Situation Analysis for Oregon's Emergent Seaweed Aquaculture Industry

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Photos

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On the cover is an aerial shot of a kelp forest on the Oregon coast (Sara Hamilton, Oregon Kelp Alliance & the University of California Davis). For the section headings, the background is an iStock photo by Michael Zeigler.

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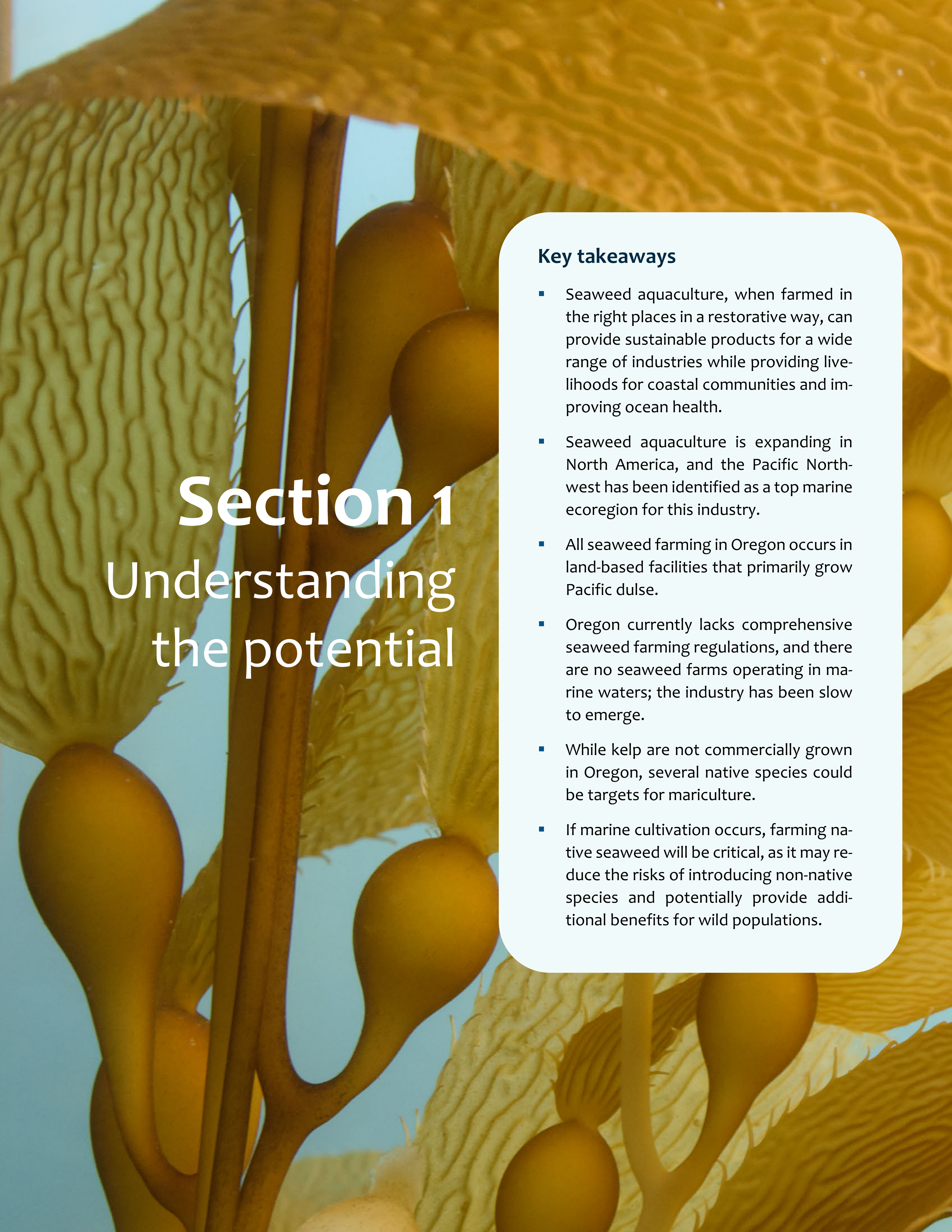
Abbreviations and acronyms

ASC	Aquaculture Stewardship Council
BAP	Best Aquaculture Practices
DSL	Oregon Department of State Lands
FAO	Food and Agriculture Organization of the United Nations
FSMA	Food Safety Modernization Act
HACCP	Hazard Analysis Critical Control Point
IMTA	integrated multi-trophic aquaculture
MSC	Marine Stewardship Council
NOAA	National Oceanic and Atmospheric Administration
OAR	Oregon Administrative Rule
OCVA	Oregon Coast Visitors Association
ODA	Oregon Department of Agriculture
ODFW	Oregon Department of Fish and Wildlife
OPRD	Oregon Parks and Recreation Department
ORKA	Oregon Kelp Alliance
ORS	Oregon Revised Statute
OSU	Oregon State University
RAIN	Regional Accelerator & Innovation Network
TNC	The Nature Conservancy



Section 1
Understanding the potential

Key takeaways

- Seaweed aquaculture, when farmed in the right places in a restorative way, can provide sustainable products for a wide range of industries while providing livelihoods for coastal communities and improving ocean health.
- Seaweed aquaculture is expanding in North America, and the Pacific Northwest has been identified as a top marine ecoregion for this industry.
- All seaweed farming in Oregon occurs in land-based facilities that primarily grow Pacific dulse.
- Oregon currently lacks comprehensive seaweed farming regulations, and there are no seaweed farms operating in marine waters; the industry has been slow to emerge.
- While kelp are not commercially grown in Oregon, several native species could be targets for mariculture.
- If marine cultivation occurs, farming native seaweed will be critical, as it may reduce the risks of introducing non-native species and potentially provide additional benefits for wild populations.

Introduction

In response to the world's growing population and need for food security, aquaculture has become one of the fastest-growing food production sectors (FAO [Food and Agriculture Organization of the United Nations] 2020). This growth has often been associated with, and in some places has resulted in, negative environmental impacts, including habitat degradation, pollution, and impacts on wild stocks (Naylor et al. 2021). Thus, with this rapid expansion, the challenge is determining how to foster development sustainably and equitably. A growing body of research demonstrates that—if deployed in the right places with the right practices and species—aquaculture can bring benefits to both ocean ecosystems and the communities that rely on them, a concept termed *restorative aquaculture* (TNC [The Nature Conservancy] 2021).

In addition to food, seaweed aquaculture has the potential to provide other sustainable products for a wide range of industries, livelihoods for coastal communities, and improved ocean health (TNC 2021). Seaweed can be a source of low-carbon food, raw materials, and energy, with product uses including human consumption, animal feed, cosmetics, pharmaceuticals, fertilizers, biofuel, and bioplastics (Piconi et al. 2020; McKinley Research Group 2021). Seaweed aquaculture also has the potential to provide seedstock for wild populations, create beneficial habitat, improve water quality, and buffer against localized ocean acidification (O'Shea et al. 2019; Gentry et al. 2020).

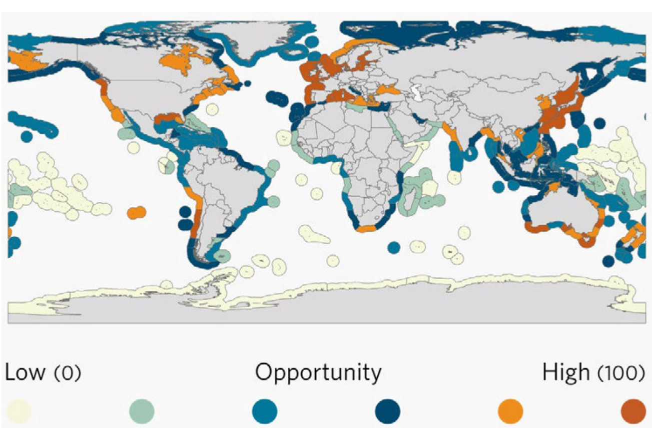


Figure 1. Restorative aquaculture opportunity index for seaweed. Adapted from Theuerkauf et al. (2019) and based on a synthesis of all environmental, socioeconomic, and human health factors included in the Theuerkauf et al. analysis.

Over 90% of the seaweed produced globally comes from the four Asian countries of China, Indonesia, Korea, and the Philippines, where there is a well-established industry for food and hydrocolloids, but the industry is expanding to other regions, such as North America (FAO 2018, 2020). In the United States, sugar kelp is the primary farmed seaweed, with most in-water grow out locations in the Northeast Atlantic and Pacific Northwest. A TNC study by Theuerkauf et al. (2019) identified Oregon, Washington, and Vancouver, British Columbia, as the top marine ecoregions in North America where seaweed aquaculture could be environmentally beneficial, socially acceptable, and economically viable (Figure 1).

Overview of Oregon's seaweed aquaculture industry

Land-based facilities support all current seaweed farming in Oregon (Figure 2). The primary seaweed grown is a strain of Pacific dulse (*Palmaria mollis*) that was originally sourced from Puget Sound and studied as a biofilter for land-based salmon farming effluent (Levine 1991). Current commercial seaweed aquaculture operations are located in Garibaldi and Bandon (Figure 3), where seawater is pumped into culture tanks during high tide. Specialty shops and high-end restaurants are the primary retail outlets for the cultivated dulse, and a secondary market exists for dulse processed into pet food. Current scientific research and product development activities may provide additional markets.

Land-based sites for dulse mariculture are also located in Port Orford and Newport, both of which operate in partnership with Oregon State University (OSU) to focus on research and development. Experimental urchin ranching is underway at these mariculture facilities, which involves collecting starved purple urchins (*Strongylocentrotus purpuratus*) from barren subtidal areas and rearing them in land-based tanks on a diet of dulse until they develop marketable gonad material (also known as *uni*). A major goal of these projects is to create economic incen-

Figure 2. A land-based seaweed aquaculture system in Garibaldi, OR (photo by Travis Thompson, Elevation 0m, Oregon Coast Visitors Association).

tives to curb the expansion of herbivorous urchins contributing to the decline of wild kelp forests.

Despite interest in seaweed farming in this region, Oregon lacks comprehensive seaweed farming regulations, and there are no seaweed farms operating in marine waters. Overall, the industry has been slow to emerge. This situation analysis aims to better understand the potential for restorative seaweed aquaculture development in Oregon, including the potential positive and negative impacts of this marine industry. The report will focus specifically on seaweed aquaculture in the marine environment and investigate basic questions concerning species options, high-potential locations and co-location opportunities for development (e.g., estuarine, nearshore, offshore), potential in-water production methods, market opportunities and supply chain analyses, ecological considerations, policy needs, and the landscape of current and potential partners. Trade-offs between land-based and in-water cultivation will be briefly discussed, but land-based aquaculture is not this document's primary focus.

Species options and production methods

Macroalgae, or seaweed, are classified into three major groups: green seaweeds (Chlorophyta), red seaweeds (Rhodophyta), and brown seaweeds (Phaeophyceae; Druehl and Clarkston 2016). Globally, the commercial seaweed sector is dominated by brown seaweeds (Laminariales), such as kelp, and red seaweeds (*Gracilaria spp.* and *Eucheuma spp.*; FAO 2020). Similarly, in the U.S., the most commonly grown seaweeds are various species of kelp and *Gracilaria* (Sea Grant 2021). In the Pacific Northwest, bull kelp (Figure 4), ribbon kelp, and sugar kelp are grown in open-water operations, while land-based tank systems are used to cultivate red macroalgae, such as Pacific dulse (Robidoux and Chadsey 2020).

As mentioned previously, only Pacific dulse is commercially grown in Oregon at this time, and culture operations are located in land-based facilities. Several strains of dulse have been collected from different locations along the West Coast, and the most commonly grown strain was sourced from Puget Sound and patented by OSU (Demetropoulos and Langdon 2001). Additionally, *Gracilaria spp.* is cultivated in the state at a smaller scale for experimental purposes. Each of these operations involves clonal propagation methods (i.e., fragmentation or division) rather than using the reproductive process, which requires setting spores. Land-based seaweed cultivation commonly uses the *tumble culture* method (Figure 5) by introducing compressed air to the bottom of the tank to maintain seaweeds in a continuous resuspension within the water column (Grote 2019). Seaweeds are maintained in a controlled setting to be able to adjust shade, temperature, and nutrient levels for optimal growth and to maximize certain functional compounds or properties for market appeal, such as protein content and color richness.

Research is underway at OSU to investigate the development of a culture system for clonally propagated dulse and other red algae that may be suitable for open marine-water cultivation (Evans et al. 2021; Kraai and Rorrer 2022). The innovative system consists of an array of mesh panels that may enhance productivity compared to traditional cultivation methods, such as tumble culture and open marine-water rope systems. Additionally, OSU researchers have extensively studied optimal conditions (i.e., salinity, temperature, nutrients, seawater exchange rate) for dulse cultivation in tank-based settings (Evans and Langdon 2000; Demetropoulos and Langdon 2004a, 2004b, 2004c, 2004d, 2004e), which may be helpful for determining prime in-water locations within the marine environment.

Although kelps are not currently grown commercially in Oregon, several native species could be targets for mariculture, and production methods could mirror other Pacific Northwest states where commercial kelp farming already occurs (Robidoux and Chadsey 2020). Kelp cultivation requires technical knowledge of the kelp life cycle and, in the U.S., commonly involves harvesting reproductive tissue from wild kelp beds, manipulating life stages to "seed" spools of rope in a hatchery setting, and placing the long lines in the marine environment for grow out (Redmond et al. 2014; Kim et al. 2017). There is also the potential for wild kelp seeding, where lines are

Figure 3. Four approved land-based seaweed cultivation sites in Oregon.

Figure 4. Wild bull kelp (photo by Jenn Burt, Nature United).

placed in the marine environment and the species of seaweed that naturally settle are grown out, which may be a useful strategy for locations like Oregon that lack a local hatchery. Kelps often grow in the subtidal zone and are able to withstand strong currents and high-wave-energy environments, such as those on Oregon's coast (Redmond et al. 2014). Optimal grow out conditions will likely be species-dependent, with a range of temperature, salinity, and desiccation tolerances.

Figure 5. The tumble culture for dulse seaweed (photo by Travis Williams, Broken Banjo Photography).

If in-water seaweed farming takes off in Oregon, the cultivation of native seaweed will be critical, as it may reduce the risks associated with introducing non-native species and potentially provide additional benefits for wild populations (Molnar et al. 2008; Kim et al. 2019; O'Shea et al. 2019). The research and cultivation of dulse in the state thus far may provide a framework and existing infrastructure to study the potential for other native seaweeds. The types (e.g., red, green, brown) and species of seaweed chosen will depend on the markets of interest and the potential for suitable grow out locations in the marine environment (Table 1).

Table 1. Number of native green, red, and brown algal species in Oregon and other U.S. states in the Pacific Northwest. Adapted from Hansen (1997).

Location	Green algae (Chlorophyta)	Red algae (Rhodophyta)	Brown algae (Phaeophyceae)	Total
Southeast Alaska – Washington	103	135	365	603
Oregon	62	85	233	380
California	80	148	490	718

Section 2
Environmental considerations & site selection

Key takeaways

- West Coast seaweed farms lack a significant history of operation, and studies are needed to ensure farms are managed appropriately.
- Nutrient mitigation and water quality benefits are the most well-studied and supported ecosystem services farmed seaweeds can provide, but emerging research has focused on farmed kelp's benefits for habitat provision and climate.
- More research is needed on potential carbon sequestration benefits. In addition, seaweed aquaculture could contribute to other climate mitigation pathways, such as animal feed, biofuels, biomaterials, and fertilizer.
- Any growth of seaweed aquaculture must consider and mitigate potential environmental impacts, including nutrient competition, the potential overharvesting of wild seedstock, and concerns about genetic diversity, biosecurity, and farm infrastructure.
- Considerations for suitable locations within Oregon's estuaries will include optimal tidal zone and salinity range for the chosen seaweed species and whether the location avoids navigable areas and user conflict.
- Siting and local environmental conditions are top considerations in determining potential benefits or impacts of aquaculture farms. State and university programs in Oregon provide a multitude of tools that could be useful in scoping in-water sites.
- There is the potential to co-culture seaweed aquaculture with existing shellfish farms, co-locate seaweed aquaculture with offshore renewable energy platforms in Oregon, and/or strategically place farms to enhance environmental benefits.

Environmental benefits and impacts

Evaluating the environmental effects of seaweed farms, both positive and negative, is critical to assessing the benefits of farming operations, building broader public support for seaweed farming in the Pacific Northwest, and informing the industry's regulatory requirements. This evaluation is particularly important given that seaweed farms lack a significant history of operation on the West Coast. Studies are needed to ensure farms are managed appropriately and can have neutral or even positive long-term restorative environmental effects.

Water quality benefits

Seaweeds are considered extractive species in that they can remove significant amounts of nitrogen and phosphorous, which can assist with decreasing nutrient loading in eutrophic areas (O'Shea et al. 2019; Gentry et al. 2020; Liang et al. 2022). Excess nutrients can cause cascading environmental impacts, such as harmful algal blooms and low dissolved oxygen conditions (Laffoley and Baxter 2019). Water quality benefits are the most well-studied seaweed ecosystem service, making seaweed aquaculture a feasible tool for nutrient pollution management, which could be helpful in some Oregon estuaries that experience nutrient loading, such as Tillamook Bay (Racine et al. 2021; TNC 2021).

Habitat and wild species benefits

The habitat services of bivalve farms are well documented, and global studies are currently underway showing the potential of seaweed aquaculture to provide similar services, although it may depend on a range of farm management practices. For example, the physical structure introduced from cultivated seaweed and farm gear can provide novel and valuable habitat that may increase foraging, breeding, or refuge opportunities for invertebrates, fish, marine mammals, and birds (Figure 6; Radulovich et al. 2015; O'Shea et al. 2019; Theuerkauf et al. 2021). It is also possible that this habitat provision may increase the productivity of commercially important species (Theuerkauf et al. 2021), although the length of time seaweed crops are kept in the water will likely impact this service (Forbes et al. 2022). Theuerkauf et al. (2021) reviewed 65 studies on habitat-related interactions associated with bivalve and seaweed farms and found that farmed sites were associated with higher abundance and species richness for fish and macroinvertebrates when compared to reference sites (Figure 7).

Figure 6. Fish swimming through a wild kelp forest in the Pacific Northwest (photo by Jenn Burt, Nature United).

While positive correlations with seaweed farms have been found, it must be noted that data were only available for and aggregated from tropical farm systems in Africa and South and Central America, as there is a dearth of literature on temperate systems. At least one study in the literature on habitat provision of farmed kelp species was done in Sweden, showing attraction from nearby species and positive impacts on the benthic infauna (Visch et al. 2020). Also, studies are underway in Maine and New Zealand that are analyzing the habitat benefits of farmed kelp (Jones et al. 2021)

When proper genetic and local adaptation considerations are considered, farming native species in areas where natural stocks are valued and in need of restoration, such as Oregon's southern coast, may assist in the provision of seedstock for wild populations via spore dispersal benefits (O'Shea et al. 2019; Theuerkauf et al. 2021).

How Much Habitat Benefit do Shellfish and Seaweed Farms Provide?

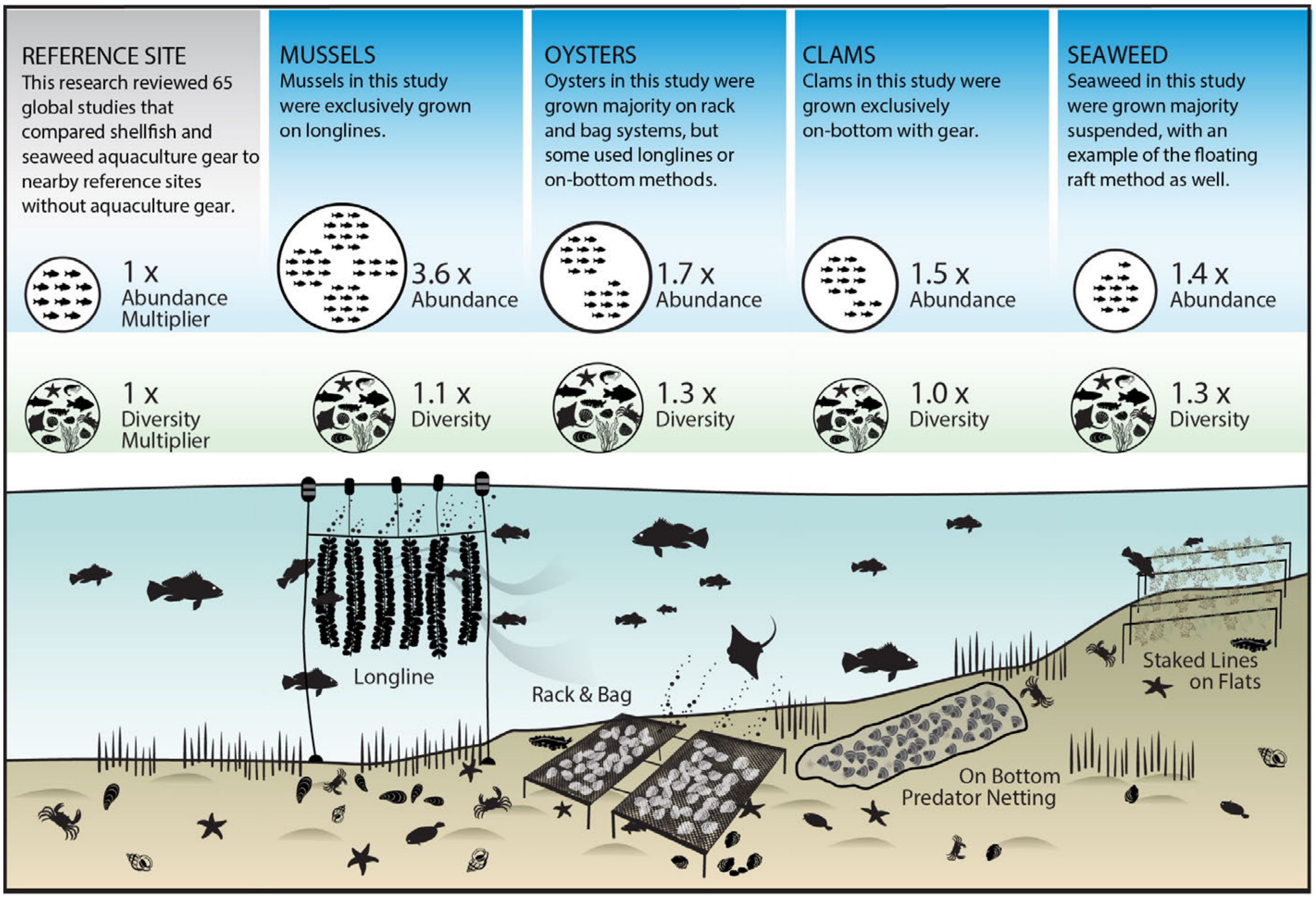


Figure 7. An illustration of the habitat benefits offered by shellfish and seaweed farms. Adapted from Theuerkauf et al. (2021).

Climate benefits

Seaweed cultivation may buffer against ocean acidification in localized areas (Mongin et al. 2016; Costa-Pierce and Chopin 2021; Xiao et al. 2021), although it is important to note that some studies have had mixed results, and buffering potential can be highly site-specific (Traiger et al. 2022). The Oregon coast experiences seasonal upwelling of CO_2-rich waters, which has negatively impacted the oyster aquaculture industry, particularly in locations with more frequent oceanic flushing, such as Netarts Bay (Barton et al. 2012). Co-culture of shellfish with seaweed has the potential to assist with mitigating these coastal acidification impacts on shellfish aquaculture, though more local research will be needed to explore this potential (Fernandez et al. 2019; Han et al. 2020; Xiao et al. 2021).

Seaweed mariculture also has the potential to sequester CO_2 transiently, such as displacing carbon-rich biomass to other places (Costa-Pierce and Chopin 2021). As a strategy for CO_2 sequestration on geological timescales—timescales that would actually reduce the anthropogenic carbon footprint—seaweed aquaculture is still being researched. While climate research for seaweeds is still emerging, initial studies are showing that the specific location of farms will likely be an important factor in how seaweeds act as carbon donors for nearshore or deep-water sediments. For long-term CO_2 storage at larger scales, seaweed may have to be buried or sunk into the deep ocean, which raises efficacy considerations and potential environmental impacts on deep-sea ecosystems (Webb et al. 2021; National Academies of Sciences, Engineering, and Medicine 2022; Ricart et al. 2022).

Seaweed aquaculture product uses, such as animal feed, biofuels, biomaterials, and fertilizer, may provide other climate mitigation pathways (Figure 8; Duarte et al. 2017; Alleway et al. 2022). For example, active compounds present in some red seaweed species may reduce methane emissions from cattle when incorporated into feed (Machado et al. 2014; Kinley and Fredeen 2015; Vijn et al. 2020). Macroalgae is also a potential biomass source for biofuels, and major U.S. federal funding has been allocated to exploring this potential further (Chen et al. 2015; Laurens et al. 2020; Coleman et al. 2022). Seaweed processed into biochar or fertilizer may also assist in enhancing soil capacity for carbon sequestration (Katakula et al. 2020; Kholssi et al. 2022). Overall, the substitution of high-emissions products with low-emissions seaweed products has significant and perhaps the greatest potential to provide major carbon benefits. Still, our understanding of both the ecosystem services and climate mitigation pathways that seaweed aquaculture can provide continues to evolve. Further research must determine the efficacy of these practices.

Overharvesting, genetic impacts, and biosecurity concerns

In addition to seaweed mariculture's potential environmental benefits, there are concerns about negative environmental impacts associated with different aspects of farming methods. For example, the kelp hatchery process in the U.S. involves harvesting and using reproductive tissue from wild populations (Redmond et al. 2014; Kim et al. 2017), which raises concerns about potentially overharvesting wild reproductive tissue, impacting the genetic diversity of wild populations, and spreading disease, parasites, or non-native hitchhiker species (Cottier-Cook et al. 2016; Grebe et al. 2019). To reduce the risks of overharvesting, the Maine Seaweed Council (2014) recommended, as a best management practice, harvesting no more than 30% of biomass each year, including wild reproductive tissue. Seedstock guidelines to reduce genetic impacts on wild populations may include using genetic strains and reproductive materials from the same bioregion as grow out sites (Yarish et al. 2017; Grebe et al. 2019). To combat biosecurity threats, hatcheries often clean reproductive tissue

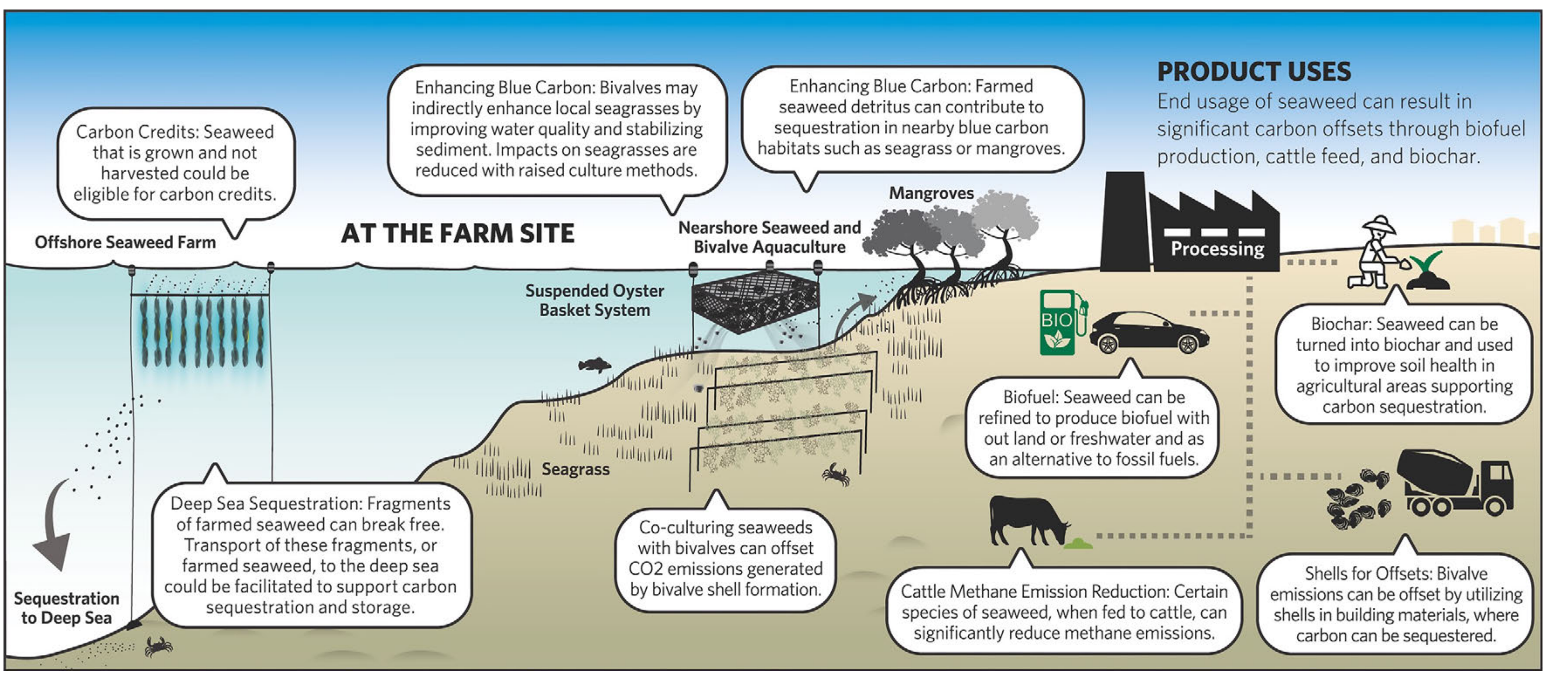


Figure 8. Potential pathways for greenhouse gas offsets, carbon storage, and sequestration from seaweed and bivalve mariculture (Jones et al. 2022).

To view this graphic at a larger scale, view it as part of the Jones et al. publication at https://academic.oup.com/view-large/figure/339230116/biab126fig5.jpg.

and remove fouling organisms with sterilized water and iodine solution (Redmond et al. 2014; Grebe et al. 2019).

Genetic diversity concerns also arise when considering the development of disease- and temperature-tolerant strains, which may be necessary for industry progress (Kim et al. 2017; Coleman et al. 2022). These concerns may also apply to Oregon's land-based seaweed farms, particularly if farm outputs are not filtered for clonal pieces or spores. Developing sterile strains may prevent crop-to-wild gene flow, similar to triploids used by oyster aquaculture industries (Loureiro et al. 2015; Grebe et al. 2019). Additionally, there is a need to map the genetic and phenotypic structures of wild seaweed populations to better understand the risks of gene flow and prevent genetic contamination from monocultures (Mao et al. 2020; Coleman et al. 2022). Applicable biosecurity and genetic diversity regulations and examples from other states, such as Alaska, are discussed further in the "Policy and regulatory considerations" section of this report.

Farm infrastructure concerns

The build-out of essential infrastructure required for seaweed mariculture may present threats to marine life. If not properly sited, it could degrade marine and estuarine habitat. For example, longlines and moorings may negatively impact benthic habitat through seafloor shading in estuarine or nearshore locations. In offshore locations, there are concerns about the potential for marine mammal entanglement (Cottier-Cook et al. 2016; Grebe et al. 2019). Dungeness crab and other fixed-gear industries in Oregon are working to develop short- and long-term options for reducing marine mammal entanglement risks, primarily focusing on ways to reduce the number of vertical lines in the water (ODFW [Oregon Department of Fish and Wildlife] 2021). Farm design and technology to limit impacts could be modeled after gear modifications proposed for these Oregon fisheries (Grebe et al. 2019). Other useful technology being explored by seaweed farms on the East Coast includes sensors that notify farmers via a smartphone app when their gear has been disturbed.

The siting process is critical to these concerns and should ensure that farms are located outside critical habitat. Also, the size and density of farms are considerations, as they may influence impacts. For example, dispersed longlines may facilitate passage for marine mammals or create less shade, thereby reducing benthic impacts (Grebe et al. 2019). Marine farms can also be configured to reduce the risk of potential entanglement through taut ropes with a breakaway design and monitoring controls. While there have been no known reports of whale entanglement in seaweed farms globally, it is unknown whether mammals on the Pacific coast will avoid or be attracted to seaweed farms. As such, marine mammal entanglement could be considered a "low probability but high impact scenario" (TNC 2021).

Plastics are commonly used in mariculture infrastructure, including seaweed aquaculture, which poses concerns about marine plastic pollution (Skirtun et al. 2022). To address this issue, Oregon's seaweed industry could use alternative and biodegradable gear materials. For example, mycelium buoys are being tested on the East Coast (Bell 2018), and companies and researchers in Europe are developing biodegradable ropes for aquaculture purposes. That said, these nonplastic products are often in the development stage, and a tiered solution could be implemented initially, ensuring that farms use higher-quality plastic gear rather than Styrofoam or low-quality plastics that degrade quickly in the marine environment.

Nutrient competition

While seaweed farming may provide bioremediation or bioextraction benefits in eutrophic locations, there are concerns about farms competing with wild marine algae if grown in very large quantities and/or nutrient-poor areas, which could negatively impact marine ecosystem productivity (Kim et al. 2017; Grebe et al. 2019; Costa-Pierce and Chopin 2021; Liang et al. 2022). Siting farms in upwelling locations could combat nutrient limitations often experienced in offshore environments (Kim et al. 2017).

Table 2. Potential environmental benefits and impacts from seaweed aquaculture within the marine environment.

Environmental effect	Relative priority* for future assessment and research
Benefit	
Nutrient pollution mitigation	**High**. Oregon's marine waters have suffered from dead zones and harmful algal blooms, which grow via excessive nutrients, warming waters, and changing climate conditions. If properly sited in Oregon's estuarine, nearshore, and offshore environments, seaweed farms have the potential to locally absorb and remove excess nitrogen and phosphorous from water, which could benefit ocean health.
Ocean acidification buffering	**High**. Oregon experiences ocean acidification seasonally via the upwelling of CO_2-rich waters, which has caused negative impacts on the oyster aquaculture industry. If sited properly and co-cultured, seaweed has the potential to buffer ocean acidification at a localized level.
Pathways for climate mitigation through product usage	**Medium to High**. Given Oregon's extensive agricultural industries, locally sourced seaweed has a high potential to provide carbon benefits and/or methane reduction via biostimulants, biochar, or animal feeds.
Habitat provision	**Medium**. Oregon's marine waters are habitat-limited for certain threatened and endangered species. Research is needed on how farmed seaweed could provide habitat for nearby species and positive impacts to benthic infauna.
Provision of seedstock for wild populations	**Low to Medium**. Strategically placing kelp farms near depleted natural kelp forests on Oregon's coast could boost spore supply and contribute to kelp restoration. Additional studies will be needed to assess local sediment conditions and if spore overflow can result in benefits and/or if supplemental restoration techniques (e.g., green graveling) would also be needed.
Impact	
Farm infrastructure impacts	**Medium to High**. Longlines and moorings have the potential to negatively impact benthic habitats through seafloor shading in estuarine or nearshore locations. Also, marine mammal entanglement could be considered a low-probability but high-impact scenario. Siting farm infrastructure is the most important consideration in providing benefits or impacts to the local environment, and smart siting should be a focus area going forward to avoid conflicts with other ocean uses and habitat.
Genetic diversity impacts on wild populations	**Medium**. Given the very novel and emerging state of the industry, Oregon currently lacks regulations or policies to safeguard genetic diversity. Regulations for seaweed aquaculture that address environmental concerns may include developing bioregional seedstock guidelines where parental plants are obtained from the same bioregion as grow out locations.
Overharvesting of wild reproductive tissue	**Medium**. Oregon currently lacks regulations or policies specific to the extraction of wild reproductive tissue for seaweed farming. Regulations and policies will be needed to set limits on the extraction of reproductive tissue and reduce the risks of overharvesting.
Biosecurity concerns	**Low to Medium.** Oregon currently lacks regulations or policies for seaweed biosecurity. Oregon has an existing administrative process within ODFW that implements biosecurity regulations for Oregon's oyster aquaculture industry, and similar regulations may be applicable to seaweed aquaculture.
Nutrient competition in oligotrophic environments	**Low**. If grown in very large quantities and/or in nutrient-poor areas, seaweed farming can compete for nutrients and impact marine ecosystem productivity. If/when the industry grows, the scale and siting of seaweed farms should be considered.

* Relative research priorities are based on qualitative assessments.

Summary

There are trade-offs in environmental impacts and benefits for in-water and land-based cultivation strategies. For example, the habitat and water quality services described herein can only be realized when seaweed is cultivated in the marine environment. Additionally, in-water seaweed cultivation requires limited land use and has low freshwater impacts. On the other hand, through closed systems, land-based cultivation avoids many of the potential negative ecological impacts associated with in-water cultivation. Many of these ecological considerations will play a large role in shaping Oregon's emerging seaweed aquaculture industry.

Some environmental benefits are more well studied than others. Many of the environmental impacts described in Table 2 can be mitigated with proper siting, advancements in technology, and regulations that promote responsible farming.

Site selection and co-location

Site selection for in-water seaweed aquaculture in Oregon will depend on a variety of ecological, economic, and social factors (O'Shea et al. 2019). The type of seaweed targeted for cultivation could inform the range of site factors considered. Conversely, the available locations may inform the species chosen. For example, some optimal environmental conditions—such as salinity, temperature, hydrodynamics, sedimentation, and tidal zone—are species-dependent (Engle et al. 2018; Redmond et al. 2014). The quality of and proximity to supporting infrastructure, downstream markets, and water and energy resources will also be important factors to assess (Engle et al. 2018; O'Shea et al. 2019). Additionally, existing ocean uses (e.g., shipping, commercial fishing) and the regulatory environment will impact the possibility of farming in certain locations (Buck and Langan 2017; Lester et al. 2022). Partners in Oregon have developed several existing tools that may assist with site selection, and pathways for seaweed farming may exist via shellfish aquaculture leases or co-location with ocean renewable energy.

Site selection tools

OSU's Libraries and Press and OSU's Institute for Natural Resources have developed an Oregon Explorer website that includes tools related to a range of topics, including aquaculture development, which may be helpful for site selection. For example, the Aquaculture Map Viewer may assist in siting land-based seaweed aquaculture farms, as it provides information on zoning, geophysical characteristics, distances to major markets, water and energy resources, and other regulatory considerations. The Estuary Shellfish Mariculture Explorer is a planning tool that may help to initially scope in-water seaweed aquaculture sites in Oregon's nearshore and estuarine waters. It provides environmental considerations (i.e., species to consider, important areas) and management considerations. While the Oregon Explorer website does not currently have resources specific to seaweed aquaculture, the existing aquaculture tools may still help, and OSU is in the process of adding new data layers to the website, which may further assist prospective seaweed growers in exploring potential locations.

Another tool that may be useful for site selection is the Oregon Coast Food Prospector website, developed by the Oregon Coast Visitors Association (OCVA). It offers detailed information on locations and access to food processing sites and potential markets. Collaborative efforts are also underway to develop an Ocean Cluster Initiative to increase capacity on Oregon's coast, making local seafood easier to find and buy. Part of this initiative will be increasing capacity for cold and dry storage as well as distribution routes and systems. These efforts to strengthen supporting infrastructure for Oregon's seafood sector are also aimed at assisting Oregon's emerging seaweed industry.

Co-culture

There is growing interest in *co-culture* opportunities, or the cultivation of several species on a given farm. In 2021, Oregon Sea Grant administered a survey to better understand the needs of and barriers to aquaculture expansion in Oregon. Results indicated that some existing oyster growers were interested in diversifying their crops with seaweed (Ehrhart and

Doerr 2022). In other U.S. states, bivalve shellfish producers have been able to cultivate seaweed on existing shellfish leases, creating easier entry for these producers (Engle et al. 2018). Additionally, shellfish growers in Oregon likely have existing facilities, equipment, and other resources that could alleviate start-up costs. Determining which seaweed species could be grown at existing sites based on ambient environmental conditions may be a next step for interested growers. The socioeconomic benefits of polyculture are discussed further in the "Potential partners and key actors" section of this report.

In Washington State, researchers at the Puget Sound Restoration Fund are working with shellfish growers to quantify the amount of seaweed that grows as a by-product on farms, which is often considered a burden that must be removed. Rather than disposing of the seaweed, this innovative project is developing a proof-of-concept supply chain to see if harvesting fouling seaweed may actually contribute to farm profits (NOAA [National Oceanic and Atmospheric Administration] 2021). This project may provide insights into portfolio diversification and market opportunities for shellfish growers in Oregon as well.

Another co-culture opportunity could be available through an integrated multi-trophic aquaculture (IMTA) system where seaweed and other extractive species, such as bivalves, are farmed in proximity to higher trophic-level species, or "fed" species, such as finfish. Bivalves and seaweed "extract" organic and inorganic nutrients produced by species at the higher trophic level, thereby maintaining a clean environment (Chopin et al. 2001; Chambers 2013; Buck et al. 2017). IMTA may be more suitable than seaweed monoculture, particularly in nutrient-limited areas (Troell et al. 2009; Buck et al. 2017). While no IMTA projects currently exist in Oregon, this evolving approach is extensively studied on the eastern coast of North America (Chopin et al. 2004; Ridler et al. 2006, 2007) and is being explored in other parts of the Pacific Northwest (Yip 2012).

Other co-culture opportunities include growing macroalgae with urchins or abalone, which has been implemented in land-based systems in this area (Figure 9). For both of these organisms, co-culture with dulse or other macroalgae provides a consistent food source while improving water quality through the macroalgae's nutrient uptake. OSU conducted co-culture research with dulse and abalone over two decades ago (Evans and Langdon 2000), and urchin ranching research is currently being conducted by OSU researchers in partnership with the Oregon Kelp Alliance (ORKA; see the "Urchin ranching case study" section).

Co-location

There may be opportunities to explore the co-location of aquaculture with offshore renewable energy platforms in Oregon. Rather than designating zones for a particular use and excluding other activities, co-location offers an opportunity for the multifunctional use of space and resources (Buck and Langan 2017; Freeman et al. 2022).

In 2022, the Bureau of Ocean Energy Management obtained public comment for two potential wind energy leasing areas in federal waters off Oregon's south coast. Additionally, PacWave, in partnership with OSU, the U.S. Department of Energy, the State of Oregon, and local stakeholders, has a pre-permitted wave energy test facility in development near Newport, Oregon, that is planned to be completely constructed by 2024. If these locations proceed, they may provide opportunities for a potential seaweed aquaculture demonstration farm(s).

Offshore aquaculture and ocean renewable energy are both new industries that may present several challenges for co-location, such as complex and lengthy regulatory processes, stakeholder concerns, environmental impacts, and negative interactions between energy devices and aquaculture activities (Freeman et al. 2022). Researchers at OSU are currently exploring regulatory pathways for the co-location of wind or wave energy systems with aquaculture (Davis 2022). A consideration for offshore seaweed aquaculture would be nutrient limitations that are often experienced in these environments (Kim et al. 2017). Crossing sandbars located at river entrances may also present a unique challenge for offshore activities in Oregon, as coastal bars can be dangerous even on a calm day, particularly during ebb tides (U.S. Coast Guard 2015). Moreover, innovations in farm designs may be required for structures to

Figure 9. Tank-based urchin culture (photo by Sara Hamilton, ORKA & University of California Davis).

withstand Oregon's high-wave-energy environment, although design systems from other locations could be adapted and provide an initial framework (Buck et al. 2017; Goseberg et al. 2017).

Strategically locating for restorative benefit

A key principle for implementing restorative aquaculture is strategically placing farms to enhance environmental benefits (TNC 2021). For example, Tillamook Bay, Oregon, has a history of pollution problems from agricultural activities (Jackson and Glendening 1982), and seaweed could be used for bioremediation (Gentry et al. 2020; Liang et al. 2022). It is important, however, to identify the specific sites within the bay that experience degraded water quality conditions and still support the growth of seaweeds. Locations along Oregon's coast, such as Netarts Bay, could benefit from localized ocean acidification buffering as well (Barton et al. 2012; Xiao et al. 2021). Additionally, placing kelp farms near depleted natural kelp forests on the south coast could boost spore supply, thereby contributing to kelp restoration efforts (Theuerkauf et al. 2021). There may also be considerations for strategically placing farms in the nearshore environment for habitat provision (Theuerkauf et al. 2021). For commercial seaweed aquaculture to be considered restorative or regenerative, spatial needs for seaweed aquaculture ecosystem services should be carefully evaluated.

Whether nearshore or offshore, the in-water potential for seaweed aquaculture in Oregon has yet to be realized. An in-depth spatial analysis is needed to better understand the extent of suitable locations within Oregon's marine environment. A pilot or demonstration seaweed farm in marine waters could be a catalyst to demonstrate these systems' feasibility. Siting successful pilot projects will require interdisciplinary partnerships between state authorities, multiple industries, academia, and local stakeholders.

Section 3
Investigating economic viability

Key takeaways

- Seaweed is more expensive to cultivate in the U.S. and is in limited supply, making it difficult to compete with well-established, low-cost Asian seaweeds. The majority of U.S.-cultivated seaweed goes towards direct human consumption as a premium product.
- The relatively low amount of seaweed produced in Oregon is tank-grown red seaweed currently sold fresh or dried to high-end restaurants, specialty shops, and farmers markets. The prices per pound vary from $10-$15 for fresh seaweed and $60-$80 for dried.
- For seaweed production in Oregon to be economically viable and to avoid direct competition with existing Asian suppliers, new diversified markets, increased efficiencies of scale, and/or higher-valued seaweed products will likely be necessary.
- A necessary supply chain consideration for Oregon's seaweed industry includes expanding upstream and downstream supporting infrastructure, which is a similar need/ trend in other parts of the U.S.
- A major catalyst for this industry could be a risk-tolerant capital investment into farms and/or supporting infrastructure paired with market pull from private companies.

Market opportunities and supply chain considerations

Markets for seaweed span human consumption, animal feed, fertilizer and biostimulants, pharmaceuticals, cosmetics, biomaterials, and biofuels. Hydrocolloid products—thickeners used in food and beverages, cosmetics, and pharmaceuticals—form the largest international market, followed by products for direct human consumption (McKinley Research Group 2021). Products for nonhuman consumption, such as fertilizer and animal feed, are also well-developed international seaweed markets (McKinley Research Group 2021). Biomaterials, biofuel, and carbon and nutrient credits are emerging markets, especially with the need to transition away from fossil fuels and growing interest in seaweed aquaculture's ecosystem services. It is noteworthy that the biochemical makeup of seaweed varies by type (e.g., red, green, brown) and species. It is noteworthy that the biochemical makeup of seaweed varies by type (e.g., red, green, brown), species, and the growing environment, making some seaweed strains more suitable than others for certain products or markets (Jard et al. 2013; Lähteenmäki-Uutela et al. 2021). Research continues to advance the knowledge of different seaweeds' various applications.

In the U.S., the majority of cultivated seaweed goes towards direct human consumption as a premium product (Table 3), such as those in high-end restaurants and health food stores. Still, there is potential for other markets to emerge domestically (Kim et al. 2019; Piconi et al. 2020; Robidoux and Chadsey 2020; McKinley Research Group 2021). Seaweed is more expensive to cultivate in the U.S. and is in limited supply, making it difficult to compete with well-established, low-cost Asian seaweeds. For example, the hydrocolloid market in the U.S. generally purchases from low-cost Asian suppliers that produce larger quantities at commodity prices (McKinley Research Group 2021). The fertilizer and animal feed markets in the U.S. purchase from domestic wild harvest seaweed due to its lower cost, though there may be an opportunity for cultivated seaweed to enter into those markets through more consumer-facing products, such as pet food or home garden fertilizer (McKinley Research Group 2021). While markets for cultivated seaweed in the U.S. are currently limited, a market analysis by Piconi et al. (2020) projected that harvesting and processing capacity in the U.S. would double by 2025 and quadruple by 2035 to meet an expected growing market demand.

Oregon seaweed markets

In Oregon, the seaweed produced is primarily sold for human consumption; market growth and other sales channels will be necessary for the industry to support new entrants. Tank-grown red seaweed in the state is sold fresh or dried to high-end restaurants, specialty shops, and farmers markets. The prices per pound are $10-$15 for fresh seaweed and $60-$80 for dried. The direct supply chain marketing for seaweed follows a similar approach to some small-scale oyster aquaculture in the area, and it allows producers to receive a higher revenue per unit (Love et al. 2020). Oregon also has an established sales channel for a pet food market. Oregon Seaweed, the primary commercial producer, is researching other markets, such as biochar, cattle feed, and alternative protein. Partnerships and projects are being established but not yet fully implemented.

Table 3. Estimated U.S. edible seaweed production by region, in wet pounds. Adapted from Piconi et al. (2020).

Location	Farmed	Wild	Total
Maine	325,000	230,000	555,000
Alaska	180,000 – 200,000	< 10,000	190,000 – 210,000*
Other Northeast (CT, RI, MA, NH, NY)	10,000 – 20,000	< 10,000	15,000 – 30,000
Other West (CA, OR, WA)	30,000 – 50,000	50,000 – 70,000	80,000 – 120,000
All Other	< 10,000	< 10,000	< 20,000

* This range is different from the totals cited in Piconi et al. (2020), which stated "200,000 – 220,000." The totals have been revised to reflect the sums from this row.

Urchin ranching case study:
A market-based tool for the recovery of wild kelp forests

Urchin ranching could help struggling kelp forests rebound. And aquaculture operators can gain a dual income stream by growing the purple urchins alongside Pacific dulse, offering more chances for success in these nascent markets.

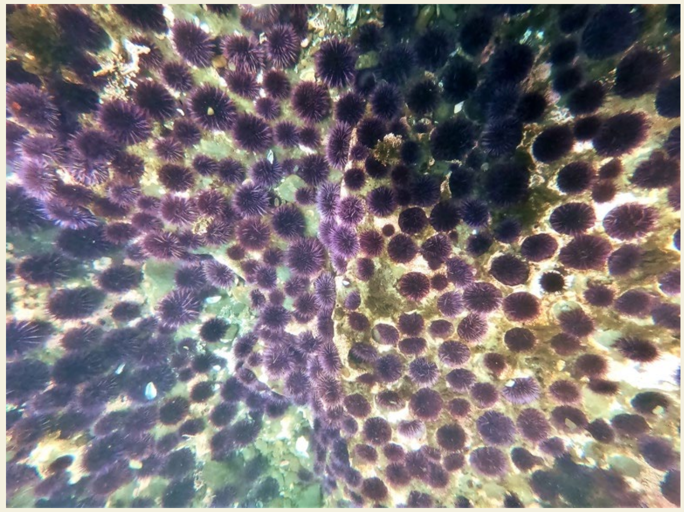


Figure 10. An urchin barren (photo by Sara Hamilton, ORKA & University of California Davis).

The majority of Oregon's kelp forests are located on the south coast at five major reef sites, and over the past two decades, two have been declining (Hamilton et al. 2020). Similar to other locations along the West Coast, degradation in Oregon's wild kelp forests could be due to many factors, including the direct effects of warming temperatures and excessive grazing by sea urchins and the indirect effects associated with the loss of urchin predators, such as the sunflower star (Rogers-Bennett and Catton 2019; Hamilton et al. 2020). Starting in 2013, sea star wasting disease decimated sunflower star populations along the West Coast, resulting in less top-down control of herbivorous purple urchins that feed on understory seaweeds and kelp. In some locations, the loss of predators has been a tipping point, leading to destructive grazing and a drastic habitat shift into less productive areas, known as urchin barrens (Figure 10; Hamilton et al. 2021). Though poorly nourished, the purple urchins creating these barrens are able to withstand long periods of starvation, even years, making it difficult for kelp forests to rebound.

In partnership with academic institutions, resource managers, and local chefs and divers, the Oregon Kelp Alliance (ORKA) is implementing a suite of strategies to combat the overpopulation of purple sea urchins and degradation of Oregon's kelp forests. One such example is a recent Oregon Sea Grant award to OSU researchers partnering with ORKA. Their work involves exploring the biological and economic feasibility of land-based urchin ranching in southern Oregon. Ranchers collect starved, empty urchins from barren sites and rear them in a land-based facility to produce marketable uni, or roe (Figure 11). Research sites are located at existing land-based seaweed cultivation locations, as co-culture with Pacific dulse provides a food source while using waste produced by the urchins. ORKA has several university students researching different aspects of this process, including consumption rates, uni growth rates, and waste output in a co-culture setup. The urchin ranching concept presents a unique diversification strategy for a grower's product portfolio and a unique market for seaweed aquaculture that may also positively impact wild kelp restoration. While urchin ranching will not be a solution on its own, ORKA and OSU researchers envision the process as another tool within a suite of other strategies to enhance Oregon's wild kelp forests.

It is important to acknowledge that although urchin ranching provides a possible pathway in Oregon to hold and feed starved urchins until they develop marketable gonads, the practice is associated with substantial costs. It has historically been subsidized by public and private funds, including substantial contributions by universities, NGOs, private investors, and other donors. The specific factors and nutritional requirements that control purple urchins' gonad development have been studied for several decades (Ebert 1968; Conor 1972; Pearse 1981; Walker et al. 2015; Cuesta-Gomez and Sánchez-Saavedra 2014, 2018). New urchin ranching activities in Oregon have explored the feasibility of developing urchin gonads based on a diet of cultivated dulse, but they have not been economically self-supporting. Further investigation is needed to determine if urchin ranching activities will be ecologically or economically viable for Oregon.

Figure 11. Urchin uni, also known as roe (iStock photo by Michele Ursi).

In a market-first approach, local demand and the targeted market inform the types of seaweed grown. A comprehensive market analysis is critical before any major financial commitments from new commercial seaweed farmers (Moehl 2021). GreenWave's Seaweed Source program could be a helpful tool for prospective growers, as it leverages GreenWave's network of buyers to open new sales channels. While the program is currently focused on New England, in 2023, the program plans to expand to other areas in the U.S. and Canada, which may include the Pacific Northwest. Local organizations and processing facilities in Oregon will likely be critical for connecting prospective and current growers to emerging and existing markets.

Product considerations

For seaweed production in Oregon to be economically viable and to avoid direct competition with existing Asian suppliers, increased efficiencies of scale and/or higher-valued seaweed products (Figure 12) will likely be necessary (Bord Iascaigh Mhara 2015; Engle et al. 2018; Piconi et al. 2020). OSU researchers are developing seaweed cultivation methods that maximize the surface area used and enhance productivity compared to traditional cultivation, such as longlines and tumble culture, which may contribute to a viable industry (Evans et al. 2021; Kraai and Rorrer 2022).

Product diversification and differentiation may assist with increasing product value and reducing economic risk. For example, shellfish growers could diversify their product line by adding seaweed, and their existing capital equipment and knowledge of the marine environment would likely reduce the economic risk associated with engaging in an emerging industry. Diversification may also involve vertical integration of some businesses, which will likely require specialized equipment and capital for staff dedicated to marketing and product development (Engle et al. 2018). Product differentiation in other states has often involved highlighting clean waters where seaweed farms are located, while some growers in the United States use water quality concerns to explicitly differentiate from Asian imports (Piconi et al. 2020; McKinley Research Group 2021). The main producer in Oregon is currently in the early stages of a carbon accounting study, aiming to label or differentiate their product as carbon neutral or carbon negative. Moreover, Oregon's foodie culture places a higher value on local foods, creating opportunities for local seaweed producers.

Supply chain considerations

A necessary supply chain consideration for Oregon's seaweed industry includes expanding upstream and downstream supporting infrastructure, which is a similar need/trend in other parts of the U.S. (Piconi et al. 2020). This infrastructure may include a nursery or hatchery, processing facilities, drying facilities, cold and dry storage space, and transportation hubs. A regionally located hatchery would be the most ideal for a successful kelp aquaculture industry in Oregon. Indeed, ORKA has expressed interest in developing a hatchery to implement active kelp restoration (e.g., green gravel techniques, which involve seeding small rocks with kelp and out-planting them in the field), which could serve the dual purposes of restoration and aquaculture. Oregon has an existing network of seafood processing facilities that could be used for larger-scale seaweed farming (Moehl 2021). Through the OCVA and Ocean Cluster Initiative, efforts are also underway to create collective distribution systems for local seafood businesses, develop food hubs that provide storage and processing space for smaller-scale businesses, and bridge gaps between small-scale efforts for a unified coast-wide approach. Spatial zoning policies for in-water grow out locations may also assist in driving the development of supply chain infrastructure (Lester et al. 2022).

Major catalysts for this industry could be risk-tolerant capital investments in farms and/or supporting infrastructure paired with market pull from private companies. Private donors' capital investment in this sector could be structured in various ways, such as return-seeking arrangements, grants, equity investments, or loans. Increased investment and engagement with downstream and upstream supply chain companies, such as processors, will be needed to meet product specifications, particularly as supply needs increase. Additionally, Oregon's blue economy efforts may offer opportunities for scaling this industry. For example, the Regional Accelerator & Innovation Network (RAIN) and the OSU Hatfield Marine Science Center's Innovation Lab assist with connecting entrepreneurs and innovators to key resources.

Beyond supply chain infrastructure, participants in Oregon's nascent seaweed industry must consider supply chain transparency and integrity. Consumer preferences are changing, and the traceability of seafood products is becoming more important (O'Shea et al. 2019). Currently, the U.S. Food and Drug Administration does not list seaweed on the Food Traceability List, meaning additional food traceability records are not explicitly required. Still, standards and certifications are addressing environmental and social dimensions of sustainable seaweed production that could be implemented in the Pacific Northwest. The emerging seaweed industry could adopt established food traceability and sustainability certification programs, such as the Seaweed Standard of the Aquaculture and Marine Stewardship Councils (ASC-MSC) or the Best Aquaculture Practices (BAP) Seaweed Farm Standard from the Global Seafood Alliance. Technology for traceability and monitoring systems also continues to improve, allowing farmed products to be traced through the retail chain (Waters et al. 2019).

Figure 12. Two photos of Pacific dulse. Fresh dulse is on the left (photo by Nolan Calisch), and dried dulse is on the right (photo by Sophia Knox).

Section 4
Policy implications & partnerships

Key takeaways

- Similar to other states in the U.S., Oregon's current marine aquaculture regulations are not favorable for seaweed aquaculture expansion.
- While there is no clear and transparent regulatory framework for in-water seaweed aquaculture in Oregon, the administrative process is well defined for oyster aquaculture, which could provide a framework for seaweed.
- Enabling policies and regulations that also address environmental concerns—such as biosecurity threats, impacts to wild stocks, and loss of genetic diversity—are important for the sustainable development of any seaweed industry. Other states and countries have seaweed regulations that could be reviewed and modified for Oregon.
- Given their traditional knowledge and seaweed harvesting expertise, coupled with formal and informal co-management rights, Tribes and First Nations can offer critical partners and educators in helping the industry meet its restorative potential in Oregon and throughout the Pacific Northwest.
- Seaweed aquaculture could also be a livelihood diversification strategy for local fisherfolk or a way to diversify crops for existing aquaculture producers in the state. Co-culture and livelihood diversification can generate off-season revenue, provide year-round employment, and improve resilience to increase socioeconomic and environmental change.

Policy and regulatory considerations

While some regions of the U.S. may be ideal for marine aquaculture development, policies and public opinion have often been unfavorable (Knapp and Rubino 2016). Regulatory standards favorable to responsible aquaculture activities are necessary to avoid negative outcomes for the environment and industry (Davies et al. 2019), yet countries with rigorous environmental standards, like the U.S., have exhibited slower growth of aquaculture enterprises (Abate et al. 2016). The complexity of environmental policies and regulations can present a particular challenge to small-scale mariculture farmers, who have less access to financial and advisory resources needed to navigate them (van Senten et al. 2020).

Lester et al. (2022) systematically reviewed mariculture policies in U.S. coastal states and identified those that may enable marine aquaculture development. Some enabling attributes include policies that attempt to make licensing and permitting more transparent, such as those specifying an identifiable contact, and documents outlining the permitting process. Funding or loan programs may help reduce barriers to entry by offsetting equipment or training costs. Developing best management practices for an aquaculture sector may also assist in stimulating the industry's sustainable growth. Lester et al. found that legal protection through the inclusion of aquaculture in a state's right-to-farm law was positively associated with aquaculture production. In Oregon, the right-to-farm law declares farm and forestry practices as critical to the welfare of the Oregon economy, which protects these operations to some extent from challenges and court decisions based on customary noises, smells, dust, or other nuisances or trespasses (ORS 30.930). Stipulations within the Oregon right-to-farm law do not extend to mariculture operations located on state-owned lands. The Lester et al. review (2022) pointed out that Oregon has a low score for enabling aquaculture policy compared to other West Coast states. This finding is due to its lack of comprehensive and supportive aquaculture legislation, no aquaculture best management practices, and the absence of aquaculture from Oregon's right-to-farm statute.

Mariculture regulations can be complex due to the distinct separation and sometimes overlapping jurisdictional authorities exercised by federal, state, and municipal agencies (Knapp and Rubino 2016; Lester et al. 2022). This section focuses on applicable state regulations for seaweed aquaculture in Oregon for the nearshore environment that falls within state waters (i.e., extending up to three nautical miles from the shore); offshore aquaculture (i.e., aquaculture occurring seaward of three nautical miles) is not a focus of this section.

Oregon regulations specific to seaweed aquaculture

Regulations pertaining to seaweed aquaculture and wild harvest for commercial and personal use are largely under the Oregon Department of State Lands (DSL) and the Oregon Parks and Recreation Department (OPRD). Oregon aquaculture facilities, including seaweed aquaculture, are authorized under Division 82 rules and require a DSL waterway lease for marine industrial/marine service activities (OAR 141-082-0255). A proposed lease site also requires a public commenting period. A corresponding removal-fill permit from the DSL may be required (ORS 196.795.990). So far, this solicitation has never been requested. Additionally, DSL's fee structure differs from the Oregon Department of Agriculture (ODA) shellfish aquaculture program, although DSL has the discretion to identify appropriate compensation for seaweed aquaculture activities upon consultation.

Regarding the harvest of wild kelp (Figure 13), rules on special uses of state-owned land prohibit the removal of wild kelp and other seaweeds for com-

Figure 13. Wild bull kelp (photo by Jenn Burt, Nature United).

mercial uses (OAR 141-125-0110), though a DSL lease for such activities may be obtained after consultation with the State Fish and Wildlife Commission (ORS 274.885; ORS 274.890; ORS 274.895). OPRD manages the Ocean Shore State Recreation Area (per ORS 390) and has rules allowing for souvenir collection of natural products from the ocean shore, including agate, driftwood, and seaweed for personal enjoyment. For the personal harvest of wild kelp and other seaweeds, it is legal to harvest up to 2,000 wet pounds beginning March 1 and ending June 15, and no lease or permit is needed for personal use. There are also specific rules that pertain to the harvesting methods used (OAR 736-021-0090; ORS 274.895).

While there currently is no clear and transparent regulatory framework for in-water seaweed aquaculture defined by the State of Oregon, the administrative process is well defined for oyster aquaculture. ODA is assigned as the lead coordinating agency for shellfish aquaculture in the state, and at this time, the ODA Shellfish Plat Leasing Program is specific to only the mariculture of molluscan shellfish. Commercial shellfish cultivation on state-owned tidelands requires an ODA-approved application to lease the site (ORS 622.210-220), followed by a commenting period from federal and state agencies, tribal governments, NGOs, shellfish growers, and other interested parties. Several printed and online ODA resources give detailed instructions for this process (e.g., see the appendix). Shellfish cultivation is limited to preapproved areas regularly monitored by ODA to ensure water quality and seafood safety, as seen on the Oregon Explorer's Estuary Shellfish Mariculture Explorer. These preapproved areas have been historically evaluated to assess and characterize water quality conditions and pollution sources, which greatly simplifies and streamlines the permitting process (Lester et al. 2022).

Government policies that make licensing and permitting clear and streamlined—such as providing a lead agency and an identifiable contact—may help enable aquaculture development (Lester et al. 2022). Oregon lacks a lead agency with sole jurisdictional authority for all aquaculture, although the Oregon Aquaculture Association, Oregon Shellfish Taskforce, and members of the Oregon legislature have expressed support for assigning jurisdiction to ODA (Ehrhart and Doerr 2022), which would provide consistency with the state's existing shellfish aquaculture. Still, it may be possible under current DSL regulations to develop a pilot project in Oregon's marine waters, providing a road map for seaweed aquaculture under current regulations.

Product safety regulations

Seaweed is known to accumulate environmental contaminants, such as heavy metals, pharmaceuticals, pathogenic bacteria, and viruses (Banach et al. 2020; Focker et al. 2022). While beneficial for the surrounding environment, seaweed's bioremediation potential can be problematic when the harvested product is intended for commercial use (Znad et al. 2022). The levels and types of contaminants are highly site-dependent, and regulations for the maximum level of contaminants may be product-use specific (Lähteenmäki-Uutela et al. 2021). For example, seaweed cultivated for human consumption, animal feed, and fertilizer may have stricter regulations than those cultivated for use as textiles or biofuel.

Regulations for food processing, such as drying or creating value-added products, may apply to seaweed. At the 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 state 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). Potential hazards may include contaminants introduced during grow out, harvesting, packing, or storage phases. It is important to note that these requirements are only in place if the product is processed; fresh product going straight from farm to store or restaurant is exempt. The ODA is the lead state agency overseeing these hazard assessments. Overall, there is a need for data-driven guidelines and regulations on water quality standards and how to safely and properly handle postharvest seaweed products (Akomea-Frempong 2022).

Biosecurity and genetic diversity considerations

Enabling policies and 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). ODFW implements biosecurity regulations for Oregon's oyster aquaculture industry, and similar regulations may be applicable to seaweed. ODFW requires interstate and intrastate transport permits for oyster aquaculture activities, which involves obtaining approval from a certified shellfish pathologist to ensure oysters are free from diseases and pests before any transportation that involves placing oysters in state waters (OAR 635-005-0900; OAR 635-056-0075; OAR 635-005-0905).

Seaweed aquaculture regulations addressing environmental concerns may include the following: setting a maximum annual harvest of reproductive tissue, 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 grow out 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). Other states with more developed seaweed aquaculture industries have regulations that can be reviewed for applicability to Oregon. For example, the State of Alaska limits the transport of seaweed stock between farms, hatcheries, or acquisition sites to approved zones, and it requires parental plants to be collected within 50 km of the grow out location. Alaska also requires nurseries to source 50 separate parental blades each production season, which helps to safeguard genetic diversity (Alaska Department of Fish and Game n.d,). While this regulation limits the possibility of optimizing culture (e.g., temperature tolerance, increased yield), it may be necessary to maintain wild kelp populations. It is likely that legislation and regulatory requirements will adapt as science progresses towards safe breeding programs and the incorporation of sterile strains into practices for responsible seaweed mariculture (Coleman et al. 2022).

Public perceptions

Negative public perceptions of aquaculture can be a major challenge to the expansion of aquaculture industries (Knapp and Rubino 2016). Froehlich et al. (2017) compiled and analyzed information from over 60 nations on the public perception of aquaculture and found that negative sentiments can be based on misunderstandings and a lack of knowledge. While negative environmental impacts can occur, many can be mitigated with technological advancements and regulations promoting responsible farming methods (Naylor et al. 2021; Ehrhart and Doerr 2022).

In Oregon in particular, negative perceptions exist for finfish aquaculture due to past incidents in the state, though these sentiments may be less notable for non-fed species, such as oysters or seaweed (Hudson 2016; Ehrhart and Doerr 2022). Overall, informed dialogue on real risks is essential, and understanding existing perceptions can inform future approaches to public engagement (Hudson 2016; Froehlich et al. 2017).

Potential partners and key actors

Seaweed aquaculture's accessibility to new entrants is a key consideration for the industry's equitable growth in the Pacific Northwest. In Oregon, at the time of this report's publication, there is only one commercial seaweed producer and multiple seaweed aquaculture research and development projects. Also, several potential partners have expressed interest, either through informal dialogue, current projects, or formal surveys. Support from NGOs, investors, and policymakers will be critical in developing enabling conditions for sustainable and equitable industry growth.

Many Tribes and First Nations in the Pacific Northwest have engaged in diverse sea gardens and the sustainable harvest of wild seaweed for millennia. Some have recently expressed interest in seaweed aquaculture as an economic development strategy that is culturally and environmentally compatible

(T Waters, pers comm). Given their traditional knowledge and seaweed harvesting expertise, coupled with formal and informal co-management rights, Tribes and First Nations can offer critical partners and educators in helping the industry meet its restorative potential in Oregon and throughout the Pacific Northwest. At the same time, concerns have been expressed over large-scale extractive industries infringing on Indigenous rights, access, and well-being. Key next steps could include launching a feasibility analysis to determine the viability of small-scale local businesses, better understanding the impact of different support models for Indigenous communities to pursue seaweed aquaculture, and ensuring the incorporation of local interests and perceptions in decision-making.

Seaweed aquaculture could also be a diversification strategy for local fisherfolk or existing aquaculture producers seeking to expand their portfolios. Actors from these adjacent industries already have infrastructure and facilities, which may ease entry into the nascent seaweed industry. Polyculture and livelihood diversification can generate off-season revenue, provide year-round employment, and improve resilience to increasing socioeconomic and environmental change (O'Shea et al. 2019; Stoll et al. 2019). Indeed, the majority of current seaweed producers in the U.S. are fisherfolk, shellfish growers, or other seafood-related workers (Piconi et al. 2020).

Following this line of thought, researchers at OSU and ORKA (Figure 14) have partnered with members of the fishing industry to explore innovative kelp aquaculture projects, urchin ranching endeavors (read the case study), and kelp restoration work, as discussed earlier in this report. Additionally, an aquaculture assessment survey administered by Oregon Sea Grant revealed that oyster growers in the state are interested in growing seaweed and diversifying their crops (Ehrhart and Doerr 2022). Nonetheless, there are challenges associated with entering into a new industry, even for industry-adjacent actors, such as acquiring skill sets for different species and production systems and understanding the market landscape.

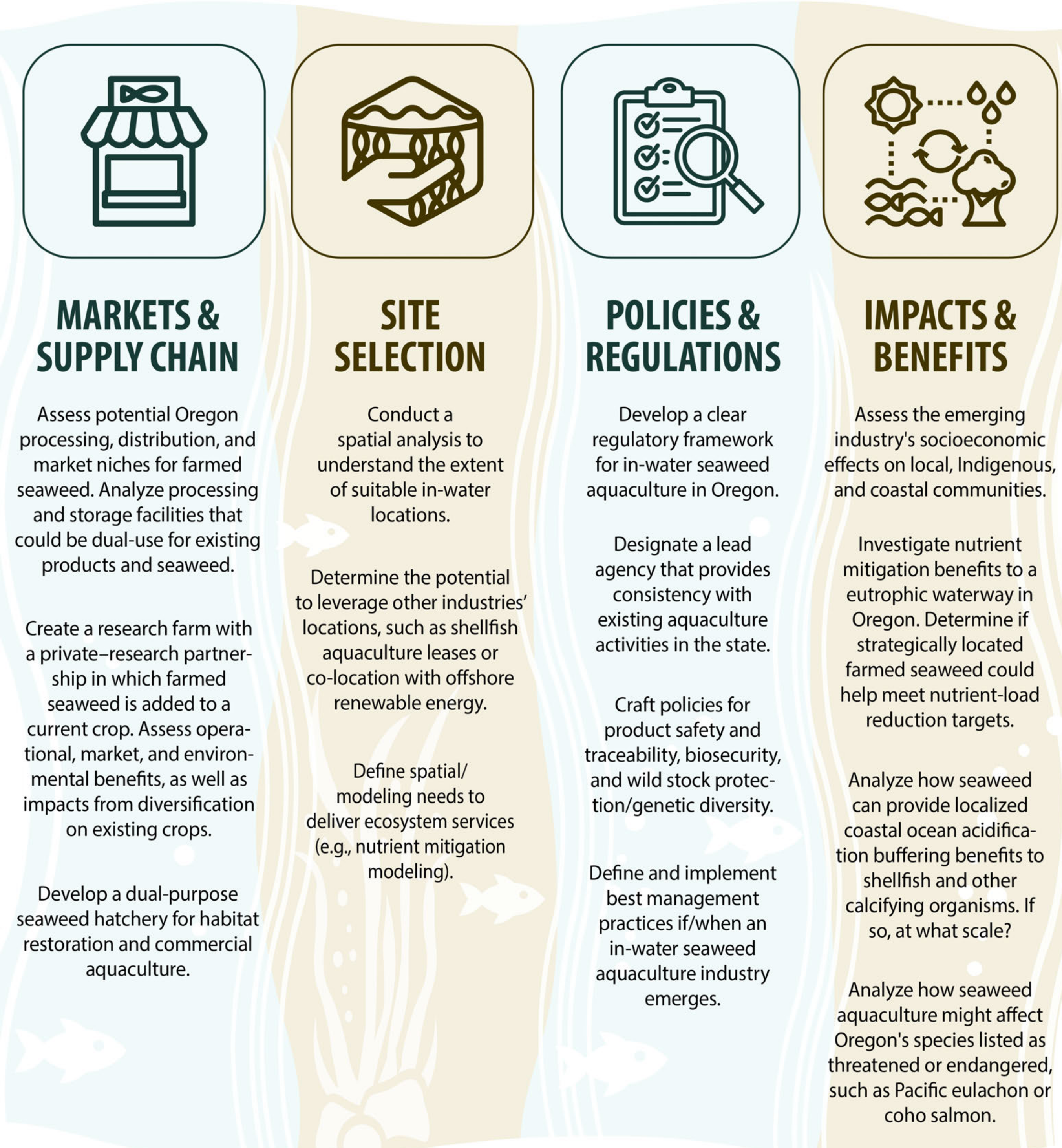
Figure 14. ORKA researchers in the field (photo by the Oregon Kelp Alliance).

It will be important for NGOs, investors, and policymakers to identify and support enabling conditions for locally accessible and sustainable seaweed aquaculture. As mentioned previously, enabling policies and programs may include making licensing and permitting more transparent and providing loans (Lester et al. 2022). Addressing public misconceptions about aquaculture will also be essential (Knapp and Rubino 2016). Developing principles, best management practices, and trainings can increase technical capacity and support sustainable industry growth (O'Shea et al. 2019; Waters et al. 2019). Additionally, working with financial institutions to recirculate investment in Oregon's coastal communities, reduce barriers to entry, and incentivize environmental practices will be critical next steps (Waters et al. 2019).

Conclusion

Decision-makers and other stakeholders have several steps (Figure 15) before them to realize a thriving industry that benefits farmers, adjacent industries, the ecosystem, coastal communities, and Oregonians more broadly. Some of the activities are already underway, or this report's project partners are exploring them.

Figure 15. Key next steps and needs for Oregon's emergent seaweed aquaculture industry.



Seaweed aquaculture is an emerging industry in the United States, and Oregon has been identified as one of the top marine ecoregions where seaweed aquaculture could be environmentally beneficial, socially acceptable, and economically viable (Theuerkauf et al. 2019). In strategically placed locations and with the right farm management practices, seaweed aquaculture can provide myriad benefits within the marine environment. Moreover, numerous respondents expressed interest in cultivating seaweed via an assessment survey for Oregon's aquaculture industry, with some referencing its restorative potential (Ehrhart and Doerr 2022).

In Oregon, all current seaweed farming uses land-based tank systems. Despite interest and high environmental and social potential for seaweed farming in this region, the industry has been slow to emerge. Its sluggishness is likely due to several challenges, ranging from limited markets to an ineffective policy and regulatory environment.

For seaweed farms across the U.S., tapping into markets outside human consumption can be difficult, particularly due to competition with low-cost wild seaweed harvested in the U.S. and low-cost farmed seaweed imported from Asian suppliers. Developing higher-value products, markets that can absorb large quantities of biomass, and/or methods for increased production will likely be necessary. Additionally, market outreach from state agencies or NGOs, combined with market pull from private companies, would greatly assist with opening sales channels and expanding opportunities.

While Oregon has limited supporting infrastructure for a seaweed aquaculture industry, opportunities do exist through several efforts on the coast. For example, ORKA has expressed interest in developing a hatchery that could serve a dual purpose for kelp restoration and aquaculture. Efforts are also underway through the OCVA and Ocean Cluster Initiative to create collective distribution systems for local seafood businesses and develop food hubs that provide storage and processing space for smaller-scale businesses.

Considerations for suitable locations within Oregon's estuaries include optimal tidal zone and salinity ranges for the chosen seaweed species, and whether the location avoids navigable areas and user conflicts. Entrants into the industry may also want to consider how they can leverage other industries' locations. Oyster growers interested in diversifying their crops may have an easier entry into seaweed aquaculture by using their existing leases. There may also be opportunities within nearshore, protected coves along Oregon's coast, particularly if the project goals include providing seedstock for kelp restoration. Co-location with offshore renewable energy platforms could be an opportunity for multifunctional use of space. Overall, an in-depth spatial analysis is needed to better understand the extent of suitable locations within Oregon's marine environment.

Under current legislation, in-water seaweed mariculture would require a DSL lease (OAR 141-082-0255). Changing the bureaucratic jurisdiction from DSL to ODA to develop regulations for seaweed aquaculture may provide consistency with existing aquaculture activities in the state. Other policy considerations include the development of regulations for product safety and traceability, biosecurity, and wild stock genetic diversity. Implementing a pilot seaweed farm could provide a regulatory road map and demonstrate the feasibility of these systems.

Lastly, socioeconomic impacts, climate, biodiversity, habitat, water quality, and broader ecosystem effects, both positive and negative, require further study, as seaweed farming operations do not have a significant history on the Pacific Northwest coast of North America.

As this report has made clear, many steps lie ahead for the development of a robust and sustainable seaweed aquaculture industry in Oregon. Partnerships between NGOs, farmers, industry, researchers, and policymakers have made this report possible and will likely be required for the future success of this emerging industry.

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Appendix: Shellfish Plat Leasing Program flowchart

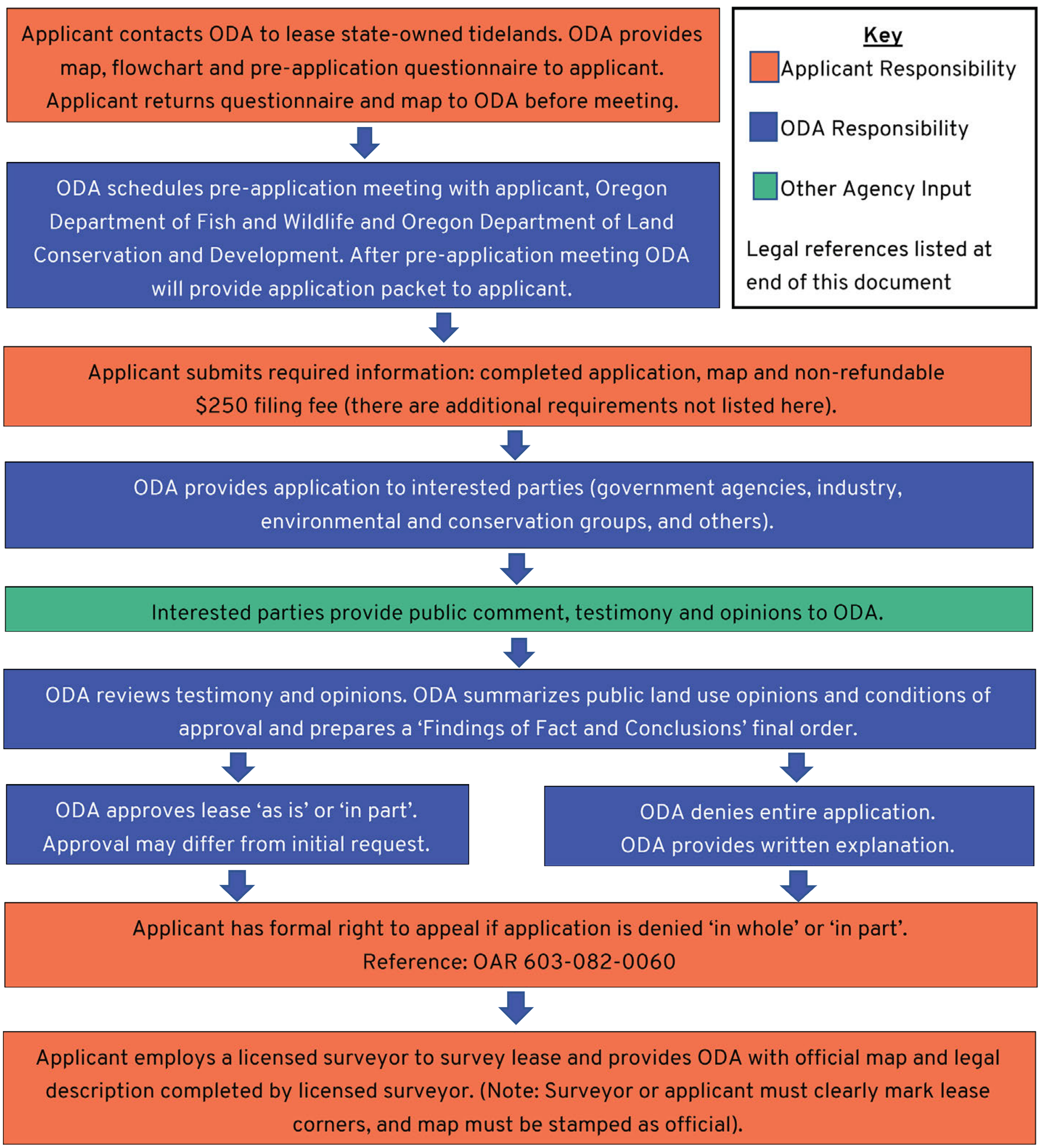
The following flowchart is from the Oregon Department of Agriculture (ODA; n.d.).

OREGON DEPARTMENT OF AGRICULTURE

Food Safety Program
635 Capitol St, NE, Salem, OR 97301-2532
503.986.4721 | Oregon.gov/ODA

Shellfish Aquaculture Leasing Process for State-Owned Lands

Note: Read this and the application instructions before completing plat application.



Food Safety Program
635 Capitol St, NE, Salem, OR 97301-2532
503.986.4721 | Oregon.gov/ODA

Final approval of lease may require County land use approval and other government agencies may add conditions of approval. (Note: some conditions of approval may have to be addressed prior to the issuance of approval called the 'Grant Certificate').

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If applicable, applicant demonstrates they have no outstanding issues related to lease approvals according to local ordinances.

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US Army Corps of Engineers evaluates your request for a Department of the Army permit for new or modified aquaculture operations in navigable waters of the U.S. (Note: ODA Director cannot approve final Grant Certificate without this permit).

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Grant Certificate is signed by ODA Director and issued to applicant.

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Applicant may begin aquaculture operations on lease plat according to the provisions of the Grant Certificate.

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Lease holder pays ODA quarterly fees for leasing state-owned lands. Lease holder must demonstrate active use and production in order to keep lease. Lease remains in effect indefinitely with no requirement to reapply unless applicant wishes to change terms of lease.

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Lease holder must obtain ODA Food Safety license prior to selling any shellfish commercially for human consumption.

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ODA may terminate lease for failure to pay quarterly lease fees or if holder does not actively farm the state-owned lease plat.

Legal References

ORS 622: Shellfish

OAR 603 Division 100: Shellfish Sanitation

OAR 603 Division 82: Oyster, Clam and Mussel Leases