Better Practices for Sustainable Seaweed Cultivation in the Caribbean

July 2024

The Nature Conservancy

THE UNIVERSITY OF CHICAGO
MARINE BIOLOGICAL LABORATORY

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Acknowledgments

Financial support for this document was provided by the U.S. Department of Energy MARINER program (i.e., the Macroalgae Research Inspiring Novel Energy Resources program).

We appreciate the assistance of the following reviewers:

- Anna-Cherice Ebanks Chin, TNC–Jamaica Program
- Amrita Mahabir, TNC Eastern Caribbean Office

Recommended citation

The Nature Conservancy. 2024. Better practices for sustainable seaweed cultivation in the Caribbean. Arlington, VA.

Photo credits

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Section cover: Each main section of this report features the following photo: *Eucheumatopsis isiformis* collected from the Florida Keys. Photo credit: Mayra A. Sánchez García, MBL.

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Abbreviations

This section includes two lists. The first list defines all the acronyms and abbreviations used in the document to ensure clarity and ease of reference for readers. The second list defines the relevant units of measure.

Acronyms and abbreviations

ARPA-E	Advanced Research Projects Agency-Energy
ASC	Aquaculture Stewardship Council
BAHA	Belize Agricultural Health Authority
BBS	Belize Bureau of Standards
BMP	Better Management Practice
CAEIH	Caribbean Aquaculture Education and Innovation Hub
CariCOOS	Caribbean Coastal Ocean Observing System
CFR	U.S. Code of Federal Regulations
CINVESTAV	Centro de Investigacio´n y de Estudios Avanzados [Center for Research and Advanced Studies]
CWA	U.S. Clean Water Act
CZMA	U.S. Coastal Zone Management Act
DW	dry weight
EEZ	exclusive economic zone
ESA	U.S. Endangered Species Act
FAO	Food and Agriculture Organization of the United Nations
FR	U.S. Federal Register
FSMA	U.S. Food Safety Modernization Act
HACCP	Hazard Analysis Critical Control Point
IUCN	International Union for the Conservation of Nature
MARINER	Macroalgae Research Inspiring Novel Energy Resources
MBL	Marine Biological Laboratory
MMPA	U.S. Marine Mammal Protection Act
MSC	Marine Stewardship Council
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
PAR	photosynthetic active radiation
PATON	Private Aids to Navigation
PPCSL	Placencia Producers Cooperative Society Limited
PR DNER	Puerto Rico Department of Natural and Environmental Resources
PVC	polyvinyl chloride
R&D	research and development
REEF	REEF - Reef Environmental Education Foundation
SOS Carbon	Sargassum Ocean Sequestration Carbon
STEM	science, technology, engineering, and mathematics
SWOT	strengths, weaknesses, opportunities, and threats
TNC	The Nature Conservancy
TTSCH	Techniques for Tropical Seaweed Cultivation and Harvesting
UNDP	United Nations Development Program
USACE	U.S. Army Corps of Engineers
U.S.C.	U.S. Code
USD	U.S. dollar
USFWS	U.S. Fish and Wildlife Service
WAS	World Aquaculture Society
WHOI	Woods Hole Oceanographic Institution
WW	wet weight

Units of measure

cm	centimeter
ha	hectare
kg	kilogram
km	kilometer
lb	pound
m	meter
mm	millimeter
MT	metric tonnes
ppm	parts per million
°C	degree Celsius

Executive summary

The Caribbean region has immense potential for developing a sustainable seaweed farming industry. Cultivating seaweed can address various socioeconomic and environmental challenges, including restoring marine ecosystems, creating new livelihoods, and providing raw materials for various industries. Unlike some forms of aquaculture, seaweed farming requires no feed or fertilizer and minimal freshwater or arable land, making it an attractive option for sustainable development. When done right, seaweed farming not only benefits the environment but also supports local economies by creating jobs and promoting food security.

Status of seaweed aquaculture in the Caribbean

Despite the region's current minimal seaweed production, the Caribbean, with its rich biodiversity and favorable tropical climate, presents significant potential for seaweed aquaculture. Historically, indigenous Caribbean communities engaged in various aquaculture practices, which evolved with European colonization and modern techniques in the 20th century. Seaweed aquaculture, specifically, has existed in the Caribbean on an artisanal scale since the 1970s. Methods were adopted from the Philippines and the Indo-Pacific to grow red seaweed species like *Hypnea* spp., *Gracilaria* spp., *Kappaphycus alvarezii*, and *Eucheumatopsis isiformis*.

Belize and St. Lucia are pioneers in the Caribbean seaweed sector. Supported by local and international partners, Belize has developed cultivation techniques and training programs, although seaweed production remains nascent with a focus on local markets. St. Lucia has seen high export demand for cultivated seaweed; government investments in capacity building, processing facilities, and export promotion have expanded the sector, with products reaching markets in Dubai, the United Kingdom, and the United States. While detailed production data for other Caribbean locations are scarce, the success in Belize and St. Lucia highlights the region's potential for expanding seaweed aquaculture.

Better Management Practices (BMPs) are used to enhance the efficiency and sustainability of operations in various fields, particularly agriculture and environmental management. They are designed to minimize negative environmental impacts, maintain the long-term productivity of resources, support compliance with regulatory requirements, and promote overall ecosystem health. This document outlines region-specific BMPs to guide the management and further establishment of sustainable seaweed farming operations in the Caribbean. These practices will help ensure that seaweed farming can meet ecological, economic, and social objectives.

Production recommendations for nearshore, small-scale seaweed farming in the Caribbean

Selecting an appropriate site is crucial for the success of a seaweed farm. Environmental suitability must be considered, ensuring the site has the right water quality, depth, and current flow to support seaweed growth without harming the environment. It is also important to minimize the impact on marine ecosystems by avoiding areas with sensitive habitats, such as coral reefs, mangroves, and seagrasses. Additionally, the farm layout should be designed to withstand local weather conditions and reduce the risk of seaweed loss or gear damage.

Nursery operations are foundational to the sustainable development of seaweed farming in the Caribbean, addressing the insufficient wild seaweed populations that cannot support industrial-scale harvesting to produce propagules or seeds for cultivation. The most common method of seed production is vegetative propagation. It involves subdividing mature organisms into smaller pieces, but this can reduce genetic diversity and increase vulnerability to disease.

An alternative, spore-based propagation, supports genetic diversity and strain development by inducing spore release in sexually reproductive individuals, leading to the growth of new individuals for outplanting. This alternative would offer a more sustainable approach despite requiring advanced nursery facilities and expertise. Nurseries should be equipped with tanks that maintain stable water temperatures and should ideally be in climate-controlled buildings to support continuous cultivation during adverse weather conditions. The nurseries should be managed through cooperative models or integrated business operations, enhancing community involvement and resource sharing by utilizing existing infrastructure, such as fishing cooperatives, to foster a collaborative approach to seaweed farming.

Sustainable farming techniques are essential for maintaining the health and productivity of seaweed farms. Using healthy, pest-free seedlings, minimizing their exposure to air and adverse conditions during planting, and regularly cleaning the farm and all gear ensure robust growth. Following a structured planting, maintenance, and harvesting schedule allows for continuous production while providing time for environmental recovery. Regularly inspecting and maintaining propagules and farming gear prevent marine plastic pollution and support long-term sustainability.

Proper harvesting practices are vital to minimize environmental impact and maintain the quality of the seaweed. Handling seaweed carefully during harvesting reduces bycatch, minimizes disturbance to the seafloor, and decreases the loss of biomass. Implementing noise-reducing practices, such as turning off boat engines while harvesting, helps minimize disruption to local wildlife and communities.

Market opportunities and supply chain considerations for Caribbean seaweed sourced from small-scale farms

Maintaining high standards in **postharvest processing** is critical for ensuring product quality and safety. Harvested seaweed should be processed in clean conditions to preserve its quality. Efficient waste management practices should be implemented to minimize environmental impact. These steps are essential for producing high-quality seaweed products that meet market demands and regulatory standards.

Engaging local communities in decision-making processes and providing training supports their participation and investment in seaweed farming. Encouraging and supporting women's involvement in seaweed farming activities recognizes their contributions and promotes gender equality in the industry. These practices help build resilient and inclusive local economies.

Adhering to **third-party sustainable sourcing standards** can add commercial value to seaweed products and ensure compliance with global sustainability criteria. These certifications enhance marketability and consumer confidence in seaweed products. Examples of notable standards are the *ASC-MSC Seaweed Standard* by the Aquaculture Stewardship Council – Marine Stewardship Council and the *Technical Guidelines on Aquaculture Certification* by the Food and Agriculture Organization of the United Nations. See this report's section called "existing and prospective seaweed farmers" for a complete list and details.

The global demand for seaweed and seaweed-derived products is increasing, driven by growing awareness of their health benefits and environmental sustainability. Caribbean seaweed farmers and businesses can tap into **emerging markets** such as nutraceuticals, cosmeceuticals, bioplastics, biostimulants, and animal feeds. The BMPs emphasize the importance of market research and the development of value-added products to capture these opportunities. Establishing efficient supply chains, cooperative processing facilities, certification programs, and partnerships with international buyers can enhance market access and competitiveness, positioning the Caribbean as a key player in the global seaweed industry.

Diversifying the species cultivated is crucial for the resilience and economic potential of the seaweed farming industry. Species such as *Hypnea* spp., *Gracilaria* spp., *E. isiformis*, and other native red seaweeds are favored for various commercial applications, ranging from food and cosmetics to biofuels and nutraceuticals. Cultivating multiple species can mitigate the risk of crop failure and enhance market opportunities, creating a more robust and sustainable industry. By focusing on species that thrive in local conditions, the Caribbean can develop a diverse seaweed farming sector that supports both environmental and economic goals.

Opportunities to support the growth of seaweed aquaculture in the Caribbean

Addressing **key research and development (R&D) areas** is vital for the growth and sustainability of the Caribbean seaweed industry. R&D investment, particularly in breeding programs and cultivation techniques, can further strengthen the region's position in the global market. By leveraging local resources and expertise, the Caribbean can innovate and produce seaweed products that meet international standards and consumer preferences. This strategic focus on emerging markets can drive sustainable economic growth and create new opportunities for local communities. Promoting the benefits of sustainable aquaculture practices among local and regional stakeholders can change perceptions and encourage broader adoption. Developing clear and transparent regulatory frameworks for seaweed farm siting, approval, processing, and distribution is essential for streamlined operations. Encouraging entrepreneurship and securing investment from both public and private sectors can drive innovation and industry expansion.

A plethora of opportunities offer options to **get involved** in the emerging Caribbean seaweed farming industry (Bjerregaard et al. 2016; World Bank 2023). For investors, focusing investments on operations using BMPs and structuring transactions to mitigate risks is essential. Seaweed companies should use flexible business models and financing strategies to adapt to market conditions. Nonprofit organizations can play a crucial role by advocating for fair wages, providing education on farmer safety, and promoting the development and adoption of BMPs. Collaboration among these stakeholders is key to the success of the industry.

Large-scale seaweed farming potential and considerations

Large-scale seaweed farms require significant financial investment, logistical support, and labor. Thus, they exceed the capabilities of small teams and currently do not exist in the Caribbean, though interest in seaweed biomass across various industries necessitates evaluating their feasibility in the region. This evaluation must consider potential environmental impacts and production challenges, learning from Asia's experiences while recognizing the Caribbean's unique conditions, requiring a precautionary approach and extensive exploratory research. **Key R&D components for large-scale farming** include site suitability analysis, specialized equipment, ecological studies, and production cost estimates to indicate economic competitiveness for seaweed biomass grown in specific locations within the Caribbean. Of note is the importance of designing, siting, and managing large-scale farms to protect marine biodiversity and minimize conflicts with other water users.

Outlook

The adoption and implementation of BMPs in the Caribbean seaweed farming industry will require collaboration among farmers, researchers, policymakers, and industry stakeholders. By following these guidelines, stakeholders can contribute to a thriving seaweed aquaculture industry that benefits both people and the planet. With the right support and investment, the Caribbean can harness the power of seaweed farming to drive sustainable development and create a brighter future for its communities and ecosystems. This document serves as a foundational resource for guiding the growth of the seaweed aquaculture sector in the Caribbean, ensuring that it is both economically viable and environmentally sustainable.

Introduction

The Nature Conservancy (TNC) is dedicated to fostering a world where both humanity and nature flourish. With a vision to propel the world toward sustainability by 2050, we draw upon our extensive 65-year legacy of safeguarding vital natural landscapes across the globe. Our key global strategies encompass combatting climate change; preserving ocean, land, and water resources; and ensuring sustainable provisioning of food and water for a burgeoning population. A pivotal aspect of our strategy involves collaborating with farmers to establish sustainable and restorative food sources for future generations. Specifically, our aquaculture conservation work aims to advance innovative solutions that not only mitigate potential adverse effects associated with food production but go beyond sustainable to achieve nature-positive results. We actively engage with farmers to optimize the environmental benefits of aquaculture while advocating for intelligent and sustainable economic development. By employing market-driven approaches in conjunction with innovative farming practices and policies, we believe that aquaculture, when farmed in the right locations and the right ways, can be the leading global regenerative food system.

TNC has been working with local partners and co-leading conservation and sustainability initiatives in the Caribbean for more than 40 years. We have programs in 17 Caribbean countries and territories, and our work across the region includes:

- encouraging sustainable seafood via education on keystone reef fish species like parrotfish,
- leading mangrove and coral restoration,
- supporting hurricane recovery,
- building resiliency to the impacts of climate change, and
- working with governments on debt-for-nature swaps designed to allow highly indebted countries to redirect resources to conservation initiatives.

A relatively new area of work for TNC in the Caribbean region is engaging in seaweed aquaculture research and conservation to benefit both people and nature.

When done well, seaweed aquaculture presents a significant opportunity to coastal communities worldwide as an eco-friendly income source. Effectively managed seaweed farming enhances water quality, acts as a buffer against local acidification, and even fosters habitats for various marine species. The practice requires no feed inputs and only minimal quantities of freshwater or arable land, with the latter two used for some nursery operations and/or for rinsing and drying harvested seaweed. In contrast, unsustainable farming practices can lead to competition for space in nearshore environments, resulting in detrimental effects on corals, mangroves, and seagrasses. Thus, any attempts to either introduce seaweed farming into new regions or expand existing operations must involve smart siting for farms as well as education and collaboration in Better Management Practices (BMPs) to ensure seaweed farming is mutually beneficial for both coastal communities and the environment. BMPs are used to enhance the efficiency and sustainability of operations in various fields, particularly agriculture and environmental management. They are designed to minimize negative impacts on the environment, maintain the long-term productivity of resources, support compliance with regulatory requirements, and promote overall ecosystem health.

We also recognize a prevalent trend within the global seaweed industry wherein women comprise a substantial portion of the seaweed aquaculture workforce. In some instances where farming conditions and culture allow, women lead all aspects of seaweed farming. In others, they are more involved in gear preparation, postharvest processing, and sales (Periyasamy et al. 2013; Msuya and Hurtado 2017; Ramirez et al. 2020). Regardless of their specific activities, in areas where women actively engage in seaweed farming, they often note a positive impact on their income and social standing, making seaweed farming an important livelihood for women globally (Msuya 2011; Msuya and Hurtado 2017). The guide presented here is intended to serve as a foundation that key players within the seaweed industry, regulators, scientists, and community leaders can use when planning for and developing seaweed aquaculture in the Caribbean region. We build on the knowledge and recommendations shared in several other resources, with the goal of providing high-level guidance applicable throughout the Caribbean.

However, we also must emphasize that the information presented here is not exhaustive. The ecology, environmental regulations, or socioeconomic conditions in a specific location or nation may differ from the broad overview provided in this guide. So, it is important that the user always check for location-specific guidance at these levels to build on the general approaches presented in this guide; this applies especially to environmental regulations and marine spatial planning. Furthermore, in cases such as Belize, where a country-specific guide for seaweed aquaculture exists, we advise the reader to defer to the local guidance there. Lastly, we acknowledge that the development, recognition, and adoption of better practices is an iterative process. As such, this guide is a living document. We welcome additional information and guidance that further enrichens or complements the information presented here, and the document will be revised accordingly. (For contact information, please refer to this document's inside cover, where the corresponding authors are listed.)

In Section I, we provide a brief overview of historical and current seaweed farming in the Caribbean. Section II introduces the most relevant production-related considerations for small-scale tropical seaweed farming and synthesizes recommendations for better practices related to each. Section III describes market opportunities and supply chain considerations for Caribbean seaweed sourced from small-scale farms. In Section IV, we highlight opportunities for individuals, organizations, and governments to support the growth of seaweed aquaculture in the Caribbean. Lastly, Section V summarizes recent research and development (R&D) focused on the potential for large-scale seaweed farming in the region.

Figure 1. Fish, including Bermuda chubs and sergeant majors, swarm a dive boat off Lighthouse Reef Atoll, Belize. Photo credit: Jennifer Adler, Jennifer Adler Photography.

Section I. Status of seaweed aquaculture in the Caribbean

Overview

The Caribbean is a geographically diverse and ecologically rich region nestled within the western North Atlantic Ocean and bounded by the islands of the Greater and Lesser Antilles (Figure 2). Its warm tropical waters, extensive coral reefs, and intricate network of oceanic currents have positioned the Caribbean as a global hotspot for marine biodiversity. The region also has a delicate interplay between environmental conservation and economic development. The Caribbean encompasses a range of political systems, from independent states to overseas territories, each with its own maritime jurisdiction and interests. Thus, the governance of marine resources, such as fisheries and exclusive economic zones (EEZs), often forms a crucial component of the Caribbean's political and socioeconomic dynamics, as these resources play a significant role in the region's food security and economic stability. Tourism, a major driver of the Caribbean's economies, relies on the allure of pristine beaches, coral reefs, and marine activities such as snorkeling and scuba diving. However, pollution, habitat loss, and fishing pressure impact coastal zones in many parts of the region, and with climate change, the region faces rising sea levels and more frequent and severe hurricanes (Diez et al. 2019; Clegg et al. 2020).

Figure 2. Countries and territories with coastlines on the Caribbean Sea. Image credit: Jim Kopp, Kopp Illustration, Inc.

Aquaculture has a long and diverse history in the Caribbean region. Indigenous Peoples in the Caribbean practiced various forms of aquaculture, including the construction of fishponds and the cultivation of mollusks, providing sustenance and economic benefits for their communities. With the arrival of European colonizers, aquaculture practices underwent significant changes, incorporating new species and techniques. In the 20th century, modern aquaculture methods were introduced, leading to the emergence of commercial aquaculture operations throughout the Caribbean. However, despite the region's vast ocean resources, production in the Caribbean is minimal. In 2018, less than 9000 metric tonnes (MT) of aquaculture products were generated, which is less than 0.5% of global aquaculture production (Ruff et al. 2019; FAO [Food and Agriculture Organization of the United Nations] 2020).

Since the 1970s, seaweed aquaculture has intermittently occurred at artisanal scales in the Caribbean (Smith et al. 1986; Smith 1997; FAO 2020). These efforts have built upon methods developed in the Philippines and Indo-Pacific, using spore recruitment or vegetative propagation on lines or solid substrates. While no large commercial-scale operations currently exist, the Caribbean's warm waters, abundant sunlight, and nutrient-rich coastal areas are believed to create favorable conditions for seaweed farming. These conditions — combined with the popularity of puddings and a blended drink made from dried red seaweed (*Hypnea musciformis*, *Kappaphycus alvarezii*, *Eucheumatopsis isiformis*, or *Gracilaria* spp.), spices, and milk — have encouraged artisanal seaweed farming on multiple islands (Smith et al. 1986; Hayashi et al. 2017). These seaweed preparations exist primarily in the English-speaking islands but also in a few Central American locations, including Honduras and Panama, where migrants from the Caribbean introduced the preparations (Rosado-Espinosa et al. 2020). More recently, seaweed has begun to be used regionally as an input for various "natural" facial and hair products (as further described in the subsection "existing markets and processing for Caribbean-grown seaweed"). In some locations, wild seaweed harvesting has occurred for some time, and seaweed aquaculture industries have developed in response to depleted natural stocks or in recognition of the demand for products growing beyond what can be met by wild harvesting alone.

Seaweed species commonly grown and harvested in the Caribbean

Seaweeds are macrophytic algae that lack true roots, stems, and leaves. They are classified as green algae (Chlorophyta), brown algae (Heterokontophyta), and red algae (Rhodophyta), so named based on the dominant pigment produced in each phylum. Species in each of these phyla have commercial value, but commercial production in tropical waters is almost entirely focused on the red algae. Red seaweeds are the largest group of marine macroalgae, consisting of between 4000 and 6000 species. They can be found attached to rocks or other hard substrata in coastal areas (Kilinç et al. 2013). The species diversity is higher in tropical and subtropical waters, such as the Caribbean, Indonesia, the Philippines, China, and other countries with similar climates (Khan and Satam 2003). Per 2019 findings, over half of recent global seaweed production by weight were red seaweeds (Cai et al. 2021). The majority of tropical red seaweed production at a global scale goes into carrageenan and agar production. Only a small portion of the total tropical red seaweed harvested goes to food, body products, or other uses. However, existing seaweed harvests in the Caribbean are almost exclusively for these purposes.

In the upcoming subsections, we briefly describe perennial red seaweed genera that have existing commercial value in the local and global markets. These seaweeds are either native to the Caribbean (e.g., *Eucheuma, Gracilaria*) or naturalized (e.g., *Kappaphycus*). A discussion about other genera with qualities potentially of commercial interest but needing additional development (e.g., *Hypnea, Solieria*) is presented in the subsection "additional candidate species."

Box 1: A note about common names

The common name "seamoss" is used to refer to at least 10 different species of seaweeds in the Caribbean. In some places, like Jamaica, the term "Irish moss" is also used. Therefore, to avoid confusion, we have used the species' scientific names whenever possible. When the species name is not provided, we have, instead, used the terms "seaweed" or "macroalgae."

Eucheuma

Eucheumatopsis isiformis (syn.: *Eucheuma isiforme*) is a species of red algae in the family Solieriaceae (Guiry and Guiry 2019; Núnez-Resendiz et al. 2019). It is closely related to *Eucheuma denticulatum* (previously *E. spinosum*), which is widely cultivated in Asia and Africa as raw feedstock for carrageenan production. However, *E. isiformis* is a native species endemic to the tropical and subtropical western Atlantic Ocean. It is found throughout the Caribbean but is nowhere locally abundant. *E. isiformis* exhibits rapid growth in the spring, ceases to grow in the summer, develops tetraspores in the fall, and then goes through sporulation, followed by the disintegration of mature plants in the winter. Its spores germinate the next spring (Dawes et al. 1974). Eucheumatoid species naturally produce high amounts of carrageenan, a compound commonly used in the food, cosmetic, and pharmaceutical industries. *E. isiformis* produces iota-carrageenan, which has been shown to typically be 40%–60% of the organism's salt-free, dry weight (DW; Guist et al. 1985; Caamal-Fuentes et al. 2017).

Historically, wild populations of *E. isiformis* have been collected for traditional foods and exported beyond the Caribbean in small amounts (Smith and Fort 1997; Smith and Renard 2002; Hayashi et al. 2017). *E. isiformis* is grown and harvested commercially in Belize, where approximately 800 kg (air-dry weight) were exported annually to the United States for use in health-food applications during the 1990s. In recent years, the export of seaweed has been much less than this, but harvesting continues for this purpose and for local consumption. The establishment of marine protected areas that include harvesting sites on the Belize barrier reef has led to renewed interest in cultivation to provide alternative sources. On average, *E. isiformis* cultivated in Belize reaches 24–30 cm after 90 days (TNC 2017). The growth of vegetative *E. isiformis* propagules in Florida and Belize averages 2%–2.4% per day (Dawes 1974; Dubon et al. 2021), and a typical cultivation cycle for *E. isiformis* in Belize is 10–12 weeks (Dubon et al. 2021).

Kappaphycus

Figure 3. *Kappaphycus alvarezii*. Photo credit: Juli-Anne Russo, CAEIH.

K. alvarezii (Rhodophyta, Gigartinales), also known commercially as *Eucheuma* [a] *cottonii* or simply cottonii, is a red alga native to the Indo-Pacific (Figure 3). *K. alvarezii* has been introduced throughout the warm tropics for commercial cultivation because it grows quickly, [b] and it produces high yields (up to 35% DW; Pong-Masak and Sarira 2020) of kappa-carrageenan, which has an established commercial value in global markets. *K. alvarezii* was introduced to the Caribbean Sea in the 1970s. Within the Caribbean, *K. alvarezii* is either currently grown or has historically been grown in Belize, St. Lucia, Mexico, Panama, Jamaica, Cuba, Venezuela, and Brazil (Cabrera et al. 2019). Caribbean seaweed farmers seem to have developed a preference for growing *K. alvarezii* over *E. isiformis* or *Gracilaria* spp.; however, it is often difficult to confirm the taxonomy of specific cultivars farmers use without molecular analysis. In many countries where it has been introduced, *K. alvarezii* remains confined to seaweed farming areas. In other parts of the world, like India and Hawaii in the United States, it has become an invasive species (Rodgers and Cox 1999; Conklin et al. 2009; Arasamuthu et al. 2023). A more in-depth review of *Kappaphycus* farming and the potential trade-offs of farming it in the Caribbean Sea is presented in Appendix A.

Gracilaria

The *Gracilaria* genus contains over 100 species. *Gracilaria* spp. are cultivated throughout the world, but China and Indonesia produce the overwhelming majority. In 2016, these two countries were responsible for 98% of the global production of farmed *Gracilaria* (FAO 2016; Kim et al. 2017). *Gracilaria* spp. naturally produce large quantities of agar; up to 25% of an individual's DW may be attributed to agar (Yudiati et al. 2021). As such, the *Gracilaria* genus is currently the principal source of agar worldwide (Freile-Pelegrìn and Murano 2005).

Numerous *Gracilaria* spp. are both native to the Caribbean and strong candidates for commercial aquaculture production, including *G. armata, G. cervicornis, G. cornea, G. crassissima, G. debilis, G. mammillaris, G. edulis*, and *G. domingensis* (Figure 4; Zertuche-Gonzalez 1993, 1996, 1998; Zertuche-Gonzalez et al. 1999; Smith 1997; Bhushan et al. 2023). These species are widespread throughout the Caribbean Sea but seldom abundant in any one location. *Gracilaria* spp. are notoriously hard to identify to the species level, and not all are readily distinguishable by their morphology. In some cases, the location of the wild population can provide a clue for species identification. For example, in St. Lucia, *G. crassissima* is found in calm areas, and *G. debilis* in areas with moderate to severe wave action, typically on rock or coral rubble (Smith et al. 1984).

The fast growth rates and relative robustness of *Gracilaria* spp., in addition to their high agar yields, make them good candidates for seaweed farming.

[a] Until 1996, *K. alvarezii* was named *Eucheuma alvarezii* or *Eucheuma cottonii*, but molecular studies of the species' genotype led to its renaming (Guiry and Guiry 2022).
[b] Under ideal conditions, *K. alvarezii* can double in size in 15 to 30 days (Azanza-Corrales et al. 1992; Trono et al. 1992).

Gracilaria grown in the Caribbean typically require at least 8 weeks to reach harvest size (Smith 1997). During this growout period, daily growth rates of 4%–7% have been observed for *G. cervicornis, G. crassissima, G. debilis, G. armata*, and *G. mammillaris* (Hayashi et al. 2017; Roberson et al. 2022). Yields of up to 2.4 kg WW per meter have been reported from farms near St. Lucia (Smith 1997).[c] Many *Gracilaria* species can also tolerate salinity levels ranging from 20 to 35, so they are particularly good candidates for sites located near estuaries or areas with high runoff.

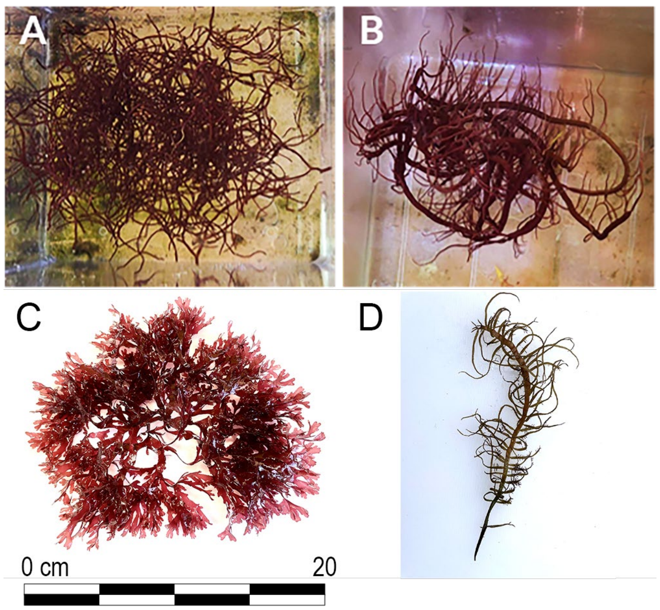

Figure 4. *Gracilaria* species for cultivation in the Caribbean: (A) *G. cervicornis*, (B) *G. cornea*, (C) *G. mammillaris*, and (D) *G. domingensis*. Photo credit: Mayra A. Sánchez García and Loretta Roberson, Marine Biological Laboratory (MBL).

Country-specific histories of seaweed farming

Within the Caribbean, two countries, Belize and St. Lucia, have pioneered seaweed farming techniques and led production. The following subsections summarize seaweed farming in each country.

Belize – a brief production overview, excerpted from TNC's *Seaweed Situation Analysis for Belize* (TNC 2024b)

Harvesting wild edible seaweeds in Belize has been ongoing for over 40 years. As recent as the 1990s, individuals from the Placencia Producers Cooperative Society Limited (PPCSL) were also harvesting wild seaweed and exporting hundreds of kilograms of dried *Eucheuma* to the United States for use in the food industry. However, it is believed that over the years, the wild stocks decreased to very low levels, no longer supporting export activities. Fishers who traditionally harvested the seaweed realized this and, with the help of local partners and nongovernmental organizations, sought out aquaculture as an alternative livelihood and a solution that would allow them to continue selling seaweed without fully depleting the wild stocks.

Seaweed farming in Belize has grown slowly for more than a decade, mainly led by small-scale producers such as the PPCSL, the Belize Women's Seaweed Farmers Association, and several philanthropic organizations. Funding for the Dangriga Development Initiative in 2002 resulted in the development of test plots off the shore of Twin Cayes in South Water Caye Marine Reserve. The World Wildlife Fund and the Belize Fishermen Cooperative Association sponsored and hosted a seaweed cultivation training workshop in 2005, which covered the cultivation methods for both *E. isiformis* and *Gracilaria* spp. The training was facilitated by the late Allan Smith of St. Lucia. Funding for farm development and expansion was provided to the cooperative through the Community Management of Protected Areas for Conservation Programme in 2010 and through the Global Environment Facility – Small Grants Programme in 2013. TNC–Belize also provided financial support to the cooperative in 2014 to improve management capacity. With the balance of its funding from the 2013 grant, the cooperative developed a seaweed cultivation training manual in 2016. To expand the scale of the training, TNC financed and co-developed a full seaweed cultivation training program in 2016 in collaboration with the PPCSL and Coral Caye. The training program consists of a manual, video, curriculum, and both theoretical and practical sessions. In 2018, The Belize Fisheries Department, TNC, and partners conducted extensive ecological and growth rate monitoring on *E. isiformis*. Additionally, Belize's first National Mariculture Policy was accepted by the government in March 2022. TNC's support of the project was and

[c] A typical wet weight to dry weight (WW:DW) ratio for *Gracilaria* is 8:1.

continues to be based on the three-tiered benefits the farms provide: social, economic, and ecological.

The Belize seaweed farming industry is in its infancy; production, governance, institutions, and markets are still being developed. On average, the local market purchased approximately 2000 lb annually of dried seaweed product (10,000 kg WW) over the last 5 years. Almost all production in the country is a part of the economy of urban and coastal populations, including the two main pilot production areas of Placencia and Turneffe Atoll (Figure 5). Seaweed is sold in the local market, which includes householders, small and midsize retailers, restaurants, and hotels. A small but unknown quantity is also believed to be shipped overseas to the diaspora market in the United States.

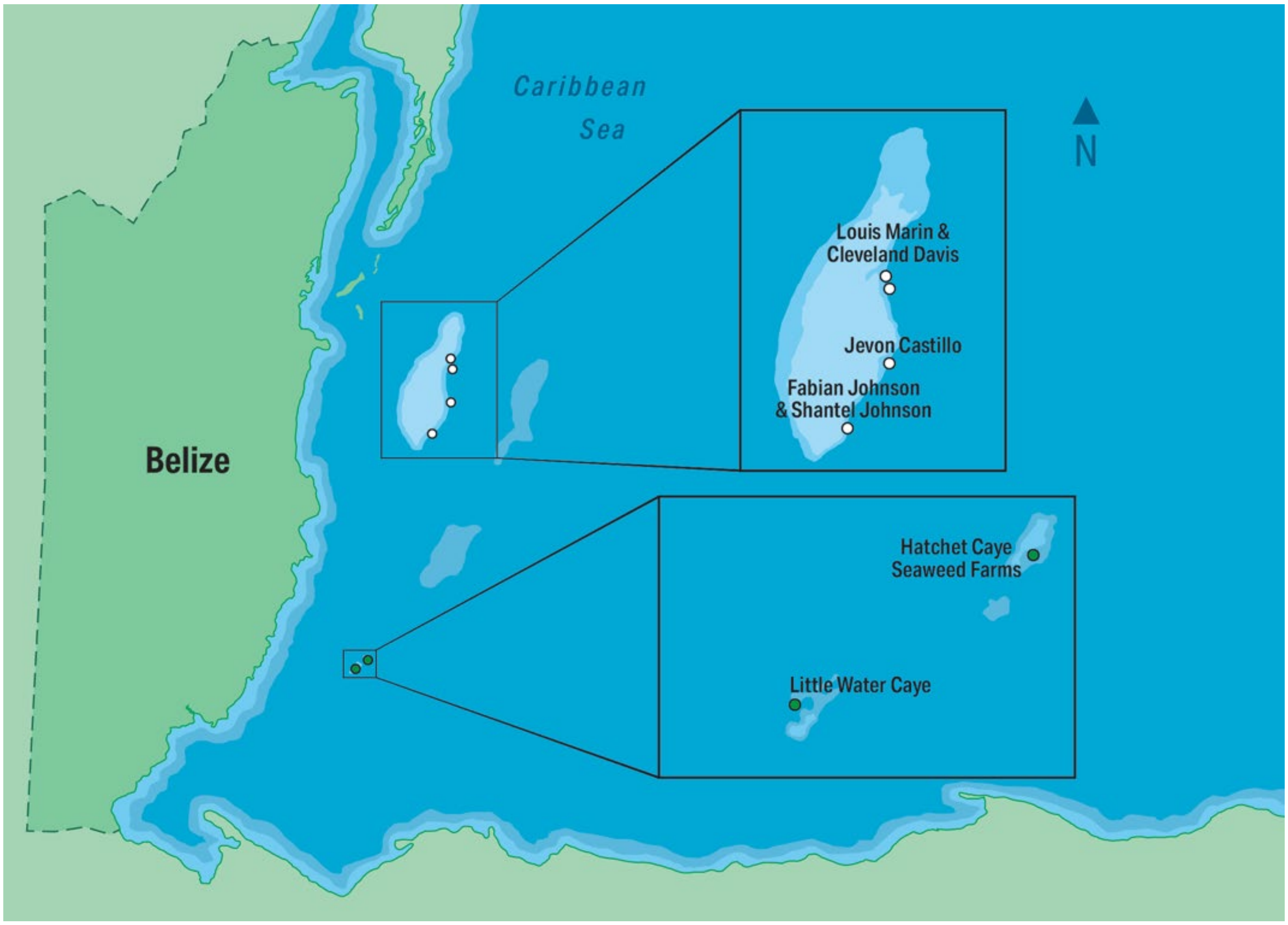

Figure 5. Map of Belize depicting regions with the highest concentrations of seaweed farms. Image credit: Jim Kopp, Kopp Illustration, Inc.

St. Lucia – a brief production overview

In 1981, a research project was started in the Department of Fisheries in St. Lucia, with support from the International Development Research Centre of Canada, to develop low-cost cultivation methods for seaweed species used for local consumption (Smith et al. 1986; Smith 1997). The first small commercial plots were established in 1985 on the island's southeast coast, following the methods used in the Philippines. Initially, seaweed farming in Saint Lucia used a *Gracilaria* species. Then, in the mid-1990s, a program in St. Lucia sought to identify species suitable for the seaweed market that would be less susceptible to the seasonal appearance of epiphytes that either reduced the quality of the *Gracilaria* crop in many areas or made cultivation impossible. *K. alvarezii* was introduced in 2013 as part of the Department of Fisheries initiative to improve the yield obtained from the plant. This, in turn, led to higher-quality drinks, foods, and cosmetic products. Over the years, farmers' preference for *K. alvarezii* seems to have increased. Still, it is difficult to determine the species many farmers use since there has been limited genetic testing within the region. *E. isiformis* had been cultivated by a few farmers in the past; however, it was not as popular because it broke off from the lines easily, and *K. alvarezii* grew larger.

Presently, the four main farm areas are Gros Islet, Eau Piquant/Savannes Bay, Praslin, and Laborie Bays, with two main seaweed cooperatives established in Eau Piquant and Praslin (Figure 7; Makeba Felix, Department of Fisheries, pers. comm.). In 2023, St. Lucia had almost 400 registered seaweed farmers; approximately 40% were women. While not all of St. Lucia's seaweed farmers are registered, the 2023 tallies represent a significant increase from 2019, when approximately 215 seaweed farmers were registered (roughly 25% of these were women). Over the last year, the number of individuals planting seaweed has dramatically increased. This increase can be attributed to the high demand, especially in the export market, and the consequential high price being offered. Moreover, unemployment due to the COVID-19 pandemic also caused many individuals to transition to seaweed farming since it is a quick and easy way to generate income.

Most of the development efforts within St. Lucia's seaweed farming sector center on increasing value-added projects since the profits from selling the raw products were not encouraging the sector's growth nationally. As a result, significant investments have been made in processing facilities in areas such as Praslin. Additionally, Export Saint Lucia, which is the national agency responsible for trade export and promotion in Saint Lucia, has contributed significantly to the sector's expansion. This additional investment by the Government of Saint Lucia has led to farmers accessing markets in Dubai, the United Kingdom, and the United States. Export Saint Lucia also assisted in creating an export development plan, which was developed and executed in late 2018 to help the industry meet international requirements. The plan incorporated export promotion in the United States and the United Kingdom and positioned the product as one of the world's best. The Department of Fisheries has also begun work on a national seaweed management plan to help alleviate some of the current issues the sector faces, including user conflicts because of a lack of marine zoning/demarcation, praedial larceny, and other issues related to climate change.

Production details for other Caribbean locations

Information on production practices and statistics for other Caribbean locations is not widely available.

Figure 6. A fishing village in Saint Lucia. Photo credit: Juli-Anne Russo, CAEIH.

Figure 7. The island of St. Lucia. Image credit: Mayra A. Sánchez García, MBL.

Section II. Production recommendations for nearshore, small-scale seaweed farming in the Caribbean

This section introduces the most relevant production-related considerations for small-scale tropical seaweed farming and synthesizes recommendations for better practices related to each. We consider seaweed farms using less than or equal to 2 ha of ocean area to be *small-scale* farms.

Site selection

Careful site selection is of utmost importance for prospective seaweed farmers. Existing floral and faunal assemblages, abiotic environmental conditions (e.g., temperature, nutrients), other water users, proximity to supporting infrastructure, and engineering constraints must all be considered. The best sites for farming in the Caribbean minimize the potential for impacts to marine organisms and other water users while meeting the environmental conditions optimal for seaweed growth.

Ecological considerations for site selection

Protecting sensitive nearshore habitat: The Caribbean Sea has a high abundance of ecologically important microcosms, such as seagrass beds, coral reefs, seamounts, reef flats, and mangroves. To prevent possible damage to these sensitive habitats, farmers should avoid siting seaweed farms over these features. Furthermore, a buffer between these sensitive habitats and seaweed farms should be established to prevent damage to them during normal farm operations or in the event of equipment failure due to storms. A 50-ft buffer has been deemed adequate in several instances (Hurley and O'Connell 2021).

Box 2: Ecological importance of seagrasses

Seagrass beds (e.g., Figure 8) are some of the most biologically productive ecosystems on the planet (Duarte et al. 2005). As keystone species, they play a critical role in supporting a diverse array of animal and plant species and are crucial components in conserving marine biodiversity. Seagrass beds provide important nursery areas for juvenile fish and foraging areas for herbivorous fish, such as parrotfish (Scaridae family) and surgeonfish (Acanthuridae family). Six turtle species inhabit the Wider Caribbean Region: green turtles, loggerhead turtles, hawksbill turtles, leatherback turtles, Kemp's ridley turtles, and olive ridleys (Eckert et al. 2020). Two of these species, the green and hawksbill turtles, travel through seagrass beds to their nesting sites on sandy beaches (Kim et al. 2017).

In addition to their provisioning services, as they supply habitat and food, seagrasses provide the ecosystem with regulating services. As they photosynthesize, seagrasses take up carbon dioxide and release oxygen. Seagrasses assimilate excess nutrients that could otherwise trigger nuisance algal blooms and help stabilize and retain sediment along the shoreline, which mitigates beach erosion. Seagrasses, coral reefs, and mangroves are connected by the species that move between them. Some species move between these habitats daily, while others may actively relocate from one system to another only once in their life cycle or only as planktonic larvae. Multiple anthropogenic and environmental stressors impact these communities, like climate change, sedimentation, and nutrient pollution.

Figure 8. An anemone stirs in the seagrass off the coast of Belize. Photo credit: Jennifer Adler, Jennifer Adler Photography.

Reducing grazers: In addition to being an environmentally responsible better practice, siting farms away from seagrass beds, coral reefs, seamounts, and mangroves has production benefits for the farms because it reduces grazer recruitment. Grazers are organisms that feed on plant and algal matter, like sea urchins, turtles, sea cucumbers, parrotfishes (Scaridae family), moonyfishes (*Monodactylus* spp.), and blennies (*Pteroscirtes* spp.), as well as surgeonfishes, tangs, and unicornfishes (Acanthuridae family). Many of these grazing organisms reside or feed in seagrass beds, corals, or mangroves. So, siting seaweed farms a distance away from these areas can help minimize the presence and impact [d] of these grazers on the crop. Similarly, siting farms in deeper water (≥ 2 m during low tide) can help prevent grazer damage because benthic, or bottom-dwelling organisms, will not be able to easily reach the crop. Grazer impact can also be addressed by preemptively increasing the seaweed density at the time of outplanting. Including an estimate of grazer impact in the outplanting serves as a buffer, increasing the likelihood of a reasonable final harvest quantity.

Minimizing epiphytes: Potential impacts from epiphytes can be minimized with seaweed farms' informed and strategic siting. Epiphytes are organisms that use the surface of another organism for habitat and nutrients. Epiphytic organisms commonly found on farmed Caribbean seaweeds include other algae, [e] worms, tunicates, and bryozoans. The likelihood and degree of epiphytes that might colonize farmed seaweed can be reduced by siting farms in areas where epiphytes are naturally low and by selecting areas with suitable currents. Regular farm maintenance and the cleaning of lines and seaweed can also keep epiphyte loads to a minimum.

Reducing marine mammal interactions: Siting decisions should also include considerations of the marine mammal abundance and behavior in the area. Marine mammals may interact with or be impacted by aquaculture gear in various ways. For example, cetaceans may be attracted to aquaculture arrays due to large aggregations of fish, which provide high-quality prey. Entanglement from farm gear and vessel strikes from farm operations may pose risks. Marine mammal interactions with seaweed farming activities have been shown to vary between culture methods and cetacean species (Díaz López and Methion 2017; TNC 2021). While there have been no known reports of entanglements with seaweed farms globally, siting farms away from areas with frequent sightings of marine mammals will help ensure that this remains the case. Additional better practices, such as keeping farm lines taught and minimizing the number of vertical lines used in the farm design, will also help minimize the perceived or actual risks of having seaweed arrays in the water. Lastly, a Marine Wildlife Observer Training and Response Protocol is essential to avoid endangering marine mammals, sea turtles, and species protected under the Endangered Species Act (ESA) and Marine Mammal Protection Act (MMPA) during farm operations. Appendix B provides an example protocol, including details for initial deployment procedures, responses to entanglement, vessel strike avoidance, and visual monitoring.

Environmental considerations for site selection

The environmental conditions at a prospective seaweed farming site will critically affect the growth and health of the cultivated seaweed. At a minimum, prospective sites should be evaluated for water temperature, salinity, turbidity, current, and nutrients across seasons. Table 1 lists a general range of tolerable and optimal values for tropical seaweeds.

Table 1. General site conditions conducive to tropical seaweed farming.

Parameter	Tolerable	Optimal
Bottom type	Silt	Sand
Water temperature	22–33 °C	22.5–28 °C
Salinity	> 20 (*Gracilaria*) > 29 to 35 (*Eucheuma*)	30–35
Photosynthetic active radiation (PAR)	125 μmol photons/m²/s	1000 μmol photons/m²/s
Turbidity	Low	Low
Current	< 0.2 m per second	0.2–0.5 m per second
Nutrients	Nitrate: 1–3 ppm Phosphate: 0.01–0.02 ppm	Nitrate: > 3 ppm Phosphate: 0.2 ppm

[d] A high abundance of grazers at a farm site can slow seaweed growth and ultimately result in a lower hydrocolloid yield.
[e] The most prolific epiphytic algae in the region are *Ulva* spp., *Cladophora* spp., *Ceramium* spp., *Centroceras* spp., *Hypnea* spp., and *Padina* spp.

Sites where the water temperature is less than 30 °C are best. In many areas of the Caribbean, establishing seaweed farms in deeper coastal waters (≥ 12 m) is preferable. Deeper water is likely to be cooler than shallow water and more consistently within the seaweed species' optimal temperature range (22–30 °C). Deeper water is also commonly located further from shore, thus reducing the likelihood of conflict with other water users (i.e., beachgoers, kayakers, swimmers, etc.) and critical habitats (i.e., seagrass beds). However, decisions to locate farms in deeper waters have social and economic implications. Many of the existing seaweed farmers cannot swim, and there have been reports of near-drowning incidents while accessing or working on their farms. So, siting farms in deeper waters may limit access to those who are comfortable in deeper waters and able to use and own boats. Should a community or country wish to guarantee access for all, there is a need to ensure that some of the nearshore areas remain available for farming and that farms are not confined to more distant and less accessible zones.

Sites with stable, higher-salinity water are preferable, and sites where fluctuations in salinity may routinely occur should be avoided, as variable salinity can exert stress on some seaweed species. For example, *Gracilaria* spp. can tolerate salinity levels as low as 20, but *Eucheumatopsis isiformis* grows best in salinity levels between 29 and 35. Highly variable salinity can also lead to algal stress and disease.

Turbidity (or water clarity) and salinity at a site may fluctuate seasonally, following weather events, or due to an anthropogenic disturbance. High turbidity for short periods may result in increased sedimentation on the crop and cultivation array. Also, high turbidity may be associated with other changes in the water at the site (such as low salinity, a change in the predominant current direction, etc.), which can be associated with biofouling or disease outbreaks. If the water is highly turbid at a specific site for long periods, it may not be suitable for seaweed cultivation because turbidity can prevent sufficient light from reaching the crop. However, some species, like *Gracilaria*, are highly tolerant, so site selection must be species-dependent.

Water motion is important for growth because diffusion makes materials move in and out of these seaweeds, bringing nutrients to the seaweed crop. Water exchange helps keep the crop cool, too. Stagnant and shallow water should be avoided.

In the Caribbean's typically oligotrophic coastal waters, sites with consistent background nitrate levels of 1 to 3 ppm and phosphate levels of 0.01 to 0.021 ppm are optimal from a nutrient perspective. Areas close to runoff or sewage outfalls should be avoided because of the potential for salinity fluctuations and because untreated or minimally treated wastewater can harbor bacteria and other pathogens that increase infection risk in the cultivated seaweeds.

Social considerations for site selection

Anthropogenic impacts and other water users

Before establishing a farm site, it is important to assess if and how other people might already use it. If marine tourism operators (e.g., dive shops, kayak outfitters, etc.) are in the area, a visit to these establishments to ask about whether they take clients to the desired site will help eliminate potential conflicts. Similarly, if local fishing cooperatives or recreational fishers are in the region, having conversations with them to ensure that the desired site is not in a heavily fished area is critical. When conversing

Figure 9. Dense seaweed farming activity close to the beach in St. Lucia. Photo credit: Juli-Anne Russo, CAEIH.

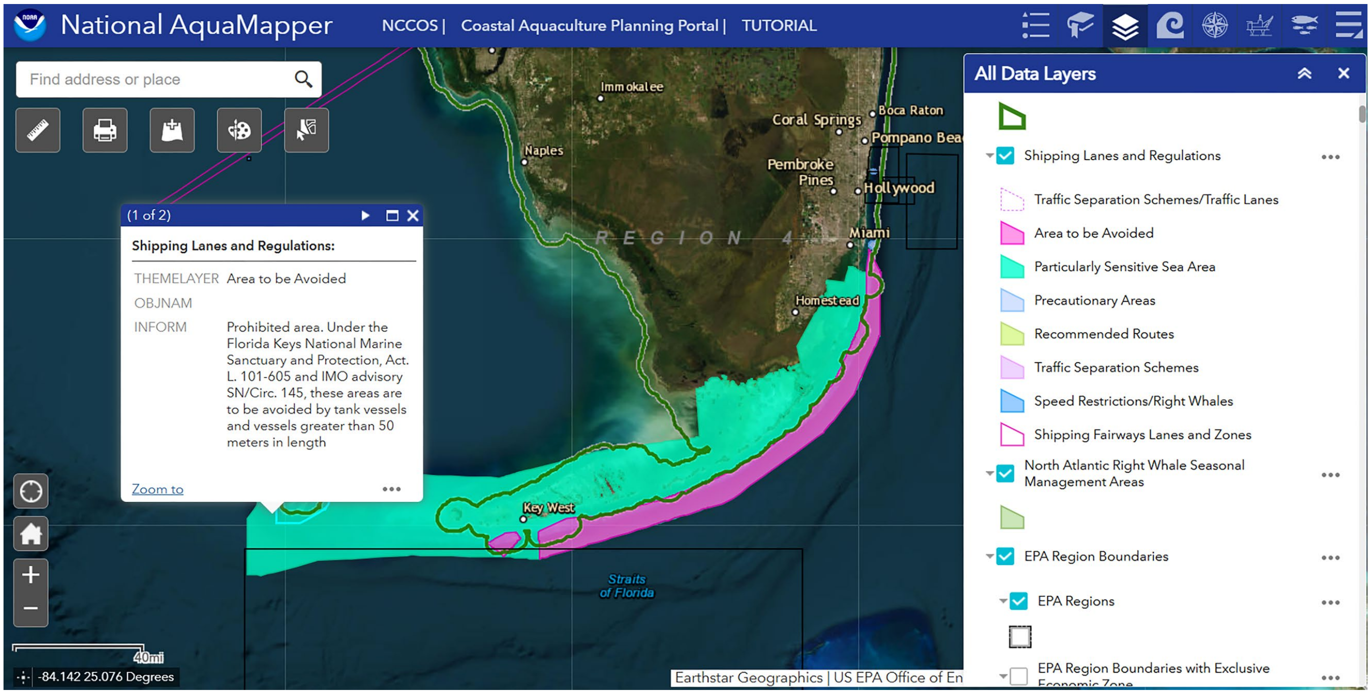

Figure 10. An example of AquaMapper's information. The aqua shading indicates a particularly sensitive sea area. Fuchsia indicates an area to be avoided. Image credit: NOAA AquaMapper.

with these important stakeholders about the prospect of a new seaweed farm in the area, a prospective farmer could highlight the shared interests between seaweed farming, tourism, and fisheries: they all require well-managed and healthy marine ecosystems. And thus, when these sectors are well-managed, benefits can be transferred between them.

In addition to these key conversations with other water users, spending some time at the site observing boat traffic at different times of the day will provide insight into whether the proposed farm is well-situated for minimizing potential collisions with vessels traveling through the area en route to another. Minimizing the potential for collision is necessary because if a boat collides with the farm, it could harm the passengers on board, the boat, the cultivation array, or the crop. In St. Lucia, there have been instances when boat operators are not able to get their boats to shore due to the high concentration of seaweed farms close to the beach (Figure 9).

In areas with many competing uses of the nearshore marine area (e.g., underwater cables, protected areas, shipping lanes), a spatial mapping and planning approach could be used to reduce user conflicts and identify the most suitable sites for aquaculture development. TNC's *Aquaculture Site Selection Checklist* (n.d.) is an example of an aquaculture site selection checklist that includes not only environmental factors but also social and economic factors. In U.S. waters, the Ocean Reports and the National Marine AquaMapper Tool (Figure 10) developed by the U.S. National Oceanic and Atmospheric Administration (NOAA) are useful resources to aid in successful site selection, including providing material such as maps and user conflicts that are required for permitting.

Site marking

Clearly marking the farm site is usually advantageous to the farmer and is dictated by an aquaculture permit. A well-marked farm can help with farm operations and prevent damage to the crop or gear from nonfarm vessels (Figure 11). Typically, obstructions in the water must also be marked for the safety of other water users. The most common boundary markers are buoys or stakes. If the farm is large, markers may be required along the perimeter rather than at just the corners.

In some cases, the type of marker, its color, and its location will be specified by the relevant coast guard [f] or the agency granting the aquaculture permit. Lights or radar reflectors may be required, and

[f] In some regions, lease boundaries may also be noted on nautical charts and chart plotters.

Figure 11. A well-marked seaweed farm in Belize. Photo credit: Maximiliano Caal, Belize Women's Seaweed Farmers Association.

if not, reflective buoy tape is advisable so that buoys can be more easily spotted during nighttime water travel. If the marker color is not mandated, then the farmer may weigh the costs and benefits of various colors according to their site location and characteristics. Generally, brightly colored buoys make it easier for other boaters to see the farm, which is advantageous in high-traffic areas. However, darker-colored buoys are usually preferable for minimizing the farm's visual impact from shore. If markers are lost or stolen, it is important for the safety of other water users that they are replaced in a timely fashion.

Security and vandalism

Some locations in the Caribbean have experienced thefts of seaweed or farming equipment (e.g., buoys). Siting a farm near an establishment where someone can watch over it can help deter unwanted visitors to the farm. Equipment theft can also be minimized by using metal instead of rope for those connections that are accessible from the surface.

Supporting infrastructure

The proximity of onshore facilities is also a consideration when choosing a farm location, and the importance of this criterion likely increases proportionally with the size of the planned operation. Prospective farmers may want to consider access to a dock and hoist for lifting seaweed and equipment, fresh water for rinsing seaweed and equipment, refrigeration, or drying facilities (depending on the target market). Farmers may also want to consider whether the landing point is accessible, and on or adjacent to a main thoroughfare. Furthermore, sharing a dock with fishers bringing in their catch can result in conflicts over space and timing (Figure 12) and could be unhygienic. If access and funding can be acquired, establishing a separate dock for seaweed farmers could reduce potential conflicts and improve quality control for the harvested seaweed.

Seed sourcing, nurseries, and breeding programs

The Caribbean's wild seaweed populations of economic importance are unable to support industrial exploitation. Even harvesting wild seaweeds for traditional use within the region has led to a decline in these seaweed populations. The species described and recommended previously in this report were selected because their wild populations are likely found in concentrations sufficient to provide an initial source of broodstocks or propagules for nurseries, yet their wild populations alone cannot support commercial harvesting. Further development of seaweed farming and/or value-added processing in the Caribbean must therefore be supported by both nursery systems and better management of the wild stocks.

Figure 12. Dock in St. Lucia shared by fishers and seaweed farmers. Photo credit: Juli-Anne Russo, CAEIH.

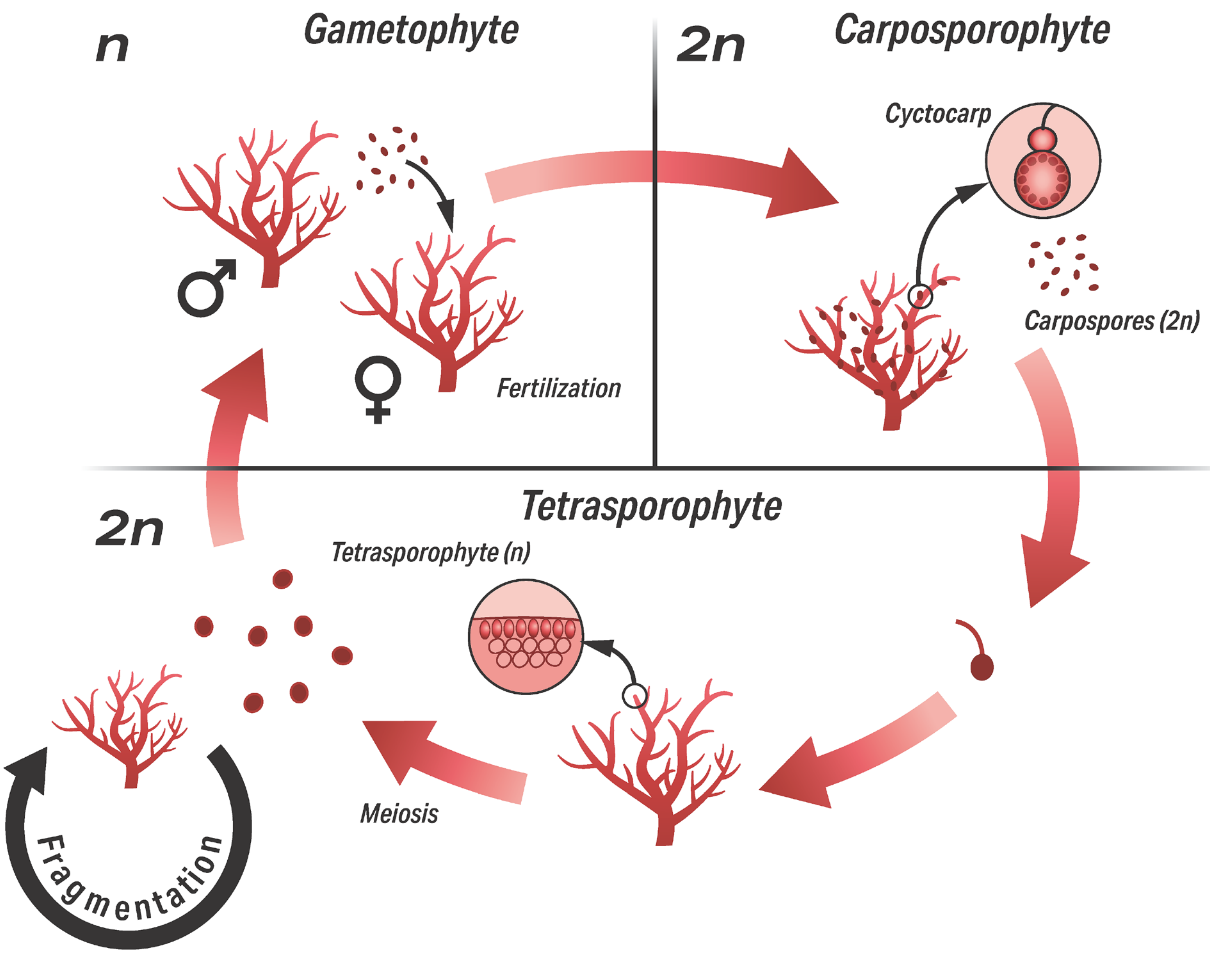

Figure 13. The triphasic life history of red seaweeds. Illustrator: Jim Kopp, Kopp Illustration, Inc.

Most tropical red seaweed farming worldwide, and specifically in the Caribbean, relies on vegetative propagation techniques. This involves subdividing a mature, larger organism into several smaller pieces, or propagules. Then, each propagule is grown to full size.

Spore-based propagation in red seaweeds is much rarer. It involves either placing suitable substrates within or nearby wild populations that have reproductive individuals or obtaining reproductive individuals from the wild or a broodstock collection. Then, spore release can be triggered in these individuals. After release, the spores settle and germinate, either giving rise to male and female gametophytes or tetrasporophytes (Figure 13). However, this has only been studied and characterized in a few species of red seaweeds (i.e., *Porphyra* or *Pyropia*), so the timings and triggers of spore release and the successful propagation in the other life history stages are unknown for most tropical species.

There are trade-offs between vegetative and spore-based propagation, namely with regard to cost/effort and the crop's genetic diversity. Vegetative propagation is sometimes referred to as clonal propagation because when it is the exclusive propagation method used, the crop's genetic diversity is never replenished. Hence, large portions of the crop may originate from a few clones. This can be problematic because species survival, adaptation potential, and resistance to biotic and abiotic stressors are enabled by intra-specific genetic diversity. A lack of genetic diversity within the farmed crop can translate to decreased resilience to disease and other stressors (Tano et al. 2015).

In contrast, the techniques involved in spore-based propagation result in a refreshed gene pool of offspring (i.e., juveniles for outplanting). Also, they support robust strain development in which desirable traits can be identified and selected for over generations, meaning that individuals with the best expression of the target trait(s) can be used as parents for the next generation of offspring. However, to use spore-based propagation techniques, the nursery must be able to successfully maintain stocks through each life stage and effectively induce transitions between specific ones (i.e., spore release). This expertise has not yet been developed for many red seaweed species, as the triphasic life cycle is more complicated than the life cycles of many commonly cultivated brown and green seaweed species. Additionally, even if the techniques are known, spore-based propagation requires a nursery facility, which comes with additional requirements for land, infrastructure, staff, and funding (Pereira et al. 2024).

Farmers using seeds produced vegetatively benefit from the support of a simple land-based nursery for maintaining vegetative material during the rainy and hurricane seasons (Roberson et al. 2024). This nursery could consist of large concrete, plastic, or fiberglass tanks equipped with flowing seawater. Ideally, these tanks would be sunk into the ground (Figure 14) or enclosed in a climate-controlled building to maintain stable water temperatures throughout diurnal and seasonal changes. These tanks should hold a supply of each cultivated seaweed species that can then be used to support the development of unique cultivars and reseed farms if a catastrophic loss occurs. A nursery of this design could potentially be communal or multipurpose. It could either support other aquaculture operations, additional land uses (e.g., solar park), or high-value products (nutraceuticals and pharmaceuticals). The nursery operations could be supported by a cooperative model, an independent business, or as part of a vertically integrated company that maintains both a nursery and a growout operation. Existing examples of Caribbean fishing cooperatives already have communal facilities that could be retrofitted with tanks for a seaweed nursery. For example, in southeastern Puerto Rico, the Commercial Fishing Association – Villa Pesquera de Naguabo has teamed up with researchers from Florida Atlantic University and the local nonprofit organization Conservación ConCiencia

Figure 14. Three photos of the sunken seaweed holding tanks at the CINVESTAV field facility near Merida, Mexico. CINVESTAV stands for Centro de Investigación y de Estudios Avanzados [Center for Research and Advanced Studies]. Photo credit: Mayra A. Sánchez García, MBL.

to design and build the Naguabo Aquaculture Center within the Fishing Association's headquarters. Davis et al. (2023) explained that "the Center's infrastructure includes a saltwater system with two 2000-gallon reservoir tanks on chillers, filtration and ultraviolet sterilization (200 ft^2); a temperature-controlled hatchery and microalgae culture area (144 ft^2); a recirculating nursery system for conch; and an aquaponic area for sea vegetables and other species (500 ft^2)." In addition to studying these examples in the Caribbean, there have also been several guides on setting up nurseries for red alga species developed by researchers from outside the region (Yarish and Edwards 1982; Yarish et al. 2012; Redmond et al. 2014).

More complex nurseries will be required for spore-based propagation techniques, including the maintenance of a broodstock and the potential establishment of breeding programs. Starting and maintaining contamination-free broodstocks will require special aseptic capabilities and facilities. For security and convenience, multiple breeding trials are likely to be initiated in small-scale controlled environments (e.g., dozens to hundreds of flasks in illuminated incubators) that mimic farm environments. Once considerable biomass of putatively superior strains is built up, this will warrant outplanting and testing on commercial farms.

In Asia, the seaweed industry has long used selective breeding for macroalgal strains with specific physical or composition qualities. Now that interest in seaweed farming has expanded beyond the historical epicenters and into new areas, the value of selective breeding practices for cultivated seaweeds is also receiving more recognition. From a producer's standpoint, breeding programs that include strain barcoding allow for the selection of more productive seedstocks that have specific physical or compositional qualities. From a resource manager's perspective, breeding programs can significantly reduce pressure on wild seaweed stocks because considerably fewer wild reproductive individuals are needed to produce seed (most nurseries with breeding programs still require some collection from wild populations).

Potential risks remain when developing, scaling, and commercializing algal strains. There could be genetic impacts on wild seaweed populations, both from the targeted harvesting of reproductive individuals for broodstocks and from the possible interbreeding between a wild individual and commercialized strain if farms are near wild populations of the same species. Modern genomic screening methods may be used to search for mutations in parents that will only produce nonreproductive offspring, thus eliminating possible interactions (Vissers et al. 2023). There is also a risk that the selection efforts do not actually achieve the desired physical or compositional qualities, or that the high performance of strains in the nursery does not translate to high performance at the farm site. Lastly, as the maintenance of cultures in a lab or tanks can require intensive efforts, there

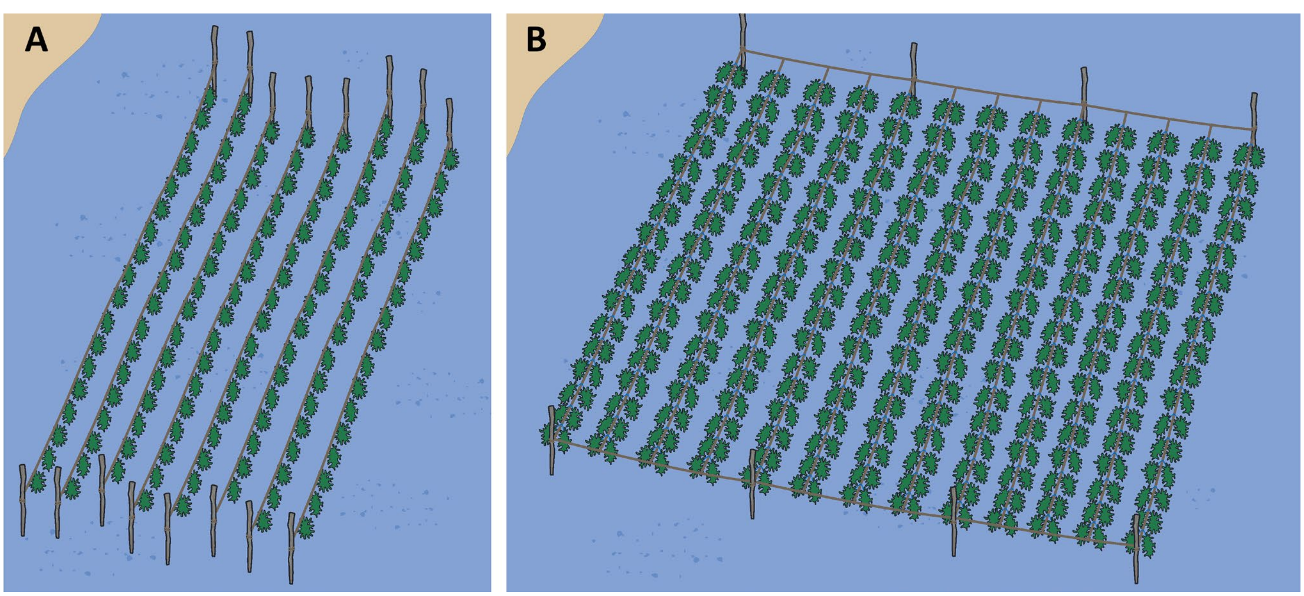

Figure 15. (A) Traditional peg and line design for a seaweed farm, using made loops. (B) Off-bottom design for a seaweed farm, using double made loops. Illustrator: Colin Hayes, Colin Hayes Illustrator, Inc.

could be a scenario where breeding programs cannot be established or carried forward due to species-specific sensitivities and/or a lack of financial or personnel support.

Regardless of whether vegetative or spore-based propagation is used, developing a tank-based stock of seaweed to reseed seaweed farms can help ensure the longevity of the wild seaweed stock as long as wild harvesting of seedstock is done responsibly. To avoid unintended impacts on wild seaweed populations, seeds or spores for cultivation should be sourced from the same bioregion as the farm site, and a diverse selection of parental material should be collected. A wild population should never be completely harvested. A good rule of thumb is that no more than 75% of the standing stock should be removed, but this guideline should be adjusted based on the species in question and the site. For example, *Gracilaria debilis* regenerates well from coalesced holdfasts, suggesting that the over-recruitment of sporelings may be more important for this species (Smith et al. 1986). Also, when harvesting, entire plants should not be removed. Instead, only a portion of the plant should be removed, leaving the holdfast and some fronds still attached to the bottom.

In many places, harvesting seaweed from the wild requires a collection permit from the fisheries department. Even if this requirement is not enforced, obtaining a permit is a better practice because it serves as a record of interest and effort that the fisheries department can track over time and geography. Resource managers working in areas that do not require permits for seaweed harvesting may consider establishing such a system. Managers could also evaluate opportunities to help maintain diversity in wild seaweed populations by establishing conservation zones with specific restrictions on the frequency, seasonality, or eligibility of seaweed harvesting.

Cultivation systems

A variety of farming array designs are currently used in the Caribbean. They include peg and line, off-bottom, floating rafts, longline, and multi-line systems. Table 2 provides an overview of the ideal water depth and anchoring system for each one. Additional details on each system follow.

Table 2. Farming arrays used in the Caribbean, their ideal water depths, and common anchoring systems.

Array type	Ideal water depth at mean low tide	Anchoring system
Peg and line	0.5–1 m	Wooden stakes or rebar
Off-bottom	0.5–1 m	Wooden stakes or rebar, cement anchors
Floating raft	3 m	Cement anchors
Multi-line	> 3 m	Drag-embedment anchors

Historically, the *peg and line* approach has been the most widely used for tropical seaweed production in other parts of the world. Peg and line systems have parallel rows of stakes with polypropylene, polyethylene, or nylon rope tied between them (Figure 15A). The seaweed seeds are manually tied to the rope using smaller-diameter lines called *made loops* or *tie-tie* (Figure 16). Because they require little capital investment and no significant equipment, the peg and line and off-bottom styles of cultivation array work well if seaweed farming activities are permitted in shallow intertidal or subtidal areas or in sheltered bays (Hayashi et al. 2017). However, the peg and line system is especially labor intensive because each peg and line must be inserted and maintained separately. Early in the development of seaweed farming in the Caribbean, some farmers experimented with the peg and line method by using mangrove stakes (Pereira et al. 2024), but for the aforementioned reasons, combined with increased protection of mangroves, this method is no longer favored in the region.

Off-bottom systems build on the peg and line approach. Instead of using a stake at the end of every growline, these systems use growlines tied to a framing line that runs perpendicular to them (Figure 15B). This design reduces the required anchor points, which, in turn, allows for a cement anchor reinforced with rebar to be used in place of stakes. The standardized off-bottom system also helps reduce the risk of seaweed loss because the farm is more resilient during storms. Off-bottom designs require less time to maintain lines because the lines are a uniform length and can be easily swapped out.

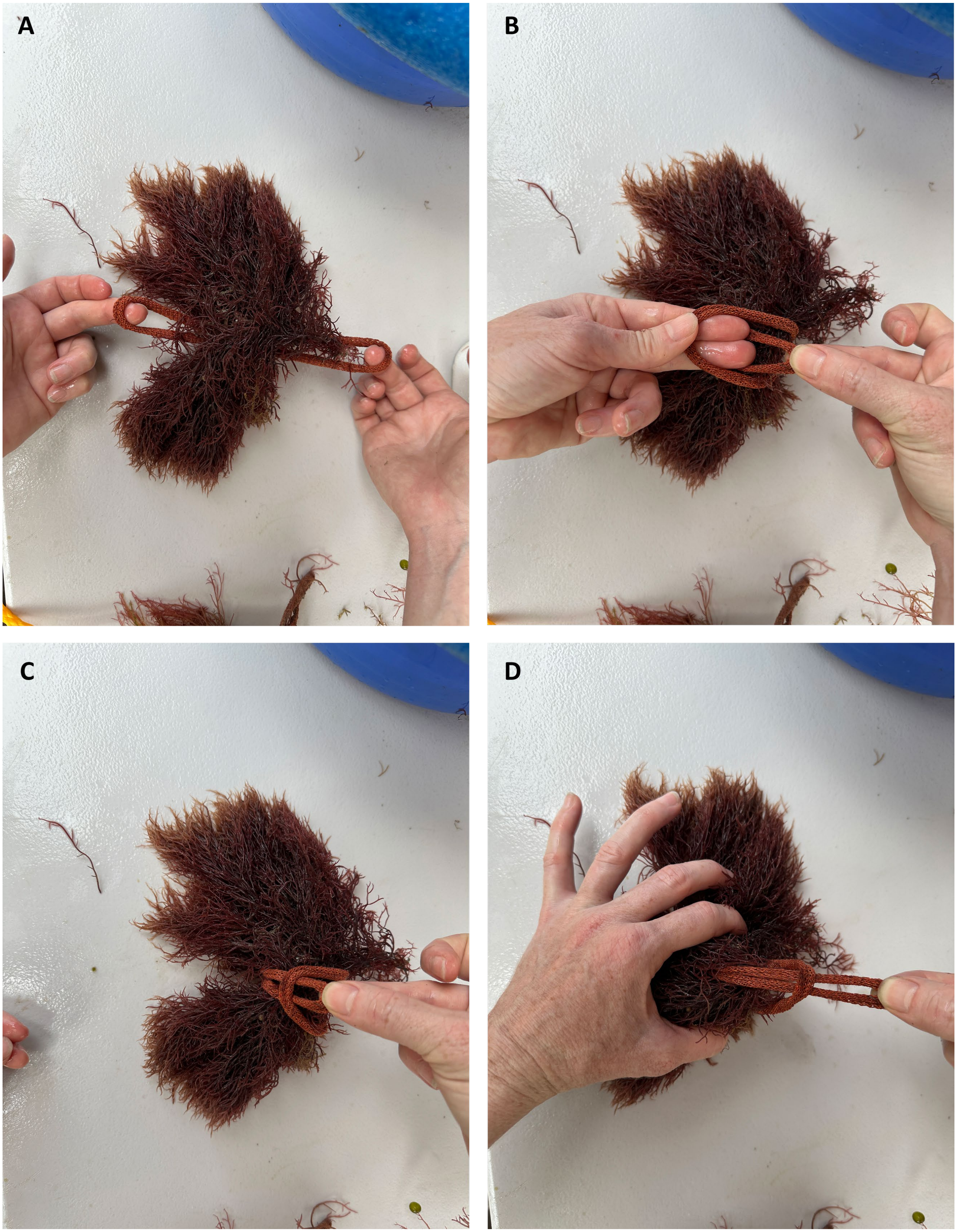

Figure 16. The made loop method. (A) The seaweed is positioned on a circular tie. (B) The tie is wrapped around the seaweed. (C) A loop is made by passing the tie through itself. (D) The tie is pulled taut. Photo credit: Rachell Hester, WHOI.

Box 3: The benefits of the double made loop

More recently, some industry members have been encouraging seaweed farmers who use made loops to change to a double made loop, which allows two propagules to be attached to the same point on the growline (Figure 17). This method requires additional effort to prepare the seedline, but it enables more biomass to be cultivated in the same amount of ocean area and with the same amount of growline. Pilot studies in Tanzania indicated that transitioning from a simple made loop to a double made loop could result in a threefold increase in production.

Figure 17. Double made loop. Photo credit: Roshni Lodhia.

In Belize and St. Lucia, floating rafts have been one of the most widely used cultivation arrays (Smith et al. 1986). [g] The floating raft structure is comprised of the same thin (≥ 3/8 in; ≥ 4.8 mm) plastic growlines strung between bamboo or polyvinyl chloride (PVC) floats (≥ 3 in; ≥ 76 mm; Figure 18 & Figure 19). While bamboo was originally used in most places, in Belize, its use was discontinued and is no longer recommended. This is because, with prolonged exposure to sunlight, the bamboo cracks; eventually, water seeps into it, causing the structure to sink. Hence, more recently, floating raft structures have been made with PVC pipes. Rafia (a fiber made from palm) or polypropylene line is used to attach the seaweed to the growline using the made loop method. Some species can also be directly inserted between the weave of the growline (e.g., *G. debilis*; Hayashi et al. 2017). The floating array is anchored to the seafloor using anchors made from cement, steel rebar, sand or gravel, construction mesh, and PVC. No additional floatation is needed if the growline length is kept between 3-5 m because bamboo and PVC are positively buoyant.

Figure 18. Seaweed attached to the growlines of a floating bamboo raft. Photo credit: Wilbur Dubon, TNC–Belize.

[g] Some farmers have also experimented with covering a rock in 10-mm mesh nylon netting and then using the netting to hold their target seaweed (*G. debilis*) in place (Hayashi et al. 2017). The propagules were observed to readily proliferate through the netting. This method has been recommended in areas with high wave action where peg and line or floating raft systems may otherwise be dislodged by the water motion. However, due to the relative effort required to establish this system and the limitations on scaling it, we do not recommend rock covering as a best practice.

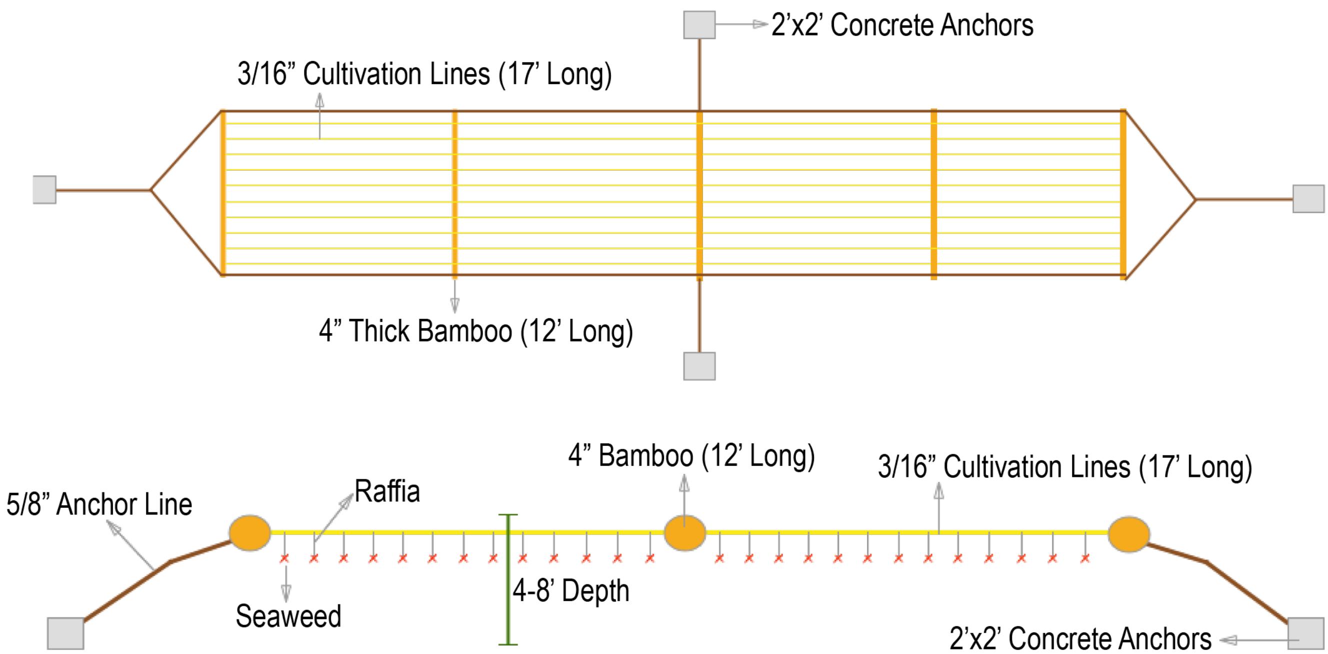

Figure 19. Plan and side view of a floating raft in Belize. Note: The term "cultivation line" in this figure is synonymous with "growline." From Dubon (2018).

Multi-line systems have the same general structure as the floating rafts, except that rather than floating on the surface, the line with the seaweed is held at the desired location and depth in the water column by a combination of buoys (or plastic bottles) and anchors (Pereira and Yarish 2008). Longline arrays for tropical seaweed farming commonly use short lengths of line spanning 10–15 m, but in the last few years, arrays with longer lines (60 m) have also been developed and tested in the region (Figure 20 and Figure 21). The seaweed can then be attached to the growline(s) via the traditional made loops or tubular nets. This method has proved to be more resilient to wave action than the raft system.

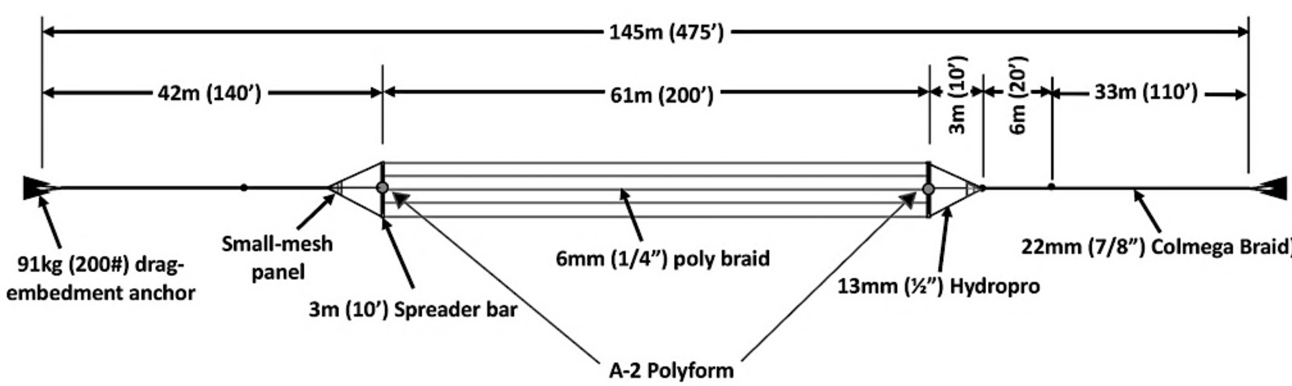

Figure 20. Plan view of a five-line array deployed and tested at several locations in the Caribbean from 2021 – 2022. Design and image credit: TendOcean, LLC.

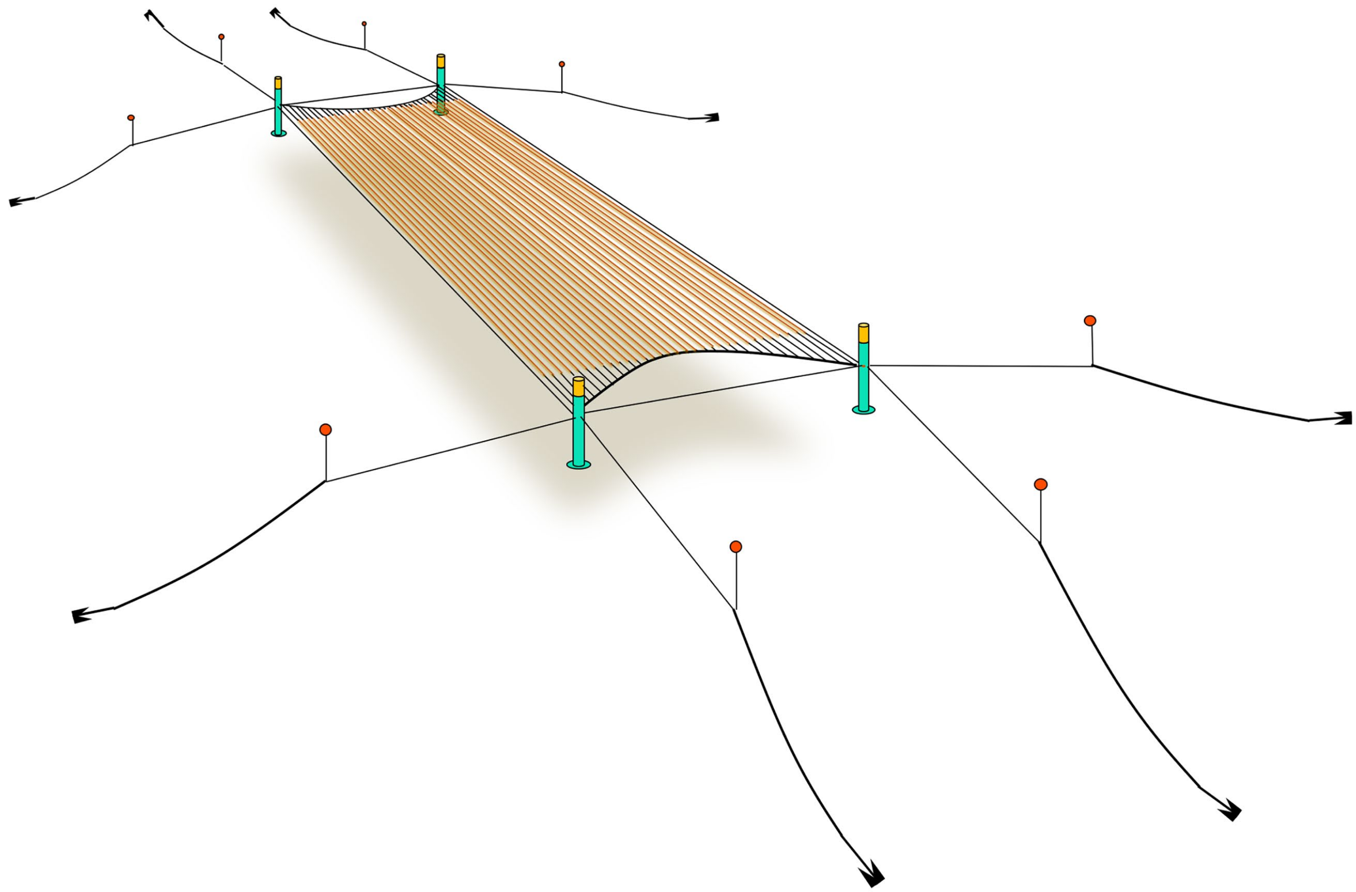

Figure 21. An example of a multi-line array developed for kelp cultivation and adapted by Roberson et al. for tropical seaweed cultivation. See Roberson et al. (2024) for more plans involving multi-line arrays. Design and image credit: C.A. Goudey & Associates.

Although made loops or tie-tie attachment methods are currently standard industry practice, several studies have shown the advantages of using tubular nets (Figure 22) over made loops (Zertuche-González et al. 2001; de Góes and Reis 2011; Pereira et al. 2024). Outplanting new seaweed in tube nets is faster than the made loop method, and it can be done either manually using a PVC pipe or mechanically. A study conducted in Brazil found that this increased efficiency lowered farming costs by 50% (Reis et al. 2015). Tube nets can also improve crop retention because if the seaweed thallus breaks in the tube net, there is a greater chance that the material will be retained within the net (rather than being lost to the environment if made loops were used; Pereira et al. 2024). The study also compared the cultivation of *Kappaphycus alvarezii* in tubular nets and made loops, and it found no significant differences between the carrageenan yield of the seaweed grown using either method. Furthermore, the researchers observed that the seaweed in the tubular nets had higher and more uniform daily growth rates (2.90% ± 4.60% day^{-1} in tubular nets vs. -2.14% ± 8.50% day^{-1} using tie-tie or made loops).

In trials conducted in southwestern Puerto Rico, researchers found that some seaweed species may be better suited for tube net cultivation than others. *Gracilaria* spp. appeared to thrive in tube nets and exhibited high growth rates (≥ 6% day^{-1}), but *E. isiformis* in tube nets quickly developed decaying tissue and grew very slowly, if at all (Freile-Pelegrìn and Murano 2005). The material used to make the tube net and the mesh size also impacted the degree of fouling observed on the tube net, which subsequently impeded water movement in and out of the net. A thin net with a medium mesh size is recommended (Freile-Pelegrìn and Murano 2005).

Above all else, the willingness to experiment and keep a crop log is the most important approach for finding gear and a site that works best for the farmer. When first sourcing components for an array, farmers should consider trying a few different types of gear to see how each style performs (if the lease/permit allows). Then, they can add additional gear as they learn more about the site and their operating needs.

Figure 22. Tube net with Gracilaria sp. ready to harvest. Photo credit: Aaron Welch, Two Docks Shellfish.

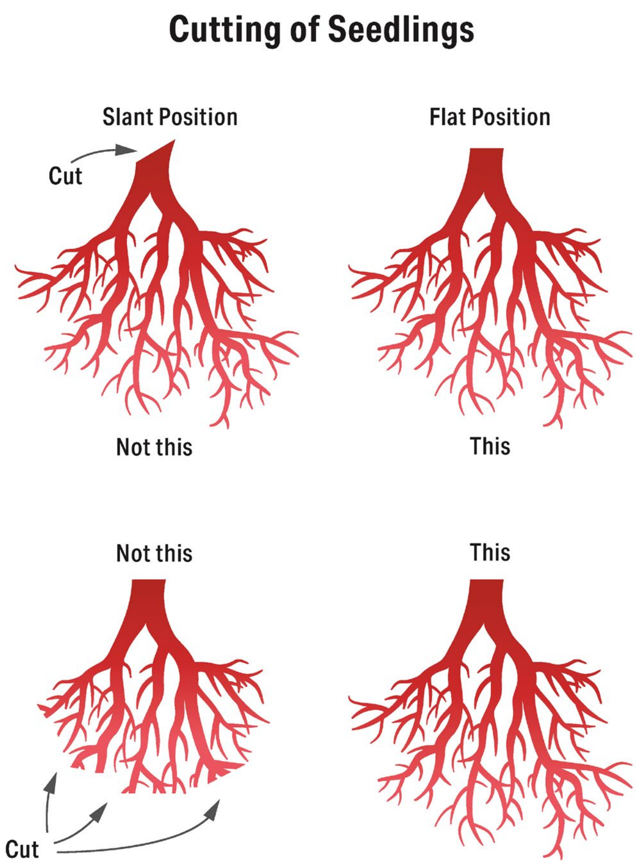

Figure 23. How to cut a red seaweed thallus. Illustrator: Jim Kopp, Kopp Illustration, Inc.

Outplanting and harvesting

Seedlings selected for outplanting should show no signs of disease or pests. In general, they should weigh 50–100 g each, but this varies somewhat by species (e.g., *Eucheuma* is denser than *Gracilaria*, so an appropriate target starting weight for *Eucheuma* clumps may be closer to 100 g, but the same-sized *Gracilaria* clump will weigh much less). A clean, sharp razor blade should be used to divide any clumps that exceed the target starting size by cutting the central thallus in a horizontal direction (Figure 23). When preparing seedlings, take care to minimize the time that they are exposed to sun, air, wind, or cool temperatures. If possible, the seedlings should be attached to the growline while submersed in water. When transporting seeds from the nursery to the farm, keeping them covered from the wind, shaded, and moist with salt water will also prevent stress or mortality. Seedlings that show signs of decay or significant fouling should be avoided and disposed of on land. Table 3 explains when outplanting occurs within the annual planting and harvesting calendar.

Table 3. Annual planting and harvesting calendar.

Months	Activity
Jan - Jun	Continual outplanting and harvest • Crop and array cleaning every ~1-3 days • Harvesting every ~6-12 weeks (species and site dependent)
Jul	Last harvest of the season
Aug - Oct	Rainy/hurricane season; pause farming operations
Nov	Outplant new propagules
Dec	First harvest of the season

Several better practices for harvesting from seaweed farms can reduce potential impacts on nearby people, animals, and the surrounding environment. While harvesting, the crew should make efforts to minimize the quantities of seaweed biomass lost to the depths and seafloor. They should also keep a careful eye out for organisms caught in the seaweed or on the lines (e.g., crabs, juvenile fish) and, to the degree possible, remove them from the seaweed gear so that they do not become bycatch. One of the most common complaints received from nearby

Figure 24. Using plastic bottles as floats for seaweed growlines. Photo credit: Juli-Anne Russo, CAEIH.

landowners is that aquaculture operations produce a lot of noise, so tying up to the array and turning off the motor while harvesting can help prevent these complaints; it will also reduce operating costs and reduce worker exposure to noise and motor exhaust, which is better for long-term health.

Lastly, there is a need to reduce or eliminate practices that could result in marine plastic pollution. Some initial actions to take toward this goal include limiting the use and transportation of single-use plastic to the farm site, replacing growlines before they splinter or break, and reducing the use of plastic bottles for buoys (Figure 24) and, instead, opting for high-quality plastic buoys that do not degrade as quickly. In service of the latter, when harvesting, the crew can dedicate additional time to inspecting lines for signs of degradation so that they can be promptly removed when signs of wear appear. Land-based harvesting operations and BMPs are described in Section III: Market Opportunities and Supply Chain Considerations.

Maintenance and biosecurity

Daily to weekly maintenance

The Caribbean's warm coastal waters contain bivalve larvae (e.g., oysters, scallops), barnacles, amphipods, drift macroalgae (e.g., *Chaetomorpha*, *Sargassum*), hydroids, tunicates, bryozoans, and filamentous algae that will readily settle on the seaweed crop and farming structure (Hayashi et al. 2017). Additionally, sediments settling on seaweed propagules have hampered farming efforts in some Caribbean locations (Figure 25; Smith et al. 1986). Thus, tropical seaweed farmers should expect to spend at least 10 days per month conducting farm maintenance (Arasamuthu et al. 2023). Frequent cleaning of the crop helps to promote algal health and high growth rates by enabling maximum sunlight, nutrients, and fresh water to reach the organism. It also minimizes the incidence of epiphytes colonizing the cultivated seaweed by keeping their populations low. If possible, epiphytes should be removed from the seaweed by hand. Any seaweed with an unhealthy appearance should be removed and disposed of on land. Seaweed lost from the made loops or tube net can be replaced with new seedlings. If silt has settled on the seaweed, it should be dislodged by shaking the growline and fanning the water surrounding the seaweed. In addition to manually cleaning, at least one study has observed that culturing more flexuous species results in reduced levels of sedimentation, and co-culturing species can create a situation where one species is "swept clean" by another more flexuous species (e.g., *Gracilaria domingensis* sweeping clean *G. debilis* tied nearby; Smith et al. 1986).

A minimum of weekly cleaning of the cultivation array is also advisable. Frequent cleaning will prevent the accumulation of fouling organisms that can weigh down the array, and it is much easier to remove encrusting species while they are small. Before

Figure 25. Sediment being dislodged from *Eucheumatopsis isiformis*. Photo credit: Luis R Rodríguez Matos, CariCOOS.

tensioning any ropes, farmers should make sure that no animals or large debris are entangled in the farm. Then, smaller debris (e.g., driftwood) and nuisance seaweed (e.g., *Sargassum* sp. or *Ulva* sp.) can be collected and removed.

Weekly to quarterly maintenance

Routine structural inspections of the cultivation array should be conducted at least quarterly to ensure that all connection points are sound. Over time, the polypropylene structural lines can chafe at the connection points, so farmers should pay close attention to signs of abrasion and preemptively apply protection or replace the lines to prevent a larger structural failure. The polypropylene or nylon growlines should also be inspected after each harvest. The constant exposure to ultraviolet radiation eventually causes the plastic to become brittle, so these lines should be removed and replaced before they begin to shed plastic particles into the water. Inspecting buoys, anchors, chains, and connections for rust is also important to prevent gear failure.

Disease identification, prevention, and management

Biosecurity protocols play an important role in safeguarding cultivated crops from harmful biological agents that may cause diseases or damage the seaweed. Disease outbreaks can have detrimental effects on seaweed farm yield and farmer income. Worldwide, the most prevalent diseases and crop issues observed on tropical seaweeds are ice-ice disease, tip discoloration and darkening, epiphytic filamentous algae, grazers and pests, epiphytic sponges and barnacles, sediment, and biofilms. To date, the incidence of these diseases on Caribbean seaweed farms has not been quantified or reported. There have been observations of suspected ice-ice disease in St. Lucia, but these were not documented or validated by a pathologist (Brian Walker, farmer, pers. comm.).

As seaweed farming activities expand in the Caribbean, the likelihood that diseases will appear on these farms also increases. Establishing strong biosecurity protocols, including the measures described below, will help prevent the spread of disease when it does appear. These protocols may also delay or prevent its onset. Educating all workers and visitors in biosecurity protocols is important to ensure consistency in their implementation. Routinely cleaning the farming array and crop in the water will also help minimize biofouling and sediment deposition that can create conditions conducive to disease outbreaks. (Refer to the previous two subsections under "maintenance and biosecurity" for more recommendations on routine cleaning).

Practicing good hygiene (including wearing proper clothing) and equipment sanitation are important first steps to minimize the transfer of microbes between old and new propagules (Matoju et al. 2021). This includes washing hands before handling seeds and equipment and, if feasible, using sanitized gloves. Additionally, all farm equipment and materials (ropes, fids, made loops, buoys, knives, etc.) should be thoroughly washed with sterilized or filtered seawater or freshwater. If available, a natural disinfectant can be applied, but it is essential to ensure that the equipment has been washed and is completely dry before returning it to the farm site.

During seed preparation, farmers should meticulously remove physical debris and inspect the algae for epiphytes, bleaching, or spots. If any of these signs are detected and additional seeds are available, it is advisable to refrain from using the compromised seeds. If they must be utilized, any dead or degrading tissue should be removed using a sharp and sanitized razor blade. Subsequently, seeds should be washed using sterilized seawater (if available) or seawater filtered through a cloth. Finally, selected seeds can be disinfected by a quick dip (30 sec) in freshwater or by using a natural disinfectant like lime water or diluted iodine.

Alongside preventing potential outbreaks, meticulous biosecurity measures are essential for quarantining and disposing of unhealthy or infested seaweeds to prevent the spread of disease. In case of suspected outbreaks or infestations, prompt action is required to remove and isolate affected seeds. The disposal of problematic seaweeds should be on land, avoiding release into the ocean. If the disease or infestation is challenging to identify, capturing a photo and documenting environmental conditions and seaweed tissue characteristics leading up to the outbreak is recommended. Then, this information can be shared with the seaweed industry association (if one exists for the region) and/or with a phycologist familiar with seaweed pathogens.

Genetically diverse and ecologically managed seaweed farms are more resilient to disease (Cottier-

Cook et al. 2016). Thus, farmers should strive to refresh propagules through nursery techniques for sexual reproduction, if possible. Individual farms can be designed and managed to support the co-cultivation of several species, and farms near one another could grow different species.

For additional recommendations on seaweed farming biosecurity protocols, we point the reader to:

- *Standard Operating Procedure of Eucheumatoid Cultivation Using Biosecurity-Based Approach* by Cicilia S. B. Kambey et al. (see Kambey et al. 2021)
- "Biosecurity Policy and Legislation for the Global Seaweed Aquaculture Industry" by Iona Campbell et al. and published in the *Journal of Applied Phycology* (see Campbell et al. 2020).

Monitoring and maximizing ecosystem benefits

Well-managed seaweed farms have the potential to provide both regulating and provisioning ecosystem services. Due to their normal biological processes, seaweeds remove nutrients, minerals, and carbon dioxide from the surrounding water. The resulting benefit for the greater ecosystem — maintenance of good water quality — is called a *regulating ecosystem service*. Most primary producers contribute to regulating ecosystem services, but mangroves, wetlands, seagrass beds, and seaweeds (wild and farmed) are especially good at it. Seaweed farms have been shown to compete with harmful algal blooms and opportunistic macroalgae like *Ulva* spp. for nutrients in the surrounding water (Valiela et al. 1997; Chopin et al. 2001; Neori et al. 2004). Additionally, by taking up carbon dioxide from the water, these seaweed farms can help alleviate the impacts of ocean acidification at a local scale.

Seaweed farms also provide refuge or food for fish and other marine organisms (Theuerkauf et al. 2022). This class of ecosystem services is referred to as *provisioning*. In most cases, tropical seaweed farms have a higher biodiversity and abundance of fish and invertebrates than sandy-bottom areas without seaweed farms or three-dimensional structures. On a seaweed farm located approximately 3 km off the southeastern shore of Puerto Rico, researchers observed a rich community comprised of pearl oysters, pen shells, tunicates, seaweeds, juvenile spiny lobsters (Figure 26), crabs, and fishes on the submerged structural lines associated with the farm (TNC 2024b). Some of the organisms using a seaweed farm for food or shelter may live out their whole lives on the array, whereas others, like the spiny lobster larvae, may use the array as a habitat just until they grow larger and relocate to rocky outcroppings or nearby seagrass beds. Aquaculture farms, more broadly, can also serve as fish aggregating devices (Gibbs 2004; Dempster et al. 2009; Akyol and Ertosluk 2010). This interaction may have both positive and negative connotations for the farmer, fishery, and wild fish populations (Clavelle et al. 2019). The floral and faunal assemblages may provide an additional source of food or refuge, but the predators attracted to the aggregating fish could cause damage to the crop or the array (Campbell et al. 2020). A higher catch per unit effort may be obtained by fishing these aggregations, but it also increases the risk that a wild population could be overexploited (Campbell et al. 2020). However, further studies are needed to determine whether these fishes were attracted to the farm site from other locations or if they were recruited as juveniles and thus represent a net positive for the overall population.

There is more to learn about how seaweed farms interact with ecosystems in the Caribbean Sea. Beyond a general understanding of the scale and type of ecosystem service provided by seaweed farms, performance levels likely vary with farm site, season, density of cultivation, etc. For more guidance on how to conduct monitoring and evaluation of ecosystem services of aquaculture farms, please consult TNC's report *A Global Monitoring, Evaluation, and Learning Framework for Regenerative and Restorative Aquaculture* (TNC 2024a), which provides suggestions for indicators, metrics, and methods to promote comparable data across geographies.

Recordkeeping

Detailed recordkeeping is essential to allow growers to review and predict changes or challenges on the farm. Waterproof notebooks can be used on the water for rudimentary recordkeeping. However, if opting to use a physical ledger, it is advisable that a two-ledger system is used: one for the field and one in the office or at home so that a back-up version is available. Oceanfarmr and ArcGIS Survey offer paid subscription programs for digital farm management that

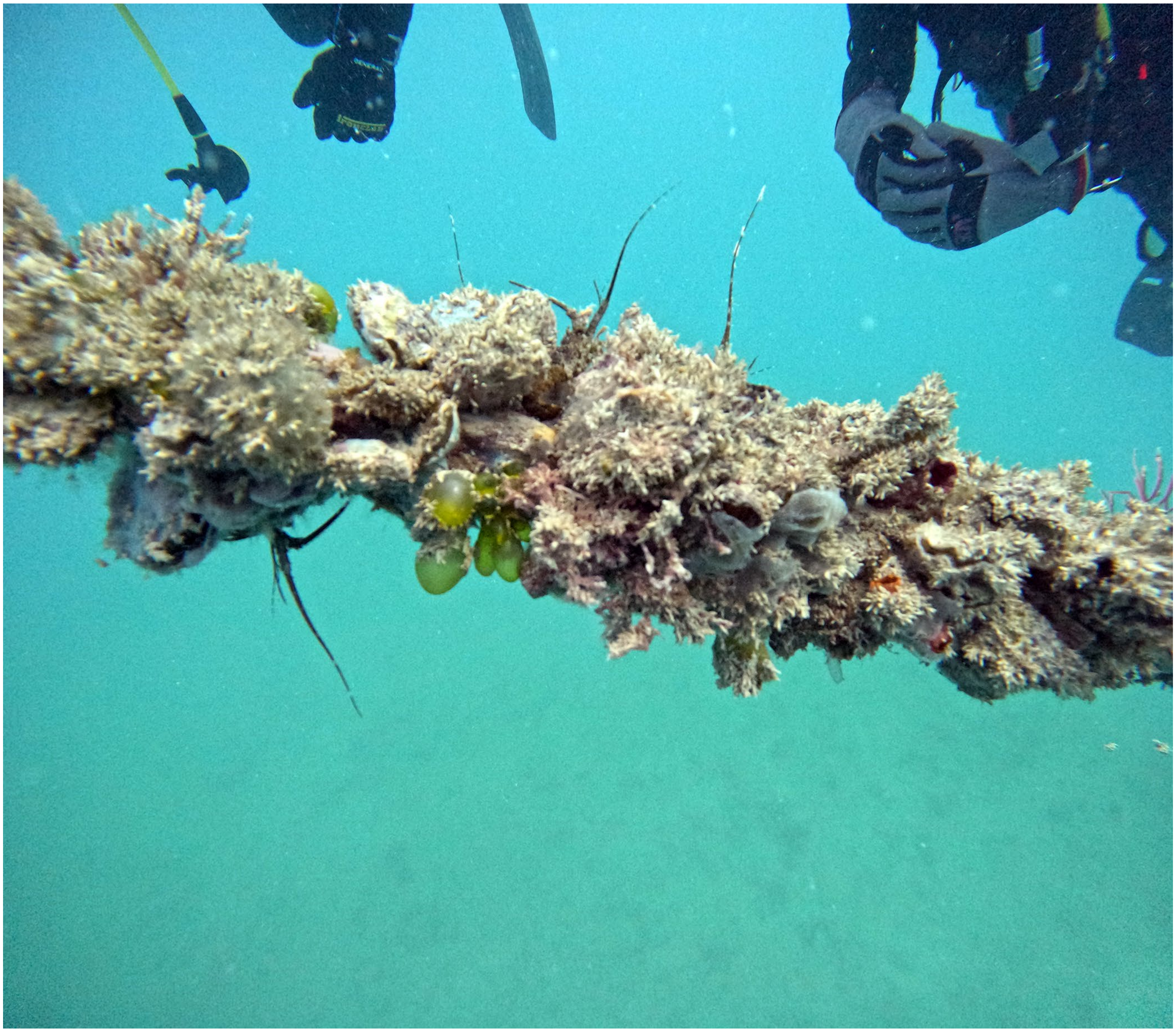

Figure 26. Juvenile spiny lobsters on a seaweed farm near Puerto Rico. Photo credit: Loretta Roberson, MBL.

allow for more sophisticated recordkeeping and analysis.

Each trip to the farm can be seen as an opportunity to learn more about the site and the conditions the crop is experiencing. Turbidity, salinity, and water temperature can all be measured with inexpensive instruments. A Secchi disk measures the turbidity, and a handheld refractometer determines the salinity. Electronic loggers that measure salinity and turbidity are available but are relatively expensive; therefore, we recommend spot measurements for farmers with limited means. Water temperature can be measured with a waterproof thermometer, but inexpensive (< USD 50), submersible electronic data loggers are available. They obtain a continuous record of the site's water temperature. A minimum of two loggers per site should be deployed to account for intra-site variability and provide redundancy if one logger is lost, stops logging, or experiences technical failure. Downloading the data routinely (i.e., monthly) will help ensure that only minimal gaps in the temperature record result if one of these events does occur. Additionally, more and more climate and oceanographic data are available online. In Puerto Rico, for example, the Caribbean Coastal Ocean Observing System (www.CariCOOS.org) provides real-time data as well as both prognostications and historical data on sea surface temperature, wind, waves, currents, and relative abundance of floating

Sargassum. Rainfall and hours of sunlight/cloud cover can be obtained from the National Weather Service (www.weather.gov/sju). The National Data Buoy Center (www.ndbc.noaa.gov) not only provides data from U.S. assets but also links to a global network of weather buoys. Other sites like weatherspark.com provide average monthly weather, including water temperature and currents, and can assist in determining the cultivation season at sites where remote monitoring is unavailable.

Understanding the nutrients present in the water at a particular location can be helpful both for site prospecting and as metadata informing observed growth rates. The surrounding geology typically influences the level of phosphate at a site, so sampling just enough to determine a baseline concentration level is likely sufficient for most farming operations. Nitrogen levels are much more likely to vary with changes in precipitation, anthropogenic activities nearby, and the scales of seaweed cultivation and the site. Therefore, collecting routine water samples for nitrogen analysis during the first few years of working at a new site, or before and after any substantial changes in growth rates, could prove useful. When collecting samples, it is advisable to do so at the same depth as the seaweed because substantial variation in the distribution of nitrogen can exist throughout the water column. Once the water sample is collected, it should be kept cool and delivered to an analytical lab for quantification. As the methodology used to analyze nitrogen can vary from lab to lab, it is important to contact a lab for instructions on sample collection before beginning this effort. While there are commercially available instruments for continuously measuring nitrogen underwater, they are relatively expensive and require semi-regular maintenance. Most small farms will be better served by collecting the "spot" or "grab" samples described here. If spot sampling is not feasible at a specific site, it is worth the time to look for any other monitoring efforts being conducted in the region to see if they might make their data available.

Making notes about anomalies and qualitative observations is equally important. The timing and duration of environmental anomalies (e.g., heat waves, big weather events, swings in salinity) can be useful, especially when paired with observations of other environmental conditions during the event. Noting the appearance of blooms (plankton or other) and biofouling organisms, watercolor, herbivory, and recent rainfall [h] will help with interpreting any quantitative measurements made. Written records of variations in seed source or starting seed condition and health, planting densities, and equipment failures can lend to the early detection of potential problems and facilitate quicker pivots in techniques, materials, sites, and sources.

In addition to recording observations and collecting data, farmers must dedicate time to analyzing the information and using it to inform changes to their operations. Keeping an eye out for relationships, like which environmental conditions are present when the highest growth rates are observed, can help a farmer reevaluate the suitability of a given site and structure the timing of seeding and harvesting to coincide with the identified optimal environment. Similarly, a farmer may be able to determine when to harvest or let the site fallow by reviewing the records to identify seasonal patterns concerning biofouling, crop mortality, and/or the timing of heat waves, major storms, etc. If done effectively, this may very well lead to increased production and lower operating costs, ultimately improving profitability.

For additional guidance on better monitoring practices, we direct the reader to *A Global Monitoring, Evaluation, and Learning Framework for Regenerative and Restorative Aquaculture* (TNC 2024a).

Forecasted costs

The capital costs of starting and operating a small-scale seaweed farm in the Caribbean vary with multiple factors, including the type of cultivation array used, the environmental conditions at the farm site, and the availability of existing equipment (e.g., boats, storage) that can be shared with or reallocated to the farming activities (Kite-Powell et al. 2022). The costs of operating said farm are heavily influenced by the cost of the seedlings, as well as the cost of living in the host country and, thus, wages paid to workers (Matoju et al. 2021). In Box 4, we present the results of a production cost analysis exploring the estimated contribution of each factor toward the cost of small-scale seaweed farming production in Puerto Rico.

[h] Cumulative rainfall may be retrieved from a local weather station's data or measured on-site using a simple rainfall gauge mounted on top of a buoy or other structure above the water.

Box 4: Production costs for a hypothetical small-scale seaweed farm in Puerto Rico

Kite-Powell et al. (2023) developed an economic model that estimates the production costs for a hypothetical small-scale seaweed farm in nearshore Puerto Rican waters. This model uses a multi-line system located on a 1.7 ha site. Five full-time workers operate the farm 8 months out of the year. They outplant seaweed seeds at 0.5 kg/m and harvest the biomass 30 days later at 1.5 kg/m using a boat with a 1000 kg payload. The estimated production costs at this scale range from roughly USD 1000 to USD 3000 per dry commercial ton. They are highly dependent on the anticipated daily growth rate of the seaweed crop and, thus, the possible harvest per meter of the growline (Figure 27A). This model estimates that wages paid to workers account for the largest share of production costs (44%), the workboat and farming gear account for approximately a quarter of the costs (12% and 17%, respectively), and expenses associated with land-based activities (e.g., onshore nursery tanks and line maintenance) account for the remainder (27%; Figure 27B). The model does not include the cost of building or operating a nursery to provide the seaweed seedstock. Rather, it assumes that a small-scale farm would obtain seaweed seedstock from a separate entity that supplies several farms.

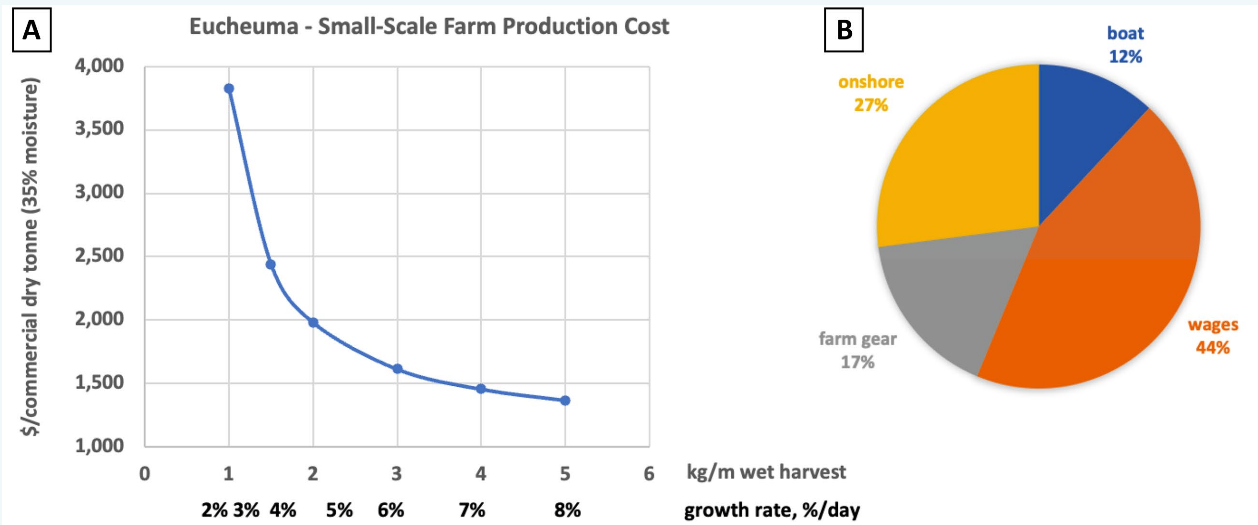

Figure 27. (A) Estimated production costs for a small-scale tropical seaweed farm as a function of the seaweed growth rate. (B) Division of production costs by category. Image credit: Kite-Powell et al. 2023.

Permitting

The process for obtaining permits to farm seaweed is different for each country and territory in the Caribbean. In some locations, no established formal process exists as of yet. In other locations, at least one, if not several, government agencies must be consulted. Often, the relevant fisheries and/or natural resources department will be the lead authority that must be consulted to obtain a lease for the use of the seabed. These leases are usually for a defined period, with the option for renewal. There is typically a fee for the lease. The cultivation array and algal species may need to be approved through a separate process. Due to the broad scope of this guide, we have refrained from providing specific permitting guidance for each country or territory. Rather, we offer a case study: a deep dive into the lease application process in Puerto Rico (Appendix C).

To expedite the permitting process, growers should prepare by researching the site and completing the necessary documentation before applying. Demonstrating a solid understanding of the social and ecological characteristics of the desired farming site is important because the managing agency will need to consider the potential impact that the proposed seaweed farming activities will have on the surrounding environment and other water users. Conducting a site survey before applying for the permit can be helpful, if not mandatory. The survey should document the type of sediment at the site, if any corals or benthic vegetation are present, pelagic species observed, and other water uses. If possible, this survey should have accompanying video and photos. The managing agency may also request detailed drawings and descriptions of the cultivation array that will be deployed at the site. The drawings should be prepared to scale and include both a side view and a bird's-eye view.

Occupational health and safety

The health and safety of all workers involved with the seaweed farming operation is of utmost importance. Careful planning and training, along with good communication, will prevent accidents and potential injuries. Weather forecasts should be checked when planning work at the farming site and again in the morning before leaving the shore. Farmers should avoid working during inclement weather conditions (see more on storm preparedness in the next section). The work vessel should be equipped with a first aid kit, sun protection, gloves, a marine radio or cell phone, flares, and life vests. Before starting work, prepare necessary equipment, including closed-toed shoes and a knife, for swift action in case of entanglement. Farmers working in water deeper than 1 m should know how to swim. Additionally, if scuba diving, all team members should know where the closest oxygen kit is located and how to use it.

Employees should undergo comprehensive training sessions to familiarize themselves with potential risks and appropriate safety protocols, including BMPs. Cardiopulmonary resuscitation and first aid training should be provided to all workers, and they should be involved in developing a plan for medical or scuba-diving emergencies (e.g., address and telephone number for the nearest hospital and/or hyperbaric chamber, transportation options to this facility). Ensuring fair remuneration for employees and prohibiting the involvement of underage individuals are also important for a safe and ethically sound working environment.

Storm preparedness, recovery, and disaster assistance

Severe storms and hurricanes frequently occur in the Caribbean. The hurricane season typically runs from June through November, with most storms forming in August, September, and October. Several options exist for managing seaweed farms during this season. One possibility is to cease farming activities during the hurricane season and completely remove the cultivation array and workboat from the water. This eliminates the risk of damage to the crop, array, vessel, and surrounding ecosystem.

A second option is to pause farming activities but leave the array (or a portion of it) in the water. Some or all of the crop can be removed and either sunk in deep water or brought to a safe, covered location on land. If the array is left in the water, farmers should conduct a thorough inspection of the array well in advance of the storm. All connection points should be checked to make sure they are securely tied, and the anchors' positioning should be examined to ensure they are firmly embedded. Once the storm has passed, the farmer should return to the site as soon as safely possible to assess the damage. Loose lines or rafts should be removed from the water immediately to prevent entanglement of marine life, vessels, or people. If necessary, additional assistance might be available from the managing marine agencies.

A third choice is to leave the array and crop deployed as in normal operations. There are several variables that may help farmers make a decision about whether to do this, including whether they have seen the farming array survive other storms of similar intensity, the total biomass (and therefore drag) on the array, the species being grown and its propensity for breakage, and the logistics and support available and required if the array were to suffer damages or failure.

A fourth possibility involves sinking the farming array and/or crop to avoid the strongest waves and storm surges. The possibility of using this strategy will depend on the cultivation system used, the depth of the site, the benthic composition at the site (i.e., Would corals, grasses, or other marine organisms nearby be impacted?), and resources required for raising the array after the storm has passed. Outfitting the work vessel with a davit and motorized winch will facilitate the recovery of the array.

Farmers should develop a written document that describes the steps to take depending on the forecasted intensity of the storm so that all team members are aware of the thresholds for each decision and the subsequent chain of actions. This plan should list pre-storm tasks and relevant emergency numbers.

Having replacement lines ready to deploy (i.e., cut to the appropriate length, spliced if necessary) is also advisable. The use of quick-release C-links, when possible, will make replacing lines easier.

Developing a regular inspection schedule to evaluate lines for chafe and anchors for rust can help reduce the likelihood of gear failure during a storm when recovery may be much harder or impossible. Regular inspection is important because there may be other priorities right before a storm, like hauling boats, personal preparations, etc. Conducting an inspection after the storm is equally important to ensure all anchors have stayed put, connections remain intact, and no debris has worked its way onto the farm.

Even with the best precautions in place, there is a high likelihood that a seaweed farm will suffer some degree of weather-related crop loss over the course of many years of operation. Depending on the location of the farming operation, agricultural programs may offer financial assistance following weather-related disasters (e.g., extreme heat or a hurricane). If such a program is available, ample documentation of pre-disaster inventory is very important. This may include starting biomass records, biomass estimates before the event, and normal mortality rates on the farm.

Figure 28. Seaweed drying on a rack in St. Lucia. Photo credit: Juli-Anne Russo, CAEIH.

Section III. Market opportunities and supply chain considerations for Caribbean seaweed sourced from small-scale farms

Global production and the use of warm water seaweeds

Per an FAO report (2022b), global seaweed production, both wild and cultured, was 34.6 million MT in 2021, valued at USD 15.5 billion. This production represented a 13% increase over the previous 5 years, continuing an exponential trajectory of between 1.0% and 2.5%, and it has increased annually since the 1970s. The same FAO report (2022b) stated that the trend in the global export of seaweed and seaweed products has followed a similar upward path since the 1970s and was valued at USD 1.2 billion in 2021. World seaweed production continues to be dominated by Asia, where the top five producers are China, with 57% of worldwide production; Indonesia, with 28% of worldwide production, and lesser, but still significant, quantities from the Republic of Korea; the Philippines; and the Democratic People's Republic of Korea (also known as North Korea). These countries account for over 97% of global production. By comparison, the top producers in the Americas, Europe, Africa, and Oceania together account for less than 2% of global production (FAO 2022b).

The increases in global seaweed production and value reflect the growing worldwide demand for seaweed due to its numerous food and nonfood uses. Over the years, consumers, especially in Asia, have become more affluent and have demanded more of what most consider a very healthy and nutritious food source rich in omega-3 and omega-6 fatty acids, vitamins (A, C, E, and B12), and other essential nutrients (Reis et al. 2015). Countries are looking to seaweed in the context of food and livelihood security for growing populations, restorative aquaculture, and carbon sequestration as a climate change mitigation strategy (FAO 2018). More industries are also demanding the bioactive compounds found in seaweed, such as carrageenan, agar, alkaloids, fatty acids, and polysaccharides, which have uses in the food, agriculture, chemical, medical, pharmaceutical, and construction industries (Zhang et al. 2022).

Most tropical seaweed production around the world is comprised of red seaweeds. In 2021, red seaweed production globally was 14.6 million MT, valued at USD 1.2 billion (Redmond et al. 2014). This production accounted for 42% of all seaweed production, the majority of which came from the genera *Gracilaria* spp. (14.8%), *Eucheuma* spp. (23%), and *Kappaphycus* spp. (4.6%; Redmond et al. 2014). These tropical red seaweeds are currently cultivated at commercial levels in Indonesia, the Philippines, Malaysia, Tanzania, and, to a much lesser degree, Morocco, South Africa, Madagascar, Egypt, Namibia, Timor-Leste, Kenya, Sri Lanka, Ecuador, and Tunisia (FAO 2022a). Seaweed production from Indonesia far exceeds that of any of the other countries. In 2019, almost 12 million MT (WW) of *Kappaphycus*/*Eucheuma* were produced, and Indonesia alone was responsible for approximately 10 million MT (Kambey et al. 2021). In the Americas, red seaweed's total production in 2021 was 21,937 MT, with a corresponding value of USD 203 million. Chile and Venezuela accounted for 91% of the volume from the Americas, with 15,571 MT and 4500 MT of *Kappaphycus* spp., respectively (Redmond et al. 2014).

The price of red seaweed products is known to fluctuate and depends on market factors such as the product origin, season, type of processing, and intended usage (Matoju et al. 2021). The average nominal price (without value-added) based on quantity produced and value of live weight (wet) red seaweed since 1984 is 0.0002 USD/kg live WW (Redmond et al. 2014). Dried *Eucheuma* and *Kappaphycus* prices have been reported as low as 0.2 USD/kg and 0.4 USD/kg, respectively, in Zanzibar (Brugere et al. 2020). *Kappaphycus* spp. often have a higher price than that of *Gracilaria* spp. and *Eucheuma* spp.

Hydrocolloids

On a global scale, almost all tropical seaweed biomass is used to produce *hydrocolloids*, which are hydrophilic substances that form gels in the presence of water. Hydrocolloids are commonly used as texturizers, thickeners, or binders in cosmetics, processed foods, animal feeds, and pharmaceuticals. Alginate, agar, and carrageenan are all commercially valuable hydrocolloids produced from seaweeds. Agar is typically the most expensive, followed by alginate and carrageenan. Temperate brown seaweeds are the primary sources used for commercial alginate production, and given the scope of this guide, no further details on alginate will be provided. However, both carrageenan and agar are routinely produced from tropical red seaweeds. More details on both hydrocolloids are presented in the following subsections.

Carrageenan

Commercial-grade carrageenan is primarily derived from the red seaweeds *Kappaphycus*, *Eucheuma*, *Chondrus,* and *Gigartina.* These species can have up

Figure 29. Dried seaweed packaged and ready for export. Photo credit: Juli-Anne Russo, CAEIH.

to three different degrees of sulfation of the carrageenan, [i] which ultimately results in carrageenan with different material properties. However, carrageenan processors are looking for seaweed with a consistent, specific carrageenan composition and high carrageenan-to-weight ratio. Typically, manufacturers purchasing carrageenan for inclusion in a product will specify what type of carrageenan they want. Additionally, the carrageenan-to-weight ratio can range between 40% and 70% depending on the seaweed species, season, and cultivation conditions. Carrageenan processors typically prefer seaweeds with a higher carrageenan-to-weight ratio because less work is required to obtain more carrageenan.

Eucheumatopsis isiformis is mostly a producer of iota-carrageenan, but its carrageenan is a hybrid structure of kappa-iota-nu with unique properties (Freile-Pelegrìn and Robledo 2008). Iota-carrageenan, the phycocolloid most abundant in *E. isiformis*, has a niche as a carrageenan used to make clear, soft, and flexible gels with minimal syneresis [j] properties. Iota-carrageenan content in *E. isiformis* collected from Nicaragua and the Gulf of Mexico has been shown to have sufficient quality and purity to substitute for *Eucheuma denticulatum* in carrageenan processing (Freile-Pelegrìn et al. 2006). However, the biochemical composition and the carrageenan content and properties of *E. isiformis* can fluctuate depending on the seaweed's origin; for example, the properties of *E. isiformis* carrageenan from Yucatan, Mexico, can be different than the material collected from Florida, potentially due to the higher salinity levels of Yucatan's water, or possibly differences in a closely related species: *Eucheumatopsis sanibelensis* (Valiela et al. 1997; about *E. sanibelensis*: Guiry and Guiry 2020). This regional variation in carrageenan composition emphasizes the importance of environmental monitoring at cultivation sites, subsequent compositional profiling, and a better taxonomical understanding of *Eucheumatopsis* species.

The carrageenan market is highly commoditized and publicly available cost data is scarce. Furthermore, the price of raw, dried seaweed used to make carrageenan fluctuates from country to country with supply, quality, distance from source to processing plant, and end use of the seaweed. [k] For example, cosmetics and health food stores need higher-quality semi-refined or refined carrageenan (1 to > 10 USD/lb; Dubon 2016). For these reasons, we currently hypothesize that the processors' willingness to pay for *E. isiformis* is likely captured by the U.S. dollars per ton (USD/ton) reported in the literature and through personal communication for a closely related species, *E. denticulatum*. In 2015, one dry MT of *E. denticulatum* ("spinosum") reportedly sold for USD 690 (Porse and Rudolph 2017). Assuming a WW:DW ratio of 10:1, this finding would equal USD 69 per WW MT.

Agar

Commercial-grade agars are primarily derived from red seaweeds, with *Gelidium* spp. and *Gracilaria*/*Gracilariopsis* spp. serving as key sources. Agar extracted from wild *Gelidium* spp. exhibits a heightened gel strength owing to its lower sulfate content, making substitution a formidable task. Widely employed in bacteriological and pharmaceutical domains, producers using these agars face a challenge due to a notable decline in wild *Gelidium* populations (Theuerkauf et al. 2022). Conversely, agar sourced from *Gracilaria*/*Gracilariopsis* spp. tends to possess weaker gelling properties due to its elevated sulfate content, rendering it more suitable for various food applications. Even when originating from the same seaweed species, agar yield, synthesis, and chemical composition can exhibit significant variations due to diverse factors such as environmental conditions, algal growth stages, seasonal fluctuations, and nutrient availability. Manipulating extraction parameters like time, temperature, and solvent-to-seaweed ratio offers the potential for enhancing the gelling ability (Arvizu-Higuera et al. 2008; Sousa et al. 2010). Notably, while the price of raw *Gracilaria* has decreased significantly in the last decade, the final cost of food-grade agar has remained relatively stable. This stability amid fluctuating raw-material costs highlights the complexity of the agar market (Theuerkauf et al. 2022).

In the Caribbean, *Gracilaria* spp. have received the most focus in assessments of commercial potential, but the taxonomy of many species remains problematic. The yield and quality of agar extracts have been

[i] Kappa-carrageenan has one sulfate group per disaccharide, iota-carrageenan has two, and lambda-carrageenan has three sulfate groups.

[j] In chemistry, syneresis is the contraction of a gel accompanied by the expulsion of liquid from the gel.

[k] The biggest importers of hydrocolloids are the United States and Germany.

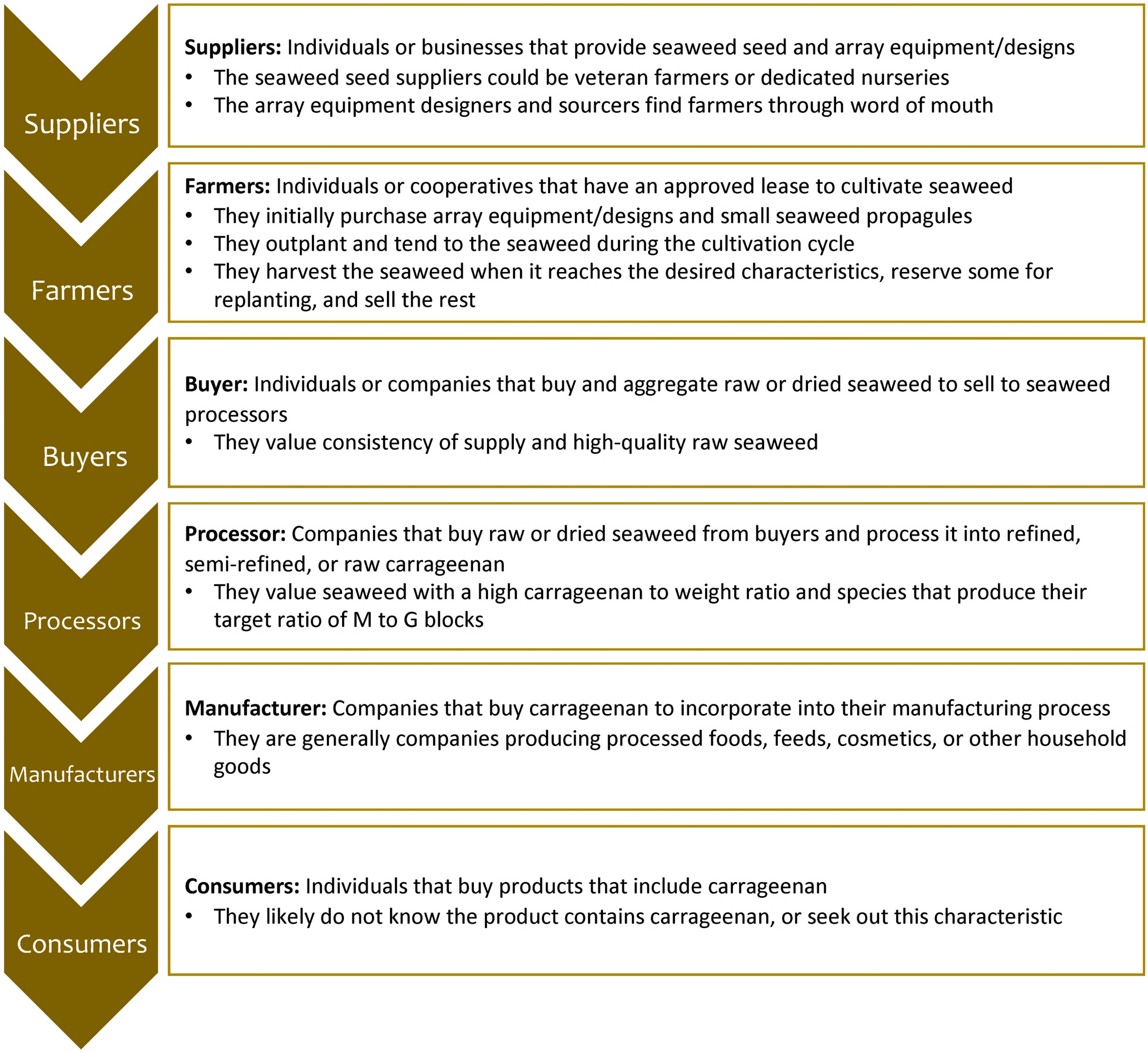

Figure 30. Key players and their characteristics in the global raw algae markets for global hydrocolloids. Image credit: Gretchen Grebe, Diadromous, LLC.

determined for many of the Caribbean Gracilariaceae. Most have extracts of poor gelling ability, but a few are of commercial quality. Lahaye et al. (1988) reported that alkali-treated extracts from *Gracilaria mammillaris* from St. Lucia contained high-quality agarose suitable for industrial and biotechnological applications. A study of five species from Barbados showed that only *Hydropuntia cornea* (as *Gracilaria debilis*) was able to form a firm gel without treatment with alkali, comparable to the weaker gels required by the food industry (Duckworth et al. 1971). Similar gel strengths were reported for this species in Venezuela (Rincones 1990). Alkali-treated extracts from *Gracilariopsis* sp. from Venezuela showed gel strengths around 1000 g per cm^2, which was considered to be the highest for a Caribbean gracilarioid (Racca et al. 1993). Murano et al. (1996) evaluated extracts from two Venezuelan species and reported that *G. mammillaris* agar was of poor quality, while *Gelidiella acerosa* was a potential source of high-quality agar. In Cuba, a number of agarophytes were identified as having commercial potential. In particular, *Bryothamnion triquetrum* was evaluated as a potential source of industrial agar. The extract yield and quality were reported to be suitable for biomedical applications (Areces 1990). A preliminary inventory of species of economic importance in the Guajira Peninsula of Colombia included five *Gracilaria* spp., but their agar content and quality were reported to be low (Gallo and Rincones 2003).

Growth and innovation in the hydrocolloid industry

Figure 30 depicts key players in the global hydrocolloid supply chain, along with some of their most notable characteristics.

In the near future, the hydrocolloid industry is expected to grow primarily via improved engineering systems at the well-established large-scale production and processing plants in Southeast Asia (Theuerkauf et al. 2022). However, several emerging food applications for hydrocolloids may result in heightened demand for them. These novel applications include the use of hydrocolloids in fast food as a fat replacer, as an edible film-forming or coating agent, and in prebiotics (Li and Nie 2016). Depending on the location of the users for these new applications and their desired hydrocolloid characteristics, small amounts of growth in hydrocolloid production may emerge outside of Asia in the years ahead.

Existing markets and processing for Caribbean-grown seaweed

Presently, none of the seaweed grown in the Caribbean is used for hydrocolloid production. This is because hydrocolloid producers require significant amounts of raw biomass to ensure cost-effective transportation of dry seaweed from its origin to processing plants; however, the current scale of seaweed production in the Caribbean falls short of meeting these manufacturers' minimum quantity demands. The insufficient volume impedes the

Figure 31. Value-added seaweed products sold in St. Lucia: (A) Seamoss Ranch, (B) Dry Seamoss, (C) Powdered Sea-moss, Purple, (D) Superfood Daily Boost Capsule, and (E) Seamoss, Eucheuma Cottonii. Photo credit: Juli-Anne Russo, CAEIH.

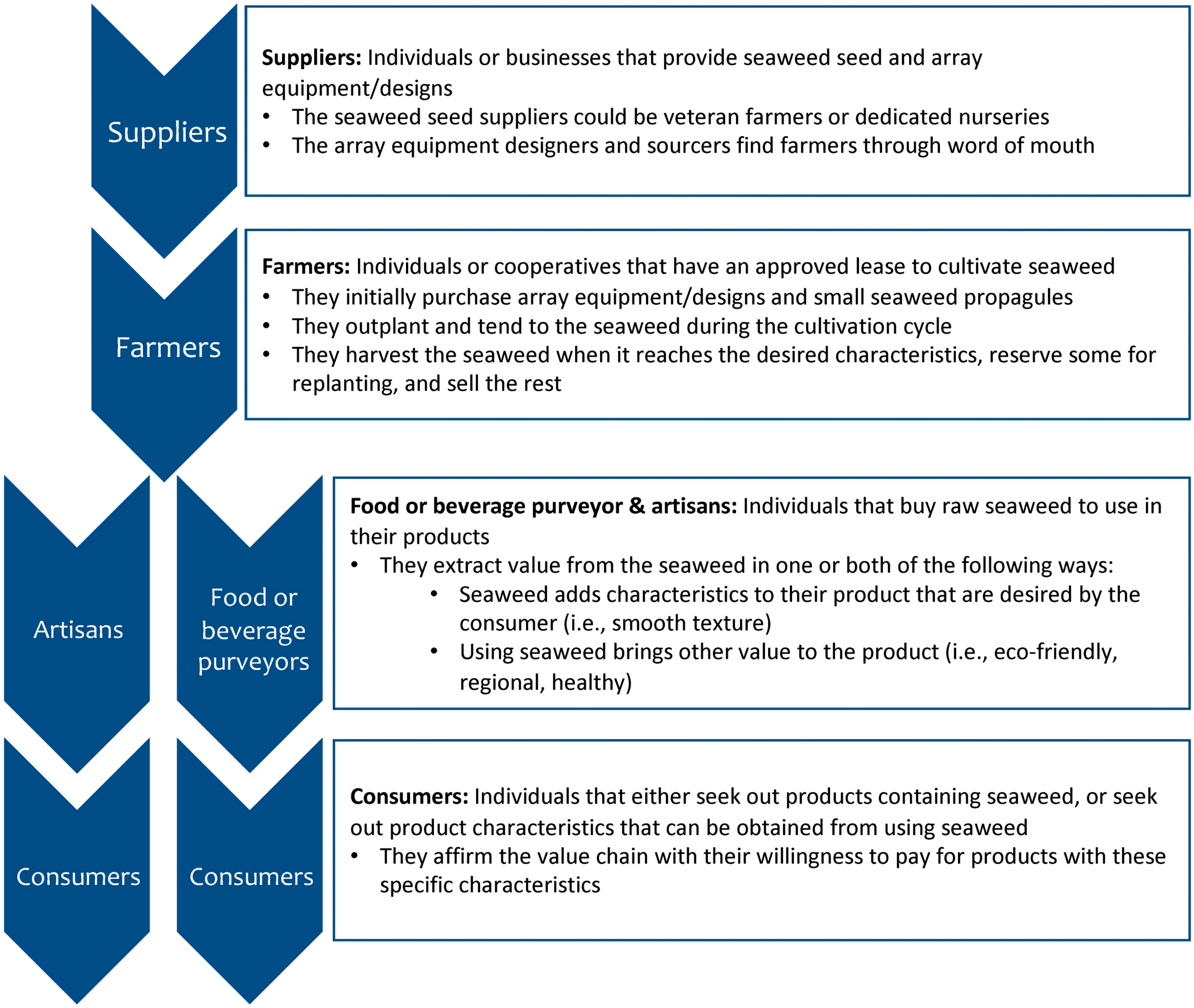

Figure 32. Key players and their characteristics in the Caribbean raw algae markets for food, beverage, and fibrous material. Image credit: Gretchen Grebe, Diadromous, LLC.

feasibility of using Caribbean seaweed for hydrocolloid production.

Thus, most of the seaweed currently produced in the Caribbean is used locally or regionally. As previously mentioned, the most ubiquitous use of these seaweeds is in fruit-flavored shakes/smoothies and in salads sold locally at shops, village pharmacies, and fairs. [1] Some entrepreneurs sell dry seaweeds, sauces, artisanal soaps, shampoos, or facial masks that integrate seaweeds (Figure 31).

See Box 5 for a list of seaweed products produced or trialed in the region. Additionally, some Caribbean-grown seaweed is dried and exported outside the region, then sold as such or further processed into seaweed gels or nutritional supplements. The key members of the existing Caribbean raw algae markets for food, beverage, and fibrous material are presented in Figure 32.

If seaweed is harvested for local sale, it should be rinsed in clean, fresh water after being removed from the farm. All debris and fouling organisms

[1] For example, the Seaweed Fair held during St. Lucia's World Food Day in October 2022 (St. Lucia Ministry of Agriculture 2022).

Box 5: Seaweed products commonly produced and sold regionally within the Caribbean

- Dried raw seaweed
- Drinks
- Jelly

Experimental/trial products that have also been sold include the following:

- Skin care products, including facial masks, soap, and others, such as those used to treat eczema (Rodgers and Cox 1999)
- Ice cream (Rodgers and Cox 1999)
- Oil
- Gummy bears
- Salt
- Agar

should be removed, and then it can be soaked in fresh water for 6–8 hours to soften the seaweed and facilitate faster drying and bleaching (Hayashi et al. 2017). For some international markets like the hydrocolloid markets, the freshwater rinse and soak should be skipped, and the seaweed can go straight from harvest to drying. This is because rinsing with fresh water can result in a premature exudation of the target polysaccharides (i.e., agar or carrageenan).

Conventional drying methods are to spread the seaweed out on a tarp or drying rack to allow the sun and warm air to dry it (Figure 33). If possible, the seaweed should be dried in the shade because solar radiation can degrade sensitive biocompounds like antioxidants. Turning the seaweed over every 3–4 hours will help it to dry thoroughly, as will covering it at night and during rainstorms. [m] Using this method, it typically takes 3–5 days in good weather for the seaweed to be sufficiently dry. However, substantial gains are possible by improving upon the conventional drying method using a drying house or greenhouse. A shortened drying time (2–3 days) and improved quality of the raw, dried seaweed have been observed (Borlongan et al. 2011).[n]

Regardless of the drying technique used, once the seaweed reaches the appropriate moisture content, it should be stored in a cool, dry location to prevent rehydration and spoilage. The target moisture content can vary substantially depending on the market. For example, the hydrocolloid industry standard for properly dried seaweed is 35% moisture content. Seaweeds destined for fresh food products or cosmeceuticals (e.g., Figure 34) may not need to be dried at all.

Expanding and emerging markets for Caribbean-grown seaweed

The largest obstacles preventing Caribbean-grown seaweed from being used in the global hydrocolloid industry are (1) the limited volume, consistency, and quality of supply and (2) pricing and regulatory barriers. To gain access to the larger global hydrocolloid markets, producers in the region will have to demonstrate production of a minimum viable amount of seaweed biomass. The production cost of this biomass will need to be close to or lower than that of existing biomass from other regions and species. It must also have distinguishable characteristics that make it attractive enough to encourage substitution

Figure 33. Eucheuma seaweed dries in a backyard in Placencia, Belize. Photo credit: Jennifer Adler, Jennifer Adler Photography.

[m] Preventing rehydration of the drying seaweed during a rainstorm will prevent gelling (the premature exudation of agar or carrageenan).

[n] In 2020, the Liamuiga Seaweed Group in St. Kitt and Nevis built a custom drying house for seaweed (Caribbean Natural Resources Institute 2020).

Figure 34. Cosmetics sold in Jamaica made from wild-harvested seaweeds. Photo credit: Juli-Anne Russo, CAEIH.

or increased consumption while still being sufficiently like existing products.

In the meantime, the Caribbean seaweed farming industry can target other markets that will accept smaller minimum harvests, like the food and beverage market and the fiber market. In these markets, seaweed producers do not need to displace demand for existing products. Rather, the manufacturers and retailers of seaweed-centric products in novel markets can focus on drawing in new consumers.

Raw seaweed could be processed in a variety of ways for incorporation into food and beverage markets. It could be air dried, as is the existing practice in the region, but it could also be consumed raw, fermented, powdered, or processed into a liquid concentrate. Processors of temperate seaweeds from the Western Hemisphere have been experimenting with these nontraditional preparations over the last decade, and they have been well-received by prepared food manufacturers and consumers because these processing methods make it easier to incorporate seaweed into foods consumers recognize. In a few places in the Caribbean, cooks have incorporated seaweed into existing recipes for ice cream, granola bars, cake, fudge, ice pops, and Ponche Kuba (TNC 2024a).

These applications suggest that there may be some potential to further integrate seaweed from the region into regional food markets. However, it may take some time for these preparations to be sought after, as studies suggest that in low- to middle-income countries where marine-based foods are consumed infrequently or in modest amounts, dramatically increasing the consumption of seaweeds as a novel food may be overly optimistic (Cai et al. 2021; Webb et al. 2023). The taste, texture, and smell of the seaweed and the final product containing it are especially important characteristics when it is destined for human consumption (Díaz López and Methion 2017). Some research suggests that highlighting the health properties of seaweed may improve the likelihood of interest and use, especially among health-conscious, high-income consumers (Kite-Powell et al. 2022).

Beyond the established hydrocolloids and food sectors, Caribbean seaweed may have value in other relatively new and emerging applications. For example, some algae are now being cultivated for the colorants that can be extracted from them; R-phycoerythrin and R-phycocyanin are currently the main targets (Baghel et al. 2014). Other entrepreneurs are interested in processing seaweed biomass using other techniques to produce plant biostimulants, fertilizer and biochar (Roberts et al. 2015), livestock feed (including methane-reducing additives; Mirera et al. 2020; Rothman et al. 2020), and pet food. In the short term, these may be the most promising new markets; globally, they are projected to reach USD 4.4 billion by 2030 (World Bank 2023). Aquarists that build and maintain saltwater tanks often use live tropical seaweeds, so some genera, like *Caulerpa* or *Halymenia*, could be grown for this purpose as well (Stuthmann et al. 2023). But one word of caution: *Caulerpa taxifolia* is a highly invasive species that can be misidentified as one of the native, noninvasive *Caulerpa* spp., so to prevent the spread of *C. taxifolia* all propagules should be obtained from a reputable source.

Medium-term opportunities, including nutritional supplements, alternative proteins, and bioplastics and fabrics, could reach USD 6 billion by 2030 (Freile-Pelegrìn and Robledo 2008). A recent analysis by TNC and Bain & Company determined that biostimulants and bioplastics were the two most promising markets for growing seaweed farming in the near term in novel geographies due both to proven use cases on the market and the ability to support growth (TNC and Bain & Co 2024). Seaweed has added benefits in these markets: providing an alternative to products that use higher levels of natural resources and potentially avoiding significant carbon emissions. However, farmed seaweed currently faces challenges within these markets due to higher costs compared to wild seaweed and/or alternative feedstocks. Pharmaceuticals and construction materials are estimated to reach USD 1.4 billion by 2030, but because they face significant regulatory challenges and require significant investments in product development, they have been recommended as long-term term emerging markets for the seaweed industry (Freile-Pelegrìn and Robledo 2008).

Payment for ecosystem services

In addition to the direct sale of seaweed biomass and derivatives, seaweed farmers may also be able to extract additional value from their activities for conservation gain (Rawson et al. 2002). For example, cultivating seaweeds for the protection of coral reefs may have potential in a payments-for-environmental-services scheme. However, for an arrangement of this category to be exacted, several hurdles must first be overcome. The service/action must be quantifiable and verifiable, meaning that it must be shown that the specific seaweed farms can intercept sediment and nutrient runoff from the coast that would otherwise be detrimental to coral health. Then, mechanisms must be put in place to monetize the ecosystem services. These could potentially be taxpayer-funded payments, tradeable credits, subsidies, production cost-sharing schemes, or increased value to consumers that results in more sales and/or a higher sale price (Van den Burg et al. 2022). Also, once the funding mechanism has been established, the producers (seaweed farmers) must be able to access and participate in the trading system. Another well-known example of payment for ecosystem services that has been discussed in relation to seaweed farming is the well-established voluntary carbon crediting schemes. TNC and Bain & Company's recent analysis concluded that while seaweed farms do sequester some carbon in many cases, the level of sequestration and price of carbon credits is currently too low to incentivize growth in seaweed farming, particularly when considering issues like discounts for uncertainty and the need to show additionality (i.e., that seaweed farming was taking place due to the carbon financing, rather than occurring regardless; Layahe et al. 1988).

Additional candidate species

Despite the richness of the Caribbean seaweed flora and its proximity to processing facilities in North America and Europe, there has been little exploration of the region's seaweed resources. One study noted almost 70 species of potential commercial interest, including six genera of green algae useful for nutritional flours, 20 species of brown algae useful for alginates, and 28 red seaweed species useful as sources of agar or carrageenan (Díaz-Piferrer 1969). Of those identified, several species listed below are particularly promising due to their production of either a compound of existing interest (carrageenan or bromoform) or other characteristics already proven desirable.

Carrageenophytes [o]

- ***Hypnea musciformis***: a widely distributed red alga known to produce large amounts of kappa-carrageenan (Arman and Qader 2012).
- ***Solieria filiformis***: a red alga found in the Mediterranean Sea and the Caribbean. This species produces iota-carrageenan: approximately one-quarter to one-half of the DW yields obtained from *E. isiformis* (Caamal-Fuentes et al. 2017). High specific growth rates have been observed when tank-culturing this species in Yucatan, Mexico, using vegetative techniques (D. Robledo, pers. comm., 2022).

[o] Species that produce carrageenan.

Box 6: *Sargassum* in the Caribbean: Turning a "nuisance" into an opportunity

Intentionally cultivated seaweeds can be beneficial for the environment and coastal communities. However, uncontrolled growth of macroalgae, like the wild *Sargassum* blooms that have washed ashore on many Caribbean beaches over the last decade (Figure 35), can be a major detriment to coastal residents, fauna, and tourism (Oxenford et al. 2021). Several startups in the Caribbean are working on technologies that would enable and valorize the large-scale harvest of this *Sargassum*. While not an exhaustive list, some of these groups include the following:

- **Sargassum Ocean Sequestration Carbon (SOS Carbon)** is creating solutions for *Sargassum* collection, disposal, and processing. The team has developed a device termed the Littoral Collection Module that can be attached to artisanal fishing vessels to collect *Sargassum*. SOS Carbon also has a patent-pending technology to pump the collected *Sargassum* to depth, thereby avoiding landfills and potentially sequestering a portion of its carbon.
- **Carbonwave** is addressing the issue of *Sargassum* waste through the development of various seaweed products, including fertilizers, fabrics and textiles, and emulsifiers for cosmetics. The group implements a biorefinery approach to maximize seaweed utilization, and their products may contribute to emissions avoided through the replacement of petroleum-based products.
- **Thalasso Ocean** has developed an automated *Sargassum* harvesting device, as well as innovative micro-biorefineries that make extracting seaweed components more accessible to coastal communities and seaweed farmers.
- **BlueGreen** has developed a construction material derived from *Sargassum* seaweed and inspired by adobe bricks. The "Sargablocks" are made from 40% *Sargassum* and 60% other organic material (UNDP [United Nations Development Program] 2020).

The development of applications for wild *Sargassum* may prove beneficial for seaweed farmers, as well. For example, preliminary attempts to extract biostimulants from other bloom-forming *Sargassum* species show improved growth of the red seaweed *Neopyropia yezoensis* under high-temperature stress (Han et al. 2022). Additionally, supporting infrastructure developed for processing *Sargassum* could also be applicable for farmed species. For example, the seaweed biorefinery concept, implemented by Carbonwave and Thalasso Ocean, maximizes the use of seaweed biomass through the extraction of valuable seaweed components that can be used in a variety of products.

Figure 35. *Sargassum* washed up on the beach in Playa del Carmen, Mexico. Photo credit: TNC iStock license.

- ***Agardhiella ramosissima****:* a red alga endemic to the tropical and subtropical western Atlantic Ocean. In addition to carrageenan, this species has been shown to possess anti-inflammatory compounds of potential pharmacological importance.
- ***Halymenia* spp.**: widely distributed red algae that produce a highly sulfated lambda-carrageenan (Freile-Pelegrín et al. 2011). Wild *Halymenia* spp. are currently collected for use in the aquarium trade.
- ***Meristiella* spp.:** red algae that produce iota-carrageenan with promising antiviral properties (De Sf-Tischer et al. 2006).

Species with other desirable characteristics

- ***Botryocladia* spp.:** red algae with branches bearing vesicles that resemble clusters of grapes. At least 10 species of *Botryocladia* exist in the western Atlantic Ocean (Ballantine and Aponte 2002; Gavio and Fredericq 2003). These species may be used in food or the aquarium trade.
- ***Laurencia spp*.:** red algae that produce bromoform (Gribble 2000), which has recently been shown to have the potential to create methane-reduction properties in animal feed (Kinley et al. 2020).
- ***Caulerpa racemosa:*** a green alga native to the Caribbean region that is pantropical and widespread in warm seas. It is commonly referred to as *sea grapes* because it has branches bearing edible vesicles [p] that resemble clusters of grapes. *Caulerpa* spp. have also been marketed as "vegan caviar." Other species of *Caulerpa* are commonly eaten in Samoa, Kiribati, and Vietnam (Butcher et al. 2020).
- ***Ulva* spp**.: edible green algae widely distributed around the world. *Ulva* sp. is currently being grown in at least one land-based tank system in the Caribbean for use as cultivated sea urchin feed. [q] Recently, *Ulva* spp. have been incorporated into snack items like chips, and the species may prove useful as biomaterial feedstock.

Supply chain strengths and challenges

Industry associations

The establishment of farmer and industry associations is a strong first step in pooling resources to attract buyers, leverage knowledge, and advocate for shared needs. At the time of publication, we are aware of farmer or industry associations in St. Kitts, Jamaica, Barbados, St. Vincent and the Grenadines, and Belize. In St. Kitts, the Liamuiga Seaweed Group was formed after several wild harvesters (agro-processors and fishers) recognized that local demand for seaweed products could not be met by wild harvesting alone. Since 2017, the group has been cultivating a small amount of seaweed near Conaree Village on St. Kitts. They use the seaweed to produce seaweed drinks and other products. They sell these products at local markets and per request. In St. Vincent and the Grenadines, *Kappaphycus alvarezii*, *E. isiformis*, and *Gracilaria* spp. are being grown for the domestic market for human consumption and for some international exports, primarily to Barbados and the United States. Regulations and formal employment are lacking, and there are an estimated 22–35 seaweed farmers (Yacov et al. 2021).

In Barbados, the Barbados Seafood Industry Association has actively promoted the cultivation of red and green (i.e., *Ulva* spp.) seaweeds. The association provides training and technical assistance to local farmers, helping them establish seaweed farms and access markets for their products. In 2022, the Export Barbados Seaweed Pilot Project commenced to demonstrate the potential economic value of seaweed cultivation. The project explores the cultivation of seaweed and the creation of value-added products, such as cosmetics, food, and beverages for export (Cox 2023).

In addition to the industry associations specific to a country or territory, several regional aquaculture and marine industry associations exist. The Caribbean Regional Fisheries Mechanism supports the exchange of information, capacity building, and policy development to support fisheries and aquaculture operations in the Caribbean. This mechanism has

[p] A vesicle is a small, fluid-filled cyst.
[q] ISER Caribe (Institute for Socio-Ecological Research); *Ulva fasciata* and *Ulva ohnoi.*

been instrumental in promoting sustainable aquaculture practices in the region, and the organization has become increasingly interested in including seaweed farming in its agenda. The World Aquaculture Society (WAS) is a global organization that promotes aquaculture's science, technology, business, and social aspects. Within WAS, there is a Latin American and Caribbean chapter that meets annually to share research updates.

Involvement of women

On a global level, women are highly involved in tropical seaweed aquaculture; they make up 70% percent of the seaweed farming workforce in East Africa or the East Pacific. In the Caribbean, women's participation in seaweed aquaculture has been mixed. In Belize, one of the largest Caribbean producers of farmed seaweed, the practice was introduced as a sustainable alternative livelihood for commercial fishers, which is a role almost exclusively controlled by men. Although fishermen-turned-farmers have trained many women, men continue to be involved at a higher rate than women. The exception to this finding may be the Belize Women's Seaweed Farming Association, which operates out of La Placencia, Belize. In St. Kitts, membership in the Liamuiga seaweed group was over 50% women (23 people total) in 2020. Ultimately, the extent to which women participate in seaweed farming in the Caribbean likely hinges on existing time and resource commitments and available livelihood opportunities for women in the region, as suggested by research in other regions (Khan and Satam 2003; Kite-Powell et al. 2022).

Infrastructure

Currently, the Caribbean does not have seaweed supply chains that can compete in international seaweed markets. If the goal is to reach this level of production, then significant investments are required throughout the value chain, far beyond simply expanding the level of production. Drying, processing, and packaging facilities will be needed (Kite-Powell et al. 2022), and ideally, these services will be clustered together to prevent the need to transport biomass or intermediary products.

Beyond the physical facilities, market infrastructure and legislation supporting quality assurance, insurability, and contractual stability will also be crucial. More information about the processing costs and required infrastructure for each existing and prospective market is needed for businesses to glean insight into how they might be able to differentiate their products and avoid competition with the existing low-cost, well-established suppliers of tropical seaweeds and their derivatives.

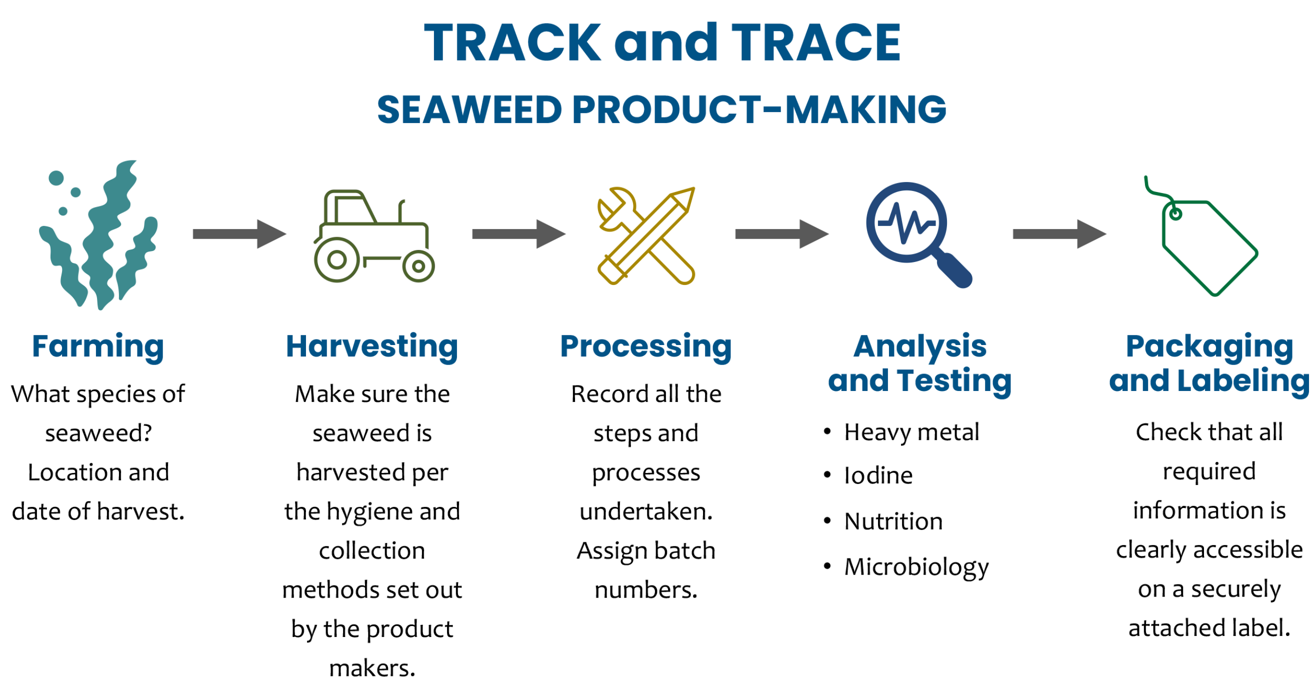

Figure 36. The key steps in establishing transparency and traceability of a seaweed product. Image credit: Juli-Anne Russo, CAEIH.

Transparency, traceability, and food safety

Building transparency and traceability (Figure 36) into the Caribbean seaweed industry from the onset will benefit both producers and consumers. Transparency in product authenticity, safety, and sustainability is important to consumers. It helps overcome risk barriers associated with trying new products, and then later, it helps build and maintain consumer trust in these products. Therefore, offering the option for producers, buyers, and consumers to track batch numbers or barcodes of sold products can make seaweed-based products more acceptable to a wider range of buyers. Farmers could use a spreadsheet-based tracking system to record:

- The genus and species of seaweed used in the product
- Where the seaweed was grown and when it was harvested
- What processing was undertaken
- Any testing of raw materials and/or finished products that was conducted

Then, this information could be included on the label applied to the product for retail and maintained in a secure location by all entities in the supply chain.

Establishing traceability measures means the measures can also be used as a tool to help seaweed farmers and processors evaluate and revise their biosecurity measures because products can be traced back to a specific farm site, harvesting date, and production batch (e.g., Box 7). If farmed seaweed is destined for the food market, it needs to be safe for human consumption. Seaweed processors and users should routinely test the seaweed they receive for bacteria, yeast, molds, and heavy metals. If the national agency overseeing food safety provides seaweed-specific testing guidelines, then these should be used. However, such guidelines are currently very rare in the region. When possible, conducting nutritional testing on food products containing seaweed will benefit both product marketing and the consumers of these products.

Box 7: Labeling requirements for packaged seaweed products in Belize

In Belize, a wide variety of seaweed products are sold locally, including dried seaweed in 100 g packages, ground and dried seaweed powders, seaweed gels, and seaweed as an ingredient in skincare products and drinks.

The Belize Bureau of Standards (BBS) provides regulations and requirements for labeling all prepackaged food products, and thus, their recommendations are applicable to prepackaged seaweed products, as well (BBS 1998; U.S. International Trade Administration 2024). The Ministry of Health sets the standards for cosmetics. The Belize Agricultural Health Authority (BAHA) Food Safety Department is responsible for ensuring that food production premises meet cleanliness and hygiene criteria (BAHA n.d.). Maximum residue limits for heavy metals have been established by the Codex Alimentarius Commission (Codex Alimentarius International Food Standards n.d.).

The BBS requires that all processed food products be labeled in both English and Spanish. The label must include the product name, description, location of farmed seaweed, manufacturer's name and address, country of origin, storage instructions, net weight/volume, quantity, list of contents, nutritional information, date of production, expiration date, and identification lot. Additionally, the BBS requires that food should have a label that does not provide false or misleading information, labels should be applied in a manner that they will not become separated from the product container, and statements are required to appear on the label in clear, prominent text that is easily read and understood by the consumer. The BBS requirements are not applicable to food sold in an open package, deposited into a package in the presence of the purchases, or packaged in bulk for resale. In addition to the BBS requirements, the BAHA recommends the following specifications for prepackaged seaweed-based foods: serving size, recommended frequency of use, the location of the seaweed harvest, and maximum measured heavy metal and iodine levels in the product. Including heavy metal and iodine information on the label ensures that the food item does not exceed the appropriate minimum level for pregnant women, children, and individuals with thyroid dysfunction.

Business and operations planning

Creating a basic business plan before starting any seaweed farming activities is highly advisable. A business plan is a tool for the prospective farmer to map out their expected costs, revenue, and timelines for each. The document may also be requested by prospective lenders or investors. At a minimum, the business plan should include the:

- executive summary,
- description of the company,
- products and services,
- market analysis,
- strategy and implementation,
- management team, and
- financial plan and projections.

In addition to a business plan, farmers may want to develop an operations plan for their own or their team's use. An operations plan can help ensure that seaweed farming activities are efficient. It can include the frequency of planning, maintenance, harvesting, and processing and the human and other resources needed to support these activities.

Figure 37. Snorkelers at a seaweed farm site in Belize. Photo credit: Seleem Chan, TNC.

Section IV. Opportunities to support the growth of seaweed aquaculture in the Caribbean

The expansion of seaweed aquaculture in the Caribbean will require deliberate and committed action from investors, nonprofit organizations, national governments, local municipalities, researchers, entrepreneurs, aggregators, and prospective farmers. In this section, we suggest initial focus areas that may be best spearheaded by each group of actors while acknowledging that advancements in many of these areas will require collaboration across groups. See the subsection titled "summary of priority R&D areas by sector," found later in Section IV, for a list of these recommendations.

Investors

Building the capacity for seaweed farming, processing, and trading in the Caribbean will require significant public and private investment. Private banks, angel investors, and philanthropic organizations can play a pivotal role in supporting the development of this industry and driving sustainable aquaculture by directing investments toward operations using BMPs (O'Shea et al. 2019). For more specific guidance on evaluating investment opportunities in aquaculture, we refer the reader to TNC's complementary publication, *Towards a Blue Revolution: Catalyzing Private Investment in Sustainable Aquaculture Production Systems* (O'Shea et al. 2019).

This comprehensive publication acknowledges that investors are especially hesitant to invest in capital-intensive aquaculture operations, especially for unproven technologies or first-time businesses. To address this concern, *Towards a Blue Revolution* (O'Shea et al. 2019) provides a framework for evaluating such investments and recommends structuring transactions to optimize capital structures and mitigate operational risks. Furthermore, it outlines three enabling conditions for increased sustainable aquaculture investment: defining and aligning government policies, supporting sustainable innovation, and establishing principles for responsible investment. For companies seeking financing, the guide suggests funding core capital expenditures through debt-financed real asset models, offering equity investment opportunities in operating companies to investors, and maintaining flexibility in business models, products, and financing strategies to adapt to changing circumstances.

Nonprofit organizations

Numerous opportunities exist for nonprofit organizations to support the development of the Caribbean seaweed farming industry. Socially oriented organizations can promote equitable and inclusive practices, such as advocating for fair wages throughout the supply chain and providing farmer safety education materials and training (e.g., swim lessons). Environmentally oriented organizations can further develop and teach BMPs for ecologically sound farming practices to simultaneously protect nearshore environments and provide technical assistance to farmers. Creative approaches to incentivize better practices may be especially effective, such as a "conservation kiosk" approach that provides discounted gear for farmers adhering to these standards. Nonprofit organizations can also offer small grants for new entrants into the industry, provide business model coaching, and boost the social license for aquaculture in a region by delivering opportunities for the public to learn about new or prospective aquaculture activities.

In 2023, the Caribbean Aquaculture Education and Innovation Hub (CAEIH) was established to facilitate the launch and growth of a Caribbean-centered aquaculture network. Its primary objectives are to:

1. support Caribbean aquaculture scientists, graduate students, and agriculture students involved or interested in aquaculture and mariculture research to enhance the sector's productivity,
2. conduct workshops and training sessions with guest speakers,
3. advocate for aquaculture integration into the STEM curriculum (for science, technology, engineering, and mathematics), and
4. support women in the aquaculture sector.

In addition to the direct outcomes of each of these individual activities, a unifying organization for aquaculture activities throughout the Caribbean is very valuable. As CAEIH continues to grow, it could help facilitate the exchange of beneficial information between industry members and resource managers across the region.

National governments and local municipalities

In the Caribbean, there is a significant association between aquaculture production and the level of mariculture governance administered by the country or territory (FAO 2020). Decentralized governance frameworks may hinder mariculture development, whereas strong governance frameworks can encourage nascent industry development and support recovery during or after industry shocks (FAO 2020).

Governance supporting sustainable aquaculture development in the tropical United States and the Caribbean is not currently strong enough to meet the enormous potential of seaweed aquaculture in the area. Additional government engagement is needed immediately at national, regional, and local levels to create and enforce better practices related to farm siting and permitting, food safety, and biosecurity measures. Establishing legal frameworks to guide and support aquaculture development will offer security for investors and processors considering investments in the Caribbean region.

Caribbean governments need to develop a streamlined and transparent process for lease applications and reviews. In most of the Caribbean, waters (marine and brackish) and submerged land belong to the relevant national government and cannot be privately owned. The provisions for exclusive use of this water, as would be preferable for a seaweed farm installation, are usually vague or nonexistent.[9] Presently, most artisanal seaweed farmers are not registered; there is minimal documentation of their practices and any production, environmental, or social issues they might be confronting. This lack of documented information presents an additional hurdle for engaging these farmers in innovative and responsible practices. Furthermore, the permit process and leasing should be financially manageable for applicants, which will include individuals from low-income families.

There are, of course, several exceptions to this general trend. For example, in Barbados, a proposed new framework for mariculture incorporates policies and regulations specific to seaweed farming, such as cultivation systems, licenses, biosecurity plans, and R&D priorities (Gallo and Rincones 2003). In St. Vincent and the Grenadines, TNC is working with local governments to develop a licensing system for seaweed farmers to stimulate and formalize a national seaweed industry. This work has included a spatial analysis to identify suitable seaweed farming locations that incorporate environmental, natural resource, social, and cultural parameters. The proposed licensing system also outlines a training program that focuses on water quality requirements, product quality standards, and strategies for avoiding impacts on critical habitats.

In Belize, the national government has already enacted a Mariculture Policy (developed with funding from TNC–Belize). Mariculture specialists, seaweed farming cooperatives, and other promoters of seaweed farming in Belize are now working with the government to draft national regulations and launch a socialization campaign on these regulations. The engagement and diligence of the Belizean government, environmental organizations, and seaweed farmers to encourage the development and regulation of seaweed farming in Belize should serve as an example of what is possible and necessary across the region.

TNC–Belize's sustainability initiatives for seaweed exemplify the potential benefits for both producers and buyers through the collaborative efforts of government and industry. In this context, TNC is actively collaborating with the BBS, the national entity tasked with defining product standards across the country, to formulate precise regulations for the seaweed aquaculture sector. By involving the BBS in this initiative, TNC is fostering an inclusive environment that allows all industry stakeholders to contribute their insights, thereby influencing the formulation of these regulations.

Governments should also anticipate that some farmers may be interested in selling their seaweed for human consumption, and thus, food safety regulations specific to seaweed are necessary to protect prospective seaweed consumers and the seaweed farming industry itself. These regulations should be developed using the best available knowledge related to potential contamination sources in the region in combination with BMPs established at a global industry level. In addition to specific guidance about what can be sold, how, and when, these regulations should also establish a monitoring plan and reporting systems to facilitate adaptive management.

Governments could also provide substantial support to a new seaweed farming effort by promoting social licenses to operate. At a high level, this approach involves including seaweed farming in food and agriculture policy agendas (Kite-Powell et al. 2022) and earmarking funds for programmatic support, such as infrastructure investments, seaweed-related research at national institutions (FAO 2022b), farmer capacity-building and education, and disaster assistance. Throughout the Caribbean, there is a general lack of the infrastructure needed to support aquaculture activities. Identifying and allocating public funds toward key infrastructure, like nursery, processing, and research facilities, will help jump-start and sustain the industry. If funds are limited, governments can also facilitate partnerships with other sectors (terrestrial agriculture, pharmaceutical, food service, etc.) while encouraging facility-sharing between the sectors (possibly alternating seasonal or hourly needs) and/or the diversion of by-products from processing. Market hubs and commercial processing facilities are essential pieces involved in establishing reliable supply chains for international export.

As interest and participation in seaweed farming grow, it is important that the appropriate government agencies also collect and publish data on in-country demand for seaweeds and seaweed products, along with these products' export potential. More data quality, quantity, and comparability are critical to support governments and businesses in decision-making on seaweed production, trade, and consumption (Kite-Powell et al. 2022).

Moreover, many regulatory actions might primarily originate from other motivations but still have secondary benefits for the seaweed farming industry. For example, the establishment of marine conservation zones or marine protected areas may not fall in the category of direct legislation for the seaweed or aquaculture industries, but it benefits them because it works to conserve wild seaweed populations, supporting genetic diversity in the wild stocks both in and outside of the conservation zone. Similarly, legislation that maintains and improves coastal water quality indirectly supports seaweed farming. Thus, a government in support of a nascent seaweed farming industry should consider seaweed farmers as key stakeholders in environmental and marine management and legislation.

Researchers

Phycologists can support the development of a Caribbean seaweed aquaculture industry by continuing to add to the existing knowledge base on seaweeds native to the Caribbean. More studies to quantify wild seaweed populations and their seasonal fluctuations constitute the first step to ensuring that these seaweeds avoid overharvesting. The basic life histories of many local species and their physiological tolerance for environmental variables are still unknown. This information will support the development of potential cultivation strategies for these seaweeds. More biological research is also needed to better understand how to improve resilience to disease and pests among cultivated seaweed strains, and for the sexual propagation of high-performing strains.

Information on the nutritional content of seaweed species endemic to the Caribbean is also limited. Additional studies exploring how their chemical composition, mineral content, and raw nutritional value vary across sites, seasons, and species would be valuable contributions to the existing body of phycological work in the region. Such studies would also provide a much-needed baseline for farmers and entrepreneurs keen on growing and selling seaweed for new market opportunities. Nutritional studies comparing the raw seaweed's material composition to the processed products currently on the market would be beneficial.

Engineers also have an important role to play in designing technology that enables efficient seaweed farming, harvesting, and processing. Tropical seaweed aquaculture in countries like China, Indonesia, the Philippines, and Tanzania relies on significant amounts of underpaid manual labor.[72] Achieving economies of scale by mechanizing repetitive tasks like planting, cleaning, harvesting, washing, and drying will be required to achieve a competitive production price and just compensation for the workers involved (Kite-Powell et al. 2022).

Entrepreneurs, aggregators, and processors

There is still much work to be done in developing uses for Caribbean seaweed that are near where it was farmed. Sustainability-minded entrepreneurs have much to offer in this realm. They can support the industry's growth by launching new, local, or regional startups that source tropical seaweed biomass and by generating increased demand for seaweed products. Minimizing the distance between the site of seaweed production and the site of consumption or processing will keep costs low and quality high.

The hydrocolloid market sources just shy of 90,000 MT of dry, raw seaweed annually (Campbell et al. 2020). The buyers of raw materials for this industry require that the seaweed is reliably available and that the composition of the material is relatively consistent. Herein lies an opportunity for an entity to serve as the aggregator of seaweed produced from several regions within the Caribbean, as it is unlikely that any single region will produce seaweed in sufficient biomass to attract buyers independently. A good rule of thumb is that given the current market conditions, a minimum of 1000 dry tons of seaweed would need to be available to attract a buyer in the global hydrocolloid market.

However, given the emerging and expanding uses of seaweeds, smaller quantities of biomass may attract buyers from outside the region. Alternatively, there may be a tipping point where enough seaweed is produced regionally to warrant establishing a regional processing facility. Little information is available to suggest what the required quantity of biomass would be to attract this level of investment, but it would likely be less if existing local resources could be leveraged (e.g., the ability to lease a processing space inside an existing facility). Additionally, infrastructure decisions will hinge on considerations like whether high-quality raw algal material can be consistently produced and whether reliable transportation of the product can be arranged.

Existing and prospective seaweed farmers

Section II details a plethora of actions that existing and prospective seaweed farmers can take to ensure that their operations mirror BMPs for seaweed farming in the Caribbean. Pursuing a third-party sustainable sourcing standard for their products is one way of extracting additional commercial value from these practices. The most prevalent third-party standards today are the following:

- *ASC-MSC Seaweed Standard* (ASC-MSC n.d.)
- *Seaweed Farm Standard* by the Global Seafood Alliance Best Aquaculture Practices (Global Seafood Alliance n.d.)
- *Technical Guidelines on Aquaculture Certification* by FAO (FAO 2011)
- *Guidance for Using the IUCN Global Standard for Nature-Based Solutions: First Edition* by the International Union for the Conservation of Nature (IUCN; see IUCN 2020)
- *Certification Criteria Checklist for Seaweed Products: Seaweed Harvesting and Farming* by the Friend of the Sea (Friend of the Sea 2014)

We point the reader to the hyperlinked web addresses above for more information on each standard. While the specific criteria used to evaluate farms can vary from one standard to another, they all typically ensure that legal and transparent practices are used, including making sure the harvest is legal and the farming methods used will not quickly deplete the wild population.

Some seaweed processors, like Cargill, have developed their own seaweed aquaculture sustainability standards and commitments (see Cargill's *Red Seaweed Promise* [Cargill 2021]). Also, retailers like Walmart, Whole Foods, Ikea, and McDonald's have more broadly committed to sourcing sustainably certified seafood (Baghel et al. 2014). While the scale of production in the Caribbean must greatly expand to serve these processors and retailers, their commitments to sourcing sustainable products have a significant influence on the growth of the certified seafood market (Duckworth et al. 1971).

Summary of the most-needed R&D

As highlighted in the sections above, there are a plethora of ways to support the Caribbean seaweed industry's development. While these sections group our recommendations by some of the most common actors, this formatting decision is not intended to suggest that these are the only roles that should participate in Caribbean seaweed initiatives. So many needs exist simultaneously that any interested individual, regardless of background or skill set, will likely find an opportunity to get involved.

In this spirit, the following list summarizes the previously mentioned R&D recommendations. Contributions toward any of these R&D needs would be beneficial. However, three needs rise above all others. First, there is an exigent need to change the perception of aquaculture practices locally and regionally so that sustainable and regenerative aquaculture practices are seen and understood to be beneficial for producers, consumers, and ecosystems. Second, it is crucial that transparent regulatory processes are developed for seaweed farm siting and approval, as well as for seaweed processing and distribution. Third, more entrepreneurship and investment in innovation from both private and public sources is needed to kickstart the growth of the Caribbean seaweed farming industry.

Summary of priority R&D areas by sector

Investors

- Direct investments toward operations using BMPs.
- Structure transactions to optimize capital structures and mitigate operational risks.

Seaweed companies

- Seek to fund core capital expenditures through debt-financed real asset models.
- Offer equity investment opportunities.
- Maintain flexibility in business models, products, and financing strategies.

Nonprofit organizations

- Advocate for fair wages throughout the seaweed supply chain.
- Provide farmer safety education.
- Develop and teach BMPs.
- Offer small grants for new entrants to the industry.
- Provide business-model coaching.
- Offer aquaculture programming to the public.

- Facilitate information exchange between industry members and resource managers.

Government

- Develop and enforce regulations that include better practices for seaweed farm siting and permitting.
- Establish a streamlined and transparent process for aquaculture lease applications and reviews.
- Develop and enforce regulations for seaweed food safety and biosecurity.
- Include seaweed farming in food and agriculture policy agendas.
- Allocate funds for infrastructure supporting and subsidizing seaweed farming and research.
- Offer seaweed farmer capacity building, education, and disaster relief.
- Collect and publish data on demand for seaweeds and seaweed products (domestic and export markets).
- Take regulatory action to ensure the conservation and health of coastal waters and resources.

Researchers

- Carry out additional studies on Caribbean seaweeds (location of wild populations, seasonal fluctuations, basic life histories, physiology, resiliency to disease and pests, nutritional value).
- Continue to improve technologies for efficient seaweed farming, harvesting, and processing.

Entrepreneurs

- Launch new startups that use tropical seaweeds.
- Aggregate seaweeds grown across the region.

Existing and prospective seaweed farmers

- Employ BMPs at seaweed farms.
- Consider pursuing third-party sustainability certification.

Figure 38. Seaweed drying on racks in St. Lucia. Photo credit: Juli-Anne Russo, CAEIH.

Section V. Large-scale seaweed farming potential and considerations

For the purposes of this document, we define *large-scale* seaweed farms as installations that require more financial investment, logistical support, and labor than what can reasonably be provided by a group of two to five people working full-time. Operations of this size do not currently exist in the Caribbean, and at the time of publication, arguably, only a few large-scale farming operations exist outside Asia. However, given the recent interest in using seaweed biomass across the various industries described in Section IV, we recommend that Caribbean seaweed producers, users, and regulators carefully assess and evaluate the possibility of large-scale seaweed farming in the region.

Careful planning and evaluation are necessary because seaweed farming's potential environmental impacts and production challenges can be accentuated with large-scale farming. Furthermore, while large-scale operations in Asia can provide some insight, a lot remains unknown about what the potential impacts and challenges might be in the Caribbean. Thus, a precautionary approach is needed, combined with more exploratory research, to help all actors in the seaweed aquaculture space anticipate what the region-specific potential impacts and challenges might be.

It is important to the success of all marine aquaculture activities in the Caribbean that any large-scale seaweed farms are designed, sited, and managed in a way that protects the surrounding marine biodiversity and minimizes potential conflicts with other water users. We point the reader to the Seaweed Commons 2022 position paper *A Precautionary Approach to Seaweed Aquaculture in North America* (Swinimer et al. 2022) for a detailed list of the primary research needed to assess the potential impacts of large-scale seaweed aquaculture (temperate and tropical) and the potential regulations that could be regionally determined using this insight.

From 2017 to 2025, a group of researchers from over 15 institutions [r] came together to conduct one such research effort. The project Techniques for Tropical Seaweed Cultivation and Harvesting (TTSCH) proposed to investigate and develop cost-effective opportunities to produce seaweed biomass in tropical areas of the U.S. EEZ. The research conducted focused on six areas critical to developing and evaluating large-scale seaweed farming:

1. Optimization of farming practices
2. Development of a farming platform with mechanized cultivation and the harvesting of climate-resistant macroalgae
3. Characterization of nutrient and hydrodynamic loads at the farm scale
4. Chemical and growth characteristics of the tropical macroalgal biomass
5. Identification of the social and environmental impacts of macroalgal farms in the Caribbean and Gulf of Mexico
6. Economic modeling and life-cycle assessment of tropical macroalgal biomass production, incorporating technological, social, and environmental factors

The approach involved scientific investigations across laboratories, in silico, and at nearshore research sites in southern Belize, western Florida, and southwestern Puerto Rico. This work was funded by the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E), specifically the Macroalgae Research Inspiring Novel Energy Resources (MARINER) program.

In the remainder of this section, we highlight the components of the TTSCH project that are most relevant to those interested in potentially farming seaweed at a large scale in the Caribbean. They are grouped by the following categories: site suitability analysis, dedicated equipment, ecological studies, and estimated production costs.

Site suitability analysis

Identifying a suitable site for a large-scale seaweed farm is incredibly important because site location has a significant effect on operational costs; distance from shore becomes increasingly important when working with larger vessels and crews (Matoju et al. 2021). The oceanographic characteristics of a site, such as mean and anticipated range of current velocity and wave height, also strongly influence capital costs due to the increased level of engineering and type of materials required for exposed sites.

Identifying locations where an array would cause zero or minimal interference with the activities of other ocean users (both human and animal) is just as important as with small farms, but it may actually be harder due to the size of the array and the need to optimize for distance from shore and minimum exposure. With the Caribbean's many atolls and barrier islands, simply siting a seaweed farm at a great distance from the main coastline may not mean that it is far from shipping lanes, communities, etc. While it is beyond this guide's scope to provide specific siting recommendations for large-scale arrays, Appendix D briefly summarizes a suitability analysis for large-scale seaweed farming arrays that was conducted for the TTSCH project by the NOAA Coastal Aquaculture Siting and Sustainability program.

Dedicated equipment

The harvesting process conventionally used for tropical seaweed farming is labor intensive. The mature propagules are cut or torn from their support, or the crop is completely removed from the water along

[r] The participating institutions included the Marine Biological Laboratory (MBL), the University of Puerto Rico, Woods Hole Oceanographic Institution, the University of Connecticut, C.A. Goudey & Associates, Two Docks Shellfish, The Nature Conservancy (TNC), the University of California Santa Barbara, Rutgers, CINVESTAV, the University of California Irvine, Makai Ocean Engineering, the Pacific Northwest National Laboratory, CariCOOS, Sea Grant Puerto Rico, and the University of Washington.

with the farm structure (Doty 1987). Efficiency in the harvesting of farmed tropical seaweeds may be achieved by leaving the growline in place after harvesting the algal biomass and, potentially, by utilizing partial harvesting methods (i.e., cutting the propagules from the line approximately 50 mm above the point of attachment so that the bases can regenerate material for subsequent harvests). Accomplishing both seeding and harvesting underwater, resulting in minimal disruption to the growline and the associated farm system, may be more efficient and minimize crop loss that can occur when large propagules are removed from the water and break under their own weight.

Marine vessels specially designed to help with seaweed farm maintenance and harvesting will also play a critical role in the expansion of seaweed farming in the Caribbean. The *Damisela* is a purpose-built seaweed farming boat built for the TTSCH project (Figure 39). The vessel is used for transporting and moving the farm array, attaching new seaweed for cultivation, harvesting mature seaweed, and performing routine maintenance of the farm structure. The *Damisela* has performed well during all these tasks, so a similar design would likely be of great use for both small- and large-scale farms.

Figure 39. The seaweed farm service vessel *Damisela*. The *Damisela* was designed to fit in a shipping container for easy transport and is therefore less than 6 m long. Photo credit: Loretta Roberson, MBL.

To achieve economies of scale with large farming operations located offshore, the labor and fuel costs associated with delivering the seaweed biomass from the farm site to the buyer or processor must be minimal. An uncrewed, autonomous vessel may facilitate this (see the upcoming Table 4 for details on the estimated cost of a drone tug, as prototyped by C.A. Goudey & Associates). Alternatively, options for processing the seaweed biomass at the farming site can also be pursued, although we note that the availability of a renewable power supply will be important for this arrangement.

Ecological studies

The TTSCH project has contributed several notable insights to our understanding of how marine flora and fauna may interact with large-scale seaweed farms in the region (see Roberson et al. 2024 for a description and discussion of these). Nonetheless, much more research is still needed. We recommend employing the precautionary principle and keeping seaweed farms in the Caribbean at decentralized, small scales until more of these knowledge gaps are filled. Then, this information can be used to develop a cohesive national regulatory framework for permitting large-scale seaweed farms in each nation's waters.

Estimated production costs for large-scale tropical seaweed farming

In 2022, Kite-Powell et al. published a study that used a techno-economic model to estimate the production costs of seaweed farms using at least 1000 ha of ocean area. The study considered the production of both the cold-water species *Saccharina latissima* and the tropical alga *Eucheumatopsis isiformis.* Their results suggest that farm-gate production costs are likely to be between USD 200 and USD 300 per dry ton of seaweed if the farm site is within 200 km of the coast. The modeling also suggests that production costs below USD 100 per dry ton could be achieved in some locations, and at this price, these cultivated seaweeds would be economically competitive with land-based biofuel feedstocks.

The baseline input values for the model are shown in Table 4:

Table 4. Baseline input values from the Kite-Powell et al. 2022 study.

Parameter	Units	Temperate	Tropical
Grow rope/net	$ per meter	0.20	0.30
Grow rope/net life	# of harvest cycles	10	24
Spacing of grow ropes	meters	0.75	1.0
Module dimensions	meters x meters	180 x 90	300 x 50
Farm boat capital cost	$	5,000,000*	1,000,000
Farm boat crew size	# of crew members	4	8
Boat crew labor rate	$ per hour	17	17
Boat capacity – planting	# growlines x m s^{-1}	5 x 0.5	10 x 0.5
Boat capacity – harvesting	# growlines x m s^{-1}	5 x 0.5	10 x 0.5
Drone tug capital cost	$	n/a	100,000
Weather days (no farm ops)	days per year	20	30
Nursery cost	$ per m grow rope	0.05	0.01
Harvest cycle	weeks	25	9
Net yield (wet weight)	kg m^{-1} per harvest	15.0	5.0
Water content of harvest	% of wet weight	85%	86%

Note. $ = USD. Access the Kite-Powell et al. study at https://doi.org/10.1080/26388081.2022.2111271.

* Portion of full cost allocated to kelp farm; boat is used for fishing during summer.

Although they provide a helpful baseline for planning and policy conversations, these cost estimates should be treated as preliminary. The assumptions used by the research team need to be further verified with data from large-scale farms and over multiple seasons. The researchers also highlight how additional practical experience with the deployment, operation, and maintenance of large-scale seaweed farms in the open sea will help corroborate these estimated production costs.

Figure 40. Nursery-grown *Gracilaria mammillaris*. Photo credit: Loretta Roberson, MBL.

Conclusion

The introduction and advancement of seaweed aquaculture in the Caribbean region present a significant opportunity for both economic development and environmental sustainability. Throughout this document, we have explored the multifaceted benefits of seaweed farming and its potential to enhance water quality, buffer against local acidification, and provide habitats for marine species. We have also delved into the socioeconomic benefits, including the substantial role of women in this industry and the positive impact on their livelihoods and social standing. The importance of smart siting for seaweed farms, coupled with education and collaboration in BMPs, cannot be overstated. This approach ensures that seaweed farming does not adversely affect other critical marine ecosystems such as coral reefs, mangroves, and seagrasses. Instead, it promotes a symbiotic relationship where aquaculture supports environmental health and community well-being.

Key points

Environmental Benefits: Seaweed farming, when properly managed, significantly enhances water quality by absorbing excess nutrients from the water, thus mitigating eutrophication. It also acts as a natural buffer against ocean acidification, which is crucial for the health of coral reefs and other marine life. The farming process itself creates habitats that foster marine biodiversity, offering shelter and food for various marine organisms. This contributes to the overall resilience of marine ecosystems.

Economic Opportunities: Seaweed farming provides a sustainable and eco-friendly source of income for coastal communities. It requires minimal inputs, making it an accessible venture for small-scale farmers and local entrepreneurs. The industry's growth can spur the development of related sectors such as processing, marketing, and export, creating a broad spectrum of job opportunities.

Social Impact: The involvement of women in seaweed farming has shown to improve household incomes and elevate social status. Encouraging and supporting women's participation in this industry can lead to more equitable economic development. Community engagement and education are critical to the successful implementation of seaweed farming projects. By involving local stakeholders in decision-making processes, the industry can ensure that practices are culturally appropriate and widely accepted.

Challenges and considerations

While the potential benefits of seaweed farming are substantial, several challenges need to be addressed to realize its full potential:

Regulatory Frameworks: Establishing clear, science-based regulations is essential to ensure that seaweed farming is conducted sustainably. These regulations should cover aspects such as farm siting, species selection, and environmental monitoring.

R&D: Continued research is needed to optimize farming techniques, improve yield, and develop new products. Collaboration between researchers, farmers, and industry stakeholders can drive innovation and enhance the overall productivity of the sector.

Market Development: Building robust markets for seaweed and seaweed-based products is crucial. This includes creating value chains that connect farmers to consumers, both locally and internationally. Marketing efforts should highlight the nutritional and environmental benefits of seaweed products to increase demand.

Takeaways

As we look to the future, the integration of seaweed aquaculture into the Caribbean's economic and environmental landscape holds immense promise. By adopting sustainable practices and fostering collaboration among stakeholders, we can ensure that seaweed farming becomes a cornerstone of the region's blue economy. This journey not only offers a pathway to economic resilience for coastal communities but also contributes to the health and vitality of our marine ecosystems. As we move forward, let us remain committed to principles of sustainability, innovation, and inclusivity, ensuring that the growth of this industry is beneficial for all stakeholders involved.

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Appendices

Photo credit: Julie Robinson, TNC.

Appendix A. A SWOT analysis for *Kappaphycus alvarezii* cultivation in the Caribbean Sea

Figure A1. *Kappaphycus alvarezii*. Photo credit: Juli-Anne Russo, CAEIH.

Introduction

Kappaphycus alvarezii [s] is a commercially important red seaweed widely cultivated around the world to obtain feedstock for carrageenan production (Figure A1; Buschmann and Camus 2019). In 2020, *K. alvarezii* was ranked fifth among the world's most cultivated macroalgae (Rudke et al. 2020). *K. alvarezii* is native to the Philippines, but it has been introduced to approximately 30 other countries for either research or the development of a commercial seaweed farming industry (Ask et al. 2020). Within the Caribbean, our region of focus, *K. alvarezii* is either currently grown or has historically been grown in Belize, St. Lucia, Mexico, Panama, Venezuela, and Brazil. In Caribbean countries and territories where *K. alvarezii* is grown, it is typically the most cultivated seaweed species. A specimen of *K. alvarezii* was also recently documented in Costa Rica, where the species is not currently cultivated (Cabrera et al. 2019).

The purpose of this document is to assess and report on the strengths, weaknesses, opportunities, and threats (SWOT) associated with *K. alvarezii* cultivation in the Caribbean as we currently understand them in 2024. To do this, we first provide a brief introduction to *K. alvarezii* biology and farming practices and the tendency of naturalized *K. alvarezii* to become invasive in some of the locations where it has been introduced. Then, we dive deeper into which characteristics of *K. alvarezii* have led it to become an invasive species in some geographies where it has been introduced and what the resulting impacts have been. We consider three management options for addressing the potential invasiveness of *K. alvarezii* in the Caribbean, providing recommendations for actions that both aquaculturists and marine resource managers can take and acknowledging that there are some potential risks associated with these actions. Lastly, we group and present the information gleaned from the SWOT analysis so that it can serve as a go-to reference for further discussions and decision-making.

Biology of *K. alvarezii* and the socioeconomic benefits associated with its cultivation

K. alvarezii Doty (Solieriaceae, Rhodophyta) is a species of red marine macroalgae that is both cultivated and found in reef ecosystems around the world. It typically has thick, spiny branches (up to 2 cm in diameter) that occur in irregular (multiaxial) patterns and narrow to acute tips. These branches are densely covered with branchlets, typically ranging from 1–8 mm long. The coloring of *K. alvarezii* individuals can range between green, yellow-orange, red, or brown depending on the alga's strain, nutrient content, and recent light exposure. In its native habitat, *K. alvarezii* is typically found in high-flow areas with limestone-rich rocky substrates or shallow reefs (Trono et al. 1992), although it has been found as deep as 48 m below the water's surface (Weber-van Bosse 1913). *K. alvarezii* exhibits the triphasic life history common for red algae (Doty 1987); however, it can also reproduce through fragmentation (Figure A2).

[s] *Kappaphycus alvarezii* is commonly referred to as "cotoni" or "cotonii" within the industry (Neish et al. 2017). Some phycologists consider *Kappaphycus striatum* and *K. alvarezii* to be the same species (Semesi 1996).

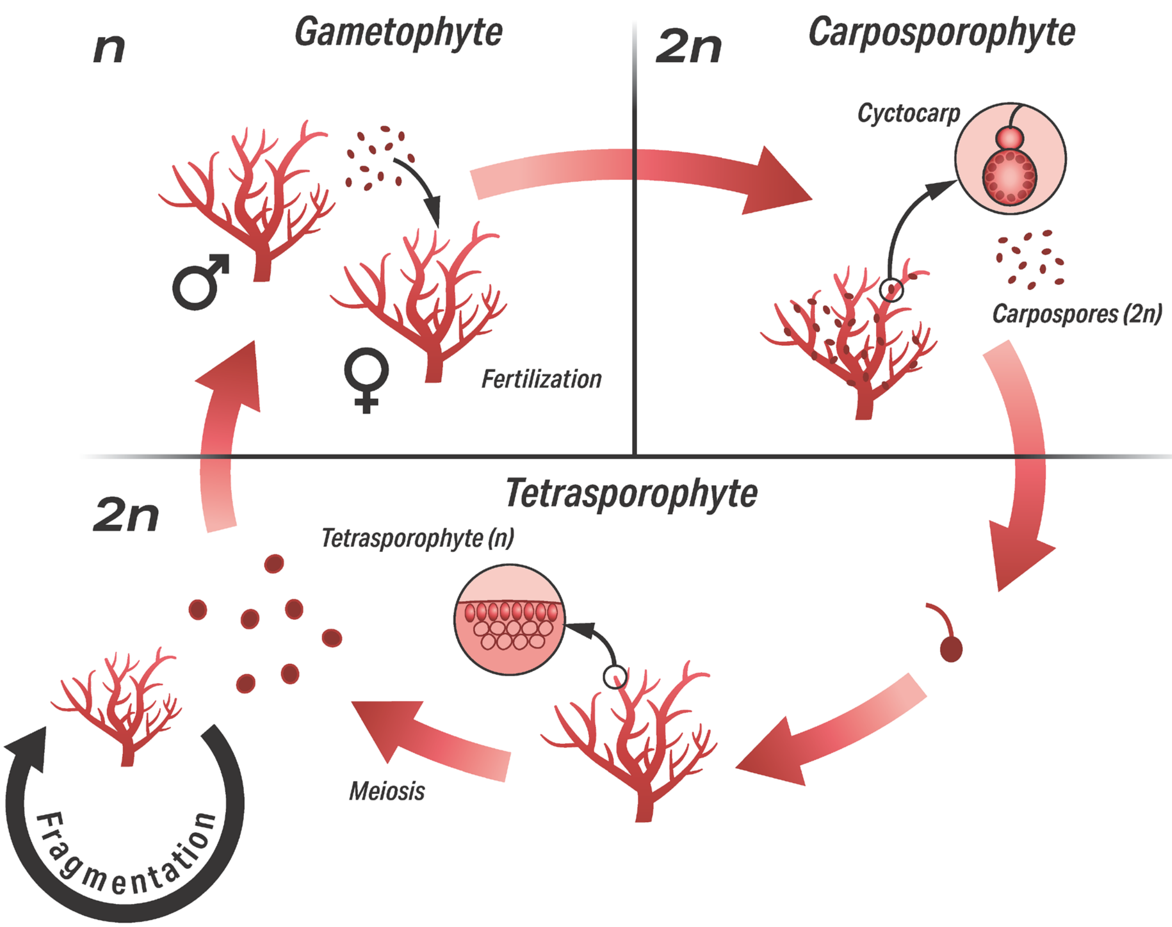

Figure A2. *Kappaphycus alvarezii* life cycle. Illustrator: Jim Kopp, Kopp Illustration, Inc.

To date, commercial farming of *K. alvarezii* completely depends on reproduction via fragmentation. A mature, vegetative bunch is cut into smaller pieces. Then, these pieces are raised to harvest size. This practice of using the same algal material for new outplanting is known as vegetative propagation or *clonal propagation*. Vegetative propagation means that the crop's genetic diversity is never replenished; large portions of *K. alvarezii* crops likely originate from just a few clones. Over time, this can be problematic because species survival, adaptation potential, and resistance to biotic and abiotic stressors are enabled by intra-specific genetic diversity.

As previously stated, *K. alvarezii* is an essential source of carrageenan and, more specifically, kappa-carrageenan, which is most often used as a food additive to create firm, brittle gels, especially from dairy-based liquids. Across the world, over 1.6 million wet weight (WW) metric tonnes (MT) of *K. alvarezii* are produced each year for carrageenan production (FAO 2022). Despite this large volume, the carrageenan market is still strong, and supply is limited. Ask et al. (2020) argued that the farming of eucheumatoid seaweeds, a group that includes and is largely dominated by *K. alvarezii*, is one of only a few successful aquaculture opportunities for coastal villagers. They estimate that 40,000–50,000 families worldwide participate in the practice (Ask et al. 2020).

Currently, Caribbean-cultivated *K. alvarezii* is primarily either grown and sold for regional use or exported for uses excluding commercial carrageenan production. The most ubiquitous regional uses of *K. alvarezii* are in fruit-flavored shakes/smoothies and in salads, which are sold locally at shops, village pharmacies, and fairs (Diez et al. 2019). Some entrepreneurs also make artisanal soaps, shampoos, or facial masks that integrate seaweeds. The *K. alvarezii* that is dried and exported outside the region is either sold as is or further processed into seaweed gels or nutritional supplements. Although Caribbean *K. alvarezii* production is extremely small in the global context, it does have the potential to provide supplemental or alternative livelihoods for both seaweed farmers and value-added processors.

Observed invasiveness of naturalized *K. alvarezii*, mechanisms, and potential impacts

In some locations where *K. alvarezii* has been introduced, it is considered simply an *exotic* species, meaning it has been moved from its original habitat range to a new one, but it is not yet reproducing in the new range. In other geographies, *K. alvarezii* is considered *naturalized*; enough individuals over time have been established to be able to begin reproducing in the new range. This is the case in Tanzanian waters, where *K. alvarezii* has been considered a naturalized species for some time, but signs of invasiveness have not been observed. Similarly, after 10 years of *K. alvarezii* cultivation in coastal waters off the state of Rio de Janeiro, Brazil, no signs of an invasion process have been observed (Castelar et al. 2009), perhaps due to specific environmental conditions that limit the development of propagules or viable spores (Cabrera et al. 2019). In regions where *K. alvarezii* has been naturalized, it is most often found on patch reefs in shallow waters or inhabiting sand-covered grooves in the reef or the reef flats and edges (Rodgers and Cox 1999). Along other coastlines, like those of Hawaii [t] and India, *K. alvarezii* has been designated an *invasive* species because it is causing ecological or economic harm to this non-native environment (Rodgers and Cox 1999; Conklin and Smith 2005; Arasamuthu et al. 2023). Additionally, in Panama, *K. alvarezii* from abandoned farms has spread to the adjacent coral reef, seagrass, and mangrove ecosystems, forming benthic mats of 70+ m^2 (Sellers et al. 2015). However, an official invasive species designation has not been issued yet.

Several characteristics of *K. alvarezii* make it a successful invader. To begin with, it can spread by fragmentation, whereby pieces of seaweed float to new locations and reestablish themselves. The recruit may remain vegetative, but it can also develop reproductive tissue. *K. alvarezii* has a high growth rate; under ideal conditions, it can double in size in 15–30 days (Azanza-Corrales et al. 1992; Trono et al. 1992). This growth rate is much faster than the rates of corals and many native seaweed species. *K. alvarezii* also exhibits phenotypic plasticity in functional traits, which enables it to survive in a wide range of environmental conditions. For example, some specific strains of *K. alvarezii* can tolerate water temperatures ranging from 17 °C to 32 °C (Borlongan et al. 2017).

If *K. alvarezii* invades an area, it can impact the functioning of nearby coral reefs and the marine organisms and people that rely on them. Because it grows faster than corals, *K. alvarezii* mats can overgrow and kill corals by shading them from sunlight (Arasamuthu et al. 2023). In Southeast India, *K. alvarezii* was observed to be overgrowing live *Acropora* corals, and in this region, the *Acropora* branching morphotype was found to be more commonly affected than other corals (Arasamuthu et al. 2023). In Panama, *K. alvarezii* has been observed smothering or overgrowing *Porites* sp. and *Millepora alcicornis* [u] (Sellers et al. 2015). When corals are overgrown and die, the habitat shifts from a diverse coral reef to a seaweed-dominated, low-diversity reef. Substantial recruitment of *K. alvarezii* or another seaweed species can also change the bottom structure of the reef because the seaweed establishes itself in crevices and holes, which reduces the access of other marine organisms to this habitat. Over time, these shifts in habitat availability and composition may impact commercial and recreational fisheries and the attractiveness of dive sites used by operators bringing tourists to the area.

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[t] Several additional dynamics may have led to the success of the invasion of *K. alvarezii* in Hawaii. The *K. alvarezii* introduced in Hawaii is genetically distinct from all other cultivars (Zuccarello et al. 2006; Sellers et al. 2015). Also, there has been intense ecosystem change in the region and a lack of economic incentives (i.e., commercial production) that would otherwise possibly encourage the collection of *K. alvarezii* from reef systems (Ask et al. 2020).

[u] Along with seagrass (*Thalassia testudinum*) and several species of sponges (*Clathria* sp., *Iotrochota* sp., *Ircinia* sp.; Sellers et al. 2015).

While the scientific community does not completely understand why naturalized *K. alvarezii* becomes invasive in some geographies and not others, the field of invasion biology has identified some general factors in host habitats that more commonly lead to the successful invasions of aquatic primary producers. Disturbed systems are generally more susceptible to invasion, as are systems that have lower biotic resistance provided by native macrophytes (Levine et al. 2004; MacDougall and Turkington 2005; Capers et al. 2007). These and other local habitat features interact with the biophysical traits of an alien species to determine whether excessive growth will occur (Alpert et al. 2000). As several factors must commonly co-occur in time and space to trigger invasiveness, time lags between the introduction of non-native species and the start of invasive behavior are common (Kowarik 1995; Crooks 2005). The fact that *K. alvarezii* is already considered invasive in other locations suggests that there is a high possibility of the aforementioned factors combining to result in successful invasions of *K. alvarezii* elsewhere.

Fortunately, to our knowledge, the locations in the Caribbean Sea where *K. alvarezii* has been introduced have not experienced an invasion. However, because there is potential for an invasion to occur and because the resulting impacts can be grave, we recommend that the precautionary principle be adopted by both individuals and organizations currently working with *K. alvarezii*, as well as resource managers responsible for overseeing the health and longevity of coastal areas. In the following subsection, we introduce four management decisions to address the threat of a potential *K. alvarezii* invasion.

Management options and considerations for *K. alvarezii* in the Caribbean

In the Caribbean locations where *K. alvarezii* is already naturalized, the most effective and least-costly management options for potentially invasive species — introduction prevention, early detection, and rapid response (Hussner et al. 2017) — are not applicable. However, at least three other management options remain: (1) status quo and increased monitoring, (2) increased containment, and (3) reduction, nuisance control, and potential eradication (Hussner et al. 2017). These options are presented in order of the effort required, and likely the investment needed. In the following paragraphs, we provide a description of actions that would support each management option, as well as a discussion of the trade-offs associated with each.

1. Status quo and increased monitoring

The first option when applying the precautionary principle to *K. alvarezii* cultivation in the Caribbean is to continue the status quo, which includes small-scale *K. alvarezii* cultivation, while increasing monitoring of the farms and nearby coral reefs for *K. alvarezii* recruits. This decision might be partially justified, given the ecosystem services that small-scale seaweed farms provide, including those growing *K. alvarezii*. Well-managed seaweed farms have the potential to provide both provisioning and regulating ecosystem services. Seaweeds remove nutrients, minerals, and carbon dioxide from the surrounding water, which works to maintain good water quality. Seaweed farms have been shown to compete with harmful algal blooms and opportunistic macroalgae like *Ulva* spp. for nutrients in the surrounding water (Valiela et al. 1997; Chopin et al. 2001; Neori et al. 2004). Additionally, by taking up carbon dioxide from the water, these seaweed farms can help alleviate the impacts of ocean acidification at a local scale. Seaweed farms also provide refuge or food for fish and other marine organisms; in most cases, tropical seaweed farms have higher biodiversity and abundances of fish and invertebrates than sandy-bottom areas without seaweed farms or three-dimensional structures (Theuerkauf et al. 2022).

If farming *K. alvarezii* in the Caribbean is going to proceed as is, we recommend that it be combined with region-specific monitoring and invasiveness assessment efforts led by the government agencies responsible for managing coastal resources. One of the first steps would be to confirm the algal species that are being grown on each farm. In some cases, *K. alvarezii* can be impossible to distinguish from the native seaweed *Eucheumatopsis isiformis*, which is also purportedly grown throughout the Caribbean in small amounts. However, molecular techniques have been developed (Conklin et al. 2009) that would allow for samples from seaweed farms to be confirmed to the species level. Along with confirming the extent and location of *K. alvarezii* farming, additional monitoring on these farms could include careful documentation and reporting of reproductive material and suspected diseases.

K. alvarezii may be a sleeper naturalized species that could become invasive if other ecosystem dynamics shift, so it could be added to a watch list for potential invasive species and monitored. Reef monitoring could be conducted by both citizen scientists and specialized researchers. Recreational divers and dive operators could be encouraged to submit suspected sightings of *K. alvarezii* to an online exotic species sitings program like the invasive species program of the [Reef Environmental Education Foundation (REEF)](). Specialized researchers could be asked to conduct more thorough studies to assess the invasiveness potential of *K. alvarezii* in specific areas. For example, a study in Brazil assessed the invasiveness potential of *K. alvarezii* at three sites in the Rio de Janeiro region by quantifying how much biomass was lost during farming activities, how much of this biomass reestablished, and whether reproductive materials (spores) were present on the reestablished biomass (Castelar et al. 2009).

The decision to maintain the status quo and increase monitoring is appealing because it is the easiest option to implement, and it requires the least investment. It is akin to a "wait and see" approach, carefully weighing the decision against the risk of a costly impact in the future. The above-mentioned monitoring could help detect a tipping point between *K. alvarezii* being naturalized versus an invader, but marine invasions are sometimes hard to identify until the invasion is substantial and their impacts start to become widespread (Locke and Hanson 2009).

2. Increased containment

Adopting a containment and maintenance strategy for *K. alvarezii* would involve acknowledging that there are sites where *K. alvarezii* is currently cultivated or established in the surrounding ecosystem. Then, a goal could be set to prevent the spread of *K. alvarezii* from these locations to new ones. The vectors and pathways for *K. alvarezii* dispersal must be disrupted in order to achieve effective containment of the alga. In the Caribbean, this primarily requires modifying existing seaweed farming practices or establishing new ones.

To prevent new fragments of *K. alvarezii* from reaching and becoming established on coral reefs, farmers can use seeding, harvesting, and management techniques that minimize the breakage of the seaweed propagules. Breakage is more likely to occur with larger individuals (> 100 g) and when hauling heavier lines out of the water. Thus, working with smaller seed and harvest sizes may reduce the loss of *K. alvarezii* to the environment. Another option is to consider harvesting in water using snorkel or scuba gear rather than bringing the entire growline onto the boat or to shore because the apparent weight of the propagules is much less in the water, making them less likely to break. Farmers can also make an extra effort to look for and collect any *K. alvarezii* fragments in the water and off the seafloor surrounding their farms (Sellers et al. 2015).

The waves and strong currents associated with tropical storms can cause increased breakage, so pre- and post-storm activities may help retain and recover material. When strong storms are forecasted, farmers could consider harvesting their crops before the storm. Following the storm, they could survey the seafloor under and around their farms to recover any propagules that may have been dislodged. Ultimately, reducing breakage and loss *of K. alvarezii* is beneficial to farmers because the more biomass they can bring to shore, the more they have available for sale (Ask et al. 2020).

In addition to minimizing breakage and collecting lost fragments, seaweed farmers could also consider heightened interception measures. Traditional line and raft methods used for cultivating seaweeds in the Caribbean allow for the free movement and loss of the seaweed propagules in the water column. During harvest and reseeding, when breakage is more likely to occur, farmers could experiment with deploying a temporary protective net to catch material that would otherwise be lost to the surrounding environment. At sites less than 3 or 4 m deep, turbidity curtains that were originally developed to control silt and sediment during marine construction and dredging could work as a sleek seaweed interception technology.

More permanent modifications to the standard design for an off-bottom farm array may also be warranted. Using tube nets instead of made loops with a growline may result in less breakage and/or lost fragments. If tube nets prove expensive or difficult to source, perforated polyethylene bags (like those used to package fruits and vegetables) could also be tried. Installing a secondary, permanent containment system around the entire farming array could also help intercept large pieces of *K. alvarezii* that break off. For example, Castelar et al. (2009) used a nylon net (60-mm mesh) to intercept material that fell off their floating rafts. One trade-off with this approach is that additional, large nets can provide entanglement hazards for marine animals like turtles, fish, and seabirds. Furthermore, if the nets are not replaced regularly or if they are damaged, they can become a source of marine plastic pollution. Also, acquiring the netting is an additional cost to the farmer. In some locations, like the tropical United States where aquaculture gear restrictions are stringent, using a secondary net may not be approved.

Vessels and farming gear can also be vectors that carry *K. alvarezii* from one location to another. Therefore, after working at a site where *K. alvarezii* is grown, farmers should check their boat(s) and equipment for fragments of *K. alvarezii*. Then, the boat(s) and gear should be rinsed in fresh water and, when possible, left in the sun to air dry before being used at another location (Bruckerhoff et al. 2015).

Resource managers deciding on a containment and maintenance strategy could also apply permitting tools to support containment and maintenance goals. They could issue permits that allow existing seaweed farmers cultivating *K. alvarezii* to continue their practices. Then, the issuing agency could apply a cap to the total number of farms or farmers allowed to work with *K. alvarezii* and/or restrict the approval of permits for *K. alvarezii* to specific bays, islands, etc. It is worth noting, however, that to be effective, this capped permitting strategy requires an established and enforced permitting system. Consequently, the issuing agency must make financial and labor investments. Lastly, as there is concern that the potential of *K. alvarezii* spread could be amplified if existing farms are abandoned (Sellers et al. 2015), it would be prudent for resource managers to require that all *K. alvarezii* be removed from a cultivation site when farming operations are paused seasonally and/or ceased entirely.

A decision to pursue a containment management strategy may be justified for *K. alvarezii* in the Caribbean if managers believe that the ecosystem and societal benefits of *K. alvarezii* farms outweigh the potential impacts. The decision may also be justified if managers determine that the tools available to them will be ineffective in reducing or eradicating *K. alvarezii* from the region (Hussner et al. 2017). A containment strategy could also be combined with other strategies (e.g., increased monitoring, containment, and reduction) as part of a larger management program (Hussner et al. 2017).

3. Reduction, nuisance control, and potential eradication

Reducing *K. alvarezii* populations and, thus, the threat of an invasion in Caribbean waters may be possible because no large infestations have occurred. However, reducing *K. alvarezii* populations will require a coordinated effort between seaweed farmers, resource managers, and likely other supporting agencies.

For reduction strategies to be effective, farmers would have to buy into them. They would need to cease farming *K. alvarezii* since the practice is a vector for its dispersal. An education campaign explaining the threats posed by its continued cultivation and proliferation would be necessary. In addition to focusing on the ecological threats, the campaign could provide more information about the increased incidences of disease, extensive herbivory, and die-offs that have occurred on *K. alvarezii* farms in locations outside the Caribbean over the past 15 years. [v] The campaign could then encourage these producers to transition to growing native seaweed species. Some candidate native Caribbean species include *E. isiformis*, *Hypnea musciformis*, *Solieria filiformis*, *Agardhiella ramosissima*, or *Meristiella* spp. Each of these species produces carrageenan like that of *K. alvarezii*, so they may be acceptable substitutes for the existing regional seaweed applications, like shakes and cosmetics. They may not be acceptable substitutes in the global carrageenan market, but acceptance would need to be determined through additional characterization of the carrageenan produced by the cultivars and in a variety of environmental conditions.

Of all the candidate alternative species, *E. isiformis* is the most closely related species to *K. alvarezii*; in fact, until 1996, *K. alvarezii* was named *Eucheuma alvarezii* or *Eucheuma cottonii*, but molecular studies of the species' genotype led to its renaming (Guiry

[v] These issues are associated with the loss of vigor due to clonal propagation, in combination with physiochemical stress resulting from higher water temperatures and greater variations in salinity associated with climate change (Msuya 2011; Tano et al. 2015; Largo et al. 2020; Rusekwa et al. 2020).

and Guiry 2022). Some farms in the Caribbean are already growing *E. isiformis*, and there is a small amount of peer-reviewed and extension literature providing guidance on cultivation strategies for this species (Smith and Gustave 2001; Roberson et al. 2024). So, transitioning *K. alvarezii* farms to *E. isiformis* farms may be the most logical first step.

The trade-off in doing so is that *E. isiformis* does not grow as fast as *K. alvarezii*. Typically, growth rates of *E. isiformis* hover around 2% per day, although growth of 4%–6% per day has been observed (Dawes 1974; Roberson et al. 2022). In contrast, *K. alvarezii* strains have been selected for maximal growth rates; they are commonly 5%-9% per day, but they have been observed to be as high as 15% during the alga's period of fastest growth [w] (Montúfar-Romero et al. 2023). Thus, transitioning from farming *K. alvarezii* to *E. isiformis* may not immediately appeal to farmers, as their yields for the same unit area and time will be reduced. More ocean area may be required to produce the same seaweed biomass. Given these limitations, the transition to cultivating native species could be greatly facilitated if government agencies or the industry can offer capacity building like government breeding programs to improve growth rates, training in cultivation practices, free or inexpensive sources of seed, and potentially other subsidies. The verification of a clear and reliable market for these new species would also derisk the transition to new species for farmers.

Reducing or eradicating *K. alvarezii* from Caribbean waters will require a coordinated, wide-scale campaign. Before launching such an effort, evidence-based assessments of both risks and benefits should be completed by research groups independent from those proposing the eradication effort (Kopf et al. 2017). These assessments should consider the perceived risks and benefits of all stakeholders, include expert estimates that quantify the potential benefits and likelihood and severity of risks, and be conducted in a transparent fashion (Kopf et al. 2017).

The importance of a thorough assessment before implementing control measures cannot be overstated. Removing or eradicating naturalized species can have unintended ecological impacts that may need secondary mitigation, and sometimes these impacts may be unanticipated because, during control, it becomes evident that the established population performs functional roles in food webs or provides habitat or other ecological roles to native species (Kopf et al. 2017). Perverse food web outcomes have been observed following the control of other species (Zavaleta et al. 2001; Ballari et al. 2016). In the case of *K. alvarezii*, its removal may result in increased herbivory of other native algae. In some locations, removal may mean that algal biomass is not available to herbivores at the quantities that it was before control, which may impact their survival. Biophysical changes — like habitat loss, habitat alteration, reduced sediment stability, or reduced nutrient transfer — have also been observed following invasive macrophyte removal (Schlaepfer et al. 2011; Lampert et al. 2014). For these reasons, when experts were asked to rank [x] possible management actions for controlling marine invasive species, they highly prioritized raising public awareness and discouraging the commercial use of invasive species over biological control actions (Giakoumi et al. 2019).

If the results of the risk-benefit analysis for a region suggest that reduction and attempted eradication of *K. alvarezii* is the best path forward, resource managers have a suite of tools to choose from. As described above, they could begin by communicating with existing users of *K. alvarezii* to explain the threats posed by its continued cultivation and proliferation, prohibit *K. alvarezii* farming, and provide alternative species and support in a transition away from *K. alvarezii* farming. Then, they could launch hand-weeding efforts on reefs where *K. alvarezii* has become established (this would likely require scuba divers anywhere where the water is deeper than 1 m). To facilitate and motivate removal, they could legalize the unlimited harvest of *K. alvarezii* from the wild. In areas with larger established populations of invasive aquatic macrophytes, a combination of hand-harvesting and targeted vacuuming has been shown to be the best combination for effective removal with the fewest impacts on nearby species (Hussner et al. 2017). Remotely operated underwater drones could also potentially be used to help

[w] Approximately 20–35 days after outplanting.
[x] According to effectiveness, feasibility, acceptability, impacts on native communities, and cost.

identify and remove *K. alvarezii* individuals from reefs (Simberloff 2021). Beyond the ongoing labor expenses, the trade-off with manual removal is that it misses the microscopic *K. alvarezii* life stages that can create the equivalent of a persistent local seed bank.

There are also several more experimental approaches, like the release of intentional biocontrols or gene silencing, which have been used in other cases of aquatic species' invasions (Simberloff 2021). In Panama and Hawaii, native sea urchins have been proposed as an effective biocontrol agent for *K. alvarezii* (Conklin and Smith 2005; Sellers et al. 2015). Gene-silencing using CRISPR-Cas9 technology has been used effectively for the population control of other nuisance species (e.g., mosquitos; National Academies of Sciences 2016), and it could also be considered as a tool for a longer-term, combined control and reduction strategy for *K. alvarezii* populations in the Caribbean.

Gene drives permit engineered genes to be spread throughout populations, even when a trait confers negative fitness or reproductive success. A sterile cultivar of *K. alvarezii* could be developed and farmed using similar techniques. It would reduce the risks that farming would lead to the recruitment of individuals on coral reefs. Sterilization has been recommended by phycologists as a tool for both preventing the invasiveness of non-native species and for preventing potential introgression of crop genetic material into wild populations when cultivating native species (Louriero et al. 2015). Applied chemical controls, although commonly applied to small, fresh waterbodies, are not recommended for large-scale marine applications. However, initiatives to reduce anthropogenic nutrient inputs to coastal waters could have a trickle-down effect on naturalized *K. alvarezii* populations. If the algae become nutrient-limited, their growth rate will drop, and their spread and recruitment may, too. Reduced nutrient inputs to the coast would also benefit other coastal marine species.

Due to their experimental nature, associated costs, and the risks of unintended consequences, we further emphasize the necessity for a thorough ecological risk assessment before implementing any experimental approaches. It must also be noted that reduction and potential eradication efforts require a long-term commitment. Innumerable projects have substantially lowered populations of target species initially, only to lose the progress made because the costs were unsustainable, or management interest waned (Hussner et al. 2017).

Also, the timing of the introduction of *K. alvarezii* in the region must be considered. The more time the non-native species has been present in the ecosystem, the harder it will be to eradicate. Many locations throughout the Caribbean have *K. alvarezii* populations that have persisted at low levels (i.e., noninvasive levels).

Summary of SWOT Analysis

In summary, cultivating and managing naturalized *K. alvarezii* in the Caribbean is a complex topic requiring additional and timely attention and discussion. Currently, no single policy and management approach is clearly superior to the rest. Rather, there are strengths, weaknesses, opportunities, and threats associated with *K. alvarezii* cultivation in the Caribbean (Figure A3).

Strengths	Weaknesses
• *K. alvarezii* is already a naturalized/established species in some parts of the Caribbean Sea (Belize, Venezuela, Costa Rica, Panama, St. Lucia, etc.). • Kappa-carrageenan, produced by *K. alvarezii*, is highly desirable in the global hydrocolloid market. • *K. alvarezii* is used locally and regionally in recipes for shakes and smoothies, as well as in formulations for body care products. • *K. alvarezii*, like all seaweeds, removes excess nutrients and carbon dioxide from ambient ocean water, which works to maintain good water quality near the farms. • *K. alvarezii* grows quickly. More biomass potentially yields higher revenue for farmers, more habitat for associated marine fauna, and a greater contribution to ecosystem services. • *K. alvarezii* is shown to be more susceptible to high water temperatures than other red seaweeds, which may restrict the extent of its establishment beyond seaweed farms that either operate seasonally and/or are sited in cooler waters.	• Strains of *K. alvarezii* are invasive in some locations where it is farmed, while invasiveness is considered minimal in other geographies. • Currently, no standard nursery process uses sexual offspring to produce new seeds. → The absence of such a process results in reduced genetic diversity of the crop over time.
Opportunities	**Threats**

• *K. alvarezii* has a ready export market. → Estimates are that if a particular Caribbean region could produce 1000 dry tons of *K. alvarezii* annually, it would be able to participate in the global carrageenan trade.
• Governments, researchers, industries, nonprofits, and other stakeholders have many opportunities to support and shape Caribbean farming practices and seaweed markets, including the following:
  ○ Conduct a farm-level molecular characterization of seaweeds currently in cultivation.
  ○ Work with agency partners to develop an early detection and containment program for *K. alvarezii* and other potentially invasive algal species.
  ○ Conduct evidence-based assessments of the economic costs of potential control or eradication measures.
  ○ Train farmers in better practices for biosecurity to minimize material loss from their farms and prevent the possible spread of *K. alvarezii* to new parts of the coastline.
  ○ Provide a seed source and training for farmers to support a transition to farming with native seaweed. → Note that more ocean area may be required to produce the same quantity of seaweed biomass.
	• Strain fatigue can arise from cultivation, meaning there would be a potential loss of vigor due to clonal propagation and a slow deviation away from desirable characteristics.
	• Water temperatures may exceed the tolerance range of *K. alvarezii* for part of the year. It is likely that this period of unsuitably warm water will lengthen.
	• *K. alvarezii* has the potential to overgrow and smother coral reefs, which would result in seaweed-dominated, low-diversity reefs and changes to the bottom structure of the reef. Potential trickle-down impacts could affect other reef-dwelling organisms and dive tourism.
	• The absence of policies or regulatory guidance around the cultivation of non-native algal species in the Caribbean could limit the feasibility and efficacy of management strategies.

Figure A3. SWOT summary for the cultivation of *K. alvarezii*

Appendix A references

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Appendix B: An example of the Marine Wildlife Observer Training and Response Protocol

Adapted from the Techniques for Tropical Seaweed Cultivation and Harvesting (TTSCH) project (Principal Investigator Loretta Roberson, Marine Biological Laboratory)

We will adopt established NOAA Fisheries mitigation and monitoring measures to avoid harassment of marine mammals, sea turtles, and species protected under the Endangered Species Act (ESA) and Marine Mammal Protection Act (MMPA) during farm operations. As all lines on the farm will be maintained under tension by the use of catenaries and buoys, we do not expect any adverse interactions between the farm and marine mammals or sea turtles or any entanglement issues, as per Bath et al. (2023). Specific procedures, protocols, and training for marine mammal and sea turtle mitigation and monitoring that will be utilized include initial deployment procedures, responses to entanglement, vessel strike avoidance, and visual monitoring:

I. Initial deployment procedures

During the initial deployment of the algae farm, we will utilize several measures to both minimize adverse interactions with protected species and respond quickly to any entanglement risks. We have partnered with the Manatee Conservation Center to aid in observation, training for farm operators, and use of the manatee rescue vessel on site. First, the Manatee Conservation Center will mobilize their rescue vessel and personnel to the farm site during the first 30 days of farm deployment. Center personnel will train the farm operators on protected species observation, data collection, and avoidance of adverse interactions with the farm system, the farm vessel, and during routine farm operations. Second, we will deploy the farm in stages to allow time to observe how species interact with the farm system. For the mini array (60 m x 3 m), we will first install the outer lines (spaced 3 m apart) and observe interactions over several days. Then, we will add an additional line so that the spacing is 1.5 m, then 0.5 m, and finally 0.25 m. The Manatee Conservation Center recommended the 0.25-m spacing so that manatees would not be able to pass through the farm system. The U.S. Fish and Wildlife Service (USFWS) recommends the staged deployment of lines. Third, farm operators and observers will visit the farm site daily during at least the first 15 days of deployment, weather permitting, to monitor the farm gear and how it performs and to monitor how marine species interact with the farm. Once we have sufficient data on the farm system and species interactions that indicate safe operations, we will reduce site visits to every 2 weeks for normal farm operations.

II. Entanglement response

Any animals seen entangled in farm gear will be reported to the appropriate authorities, and protective measures will be initiated immediately. This may include cutting farm lines or raising and lowering the entire array. During the first 30 days of deployment, we will have a manatee rescue vessel on site, as well as personnel from the Manatee Conservation Center, to aid in observing and training farm operators and performing a rescue if necessary, weather permitting.

Any incidence will be reported immediately to:

Puerto Rico Department of Natural and Environmental Resources (PR DNER)
Phone: 787-724-5700 or 787-645-5593 or 787-538-4684

U.S. Fish and Wildlife Service (USFWS)
José A. Cruz-Burgos, Fish and Wildlife Biologist, Endangered Species Program Coordinator
Phone: 787-851-7297 ext. 218
Email: jose_cruz-burgos@fws.gov

Manatee Conservation Center (http://manatipr.org/)
Dr. Antonio A. Mignucci-Giannoni, VT PhD (Director)
Carla I. Rivera-Pérez, MS (Subdirectora)
Phone: 787-400-2782

NOAA Fisheries - Sea Turtle Stranding and Salvage Network Coordinators
SOUTHEAST
Wendy Teas, Sea Turtle Stranding and Salvage Network Coordinator
Southeast Fisheries Science Center
Phone: 305-361-4595
Email: wendy.teas@noaa.gov

III. Vessel Strike Avoidance

Based on the best available information on marine mammal sightings in and around the farm site, there is not a high occurrence of marine mammals. However, if marine mammals are encountered, precautionary measures will be taken to avoid a vessel strike or hit to the animal. The U.S. National Marine Fisheries Service (NMFS) has developed standard measures to be followed by vessels in order to avoid collisions and reduce the risk of strikes with marine mammals and other protected species, and they are as follows:

1. Vessel operators and crews should maintain a vigilant watch for marine mammals and sea turtles to avoid striking sighted protected species.
2. When whales are sighted, maintain a distance of 100 yards or greater between the whale and the vessel.
3. When sea turtles or small cetaceans are sighted, attempt to maintain a distance of 50 yards or greater between the animal and the vessel whenever possible.
4. When small cetaceans are sighted while a vessel is underway (e.g., bow-riding), attempt to remain parallel to the animal's course. Avoid excessive speed or abrupt changes in direction until the cetacean has left the area.
5. Reduce vessel speed to 10 knots or less when mother/calf pairs, groups, or large assemblages of cetaceans are observed near an underway vessel, when safety permits. A single cetacean at the surface may indicate the presence of submerged animals in the vicinity; therefore, prudent precautionary measures should always be exercised. The vessel should attempt to route around the animals, maintaining a minimum distance of 100 yards whenever possible.
6. Whales may surface in unpredictable locations or approach slowly moving vessels. When an animal is sighted in the vessel's path or in close proximity to a moving vessel and when safety permits, reduce speed and shift the engine to neutral. Do not engage the engines until the animals are clear of the area.

In order to avoid the potential for vessel impacts and strikes to marine mammals in the project area, vessel operators and crew members will follow NMFS protocol. Vessel operators and crews will use precautionary measures to avoid marine mammals and be aware of cetaceans' expected occurrence due to seasonality and potential foraging and breeding grounds.

IV. Visual Monitoring Program

All individuals aboard work vessels responsible for navigation duties and any other personnel who could be assigned to monitor for marine mammals and sea turtles shall receive training on marine mammal and turtle sighting/reporting and vessel strike avoidance measures.

Animal data to be collected include number, species, position, distance, behavior, direction of movement, and apparent reaction to construction activity. All data will be entered at the time of observation. Notes of activities will be kept, and a daily report will be prepared, including but not limited to the following information:

- Dates and locations of operations;
- Weather and sea-state conditions;
- Time of observation;
- Approximate location (latitude and longitude) at the time of the sighting;
- Details of sighting (species, numbers, behavior, photography log);
- General direction of animal's travel and distance of sighting from the vessel (distance should be recorded in meters);
- Activity of the vessels at the time of sighting; and
- Action taken by the Protected Species Observer.

These data will be shared with the USFWS, the PR DNER, and the Manatee Conservation Center.

Appendix B reference

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Appendix C. Mariculture policies and regulations in Puerto Rico, January 2024

Introduction

Marine aquaculture in Puerto Rico is at a small experimental stage, but the industry has the potential to offer alternative or supplemental livelihoods and positive environmental impacts if a restorative aquaculture approach is implemented. Currently, two research projects in Puerto Rico have gone through the mariculture permitting process for in-water farms. First, in La Parguera, the Marine Biological Laboratory was awarded U.S. Department of Energy funding for a seaweed aquaculture project: Techniques for Tropical Seaweed Cultivation and Harvesting (TTSCH). The project uses an offshore array design with an innovative storm avoidance system to cultivate *Gracilaria* and *Eucheuma* species. Beyond the growout phase, the team is running a techno-economic assessment model to determine the economic viability of seaweed farming in Puerto Rico. The second project is in Culebra. The local organization Mujeres de Islas, in collaboration with Asociación Pesquera de Culebra, was recently awarded funding from the U.S. National Oceanic and Atmospheric Administration (NOAA) for a community-based native oyster aquaculture project. It will have several components across the supply chain that assess the viability of a native oyster aquaculture industry in Puerto Rico.

Current mariculture permitting process in Puerto Rico

Mariculture farms in Puerto Rico require several permits that cover the siting of farms, leasing of the seabed, specific infrastructure or farm gear used, farm inputs like the use of feed and nutrients, and the capture, importation, and exportation of marine organisms (Table B1).

Table B1: Permits and regulatory requirements of federal and local agencies for commercial and research-based aquaculture in Puerto Rico.

Permits and authorizations	U.S. agency	Facilities and/or activities requiring coverage	U.S. statutes and authorities
Department of the Army. General or individual permit. Applied through the Puerto Rico Department of Natural and Environmental Resources (PR DNER) Joint Permit Application process.	Issued by the U.S. Army Corps of Engineers (USACE)	Aquaculture activities affecting navigable waters and/or resulting in discharges of dredged or fill material into U.S. waters	Section 10 of the Rivers and Harbors Act (33 U.S.C. 403); Section 404 of the Clean Water Act (CWA)
Endangered Species Act (ESA) consultation. Conducted by the lead federal agency (e.g., USACE during the permit application review process).	U.S. Fish and Wildlife Service (USFWS) and NOAA Fisheries	Direct or indirect impacts associated with proposed aquaculture activity on all federally listed threatened or endangered species and their critical habitat	Section 7 of the ESA
National Historic Preservation Act Consultation. Conducted by the lead federal agency (e.g., USACE during the permit application review process).	Puerto Rico State Historic Preservation Office	Required for any federal funding, license, or permit that has the potential to affect historic properties	Section 106 of the National Historic Preservation Act

Permits and authorizations	U.S. agency	Facilities and/or activities requiring coverage	U.S. statutes and authorities
Private Aids to Navigation (PATON).	U.S. Coast Guard	Lighted structures, day beacons, and lighted and unlighted buoys for marking structures in navigable waters; noncommercial buoys normally do not require a permit	PATON (33 CFR 66)
National Pollution Discharge Elimination System (NPDES) permit.	U.S. Environmental Protection Agency	Required for the discharge of pollutants to waters of the United States, which includes the addition of feed, nutrients, pharmaceuticals, or other substances	CWA Sections 402 and 403
Water Quality Certificate (will receive a copy of the Joint Permit Application).	PR DNER, Point Sources Permits Division	Certification or waiver required for any federal license or permit that authorizes any activity that may result in any discharge from a point source into waters of the United States	CWA Section 401, Water Quality Certification Improvement (Rule: 88 FR 66558)
Coastal Zone Management Act (CZMA) Federal Consistency Certification (will receive a copy of the Joint Permit Application).	Puerto Rico Planning Board	Requires that federal actions within and outside the coastal zone — that have reasonably foreseeable effects on any coastal use (land or water) or natural resource of the coastal zone — be consistent with the enforceable policies of a state's federally approved coastal management program	CZMA
Authorization of a concession	PR DNER	Leasing of submerged lands for "water-dependent uses," including aquaculture	Regulation for the Use, Surveillance, Conservation and Management of the Territorial Waters, Submerged Lands Thereunder and the Maritime Zone (Reglamento 4860)
Special fishing permits: (1) Scientific Permit or (2) Mariculture/ Aquaculture Permit	PR DNER (including approval from the Department of Agriculture if mariculture/ aquaculture permit)	Capture, importation, exportation, and tenure of aquatic organisms for (1) scientific or (2) commercial purposes	Law Number 278 of November 29, 1998, as amended (known as Puerto Rico Fisheries Law); Regulation 7949
Development, Land Use, and Business Operation Permit	Puerto Rico Department of Economic Development and Commerce, Permit Management Office	Commercial aquaculture businesses	Law Number 416 Environmental Public Policy Act; Joint Regulation 9233

Policy and regulatory considerations

Overall, a comprehensive regulatory framework for mariculture development is lacking in Puerto Rico, as are enabling policies. The following measures are recommended to grow the mariculture industry in a sustainable and equitable way within Puerto Rico.

1. Clear, transparent, and streamlined permitting process

Currently, there is no central location for information on the permitting process. Puerto Rico needs comprehensive regulatory guidance for prospective farmers to navigate these requirements. Resources could include a checklist or flowchart of permitting steps, a web page with links to all permit applications, and a list of identifiable contacts at all relevant agencies.

Having dedicated staff for mariculture activities is important. It may be helpful for prospective farmers to have one agency contact who fully coordinates among all agencies for permits, beyond just the USACE-DNER joint permit, and helps convene agencies for any pre-consultation.

A lead agency for aquaculture is desirable. Its focus would be to coordinate, plan, establish, and integrate regulatory requirements for the industry (i.e., aquaculture policy). If a lead agency does not exist, then the establishment of a lead agency should be a priority.

The development of siting tools, preapproved areas, or zoning could also streamline the permitting process. An example is The Nature Conservancy's (TNC's) Palau Aquaculture Suitability tool (n.d.), which assists with site suitability analysis and prints a report for the selected site that can be used in permit applications. Currently, in Puerto Rico, prospective farmers must hire a consultant to do benthic surveys and site suitability analysis, which can be a significant regulatory and economic burden, particularly for small-scale producers. In August 2023, a U.S. Caribbean Marine Spatial Planning Workshop was hosted in San Juan to identify spatial data to inform and build capacity for marine planning in the region, which could be applicable for aquaculture siting or an Aquaculture Opportunity Area. This workshop may be the first step toward the siting assistance that is needed.

2. Leasing of submerged lands

It would be beneficial to have a separate leasing structure specific to aquaculture activities. The current leasing structure or authorization of a concession treats aquaculture the same as other marine industries (i.e., marina construction, dredging for navigational channels, power lines, etc.), and the annual fee is based on the appraisal value, which may consider all marine uses. The filing fee plus the annual fee may not be affordable for small-scale aquaculture producers. It would be beneficial to have filing fees and annual fees scalable to the size and type of activity. Other U.S. states have separate leasing structures specific to aquaculture, with filing fees and annual fees varying though generally lower than those required in Puerto Rico (Beck et al. 2004).

For the authorization of a concession, there is also a requirement to publish a public notice, with all documents open to public scrutiny. This requirement does not have a distinction for the scale or type of aquaculture. It would be preferable to only have this requirement when activities pose greater concerns for environmental impact (e.g., new farm gear testing, fed aquaculture). Restorative aquaculture practices may not need this type of requirement, and opening all aquaculture activities for public scrutiny may impede development, considering issues with NIMBYism and the negative public perception of aquaculture that can be based on misunderstandings and lack of knowledge (Froehlich et al. 2017).

3. Environmental considerations and biosecurity concerns

Regulations that also address environmental concerns — such as biosecurity threats, impacts on wild stocks, and loss of genetic diversity — are vital for the sustainable development of aquaculture industries (Davies et al. 2019).

The approved species list for importation in Puerto Rico could be reconsidered or updated, as it currently does not approve or prohibit any algal species and allows for the farming of some non-native species. For example, *Kappaphycus alvarezii* is a common tropical seaweed species widely introduced and cultivated due to its high growth rates and source of carrageenan; however, it has become an invader in several locations, causing impacts on coral reefs and other ecosystems (Conklin and Smith 2005; Sellers et al. 2015). The consideration of farming non-native species is important, and if farming is allowed, a quarantine period should be established to determine potential impacts.

Other seaweed aquaculture regulations addressing environmental concerns may include setting a maximum annual harvest of parental plants, sanitary requirements for nursery operations to limit the spread of pests and disease, developing bioregional seedstock guidelines where parental plants are obtained from the same bioregion as growout locations, setting a required minimum distance of farms from sensitive habitats, and recommending farm equipment designed to reduce potential marine mammal entanglements (Yarish et al. 2017). The formal adoption of mariculture Better Management Practices (BMPs) by the local government may assist with addressing these environmental concerns.

4. Food safety regulations

With the development of seaweed industries, the implementation of food safety regulations will be vital. Regulations for food processing, such as drying or creating value-added products, may apply to seaweed. At the U.S. federal level, seaweed in its whole form is not regulated as a food product (Engle et al. 2018; Janasie and Nichols 2019). Still, there are two federal models to potentially regulate seaweed processing at the territorial level: (1) the Hazard Analysis Critical Control Point (HACCP) plans and (2) the Food Safety Modernization Act (FSMA), both of which require an internal analysis of potential hazards and a written plan to address identified hazards (Janasie and Nichols 2019).

Appendix C references

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Appendix D. Summary of a siting analysis conducted for the Techniques for Tropical Seaweed Cultivation and Harvesting (TTSCH) project

In 2019, a small team of analysts from the Coastal Aquaculture Siting and Sustainability program of the U.S. National Oceanic and Atmospheric Administration (NOAA) conducted a seaweed farming scalability analysis for the U.S. Caribbean (i.e., Puerto Rico). Its purpose was to identify negotiable area for the farming of macroalgae (Jossart et al., 2019a). An exclusionary analysis was performed using a variety of siting and environmental constraints (Table C1). Then, a relative suitability analysis was performed using additional criteria (Table C2).

Table C1. Parameters used in the exclusionary analysis. From Jossart et al. (2019a).

Parameter	Response
Spatial extent (N/S/E/W boundaries) of region of interest	Within the 20–30 °C isotherm, roughly S of 30 N
Approximate farm size (e.g., 5 km^2)	10 km^2 (multiple 2 km^2 arrays or two 5 km^2 arrays)
Preferred port(s)	None
Maximum distance from port for farm location (e.g., 8–10 nm)	None (within the exclusive economic zone [EEZ])
Macroalgae species to be farmed	*Eucheumatopsis isiformis*
Gear type to be used	Multi-line arrays
Acceptable depth range for farm (e.g., 30–100 m)	10–100 m
Sea water temperature range (e.g., 10–25 °C)	18–30 °C
Current velocity range (e.g., 0.1–0.6 m/s)	< 1.5 m/s
Maximum wave energy allowable or wave energy range (if applicable)	< 3 m
Ocean uses not allowed to overlap with a 1 ha grid cell	Submarine cables, pipelines, ocean disposal sites, hard bottom (colonized and uncolonized), coastal maintained channels, pilot boarding areas, and areas where vessel traffic is > 500 vessels recorded passing through the grid cell annually

Rather than excluding some areas completely, they were ranked according to their relative suitability, with 1 = suitable and 0 = not suitable (Table C2).

Table C2. Areas ranked per their relative suitability. From Jossart et al. (2019a).

Layer	Ranking (0–1)
Danger and restricted zones	0.1
Unexploded ordnance	0.1
Submerged vegetation	0.1
Anchorage areas	0.1
Shipwreck	0.2
Obstruction	0.2
Deep sea coral	0.3
Protected areas	0.3
Aids to navigation	0.5
Artificial reefs	0.5
Buoy locations	0.8

The results of the analysis identified over 500,000 ha of potentially suitable ocean area around Puerto Rico. Maps showing the geographic distribution of these potentially suitable areas and their relative suitability follow (Figures C1–C4).

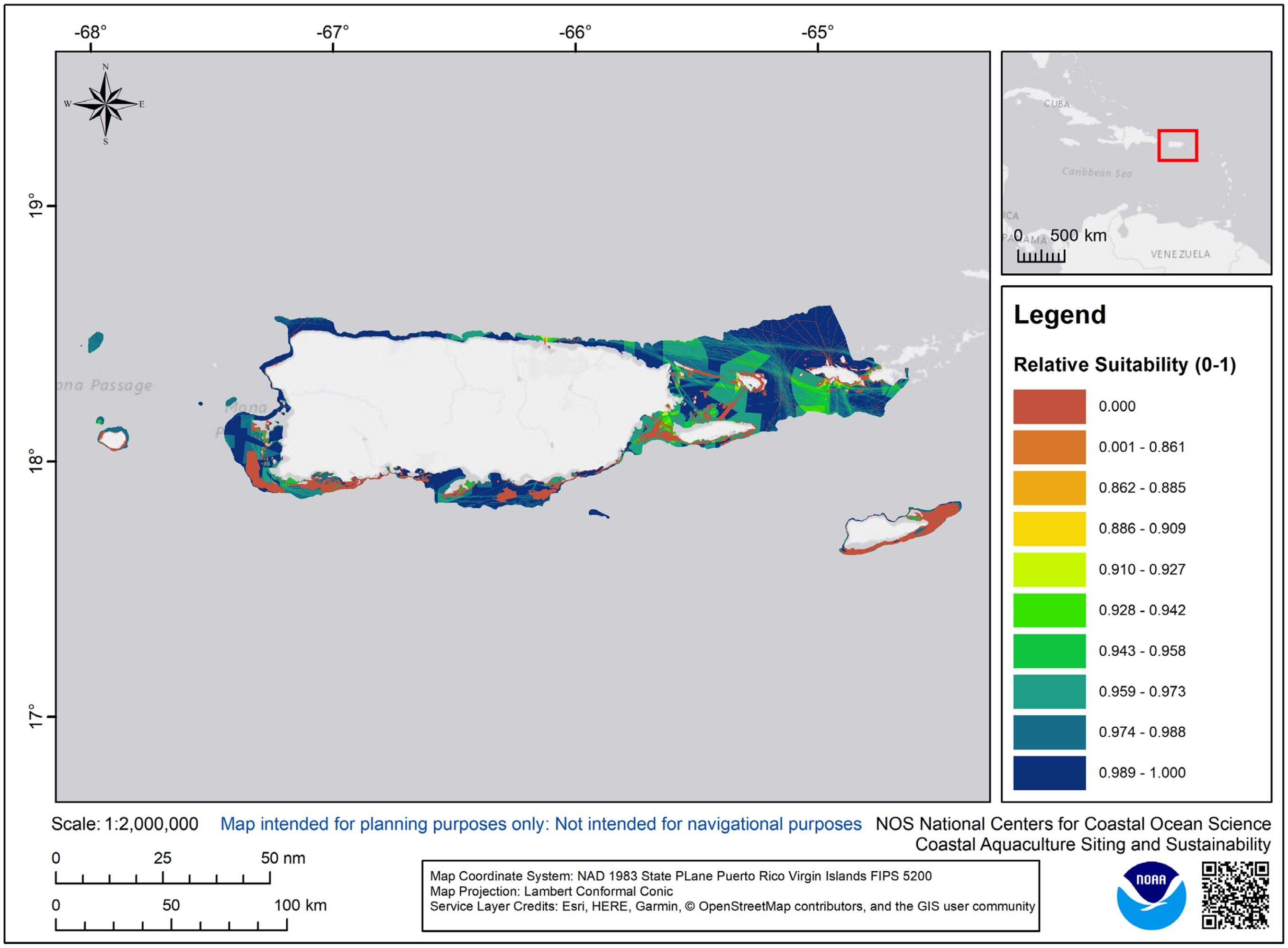

Figure C1. U.S. Caribbean 10–100 m depths, with 640,768 grid cells (1 grid cell = 1 ha). From Jossart et al. (2019b).

As shown in Figure C1, overall, 640,768 ha were examined, of which 106,331 ha were deemed unsuitable because of benthic habitat, vessel traffic, or industry conflict. This leaves about 534,437 ha of area considered negotiable. *Note that the northern swells can be severe, and siting on the northern side of Puerto Rico, Culebra, or St. Thomas should be done with extreme caution.*

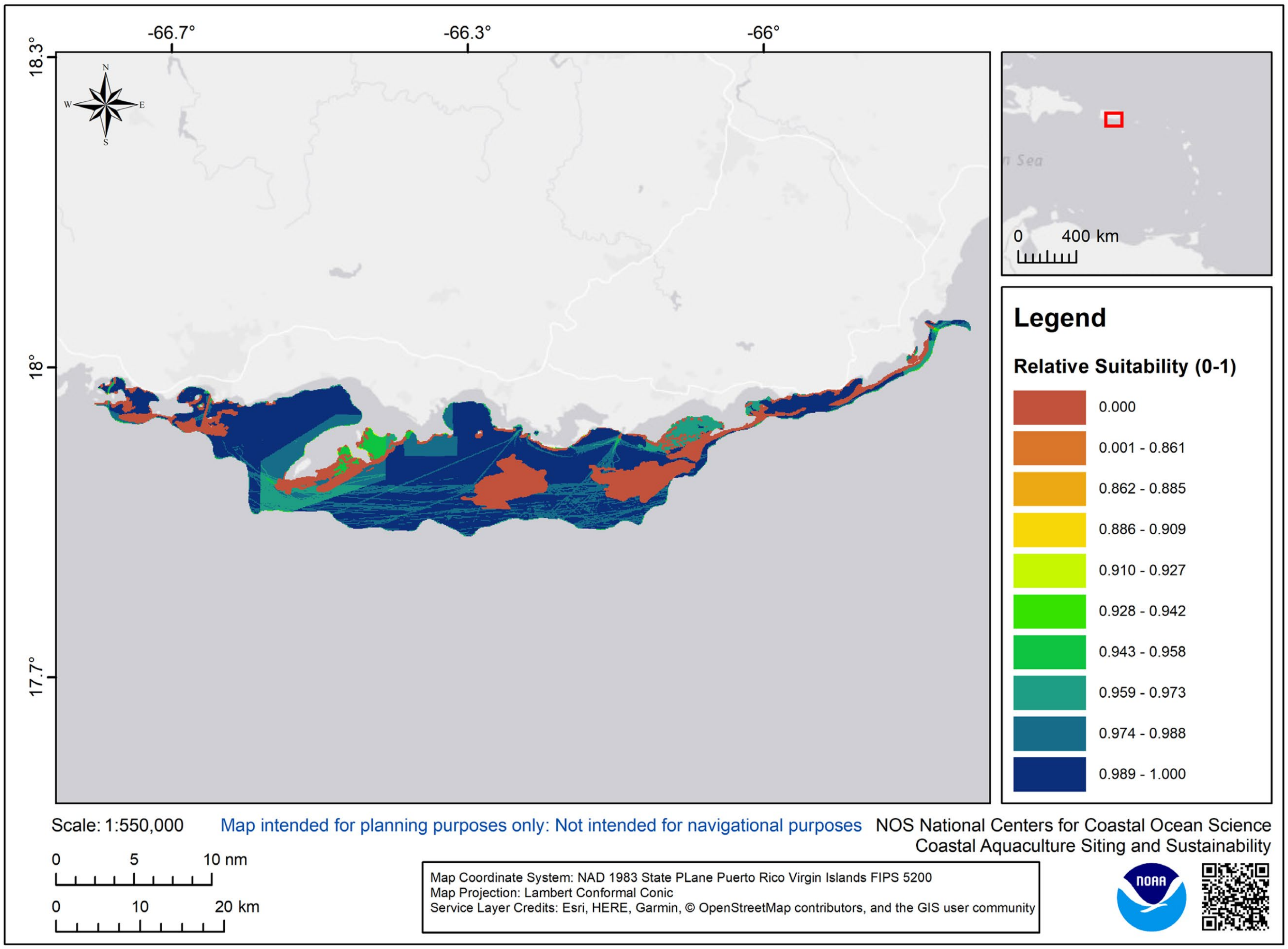

Figure C2. On the southern side of Puerto Rico, between 10 to 100-m depth. From Jossart et al. (2019b).

An area of 73,118 ha was examined on the southern side of Puerto Rico (Figure C2). Largely due to colonized and uncolonized hard bottom, 15,516 ha were deemed unsuitable, leaving 57,602 ha of negotiable space for siting.

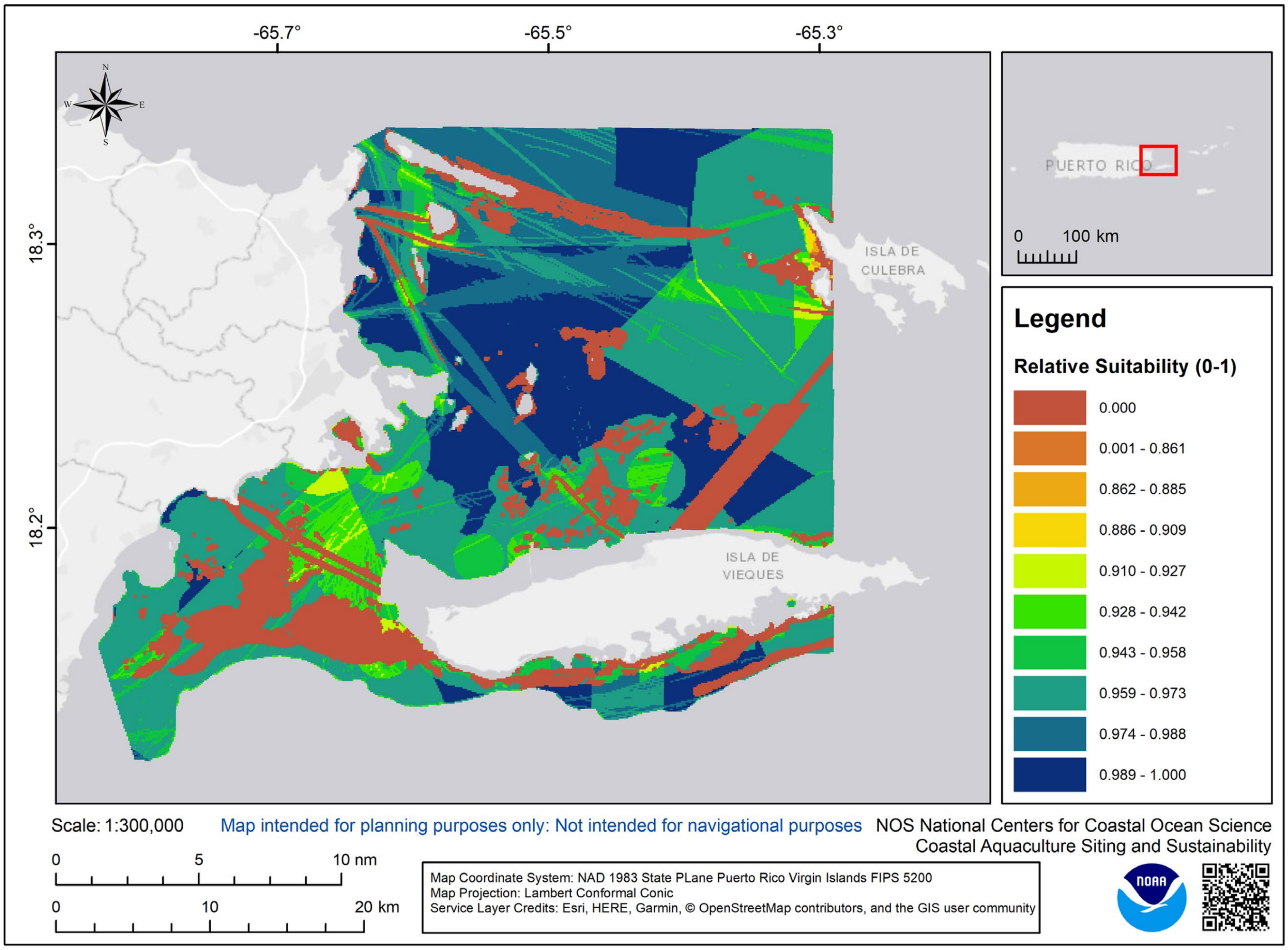

Figure C3. On the eastern side of Puerto Rico, between 10 to 100-m depth. From Jossart et al. (2019b).

On Puerto Rico's eastern side, an area of 110,027 ha was examined (Figure C3). Largely due to colonized and uncolonized hard bottom, submarine cable and pipeline areas, and high vessel traffic, 21,429 ha were deemed unsuitable, leaving 88,598 ha of negotiable space for siting. Note that areas around Vieques and Culebra have a high potential for unexploded ordnance and military-regulated areas, which will require discussions with the military.

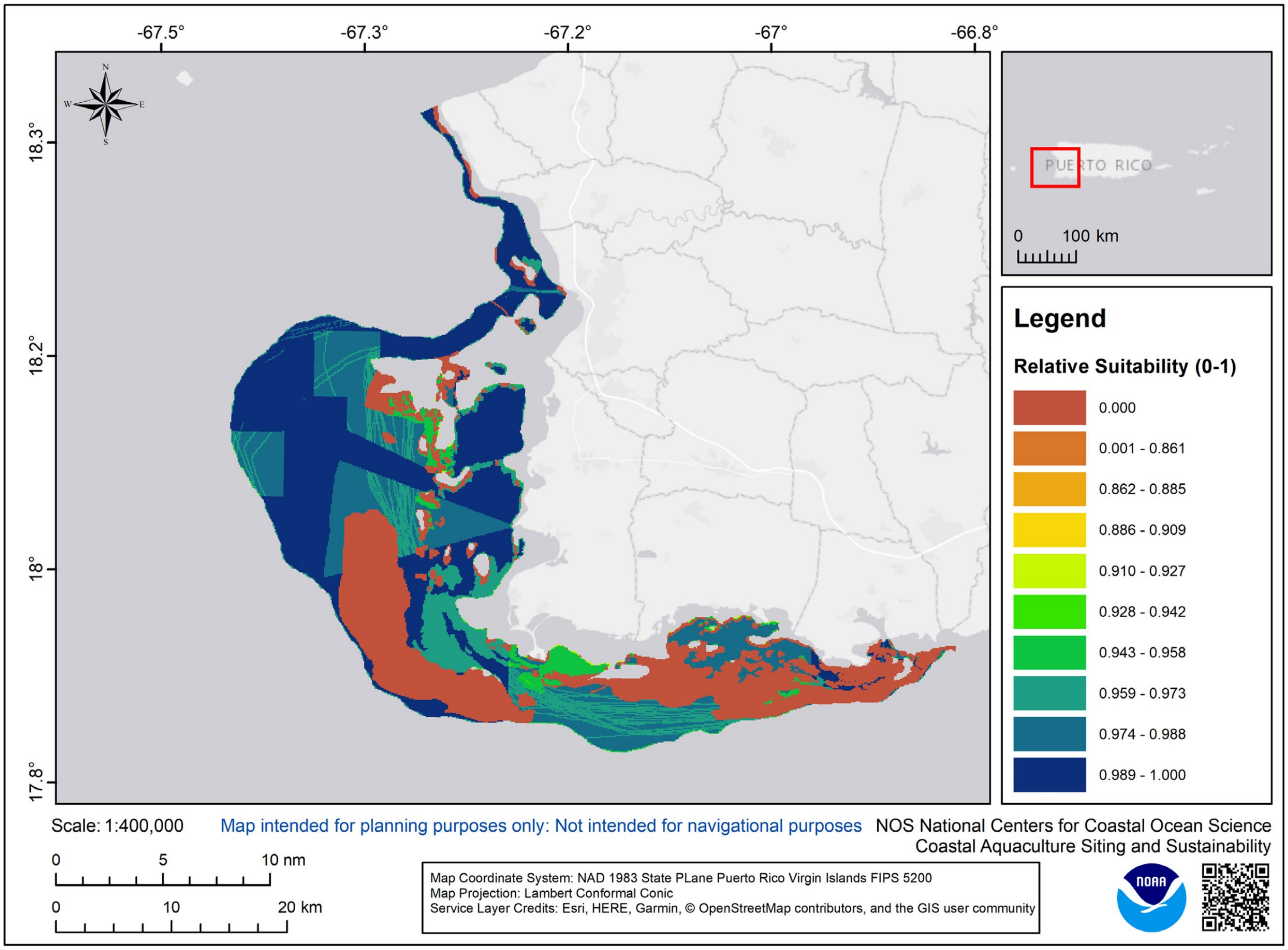

Figure C4. On the western side of Puerto Rico, between 10 to 100-m depth. From Jossart et al. (2019b).

On Puerto Rico's western side, an area of 86,097 ha was examined (Figure C4). Largely due to colonized and uncolonized hard bottom, 25,381 ha were excluded, leaving 60,716 ha of negotiable area.

Appendix D references

Jossart, J., Wickliffe, L.C., Riley, K.L., Morris, J.A. Jr. (2019a). *Relative site suitability analysis for Marine Biological Lab's ARPA-E experimental Eucheuma isiforme farm in La Parguera, Puerto Rico* (CASS Technical Report). NOAA, National Ocean Service (NOS), National Centers for Coastal Ocean Science (NCCOS).

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