

## Opportunities and challenges for Alaska kelp aquaculture

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**Abstract:** Kelp aquaculture is a nascent and growing industry in Alaska where cold, nutrient-rich, and clean waters result in high-quality biomass. There is considerable support from regional and federal initiatives to expand the blue economy sector, and in Alaska much of that support is focused on kelp and shellfish aquaculture. This paper reviews the opportunities, challenges, and ongoing research in three select topics that are key to sustainable industry expansion: (1) aquaculture site suitability, (2) ecosystem interactions with aquaculture, and (3) kelp stabilizing and processing. Regarding site suitability, there are ample opportunities for aquaculture expansion in the extensive coastal zone of Alaska, however low population densities and vast distances between inhabited communities result in infrastructure and logistical challenges for cultivating kelp and getting it to target markets. Investigations are underway that will inform optimized farm placement from both marine spatial planning and organismal physiology perspectives. Ecosystem interactions can constitute a service or a detriment depending on the nature of the interaction, which may also vary spatially and temporally. We are conducting research to understand how species of interest are interacting with kelp aquaculture and are developing *in situ* strategies to maximize benefits and regulatory efficiencies while minimizing interactions seen as harmful. Finally, stabilizing cultivated kelp in a cost-effective manner has proved challenging in Alaska's cold and wet climate. Research is underway to develop processing methods suitable to the climate and economies of Alaska, and local products are being developed to incorporate kelp into local manufacturing that may require less transport and stabilization. The expansion of the kelp aquaculture industry is full of exciting possibilities and formidable challenges. Knowledge exchange with regions that have mature kelp aquaculture industries, such as Japan, will likely aid in sector growth in Alaska.

**Key words:** Site suitability, ecosystem interactions, stabilization, processing

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### Introduction

Kelp aquaculture is an extremely new industry in the United States, especially when compared to countries such as Japan that have been consuming kelp for millennia and farming it for over half a century (Tanaka *et al.* 2020). Kelp are large, brown macroalgae in the Order Laminariales with a global temperate distribution. Millions of metric tons of two genera of kelp, *Saccharina* and *Undaria*, are commercially cultivated for food and other uses in China, Korea, and Japan (FAO 2024).

Cultivation efforts in the West are at a much smaller scale and farms can be found in the United States, Canada, Ireland, Faroe Islands, and Norway, among others (Canvin *et al.* 2025). The initial motivation for kelp aquaculture development in the United States was for energy production in the 1970s, with a focus on biomass cultivation for methane production (Kim *et al.* 2019). Attempts at cultivation for food production in the country are even more recent, with the first commercial farms becoming operational in the 2010s in the State of Maine (Kim *et al.* 2019). Attempts to commercially cultivate kelp in Alaska

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began with the first experimental operation in 2016. In the past decade, the industry in Alaska, Washington, and the U.S. Northeast, including Maine, has grown rapidly, in part due to federal and state investment in research and development.

The Alaska kelp industry has grown substantially in recent years, and it has benefitted from investments in research and development from state and federal sources. In 2014, the Alaska Fisheries Development Foundation received a Saltonstall-Kennedy Grant of \$217 thousand from NOAA Fisheries for the Alaska Mariculture Initiative, kick-starting the Alaska Mariculture Task Force through Governor Walker. In 2016, the U.S. Department of Energy Advanced Research Projects Agency awarded over \$3 million to the University of Alaska Fairbanks as part of the Macroalgae Research Inspiring Novel Energy Resources program to develop methods to scale up kelp cultivation for biofuel production (ARPAE 2025). This resulted in important innovations and jump-started the industry in Kodiak, Alaska. In 2022, the U.S. Economic Development Administration awarded a \$49 million grant to Southeast Conference, a regional economic development organization, to catalyze development of the kelp and shellfish aquaculture industry as part of the Build Back Better Regional Challenge grant competition (Alaska Mariculture Cluster 2025a). Concurrently, the Exxon Valdez Oil Spill Trustee Council awarded over \$32 million of grant funds over ten years to kelp and shellfish aquaculture research (EVOSTC 2022) and the State of Alaska developed a revolving loan fund for kelp and shellfish aquaculture operations to lower economic barriers to entry (AS 16.10.900). These investments, among other workforce development efforts, have resulted in substantial industry growth since the first kelp farm in 2015. In 2023, there were 30 kelp-only farms (out of 87 total aquatic farm operation permits) that were permitted and active during the year. Of that total, 15 kelp-only along with other multi-species farms, harvested a total of approximately 384,000 pounds, which was a decrease from 2022 when almost 872,000 pounds were harvested (ADFG 2025). Current market targets are human food, animal food, fertilizer and biostimulants, and commodity markets (biofuel, industrial additives).

Investment in and expansion of the kelp aquaculture industry has revealed important considerations in recent years, including where new farms should be sited and how to ensure environmental and economic sustainability. Kelp aquaculture operations must obtain leases and permits from local, state, and federal organizations and agencies with the goal of limiting negative or incompatible interactions with

other industries and navigation, and ensure compliance with laws such as the Endangered Species Act (16 U.S.C. 1531-1544) and the Magnuson-Stevens Fishery Conservation and Management Act (16 U.S.C. ch. 38 § 1801 et seq.). However, little research exists on kelp aquaculture, generally, and kelp aquaculture in Alaska, specifically, to aid in regulatory decision-making. Likewise, little guidance exists for farmers to aid them in selecting optimal sites to maximize both likelihood of permitting success and biomass quality for the desired markets. Access to non-local markets is likewise necessary and a challenge for industry growth given the remoteness and rainy climate of coastal Alaska. Despite these challenges, there remains immense opportunity for growth of this sector.

This paper examines the opportunities, challenges, and ongoing research of three of the major topics arising as the industry expands. The first is the question of site suitability, or where to put new farms to maximize success for the farmer. The second is how to ensure environmental sustainability by improving our understanding of ecosystem interactions, and therefore compliance with aforementioned federal laws. The third is how to most efficiently stabilize and process cultivated kelp to best access non-local or year-round markets. This topic list is non-exhaustive and the three were selected based on extensive conversations with industry and regulators, as well as the authors' personal observations.

### Site suitability

Kelp aquaculture is limited to the coastal Gulf of Alaska where sea ice does not form. This vast area includes over 50,000 km of coastline with limited coastal development and low human population densities. Coastal Gulf of Alaska is a geologically diverse and highly biologically productive region. Areas with aquaculture operations vary from exposed, marine habitats, most commonly found around the Kodiak Archipelago or outer coast of Southeast Alaska, to sheltered coves or inlets that can vary from marine to brackish. Farms in Kachemak Bay, Prince William Sound, and parts of Southeast Alaska can also be influenced by glacial runoff. This vast area and variability creates opportunities and challenges for siting kelp farms.

#### 1. Opportunities

Low population densities and limited industrial and agricultural activities limit sources of potential anthropogenic terrestrial pollutants that could enter the nearshore realm

and influence farming activities. Surveys by the Alaska Department of Environmental Conservation (ADEC) consistently find bacterial and heavy metal levels to be well below regulatory thresholds in sites where monitoring occurs (ADEC 2024). Nearshore nutrient concentrations, necessary for kelp growth, are consistently high during winter and spring before massive phytoplankton blooms reduce summer nutrient concentrations in most nearshore areas (Cates *et al.* 2025; Weingartner *et al.* 2009). While lower-latitude states on the U.S. West Coast have observed significant declines in wild kelp biomass and canopy cover in the past few decades, kelp populations in Alaska remain robust (Berry *et al.* 2021; Hollarsmith *et al.* 2024; Nicholson *et al.* 2024). Stable wild kelp populations are both an indication of suitable environmental conditions for kelp growth, and they are necessary for the industry as kelp spores must be collected annually from within 50 km of the farm site to seed it out (Gruenthal and Habicht 2022).

## 2. Challenges

While the remote nature of coastal Alaska can mean limited input of anthropogenic nutrients and contaminants, it also presents logistical and workforce challenges. Many kelp farms are in sites or communities that are not connected to the broader road system so materials and harvested biomass must be shipped in or out via boat or plane, which is often a costly endeavor (State of Alaska Geoportal 2025). Likewise, small and isolated communities can result in workforce challenges, especially with the seasonal nature of kelp aquaculture (Alaska Sea Grant 2023). Despite low population densities and vast distances, there are many uses of the nearshore zone which permitted farms must be compatible with. These uses include commercial fisheries, tourism, subsistence harvests, military operations, navigational channels, among other potential uses that permitting agencies must consider. Ecological interactions are also considered, including marine mammal migration corridors and feeding grounds, fish spawning areas, Essential Fish Habitat, and other interactions with endangered or protected species (Schillaci *et al.* 2025). The oceanographic diversity of the nearshore zone of the Gulf of Alaska, including variations in exposure, salinity, temperature, and nutrient concentrations, means different sites are likely more suitable to some kelp species over others.

## 3. Research

Research to aid in site suitability falls broadly into two categories: determining where it makes logistical sense to site

farms and investigating how potential farm production may vary across different oceanographic contexts. Regarding logistical considerations, the National Oceanic and Atmospheric Administration (NOAA) is identifying Aquaculture Opportunity Areas (AOAs) in Alaska in partnership with the State of Alaska (Schillaci *et al.* 2025). AOAs are defined geographical areas that may be suitable for commercial aquaculture development based on economic, environmental, and social considerations. To identify these areas, NOAA solicits extensive public input, conducts spatial suitability modeling that includes multiple data layers of other uses of the nearshore zone that may be fully or partially incompatible with aquaculture, and conducts an environmental review through the National Environmental Policy Act (NEPA). Suitability modeling in Alaska also includes logistical considerations such as proximity to population centers, ports, and processing infrastructure. One of the resulting products will be a peer reviewed atlas with geospatial planning information and maps that identify areas of higher and lower suitability for aquaculture. This will be one source of information to assist NOAA and the State of Alaska in developing alternatives for consideration in the NEPA process.

There are also multiple research efforts completed or underway to better understand where to site farms from a species perspective. The Mariculture Research and Restoration Consortium (Mar ReCon) is a multi-partner research group funded by the Exxon Valdez Oil Spill Trustee Council. Researchers within the consortium include state and federal agencies, a non-governmental and non-profit regional science center, academic institutions, and an Alaska Native tribe. The aim of the consortium is to better understand how aquatic farms interact with the surrounding environment and biological communities across the diverse oceanographic and ecological conditions found in the areas impacted by the 1989 Exxon Valdez oil spill, namely Prince William Sound, Kachemak Bay, and the Kodiak Archipelago (PWSSC 2025). Where relevant, results will be incorporated into the permitting process to minimize negative ecological interactions and maximize ecosystem services. Studies within this consortium also investigate regional variation in farm production to improve understanding of how the productivity and tissue chemistry of cultivated kelp and oysters are influenced by oceanography. These results will aid current and prospective farmers in selecting sites to maximize the traits and growth rates they desire in their products. Research has also revealed how differences in seawater nitrogen can impact kelp farm productivity. The authors concluded that sites should be

selected where the total seawater nitrogen does not dip below 0.6-1.0  $\mu\text{M}$  during the farming season and if a site does experience seasonally reduced nitrogen levels, the farmer should increase the spacing between the grow lines to maximize the flow and nutrient transfer (Stephens *et al.* 2024).

Additional research is underway to optimize farm design for a given site, species, and desired morphology. Bull kelp (*Nereocystis luetkeana*) is of particular interest given the diverse morphological forms it can take, and it is being coordinated by the Bull Kelp Research Squad (BKRS 2025), a group of growers and researchers with the shared goal of improving methods for growing this locally valuable species that is endemic to the northeast Pacific. Other projects focusing on growing methods tailored to specific site conditions include focusing on optimizing line spacing, depth, and orientation, exploring the down-stream effects of hatchery conditions, and the effects of combining species of different morphologies (e.g. floating and non-floating) within the same farm site (Alaska Mariculture Cluster 2025a).

### Ecosystem interactions

Alaska's aquatic farms are indelibly connected to the nearshore environment where they have the potential to interact with and be influenced by the surrounding flora and fauna. The nearshore zone provides nursery habitat for juvenile phases of economically important fish and invertebrate species, including the Pacific halibut (*Hippoglossus stenolepis*), walleye pollock (*Theragra chalcogrammus*), Pacific cod (*Gadus macrocephalus*), Pacific herring (*Clupea pallasii*), Pacific salmon (*Oncorhynchus* spp.), Dungeness crab (*Metacarcinus magister*), and king crab (*Paralithodes camtschaticus*), among many other species (Johnson *et al.* 2003). It also serves as a migration and feeding ground for multiple species of whales and pinnipeds, all protected under the Marine Mammal Protection Act (16 U.S.C. 1361-1407). Regulators recommend siting farms away from known Essential Fish Habitat (16 U.S.C. ch. 38 § 1801 et seq.), biologically important areas, and Pacific herring spawning locations, among other biological and physical siting considerations. However, much remains unknown about how these species may interact with aquaculture infrastructure and where these species are distributed in Alaska's vast coastline. Likewise, evidence suggests that kelp farms may provide valuable habitat for some organisms, therefore aquaculture siting could be done in a way that maximizes these

ecosystem services (Theuerkauf *et al.* 2022).

### 1. Opportunities

Kelp aquaculture introduces complex midwater structures that may serve as a source of food and shelter for benthic and midwater fish and invertebrate species, especially during vulnerable early life stages. A meta-analysis of available literature found that seaweed farming was associated with a small increase in wild fish and mobile invertebrate abundance and a large though variable increase in species richness (Theuerkauf *et al.* 2022). Notably, the meta-analysis included mainly tropical seaweed farms, which highlights the dearth of ecological studies on temperate kelp aquaculture. In Alaska, kelp is usually harvested in the late spring which can coincide with the timing of salmon outmigration into the nearshore, the presence of schooling fish species such as Pacific herring, and the post-settlement juvenile phases of gadids and crabs (Laurel *et al.* 2016; Park and Shirley 2008; Vulstek *et al.* 2024). More information is needed to understand the true spatial and temporal overlap of kelp aquaculture and these organisms and the impact of harvest on the survival and distribution of these species. At the time of writing, the authors could find no evidence from published literature or other data sources of instances of negative interactions between kelp aquaculture and protected species, such as marine mammals, though reporting requirements differ widely between countries and regions. A risk assessment conducted by the Australian Seaweed Institute and based on best available data determined the risk of negative impacts from the kelp farm to habitat or protected species to be low to negligible (Kelly 2023).

Aside from potential ecosystem services of habitat provisioning and food, there is interest in the potential of kelp farms to capture and store carbon, thereby creating local refugia from ocean acidification and potentially reducing atmospheric CO<sub>2</sub> levels. A recent field study of multiple seaweed farm sites around the world found that organic carbon stocks beneath the farms was positively correlated with farm age, suggesting that burial and storage of carbon was occurring. The authors concluded that these farm sites act similarly to Blue Carbon habitats (Duarte *et al.* 2025). Experimental studies have also found that the commonly cultivated sugar kelp (*Saccharina latissima*) removed measurable levels of dissolved inorganic carbon and altered pH and saturation state, and this effect increased as CO<sub>2</sub> levels increased, suggesting this species has a high potential for creating local refuges from low-pH conditions (Ricart *et al.* 2023).

## 2. Challenges

While hypotheses on ecosystem interactions can be formed based on existing researchers, the fact remains that the available data are obtained from studies conducted in environments and ecosystems outside of Alaska and often based on growing methods that differ from the preferred catenary array design often used on Alaska farms, a design that maintains all grow lines at high tension. Alaska is also home to a particularly high concentration of protected species, including whales, seabirds, and pinnipeds (Young *et al.* 2024). This may increase opportunities for negative interactions, such as gear entanglement, though the authors could find no reports to date of any instances of entanglement in the region or outside. There is one record of a potentially negative ecological interaction with a fish species when a Southeast Alaska farm experienced a mass spawning event of Pacific herring. Alaska regulations prohibit the harvest of kelp if herring have spawned on the farm. The result was an almost complete loss of crop for the farmer, and further monitoring of the site by farm staff suggested low hatch rates of the herring eggs (Hollarsmith *et al.* 2025). Pacific herring numbers remain high in coastal Alaska and herring can shift their spawning grounds unpredictably, introducing the chance for additional interactions between farms and spawning fish.

## 3. Research

Research is underway to address known challenges, such as methods to deter Pacific herring from spawning on kelp farms, and to improve understanding of general interactions with surrounding flora and fauna. Using captive herring, researchers tested the effects of various deterrent strategies focused on the fish's behavior, including bubble curtains, active acoustics, strobing lights, and moving and suspended mid-water objects. Of all methods tested, only the bubble curtain had a deterring effect on the fish. This method mimics the predation strategy of humpback whales, a major predator of herring in Alaska (Hollarsmith *et al.* 2025). The logistics of installing this type of technology onto remote farms is considerable, so research efforts are ongoing to optimize these methods. Various projects are also underway to record species use of kelp farm infrastructure and how that use differs seasonally and across regions. The Mar ReCon project includes various monitoring efforts to track species presence or absence around farm sites, including marine birds, pinnipeds, mid-water and benthic fish, and benthic invertebrates, focusing on Southcentral Alaska and using primarily visual boat-based or SCUBA techniques, with some

acoustic monitoring in select sites (PWSSC 2025). Researchers in this consortium are also investigating the carbon dynamics inside and outside of farm sites to assess whether the carbon uptake rates and ocean acidification amelioration reported from other areas is present in the highly tidal and dynamic oceanographic context of Southcentral Alaska. In Southeast Alaska and the Kodiak Archipelago, NOAA's Alaska Fisheries Science Center researchers are using visual surveys and environmental DNA to assess species use of kelp farms in the inner waterways. Results from all efforts will aid in permitting and siting to enhance positive ecosystem services and minimize negative ecosystem impacts.

### Kelp stabilizing and processing

Cultivated kelp degrades rapidly after harvest, requiring harvesters and processors to stabilize the kelp in order to bring it to market in sufficient quantity and quality. Freezing and drying are currently the two primary stabilization methods for processing kelp in Alaska (Good *et al.* 2021; Serin 2024). Stabilizing cultivated kelp in a cost-effective manner has proved challenging in Alaska's cold and wet climate, and it is a major industry concern (Carovano *et al.* 2025). Cold-chain export of frozen kelp is an expensive shipping option, and drying kelp is extremely energy-intensive in a region with high energy and operational costs (McDowell Group 2017). Without preparation methods suitable for Alaska's often remote coastline and high energy costs, Alaska's kelp industry is at an economic disadvantage to other kelp growing regions. Providing kelp farms in Alaska with affordable and innovative stabilization technology is key to extending the shelf life of their product and increasing access to markets.

### 1. Opportunities

Alaska offers numerous processing opportunities for cultivated kelp including developing new products, leveraging existing seafood processing infrastructure and workforces, and exploring specialized markets. Currently, most cultured kelp in Alaska is sold into minimally processed whole food markets but there is potential to capitalize on more specialized markets such as food additives, cosmetics, dietary supplements, animal feeds, and biostimulants (Serin 2024). Potential synergies with existing seafood processing infrastructure may prove important to the industry's development. Repurposed fish-processing facilities and other uses of pre-existing infrastructure during the kelp harvest season align with the off-season of other fishing industries and

can provide freezer space and resources, including labor, to process cultivated kelp (Good *et al.* 2021). Cost structures and distance from markets limit current opportunities, but it may be offset by technological innovation, coordination among growers and markets, and other opportunities to share costs and pool resources (Carovano *et al.* 2025; Serin 2024). Local Alaskan start-ups prioritizing direct sourcing of kelp from farmers to produce kelp-based products have successfully tapped into local, online, and wholesale markets (i.e. Barnacle Foods and Kachemak Kelp Hub). These businesses are orientated around small volumes of seaweed processed into an evolving line of specialty food products.

## 2. Challenges

There are significant challenges that farmers face to access markets including high perishability of kelp, high energy and operational costs, and distance to market (Barnacle Foods and Spruce Root 2025). Kelp stabilizing in many regions, including Japan, relies on manually laying kelp on shorelines and drying from the sun (N. Yotsukura, Hokkaido Univ., Japan, personal communication). The large biomass, cost of labor and wet climate of coastal Alaska make this an unfeasible option and energy costs for non-solar drying are too high in many areas to be cost-effective without further innovation. Each coastal community in Alaska often operates on its own electrical grid, with varying energy sources including diesel which are expensive to operate (U.S. Energy Information Administration 2024). The cost of energy can thus impact the types of processing techniques that are feasible for individual farms. Cold chain export in order to access out-of-state or otherwise non-local markets can be cost-prohibitive. Alaska has few dedicated kelp processing facilities, making it difficult and expensive to handle the large volume of kelp produced, and the lack of local processing facilities can lead to increased transportation costs and time delay. As the kelp aquaculture industry in Alaska continues to grow, developing efficient, cost-effective processing systems will be key to increasing kelp's marketability and reducing operational costs. However, several key factors, including high energy costs, remote geographic locations, and labor constraints must be taken into account when selecting equipment.

## 3. Research

Research is underway to develop processing and stabilizing methods suitable to the climate and economies of Alaska. Investments into processing technologies have increased

greatly and include an on-water mobile seaweed processor, an open-source primary processing line, and a kelp processing facility housed in a freight container. New processing technologies highlight innovative mobile designs that can be deployed in rural Alaskan communities and/or affordable stabilization technology. Recent testing of kelp stabilization methods include fermentation, bioactive compound extractions, high pressure processing, freeze drying, high-tunnel drying, and creating intermediate stabilized “slurries” (Alaska Mariculture Cluster 2025a). Additionally, new species are being grown and products are being developed to incorporate kelp into local manufacturing chains that may require less transport and stabilization, and expand upon existing markets (i.e. Kachemak Kelp Hub).

Additional research is being conducted to improve understanding of kelp nutritional value and bioactive compounds as these can vary depending on kelp species, life history, tissue type, season, and environmental conditions (Jardell 2024). Improved understanding of seaweed tissue has many benefits. It can support product innovation, diversify income streams, enable processors to refine extraction techniques for high-value compounds, inform future seaweed farming and harvesting strategies, establish industry standards for seaweed quality and composition, and attract investment and market interest (Alaska Mariculture Cluster 2025b).

## Conclusion

Despite considerable challenges, the opportunities and potential remain high for growing a successful kelp aquaculture industry in Alaska. Research is underway that will help to determine where future farms should go from both a logistical and organismal perspective. Ecosystem interactions are a major regulatory concern and research efforts are beginning to fill knowledge gaps in how kelp aquaculture interacts with nearshore flora and fauna. Finally, cost-effective methods to stabilize kelp and improve access to markets are a high priority for the industry. Continued collaborations with other kelp-growing regions in the U.S. and the world, such as Japan, will aid Alaska in overcoming challenges and seizing opportunities for industry growth.

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