Cultivating with Care

Environmental Effects and Monitoring Indicators for the Seaweed Farming Sector in Alaska and British Columbia

Volume 1 - Science Synthesis

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The Alaska Fisheries Science Center conducts research and monitoring to support the sustainable management and conservation of marine life, habitats, and fisheries across Alaska's vast ocean waters. It provides scientific information, including strategic research on shellfish and seaweed aquaculture, to inform policy, regulatory agencies, and coastal communities, helping ensure environmentally and economically sustainable development of marine resources, including providing technical expertise for this report. The conclusions and any views or opinions expressed herein are those of the author and do not necessarily reflect those of NOAA or the U.S. Department of Commerce. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U. S. Government.

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Cover Photo: Photo Courtesy of Alaska Mariculture Alliance

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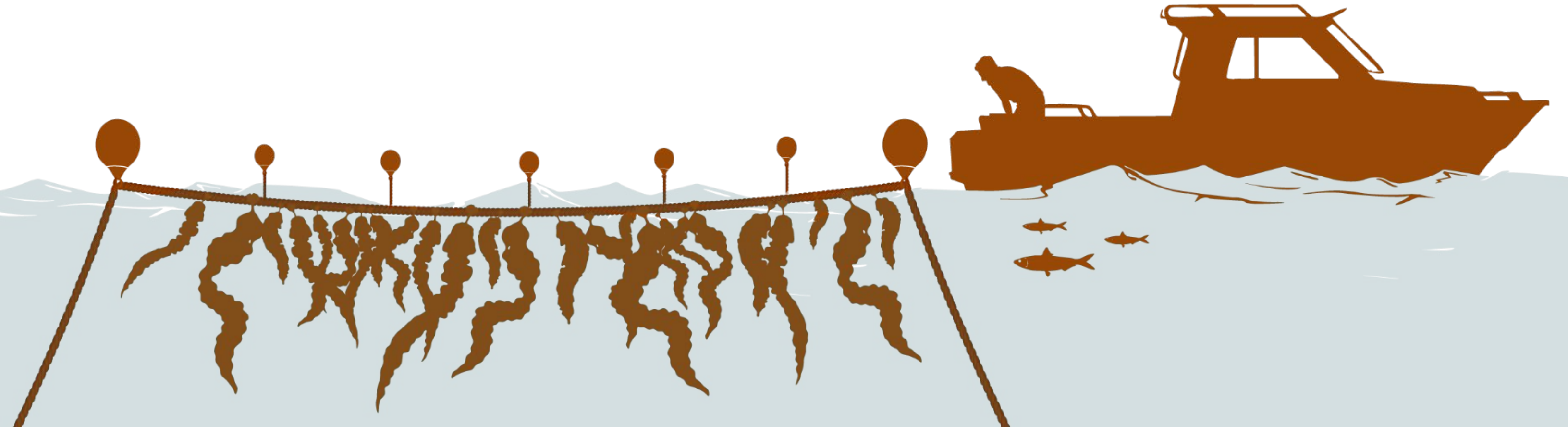


Executive Summary

Overview

Seaweed farming is expanding rapidly across North America and globally in response to growing interest in food production, bioproducts, ecosystem services, and coastal economic development. As the industry grows, so has interest in understanding and monitoring the environmental interactions and effects associated with seaweed cultivation. However, monitoring approaches remain highly variable across regions, farm types, regulatory systems, and operational contexts. Many potential environmental interactions are also highly site- and scale-dependent, and available scientific evidence remains uneven across indicators and farming conditions. In Alaska and British Columbia, growing interest in seaweed farming—alongside evolving regulatory frameworks and long-standing Indigenous stewardship—presents an opportunity to better understand how environmental interactions may occur, what information already exists to describe them, and where important uncertainties remain as the sector develops.

This report synthesizes scientific literature, expert input from 34 workshop participants, and 34 interviews with farmers, regulators, researchers, and Indigenous community members to evaluate environmental monitoring indicators relevant to seaweed farming in Alaska and British Columbia. The synthesis is intended to inform monitoring discussions and program development—not to prescribe monitoring requirements, establish regulatory standards, or define baselines for responsible development.

This report brings together, for the first time in this region, a systematic evaluation of environmental indicators tailored to Alaska and British Columbia. It identifies and evaluates 38 candidate indicators drawn from the scientific literature and practitioner input, scoring each against a common set of criteria to characterize how well each indicator is supported by current regional evidence and practitioner experience. It then shows how the indicators can be applied in practice and connected to real decisions across the farming life cycle. The work is set within a broader picture of the sector's regional context, the current state of environmental knowledge, and the trends likely to shape monitoring needs as seaweed farming grows. This is Volume 1 of a two-part report; Volume 2 (Monitoring Indicator Factsheets) takes each indicator evaluated here and translates it into a standalone factsheet — covering rationale, scoring, methods, and existing data — for direct use by farmers, regulators, researchers, and other practitioners.

This report draws primarily on Western scientific literature and practitioner input, and it does not evaluate the many social, cultural, and economic dimensions of seaweed farming that also inform monitoring and decision-making. Indigenous Nations have stewarded these coastal waters and seaweed resources for millennia, and Indigenous Knowledge systems and governance are foundational—not supplementary—to monitoring and

Photo Courtesy of Alaska Mariculture Alliance managing them. This report is therefore offered as one contribution within a broader body of work, intended to sit alongside Indigenous-led, community-based, and place-specific efforts already shaping the future of the sector. It does not assess the feasibility or appropriateness of implementing any given monitoring indicator in a particular place, including considerations such as capacity, funding, consultation with rightsholders and stakeholders, or weaving of Western and Indigenous Knowledge systems.

Intended Use and Audience

This report is designed as a flexible reference tool to support monitoring discussions in Alaska and British Columbia. It may be useful to a wide range of audiences, including seaweed farmers and industry organizations, regulators and permitting agencies, Indigenous Nations and stewardship initiatives, researchers and monitoring practitioners, certification bodies and sustainability initiatives, and organizations evaluating environmental performance or funding seaweed-related projects.

The report may also help identify areas for future research, monitoring coordination, methodological development, and adaptive governance as the regional seaweed farming industry continues to develop.

Any future policy or regulatory recommendations would need to be developed through separate, collaborative processes that build on this scientific work and should proceed in parallel with Indigenous-led and community-based efforts, rather than being implied by this report. In governance contexts where monitoring priorities are defined collaboratively, the indicators described in this science synthesis may be adapted, supplemented, or interpreted differently to reflect cultural, social, or place-specific priorities that are not evaluated in this report.

Key Findings

1. **Site selection is the single most important preventative tool for managing environmental effects**

   Across interviews and workshops, practitioners consistently identified site selection as the most important factor determining whether environmental effects occur. Many potential effects can be addressed with careful planning and site suitability assessments before farming begins rather than through extensive downstream monitoring requirements. Existing permitting processes in Alaska and British Columbia already incorporate precautionary siting measures intended to avoid sensitive habitats and reduce interactions with wildlife.

2. **Some environmental effects are more likely than others, but distinguishing farm effects from natural variation remains difficult**

   The 38 environmental indicators were sorted into three groups: well-supported effects commonly observed at farms, raised by stakeholders, and supported by the literature (Group A); partially-supported effects observed in some cases but not extensively monitored (Group B); and limited-support effects that remain largely hypothetical for this region, with less stakeholder discussion or associated literature (Group C). How likely an effect is to occur, based on the current state of knowledge and literature, was the strongest factor separating these groups. However, across all indicators, reliability for predicting causality and robustness (i.e., how consistently a signal can be detected amid natural noise) scored lowest – and for several indicators, there simply isn't enough information yet to know how likely an effect is or how reliably it could be attributed to farming.

3. **Relevant data exists – but rarely where farms are, or for the questions farms raise**

   Part of what makes farm effects hard to attribute at present is that most available baseline data was collected for other purposes rather than farm-oriented monitoring efforts. Existing regulatory programs, baseline datasets, marine spatial planning, Indigenous stewardship, and routine farm observations all gather information on many of these indicators — but often not to understand farm effects, not at the scales at which farms operate, and not in the places where farms are located. As a result, existing data sources are a valuable starting point, yet frequently cannot be used to show whether a farm is causing change, even for well-studied indicators, because the data near farms was rarely designed to separate a farm's influence from natural variation. Closing that gap will require fit-for-purpose monitoring data collected at farms, alongside comparison sites, and designed around farm-effect questions.

4. **Monitoring needs depend strongly on context, scale, and purpose**

   What to monitor, and how intensively, therefore depends on the questions being asked, the scale of farming activity, local environmental conditions, available resources, and the intended use of monitoring data. Some indicators are most useful for farm-scale operational management, while others may be more relevant for regional planning, cumulative effects assessment, scientific research, or policy development. Monitoring approaches vary substantially in complexity and intensity—from simple observational methods to specialized, long-term, or technically intensive analyses. This report emphasizes proportional and context-dependent monitoring approaches rather than uniform monitoring expectations across all farms and regions.

5. **Effective monitoring must be both feasible and shared across actors**

   Because seaweed farming in Alaska and British Columbia is an emerging sector, often operating on narrow margins and in remote locations, the practicality of monitoring matters as much as its scientific value, and poorly targeted monitoring carries real financial and logistical costs. No single actor can carry it alone: monitoring is most durable when simple, standardized field sampling is folded into farm routines and the analytical work is shared across farmers, governments, researchers, communities, and Indigenous Nations, drawing on both Western science and Indigenous Knowledge in complementary ways.

6. **Monitoring approaches will need to evolve alongside the industry**

   As seaweed farming expands in scale, geographic extent, and market diversity, monitoring priorities and information needs will likely continue to evolve. Future monitoring efforts may increasingly focus on cumulative effects, climate-related interactions, ecosystem-scale processes, product quality and traceability, and social and ecological considerations. Meeting these needs will require building on existing regional baseline information and monitoring approaches, and developing farming-specific long-term datasets and standardized monitoring methods that allow data to be compared across sites and scaled up to regional or cumulative effects. These efforts will depend on sustained collaboration among farmers, Indigenous Nations and communities, regulators, researchers, and industry organizations, which will be important for refining indicators, improving monitoring consistency, and supporting adaptive management over time.

Taken together, these findings offer something that did not previously exist for Alaska and British Columbia: a single, region-specific picture of what is known about the environmental effects of seaweed farming, what remains uncertain, and where monitoring can add the most value. It is meant as a shared starting point—one that farmers, communities, regulators, researchers, and Indigenous Nations can build on as the sector, and the science behind it, continue to grow.

All materials associated with this report are available for download from: http://pew.org/CultivatingWithCare

Glossary

Adaptive management	An approach in which management actions are adjusted over time in response to monitoring results, experience, Indigenous Knowledge, and other sources of new information.
Baseline	Information describing environmental conditions before a change occurs providing a reference for identifying impacts.
Benthic	Relating to the seabed or to organisms that live on, in, or close to the bottom.
Biodiversity	The variety of living organisms in an area, including variation among species, habitats, and genetic characteristics.
Biofouling	The growth or accumulation of organisms such as algae, mussels, barnacles, or tunicates on farmed seaweed, ropes, buoys, and other submerged structures.
Biosecurity	Practices intended to prevent the introduction or spread of diseases, pathogens, pests, and invasive species.
Biomass	The total amount or weight of living material in a particular area or sample.
Carrying capacity	The amount or intensity of a species or activity that an area can support without unacceptable effects on environmental conditions or ecosystem processes.
Causal relationship or causality	Evidence that an observed environmental change was caused by the activity of interest, rather than by natural variation or another human activity.
Co-governance	A government-to-government arrangement in which Indigenous Nations and other governments share responsibilities and decision-making for the stewardship or management of lands, waters, or resources.
Cumulative effects	The combined effects of multiple activities or environmental pressures over space and time.
Dissolved oxygen (DO)	Oxygen mixed into the water and available to fish, shellfish, plants, and other aquatic organisms.
Environmental DNA (eDNA)	Genetic material released by organisms into water or sediment.
Environmental indicator	A measurable feature, condition, or process used to describe environmental status, detect change, or assess a potential effect.
Environmental monitoring	The repeated collection and evaluation of environmental information to understand conditions, detect changes, and support decisions.
Epibiota	Organisms that live attached to, or on the surface of, another organism or submerged structure.
Epibenthic	Organisms living on the top surface of the sea floor rather than burrowing into the sediment.
Eutrophication	Excessive nutrient enrichment of water, which can stimulate algal growth and sometimes contribute to low oxygen, harmful algal blooms, or other ecosystem changes.
Gametophyte	The reproductive stage of a seaweed's life cycle that produces eggs or sperm. In kelp aquaculture, microscopic gametophytes may be maintained in culture to produce seedlings for farming.
Genetic diversity	The variety of inherited characteristics within a species or population. Genetic diversity can help populations adapt to changing conditions.
Group A, B, or C (indicator groups)	A classification of the 38 environmental indicators in this study based on their combined score across 9 evaluation criteria (maximum 27). Group A indicators scored highest (≥20), reflecting effects that are commonly observed at farms, well-documented in the literature, and of strong interest to stakeholders; Group B scored moderately (15-19); and Group C scored lowest (<15), often reflecting less evidence or stakeholder attention rather than lower ecological importance.
Hydrodynamics	The movement of water, including currents, tides, waves, mixing, and circulation.

Indigenous Knowledge	Knowledge, practices, and ways of understanding developed by Indigenous Nations through long-term relationships with their lands, waters, and cultures. In this report, Indigenous Knowledge is recognized as an important source of information that can inform environmental stewardship, monitoring, and decision-making alongside other knowledge systems.
Indigenous Nations	In this report, the term Indigenous Nations is used to refer collectively to Indigenous governing entities in British Columbia and Alaska when a discussion applies broadly across both regions.
Invasive species	A species introduced outside its natural range that spreads and causes, or has the potential to cause, ecological, economic, cultural, or social harm.
Macroalgae	Large algae that can generally be seen without a microscope. Seaweeds, including kelps and nori, are macroalgae.
Marine debris	Human-made material that is lost, discarded, or abandoned in the marine environment, including ropes, nets, floats, plastics, and damaged farm equipment.
Marine Stewardship Council	An international organization that assesses and certifies fisheries and aquaculture operations as sustainable operations.
Microplastics	Plastic particles less than 5 millimeters in size that may originate from the breakdown or wear of larger plastic items, ropes, coatings, or other materials.
Monitoring strategy	An overall plan that identifies what information is needed, who will use it, and how results will inform decisions.
Ocean acidification	The long-term reduction in seawater pH caused mainly by the ocean absorbing carbon dioxide from the atmosphere.
Organic matter	Material derived from living or formerly living organisms, such as seaweed fragments, animal waste, or decaying tissue.
Ocean observing system (OOS)	Networks of oceanographic and water quality sensors across coastal waters that collect baseline environmental data on ocean conditions for a broad range of purposes. There are many regional OOS networks, including the Alaska Ocean Observing System (AOOS) and Canadian Integrated Ocean Observing System (CIOOS) Pacific in this region.
Outplant	To move a growing plant or organism from a protected indoor space (e.g., nursery) and place it into an outdoor environment or the wild.
Pathogen	A virus, bacterium, fungus, parasite, or other biological agent capable of causing disease.
Pelagic	Relating to the open-water column, rather than the seafloor or shoreline. Pelagic fish live and move primarily within this water column.
pH	A measure of how acidic or alkaline water is. Lower values are more acidic, higher are more alkaline.
Salinity	The concentration of dissolved salts in water. Salinity varies with freshwater input, evaporation, tides, and water circulation.
Sampling design	The plan for deciding where, when, how often, and how many times measurements or samples will be collected so that the resulting data can answer a specific question.
Seed source or seed sourcing	The specific geographic location, individual seaweed, or group of seaweeds (i.e., a kelp bed) from which sori are collected for propagation and outplanting.
Turbidity	The cloudiness of water caused by suspended particles such as sediment, plankton, or organic material. High turbidity reduces light penetration.

Note to Readers

This report synthesizes scientific literature and practitioner input to describe environmental monitoring indicators relevant to seaweed farming in Alaska and British Columbia. It is intended to be a science-based reference, not a monitoring standard. The synthesis draws on published research, an international expert workshop involving 34 participants, and 34 practitioner interviews with regulators, researchers, Indigenous community members, NGOs, and industry representatives across Alaska, British Columbia, and other seaweed-producing regions. These inputs were used to evaluate the relevance of 38 candidate environmental indicators to the Alaska and British Columbia context.

Seaweed farming in Alaska and British Columbia is developing within diverse contexts (including commercial opportunity, food security, Indigenous stewardship, and coastal resilience) and with varying levels of financial, logistical, and institutional capacity. This report synthesizes indicators and approaches described in Western scientific and practitioner sources but does not assess the feasibility or appropriateness of implementing monitoring indicators across different contexts, including those which may differ in capacity, funding, consultation with rightsholders and stakeholders, or weaving of Western and Indigenous Knowledge systems. Further, this report is focused on monitoring of the farm's influence on the surrounding environment and not monitoring of the environment's effects on farm production.

In this report, the term Indigenous Nations is used to refer collectively to Indigenous governing entities in British Columbia and Alaska when a discussion applies broadly across both regions. Where a discussion is specific to one jurisdiction's laws, policies, or programs, the corresponding regional term (e.g., First Nations in British Columbia or Alaska Native Tribal governments in Alaska, as applicable) is used instead.

Report Layout

The report is organized into five main parts, each addressing a different set of questions. Readers are encouraged to engage selectively with the sections most relevant to their interests.

- **Part I - Seaweed Farming in Alaska and British Columbia:** Where and how farming happens, what's grown, and current policy, permitting, and research context by region.
- **Part II - Environmental Effects: State of Knowledge and Gaps:** What's known about environmental effects in this region, and where evidence is still limited.
- **Part III – Identifying and Evaluating Environmental Indicators:** Candidate indicators (**Table 1**), with structured indicator profile tables covering rationale, scoring, methods, and existing data. Extended, standalone versions of these are available in the companion Volume 2 (Monitoring Indicator Factsheets).
- **Part IV – Applying Chosen Indicators in Monitoring Programs:** How indicators can be put to work in practice — matched to farming life-cycle stages, streamlined field-to-lab sampling methods, and sampling designs suited to different monitoring questions.
- **Part V – Lessons Learned and Future Directions:** Key lessons and emerging trends to consider as the sector evolves.

Report Goals

This report aims to provide a shared reference point to support informed discussion, future research, and context-specific decision-making as the sector evolves. This report is one contribution within a broader body of ongoing initiatives which are advancing the monitoring and management of seaweed farming. This report is not intended to stand alone, but rather to sit alongside Indigenous-led, community-based, and place-specific efforts already shaping the future of the seaweed sector.

Photo: Longline floats at a kelp farm participating in the MarReCon study, courtesy of NOAA

Part I - Seaweed Farming in Alaska and British Columbia

Part I provides a snapshot of where seaweed farming stands today in Alaska and British Columbia, including where farms are located, what species are cultivated and how, the scale of current production, and the permitting and policy context in each region. It also summarizes current monitoring and research activities.

Regional Context

Coastal communities around the globe have been tending and harvesting of seaweeds for millennia, including those established along the cold, complex, and productive coastal waters of the Northeast Pacific.[1–3] The Indigenous Nations of Alaska and British Columbia have stewarded their lands and waters for at least 15,000 years.[4–7] For example, Indigenous Nations have engaged in tending and rotational harvest practices to increase yield and sustain harvests of 'black seaweed' (*Pyropia* sp.) and other species as part of reciprocal relationships maintained over generations. Indigenous Nations continue to harvest and use diverse seaweeds for food, medicine, materials, cultural practices, and trade.[8–14]

Globally, there is growing interest in revitalizing and expanding seaweed harvest and cultivation as a sustainable, regenerative, and culturally-aligned pathway to food security, economic diversification, and environmental remediation.[9,15–17] Though the expansion of industrial seaweed farming as a commercial activity occurred first and fastest in the warm western Pacific[18], studies suggest significant untapped potential for production in temperate regions such as Alaska and British Columbia.[19,20]

Alaska and British Columbia are ideal locations for seaweed farming, with more than 82,000 miles (132,000 km) of complex coastline fed by cold, nutrient-rich water that naturally support nearly 600 species of macroalgae.[21] In each region, a similar suite of cold-water kelps is the ecological backbone of the seaweed sector (**Figure 1**). Interest in the expansion of the sector in this region has grown with public support,[22,23] accelerator funding, and the ability to adapt existing fisheries infrastructure and skilled labor for new seaweed farming applications.[24,25] This includes interest and participation from Indigenous Nations to varying degrees as rights holders, partners, and proponents in tenure or leasing systems,[12,26–30] where the long history of subsistence and cultural seaweed use across Alaska and British Columbia contributes region-specific knowledge that influences Indigenous Nations' priorities, site use expectations, and monitoring needs.

Indeed, seaweed farming in both Alaska and British Columbia is emerging at the intersection of coastal livelihoods, environmental opportunity, and evolving ocean governance which includes a throughline of Indigenous rights, title, and equitable participation. Both jurisdictions grapple with the same "social and spatial" reality of marine development—seaweed farms must fit into a crowded seascape where fisheries, conservation, recreation, and community priorities overlap, and where social license is as important as technical feasibility for successful establishment.

Thus, despite seaweed farming opportunities in Alaska and British Columbia, there are also concerns about the pace of expansion and calls for a more deliberate approach to environmental monitoring. Environmental monitoring can help better understand ecological benefits and impacts of the sector and inform progress towards its sustainable development while considering the practical constraints and diverse community priorities that shape the sector today.

Photo of seaweed farm in Alaska courtesy of NOAA

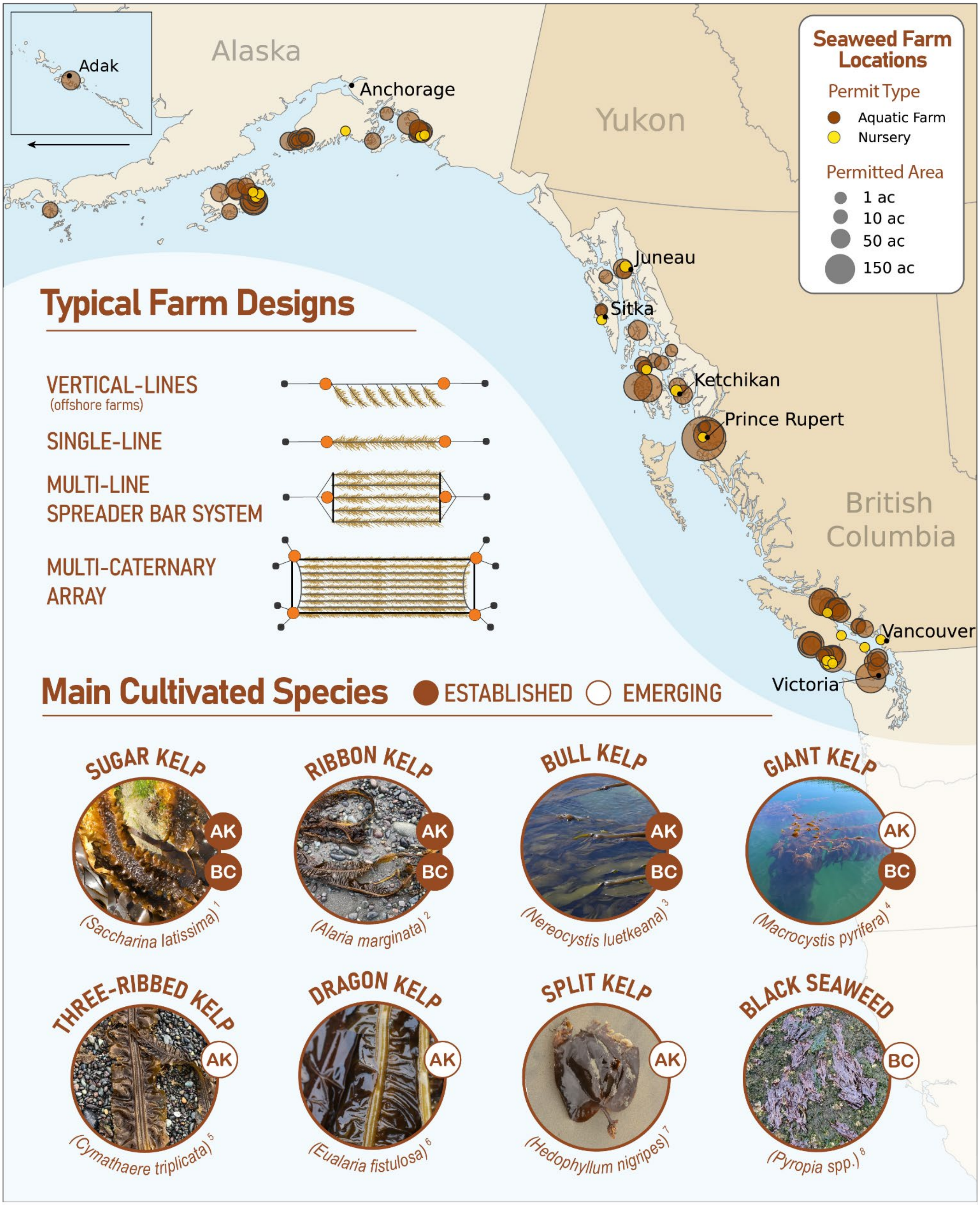


Figure 1. Locations of active or pending permits for seaweed farms (F) and nurseries (N) in Alaska (F = 47, N = 11, as of 2026)[31] and British Columbia (F = 28, N = 9, as of 2025), along with typical farm designs and key species cultivated. Seaweed photo credits: 1-Summer Grundy, 2-Jason Grant, 3-Eric Knight, 4-Carolyn Prentice, 5- Jason Grant, 6- Erin McKittrick,7-Julia Carr, 8-Jenny Kirkpatrick, licensed as public domain or under CC by 4.0.

Alaska

Species and Methods

In Alaska, seaweed farmers primarily grow **sugar kelp** (*Saccharina latissima*), **ribbon kelp** (*Alaria marginata*), and **bull kelp** (*Nereocystis luetkeana*) with some farms experimenting with **three-ribbed kelp** (*Cymathaere triplicata*), **dragon kelp** (*Eualaria fistulosa*), **giant kelp** (*Macrocystis pyrifera,* recently suggested to be reclassified as *M. tenuifolia* north of California)[32], and **split kelp** (*Hedophyllum nigripes*). In addition, there is interest in cultivating **Pacific dulse** (*Devaleraea mollis*), with ongoing pilot lab-based and open ocean suspended culture and permit applications for prospective future suspended culture[33–35], as well as **black seaweed** (*Pyropia sp.*), which has particular cultural significance to Alaska Tribes.[12,36,37] Many farms are permitted for growing more than one species. Kelp is generally grown utilizing multi-line and catenary arrays (where a curved horizontal catenary line secures the seeded lines to the anchor system, **Figure 1**) with harvest typically occurring in April to June.[24,38] One farm in Prince William Sound is experimenting with an offshore farming design featuring one surface line with multiple vertical cultivation lines,[39] following a model used in the Faroe Islands,[40,41] and regional interest for offshore culture.[42]

Participation and Production

Seaweed farming activities in Alaska began in 2016/2017[25] and active farms and farm leases are now prevalent from southeast to western Alaska around the Gulf of Alaska, with the largest farms found in the Kodiak Archipelago, followed by Southeast Alaska (Alexander Archipelago), and smaller farms in Kachemak Bay and Prince William Sound. As of 2026, this area encompassed 47 permitted farms, ranging from 1 to 132 acres (0.4 – 53 ha), and at least 11 nurseries (**Figure 1**).[31]

However, not all permitted sites nor entire permitted areas are necessarily utilized. For instance in the 2023/2024 growing season only 75 acres were estimated to be in active production relative to the total 2,723 acres of proposed and authorized farm area.[43] Alaska seaweed production peaked in 2022 at roughly 870,000 lbs (395,000 kg) wet weight (WW) harvested, after which production declined. Production in 2025 totaled roughly 350,000 lbs (158,000 kg) wet weight harvested, representing a decline from peak 2022 production due to a variety of factors, including market demand and hatchery failures resulting in lost crop. That said, harvest is forecasted to increase to 650,000 lbs (295,000 kg) or more in 2026 based on expectations of higher yield, although this was unconfirmed at the time of writing.[43–45] Although farmers submit harvest reports at a species level (see Permitting and Policy), state reporting of production is aggregated across species.

Alaska has prioritized seaweed sector development since 2016[25]. At the time of writing, the Alaska Mariculture Alliance, a group of mariculture stakeholders, continues to identify needs and address bottlenecks to growth of the mariculture industry.[24] Federal funding has been a key player in advancing seaweed mariculture and its monitoring in Alaska;[25] however, some funding sources are nearing the end of their grant terms and other funding sources will be necessary to continue monitoring efforts.

Permitting and Policy

In Alaska, seaweed farms are permitted through various state agencies (Alaska Department of Natural Resources, Alaska Department of Fish and Game, as well as the Alaska Department of Environmental Conservation post-harvest) and federal agencies (US Army Corps of Engineers, in consultation with the National Marine Fisheries Service), and permits are granted for a period of 10 years with renewal subject to review for another 20 years[46].

Permitting requirements are motivated by both the Alaska State constitutional mandate to safeguard natural resources and manage them as a public trust, and to ensure consumer health and safety (Alaska Const. Art. VIII). Farmers must submit detailed site plans with their application that specify farm species, design, location, and proximity of nearby sensitive habitats (e.g., wild kelp, eelgrass beds, salmon streams, marine mammal rockeries and haulouts). Farm applications go through review periods to allow for public comment, and Tribal consultation is encouraged but not an explicit permit requirement.[26]

Farmers with ADF&G permits must submit annual reports including details on sales, stocking, and inventory, by species, as well as narrative comments on weather, environmental interactions, spore acquisition, and more.[47] Permits require farmers to collect wild kelp reproductive tissue (sori) from 50 adult, fertile kelp within 50 km of their leased farm and seed their farm with the resulting spores each year. Gametophyte culture, which involves reuse of the same lab-cultured strains of kelp year after year, is not permitted. Guidance and tools to assist in the planning, site selection, and permitting process can be found at the Alaska Aquaculture Permitting portal as well as on the Alaska Mariculture Insights dashboard.

Other government entities are involved in the permitting process include local Alaska Native Tribal governments and as well as federal agencies (US Fish and Wildlife Service, US Army Corps of Engineers, National Marine Fisheries Service).[48] Finally, the Food and Drug Administration (FDA) and United States Department of Agriculture (USDA) regulate the use of seaweed depending on end use (e.g., food additives, livestock feed, fertilizer, organic certification).[49]

Monitoring and Research

Research and monitoring related to seaweed mariculture in Alaska is highly applied, with several dedicated initiatives focused on optimizing yield, characterizing environmental effects, and developing processing methods and market applications. Current mariculture-specific monitoring efforts include the following:

- **Mariculture Research and Restoration Consortium (Mar ReCon).** Mar ReCon is funded by the Exxon Valdez Oil Spill Trustee Council and includes components addressing the physicochemical environment and biological communities including plankton, benthic, pelagic fish, marine birds, and marine mammals.[50,51] Monitoring efforts take place at 9 farms of varying sizes with 3 in each region, including Prince William Sound, Kodiak Island, and Kachemak Bay. For the physicochemical environment, researchers, in collaboration with farmers, deploy conductivity, temperature, and depth (CTD) sensors and collect water samples for nutrient concentrations. Sampling frequency depends on the given metric and time of year, with some variables sampled continuously (e.g., every 5-10 minutes) while some are sampled discretely (e.g., bi-monthly or opportunistically). Additional work in Prince William Sound includes spring and fall plankton tows in bays that include seaweed farms. Epibenthic and infaunal surveys are conducted in the spring and fall at farm and control sites. Imaging sonars, echosounders, and cameras are used in the spring and fall to evaluate fish observations at and near farm sites and at respective control sites in Prince William Sound. The distributions and abundance of marine birds and mammals are monitored along transects in all three regions in areas with varying farm density in the spring and fall. All datasets are legally required to be made public 2 years after collection and are carefully documented via metadata and unique Digital Object Identifiers (DOIs). It is worth noting that the geographic concentration of Mar ReCon sites may limit generalization to the full diversity of Alaska's coast, and that extrapolation of results from small-sized farms to larger farms should proceed with caution.
- **GreenWave Kelp Climate Fund.** Compensates farmers for submitting monthly measurements on their farm through the My Kelp app, which are used to estimate carbon and nutrient removal. In 2024-2025, the fund gathered data from 11 farms with 4 in Kodiak, 4 in Prince William Sound, 1 in southcentral Alaska, 1 in Kachemak Bay, and 1 in southeast Alaska.
- **Prince William Sound Productivity Project.** The Native Conservancy and Chugach Regional Resources Commission have conducted monthly monitoring at 7 test sites in Prince William Sound since 2022 to collect tissue samples and assess water quality. This project aims to describe environmental control on kelp productivity, but also collects temperature, salinity, pH, dissolved oxygen (DO), aqueous nutrients, conductivity, and kelp biomass/biometrics.
- **University of Alaska Southeast (UAS).** UAS researchers, graduate students, and undergraduates have participated in monitoring of seaweed farm test lines in Krestof Sound, Crescent Bay, and Deep inlet in southeast Alaska. This combined work has contributed water quality (temperature, salinity, DO) data, as well as additional nutrient data, at varying times from 2022 to present.
- **University of Alaska Fairbanks (UAF).** Researchers with the College of Fisheries and Ocean Sciences have

developed a Nutrient Extraction Toolkit and protocol for standardized water and kelp tissue sampling to quantify the amount of carbon and nitrogen removal by seaweeds each growing season [52,53]. Since 2020, data has been collected at four sites on Kodiak Island, seven sites in Prince William Sound, and two sites in southeast Alaska.

There are also numerous non-mariculture focused marine monitoring programs in Alaska that provide important environmental baseline data for informing site selection and tracking broader environmental change over time as the sector grows. These include the Exxon Valdez Oil Spill Trustee Council-funded Gulf Watch Alaska program, the National Science Foundation-funded Northern Gulf of Alaska Long-term Ecological Research program, the Alaska Ocean Observing System (AOOS), Global Ocean Ecosystem Dynamics program, and others. For more information on these monitoring programs, see information on the Data Catalogue in **Appendix A**.

Baseline environmental data from multiple existing marine monitoring programs have been brought together to develop site selection decision-support tools for mariculture. Among these are the Aquaculture Opportunity Areas for the Gulf of Alaska, which is focused on identifying areas that minimize conflict with other marine resources and uses.[54] Some farmers[39,55] have reported that this is a useful tool to screen broad areas for suitability but is too coarse in scale and lacking in biophysical data to inform local site selection. Another tool in active use is the AOOS Mariculture Portal, which aggregates the results of multiple marine environmental monitoring programs into themes relevant for mariculture site selection, and includes biophysical parameters like temperature and salinity at finer scales that farmers[55] have found helpful for fine-scale site selection for conditions that will support farm productivity.

Together, these examples illustrate the range of research and monitoring activities currently underway in Alaska. Their inclusion here reflects documented activity to date and does not imply consistency, comparability, or broad applicability across all farms or regions.

British Columbia

Species and Methods

In British Columbia, the main seaweed species cultivated are **sugar kelp** (*Saccharina latissima),* **bull kelp** *(Nereocystis luetkeana*, **ribbon kelp** (*Alaria marginata*), and **giant kelp (***Macrocystis pyrifera / tenuifolia),*[32] (internal dataset, Province of British Columbia), while there is also some land-based tumble culture of **Pacific dulse** (*Devaleraea mollis*)[27]. Some Indigenous communities are experimenting with the culture of **black seaweed** (*Pyropia sp.*), a culturally significant food.[56] Many farms are permitted to grow multiple species. Seaweed is outplanted to farms in the fall, growth then occurs during the winter months, and by March or April the fronds are ready for harvest.[27,57]

Participation and Production

Despite the long history of people and seaweed, the contemporary seaweed farming sector in British Columbia is quite young. In 2012, just two seaweed cultivation companies held tenure, and as of 2025, there were 21 active seaweed farming companies in the region, and these are mostly located in the southern part of the province (**Figure 1**; internal dataset, Ministry of Agriculture and Food, Province of British Columbia). As of 2025, BC had 28 individual farms with active or pending permits for aquatic plants alone or aquatic plants and shellfish covering areas ranging from ~1 - 195 hectares (~ 2 – 480 acres), and at least 9 nurseries (**Figure 1**; BC Ministry of Water, Land and Resource Stewardship Crown Land Registry). However, not all licenced sites actively produce seaweed, with only 3 out of 19 authorized sites reporting harvests in 2022 and visual inspection of sites on satellite imagery showing that many active farms are cultivating far less area than authorized. The seaweed farming industry's production varies widely as do the objectives of cultivation (e.g., from growing for restoration purposes to the sale of seaweed biomass). Total harvests remained below 200 kg (~450 lbs) per year before 2019 and grew to 40,000 kg (~88,000 lbs) by 2022 and 146,000 kg (~322,000 lbs) by 2025, with one producer responsible for roughly half or more of all production (internal dataset, BC Ministry of Agriculture and Food). Some farms do not currently report production by species, but in aggregate.

Permitting and Policy

Presently, permitting in British Columbia is regulated at multiple levels via a harmonized review process.[57] The Province of British Columbia has jurisdiction over seaweed farm establishment for any purpose within 12 nautical miles from shore via a tenure system under the *Land Act*. Licences for farms producing seaweed for human consumption are issued under the *British Columbia Fish and Seafood Act*, under oversight of the British Columbia Ministry of Water, Land and Resource Stewardship (WLRS). However, the Fish and Seafood Act only enables regulatory oversight for cultivation of seaweed intended for human consumption, leaving a gap in oversight for cultivation for other purposes (e.g., for restoration, fertilizers, or biostimulants).[58] Culture licences are granted for a maximum period of 10 years, and tenure for up to 30 years.[57]

At the federal level, Fisheries and Oceans Canada (DFO) issues shellfish and finfish Aquaculture Licences, and WLRS and DFO co-regulate any aquatic plant culture sites that co-occur with shellfish or fish aquaculture. Moreover, DFO regulates any applications with potential impacts to fish and fish habitat (for example, sites where there could be herring spawning occurring on cultured kelp) through the *Fisheries Act;* if there are any anticipated effects to species at risk (e.g., northern abalone) or critical habitat, DFO applies the *Species at Risk Act.* Finally, Transport Canada reviews aquaculture applications that are in navigable waters. Licences beyond the 12 nm boundary are administered by a federal agency, Public Services and Procurement Canada. Some permitting and regulatory requirements are also contingent on the product's end use. Depending on end use, farmed seaweed products may also have to meet various product safety requirements, such as Health Canada's Food and Drug Regulations for human consumption, or the Canadian Food Inspection Agency (CFIA)'s Feed Regulations for consumption as animal feed and/or *Fertilizer Act* for use as fertilizers.[57]

When submitting a permit application, farmers are required to provide baseline information about their proposed site, the surrounding environment, depth, farm design, culture species, and source of seed. As part of the harmonized review process, the province also requires applicants to submit a debris management plan that contains details about farm infrastructure. [59]

The province has guidelines that require seed stock to be wild-harvested from at least 30 individuals within a 50-km radius of the farm to reduce the possibility of genetic mixing, although no formal regulations are in place.[27,28,57] The province also provides guidelines on site selection, including avoiding sensitive habitat or species (e.g., understory kelp, eelgrass, abalone), protected areas, or a history of contamination.[59] At present, applicants are responsible for assembling information to inform site selection from field investigations or public datasets (identified in the application guide) on the distribution of sensitive species and habitats to avoid (e.g., eelgrass, abalone), and there is no centralized tool to support site selection.[60,61]

In Canada, Aboriginal and Treaty rights are constitutionally protected under section 35 of the Constitution Act (1982) which means that the province of British Columbia has the legal obligation to consult on any development that may impact these rights. Moreover, Canada and the Province of British Columbia have legislated the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) as frameworks for reconciliation and reaffirming Indigenous Peoples' rights to self-governance.[62,63] Potential seaweed farmers are therefore encouraged to engage early with the First Nations whose territories overlap with intended seaweed farms and include these engagement details in their application process. Once an application is submitted, it goes through a provincially run review and referral process for aquaculture developments in First Nations territories.[64] Aquaculture applications are reviewed by First Nations' governing bodies for potential impacts, allowing them to raise concerns and propose mitigation. The process attempts to reach consensus and is guided by co-governance agreements or reconciliation protocols between First Nations and the province.

Once approved, agencies have limited capacity for monitoring, but do collaborate on periodic inspections to verify that farms are adhering to submitted plans and conditions of licence.[58] All seaweed producers licensed under the British Columbia *Fish and Seafood Act*, including producers of marine plants and algae, must also submit annual reports on their operations under each individual licence to British Columbia Ministry of Agriculture and Food through an online reporting form with separate reporting for food market and non-food market production. Data collected includes company, area, and total harvest (species, volume, unit, value, intended use; although current data is not disaggregated by species), and these internal data (available on request) are used in economic analysis, sector funding decisions, as well as program and policy development.

At the time of writing, the Province of British Columbia was actively developing an Interim Aquatic Plant Authorization Policy. Moreover, seaweed farming intersects with broader marine policy development currently underway. For instance, seaweed aquaculture sits within the broader context of Blue Economy planning in Canada, which is in its initial stages, as well as various international commitments (e.g., Paris Agreement, 2030 Agenda).[65] The Province of British Columbia has also co-developed a B.C. Coastal Marine Strategy with many First Nations from across the coast. The B.C. Coastal Marine Strategy is the province's first shared, coastwide vision for the stewardship of marine resources that highlights aquatic plants and particularly seaweed as a priority area for monitoring, climate change adaptation, and sustainable economic development. This planning work is done in a manner which acknowledges the specific rights, interests, priorities and concerns of distinct First Nations and respects their unique cultures, histories, rights, laws, treaties and governments.[66]

Monitoring and Research

In British Columbia, existing regulations for licensed seafood growers require reporting on the species grown and how harvest is distributed, but little other monitoring is required outside of that needed to adhere to debris management plans.[27,28] As such, most environmental monitoring activities occurring on seaweed farms in British Columbia are being done by growers to directly inform operations (e.g., monitoring of water quality, growth, and biofouling) or as part of science-oriented research programs led by larger growers and/or through partnerships with academic or non-profit organizations (e.g., monitoring of physical parameters and habitat use by fish).[60,67–69] Although there are no long-term seaweed aquaculture monitoring programs at present, there are many other monitoring programs that focus on wild seaweeds and marine ecosystems which may be useful for site specific baseline data:

- **Marine Plan Partnership (MaPP) Regional Kelp Monitoring Program** is a community-based wild kelp monitoring program focused on giant kelp and bull kelp under a collaborative governance structure that brings together 17 First Nations and the Government of British Columbia;
- **The Hakai Institute**, collects data on wild kelp through various methods including aerial (Airborne Coastal Observatory, UAV/drone) and remote sensing for kelp extent data, as well as SCUBA surveys (nearshore research program) for data on kelp density and biomass. Data is comanaged with partners and is accessible in their data repository and Kelp Explorer web map showing changing distributions over time.
- **The Sentinels of Change Project** that investigates invertebrate recruitment and biodiversity, including around wild kelp beds across coastal British Columbia;
- **The Coastal First Nations Regional Monitoring System** provides digital data collection tools for First Nations monitoring coastal regions; and
- **The Canadian Integrated Ocean Observing System (CIOOS)** aggregates a wide range of oceanographic data on variables that influence kelp growth which can be viewed in a public map explorer similar to AOOS.

In addition, **North Island College's Seaweed Innovation Hub** acts as an industry catalyst through conducting applied research and training in seaweed cultivation, processing, and marketing. For more information on existing programs, see the Data Catalogue in **Appendix A**.

Closing

At present, seaweed farming in Alaska and British Columbia is developing with logistical, financial, regulatory, and capacity constraints that shape where and how activity occurs. While interest in the sector is often linked to commercial opportunity, for some communities—particularly Indigenous and remote coastal communities—engagement with seaweed farming may also be motivated by food security, stewardship, and local benefit, provided activities remain economically sustainable. Recognizing this diversity of context and motivation is important for interpreting the evidence on environmental effects summarized below, and for avoiding assumptions about uniform trajectories or future expansion across the region.

Part II - Environmental Effects: State of Knowledge and Gaps

Part II synthesizes what is currently known, and not yet known, about the environmental effects of seaweed farming in Alaska and British Columbia. High-level synthesis tables summarize documented effects, organized by regional evidence and key uncertainties as documented to date.

The environmental effects of seaweed farming in temperate ecosystems have been reviewed extensively[27,70–75] and seaweed farming at the current scale is generally perceived to have a lower environmental effect profile than most other forms of aquaculture.[27,28,76] However, specific biological risks, notably related to genetics[77], biosecurity, and interactions with wildlife, require careful management.[71,73] Further, seaweed farm infrastructure and dense biomass can interact directly with the marine environment by modifying local hydrodynamics, seabed topography and composition, and water chemistry, resulting in both potential benefits and impacts. However, outcomes are often dependent on species, scale, density, and local oceanographic conditions.[70,74]

This section briefly summarizes the current state of knowledge on the environmental effects of seaweed farming in temperate ecosystems, with an emphasis on evidence emerging from farming practice and research in Alaska and British Columbia, of which most is focused on kelp species specifically given the focus on mariculture of these species in the region. This body of knowledge provided the foundation for the review, prioritization, and selection of essential monitoring indicators that followed. The summaries below reflect how environmental effects have been examined and reported in existing literature; they should not be interpreted as evidence that observed patterns are guaranteed, consistent across sites, or broadly generalizable beyond the contexts in which they were examined.

Biological and Ecosystem Effects	
Overview	• Seaweed farms can benefit **biodiversity and habitat use** by providing structure and habitat during the growing season. While studies to date have found increased biodiversity at seaweed farms compared to reference sites without farms, these habitats do not support communities as distinct or diverse as those in natural kelp forests.[27,67,78–81] Several studies have found no evidence that seaweed farming negatively affects bottom habitat and invertebrate communities, while others have found potentially positive effects of habitat provisioning, refuge, spawning, and associated changes to fish (including Pacific salmon and herring).[70,71,73,74,79,80,82–89] • Broader ecological benefits may include **food provisioning** for fish and other animals feeding on farmed kelp or smaller animals living within it, which could benefit local fisheries;[87,90] and **nutrient cycling** through uptake of nitrogen and carbon and the redistribution of these nutrients in the ecosystem through fragmentation and drift.[91–94] • Documented risks include **genetic interactions with wild kelp**,[95] and **biosecurity** risks from the potential to contribute to the spread of diseases and pathogens,[83,96,97] biofouling,[56,96] and invasive species.[85] There are also concerns around physical habitat alterations to areas underneath or surrounding seaweed farms (e.g., shading or nutrient competition, see below)
Regional Insights	• Extensive monitoring in Alaska takes place through **Mariculture Research and Restoration Consortium (Mar ReCon) project and other research projects,** which monitor plankton, benthic communities, fish, birds, and marine mammals, harmful algal blooms, as well as nutrient uptake and release at multiple kelp farm and control sites. Studies are ongoing, but early results suggest small or no measurable effects at small-scale kelp farms.[50,51,98–100]

Photo Courtesy of Alaska Mariculture Alliance

Knowledge Gaps

- Existing **monitoring is sparser in British Columbia** and mostly focused on biodiversity and habitat use, with some operators piloting new monitoring tools and technologies to inform sustainable operations.[60,67,74] Local studies have detected a novel 'pink spot' disease in seed nurseries within the region.[101]
- **Whether changes in the environment are caused by farms or by natural variation is difficult to establish** due to limited baselines and small farm sizes. Kelp farms may aggregate fish or modify habitat use by transient species,[78] [102] but evidence remains largely anecdotal and site-specific. [103–105]
- Although documented as impacts of seaweed farming elsewhere, the potential for **genetic impacts, disease transmission, and invasive species spread associated with farming in Alaska and British Columbia is not well understood**, especially as farm scale increases.[95,96]
- There is little evidence of **cumulative effects, food web effects, or ecological function** relative to natural kelp forests.[27,70,71]

Physical and Chemical Effects

Overview

- Seaweed farms can alter **water quality**, including potential changes to turbidity, light penetration, oxygen, nutrients, organic matter, and temperature, but the effects are generally small or seasonal for small-scale farms.[70,83,106,107]
- Seaweed's influence on water quality can benefit local ecosystems through **absorbing excess nutrient inputs (nitrogen, phosphorus)**, **absorbing carbon** from the atmosphere (but generally does not remain sequestered long enough to contribute to climate change mitigation), **buffering local pH** to reduce the effects of ocean acidification,[73,74] and **bioremediating polluted waters**[108–110] (but may bioaccumulate contaminants[111] and transfer them to higher trophic levels[112–115]).
- Seaweed farms can also **affect local water flows and currents**[116] – slowing flows and contributing to greater stratification of surface waters, acting as a breakwater for surface flows and waves, [71] and squeezing flows under the farm where they can influence bottom sediment resuspension, transport, and topography.[117–119] The magnitude of these effects depends heavily on local context.[70,71,73]
- Studies document **shading and deposition of kelp detritus** beneath farms, influencing benthic processes.[83,118,120]

Regional Insights

- The Mar ReCon program in Alaska and some farms in British Columbia monitor diverse physical and chemical parameters around farms, including **temperature, salinity, nutrients, chlorophyll, light, and water flow**.[50,51,56,60,103,105,106]
- Kelp farms are considered excellent breakwaters with potential to protect sensitive shorelines and towns. [56,61,98,103,121]
- Seasonal kelp tissue studies show strong links between nutrient availability, tissue nitrogen, and harvest timing.[52,122]

Knowledge Gaps

- There is **limited data for physical effects** related to alteration of flows, sediment changes, nutrient flux, pH buffering, bioremediation potential,[121] and carbon deposition beneath farms in Alaska and British Columbia, particularly over longer timeframes.[105,123]
- There is **uncertainty about the cumulative effects of nutrient uptake,** although practitioners[68] and recent research[124] suggest that nutrients are not broadly a limiting factor at the current scale of seaweed farming in Alaska and British Columbia; however, nutrient uptake can vary by species[52,125] and location.[110]
- There is a need **for research on the influence of farm configuration, density, and depth** on hydrodynamic and biogeochemical effects,[27,74,116,117] including potential for resuspension of legacy contaminants within seabed sediments.[126,127]

Farm Infrastructure and Operation

Overview

- Farm infrastructure (e.g., lines) may pose a **risk of entanglement or collision** for marine megafauna[70,71,73,74,95] though reports of aquaculture entanglements are rare[56,128,129] and the regional risk is considered low.[56,68,130,131]
- Lost, discarded, or damaged synthetic farm infrastructure (e.g., ropes and buoys) can contribute to **marine debris and microplastic pollution**,[27,70,74,132–134] with early research being done on alternatives like cotton, hemp, or silk.[135]
- Microplastics from farms can be trapped by cultured and wild seaweed,[136] acting as a sink for microplastics and introducing a risk of ingestion by macrofauna and fish.[73,136–139]
- **Underwater noise** from vessels during site visits and harvest can cause behavioral disturbance and mask marine mammal communications,[140,141] while the seaweed itself may attenuate underwater noise.[142–144]

Regional Insights

- The Mar ReCon program in Alaska is actively investigating potential **wildlife interactions with farm infrastructure** through seabird surveys, geo-linked marine mammal observations and gear damage, and seal haulout trail cameras.[50,51] Some farmers note extensive marine mammal activity around farms without incident to date,[56] and others point out benefits of having sea otters present as they will eat bivalves off of farm infrastructure.[145]
- Farmers in Alaska and British Columbia noted that vessel activity for farm operations is infrequent and likely far surpassed by **noise** associated with more common activities (e.g. fishing, shipping, passenger vessels),[39,56,60,146] though this noise would increase should monitoring activities associated with farm operations become more regular.[98]
- With respect to seaweed amalgamating microplastics, regional studies have investigated **microplastic loads** in Alaska[133,134] and British Columbia[149–151] but there is no specific work investigating loads specifically in relation to seaweed farming.

Knowledge Gaps

- There is no data on **gear loss, microplastic contributions, or wildlife entanglement** for Alaska and British Columbia farms.[39,56,98,146,152]
- There is no systematic data on **noise** which distinguishes between farm operated vessels and other marine activities.
- There is a need to further explore the documented capacity of seaweed farms to effectively reduce noise pollution from marine vessels and quantify the potential benefits for marine life.

Climate Change

Overview

- The potential **mitigation** benefits of seaweed farming would come via carbon sequestration [92,153,154]; however, the carbon fixed by farmed seaweeds is directed to short-term carbon reservoirs (e.g. food, livestock feed) rather than long-term storage pathways[154,155] and the current scale of the sector is too small (0.06% of wild kelp extent) to have significant regional impacts.[154] Life cycle assessments suggest that **greenhouse gas emissions** associated with farm operations (fossil fuel use by boats and generators) offset the limited carbon removal capacity of farmed kelp and result in net CO_2 emissions.[152,154,155]
- Seaweed-based products may be better pathways for carbon mitigation (as opposed to seaweed farming itself) if they replace those with a larger carbon footprint (e.g., biofuels, biostimulants, or fertilizer).[123]
- Wild and farmed kelp can contribute to pH buffering, creating local refugia from ocean acidification, but this effect can be minimized or even reversed by respiration from associated microbial and invertebrate fouling communities, especially on kelp farm infrastructure.[25,153,156–159]
- Kelp farms are recognized for their potential to attenuate wave energy associated with sea level rise and storm surge as a climate change **adaptation option for coastal protection**, though attenuation is highly dependent on design factors like kelp density, canopy length, and blade rigidity.[123,160–165]

Regional Insights

- Studies on **mitigation potential** of kelp farming in the Northeast Pacific have determined that carbon mitigation benefits are likely relatively small and context-dependent.[123,153]
- Kelp farms studied in Southcentral Alaska acted as a sink or a source of carbon dioxide into the atmosphere depending on the site-specific characteristics.[159]
- Farmers' lived experience in British Columbia[56] and one study in Alaska[166] point to water velocity-dampening function of seaweed farming.

Knowledge Gaps

- There is a need to develop robust monitoring, reporting, and verification standards for **carbon sequestration** and to identify long-term carbon storage options for biomass. [154,167]
- The specific role and value of kelp farms for **coastal protection** in Alaska[160] and British Columbia remains largely unknown.

Part III – Identifying and Evaluating Environmental Indicators

Part III describes how the indicators in this report were identified, evaluated, and organized. It explains the analytical methods — a literature review, an international expert workshop, and practitioner interviews — that informed assessment and ranking of 38 candidate indicators for broad relevance in this region (Table 1). It also presents detailed summary tables for select indicators that summarize their relevance, potential monitoring objectives, methods, implementation considerations, and existing data sources.

A wide range of environmental indicators have been proposed for monitoring the effects of seaweed farming, spanning biological communities, water quality, genetics, wildlife interactions, nutrient cycling, and farm operations. However, monitoring capacity in Alaska and British Columbia remains constrained by limited baseline data, funding, technical capacity, and long-term monitoring infrastructure.

Importantly, not all indicators are equally informative, feasible, or relevant within the regional context. Some are supported by relatively strong scientific evidence and existing monitoring efforts, while others remain uncertain, difficult to interpret, costly to implement, or only relevant under specific conditions. Interviews and engagement conducted for this project also highlighted that monitoring priorities are shaped not only by scientific evidence, but also by operational realities, regulatory contexts, and practitioner concerns.

As a result, this report does not suggest monitoring of all possible environmental effects associated with seaweed farming. Instead, candidate indicators were evaluated and scored using a set of **9 complementary criteria**, including scientific support, regional relevance, practitioner input, and feasibility of implementation, to identify a smaller set of indicators currently most relevant for environmental monitoring and decision-making in Alaska and British Columbia (details in **Appendix A**). This work is primarily a science-based reference for research, future monitoring design, and discussion, rather than an operational tool for direct implementation by farmers or regulators.

Indicator Compilation & Evaluation

As described below, our seaweed indicator list was compiled through 5 main steps, specifically: **1)** a literature review, **2)** refining for regional relevance, **3)** an expert workshop **4)** interviews with practitioners, researchers, regulators, NGOs, and Indigenous organizations, and **5)** multi-criteria scoring. While this process relied primarily on Western science resources, interviews with Indigenous seaweed farmers also informed indicator selection. We recognize that this does not capture the full depth of Indigenous Knowledge systems related to local ecosystems, stewardship, and seaweed cultivation practices in the region.

Indicator selection began by compiling a list of candidate indicators from a literature review and existing seaweed farming monitoring frameworks. **Overall, the literature review catalogued 309 references at the time of scoring**. Key documents included risk assessments or monitoring frameworks for the seaweed farming sectors of Aotearoa New Zealand,[71] the Faroe Islands,[73] Europe,[70] as well as a global mariculture monitoring framework developed by The Nature Conservancy[72]. Additional key resources included monitoring frameworks for Marine Protected Areas and broader Pressure-State-Response ecological monitoring.[168–170]

Our initial indicator list was **refined for regional relevance** in Alaska and British Columbia via cross-referencing with key regional resources, including the Alaska Mariculture Development Plan,[171] a Seaweed Industry Development Plan developed for the district of Mount Waddington in

Photo Courtesy of Alaska Mariculture Alliance

British Columbia,[57]and a review of current seaweed farming issues and policy for British Columbia.[27] Data collection by current mariculture monitoring programs like Alaska's Mariculture Research and Restoration Consortium (Mar ReCon) was also considered.

The indicator list was **evaluated through an expert workshop** (34 participants) held at the 25th International Seaweed Symposium (Victoria, British Columbia). Steps 1-3 resulted in a list of 38 potential indicators.

Finally, feedback was collected on perceived importance and relevance of these 38 candidate indicators through **interviews with practitioners, researchers, regulators, NGOs, and Indigenous organizations** (34 participants) from across Alaska and British Columbia, and other regions.

Our 38 indicators were **evaluated using a multi-criteria scoring framework** that balanced scientific support, regional relevance, practitioner concerns, and implementation feasibility. Indicators were assessed across 9 evaluation criteria: relevance to management, literature support, sensitivity and responsiveness, robustness, feasibility, cost-effectiveness, reliability for predicting causality, likelihood of effect, and community interest or concern. See **Appendix A** for full scoring criteria, rubrics, and outcomes and the separate Volume 2 for detailed factsheets on all indicators.

Rather than recommend all possible environmental effects associated with seaweed farming are monitored, this process aimed identify a smaller set of indicators which are currently the most relevant and feasible for environmental monitoring and decision-making in Alaska and British Columbia. Indicators with the strongest combined performance across all 9 evaluation criteria listed in **Appendix A** (scores ≥20) were identified as "Group A Indicators". Indicators with moderate combined scores (15–19) were categorized as "Group B Indicators", while those with lower combined scores (<15) were categorized as "Group C Indicators". Where Groups A, B, and C differed the most, indicators in Group A tended to be commonly observed at farms, of interest to stakeholders, and well-supported in the literature. Group B indicators were related to effects that tended to be less frequently observed and/or not extensively monitored. Finally, Group C indicators were related to effects that remain largely hypothetical for this region, were of limited interest during stakeholder discussions, were associated with gaps in literature, or perceived to be less reliable. Group C indicators may still be important but require more research. Overall, across all indicators, reliability for predicting causality and robustness (i.e., how consistently a signal can be detected amid natural noise) scored lowest, reflecting the inherent difficulty of isolating farm-driven effects from background environmental variability. Likelihood of effect and reliability for predicting causality also carried the most knowledge gaps of any criteria. For several indicators, especially in Group C, there simply isn't enough information yet to know how likely an effect is or how reliability it could be attributed to farming.

Indicator groupings (A-C) are intended to help interpret the relative importance of indicators within the context of this report, rather than to prescribe fixed monitoring requirements or exclude lower scoring indicators from future monitoring efforts. Indicator scores and their respective groupings reflect patterns in how frequently indicators appear and are emphasized across the reviewed literature and practitioner sources, rather than priorities, requirements, or expectations for implementation which may differ in a place-specific manner. Further, while our approach organizes indicators conceptually, questions related to data storage, management, long-term analysis, and sustained resourcing are not resolved in this report and remain key practical challenges.

In the sections that follow, we provide details on these Indicators, links to decision-making throughout the seaweed farming process, and future directions for implementation of environmental monitoring.

Indicators At-A-Glance

Table 1 summarizes the list of 38 indicators identified and evaluated through the indicator scoring process described above. Indicators are organized into six environmental effect classes (farm interactions, biodiversity, ecological health, biogeochemistry, water quality and flow, and pollution) and three groups (Groups A, B, C) based on their combined scores for 9 criteria, including scientific support, regional relevance, practitioner interest, and feasibility of implementation within the current context of seaweed farming in Alaska and British Columbia.

Table 1. Candidate indicators, definitions, anticipated effects of farms on indicators (+ positive impact, - negative impact, ~ no documented effect), and color-coded by score (Group A: indicators with scores ≥20, Group B: indicators with scores between 15–19, and, Group C: indicators scores <15). Groupings are descriptive and comparative, and are not intended to define minimum requirements, benchmarks, or expectations for responsible practice. See and Appendix A for details on criteria scoring and Volume 2 for extended indicator factsheets.

Class	Indicator	Definition Relevant to Seaweed Farming	Effect	Group
Farm Interactions	Farm Infrastructure	Amount and type of farm infrastructure (e.g., feet of line), which influences other effects	+/-	A
	Farm Biomass	Amount of kelp biomass grown and harvested from a farm, which influences other effects	+/-	A
	Habitat Use**	Organisms benefitting from farms as habitat (e.g., food, shelter, breeding site).	+	A
	Entanglement*	Occurrence of an animal entangled in farm infrastructure (e.g., lines)	-	B
	Habitat Disturbance Farm	Physical disturbance through farm maintenance visits (e.g., vessel presence, wake, flushing)	-	B
	Habitat Disturbance Harvest	Physical disturbance through harvesting and removal of farmed kelp biomass	-	C
Biodiversity	Epibiota	Presence and diversity of organisms living on kelp tissue (e.g., bryozoans, tunicates)	+	A
	Fish	Presence and diversity of pelagic fish found in or around farms	+	A
	Benthic	Presence and diversity of organisms that live on the seafloor under or near a farm	+	B
	Bird	Presence and diversity of marine birds found in or around farms	+	B
	Marine Mammals*	Presence and diversity of marine mammals found in or around farms	+	C
	Phyto/zooplankton	Presence and diversity of these drifting organisms found in or around farms	+	C
Ecological Health	Biofouling	Settlement and accumulation of organisms onto farm infrastructure or kelp	+/-	B
	Genetic Influence***	Genetic diversity and relatedness of wild seaweeds to farmed seaweeds	-	B
	Invasive Species	Harmful spread of non-native species at farms to ecosystems (e.g., invasive tunicates)	-	B
	Disease	Spread of an infection in farmed seaweeds (e.g., virus, bacteria) to surrounding ecosystems	-	C
	Harmful Algal Blooms	Farm influence on the growth of toxin-producing algae in the water column	-	C
Biogeochemistry	Nutrients In Tissue	Assimilation of carbon, nitrogen, and phosphorus into farmed seaweed	+	A
	Nutrients In Seawater	Available carbon, nitrogen, and phosphorus in seawater to support assimilation	+/-	A
	Carbon Cycling	Removal and redistribution of carbon through storage in farmed seaweed biomass	+	C
	Organic Matter	Release of organic material from farmed seaweed biomass	+/-	C
	Organic Enrichment	Deposition of organic material from farmed seaweed biomass to sea floor	+/-	C
	Sediment Composition	Carbon, nutrient, and oxygen content of sediment below seaweed farms	+/-	C
Water Quality and Flow	Acidification	Level of aqueous pH in and around farms	+	B
	Dissolved Oxygen	Concentration of oxygen dissolved in sea surface	+	B
	Flow	Rate and direction of water movement through farm	+/-	B
	Light	Penetration of light (photosynthetic active radiation) below farms	-	B
	Turbidity	Cloudiness of the water due to suspended sediment in and around farms	-	B
	Wave Energy	Kinetic energy exerted by waves in and around farms	+	B
	Chlorophyll *a*	Concentration of this pigment is an indicator of primary production by algae in and around farms	+/-	C
	Salinity	Dissolved salt content in and around farms	~	C
	Temperature	Temperature of the sea surface in and around farms	~	C
Pollution	Contaminants In Tissue	Concentration of pollutants around farms assimilated into seaweed tissue.	-	A
	Marine Debris and Plastic	Debris due to gear loss from farms or other activities	-	A
	Aqueous Pollutants	Concentration of pollutants in water from sources associated with farms (e.g., boats)	-	B
	Airborne Pollutants	Concentrations of pollutants in air from sources associated with farms (e.g., boats)	-	B
	Noise	Underwater sound produced through farm operations (e.g., boat engines)	-	B
	Sewage	Wastewater effluent from sources associated with farms (e.g., boats)	-	C

Regulatory Linkages: *Reporting of marine mammal entanglement is required by regulatory agencies **Regulations around fish and fish habitat may lead to the farm being designated as essential fish habitat if herring spawn on it and harvest is prohibited until after hatching in British Columbia and Alaska; *** Permitting guidelines require harvest of parent seed stock from 30 (British Columbia) to 50 (Alaska) wild individuals within 50 km of the farm site, but there is not requirement for genetic monitoring or verification.

Monitoring Indicator Profiles

The following **Indicator Profile Tables** provide a practical reference for a selected subset of indicators identified through this science synthesis. This subset does not represent all possible indicators associated with seaweed farming, nor is it intended to function as a fixed checklist, monitoring standard, or prescribed set of requirements. Instead, the tables highlight indicators for which there is currently stronger evidence, practitioner interest, or regional relevance in Alaska and British Columbia. This includes several higher-scoring indicators, as well as selected indicators associated with rare but potentially important environmental effects that may warrant attention under specific contexts. Therefore, these are mostly indicators from Group A, as well as some from Groups B and C. Indicators should not be interpreted in isolation – appropriate monitoring will vary by monitoring purpose, site, scale, governance context, community values, and available resources and constraints as discussed further in the next chapter.[74,75,86]

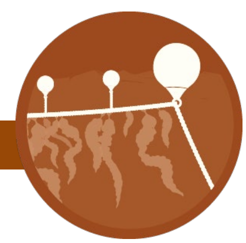
Each table summarizes what the indicator measures, why it may be useful, how it could be monitored and whether monitoring programs or data already exist, and who may be able to contribute to monitoring for this indicator.

WHAT? describes the indicator, the environmental effect it represents, and example metrics that may be used to measure it.

WHY? explains how it could produce actionable information for environmental management, operations, permitting, certification, adaptive management, or broader learning.

HOW? outlines potential methods, monitoring frequencies, relative costs, technical complexity, and examples of existing programs or datasets in Alaska and British Columbia. Methods are generally presented from lower to higher field effort and technical complexity, rather than as a strict ranking of scientific quality. Frequencies and cost or complexity ratings are indicative and should be adapted to the monitoring question, site, available capacity, and required strength of evidence.

WHO? identifies some organizations, programs, researchers, or other partners that may contribute data, expertise, coordination, or analytical support. These examples are not exhaustive and do not assign monitoring responsibility.



Farm Infrastructure

WHAT	**Description:** Infrastructure characteristics of the seaweed farm. **Metrics:** **farm size, gear type, cultured species, farm density in an area**	
WHY	**Relevance:** Required by regulatory agencies in both Alaska and British Columbia to issue permits for farm leases, informed by Indigenous (with a duty to consult in British Columbia) and public comments on size, location, and gear type.[48,59] Farm size will have size-dependent effects on benefits or impacts of seaweed farming.[95] Gear type will influence the farm's habitat features, though may be less relevant for assessing effects of farming on nutrients or biomass compared to other factors like site location.	
HOW	**Methods:**	Reporting of farm structure, gear, and cultivated species; within reporting, consider submitting key metrics in numeric, machine-readable format
HOW	**Frequency:**	At minimum, once during permitting process through submission of farm designs and maps (e.g., site plan maps required in both regions). Collect data seasonally if structure changes.
HOW	**Relative Cost:**	Low; data is already documented as part of the permit application process.
HOW	**Complexity:**	Low as values of farm infrastructure metrics are usually already documented during permitting process.
HOW	**Existing Programs and Data:** **Alaska:** AOOS Mariculture Map, ADF&G Aquatic Farming Operations Mapper **British Columbia:** Data request to British Columbia Ministry of Agriculture and Food, summarized in this report	

WHO

Potential Monitoring Partners: Already documented as part of permit application, but modifications to the permit application process (e.g., centralizing numeric reporting in a fillable spreadsheet) would help to make this data more accessible for analysis.

Farmed Biomass

WHAT

Description: The total mass of seaweed produced by a farm, where the biomass per foot of seeded line will influence habitat provision,[78] light attenuation,[83] and organic matter contributed to water and sediment.[95,172]

Metrics: **% permitted area used, wet weight, length of seeded line, seed spool quality, biomass density in set area**

WHY

Relevance:

Alaska: ADF&G and ADNR require annual harvest permits from aquatic farmers including total sale by species, footage of seeded line or poundage of seed, and amount of stock added during outplanting.

British Columbia: British Columbia Ministry of Aquaculture requires annual reporting of wet weight (tons) of seaweed harvested.

HOW

Methods:	Direct biomass sampling, wet weight at time of harvest; documentation via drone or aerial photos, visual rating (e.g., GreenWave's Seed Spool Quality Grading Guidelines)
Frequency:	Monthly, seasonally.
Relative Cost:	Variable depending on methods and site location (e.g., drone or aerial photos may be expensive at remote farms)
Complexity:	Low as biomass metrics are already measured by farmers as a part of their general operations to track growth and yield for the purpose of optimizing operations.

Existing Programs and Data:

Alaska: Data collected annually by ADF&G (accessible on their webpage), MyKelp App run by The GreenWave Kelp Climate Fund (monthly measurements of blade length and weight).

British Columbia: British Columbia Ministry of Agriculture and Food collects annual harvest data (wet weight in tons of harvested kelp, aggregated by company or species) with data available upon request.

WHO

Potential Monitoring Partners: The GreenWave Kelp Climate Fund has worked with participating farmers to collect data to the MyKelp App. Mar ReCon monitors kelp biomass on production arrays. The MaPP Regional Kelp Monitoring Project supports community-based wild kelp monitoring using standardized protocols, though they do not monitor farms themselves. Wild kelp beds are also tracked by many individual First Nations, including the Council of the Haida Nation Marine Planning Program.

Habitat Use

WHAT

Description: Seaweed aquaculture can transform the marine environment by introducing novel 3D structured habitat via buoys, lines, platforms, and kelp biomass.[78,79] This can be used by some flora and fauna (especially low- to mid-trophic level fish species and juvenile fish) as habitat[79,105] but may displace others (those not adapted for midwater structured habitats).[78,79] Physical presence of kelp biomass can alter hydrodynamics by slowing flows,[78,79,116] offering refuge for animals to reduce energy expenditure[79] and recruiting larvae.[78]

Metrics: **presence, residence time, feeding, sheltering from current or predators, spawning and rearing, growth and survival.** [72,78,79]

WHY

Relevance: Baseline biodiversity surveys prior to start of operations can inform siting and help minimize impacts of farm location, extent, and density of gear.[27,78] Quantitative evidence on habitat use can demonstrate adherence to licensing or certification standards and support social license.[78] Understanding when specific species are at critical life stages (e.g., herring spawn) allows farmers to adjust harvest schedules to minimize impacts.[78] Ongoing monitoring can inform adaptive management to mitigate undesired habitat uses.[78,173]

HOW

Methods:	Evidence of habitat use, and benefits is challenging to establish and requires documenting and interpreting behavior or diet over time. Methods include diver or snorkel surveys (limited time window),[72,78] unbaited or baited underwater video (limited field of view, visibility, data storage, and time or technology-intensive image interpretation),[67,70,82,88,174] acoustic monitoring using sonar,[50,51,175] destructive sampling by fishing[88,99] that may be paired with eDNA to understand

HOW

presence and identify gut contents, alongside visual analysis to distinguish eDNA of directly consumed prey from diet of prey itself).[176–181] See **BOX 2** for more comparison of methods for monitoring key indicators.

Frequency: Weekly, monthly, seasonally.

Relative Cost: Costs range widely (e.g., dive surveys are inexpensive if self-led or expensive if hiring divers, underwater cameras can be mass-produced and inexpensive (e.g., GoPros) or custom-built and expensive, and may require fee-based proprietary software for image analysis, eDNA sample analysis is becoming less expensive).

Complexity: Varies by metric, but moderately complex with some possible for farmers to collect with support from scientists, though documenting underwater habitat use is more technically difficult, labor intensive, and costly.

Existing Programs and Data:

Alaska: Mar ReCon monitors pelagic fish interactions using imaging sonar (120 kHz) and GoPro cameras, with results to date indicating fish (dominated by smaller fish species) encounters are higher during fall sampling compared to spring sampling at farms.[50,51] There are also Pacific herring spawning on kelp farms in Alaska.[173] Mar ReCon also conducts quarterly dive surveys to assess invertebrate and benthic fish communities in and around kelp farms and NOAA Auke Bay Laboratories conducted a study on fish and invertebrate use of kelp farms seasonally in Southeast Alaska using dive visual surveys and eDNA.

British Columbia: Research and monitoring for habitat use has been done, or is being done, using eDNA and baited remote underwater video (BRUV) setups[61,182] as well as diving or snorkeling surveys[61]. Underwater cameras have been used to collect over 9,000 hours of footage subsequently analyzed to identify species, also potentially (but not yet reported) capturing behavior related to habitat use.[67,80]

WHO

Potential Monitoring Partners: Several entities monitor or provide information on habitat use, including the Mar ReCon, Alaska ShoreZone, British Columbia ShoreZone, and DFO (e.g., pelagic acoustic surveys and subtidal surveys). The Council of the Haida Nation Marine Planning Program and Marine Plan Partnership (MaPP) for the North Pacific Coast track habitat use of wild kelp but not farmed kelp. Relevant expertise and support could also come from eDNA research labs (e.g., University of Victoria) and funders (e.g. Genome BC, Genome Canada).

Epibiota Biodiversity

WHAT

Description: Species living on seaweeds and farm infrastructure such as bryozoans and mussels (sessile) or marine snails (mobile) that contribute to biofouling and can inhibit photosynthesis or growth and weigh down lines),[39,56,78,96,176,183] biosecurity (infrastructure acts as substrate for fouling marine invasive species, facilitating spread),[39,73,82,95,184–186] and habitat or food provisioning (linked to **Habitat Use** indicator).[78,82,87,90,183]

Metrics: Sessile[87,183] **and mobile epibiont abundance,**[87,96,183] **taxa richness/diversity,**[72,84,87,183] **epibiont biomass**[84,87,88,183]

WHY

Relevance: Biofouling and invasive species can have impacts on crop quality and local ecosystems. A marine integrated pest management approach hinges on epibiota data to assess pest or disease presence based on physical drivers (e.g., currents)[82,83,96] and biological drivers (e.g., species life cycles),[96,176,187] and identify environmental impacts to crops.[187] Monitoring epibiont larval supply, biofouling, and pest detection provides an "early detection" warning that informs operations and harvest timing (e.g., before product quality is compromised by fouling).[56,82,176,183] These data can help assess infestation potential and economic impact to support decision-making, [96] which may inform broader discussions about biosecurity risk and management.[73]

HOW

Methods: Direct visual observation or collection of epibiota biomass at surface or during harvest,[72,82,87,183] ,[176–179] invertebrate collector devices,[72,84,177,188] plankton tows,[56,176] – all these visual methods requires taxonomic expertise for ID; eDNA analysis of farmed tissue, swabs of gear, or settlement plates preferred over water samples for epibiota – often identifies greater range of species than visual observation, but may be limited by gaps in genetic reference databases.[177,189]

Frequency: Weekly, monthly, or seasonally (consistent and time-sensitive for early warning monitoring to be effective).

Relative Cost: Moderate; can be sampled with minimal expertise, but requires scientific / taxonomic knowledge for species ID.

Complexity: Moderate technical experience and time (e.g., photos for % cover, preservation of blade samples, etc.).

HOW

Existing Programs and Data:

Alaska: Epibiota monitoring of farm infrastructure on oyster farms is part of the Mar ReCon program[50,51], with some methods potentially transferrable to kelp farms.

British Columbia: Epibiota are regularly monitored by DFO and regional partners to assess risk of invasive species colonization based on location. Invasive species monitoring includes deployment of settlement plates (with data archived in the Ocean Biodiversity Information System, also contains information on native species and relative abundance of fouling across space and time) and eDNA assays and have been used to develop species distribution models.

WHO

Potential Monitoring Partners: Collaborators monitoring or studying biofouling including the Mar ReCon program, MaPP Regional Kelp Monitoring Project, Council of the Haida Nation Marine Planning Program, and DFO. Relevant expertise and support could also come from eDNA research labs (e.g., University of Victoria) and funders (e.g. Genome BC, Genome Canada).

Fish Biodiversity

WHAT

Description: Fish presence and diversity may be influenced by kelp farms, with kelp farms functioning as 'restorative' or 'regenerative' habitats,[72,100,190] and can provide ecological benefits such as refugia, nursery areas, and feeding grounds.[79,88] Fish biodiversity can be paired with **Habitat Use** indicator to understand farm benefits for fish.[82,83]

Metrics: Species / taxonomic richness,[88,191] Shannon Diversity Index,[191] community composition or assemblage structure,[83,88,177,191] abundance counts of mobile fauna.[67,88,174]

WHY

Relevance: Data on **fish abundance and diversity** can inform farm infrastructure design and refinement (to either minimize habitat disruption or maximize habitat provision)[27,74,191] and harvest timing (to minimize disruption to key fish life stages, although harvest timing is also driven by market demand).[173] Fish abundance and diversity data can also provide evidence for ecological benefits (i.e., farms as regenerative habitats)[79,88,190], which can influence management practices and social license.[39,55]

HOW

Methods:	eDNA sampling[100,192–194] can detect fine-scale (down to ~5 m) spatial and depth differences in kelp-associated communities and recover a broader range of species with less field effort than conventional visual surveys [176–179,195,196]. Its spatial precision can decline in areas of very high currents or wave action [194], but farms are rarely sited in these conditions[81,197]. More labor intensive methods include direct observation via snorkel / SCUBA surveys, destructive sampling (e.g., fishing),[72,78,88] unbaited and baited underwater video,[67,70,82,88,174] acoustic monitoring (e.g., imaging sonar).[50,51]
Frequency:	Monthly, seasonally.
Relative Cost:	Moderate; video monitoring costs vary with equipment costs (e.g., inexpensive GoPro, custom-designed systems) and time or proprietary software fees spent on video analysis. eDNA methods are relatively inexpensive and becoming less expensive.
Complexity:	Low technical experience and time for sampling; can be completed with eDNA methods from surface sampling or dive surveys (less temporal coverage and data to process, but high technical expertise required to interpret eDNA data so must be done by lab), or automated video monitoring (greater temporal coverage but intensive data processing, could leverage AI-assisted image analysis).

Existing Programs and Data:

Alaska: Mar ReCon monitors fish presence, diversity, and habitat use using sonar sampling and eDNA, with preliminary results (as of 2024/2025) indicating fish (dominated by smaller fish species) encounters are higher during fall sampling compared to spring sampling at farms.[50,51] Other studies have characterized nearshore fish communities across different habitat types in Southeast Alaska,[198] and collected eDNA data to link salmon presence and abundance to factors like site and oceanographic conditions.[199]

HOW

British Columbia: Cameras deployed by Cascadia at their farms have collected over 9,000 hours of footage, monitoring fish populations inside two kelp farms and reference sites.[67,200] Baseline data is also available on general local fish biodiversity, including rockfish,[201] juvenile salmon,[202] and subtidal surveys (using subtidal methods[203] or alternative methods[204]). Standardized snorkel and video methods for monitoring fish in wild kelp forests have been developed and may be useful for reference site data collection.[205]

WHO

Potential Monitoring Partners: Several initiatives monitor(ed) fish biodiversity, including the Mar ReCon, Alaska ShoreZone Mapping Website, British Columbia ShoreZone, DFO (e.g., pelagic acoustic surveys and subtidal surveys), and NOAA.[173] Relevant expertise and support could also come from eDNA research labs (e.g., University of Victoria) and funders (e.g. Genome BC, Genome Canada).

Nutrients in Seawater

WHAT

Description: Nutrients in seawater are primarily dissolved nitrogen-, phosphorus-, and carbon-based compounds (e.g., nitrate, phosphate, bicarbonate). These nutrients drive (and limit) seaweed biomass and quality,[52,122,206–208] with productivity in the inner shelf region of the eastern North Pacific being typically high from March to May and falling off from spring into summer.[27,122,206] Dissolved nutrients (particularly nitrate) are often negatively correlated with seawater temperature and are thus affected by climate change.[209,210]

Metrics: dissolved inorganic nitrogen (nitrate, nitrite, ammonium, or total nitrogen), dissolved inorganic phosphorus [52,122,206,211]

WHY

Relevance: Baseline surveys prior to start of operations can help assess site suitability (given heterogeneity of nutrient availability across regions),[52,117,122,206,211] and ongoing monitoring can inform design decisions such as line spacing (to mitigate nutrient depletion and kelp starvation)[117,122,206,212] and optimal harvest timing (given seasonal decline in nutrients).[52,122,206,209] Seawater nutrient data is important for parametrization and validation of models (e.g., Macroalgal Cultivation Modeling System, MACMODS)[117], and supporting marine spatial planning initiatives informed by evidence of ecological carrying capacity.[213–215] This information can be used to examine nutrient dynamics associated with farming and, where appropriate, help address questions about farm effects on local nutrient availability.[53,105,206,213,216–219]

HOW

Methods:	Standardized field sampling (Nutrient Extraction Toolkit).[52,53]; seawater sampling and lab analysis (for dissolved nutrients),[53,206,211] smart buoys with real-time in situ nutrient measurements.[70]
Frequency:	Weekly, monthly, seasonally.
Relative Cost:	Low; farmers can help collect samples and processing is inexpensive with the appropriate laboratory.
Complexity:	Low as farmers can help collect samples and processing is easy with the appropriate laboratory.

Existing Programs and Data: AOOS Mariculture Map shows locations of permitted sewage outfalls and seafood processing discharge locations (source of nutrients and potential opportunity for bioremediation).

Alaska: Gulf of Alaska Regional Oceanic Model System data on nutrients accessible via AOOS Data Portal. Ongoing water quality monitoring with stations near existing farms by NOAA Fisheries and Alaska Department of Environmental Conservation.

British Columbia: DFO's Institute of Ocean Sciences conducts long-term water quality monitoring via rosette bottle water samples, with point data compiled in the CIOOS Data Portal under IOS Rosette Bottle Data.

WHO

Potential Monitoring Partners: Oceanographic monitoring is done by DFO, the CIOOS, AOOS, NOAA, and Mar ReCon. Seawater nutrient monitoring could be useful to pair with data from regional harmful algal bloom (HAB) monitoring programs including the Alaska Harmful Algal Bloom Network associated with AOOS and British Columbia's We All Take Care of the Harvest (WATCH) community-based HAB monitoring program. In British Columbia, First Nations stewardship programs may also be conducting marine water quality monitoring or testing in their territories.

Nutrients in Seaweed Tissues

WHAT

Description: Nutrient content of kelp tissue is shaped by environmental concentrations and conditions as kelp absorbs nutrients directly from the surrounding seawater.[52,206,209] Nutrients in tissue determine nutritional quality,[52,206,209] and nutrient content of kelp can affect provisioning and nutrient cycle benefits as well as influence primary consumer behavior (linked to higher trophic levels).[209] Kelp act as a source of organic matter to benefit oysters and mussels) and mitigate eutrophication (by nutrient removal).[52,122,206]

Metrics: tissue nitrogen (N), carbon (C) and phosphorous (P), carbon-to-nitrogen ratio (C:N), stable isotope signatures ($\delta^{15}N$, $\delta^{13}C$).

WHY

Relevance: Similar to monitoring nutrients in seawater, monitoring nutrients in kelp tissue can inform design adjustments such as line depth (in-season), line spacing (between seasons)[53,122], and optimal harvest timing (as tissue N concentrations decrease later in the growing season).[52,206] This information can be used to examine nutrient dynamics associated with farming and, where relevant, contribute to broader assessments of nutrient uptake as an ecosystem service, including exploratory considerations of payment for ecosystem services under appropriate site- and scale-specific conditions.[220–222]

HOW

Methods:	Standardized sampling (Nutrient Extraction Toolkit).[52,53] ; alternative standardized sampling (tissue collection and lab analysis),[53,122,211] elemental analysis for C, N (using elemental analyzer or continuous-flow isotope-ratio mass spectrometer [CF-IRMS]),[122,206,209,211] stable isotope analysis for $\delta^{15}N$ and $\delta^{13}C$ (CF-IRMS coupled to elemental analyzer),[51,122] dry mass and ash determination for salts, metals, minerals (gravimetrically then by combustion).[206]
Frequency:	Monthly, seasonally.
Relative Cost:	Moderate; field sampling inexpensive but laboratory analysis can be more costly.
Complexity:	Moderate as farmers can assist with sample collection and processing is easy with the appropriate laboratory.

Existing Programs and Data:

Alaska: Current monitoring for nutrients in kelp exists in Alaska. The University of Alaska Fairbanks has conducted nutrient analysis (%C and N) in seaweed tissue at multiple sites throughout Alaska (Kodiak, Prince William Sound, and southeast Alaska) as part of Mar ReCon. [98] The Alaska Fisheries Development Foundation has also published a detailed seaweed tissue analysis reporting levels of nutrients, heavy metals and iodine, carbohydrates, and bioactive compounds for multiple species.[223]

British Columbia: Not at farms, but useful as a baseline study, Hakai Institute researchers have measured mean %N per mg tissue in kelp in response to environmental conditions at sites on the Central Coast of British Columbia.[224]

WHO

Potential Monitoring Partners: University of Alaska Fairbanks; Hakai Institute.

Contaminants in Seaweed Tissues

WHAT

Description: Seaweeds are known to accumulate contaminants like arsenic, iodine, and heavy metals (e.g. Cd, Pb, Hg, Cu)[111,225–227] from the environment (e.g., via ongoing or legacy contaminants from urban runoff,[228] mine and pulp mill effluent,[126,127,229] and routine discharges from marine shipping[230]). Concentrations may exceed safe levels for human consumption.[231] Some contaminants may also transfer to consumers like sea urchins[115] or shellfish.[112]

Metrics: heavy metal concentrations in mg / kg dry weight (e.g., cadmium, total and inorganic arsenic, lead, mercury). [111,112,226,227,231]

WHY

Relevance: Ambient contamination levels can inform site selection and design by selecting sites away from areas with known high legacy or ongoing contamination.[225,226,231] Monitoring is critical for food safety protocols to minimize risk to human health from consumption.[111,112,225,226] If high levels of contaminants are detected, this information can inform selective harvesting (e.g., if concentrated in the young tissue at base of kelp blades) and additional processing techniques (e.g., inorganic arsenic may require blanching to reduce levels in kelp tissues).[231]

HOW

Methods:	Tissue sample collection and preparation (following protocols to limit contamination, shipped on ice to a lab)[111,112,227,231] followed by chemical analysis (e.g., gas chromatography and mass spectrometry).[111,112,231]
Frequency:	Monthly, seasonally; periodic or event-triggered sampling with frequency dependent on site conditions, production scale, and regulatory context.
Relative Cost:	Moderate; tissue sample collection has low labor and equipment costs; lab analysis is more expensive.
Complexity:	Moderate as tissue samples can be easily collected, though samples must be processed or analyzed in a lab with more technical experience and time.

HOW

Existing Programs and Data:

Alaska: Current monitoring for heavy metals in kelp tissues exists in Alaska.[98] NOAA National Mussel Watch Program and National Park Service monitor chemical contaminants in marine environments, with trace metals detected at 100% of sites analyzed between 2007 and 2018.[232] Other monitoring of kelp tissue has found Cd, Pb, and Se present at levels suggesting potential impacts to human consumers.[227] Alaska waters are naturally rich in heavy metals (As, Cd, Hg) and Formerly Used Defense Sites need to be considered as some are still leaching metals of concern.[145] The Alaska Fisheries Development Foundation has also published a detailed seaweed tissue analysis reporting levels of nutrients, heavy metals and iodine, carbohydrates, and bioactive compounds for multiple species.[223]

British Columbia: Monitoring in the Salish Sea consistently detected total Cd and As, with total As exceeding US risk-based screen levels.[111] Ocean Wise and the Pollution Tracker program tested marine sediments (and mussel tissue) for contaminants between 2015 and 2023, providing baseline information on distribution and biological uptake of contaminants across British Columbia coast published in a final technical report[233], scientific publications[126,127], and data available on request.

WHO

Potential Monitoring Partners: Ocean Wise (operating the Pollution Tracker program), NOAA.

Marine Debris and Plastics

WHAT

Description: Like other marine infrastructure, kelp farm infrastructure may shed plastic debris and microplastics (< 5 mm)[149,234] from synthetic, non-biodegradable polymers[235] such as ropes, longlines, buoyant balls, and nets.[235] These plastics (rope in particular) may be embrittled by UV exposure and abrasion, leading to the shedding of microplastics.[236,237] Plastics adsorb some types of contaminants (including some that are Persistent Organic Pollutants and Persistent, Bioaccumulative Toxic compounds) and can degrade and leach chemical additives (e.g., phthalates and Bisphenol A).[234] Kelp itself can also accumulate and become a vehicle for microplastics and contaminants into food webs.[136,238,239]

Metrics: **microplastic abundance in biota,**[149,234] **microplastic concentration in water,**[240,241] **particle size and shape,**[149,234] **polymer composition,**[149,234,238] **plastic mass and recyclability rank.**[242,243]

WHY

Relevance: Monitoring plastic release from farms helps confirm sources of plastics and support development of management measures targeted to primary sources,[136,149,235] inform material choice to maximize recyclability[242,243] and minimize plastic release,[235,236,244] and inform human health risk assessment from consumption.[234,238] Data can inform gear marking standards to enhance traceability, prevent illegal dumping, and support Extended Producer Responsibility strategies;[242,243] however, these measures target debris recovery and not the microplastic shedding that continues from gear while still in use, which is driven more by material choice.

HOW

Methods:	Visual inspection for gear damage or loss via debris management plans, water sampling and filtering (e.g. 10 µm)[240,241,245] following protocols to avoid contamination (e.g., control samples, plastic-free equipment)[149,234,246]; biota sampling and chemical or enzymatic digestion (e.g., Fenton's reagent) followed by filtering,[234,247,248] spectroscopic analysis (via Fournier Transform Infrared Spectroscopy [FT-IR] or micro-FT-IR)[136,234]
Frequency:	Seasonally. Periodic or event-based, particularly following storms, gear damage, or maintenance activities.
Relative Cost:	Moderate; tissue sample collection has low labor and equipment costs, while lab analysis is more expensive.
Complexity:	Moderate as tissue, water, beach, and sediment samples can be easily collected, however, samples must be processed and analyzed in a lab (e.g., microscopy).

Existing Programs and Data:

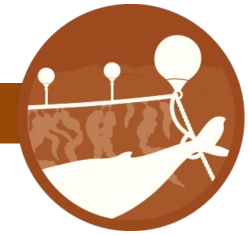
Alaska: NOAA's Office of Response and Restoration operates a Marine Debris Program, with a data repository collaboratively managed with the National Centers for Environmental Information and have studied microplastics in Alaska.[249]

British Columbia: The Ocean Wise PollutionTracker program tested marine sediments and mussel tissue for microplastics between 2015 and 2023, providing baseline information on distribution and biological uptake of contaminants across the British Columbia coast, where microfibers < 1000 µm were found to be the dominant shape, with polyester and polyethylene the dominant material.[149,233,240] NOAA's National Centers for Environmental Monitoring microplastics database and web map include British Columbia entries.

WHO

Potential Monitoring Partners: Ocean Wise and marine debris and ghost gear projects operated by DFO, NOAA, other local organizations, and community shoreline cleanup initiatives.

Entanglement



WHAT

Description: Interactions between marine fauna, like marine mammals and seabirds, and farm infrastructure like longlines, anchor lines, or buoys that may result in injury, restricted movement, or mortality.[128,141]

Metrics: **Wildlife presence and behavior near farms, confirmed entanglement events, evidence of gear interaction or injuries, incidents reported by official response networks** [50,51]

WHY

Relevance: Although entanglement incidents in seaweed farming are globally rare, the issue is closely scrutinized due to the severity of potential outcomes and public concern. [70,128,129,141,250] Seaweed farms generally pose lower entanglement risk than finfish aquaculture or some fishing gear due to higher line tension and strategic site selection (avoiding foraging areas or migration routes). [71,95,251,252] Nonetheless, migratory marine mammals like grey and humpback whales frequently occur in farming areas, elevating perceived risk even where empirical evidence is limited. Reporting entanglement incidents will mobilize marine mammal response teams in Alaska and British Columbia to support individual disentanglement, and help track potential entanglement trends across the region. Protecting endangered, threatened, or protected species is also a consideration for sustainability certification requirements (e.g., Marine Stewardship Council [MSC]).

HOW

Methods:	Opportunistic visual observations during routine site visits, recording of marine mammal presence; mandatory reporting of entanglement incidents; optional use of remote cameras or shore-based observations in high-use areas.
Frequency:	Ongoing informal observation during normal farm activities, with formal documentation and reporting triggered if entanglement or credible evidence of interaction is observed.[103]
Relative Cost:	Low
Complexity:	Low

Existing Programs and Data: There is **regulated mandatory reporting of marine mammal incidents** through existing programs complemented by regional marine mammal population and health monitoring programs in both regions.[129,250]

Alaska: Marine mammal incidents are reported through NOAA and Alaska Department of Fish and Game (ADF&G). Habitat use data exists from surveys,[253,254] NOAA's Cetacean and Sound Mapping initiative and US Navy Marine Species Density Database, but the focus is on offshore areas. Mar ReCon is also studying seaweed farm specific wildlife interactions through seabird surveys, geo-linked marine mammal and gear damage, and time-lapse trail cameras at seal haulouts near farm sites.[50,51]

British Columbia: Incidents are reported through DFO and its partners (e.g., British Columbia Marine Mammal Response Network); habitat use is tracked via systematic government surveys[255–257] and citizen science monitoring (e.g., Ocean Wise Sightings Network).[258,259]

Other: Global data on marine mammals like the Ocean Biodiversity Information System (OBIS) Spatial Ecological Analysis of Megavertebrate Populations (SEAMAP) may help to fill gaps in regional datasets.

WHO

Potential Monitoring Partners: Event-based reporting by farmers, federal agencies, regional conservation organizations, data collection programs run by whale watching operators.

Genetic Influence

WHAT

Description: The potential for farmed seaweeds to influence the genetic diversity, structure, or local adaptation of wild populations via spore and tissue dispersal or repeated use of limited broodstock.[74,260–262]

Metrics: **Broodstock source compliance** (distance, number of parent plants), **genetic structure and diversity metrics** (e.g., allele richness, heterozygosity) of farmed and wild populations to assess differentiation and gene flow, frequency of **non-local or selectively bred genotypes**[263–267]

WHY

Relevance: The release of reproductive material (spores) from farmed kelp into the environment is considered one of the most concerning potential environmental impacts of seaweed farming.[71,74,95] Both Alaska regulations and British Columbia guidelines emphasize the use of locally sourced wild broodstock to minimize impact, but focus on inputs and not outcomes.[48,59] In addition, MSC certification requires third party auditors to report on genetic impact on wild populations. [268] Studies to date have found little evidence of genetic influence of farmed kelp on nearby wild populations,[263,265,266] but documented instances of long-distance dispersal of kelp provide a pathway for gene flow even under precautionary seed sourcing rules.[269]

WHY

Genetic impacts are expected to be highest in areas with small wild populations as introduced genetic material has a greater potential to 'swamp' local genetic diversity.[77] As interest grows in domestication, strain selection, and gametophyte culture to improve yield and crop reliability, genetic monitoring can play a role in addressing compliance-related questions associated with cultivation practices, detect potential cumulative effects on wild population diversity, and inform future policy.[27,50,77,262,270] Genetic monitoring can also inform predictions of climate risk and identify more resilient seaweed strains.[77,271,272]

HOW

Methods:	Documentation of broodstock collection practices, periodic tissue sampling and genetic comparison of farmed kelp and adjacent wild populations using molecular markers (e.g., SNPs, microsatellites); integration with regional baseline genetic surveys, conducting such baseline surveys to fill gaps for cultivated species (e.g., genetic structure of sugar kelp in British Columbia, emerging cultivars)[146,273,274].
Frequency:	Annual reporting of broodstock practices; episodic genetic sampling (e.g., every 3-5 years or by discrete project)
Relative Cost:	Low for compliance documentation, farmer tissue sampling; Moderate-High for subsequent genetic analysis
Complexity:	Moderate - High

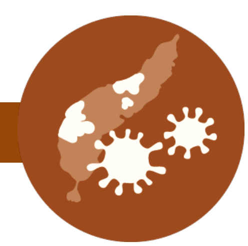
Existing Programs and Data: Both regions require documentation of broodstock sourcing requirements as part of the permitting process, although there is no documented evidence of verification through genetic or other means. Once genetic sampling and testing of farmed and wild seaweeds is mainstreamed, seed banks and wild genetic baseline studies of sugar kelp (Alaska only),[275] bull kelp,[276,277] and giant kelp[277,278] are available for comparison. With growing scientific understanding of kelp genetics, developing genetic-based guidelines for seed stock are of interest to practitioners and regulators in Alaska and British Columbia.[77]

Alaska: The Gene Conservation Laboratory at ADF&G collects genetic baseline samples for many species of commercial importance, including seaweeds, and makes them available on its Baseline Genetics Collections Mapper to support management that maintains their genetic integrity. Alaska kelp are represented in local gametophyte collections at nurseries as well as in two established seaweed seed banks in the US (Bigelow Laboratory's National Center for Marine Algae and Microbiota in Maine and Kelp Ark in California), and Kelp Ark and UAF have recently secured funding for further genetic studies and biobanking of Alaska strains of sugar, ribbon, and bull kelp.[121]

British Columbia: The Kelp Rescue Initiative (KRI) carries out population genomics studies of wild kelp, and also maintains a gametophyte collection along with other local researchers and producers, with ongoing collective efforts to secure funding for maintaining a coordinated de-centralized biobank network for kelp in British Columbia.[279]

WHO

Potential Monitoring Partners: Government agencies focused on molecular genetics of marine resources (e.g., ADF&G Gene Conservation Lab, DFO Molecular Genetics Lab), research organizations already studying kelp genetics (e.g., Kelp Rescue Initiative, GenomeBC, University of Victoria, Simon Fraser University, UAF), and farmers for gathering samples.



Disease

WHAT

Description: Disease monitoring addresses the presence, emergence, and spread of pathogens affecting farmed seaweeds, including bacterial, viral, and fungal agents. Disease can reduce crop yield and quality and may cause ecological impacts if pathogens spread to wild populations.[96]

Metrics: **Visual signs** of disease or abnormal tissue, **frequency and spatial distribution of disease observations**, **laboratory confirmation of pathogens** (e.g., isolation, culture, genetic evidence of infections)

WHY

Relevance: Seaweed diseases are not well studied in cold-water aquaculture systems, particularly in North America.[101,280–282] Nonetheless, several pathogens of regionally cultivated species and their relatives have been documented elsewhere.[280,282–285] As macroalgal cultivation intensifies globally, the frequency and severity of disease outbreaks are expected to rise, and recent observations of novel disease symptoms in kelp nurseries in the region underscore the need for improved early detection and information sharing.[101] Disease may impact sales of farmed seaweed depending on the end market (e.g., food product).

HOW

Methods:	Visual inspection of kelp for abnormalities in nursery, harvest, and processing; requires robust reference materials, training, and a reporting mechanism to enable identification by farmers[286]; laboratory confirmation of pathogens from abnormal tissue samples,[281,285,286] baseline research on farmed and wild seaweeds for signs of already circulating diseases without visual signs[284,287]
Frequency:	Continuous passive surveillance, event-based reporting and investigation (on signs of disease)
Relative Cost:	Low for visual inspection, farmer tissue sampling; Moderate-High for pathogen investigations in laboratory
Complexity:	Moderate - High

Existing Programs and Data: There are no published or ongoing initiatives studying seaweed pathogens in the region, other than a research project that sought to isolate a pathogen associated with detection of the novel pink-spot disease in North American kelp nurseries through stakeholder surveys, opportunistic sampling, and laboratory analysis.[285]

Other: Surveillance and reporting during operations could follow the citizen science reporting model from the community-based "My Seaweed Looks Weird" pathogen monitoring initiative piloted in Scotland and Chile.[286]

WHO

Potential Monitoring Partners: Building awareness and capacity for studying seaweed pathogens at regional research organizations focused on pathogens in aquatic resources, but not necessarily studying seaweeds yet (e.g., Fish Pathology Laboratory at ADF&G, Marine Microbiology and Virology Lab and Parfrey Lab at University of British Columbia); collaborating with the developers of existing citizen science apps to facilitate reporting (e.g., GreenWave's My Kelp app).[121]

Water Quality and Flows

WHAT

Description: Water quality variables are physical and chemical indicators that allow practitioners to contextualize other indicators. These broadly include temperature, salinity, acidification, dissolved oxygen (DO), light, turbidity, flow, and wave energy. These indicators are measured directly through standard oceanographic monitoring and may also involve data collection at reference or control sites. They may interact with other indicators (e.g. nutrient availability, disease dynamics) or influence other farming concerns like biofouling. [82,124,156,213,288]

Metrics: temperature (i.e., sea surface temperature), salinity (i.e., dissolved salt concentration), DO, pH (pCO_2 dissolved CO_2), light (e.g., Photosynthetic Active Radiation [PAR]), flow and current (velocity, direction, wave height)

WHY

Relevance: Integrating physical, chemical, and biological monitoring improves interpretation of observed changes in growth, health, and farm performance.[82,124] Environmental context helps practitioners interpret other monitoring results and attribute effects to the farm rather than external confounding factors (i.e., rule out effects caused by broader environmental changes not attributable to a farm site). These variables can also inform site selection and harvest timing.

HOW

Methods:	HOBO data logger for water temperature and water quality parameters[39], clod cards or acoustic Doppler current profilers (ADCP)s for measuring flow and current where resources allow.[103] Reference site monitoring (to establish a control) can be accomplished by piggybacking monitoring activities to visit wild beds to collect parent material.
Frequency:	Continuous monitoring with deployed sensors, or sampling daily, weekly, monthly, seasonally if not continuous depending on objectives.
Relative Cost:	Low – medium; many of these variables can be monitored with inexpensive deployable equipment.[50,51,83]
Complexity:	Low to moderate as deployable sensors require low technical experience, though pH, wave and flow data may require some technical analysis.

Existing Programs and Data: Basic oceanographic monitoring of light, flow, temperature and salinity are routinely collected by many farmers in both regions via HOBO data loggers, conductivity, temperature and depth probes (CTDs), and Acoustic Doppler Current Profilers (ADCP), and Secchi disks.[39,60,98,102,103]

Alaska: Temperature and salinity data available through government, academia, and community-based monitoring programs such as Gulf Watch Alaska (e.g. Prince William Sound), Mar ReCon, Alaska Ocean Acidification Network, AOOS, UAF's Ocean Acidification Research Center, and Gulf of Alaska Ecosystem Observatory. An autonomous profiler in Prince William Sound collects turbidity data, as do the Alaska Department of Environmental Conservation and Alaska Center for Conservation Science. Flow and current data is available from the National Data Bouy Centre run by NOAA.

British Columbia: Water quality and light data from DFO's Coastal Environmental Baseline Program, DFO's oceanographic monitoring, MaPP Kelp Monitoring Program and 12 light stations collecting daily temperature and salinity measurements. Platforms that host data include CIOOS and Ocean Networks Canada Oceans 3.0 hub. Flow and current data are available from the National Data Bouy Center run by NOAA (some British Columbia sensors).

WHO

Potential Monitoring Partners: Several governments and initiatives running ongoing environmental monitoring including University of Alaska Fairbanks, Alaska Department of Environmental Conservation, Alaska Centre for Conservation Science, NOAA, DFO, CIOOS, and the Marine Plan Partnership for the North Pacific Coast (MaPP).

Photo of kelp farm water nutrient monitoring courtesy of Schery Umanzor

Part IV – Applying Chosen Indicators in Monitoring Programs

Part IV explores how prioritized indicators can be applied in practice. It introduces key considerations for designing monitoring programs, including monitoring objectives, farming stage, sampling methods, and study design, recognizing that effective monitoring depends on matching indicators and sampling approaches to specific questions, decision needs, and operational contexts.

Practical Considerations for Monitoring Implementation

Selecting environmental indicators is only the first step in designing an effective monitoring program. Individual indicators—such as nutrients, fish abundance, or biofouling—provide pieces of information, but on their own they rarely answer the questions that farmers, regulators, or researchers need to make decisions.

Effective monitoring begins by defining the management questions to be answered. Once these questions are clear, practitioners can develop a **monitoring strategy**, an overall plan that identifies what information is needed, who will use it, and how the results will inform decisions. The strategy is then translated into a **sampling design**, which specifies exactly which indicators will be measured, where, when, how often, and using what methods so that the resulting data is scientifically defensible and fit for purpose. [289,290]

This chapter provides practical guidance for designing fit-for-purpose monitoring programs around specific management questions, decision needs, and required levels of evidence. The appropriate indicators, sampling locations, methods, timing, frequency, and level of effort will vary depending on the monitoring objective, farm context, regulatory requirements (see **BOX 1**), available resources, and community priorities.

The chapter is organized around the key questions involved in designing a monitoring program. It first considers how monitoring objectives differ across the seaweed farming life cycle, from site selection through operations and post-harvest activities. It then discusses practical monitoring methods, and opportunities to streamline data collection across multiple indicators. It also describes approaches to sampling design for different objectives, including operational learning, detecting rare or high-consequence events, assessing causal relationships, and evaluating cumulative effects. Throughout, the emphasis is on generating actionable information that supports adaptive management while remaining practical, proportionate, and scientifically robust within ecological, operational, economic, and regulatory constraints. [74,75,86]

1. Identifying Monitoring Needs Across Stages of the Farm Life Cycle

Monitoring priorities often shift across the farming life cycle as practitioner questions and decision needs evolve over time (**Figure 2**).[105] Some indicators are most relevant during site selection and planning, while others become important during operations, harvest, or post-harvest activities to detect environmental change and support adaptive management. However, monitoring must be balanced with financial and logistical costs. This section considers indicators by the stages where they are expected to provide the greatest decision value.

Photo of surface water sampling at seaweed farm in Alaska, via NOAA

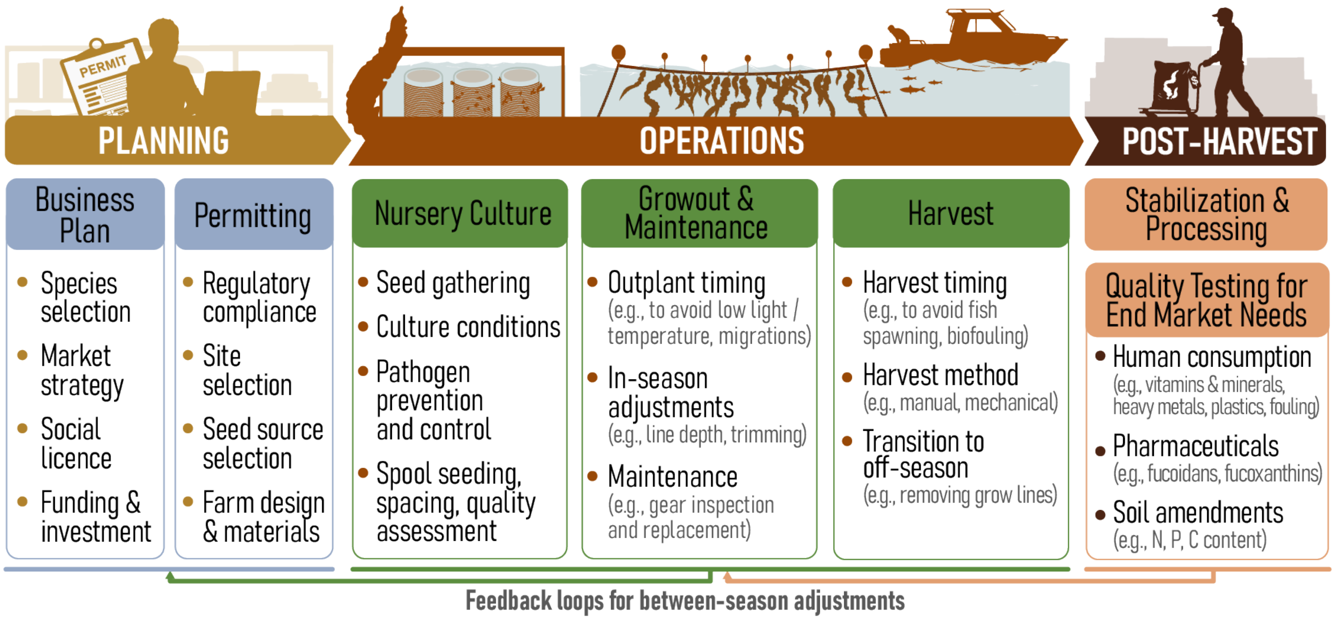


Figure 2. Some key stages in the life cycle of a seaweed farm and the activities and decisions associated with each.

Monitoring during the Planning Stage

Planning decisions related to species and site selection, farm design, permitting, financing, and community engagement strongly influence the environmental outcomes of seaweed farms.[291,292]

Importance: **Decisions made during planning, and particularly site selection, have a disproportionate influence on future environmental outcomes of seaweed farms.** Across interviews and workshops, practitioners consistently identified site selection as the most important factor determining whether environmental effects occur, and whether monitoring or mitigation is needed.[60,103,131,274,293] Existing permitting procedures in Alaska and British Columbia incorporate basic precautionary site-selection guidance to help avoid sensitive habitats, reduce interaction with wildlife, [74,146] and minimize hydrodynamic or benthic effects, preventing many potential impacts before farming begins.[27,39,47,48,103,130,146,294] Emerging regional research will help further refine general precautionary guidance for site selection by defining a more specific "sustainable operating window" for cultivation.[75] More robust site selection guidance also enables more detailed site-specific monitoring for focal indicators not mitigated by site selection, rather than blanket requirements to "monitor everything."[273]

Key Indicators: **Indicators relevant at this stage focus on baseline environmental suitability and avoidance of potential effects.** These include competing marine uses, physical conditions that can affect farm integrity and productivity (e.g., depth, exposure, circulation, temperature, nutrient availability), proximity to sensitive benthic habitats (e.g., wild kelp beds, eelgrass, or understory seaweeds) or species (e.g., fish spawning grounds, marine mammal foraging areas or haul areas, bird colony areas) that could be impacted by farms. Background contaminant and nutrient levels may also inform site screening and permitting due to their implications for product quality and safety.

How Data Informs Decisions: **Information used for planning and site selection typically comes from existing environmental baseline datasets, models, site selection tools and surveys (e.g., fish and fish habitat surveys), supplemented where necessary by one-off site suitability investigations**. These indicators inform decisions about site suitability, farm design considerations, and whether proposed locations present environmental or regulatory risks that warrant further evaluation. This data also supports sustainability assurance and messaging to regulators, investors, organic or sustainability certifiers, and consumers who have raised ecosystem impacts of mariculture as a concern. [22,295–297] Because these decisions are episodic and preventative, indicators of site suitability are not necessarily intended for ongoing monitoring.

Monitoring during the Operational Stage

Operational decisions involve seed sourcing, hatchery practices, outplanting and harvest timing, and farm maintenance.[27,43,44,101,173,298] Operational decisions are influenced by policy, environmental variability, genetic considerations, and seasonal ecological interactions, yet many of these relationships remain poorly understood. [27,43,44,101,173,298] Farmers may need to rely on experience rather than data to manage trade-offs between productivity, environmental effects, and regulatory constraints.

Importance: **Most operational decisions cannot be fully reversed within a season, but monitoring can inform adaptive management across seasons** by identifying patterns, trade-offs, and cumulative effects of practices.

Key Indicators: **Indicators such as farmed biomass and growth, biofouling dynamics, and habitat use by fish and invertebrates are most likely to respond to farming practices and may be the most informative for routine management decisions**, while data on the physical environment helps to interpret results. Additional indicators related to entanglement, genetic influence, and disease transmission can be used to monitor effects that are low in likelihood but high in potential ecosystem consequences, while yet other indicators address less likely, more variable, or more uncertain effects.

How Data Informs Decisions: **Operational monitoring supports decisions related to farm spacing, line depth and orientation adjustments, maintenance schedules, and harvest timing.** While some practices (e.g., timing of outplanting or harvest to avoid species spawning and migration windows, changing depth of lines to avoid biofouling or to increase biomass)[27,56,173,299,300] may be adjusted in season, more significant changes to species or farm designs are informed by monitoring outcomes from prior seasons, with the potential need for permit amendments.

Monitoring during the Post-Harvest Stage

Post-harvest decisions are often shaped by market requirements for specific biochemical compounds and economic or regulatory concerns.[223]

Importance: **Post-harvest decisions influence product quality, market access, and the ability to demonstrate environmental performance to regulators, buyers, and communities.** Although post-harvest monitoring is not the primary focus of this science synthesis, it plays an important role in connecting environmental outcomes to economic viability and certification requirements.

Key indicators: **Relevant indicators at this stage include tissue chemistry** of interest to end users (e.g., nutrients and contaminants), food safety metrics, and documentation needed to meet certification or auditing standards (e.g., organic labeling, nutrient or carbon accounting credit schemes). Many post-harvest indicators overlap with operational indicators but are interpreted through a market or compliance lens.

How Data Informs Decisions: **Post-harvest data inform decisions about harvest timing to optimize target compounds, processing methods, and end-use targeting.**[111,206,211,301,302] Results may feed back into earlier stages by influencing species selection, harvest schedules, or operational practices needed to meet specific market or certification requirements. While not a central focus of environmental effects monitoring, post-harvest indicators help link earlier environmental conditions and operational practices to downstream sustainability, well-being, economic, regulatory, and assurance outcomes.

BOX 1: Are there "required" indicators for monitoring?

While some environmental requirements must be met for permitting (e.g., appropriate site selection, seed sourcing), there are few explicit legal requirements for ongoing environmental monitoring of seaweed farming in this region. From a regulator standpoint, environmental protection laws are focused on preventing or eliminating impacts and have no clear mechanism for recognizing benefits provided by the sector. As a result, regulatory attention is primarily focused on indicators related to potential environmental risks and impacts (e.g., entanglement, genetics, disease, pollution, etc.), some of which have direct legal requirements (e.g., marine mammal protection, fish habitat protection) while others have policy directives (e.g., "50-50 rule" to reduce genetic influence) but no legal requirements for monitoring or verification. Farmers, communities, and researchers may also choose to examine benefit-oriented indicators (e.g., biodiversity, habitat use, or nutrient dynamics) that can support sustainability goals, social license, and access to emerging markets.

2. Choosing Monitoring Methods

Once monitoring priorities and objectives have been identified, practical considerations influence how indicators can be implemented in the field. Indicators differ in the methods, expertise, equipment, cost, and level of effort required for data collection and interpretation. In practice, monitoring programs often combine multiple methods depending on available capacity, technical support, operational constraints, and the complexity of the questions being addressed.

Any monitoring conducted by or in partnership with farmers carries a trade-off, either through direct expenditures such as sensors and consumables or through time diverted from farming activities.[61,69,102,103,182] Sampling designs requiring multiple visits are often compromised when farmers must choose between farming and monitoring during short weather windows. Interviews with practitioners suggest that, where trade-offs exist, farmers are more likely to absorb modest financial costs than ongoing time commitments, particularly during peak operational periods. See **BOX 2** for example trade-offs.

In addition, many effects of interest to communities, regulators, and researchers are not readily observable in the field and require laboratory analysis, such as biodiversity change, nutrient drawdown, genetic influence, disease agents, contaminants, or microplastic pollution. Together, these factors point to the need for tiered and distributed farm-to-lab monitoring approaches in which farmers integrate limited, standardized field sampling into routine operations, while analytical processing and interpretation are carried out by specialized research, government, or private laboratory partners. The overarching goal of this approach is to mainstream monitoring into existing farming workflows, reduce disruption to current practice, and maximize participation by offloading labor and technical complexity from the farmer where possible.

Streamlined Sampling Designs Across Indicators

Streamlining sampling to the smallest feasible number of sampling types, events, and time periods can reduce barriers to participation and improve long-term viability. Deliberate co-location of sampling in space and time, particularly in the lead-up to harvest when biomass and farm effects are expected to peak, can improve efficiency by allowing multiple indicators to be assessed from the same site visit, samples, or methods.

To support this, the report organizes commonly cited sampling methods into four complementary components—**SEE, DIP, SNIP**, and **SHIP**—that illustrate how field effort can be consolidated while supporting analysis of multiple indicators from shared samples.

These monitoring methods are organized along an escalating continuum of effort and information, from basic observation to increasingly targeted sampling and analysis. These are not intended to define required practices or implementation pathways. Rather, they provide a practical way to think about how different indicators can be monitored efficiently across farms and regions. Together, these methods tend to provide the broadest value of information across indicators, while recognizing that additional methods exist but are not featured here due to their technical complexity, cost, or logistical and reliability constraints in remote regions.

Where capacity allows, priority supplementary monitoring for selected indicators may also include fish observation, capture, and/or gut contents analysis to establish habitat use and food provisioning benefits of seaweed farms, with a focus on key fished and/or culturally important species of interest including herring and salmon. Methods may include underwater video using commercial 'action cameras' or custom cameras, baited remote underwater video (BRUV) stations, or fishing around sites and submitting stomachs for visual or eDNA gut content analysis to match with species detected through on-farm eDNA monitoring.

General Sampling Methods

Visual observation and reporting pathways

Routine visual observation during farm operations, maintenance, and harvest activities, combined with standardized documentation and reporting through logbooks, checklists, or annual reporting forms. These methods support early detection and tracking of visible conditions or events such as entanglement risk, disease symptoms, gear interactions, or unusual biofouling. They also provide a low-burden foundation for the detection of rare events. Consistent observation and documentation also help establish baseline context and when to escalate to more intensive methods (e.g., sampling or lab analysis).

Immersed data loggers and water sampling

Deployment of low-maintenance data loggers (e.g., HOBO loggers for temperature or light) can be used to capture contextual environmental variables that are important for interpreting biological observations and distinguishing farm-related changes from broader environmental variability. These tools can be combined with standardized surface water sampling using simple collection jars or bottles. Water samples can be processed in laboratories for multiple indicators, including eDNA for epibiont and fish biodiversity assessment, dissolved nutrients, and microplastics.

Standardized kelp tissue sampling

Periodic collection of farmed kelp tissue, with optional opportunistic sampling of nearby wild kelp where appropriate, can support analysis of tissue nutrient content, tissue contaminants, genetics, disease agents, and microplastics. Where existing standardized protocols are available (e.g., Nutrient Extraction Toolkit, see **BOX 2**), tissue sampling can reduce the need for individual indicator field efforts and allow multiple analyses from shared samples.

Sample handling, lab analysis by partners or service providers

Packaging and shipping collected samples to regional government, university, or private laboratories for analysis has been successfully piloted in Alaska for nutrient monitoring and aligns with broader citizen science and collaborative monitoring programs. Analytical results can be returned to farmers and regulators in standardized formats that support interpretation and decision-making.

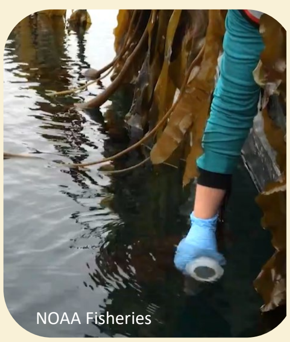
Figure 3 on the next page summarizes the full suite of monitoring indicators identified in this science synthesis and links them to the major phases of the seaweed farming life cycle and associated monitoring methods. The figure is intended to provide a practical overview of when different indicators are most relevant, how they are commonly monitored, and where monitoring activities align with regulatory considerations. Overall, the figure highlights how monitoring requirements and priorities shift across the life cycle of a farm, from site selection and installation through operation, harvest, and decommissioning.

BOX 2: How do traditional and emerging monitoring methods measure up?

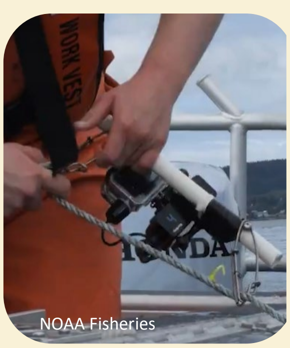
New monitoring technologies can make biodiversity monitoring more efficient and scalable but may also introduce unresolved limitations or shift costs from fieldwork to laboratories, software, and data processing. Method selection should therefore be guided by the monitoring question, the evidence required, and available capacity.


NOAA Fisheries

Underwater visual surveys: Traditional snorkel and SCUBA surveys allow trained observers to identify and count organisms and record size, behavior, and interactions with farm structures. Snorkeling is simpler but limited to shallow water; SCUBA extends depth but requires certified divers, specialized equipment, safety procedures, suitable conditions, and taxonomic expertise. Both provide direct evidence of abundance and habitat use within typical 45-60-minute dive times, but are labor-intensive and affected by visibility, observer bias, and animal responses to divers.[303,304]


NOAA Fisheries

Environmental DNA (eDNA): One eDNA sample can be collected and filtered from the surface in about 35 minutes using inexpensive equipment and protocols requiring limited training, while laboratory analysis can be outsourced.[305] A single metabarcoding assay can screen simultaneously for many species within a taxonomic group (e.g., fish assay for salmon, herring, rockfish, other species). Commercial processing typically costs about US$115–150 per submitted filter and assay.[306] In kelp habitats, eDNA can resolve fine-scale spatial and depth patterns and detect more taxa, including cryptic or uncommon species, with less field effort than diver surveys. Newer techniques can also be used to assess relative abundance across species based on eDNA sequencing read counts.[100] However, it does not directly measure abundance, behavior, or interaction structures, and results depend on currents, marker performance, and reference databases.[192,193,195,305,307,308]



NOAA Fisheries

Underwater video: Systems range from inexpensive action cameras to custom installations and provide direct, reviewable evidence of species presence, relative abundance, behavior, and farm interactions over longer periods than diver surveys or individual eDNA samples. Trade-offs include deployment and maintenance, data storage, limited field of view and visibility, and significant data processing. For example, a short-deployment action camera baited remote underwater video (BRUV) unit required roughly 7 hours for deployment, retrieval, and manual analysis of 75 minutes of footage from one site[305], while long-deployment cameras at two British Columbia kelp farms yielded over 9,000 hours of footage requiring computer-assisted review.[67] Automation reduces review time but may involve software fees and still requires training data, validation, and quality control.[309]

No single method answers every question, and each method has trade-offs between level of information, financial and labor costs, and how much of those costs can or should be borne by farmers, research partners, or fee-for-service providers. In practice, methods are sometimes combined to overcome trade-offs, where resources allow.

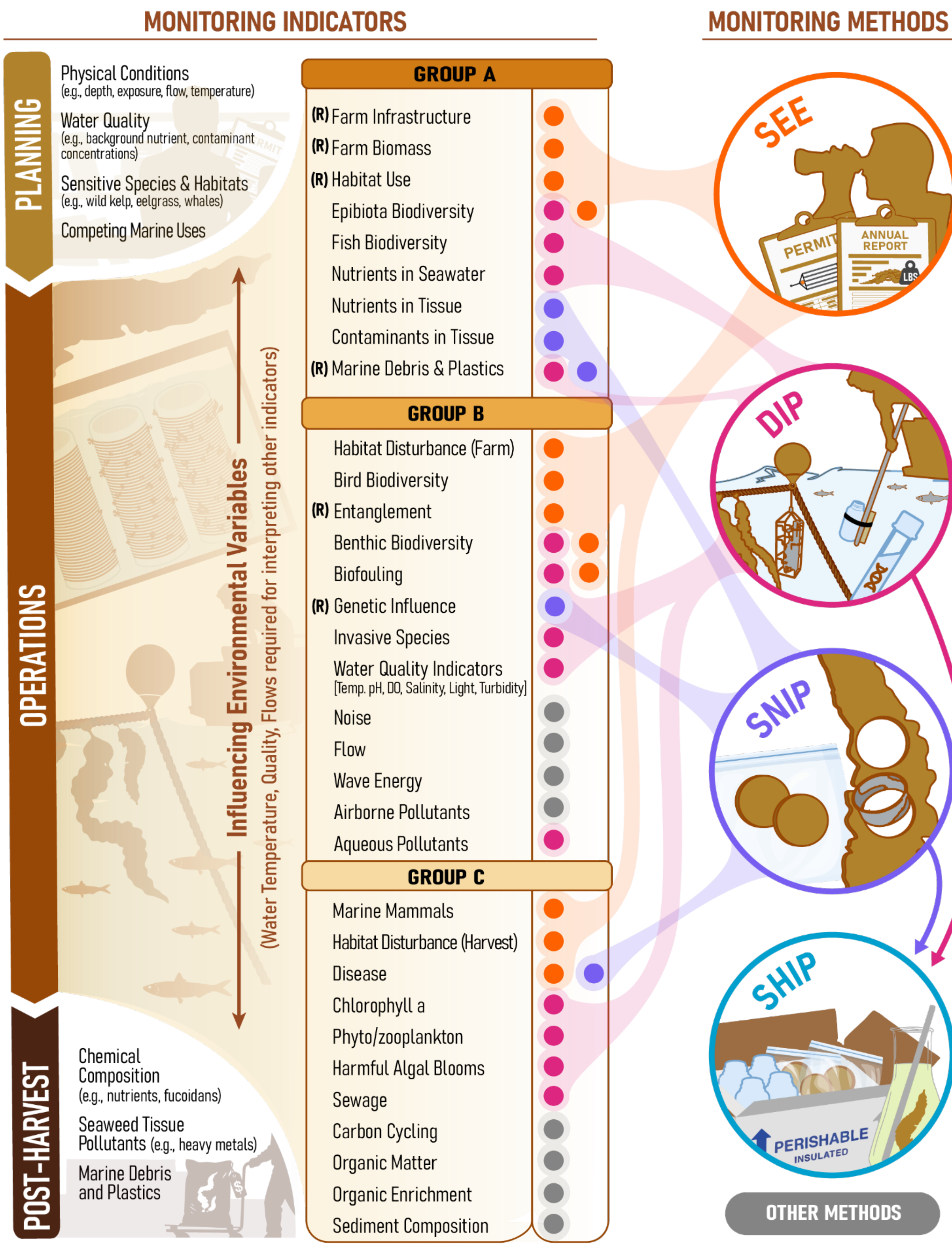


Figure 3. Summary of all monitoring indicators by phase of the seaweed farming life cycle and key associated monitoring methods, with (R) indicating linkages to regulations discussed further in the report.

Standardization, Training, and Toolkits

A critical requirement for this approach is the use of standardized sampling protocols and basic training for each sampling method, or the use of standardized toolkits to ensure data is comparable across farms, seasons, and regions (see **BOX 3** for more on standard monitoring kits). Consistent protocols — for sample collection, handling, preservation, and documentation — are essential for pooling results, detecting regional patterns, and supporting cumulative effects assessment. Training can be delivered through short guidance documents, videos, or workshops, and does not require farmers to develop extensive technical expertise.

While this approach will require pilot testing and refinement, it can reduce monitoring burden by minimizing field effort, consolidating sampling events, and leveraging external analytical capacity. Over time, it may create opportunities for regional coordination, cost sharing, and learning across farms and jurisdictions.

BOX 3: Standardized toolkits lower barriers to monitoring

Standardized, pre-prepared monitoring toolkits are an effective way to support farmer-led data collection while minimizing disruption to routine farm operations. By providing clear instructions, standardized materials, and logistics support in an all-in-one format, toolkits reduce time and capacity barriers and help establish a consistent "culture of data collection" in an emerging sector where intensive methods are often impractical. [53,121,310]

Figure 4: Site *Assessment Toolkit, Alaska Sea Grant.*

Several toolkits already demonstrate this approach in Alaska and British Columbia. The **Site Assessment Toolkit** supports baseline monitoring and rapid site assessment for site selection.[311] The **Nutrient Extraction Toolkit** standardizes kelp tissue and water sampling to assess carbon and nitrogen removal and was refined through iterative testing with farmers.[53] **GreenWave** provides a **farmer monitoring toolkit** that focuses on simple, standardized measurements—such as blade length and biofouling—reported via the My Kelp app and aggregated to assess regional trends.[121]

Comparable microplastics and eDNA toolkits reflect successful citizen science models that enable large-scale marine monitoring through standardized methods.[312–314] By lowering technical and logistical barriers, toolkits broaden participation across farm types and communities. [55,60,103,182]

3. Developing Sampling Designs to Match Monitoring Questions

The types of questions monitoring aims to answer also influence the purpose, intensity, and frequency of monitoring. Some indicators are better suited for routine operational monitoring, while others may be more appropriate for lower-frequency vigilance monitoring focused on rare but potentially high-consequence effects. Additional contextual indicators may also be needed to help interpret broader environmental variability and distinguish farm-related changes from natural background conditions.

Monitoring for Routine Operational Learning

Routine operational monitoring focuses on **environmental effects that are most likely to occur, most directly influenced by farm operations, and most informative for ongoing management decisions**. Routine monitoring can support adaptive management and can provide actionable information within practical operational and regulatory constraints. Indicators are typically monitored regularly to support comparison across time and, where possible, across sites. Routine monitoring may focus on indicators which measure:

- effects which are expected to scale with farm presence, design, or biomass,
- effects where repeated measures improve understanding of trends, thresholds, and cumulative effects,
- effects that can be influenced through operational choices such as spacing, timing, harvest, and
- influencing environmental variables that provide context when interpreting patterns in other indicators.

Priorities for routine monitoring may evolve with changing environmental conditions or community context, making ongoing community engagement important to validate priorities while maintaining continuity for long-term comparison.

Monitoring for Rare but High-Impact Events

Some monitoring questions focus on environmental effects that are **less likely to occur but have potentially high ecological, social, or regulatory consequences**. Examples include entanglement, genetic influence, disease, invasive species, or certain pollution events. These effects may not be well suited to intensive routine monitoring at every farm because they are rare, irregular, or difficult to detect using standard field methods. Instead, they may be better addressed through vigilance approaches focused on early detection, documentation, verification, and transparent reporting when events or warning signs occur.

For rare or high-consequence indicators, useful sampling strategies may include:

- opportunistic or event-triggered observation during normal farm operations,
- clear reporting pathways for unusual events or warning signs,
- integration with existing regulatory reporting requirements and regional response networks,
- periodic targeted sampling at a subset of farms or regions,
- specialist verification by research, government, or laboratory partners, and
- regional coordination so isolated observations can be interpreted in broader context.

This approach reflects both the precautionary importance of these issues and the practical constraints of an emerging sector. By focusing on vigilance, documentation, and response rather than exhaustive sampling, monitoring can support ecosystem health, regulatory confidence, and social license in a manner proportional to risk. However, monitoring programs should remain adaptable because climate change, industry expansion, new culture practices, or increased farm density may alter the likelihood or importance of some indicators over time.

Monitoring for Causal Relationships

Distinguishing farm-related effects from background environmental variability is an important and persistent challenge in environmental monitoring.[61] Descriptive comparisons or opportunistic observations are limited in their ability to support determination of cause, particularly in dynamic coastal systems.

Monitoring designs for detection of causal relationships should be explicitly aligned with management questions and structured to capture contrasts across space, time, or intensity of farming activity. This does not require fully controlled experiments at every farm, but it does require intentional sampling design choices, such as:

- prioritizing indicators and metrics with known or hypothesized links to farming practices,

- pairing farm sites with appropriate reference or comparison areas where feasible, [168,289]
- collecting time series data that capture conditions before and during farming operations, and also align with existing long-term environmental baseline monitoring programs, [103,104]
- applying analyses that consider nonlinear relationships and multiple drivers of effects (e.g., nonlinear model fitting, or machine learning),[315,316] and
- coordinating sampling methods and timing across farms to enable cross-site comparisons.

Contextual environmental variables are especially important for causal interpretation. Variables such as temperature, salinity, nutrient availability, light, flow, and water column dynamics can influence habitat use, biofouling, disease dynamics, growth, nutrient uptake, and dispersal independently of farm operations. Monitoring these variables helps distinguish farm-related effects from broader environmental variability and reduces the risk of misattributing observed changes to seaweed farming. However, even with appropriate sampling designs, it may be difficult to detect and attribute effects purely due to the very small size and limited environmental influence of some farms.[98]

Importantly, not all farms need to contribute equally to causal analysis. A **networked approach**, in which more intensive monitoring is conducted at a subset of intensely studied farms with paired reference sites (similar to approaches modelled in Mar ReCon) can generate insights that inform interpretation of lower-intensity monitoring elsewhere. This approach aligns with lessons from other marine sectors, where targeted investments in robust study design have proven more informative—and cost-effective—than diffuse, uniform sampling that generates large volumes of data with limited interpretive value.

Monitoring for Cumulative Effects

Understanding cumulative effects across scales becomes increasingly important as seaweed farming expands from individual farms to multiple operations within shared bays, coastlines, and regions.[105] Effects that are negligible for a single farm may emerge when activities are aggregated across multiple farms over space or time, particularly for indicators related to larger-scale ecological processes such as current flows, nutrient dynamics, genetic exchange, disease risk, habitat alteration, and cumulative marine use conflicts.

Effective detection of cumulative effects requires monitoring designs that operate at multiple, linked spatial scales, including the farm, bay or embayment, and broader regional context (**Figure 5**).

- **At the farm scale**, standardized measurements provide information on local conditions and effects associated with individual operations. Farm-level indicators can also help farmers understand operational factors such as harvest timing, seaweed quality, timing of fouling, and farm performance.
- **At the bay scale**, data from multiple farms can be pooled to assess combined effects within shared water bodies, where circulation, connectivity, and ecological interactions are strongest.
- **At the regional scale**, synthesis across bays and coastlines supports assessment of broader patterns, thresholds, and emerging risks relevant to policy and planning.

A key requirement for scaling across these levels is the use of consistent indicators, metrics, metadata, and sampling methods to enable data aggregation and comparison. Standardization enables farm-level observations to be scaled up to estimate whole-farm effects, compared across sites and years, and aggregated across multiple farms. Where cumulative effects are a concern, priority should be given to indicators that scale with farm size and to monitoring approaches that support trend analysis at bay or regional scales.

Cumulative effects assessment also depends on appropriate analytical approaches that move beyond simple comparisons. These include:

- scaling point measurements collected within farms to represent whole-farm effects using functional relationships developed through prior research (e.g., GreenWave's "My Kelp" app estimates farm-scale nutrient and carbon uptake based on total harvest using published relationships).

- combining data on single farm effects within a bay to estimate local cumulative effects of farms, and
- using real-world monitoring data as inputs to physical and ecosystem models (e.g., MACMODS[117], EcoPath[317]) to assess safe operating space, regional carrying capacity, and management benchmarks.[60,274]

Practitioners emphasized the importance of spatial planning as a tool for managing cumulative effects as information emerges.[60,274] In the absence of concrete guidance, Alaska regulators have taken a precautionary approach by limiting farm permits to one-third of the area of a given bay, bight, or cove,[318] with some areas already approaching this limit.[39.] However, no such guidelines currently exist in British Columbia. As environmental data accumulate, Alaska and British Columbia could consider formal processes to evaluate farm density based on site-specific conditions such as flushing rates, nutrient levels, sensitive habitat proximity, hydrographic connectivity, and cumulative interactions across aquaculture types and marine uses.[131]

However, some practitioners interviewed felt cumulative effects assessment of seaweed farming is not a near-term priority, because of the small, ephemeral nature of many farms,[152,319] limited standardization currently present in monitoring efforts,[99] and broad agreement that social carrying capacity is likely to be exceeded before ecological carrying capacity.[47,55,121] For example, practitioners cited social concerns related to visual disturbance, conflict with other marine uses, and equitable participation in the sector.[55]

Together, these considerations highlight that effective monitoring is not just a matter of selecting indicators, but also how monitoring is designed, implemented, analyzed, and coordinated. By defining monitoring objectives clearly, aligning indicators with farming stages, consolidating field methods, and matching sampling rigor to the questions being asked, monitoring programs can generate credible, decision-relevant information while remaining proportionate to the capacity of an emerging seaweed farming sector.

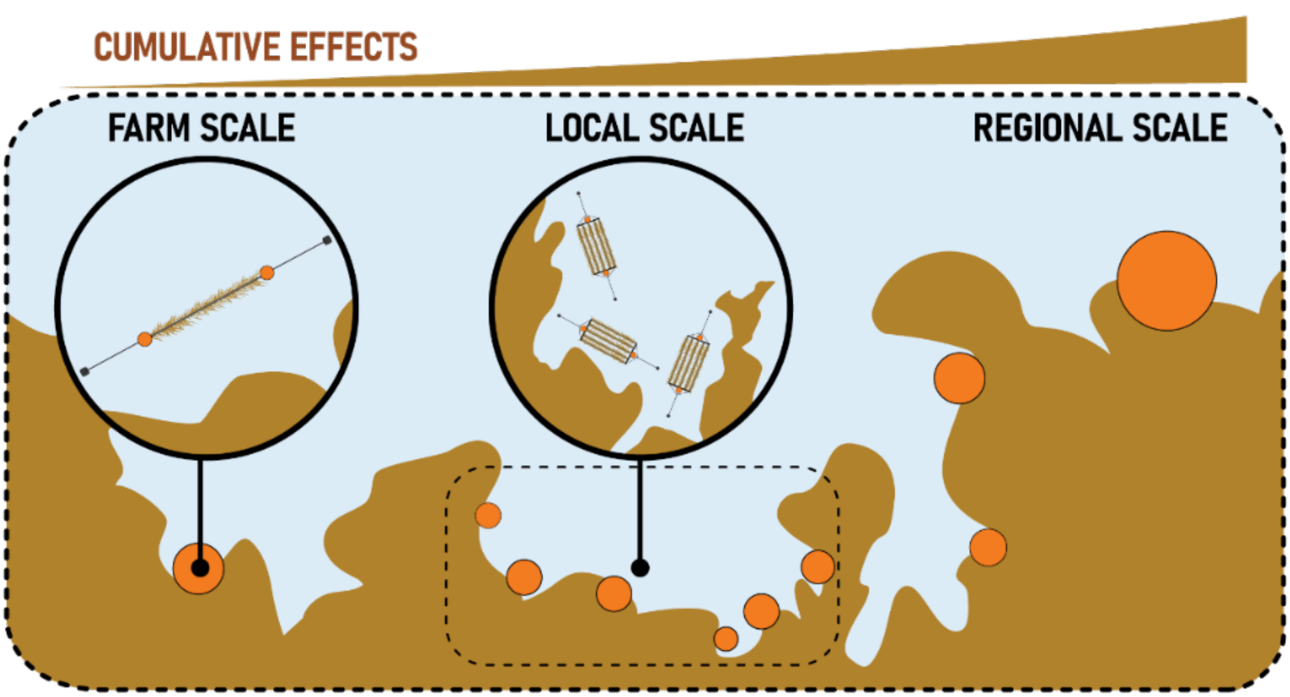


Figure 5: The potential cumulative effects of seaweed farms accumulate across spatial scales.

Part V – Lessons Learned and Future Directions

Part V draws together cross-cutting themes that emerge across the report — key trade-offs, sources of uncertainty, and practical realities that shape how environmental monitoring has been approached to date. It also identifies lessons learned and emerging trends that may influence monitoring going forward. These are intended to support reflection and discussions, recognizing that monitoring needs, capacity, and experience vary widely across places and operations.

Across interviews, participants emphasized that effective monitoring must balance credibility, practicality, and inclusivity to ensure that it is financially viable, scientifically sound, and community informed. They noted that success across farming contexts depends not only on combining traditional sampling, low-cost sensors, and emerging digital tools, but also on ensuring strong communication networks, standardization, funding, and alignment with farmer workflows. Five themes emerged consistently across interviews:

1. **Monitoring requires balance between practicality and precision:** While many new high-tech tools exist, farmers and researchers emphasized affordability, reliability, and ease of use as key criteria with many viewing low-tech methods as the most practical and reliable option, particularly in remote locations.[39,61,121]
2. **Monitoring is constrained by inconsistent standardization and training:** Interviewees described how inconsistent protocols and limited training for farmers and communities undermine data comparability. They also noted that inconsistent feedback on what and how to monitor from regulators—even within the same agency—creates confusion and operational inefficiencies that compound these challenges.[121,131,152]
3. **Technological and logistical constraints shape what monitoring is feasible and comparable:** Challenges such as equipment maintenance, power and network connectivity, and cost were commonly cited in interviews, with methods used in tropical or less remote regions often not directly transferable to much of Alaska and British Columbia.[121,131,152] Many monitoring programs were also described as relying heavily on grants or external support, which limits long-term continuity and data comparability.[56,152]
4. **Indigenous Knowledge and Western contribute to monitoring in complementary ways:** Monitoring efforts are often shaped by Indigenous Knowledge or community-based needs, alongside Western scientific approaches that contribute additional tools such as sensors and analytical methods. These approaches draw on local observation and monitoring carried out by farmers, scientists, and Indigenous stewardship teams, and contribute in complementary ways shaped by context.[56,99]
5. **Monitoring depends on shared responsibility and capacity across actors:** Partnerships were consistently described as critical for credibility and for addressing capacity constraints across actors.[104,152]

Balancing Needs with Practicality

Monitoring efforts are at risk of becoming "Data-Rich, Information-Poor" (DRIP) initiatives[39,121,320] when data collection expands without clear linkages to data needs. Monitoring efforts that focus on a core set of indicators that are feasible to implement, likely to reflect farm-related effects, responsive to public concern, and relevant to regulatory and operational decision-making can reduce that risk.[48,74,320] In fact, for some Alaska mariculture farmers, current monitoring conducted for regulatory and research needs has become burdensome as it is costly and time-intensive, especially during winter

Photo Courtesy of Alaska Mariculture Alliance

or at remote sites. Farmers also emphasized the need to balance environmental monitoring with the associated environmental footprint, citing impacts from increased vessel noise, debris, and fuel use during more frequent visits required for some monitoring.[98] Excessive monitoring can therefore have social, economic, and environmental downsides. To mitigate this, some interviewees suggested adaptive, question-driven monitoring, where not all farms need to be studied, and sampling is tailored to the research goal.[102] Some interviewees noted the growing role of automated sensors and digital data tools for more efficient, standardized monitoring,[68,131] while others reported that technology like smart buoys, game cameras, and satellite imagery have proven unreliable or impractical.[98]

Overall, farmers expressed a desire for greater standardization and clarity in regulatory expectations. [98] Existing monitoring efforts often suffer from inconsistent methods, irregular sampling, and missing metadata, limiting data comparability.[152,293] Improved study designs and standardized data entry could address these gaps.[293]For example, one interviewee shared their positive experience with a farmer-driven approach that involves using an app and standardized monitoring kits to track metrics like color, texture, and size.[121]

Because participation in monitoring within an emerging industry (which is already operating on low profit margins) carries financial and capacity costs for farmers, most of the current monitoring initiatives will not be feasible to continue without ongoing external funding and support.[61,69,102,103,182] Many practitioners expressed concern about long-term funding for monitoring,[102,103] and at least one British Columbia practitioner discontinued participation in a long-term monitoring program due to lack of funding.[182] Taken together, these logistical considerations highlight the importance of working monitoring into existing farming workflows and offloading analytical work to external technical teams to increase the likelihood of broader participation in monitoring programs.[55,121]

Sharing Roles and Responsibilities

Interviewees widely agreed that monitoring should be a shared responsibility involving farmers, researchers, governments, communities, and non-profits, as no single actor can or should bear the full burden.[103]

- **Farmers:** Many interviewees emphasized that farmers lack the financial and technical capacity to conduct extensive monitoring, and that requiring it can threaten business viability.[69,104,293] Monitoring costs, limited weather windows, and the effort required for monitoring make it impractical without external funding or compensation.[102,293] Several interviewees stressed the importance of incentivizing or funding farmers' participation, since they already operate under narrow profit margins.[102,152] Farmers' motivations often center on improving production, gear integrity, and site management, though some are also driven by interest in environmental impacts and social license.[121]
- **Government:** Interviewees held differing views on the role of government. Some individuals argued that federal and state/provincial agencies should take greater responsibility,[98] while others pointed out that regulators' dual mandates can lead to public distrust, highlighting the need for transparent, multi-party approaches.[68] Government funding is an important factor for supporting farmer-led monitoring; for example, in Korea, substantial government grants aimed at seaweed sector development assist farmers in prioritizing monitoring.[268] At the same time, it is important that permitting processes are flexible enough to adjust operations in response to monitoring data. Under existing regulations, even small changes to farm design such as rotating line orientation or moving anchor blocks within the existing footprint can trigger a new and expensive multi-year permitting process.[58,121] However, British Columbia has recently implemented the option of a 'variable operations plan' allowing pre-approval of multiple design configurations to provide more flexibility for in-season adjustments.[58]
- **Non-profits and universities:** Non-profits and academic institutions were frequently cited as valuable partners due to their expertise and credibility and can also contribute to capacity-building for monitoring by others.[104,152] Programs like Mar ReCon successfully improved data quality by training farmers to collect samples. However, sustaining these skills requires long-term funding for retraining over time.[152]

- **Local communities:** Local community members may be willing to participate in monitoring efforts, especially if guided and compensated. Involving local communities in monitoring may help to build trust and increase seaweed farming social license.
- **Indigenous Nations:** Monitoring approaches developed through Indigenous-led or co-designed processes are grounded in Indigenous Knowledge systems and build local capacity. Indigenous Knowledge can inform site selection, helping avoid sensitive areas like herring spawning sites that may be overlooked without community input, and complement baseline monitoring by drawing upon local understanding of historical ecosystem conditions.[55] Recent assessments of the sector have noted that permitting and consultation processes can sometimes serve as early points of engagement where monitoring-relevant discussions occur, particularly around baseline conditions. For example, where Indigenous Nations choose to share such information, documentation of Indigenous Knowledge related to site baseline conditions during permit review may create opportunities for ongoing knowledge braiding to inform adaptive management.[26] For approved farms, Indigenous-led research and monitoring also inform product prospecting and harvest timing decisions within Indigenous-led operations.[56,182] Across these efforts, respect for Indigenous data sovereignty is essential for all Indigenous-led or Indigenous-partnered monitoring and is discussed further below.

Collaborative monitoring across organizations, Indigenous Nations, and jurisdictions has proven to be successful in British Columbia and Alaska in promoting shared learning and avoiding duplicated effort.[61,99,182] In British Columbia, Indigenous-led and community-based involvement, including data sharing in seaweed monitoring, currently occurs through "ground-up" initiatives such as the Marine Plan Partnership for the North Pacific Coast (MaPP), the Integrated Community Observatory (ICO) for eDNA, and Sentinels of Change. In Alaska, existing collaborative programs like the Mariculture Alliance, Alaska Mariculture Research and Training Center, AOOS's harmful algal bloom (HAB) monitoring, and the Bull Kelp Research Squad (BKRS) likewise provide spaces for data sharing and training. However, regional programs such as these can be challenged by participation and trust constraints shaped by historical and institutional factors,[103] and their longevity is difficult without dedicated support.[182]

Indigenous Co-governance and Data Sovereignty

Collaborative programs work best when grounded in co-governance, co-management, and community participation. Several interviewees from British Columbia expressed that Indigenous data sovereignty is essential, as each Nation has unique sharing protocols, and that excluding local or Indigenous Knowledge reduces program effectiveness.[61] Some interviewees noted that monitoring should be overseen by a co-governance body that sets priorities and manages shared data platforms.

Thus, as the industry evolves, it must endeavor to root monitoring in Indigenous data sovereignty, co-leadership, and Indigenous Knowledge. In British Columbia, these principles are reinforced through provincial legislation—complemented by federal commitments—that affirms the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), while governance in Alaska is shaped by federally recognized Tribal sovereignty and related statutory authorities. However, in Alaska, there are notable gaps in consultation processes with Alaska Native Tribal governments around acknowledging and upholding Tribal sovereignty and Indigenous Knowledge.[26]

Expecting Indigenous Nations to contribute data, participation, or knowledge without corresponding authority, capacity support, or direct benefit risks reproducing inequities and, in some cases, tokenism.[321] Meaningful participation in monitoring and co-governance of the seaweed sector will thus require supports for capacity-strengthening, benefit sharing, and leadership. In governance contexts where monitoring priorities are defined collaboratively, the indicators described in this science synthesis may be adapted, supplemented, or interpreted differently to reflect cultural, social, or place-specific priorities that are not evaluated in this report.

For instance, seaweed farming can help Indigenous Nations assert control over local waters, prevent external claims, and ensure activities reflect community values.[9] Seaweed farming can offer an avenue of economic diversification by providing off-season employment for fishers. Local ownership of seaweed farms also strengthens connections to traditional territories, maintains cultural presence on the water, and enables community members to act as environmental stewards.[9,55] In Alaska, one interviewee described Indigenous participation in seaweed farming as being driven by principles of sovereignty, economic diversification, and community service.[55] Social and cultural benefits and monitoring of seaweed farming are not covered in this report, but were consistently identified by interviewees as important considerations for future Indigenous-led, community-based, or governance-driven efforts, where social, environmental, and cultural benefits may be prioritized alongside economic viability.[65]

Adapting to Emerging Trends

As seaweed farming expands and conditions change, interviewees and the scientific literature describe a range of emerging technologies, policies, and environmental pressures that may influence both farm-level impacts and future monitoring needs. This section synthesizes developments discussed in peer-reviewed studies and practitioner interviews to highlight trends that may shape how environmental effects are assessed and managed over time.

Nursery Culture Practices

One of the most significant future changes to the sector may be gametophyte culture or selective breeding, a technique that involves purposefully mating seaweeds with desired traits to create new seaweed varieties that are more resistant to higher temperatures, disease, and fouling organisms.[322,323] Selective breeding for sterile seaweed has also been suggested as mitigation measures for improving cultivar performance and resilience while reducing the potential genetic effects of farmed seaweeds on wild populations.[324,325] Emerging techniques like genome editing could also help to accelerate these efforts.[326] Some farmers in Alaska expect that gametophyte culture will help decrease the financial and time burdens created by annually sourcing seed, therefore improving farmer costs to operate.[50] Recent studies have shown that sugar kelp hybrids demonstrate superior performance for traits like blade length. This suggests that selective breeding processes could be important for improving yields, decreasing costs, and improving resistance to environmental stressors, including climate change.[327]

Others are experimenting with thermal priming. This approach exposes nursery stock to moderate temperature stress to improve temperature tolerance in offspring of young seaweed via epigenetic alterations. While this avoids genetic modification, the potential long-term effects of this practice are still under investigation.[328,329]

Diversifying Farm Designs & Operations

Other emerging developments in the seaweed farming sector include expansions in farm location, design, size, and seasonality. For example, there is global interest in expanding to offshore environments.[330,331] Expanding farms beyond shallow areas has been theorized in British Columbia[123] and more substantively planned for in the US, including in Washington and Alaska through the US federal government's Macroalgae Research Inspiring Novel Energy Resources (MARINER) program, which aims to develop tools to expand the deployment of seaweed aquaculture in offshore areas.[42] At least one farm in Prince William Sound is experimenting with an offshore farming design[39] following a model first piloted in the Faroe Islands.[40,41] At present, however, offshore development is generally constrained by cost, regulations, and uncertain environmental risks.[332] Offshore aquaculture has been proposed largely to avoid stakeholder conflicts in the nearshore,[331] particularly through co-location with existing uses (e.g., offshore energy),[330] as well as to reduce ecological impacts.[333] It requires new designs and approaches, including new strain development, species-specific modes of harvesting (e.g., multiple partial harvest), transport, and processing, and advanced sensing systems.[323,334] Moving into deeper waters would also present farm-environment interactions that are different from those in nearshore environments, such as increased entanglement risk[117,335] as well as potentially alter the jurisdictional landscape. For example, in British Columbia, as the province is the jurisdictional lead authority for aquatic plant cultivation, there is a jurisdictional gap for offshore farming since provincial jurisdiction ends 12 nautical miles from the outer coast.[27]

Seasonally, in contrast to annual farming of sugar kelp, perennial farming of giant kelp has been successfully trialed near Juneau, Alaska, and could extend the timeframe of environmental effects.[336] Finally, there is the potential for multi-species co-culture and Integrated Multi-Trophic Aquaculture[330,337–339] where co-cultured species may also need to be monitored for impacts (e.g., co-cultured bivalves for seaweed- tissue derived pollutants)[112].

Novel materials for seaweed farming are also under development to mitigate existing environmental impacts. Studies have examined the potential for farming lines and seed twine made of natural fibers such as wool and silk to replace synthetic rope and reduce plastic pollution.[135,244] Mushroom mycelium-based buoys have been developed as well.[340] Fiberglass rods have been proposed for farms in offshore environments, as they can withstand stronger offshore current and wave action, while reducing the risk of marine mammal entanglement.[331,341] However, the uptake of new materials is often limited by cost. Additionally, "low breaking-strength" gear (i.e., weak links or rope) designed to break under a certain amount of force are currently being used in certain fisheries in the US and Canada to minimize potential impacts from marine mammal entanglement.[98,342] However, the effectiveness of breakable gear in seaweed farming contexts has not yet been established, and farmers are concerned that the drag created by growing kelp would itself break the gear resulting in an increased entanglement risk as well as the loss of crop.[145]

Growing Markets

Multiple practitioners interviewed expressed concerns about long-term financial viability, funding support, and market availability as major hurdles to the growth of the sector.[61,69,102,103,182] In both British Columbia and Alaska, markets currently include local food production (e.g. Barnacle Foods, Kachemak Kelp) and biostimulants (e.g., Cascadia Seaweed, Pacific Kelp Co). Both regions experience barriers to entry, including obtaining high quality seed, overcoming bottlenecks in processing, the high costs of energy and transportation, and the lack of developed markets for harvested kelp.[24,343] Funding initiatives, like MARINER in the USA, can help spur research into diverse market applications as well as into technology to reduce production costs[42]. Interviewees did note that indicators relevant to **nutrient or biodiversity credits** could be useful for future financial models, although applications remain exploratory. [98,103–105,121,130]

Climate Change

Climate change is anticipated to influence many environmental effects of farms as well as the relative importance of their respective indicators.[102] For example, ocean warming and shifting seasonality can impact nutrient availability[344–346], turbidity[347], yield and biochemical composition of farmed seaweed, while more frequent extreme weather events can cause infrastructure damage and loss.[348] Climate change is also anticipated to increase dispersal of and susceptibility to disease agents,[349,350] and promote the colonization and spread of invasive species. On the other hand, climate change may also create new markets for seaweed farming as a service for climate adaptation (e.g., through coastal protection).[160,161] As farmers, regulators, and researchers alike grapple with climate uncertainty, ongoing monitoring of confounding environmental indicators, climate modelling, and scenario planning offer avenues to identify and prepare for possible futures.

Using This Science Synthesis

This report presents practical, decision-focused insights for monitoring the environmental effects of seaweed farming in Alaska and British Columbia. It brings together scientific evidence, practitioner experience, and regional context, to inform discussions about priorities for monitoring, research, and data mobilization for decision-making in a way that is proportionate to risk, responsive to stakeholder concerns, and feasible for an emerging sector.

A central contribution of this science synthesis is its emphasis on linking indicators to **decision points during the seaweed farming lifecycle**. Rather than treating monitoring as a standalone compliance exercise, indicators are explicitly connected to operational choices, permitting and regulatory oversight, regional planning, research priorities, and emerging market opportunities. As discussed, monitoring data may inform site selection, farm design, harvest timing, product development, sustainability communication, permitting, site-scale and regional management, precautionary oversight, and research prioritization across the sector.

The usefulness of this report depends on collaboration and shared responsibility across stakeholders. The monitoring of many indicators will benefit from coordinated efforts among farmers, regulators, researchers, and Indigenous and local communities, including shared protocols, regional laboratories, training, and data systems. Such collaborations can reduce individual burden, improve data quality, and enhance trust and social license, while respecting data sovereignty and confidentiality.

Additional Considerations and Ongoing Work

While this report synthesizes multiple lines of evidence regarding monitoring approaches, it also acknowledges important limitations and areas for continued refinement. Monitoring needs will evolve as the sector grows, as new technologies emerge, as other species are farmed (e.g., *Pyropia*), and as cumulative and climate-driven effects become more prominent.

This science synthesis draws primarily on Western scientific approaches. Indigenous Knowledge systems are rooted in place-based observation, long-term stewardship, enduring cultural relationships with seaweeds and coastal ecosystems, and longstanding systems of exchange and trade. These systems are foundational — not supplementary — to comprehensive and equitable monitoring, management, and economic development. Approaches that intentionally weave multiple knowledge systems with Indigenous governance and decision-making authority are a necessary complement to the potential monitoring options described in this report. Indeed, Indigenous Nations in North America have been stewarding seaweed for millennia;[5,9,351,352] it is their practices that lay the foundation for the current industry. Current Indigenous industry leaders include the Shinnecock Kelp Farmers in the Northeastern US[353] the Alutiiq Pride Marine Institute and Native Conservancy in Alaska, and the Tsawout First Nation, T'Sou-ke First Nation, and Metlakatla First Nation in British Columbia.[29]

A range of ongoing initiatives in Alaska and British Columbia—led by Indigenous Nations, organizations, and knowledge holders—are advancing governance, monitoring, and management approaches within the seaweed sector. For example, in Alaska, Native Conservancy is leading community visioning to co-develop an Indigenous mariculture plan grounded in Alaska Native knowledge, values, and stewardship relationships as well as leading permit acquisition initiatives. In British Columbia, Luminary (Indigenous Works) and the Pacific Seaweed Industry Association have created the Seaweed Project, which is developing a strategy for an Indigenous-led seaweed industry. And, in collaboration with 23 First Nations, the province of British Columbia has also recently committed to investing more than $2.5 million towards enhancing marine stewardship projects across the coast, including those for kelp monitoring and traditional seafood systems.[354]

The Pew Charitable Trusts provides support for work carried out by Indigenous-led and community-based organizations. Pew supports work which is complementary to this science synthesis being led by Ecotrust (U.S.) to convene Indigenous scholars from Alaska and British Columbia to develop recommendations on weaving Western scientific approaches with Indigenous Knowledge systems and Indigenous governance. Together, these efforts reflect the broader context in which this science synthesis is intended to be used.

Closing Reflections

Collectively, the knowledge and insights presented here are intended to support development of monitoring strategies that are adaptive, transparent, and fit for purpose, helping the seaweed farming sector develop in ways that are environmentally responsible, socially grounded, and resilient to future uncertainty.

Meaningful and lasting stewardship of seaweed resources will depend on continued alignment between Western scientific approaches and Indigenous Knowledge systems, grounded in Indigenous governance and decision-making authority. It will require the upholding of Indigenous rights and governing authority. Additionally, monitoring and management practices must be shaped through collaboration, respect, and accountability to the communities most closely connected to these coastal ecosystems, and in service of their priorities and leadership.

Photo Courtesy of Alaska Mariculture Alliance

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Appendix A: Supplementary Information

Data Catalogue

This data catalogue contains the data which underpin this scientific report, available for download from: http://pew.org/CultivatingWithCare

- **Indicators and Metrics**
    - This spreadsheet catalogue provides an overview of all candidate seaweed farming monitoring indicators and data sources in AK and BC. Entries are tagged by effect type and other attributes to allow for easy searching and filtering. Scoring rationale is provided on a separate sheet.
- **Knowledge Gaps**
    - This spreadsheet compares known monitoring programs across AK and BC with the indicators evaluated by this study. Individual research projects are not included.
      Note that this table is reproduced at the end of this Appendix.
- **References**
    - This spreadsheet catalogue provides a list and detailed descriptions of references and existing data monitoring pertaining to seaweed farming monitoring in AK, BC, and internationally. Entries are tagged by effect type and other attributes to allow for easy searching and filtering.

Workshop Report

An international workshop on environmental effects monitoring for seaweed farming was convened in May 2025 in conjunction with the International Seaweed Symposium (ISS). The workshop brought together 34 practitioners, regulators, researchers, and monitoring experts with experience spanning Alaska, British Columbia, and other seaweed-producing regions. Participants discussed priority environmental effects, reviewed potential monitoring indicators and methods, and shared lessons learned from existing seaweed and aquaculture monitoring programs. The workshop emphasized the need for proportional, decision-relevant monitoring approaches; clearer differentiation between routine, surveillance, and contextual indicators; and practical methods that balance scientific credibility with feasibility for farmers. Insights from the workshop directly informed indicator prioritization, monitoring method selection, and the overall structure of the monitoring science synthesis presented in this report.

Available for download from: http://pew.org/CultivatingWithCare

Interview Summary

For this project, we interviewed a total of **34 participants**. Of the interviewees, 11 were from Alaska, 9 were from BC, 3 were from the US (outside of Alaska), and 5 were international. Interview participants are further summarized in **Table A-1,** though interviewees have been anonymized for citation in the report. Interviewees were assigned affiliation types to help ensure a balanced representation of perspectives across all interviews. Note that not all potential interview candidates (e.g., commercial seaweed farmers in Alaska specifically) initially contacted were willing or able to participate.

Table A-1. Interview participant list, with perspectives captured in report represented by anonymized codes.

Name	Affiliation	Affiliation Type				
		Seaweed Farmer	Seaweed / Farming Researcher	Government / Regulator	Other Mon Program	Indigenous / Org
Angie Bowers	University of Alaska Southeast		●			
Briana Murphy	Alutiiq Pride Marine Institute	●	●			●
Caitlin McKinstry	Native Village of Eyak Mariculture	●	●			●
Chris Neufeld	LGL Limited; independent researcher		●			●
Colin Bates	University of British Columbia; Cascadia Seaweed	●	●			
Dana Clark	Cawthron Institute (New Zealand)		●		●	
Ginny Eckert	Alaska Sea Grant; University of Alaska Fairbanks		●		●	
Jarrod Yelton	Alaska Department of Natural Resources			●		
Kendall Barbery	Greenwave US	●	●			
Logan Zeinert	North Island College		●		●	
Margot Hessing-Lewis	Hakai Institute				●	
Michael Stekoll	University of Alaska Fairbanks		●			
Willow Battista, Mike Spranger, Mike Kollins	Willow Battista (Washington Maritime Blue); Mike Spranger (Pacific Sea Farms); Mike Kollins (Vashon Kelp)	●	●		●	
Miki Takada, Andy Yi	Aquaculture Stewardship Council, Marine Stewardship Council				●	
Olivia Rhoades	Fisheries and Oceans Canada				●	
Rebecca Martone	Independent consultant		●			●
Reinier Nauta	Wageningen Marine Research		●			
Roderick Haesevoets, Laura O'Hearn, Christopher Marrie	Fisheries and Oceans Canada			●		
Schery Umanzor	University of Alaska Fairbanks		●			
Sophie Corrigan	Natural History Museum, London		●			
Thomas Farrugia	Alaska Ocean Observing System				●	
Heidi Alleway	The Nature Conservancy		●		●	
Troy Moth	Metlakatla First Nation	●				●
Keolani Booth	Native Conservancy	●				●
Hayley Farrer	US Army Corps of Engineers (USACE)			●		
Michelle Morris	Alaska Department of Fish and Game			●		
Danielle Denley, Kylee Pawluk	Ministry of Water, Land, and Resource Stewardship, Province of BC			●		
Ling Cao	Xiamen University, China		●			

Indicator Selection Criteria

Indicators were scored based on several criteria relevant for prioritization (**Table A-2**) including 1) relevance to management, 2) literature support, 3) sensitivity and responsiveness, 4) robustness, 5) feasibility, 6) cost effectiveness, 7) reliability for predicting causality, 8) likelihood of occurrence, and 9) stakeholder interest or concern. A scoring rubric was created for each of these criteria, rated on a scale of 0-3. Each scoring criterion was evaluated using insights from primary literature and knowledge communicated during interviews with experts and stakeholders in the seaweed industry. For each criterion, the following approach was applied.

Table A-2. A brief summary of the criteria for 9 scoring rubrics (left column) ranked from 0-3 with 0 indicating not enough information, 1 indicating a low, unfavorable score, 2 indicating a moderate score, and 3 indicating a favorable score based on information gathered during project engagement.

Scoring Rubric	Rank	Description by Rank
1. Relevance to Management	1	The indicator is relatively unimportant to anticipated or current management.
	2	The indicator is moderately important to anticipated or current management.
	3	The indicator is important to anticipated or current management goals.
	0	Not enough information
2. Literature Support	1	Little to no support for monitoring or predicting response to change.
	2	Moderate support for monitoring or predicting response, but not for seaweed farming.
	3	Abundant support for monitoring or predicting response, particularly for seaweed farming.
	0	Not enough information
3. Sensitivity and Responsiveness	1	A greater degree of change or time (months to years) is needed to detect differences.
	2	A moderate degree of change or time (days to weeks) is needed to detect differences.
	3	A lesser degree of change or time (minutes to hours) is needed to detect differences.
	0	Not enough information
4. Robustness	1	Highly variable data that is influenced by confounding factors, outliers, or error.
	2	Moderately variable data is influenced by confounding factors, outliers, and/or error.
	3	Minimal variability in data that is less influenced by confounding factors, outliers, and error.
	0	Not enough information
5. Feasibility	1	Advanced technical experience required and greater time required
	2	Moderate technical experience required and moderate time required
	3	Low technical experience required and low time requirement
	0	Not enough information.
6. Cost-effectiveness	1	High equipment, survey or sampling, and labor costs (>5k USD/yr)
	2	Moderate equipment, survey or sampling, and/or labor costs (1-5k USD/yr).

Scoring Rubric	Rank	Description by Rank
	3	Low equipment, survey or sampling, and low labor cost (<1k USD/yr)
	0	Not enough information.
7. Reliability for Predicting Causality	1	Uncertain or low causal relationship between indicator and seaweed farming.
	2	Moderately well-supported causal relationship between indicator and seaweed farming.
	3	Well-supported causal relationship between the indicator variable and seaweed farming.
	0	Not enough information
8. Relevance of indicator given likelihood of measured effect	1	Occurrence is hypothesized but has not been documented.
	2	Occurrence has been occasionally observed at farms, or is not monitored.
	3	Occurrence is monitored and is commonly observed.
	0	Not enough information
9. Community Interest or Concern	1	Rarely mentioned, with no mention of local observations.
	2	Occasionally mentioned, with some mention of local observations.
	3	Frequently mentioned, with specific examples of local observations.
	0	Not mentioned in the context of effects of the farm.

Criteria Definitions

1. **Relevance to management**
   The relevance of each indicator toward decision-making or management of mariculture as it pertains to managing growth of the seaweed industry. Scoring of this criterion was based on mentions in the literature of theoretical importance to regulatory management or specification in development plans specific to AK (Alaska Mariculture Task Force 2021) or BC (LGL 2024). We also incorporated input from interviews by mentions of importance to regulatory agencies.

2. **Literature support**
   The degree of primary and secondary literature support for the use and relevance of each indicator in monitoring. Scoring of this criterion was based on finding relevant primary literature and evaluating the quality of literature as well as the regions where research was conducted.

3. **Sensitivity and responsiveness**
   A measure of the degree and rate that an indicator is able to respond to and measure change. Scoring of this criterion was based on evaluating data for the relevant indicator presented in the primary literature and determining if statistically significant differences were discernable and if so, on what scale.

4. **Robustness**
   The precision and repeatability of indicator data to reliably detect a response to change. Scoring of this criterion was based on evaluating data for the relevant indicator presented in the primary literature and determining if the data had evident signs of high variability or significant issues with outliers. Authors' issues with data reliability were also noted.

5. **Feasibility**
   The feasibility to carry out monitoring for each indicator. Scoring of this criterion was based on methodology options for measuring each indicator and what level of technical experience is required for sampling, processing, and data interpretation. If scientific or industry experts are required for much of the process, then the indicator scored poorly. However, if farmers can assist with much of the data collection, the indicator scored more favorably.

6. **Cost effectiveness**
   The relative cost of monitoring this metric on a continual basis including upfront, operational, and labor costs. Scoring of this criterion was based on what equipment and other funding costs are required to properly measure the indicator. If an indicator requires expensive equipment and has high labor costs, it scores poorly. However, if the indicator can be reliably measured at low cost, then scored more favorably.

7. **Reliability for predicting causality**
   The ability of the indicator data to reliably predict how an effect will respond to a cause. Scoring of this rubric depended on whether there were cases in the primary literature that noted causal relationships between the establishment of a farm and an ecological effect. This was primarily influenced by the experiment design chosen by the researchers with before-after control-impact (BACI) designs having the most reliability for predicting causality.

8. **Relevance of indicator given likelihood of measured effect**
   The importance of the indicator to measure an effect given how likely that effect is to occur in the region of interest. Scoring for this indicator relied on documentation of the indicator at farms in the region and whether or not it is monitored. Indicators with low scores, for instance, may capture an effect which is hypothesized to occur in AK and BC but the effect has not been observed.

9. **Community interest or concern**
   The degree to which farmers, stakeholders, and rightsholders are interested and/or concerned about the indicator. Scoring of this rubric relied upon mentions in the literature specific to Alaska and British Columbia and interviews conducted with industry experts and practitioners. Frequent mentions of an indicator during interviews or in relevant literature produced a higher score.

For each criterion, a scoring rubric was generated to rate each indicator on a scale of 0-3 based on relevant justifications outlined in Table 3. Multiple information sources (literature review, conference engagement, and interviews) were incorporated into how each score was decided to maximize objectivity. Once each criterion was scored for all 38 indicators, scores were added together to generate a total score. The distribution of total scores amongst indicators (**Figure B-1**) had a range of 18 with a maximum score of 26 (on a scale going up to 27), median score of 16, and minimum score of 8. The average score was 16.4 ± 3.8 (ave ± st. dev).

Because the goal of this exercise was to narrow down a list of essential, core indicators (Group A), we chose a cutoff total score of ≥ 20, which yielded a manageable set of 9 indicators that aligned with interests and concerns of stakeholders engaged during this project. The remaining indicators were deemed as optional and should be added when resources and circumstances allowed for their inclusion. These optional metrics were distributed into Group B

(15-19) and Group C (<15) to emphasize indicators of moderate importance for monitoring (Group B) and lesser importance for monitoring (Group C), based on the outcomes of this work.

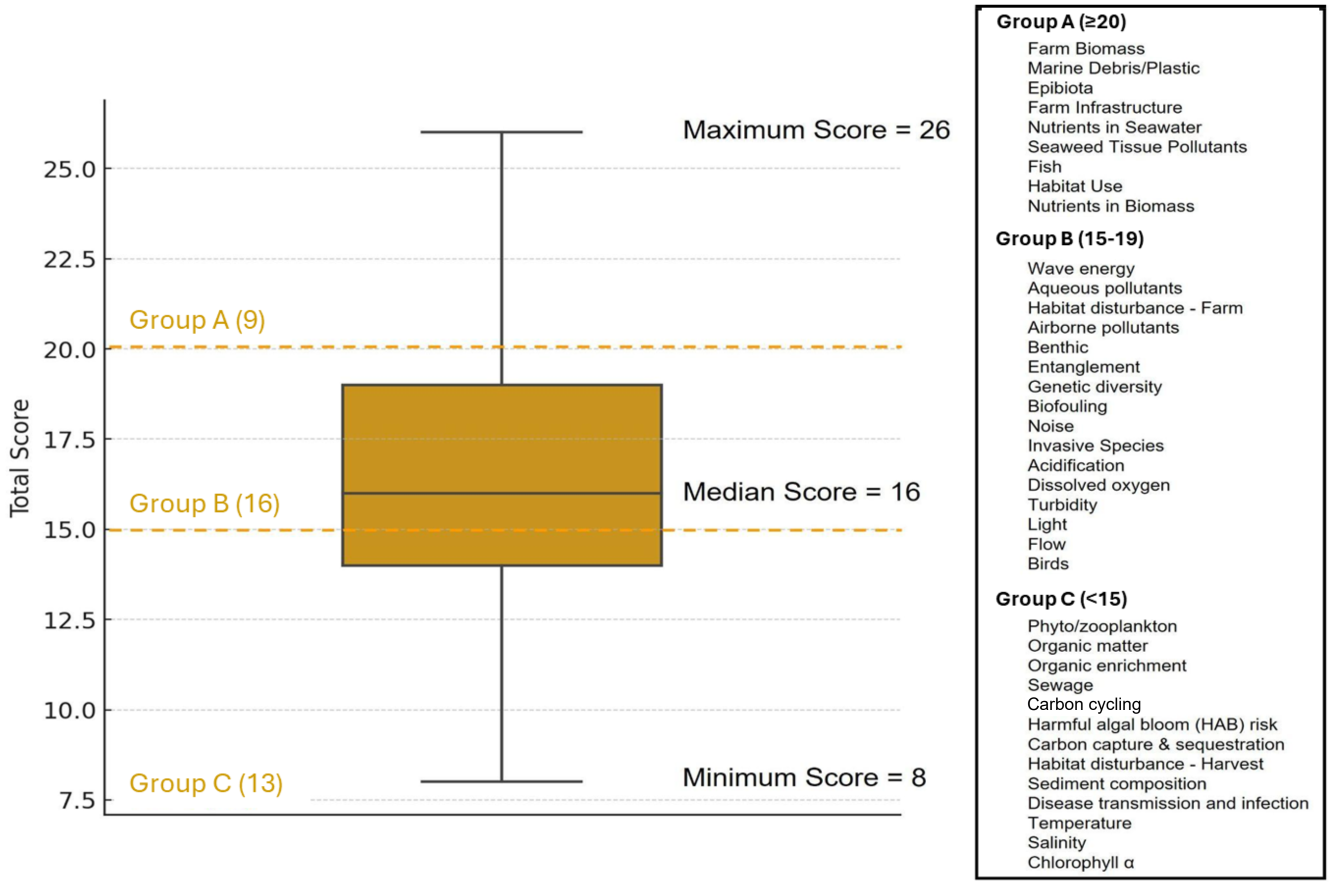

Figure A-1. A boxplot summarizing total scores for each indicator divided into Group A: indicators with scores ≥20, Group B: indicators with scores between 15–19, and Group C: indicators scores <15. Groupings are descriptive and comparative, and are not intended to define minimum requirements, benchmarks, or expectations for responsible practice. The number of indicators within each Group is indicated in parentheses at each dashed line at the cutoff for each Group. The box on the right lists what indicators fell into each Group in order of score from high to low.

Indicators vs. Other Frameworks

Table A-3. The scoring given to indicators from this study compared to recommendations provided by other monitoring frameworks and regulatory requirements in BC and AK. Ind = indirect.

Source	Selected Indicators (x = included, Ind = indirect coverage, blank = not included)																																					
	Biodiversity						Farm interactions						Ecological health					Biogeochemistry						Water quality									Pollution					
	Epibiota	Phytoplankton/zooplankton	Benthic	Fish	Birds	Mammals	Habitat use	Farm Infrastructure	Farm Biomass	Habitat disturbance (harvest)	Habitat disturbance (farm)	Entanglement	Genetic diversity	Biofouling	Harmful algal bloom (HAB) risk	Disease	Invasive species	Nutrients in seawater	Nutrients in tissue	Carbon Cycling	Organic matter	Organic enrichment	Sediment composition	Temperature	Salinity	Acidification	Dissolved oxygen	Turbidity	Light	Flow	Wave energy	Chlorophyll a (microalgae)	Aqueous pollutants	Airborne pollutants	Seaweed tissue pollutants	Marine Debris and Plastics	Sewage	Noise
This study	22	14	17	20	15	13	20	21	26	12	18	17	17	17	13	11	16	21	20	13	14	14	12	11	11	16	16	16	16	16	19	8	19	18	21	23	14	17
Monitoring Recommendations																																						
BC reg. requirements							Ind	x	x			x	Ind																							Ind		
AK reg. requirements							Ind	x	x			x	Ind																								Ind	
Martone et al. 2025							x			x		x	x		x	x	x	x		x	x	x				x			x		x	x	x			x		x
Tonk et al. 2021	x	x	x	x	x	x	x			x	x	x	x			x	x	x		x		x					x		x	x	x	x	x	x	x	x		x
NCM 2023		x	x	x	x	x	x				x	x	x	x		x	x	x		x	x	x	x				x		x	x		x				x		
TNC 2024	x	x	x	x	x	x	x		x			x	x	x					x	x	x		x	x	x	x	x			x		x						
Byron et al. 2024																		x			x	x	x					x	x	x								

References:

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- Byron, C. J., Koch, S. J., Callier, M. D., Kluger, L., Angel, D. L., Vanaverbeke, J., & Filgueira, R. (2024). Indicators for ecological carrying capacity of bivalve and seaweed aquaculture. Reviews in Aquaculture, 16(4), 2010–2022.

Indicator Data Knowledge Gaps

Table A-4. The scoring given to indicators from this study compared to data availability from select monitoring programs and data portals in BC and AK. Ind = indirect. Full version containing URL links to each program can be found within the Data Catalogue available for download from: http://pew.org/CultivatingWithCare.

Source	Region	Focus	Indicators (x = included, Ind = indirect coverage, blank = not included)																																					
			Biodiversity						Farm Interactions						Ecological Health					Biogeochemistry						Water Quality									Pollution					
			Epibiota	Phyto/zooplankton	Benthic	Fish	Birds	Mammals	Habitat use (farm)	Farm Infrastructure	Farm Biomass	Habitat disturbance (harvest)	Habitat disturbance (farm)	Entanglement	Genetic diversity	Biofouling	Harmful algal blooms	Disease	Invasive species	Nutrients in seawater	Nutrients in tissue	Carbon Cycling	Organic matter	Organic enrichment	Sediment composition	Temperature	Salinity	Acidification	Dissolved oxygen	Turbidity	Light	Flow	Wave energy	Chlorophyll a (microalgae)	Aqueous pollutants	Airborne pollutants	Seaweed tissue pollutants	Marine Debris and Plastics	Sewage	Noise
This study	**AK / BC**	**Indicator Scoring**	22	14	17	20	15	13	20	21	26	12	18	17	17	17	13	11	16	21	20	13	14	14	12	11	11	16	16	16	16	16	19	8	19	18	21	23	14	17
Monitoring Programs																																								
AK Ecosystem monitoring and assessment	AK	Ecological monitoring		x		x														x						x	x		x											
Alaska Beach Monitoring Program	AK	Beach water quality																																					x	
Continuous Plankton Recorder	AK	Phytoplankton		x																																				
GLOBEC Northeast Pacific Program	AK	Fish productivity		x		x	x	x																								x								
GreenWave Kelp Climate Fund	AK	Farmed biomass									x										Ind	Ind																		
Gulf of Alaska Ocean Observatory	AK	Oceanographic		x																x			x		x	x	x	x	x		x	x		x						x
Gulf Watch Alaska	AK	Ecological monitoring		x	x	x	x	x									x			x						x	x	x	x	x				x						
Mariculture Research & Restoration Consortium (Mar ReCon)	AK	Mariculture impacts	x	x	x	x	x	x	x				Ind									x				x	x	x	x	x	x			x						
Marine Mammal Laboratory Passive acoustic monitoring	AK	Underwater noise																																						x
NOAA National Buoy Data Center	AK	Marine weather																															x							
NOAA National Mussel Watch Program	AK	Chemical contaminants																							x										x					

Source	Region	Focus	Indicators (x = included, Ind = indirect coverage, blank = not included)																																						
			Biodiversity						Farm Interactions						Ecological Health					Biogeochemistry						Water Quality									Pollution					
			Epibiota	Phyto/zooplankton	Benthic	Fish	Birds	Mammals	Habitat use (farm)	Farm Infrastructure	Farm Biomass	Habitat disturbance (harvest)	Habitat disturbance (farm)	Entanglement	Genetic diversity	Biofouling	Harmful algal blooms	Disease	Invasive species	Nutrients in seawater	Nutrients in tissue	Carbon Cycling	Organic matter	Organic enrichment	Sediment composition	Temperature	Salinity	Acidification	Dissolved oxygen	Turbidity	Light	Flow	Wave energy	Chlorophyll a (microalgae)	Aqueous pollutants	Airborne pollutants	Seaweed tissue pollutants	Marine Debris and Plastics	Sewage	Noise
Northern Gulf of Alaska National Science Foundation Long Term Ecological Research, inc. Seward Line	AK	Ecological monitoring		x		x														x						x	x					x								x
Southeast Alaska Network environmental contaminants monitoring	AK	Environmental contaminants																																	x	x				
The State of Alaska Department of Environmental Conservation's Fish Monitoring Program	AK	Fish tissue contaminants																																	Ind					
Birds Canada Waterbird Survey	BC	Birds					x																																	
Capital Regional District water quality monitoring	BC	Beach water quality																																					x	
DFO Aquaculture Monitoring Program	BC	Finfish Aquaculture																																						
DFO Aquatic Invasive Species Monitoring	BC	Invasive species														x			x																					
DFO Benthic Habitat Mapping	BC	Benthic habitat			x								Ind																											
DFO Coastal Biodiversity Survey	BC	Intertidal habitat			x	x	x	x																																
DFO Dive Survey - Algae and Substrate	BC	Wild seaweed			x								Ind																											
DFO Herring Spawn Index	BC	Herring fisheries				x																																		
DFO Marine Biotoxin Monitoring	BC	Phytoplankton															x			x			x			x	x		x					x						
DFO Oceanographic Monitoring	BC	Oceanographic		x													x			x			x	x	x	x		x	x											
DFO Pelagic Ecosystem Acoustic Survey	BC	Fish biodiversity				x																																		
DFO-UVic Historical distribution of kelp forests on the coast of British Columbia: 1858 - 1956	BC	Wild seaweed (kelp)											Ind																											
Hakai Institute monitoring programs	BC	Biodiversity	x	x	x	x	x	x					Ind		x					x	x	x	x			x	x		x			x								
MaPP Regional Kelp Monitoring Program	BC	Wild seaweed (kelp)	x		x	x							Ind													x	x				x									

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CHN Marine Planning Program kelp monitoring	BC	Wild seaweed (kelp)			x	x							Ind		x	x		x																						
Marine Life Sanctuaries Society	BC	Rockfish				x																																		
Metro Vancouver water quality monitoring	BC	Wastewater quality																																					x	
Ocean Wise Sightings Network	BC	Marine mammals						x																																
OceanObserver Underwater Listening Stations	BC	Underwater noise																																						x
PSF Citizen Science Oceanography Program	BC	Oceanographic		x													x			x						x	x		x	x										
Raincoast Conservation Foundation Noise Tracker	BC	Underwater noise																																						x
The Coastal First Nations Regional Monitoring System	BC	Member Nation Priorities			x	x		x					x						x																					
Selected Data Compilation Platforms																																								
Alaska Ocean Observing System (AOOS)	AK	Data compilation		x	x	x	x	x									x			x		x	x	x	x	x	x	x	x	x	x	x	x	x						x
Aquaculture Opportunity Areas	AK	Data compilation			x	x	x	x																								x	x							
ADF&G Alaska Fish Resource Monitor	AK	Data compilation				x				x																														
ADF&G Gene Conservation Laboratory's Baseline Genetics Collections Mapper	AK	Data compilation													x																									
The Canadian Integrated Ocean Observing System (CIOOS)	Canada	Data compilation		x	x	x	x	x									x		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x			x		x
Ocean Networks Canada: Oceans 3.0	Canada	Data compilation		x	x	x		x												x		x	x			x	x	x	x	x	x	x	x	x						x
Ocean Biodiversity Information System	Global	Data compilation		x	x	x	x	x								x			x																					
Modern Ocean Sediment Archive and Inventory (MOSAIC)	Global	Data compilation																				x	x	x	x															