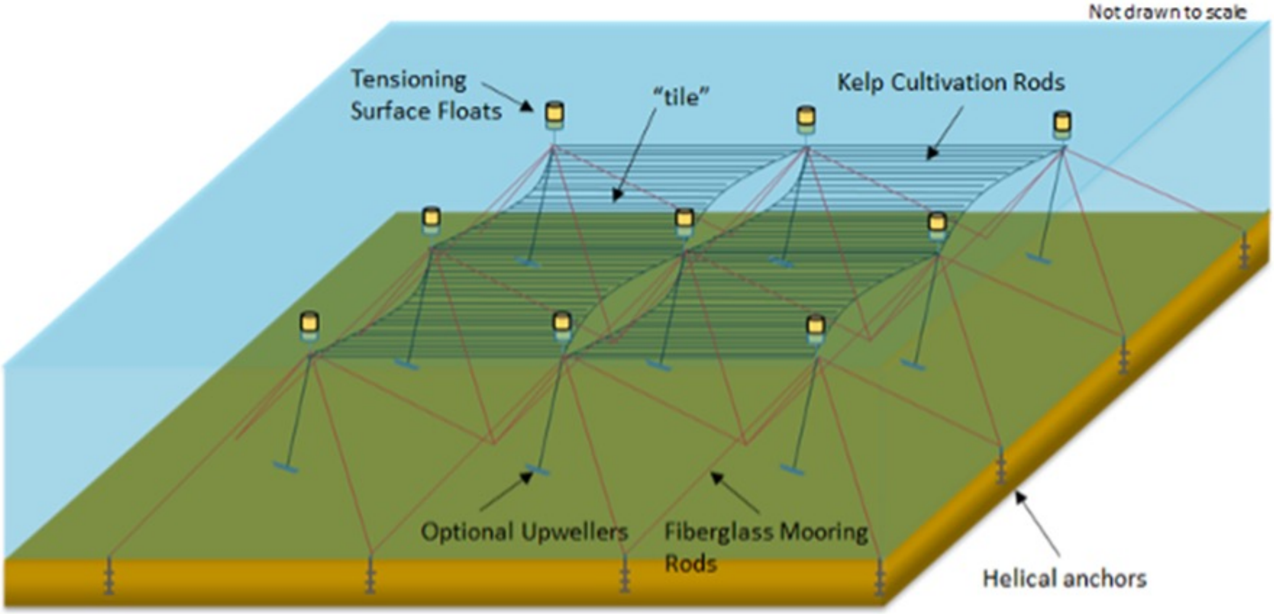

Figure 31. Rendering showing the components of an open-ocean macroalgae farm using a novel mooring system and wave-powered upwellers, developed through the ARPA-E funded project.

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[369] Moscicki et al., "Using Finite Element Analysis," 1–11; Zachary Moscicki et al., "Design, Deployment, and Operation of an Experimental Offshore Seaweed Cultivation Structure," *Aquacultural Engineering* 105 (2024): 102413; Zachary Moscicki et al., "Evaluation of an Experimental Kelp Farm's Structural Behavior Using Regression Modelling and Response Amplitude Operators Derived from In situ Measurements," *Ocean Engineering* 305 (2024): 117877.

Figure 32. A composite image: a three-dimensional rendering of the mooring and cultivation pilot scale system deployed in Saco Bay, ME with an overlaid photo of the actual surface components at the site.

Other novel components that were developed on the project included a Robotic ROV to deploy helical anchors and an Upweller device to bring deep, nutrient rich water to the surface to feed the kelp. These important tools decrease the cost of deploying the farm moorings and increases the growth and biomass of the kelp.

Conclusion: In the spring of 2022, the farm was harvested, and all structures were removed from the site. Analysis of the composite rod after deployment is ongoing. The composite kelp farm survived winter storms with seas over 6 meters in height. Kelp was seeded and harvested from the composite rod at a biomass of 8 kg/m. No interactions with marine mammals occurred during the deployment. We believe the composite rod may be used in other aquaculture applications, such as mooring a fish cage, or may be used as a subsurface headline to grow mussels. Future research will explore custom fabricated rods that break cleanly with a bending radius smaller than an appendage of a whale fluke or tail.

Appendix 10. Hatchery Improvements Case Studies

Contributing Authors: Scott Lindell and Charles Yarish

1. Germplasm

DOE-funded research, led by the Woods Hole Oceanographic Institution, initiated a sugar kelp selective breeding program five years ago. The program now produces cultivars with double the average commercial harvest yield in Maine, aided by a sophisticated genomic prediction model.[370] The program started with a study of the genetic diversity of 18 sugar kelp populations in the Gulf of Maine and Southern New England using modern whole genome sequencing. These populations formed the basis for two selective breeding programs; one program relies on hundreds of individual kelp blades collected between Lubec and the Cape Cod Canal, and the other program consists of collections from southern New England and the Long Island Sound. In a "principal component analysis," kelp populations from the Gulf of Maine are generally indistinguishable from other populations sampled in the Gulf of Maine.[371] An independent scientific risk analysis commissioned by Maine Department of Marine Resources in 2022 concluded that, "the entire GOM could reasonably constitute one large seed zone. Significant species and genetic differences exist between the GOM, and those areas south of Cape Cod or north of the Bay of Fundy.[372] Within the GOM, there is sufficient evidence of genetic mixing to justify free movement of "seed" within the Gulf."

At the same time, the proponents of kelp selective breeding and the risk assessment cited above recognize that the genetic diversity of farmed kelp will generally be reduced by selective breeding, which exploits only a subset of wild parents, and they may extend selection to the best-performing parents from farms.[373] Genetic diversity on farms could be increased by out-planting multiple crosses or cultivars which is, in fact, the objective of the DOE-funded breeding project that helps mitigate any potential introgression of genes from farmed to wild kelp. The pursuit of high performing cultivars should be moderated with maintenance of genetic diversity on farms.[374] The DOE-funded research has been successful in developing sporeless (infertile) cultivars which may be important for eliminating the potential of genetic introgression and possible impacts on wild populations in future.[375]

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[370] M. Huang et al., "Genomic Selection in Algae with Biphasic Lifecycles: A *Saccharina latissima* (Sugar Kelp) Case Study," *Frontiers in Marine Science* 10 (2023).

[371] Mao, X., Augyte, S., Huang, M., Hare, M. P., Bailey, D., Umanzor, S., Marty-Rivera, M., Robbins, K. R., Yarish, C., Lindell, S., & Jannink, J.-L. 2020. "Population genetics of sugar kelp in the Northwest Atlantic region using genome-wide markers." Frontiers in Marine Science. doi.org/10.3389/fmars.2020.00694

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2. Direct binding seed

An alternative method to traditional sporulation and passive settling of meiospores on spools wound with twine involves cultivating sporophytes in a tumble culture from gametophytes that have been stored over time. These juvenile sporophytes are then bound onto ropes using direct seeding binders, such as the proprietary binder "AtSea" from AtSeaNova Technologies in Ronse, Belgium, or open-access sodium alginate.[376] Notably, University of Connecticut, Woods Hole Oceanographic Institution and University of Alaska Fairbanks researchers have experimented with binding juvenile sporophytes directly onto seed strings and ropes.[377] These experiments, funded by ARPA-E, have been conducted under controlled conditions and at commercial farms. Despite the potential advantages of this approach, the market's lack of low-cost direct seeding binders is a notable limitation. Embracing direct seeding with binders could offer flexibility in farming schedules, reduce the need for extensive nursery operations and lead to savings in labor and capital costs. Embracing direct seeding with binders involves minimizing hatchery space, energy and effort requirements. But importantly, no single efficient method has consistently delivered results that fully support these claims.

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[376] P.D. Kerrison, M.S. Stanley, and A.D. Hughes, "Textile Substrate Seeding of *Saccharina latissima* Sporophytes Using a Binder: An Effective Method for the Aquaculture of Kelp," *Algal Research* 33 (2018): 352–57; and S. Umanzor, Y. Li, and C. Yarish, "Effect of Direct 'Seeding' Binders and Embryonic Sporophyte Sizes on the Development of the Sugar Kelp, *Saccharina latissima*," *Journal of Applied Phycology* 32, no. 6 (2020): 4137–43.

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Appendix 11. Additional Results from Pilot Studies

1. Carbon Capture and Deacidification by Marine Seaweeds

Under Objective 1, we developed a re-circulating flow system to measure the real time CO2 capture by seaweed with highly-branched thalli under controlled environmental and hydrodynamic conditions. Clean clonal cultures the red seaweed *Gracilaria* served as the model organism. Artificial seawater was used as the cultivation medium to eliminate the presence of competing organisms. The seaweed was inoculated onto mesh panels, the panels were positioned parallel to the direction of flow. After about 10 days, a dense, porous mass of tissue grew on the support. After 28 days, the tissue proliferated outward from the mesh support and filled the channel of the recirculation tank to create a contiguous bed. pH electrodes were positioned at the entrance, exit and midpoint of the seaweed bed to capture the real-time pH profile.

Under Objective 2, we characterized carbon dioxide capture under flow conditions. During the light phase of the photoperiod, carbon demand by the seaweed biomass reduced the outlet CO_2 concentration. During the dark phase of the photoperiod, the CO_2 concentration increased back up to the inlet CO_2 concentration. From this data, the real-time rates CO_2 uptake and the cumulative CO_2 capture were estimated. Increasing the bulk fluid velocity from 4 to 37 cm/s linearly increased the specific CO_2 uptake rate of the seaweed bed from 3.0 to 4.2 mmol CO_2/g AFDW-day (ash free dry weight; **Figure 33**). Under these active growth conditions, no dissolved organic carbon (DOC) release to the seawater was observed.

Under Objective 3, we characterized the seawater de-acidification potential of the seaweed bed. Once the seaweed bed was grown up, the aeration rate was turned off and the DIC ballast in the liquid was used as the sole carbon source. The DIC consumption consumed hydrogen ions and increased the pH. The pH profile in the bed was then measured over time in the recirculation tank, and then converted to equivalent bed volume.

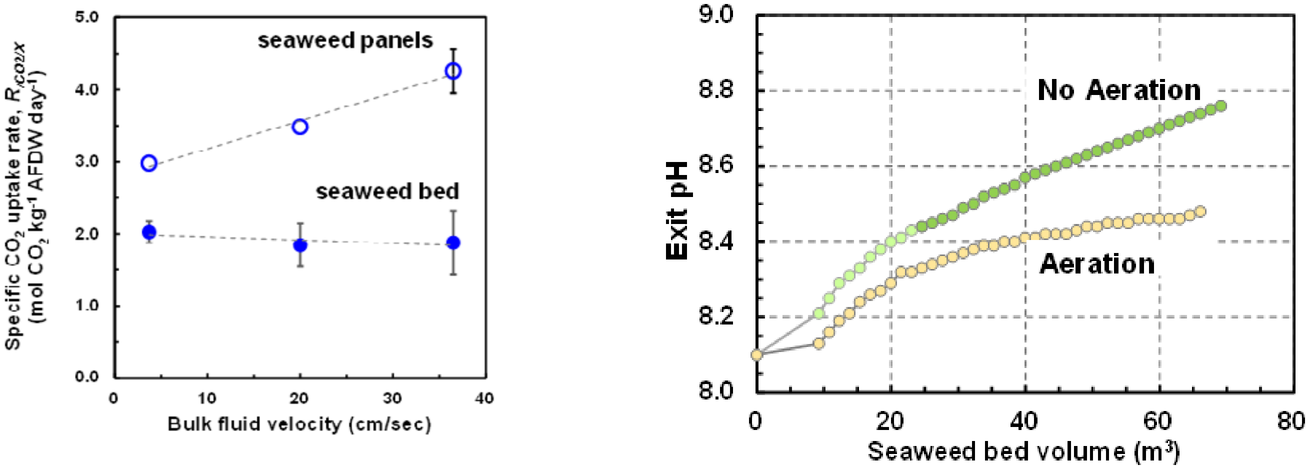


Figure 33. (A) Influence of seawater velocity on CO_2 uptake rate of the seaweed panels and of the seaweed bed, and (B) resultant change in seawater pH dependent on the bed volume.

2. Use of Seaweed to Protect Shellfish Farming from Ocean Acidification

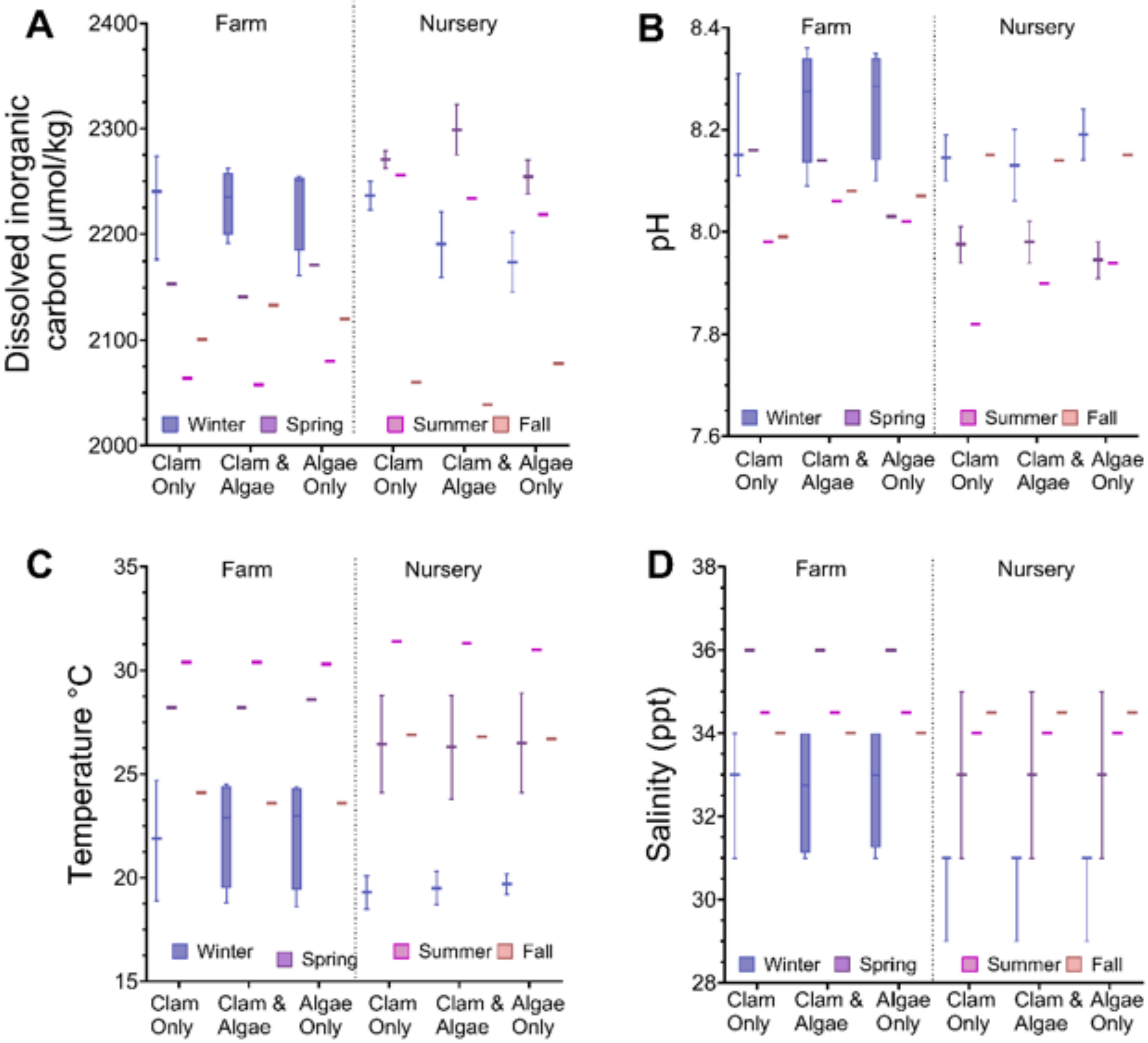


Figure 34. Water quality at the farm and nursery by treatment and season. Water quality parameters varied significantly between treatment, location, and season ($F_{(15,14)} = 3.647$, $P = 0.0101$). Treatment and location, however, were not significantly different ($F_{(5,17)} = 0.9341$, $P = 0.4836$), but there was a statistically significant effect of season on all parameters ($F_{(3, 17)} = 8.914$, $P < 0.001$).

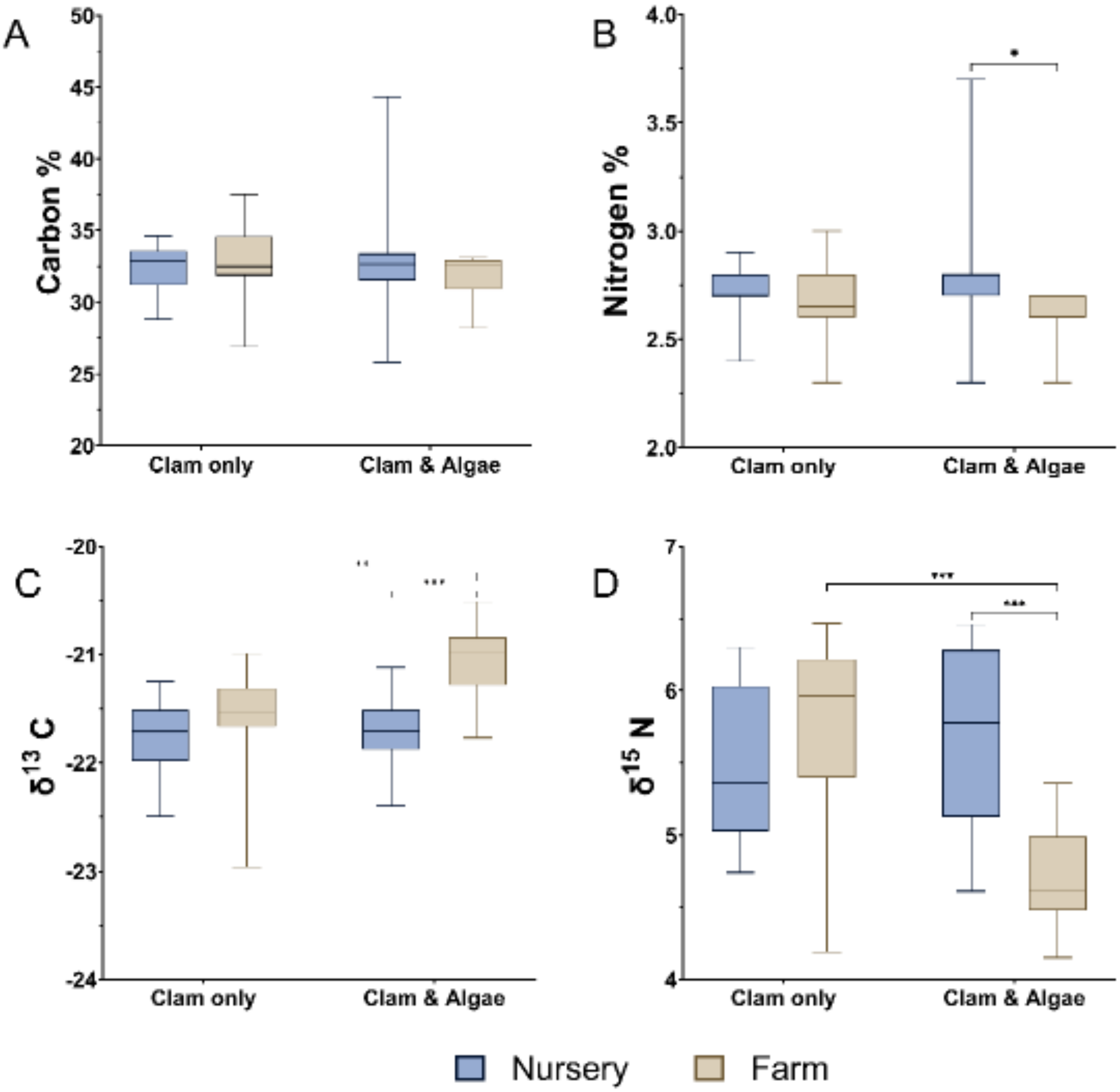


Figure 35. Stable isotope analysis of sunray venus clams by treatment. There was no significant difference in percent carbon (A) or percent nitrogen (B) by treatment or location, but nitrogen content as heavier in the algae treatment at the nursery than the farm (B). The δ^{13}C was significantly higher in the clam and algae treatment ($F_{(1, 65)}$ = 8.289, P = 0.0064) and on the farm ($F_{(1, 65)}$ = 20.66, P<0.0001; C). The δ^{15}N was significantly heavier in the clam only treatment ($F_{(1, 65)}$ = 8.670, P = 0.0045; D), but was significantly lower on the farm in the clam and algae treatment ($F_{(1, 65)}$ = 6.708, P = 0.0118; D). These data were leveraged from a related project funded by a NOAA Saltonstall-Kennedy grant led by Two Docks Shellfish.

3. Evaluation of Potential Ocean Acidification Mitigation Effects from Sugar Kelp Growth in a Point Judith, RI Kelp Farm

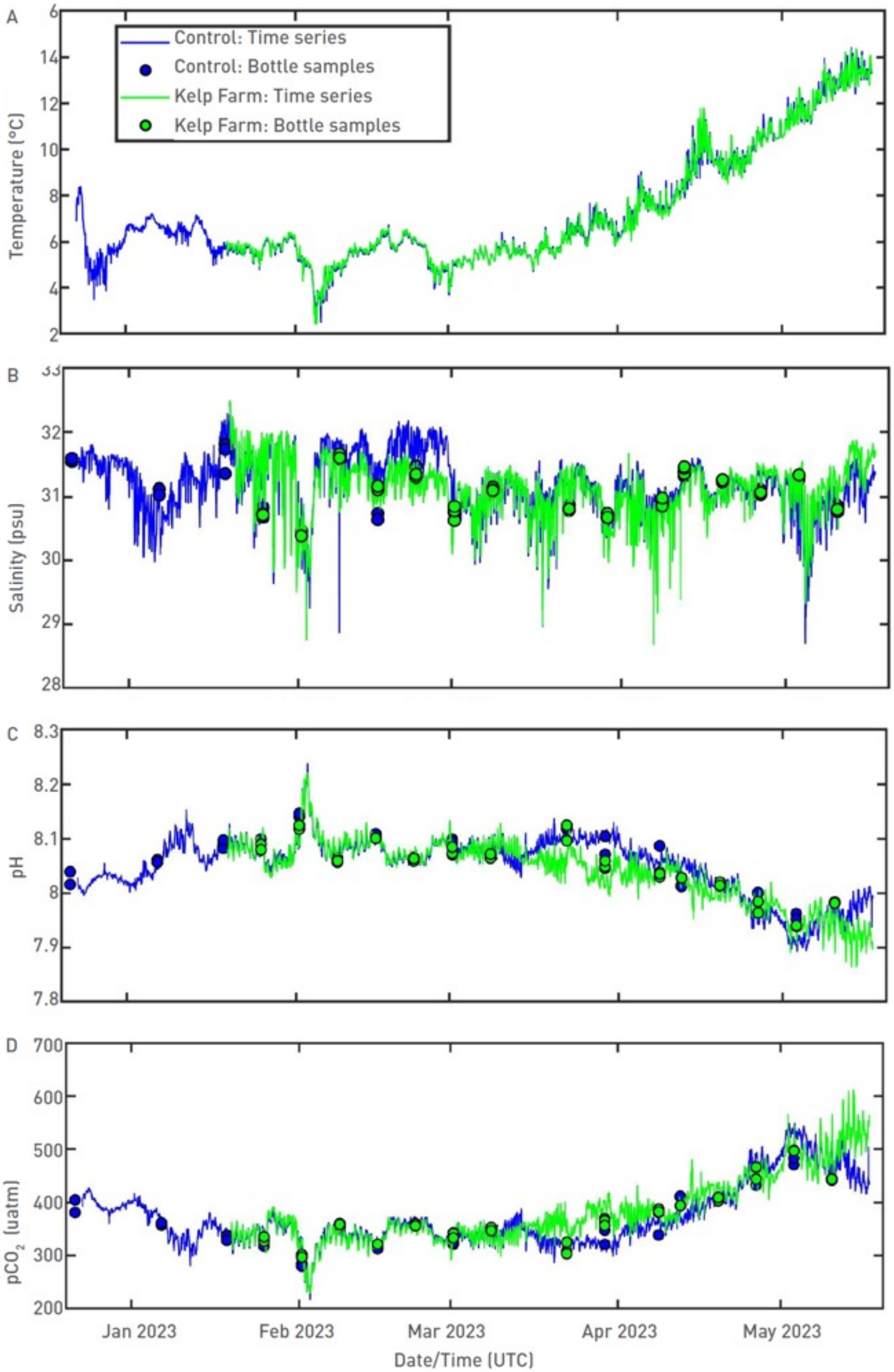


Figure 36. Evaluation of potential OA mitigation effects from sugar kelp growth in a Point Judith, RI kelp farm. The weekly (A) temperature, (B) salinity, (C) seawater pH, and (D) pCO_2 change resulted from sugar kelp growth compared to the control site. Note, we assumed that the phytoplankton-formed primary productivity is the same between these two sites.

4. Leveraging the Sustainability of Macrocystis pyrifera as a Feedstock to Produce Ingredients for Food, Animal and Industrial Applications Seaweeds

To understand the effects of extraction parameters for the aqueous (AEP) and enzyme-assisted-aqueous (EAEP) extraction processes (**Figure 37**) on the extractability of key compounds (alginates, laminarin, fucoidan, protein, phenolics) and biological properties of the extracts, the impacts of pH (4, 7, &10), BWR [g freeze-dried (FD) kelp/ mL water] (1:50 &1:30), reaction time (2 - 8 hours), and enzyme use (carbohydrase and protease) were evaluated. The use of a carbohydrase pretreatment followed by proteolysis produced extracts with high yields for most components. AEP (6 h, 1:30 BWR, 60 °C, at pH 4, 7, and 10), and EAEP conditions (5% carbohydrase, 2 h followed by 2.5% neutral protease, 2 h), were selected as optimum conditions for more complete characterization and profiling. AEP at pH 4 resulted in the highest fucose levels (13.07 mg fucose Eq/ g FD kelp) in the extracts, and alginate with the lowest M/G ratios. The use of enzymes in the EAEP resulted in extracts with the highest bioactivities (antioxidant activity of 213.10 ± 22.58 µmol TE/ g FD extract, 54% ACE inhibition, and 92% α-glucosidase inhibition).

Microwave-assisted (MAE) extraction (**Figure 38**) was evaluated at pH and BWR values matching the AEP for time 15 to 60 minutes, from 60 to 80 °C. Additionally, enzymes use was evaluated in the microwave-enzyme-assisted (MEAE) extraction process. Overall, acidic conditions led to a greater release of carbohydrates. Additionally, the use of higher temperatures led to enhanced extractability, likely due to decreased slurry viscosity. Dipole-dipole interactions from microwaves enhanced compound extractability allowing for faster extractions, which was reflected in the high yields obtained at 15 min. Furthermore, the integration of enzymes and microwaves lead to the release of more intracellular compounds (laminarin and peptides). Based on yields and resource utilization, MAE (15 to 30 min, 1:30 BWR, 70 °C, pH values of 4, 7, 10, and 4 shifted to 7) and MEAE conditions (5% carbohydrase pretreatment, 15 min followed using 2.5% neutral protease, 15 min) were selected for further characterization with respect to their composition and biological activities. MEAE yielded extracts displaying high bioactivities, including antioxidant capacity of 210.67 µmol TE/ g freeze-dried extract, 46% ACE inhibition, and 94% α-glucosidase inhibition.

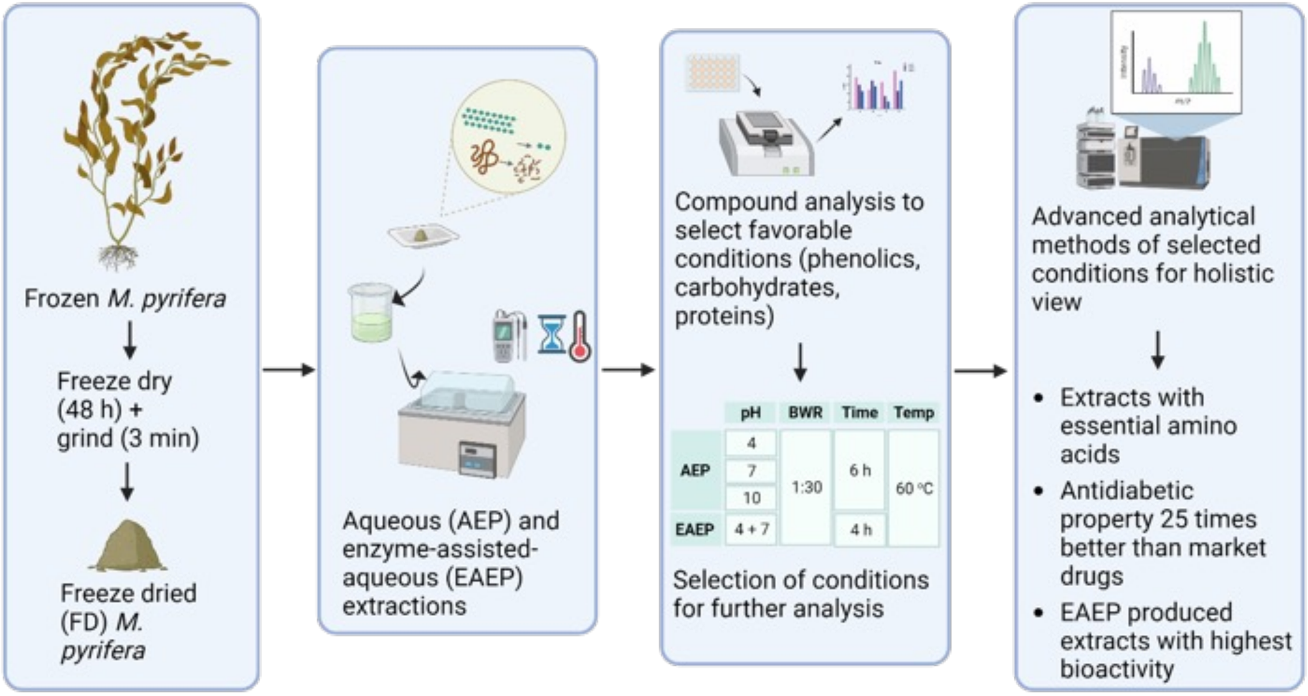
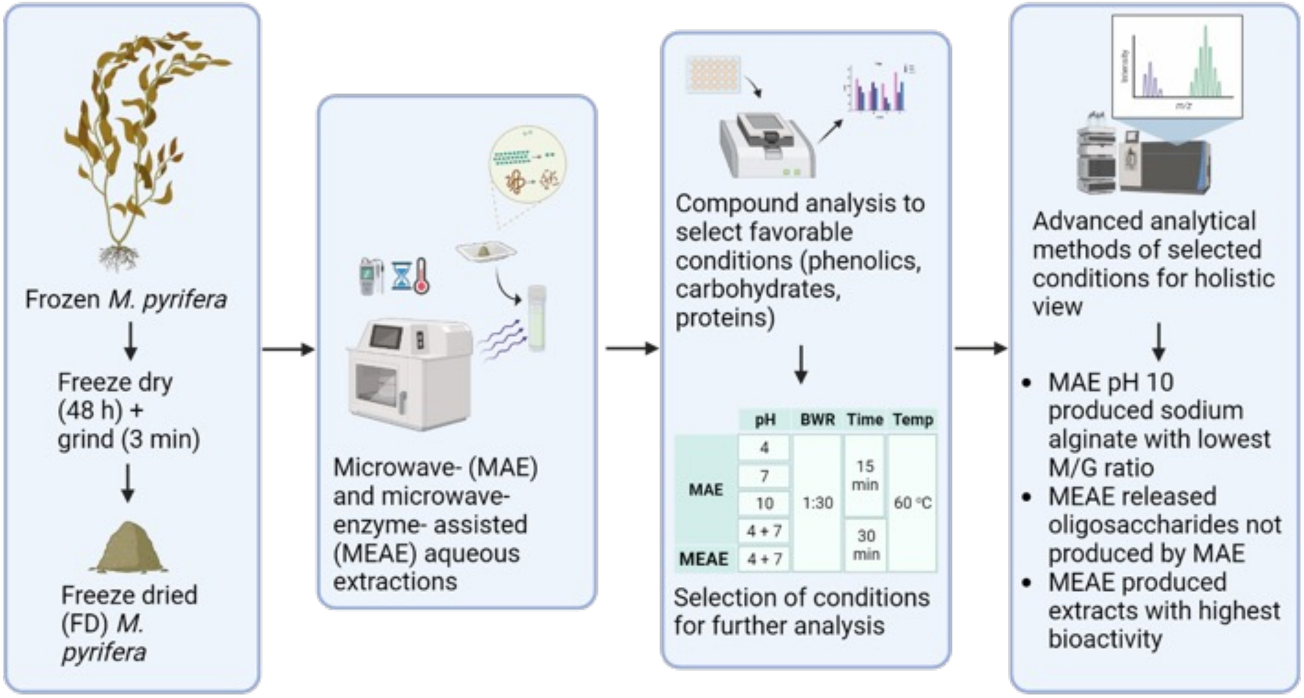


Figure 37. Graphical overview of aqueous and enzyme-assisted aqueous extraction processes. Created with BioRender.com.



Frozen *M. pyrifera*

Freeze dry (48 h) + grind (3 min)

Freeze dried (FD) *M. pyrifera*

Microwave- (MAE) and microwave-enzyme- assisted (MEAE) aqueous extractions

Compound analysis to select favorable conditions (phenolics, carbohydrates, proteins)

	pH	BWR	Time	Temp
MAE	4	1:30	15 min	60 °C
	7			
	10			
	4 + 7		30 min	
MEAE	4 + 7			

Selection of conditions for further analysis

Advanced analytical methods of selected conditions for holistic view

- MAE pH 10 produced sodium alginate with lowest M/G ratio
- MEAE released oligosaccharides not produced by MAE
- MEAE produced extracts with highest bioactivity

Figure 38. Graphical overview of microwave and microwave-enzyme-assisted aqueous extraction processes. Created with BioRender.com.

5. Offshore Platform-Based Macroalgae Production

Modeling Seaweed Farming Potential in the Gulf of Mexico

The UCI modeling team developed an estimate of seaweed aquaculture potential in the Gulf of Mexico using the latest calibrated tools and datasets. The Gulf of Mexico is a promising location for seaweed aquaculture among U.S. and state waters given its high productivity, wide shelf / shallow depths, and the potential for ecosystem co-benefits. Specifically, the Gulf of Mexico suffers from high levels of macronutrients from agricultural and water treatment runoff, with induced harmful algal blooms and associated low-oxygen dead zones. Seaweed aquaculture requires abundant macronutrients and could potentially reduce the impacts of anthropogenic nutrient loads.

The g-MACMODS model (Arzeno-Soltero et al., 2023)[378] has been further updated to include sub-daily time stepping and more accurate nutrient limitation methods after calibration using Ocean Era tank growth datasets. This enables operating g-MACMODS with a wider variety of forcing data sources. In the Gulf of Mexico, the PICES II biogeochemistry model has produced a series of hindcast simulations that include estimates of nutrient inputs from freshwater sources, including rivers along the Gulf of Mexico coastline. Nitrate from the top 20m of the water column was extracted from these hindcasts for use in g-MACMODS. PAR data from the ECMWF ERA5 reanalysis were interpolated to 3-hour values, and a 3-hour time step was used in simulations. Forcing data were acquired for the years 2003-2019, and 16 years of simulations were used to create macroalga yield and nitrogen uptake maps across the Gulf of Mexico. (**Figure 39A**).

Extrapolating g-MACMODS macroalgal yield and nitrogen over any particular area is fraught with issues, including competing uses, permits and regulations, and in the case of un-coupled models, the total yield that could be supported based on the ecosystem limits. In the Gulf of Mexico, the NOAA NCCOS effort to identify Area of Opportunity (AOA) for aquaculture produced maps higher potential for aquaculture development in the Gulf of Mexico, however these areas appear more suited toward finfish aquaculture efforts, as they are in deeper water with lower nutrients (**Figure 39B**). The UCI modeling team has compiled data layers used in the Gulf of Mexico NOAA NCCOS AOA process, as well as other near-shore layers that are likely to cause exclusion of aquaculture (**Figure 39B**). Work is in process to produce appropriate buffers around these layers to enable mapping of macroalgae potential. Analyses will include ranking which competing uses are most significant in reducing macroalgae potential in high-yield areas, and comparing the anthropogenic inputs and locations to the nitrogen update potential from possible macroalgae aquaculture.

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[378] Arzeno-Soltero, IB*, CA Frieder, BT Saenz, MC Long, J DeAngelo*, SJ Davis, and KA Davis. Large global variations in the carbon dioxide removal potential of seaweed farming due to biophysical constraints. Communications Earth & Environment, 4(1), 185.

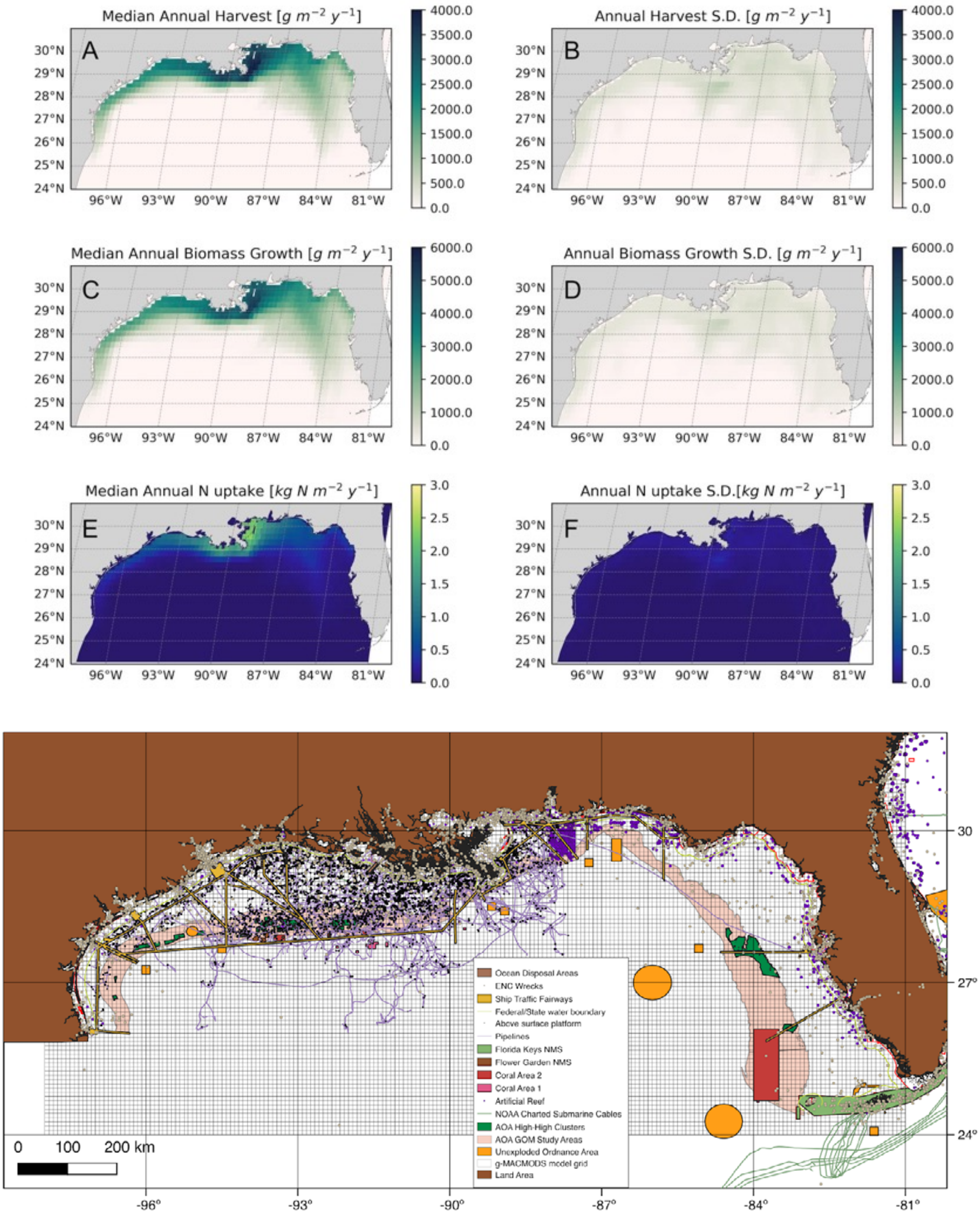

Figure 39. (A) Median and standard deviation (S.D.) of potential harvest (A-B), total biomass production (C-D), and nitrogen uptake (D-E) from Eucheuma-type tropical red macroalgae in the Gulf of Mexico produced by g-MACMODS, over years 2003-2019 and (B) Map of potential conflicting objects, structures, uses and protected areas when considering macroalgal cultivation potential in the Gulf of Mexico.

Observational Study at Two Oil Platforms in the Gulf of Mexico

Physical oceanographic observations were collected at West Delta 117 (site of seaweed farm trial) and South Pass 83 oil platforms in fall 2023. **Figure 40** shows depth profiles of water temperature, salinity, and density for each platform site on 06 September 2023 and illustrates expected density variation with depth, including the presence of a freshwater plume near the surface at West Delta 117 during the sampling period. Additionally, an oceanographic mooring was located at South Pass 83 for approximately two months from 09 September – 19 November 2023. Measurements included currents, pressure, water temperature, conductivity, salinity, oxygen, and photosynthetically active radiation (PAR) at 22 meters depth on a mooring attached to the platform cross-supports (**Figure 41**). Tidal range in sea surface height during the deployment was 0.5 meters. Currents in the upper 10m of the water column are on average 15 cm/s (**Figure 42**). Oceanographic conditions as measured in this study are conducive to seaweed growth.

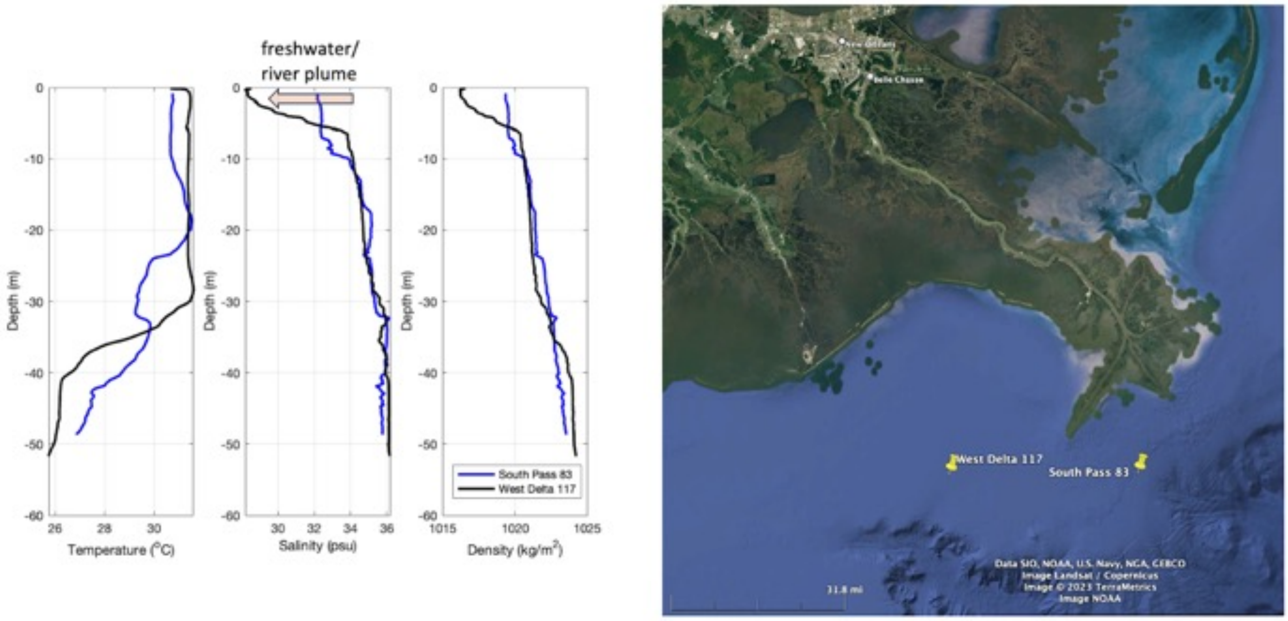

Figure 40. (Left) Water temperature, salinity, and density profiles from CTD casts taken on 06 September 2023 at two oil platforms in the study region – West Delta 117 and South Pass 83 (right).

Figure 41. (left) South Pass 83 oil platform, (center) ADCP, CTD, and PAR sensors, (right) sensors in place on South Pass 83.

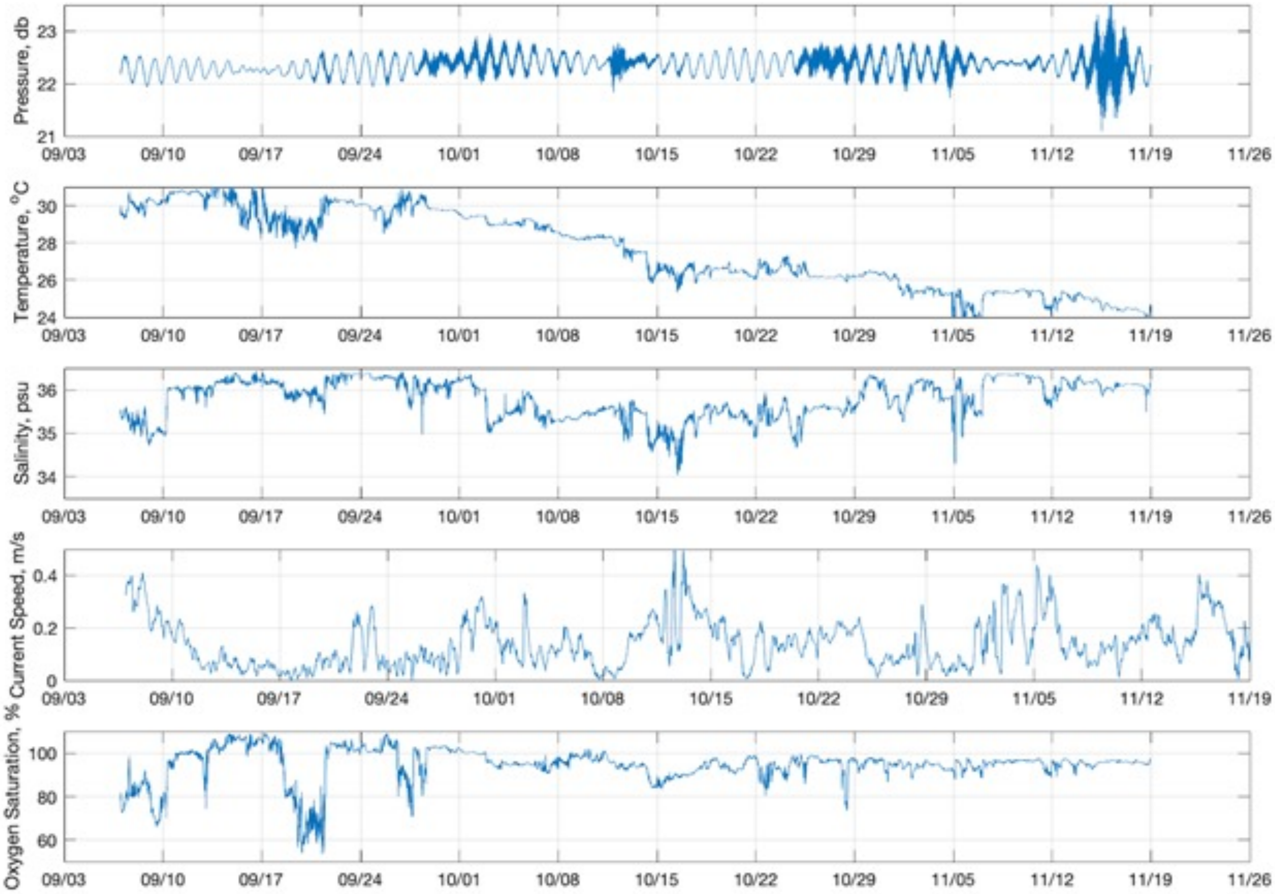

Figure 42. Time series of pressure, water temperature, salinity, current speed, and oxygen saturation from an oceanographic mooring placed on South Pass 83 oil platform at 22m depth in Fall 2023.

6. Bull Kelp Farm Improvements to Enable Scaling of Innovative Food Products

Researchers collaborated with two kelp farmers tending three farm sites to preliminarily examine how depth, water flow, and seeding density affected stipe morphometrics of bull kelp (highest valued portion per sporophyte). Objectives were to:

1. Determine if morphological differences occur between bull kelp farmed at lower vs. higher water flow. Assessments were conducted at two sites, one with water velocity measured at 0.4 m/s with bidirectional flow and the other at 0.11 m/s with unidirectional flow.
2. Determine if seeding at a lower density contributes to increased stipe size (length and thickness). Assessments were conducted at three farm sites comparing continuous vs intermittent seeding (10cm of seedstring placed every meter of growout line) seeded at a density of 2500 spores/ml.
3. Determine if the depth at which farming occurs contributes to producing larger bull kelp. Seeding was done continuously at the density above with growout lines installed at three vs six meters deep.

Results indicate that cultivation at six meters depth generates greater biomass yields (**Table 16**).

Table 17. Average bull kelp morphological characteristics at 3 & 6 meters deep

Depth	Stipe length (cm)	Number of blades/ plant	Stipe diameter (mm)	Bulb diameter (mm)	Sporophyte length (cm)
3 m	244	18	39	62	511
6 m	307	21	41	68	556

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