Cultivating with Care

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

Volume 2 – Monitoring Indicator Factsheets

September 2026

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ESSA is an employee-owned Canadian environmental consulting firm founded in 1979 that brings together people, science, and analytical tools to sustain healthy ecosystems and human communities. It specializes in applied research, participatory engagement, and strategic planning for cross-cutting environmental issues across the globe, and acted as technical lead for this report.

The Prince William Sound Science Center advances scientific understanding and sustained monitoring of ecosystems in Prince William Sound, the Copper River, and adjacent Gulf of Alaska waters to support resilient communities and healthy ecosystems. It produces practical research and data for resource managers and the public, contributing to long-term ecological understanding and sustainable use of renewable marine resources, including providing technical expertise for this report.

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.

Founded in 1948, The Pew Charitable Trusts uses data to make a difference. Pew addresses the challenges of a changing world by illuminating issues, creating common ground, and advancing ambitious projects that lead to tangible progress. Pew provided funding and technical support for this report. The views and opinions of the authors expressed herein do not necessarily state or reflect those of Pew.

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Cover Photo: Seaweed monitoring, Kachemak Bay, AK, by Sierra Greene, UAF.

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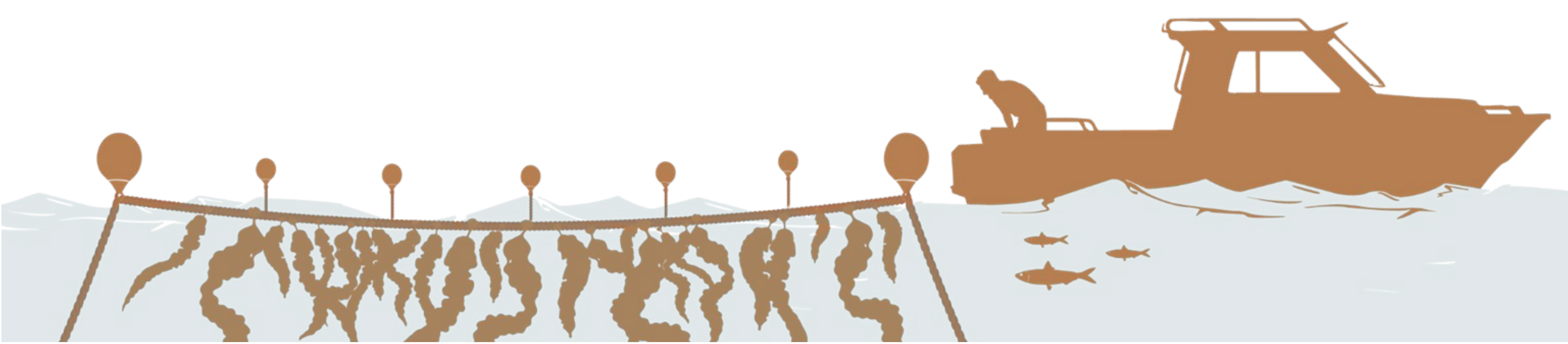

Overview

Seaweed farming in both Alaska (AK) and British Columbia (BC) is emerging at the intersection of coastal livelihoods, environmental opportunity, and evolving ocean governance. As the sector grows, effective monitoring must balance credibility, practicality, and inclusivity to ensure that it is financially viable, scientifically sound, and community informed. Yet monitoring approaches for seaweed farming's environmental effects remain highly variable across regions, farm types, and regulatory systems, and no single, practical reference has consolidated and translated information on monitoring indicators into practical, ready-to-use guidance for the people that wish to apply them. This volume is intended to help close that gap, as Volume 2 of a two-part report co-authored by ESSA Technologies Ltd. (ESSA), the Prince William Sound Science Center (PWSSC), NOAA's Alaska Fisheries Science Center (AFSC), and The Pew Charitable Trusts.

Volume 1 (Science Synthesis) presents the underlying research and methodology behind this work – the first systematic evaluation of environmental monitoring indicators tailored to this region. This volume, *Monitoring Indicator Factsheets*, is the practical companion: it takes each monitoring indicator from that evaluation and turns it into a standalone factsheet of key metrics, methods, and potential data sources or monitoring partners that can be used by the people and organizations who want to put monitoring into practice.

What's in This Volume

This volume includes factsheets for the 38 monitoring indicators evaluated in Volume 1, organized into six categories based on the type of environmental effect: farm interactions, biodiversity, ecological health, biogeochemistry, water quality and flow, and pollution. Each indicator is assigned to Group A (≥20), B (15-19), or C (<15) based on its combined score across the report's evaluation criteria – reflecting how strongly it is supported by current literature, regional relevance, and practitioner input, not a measure of monitoring priority. Factsheets are ordered to roughly match Table 1 in Volume 1, though closely related indicators are sometimes combined into a single factsheet – 25 factsheets cover all 38 indicators. More detailed indicator information and scoring rationale are available in the supplementary **Data Catalogue** available at the link below.

How to Use These Factsheets

Each factsheet explains why the indicator matters, shows how it scored against the report's evaluation criteria, defines the key metrics used to measure it, outlines methods and protocols for monitoring it, describes its relevance to decision-making, summarizes related data and monitoring efforts already underway in AK and BC, and points to select references for further reading. As with Volume 1, these factsheets are intended to inform monitoring discussions and support practical implementation — not to prescribe monitoring requirements, establish regulatory standards, or imply policy or regulatory recommendations. A supplementary data sheet with information on indicator scoring criteria, rationale, and data sources is also available alongside these reports.

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

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

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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.
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.
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 Peoples 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.
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 (MSC)	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.
Sedimentation	The process where solid particles—like mud, sand, silt, and organic debris—sink through the water and settle onto the seafloor, forming a layer of sediment.
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.
Seed spool	A hatchery-produced spool of seaweed seed used to inoculate grow lines, graded by hatchery operators for coverage, coloration, and consistency before outplanting.
Turbidity	The cloudiness of water caused by suspended particles such as sediment, plankton, or organic material. High turbidity reduces light penetration.

Photo: PWSSC

FARM INTERACTIONS – Farm Infrastructure

Rationale: The environmental benefits or impacts of seaweed farming will depend in part on farm infrastructure. Farms in AK and BC use small-scale, nearshore farming infrastructure such as single line, five line, and catenary array systems anchored to the seafloor. The depth of the grow lines varies with species. However, there is developing interest in establishing larger, offshore seaweed farms. We can also expect that as seaweed farming becomes more profitable, innovative farming methods and infrastructure may change how farms affect coastal ecosystems. Farms with more infrastructure may also require more maintenance which may contribute to habitat disturbance or pollution.

- **Nearshore:** Nearshore farms are situated within shallow, protected areas like bays that are within 3 nautical miles from shorelines. They can be restricted by available space or conflict with other users (e.g., commercial fishing, subsistence activities, recreation, tourism) and are likely to interact with biological communities.
- **Offshore:** Offshore farms are located at least 3 nautical miles away from shore, situated in deeper, open ocean conditions with high wave and wind exposure. They may be adapted in combination with existing offshore infrastructure (e.g., wind turbines, oil and gas infrastructure). Currently, offshore seaweed farms have been tested or established in Germany and China.
- **Multi-trophic:** Seaweed cultivation in combination with other species such as oysters, mussels, and finfish (BC only) has the potential to enhance growth and mitigate nutrient loads from other species.

Indicator Scoring: Farm infrastructure was identified as a **Group A** monitoring indicator due to its necessity for correlating environmental effects with farm establishment and the scale of these effects.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	3
Sensitivity and Responsiveness	0
Robustness	3
Feasibility	3
Cost-effectiveness	3
Reliability for Predicting Causality	0
Likelihood of Interaction	3
Community Interest / Concern	3
Total Score (Max = 27)	**21**

Key Metrics	Definition
Acreage	Farm Size
Gear Type	Number and type of anchors, buoys, lines
Cultured Species	Number and type of species cultivated
Farm Density	Number of farms in an area

Methods and Protocols: During the AK aquaculture permitting process, farmers are required to provide detailed information in the form of a Site Plan Map. This map includes details like acreage, cultivated species, all in-water structures and anchoring systems, equipment and support facilities, and distance between gear/equipment and the proposed farm site. In BC, applicants are likewise required to provide detailed operational schematics, including all farm infrastructure and alternative layouts, as part of the permitting process.

Decision-relevance: Farm acreage, gear type, and cultured species are required by regulatory agencies in both AK and BC to issue permits for farm leases. In AK and BC, farm lease applications are also released to the public for a comment period, where other users can voice concerns about the size, location, and gear type of the proposed farm. Monitoring farm characteristics in relation to other environmental effects could also help to identify thresholds or tipping points of farm size or complexity where effects begin to appear, which could influence decision-making on future farm design and approvals.

Existing Data and Monitoring Efforts:

AK: There are two key resources, including the AOOS Mariculture Map and the Alaska Department of Fish and Game Aquatic Farming Operations Mapper, which includes acreage, a brief description of gear type, and a list of species for each farm. Aquatic farm applications are available per the State of Alaska Online Public Notices site.

BC: The provincial Natural Resource Online Services or the iMapBC mapping tool can provide information on existing marine use areas, including seaweed tenures, although infrastructure is not specifically depicted.

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FARM INTERACTIONS – Farmed Biomass

Rationale: Farmed biomass, or the total mass of seaweed produced by a farm, will influence how organisms use the farm as habitat, affect light attenuation, and how much organic matter is contributed to the water and sediment. Depth-cycling farm lines as a strategy has been found to increase giant kelp biomass growth rates, but is expensive. Farms with higher biomass may also require more maintenance which may contribute to habitat disturbance or pollution.

Indicator Scoring: Farmed biomass was identified as a **Group A** variable due to its importance to regulatory agencies and interviewed stakeholders, adequate data quality, and relative feasibility and cost for estimating.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	3
Sensitivity and Responsiveness	3
Robustness	2
Feasibility	3
Cost-effectiveness	3
Reliability for Predicting Causality	3
Likelihood of Interaction	3
Community Interest / Concern	3
Total Score (Max = 27)	**26**

Key Metrics	Definition
% of farm outplanted	Proportion of farm that is seeded
Weight	Wet weight of seaweed sub-sampled (e.g., pounds/kilograms per foot of line)
Length of seeded line	Footage of seeded line outplanted
Seed spool quality	Quality and consistency of seeded line outplanted
Biomass Density	The amount of seaweed in a set area

Methods and Protocols: Farmed biomass can be estimated by weighing poundage of seaweed blades from multiple locations throughout the farm and extrapolating by the length of seeded line outplanted. These estimates can be influenced by heterogeneity in growth throughout the farm due to inconsistency in quality of seed from the hatchery, competition between grow lines for nutrients and light, or differences in conditions through the farm. Hatchery operators grade seed spools at the end of the hatchery season based on coverage, coloration, consistency, and unwanted growth (GreenWave). This information has not yet been used for estimation of farmed biomass.

Decision-relevance: The Alaska Department of Fish and Game (ADF&G) and Alaska Department of Natural Resources (ADNR) both require an annual harvest permit from aquatic farmers that includes total sales by species, the footage of seeded line or poundage of seed, and amount of stock added to the farm during outplanting. The BC Ministry of Agriculture and Food also requires annual reporting of wet weight (tons) of seaweed harvested.

Existing Data and Monitoring Efforts: Farmed biomass is reported in both AK and BC but better access to harvest reporting would be helpful for contextualizing data collected from monitoring programs.

AK: Production data is collected annually by the ADF&G and can be accessed through their Aquatic Farm Operations web page. Harvest estimates provided by ADF&G are not yet available for individual species. The GreenWave Kelp Climate Fund also collects data from participating farmers via the MyKelp App where farmers are measure and submit monthly biomass measurements and may be available upon request.

BC: The BC Ministry of Agriculture and Food collects annual harvest data for wet weight (tonnes) of harvested seaweed. This data is available upon request but does not currently include breakdowns of wet weight from individual farm sites (often aggregated by company) or species (for farms that grow more than one species).

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FARM INTERACTIONS – Habitat Use

Rationale: Seaweed farms transform the marine environment by introducing novel, three-dimensional structured habitat. Monitoring is essential to understand wildlife interactions and evaluate farm benefits and impacts (e.g., how different animals use the farm). For example, forage fish like Pacific herring (*Clupea pallasii*) may use farm structures as spawning substrate, representing habitat use, but causing crop loss for farmers. Higher trophic level organisms may feed on epibionts (e.g., amphipods) that are prevalent in and around farmed seaweed and mussel lines, providing valuable foraging grounds, but potentially damaging crops. Researchers should also be careful about delineating positive and negative impacts to benthic communities based only on species richness or diversity and should consider variables like trophic linkages, habitat provisioning, or ecosystem service provisions as more reliable indicators of use.

Indicator Scoring: Habitat Use was identified as a **Group A** indicator due to its relevance to management and high community interest. This indicator's relevance to management has mostly been documented and discussed with respect to fish.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	2
Sensitivity and Responsiveness	2
Robustness	2
Feasibility	2
Cost-effectiveness	2
Reliability for Predicting Causality	2
Likelihood of Interaction	2
Community Interest / Concern	3
Total Score (Max = 27)	**20**

Key Metrics	Definition
Presence	Presence at the site
Residence Time	Amount of time spent at the site
Feeding	Use of seaweed or epibiota as a food source (e.g., direct observations of feeding, gut contents, isotopes)
Sheltering	Refugia behaviors, presence of current or predators potentially driving refuge
Spawning & Rearing	Spawning on farms, fecundity on farms
Growth & Survival	Body mass/length, estimate mortality

Methods and Protocols:

Visual Surveys (Diver/Snorkeling): Observations of fish through underwater visual census. However, these surveys can be limited by visibility, do not account for diurnal movements, and can be difficult in areas with low biodiversity.

In situ/Remote Video and Cameras: Stationary remote video cameras are used to monitor fish with less disturbance than visual surveys. These systems provide imagery relevant for tracking refugia usage and wildlife interactions.

Acoustics/Imaging Sonar: Echosounders or advanced imaging sonar can be coupled with mounted cameras to detect and track fish distribution and behavior.

Destructive Sampling: Sampling captured organisms around farms can provide information on use of the farm site and may be paired with visual or eDNA analysis to understand trophic interactions at farm sites.

Environmental DNA (eDNA): eDNA can be used alongside visual analysis to identify species in the gut contents of fish at farm sites to determine whether they are feeding on the lower trophic level species within farms in comparison to reference sites. New technology like sub-surface automated eDNA samplers (SASe) can be used as a low-cost tool to take more complete eDNA profiles from sites compared to manual eDNA collections.

Decision-relevance:

Inform Site Selection and Design: Baseline surveys are essential prior to farm operation to ensure appropriate siting. Such data can guide decisions regarding the optimal location, extent, and density of cultivation gear, helping to mitigate impacts on sensitive natural habitats like seagrass beds.

Social License: Habitat use monitoring can support social licensing and adhere to certification requirements for sustainable practices.

Optimize Timing of Operations: Understanding when observed species are engaging in critical life stages (e.g., salmon migration or herring spawning) allows farm managers to adjust harvest schedules to reduce disturbance.

Adaptive Management and Mitigation: Monitoring can inform management strategies which respond to the undesired presence of non-native species or marine mammal entanglement.

Existing Data and Monitoring Efforts:

AK: The Mariculture Research and Restoration Consortium (Mar ReCon) project monitors fish interactions, size, species, and usage of seaweed farms as habitat using an imaging sonar and cameras. There have also been reports of Pacific herring spawning on kelp farms in Alaska. Mar ReCon also conducts quarterly dive surveys to assess invertebrate and benthic fish communities in and around kelp farms, and NOAA Auke Bay Laboratories are conducting a study on fish and invertebrate use of kelp farms seasonally in Southeast Alaska.

BC: Cameras deployed by Cascadia at their farms have captured >9,000 hours of underwater footage. Video can be used to identify species, and capture information on habitat use. Fisheries and Oceans Canada (DFO) also collects Herring Spawn Index data both at the surface at low tide and on giant kelp and other substrates.

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Photo: PWSSC

FARM INTERACTIONS – Habitat Disturbance (Operations vs. Harvest)

Rationale: The deployment and maintenance of seaweed farms requires on-water vessel activity that generates noise and can temporarily displace wildlife at the sea surface or disturb the seafloor. Farm infrastructure may also attract wildlife that use surfaces for refugia, such as perching by birds or haulout for marine mammals; however, that could lead to wildlife being disturbed or displaced during farming activities. The removal of kelp biomass during harvest may remove, destroy, or displace associated organisms. Distinguishing between disturbance from farm presence and maintenance versus disturbance from harvest activities allows for more targeted monitoring and management to be less disruptive to each phase of the farm production cycle.

Indicator Scoring: Habitat disturbance was divided into two indicators, disturbance from the farm and from harvest. Disturbance from operations (i.e., maintenance, deployment, presence) was designated as a **Group B** indicator due to its high relevance to management, support from the literature, and moderate concern from the farming community. Disturbance by harvest was designated as a **Group C** indicator with relevance to management but less support in literature. Monitoring for these two aspects of habitat disturbance relies on similar metrics, but measured at different timeframes (i.e., lead up to harvest vs. during and after harvest).

Indicator Selection Criteria Scores (0-3)	Farm	Harvest
Relevance to Management	3	3
Literature Support	3	1
Sensitivity and Responsiveness	3	2
Robustness	1	1
Feasibility	2	1
Cost-effectiveness	2	1
Reliability for Predicting Causality	1	1
Likelihood of Interaction	1	0
Community Interest / Concern	2	2
Total Score (Max = 27)	**18**	**12**

Key Metrics	Definition
Vessel presence	Time or frequency of vessel visits
Animal displacement	Observations of wildlife leaving site
Noise	Decibels
Recovery rate	Return to a pre-disturbance state

Methods and Protocols:

Surveys: Visual surveys from vessels or shore-based vantage points are commonly used to document wildlife presence, behavior, and displacement before, during, and after farm or harvest activities. Surveys may record species presence, abundance, distance from operations, and observable behavioral responses such as avoidance.

Remote Video: Fixed or mobile remote video systems can provide continuous or time-lapse observation of farm areas with minimal additional disturbance. Video monitoring is particularly useful for documenting wildlife interactions with farm infrastructure and for observing recovery following disturbance events.

Acoustic Monitoring: Passive acoustic monitoring can be used to characterize underwater noise associated with vessel presence, farm maintenance, and harvest operations. Acoustic data support assessment of noise levels relative to background conditions and may help interpret wildlife responses, particularly for acoustically sensitive species.

Activity logs: Capture the number of visits, vessel and engine characteristics, fuel use (to calculate emissions), as well as ship maintenance and incidents of oiling at farms (e.g., leaking of hydraulic fluid).

Decision-relevance:

Inform Site Selection and Design: Habitat disturbance data can inform site selection by identifying areas with high wildlife use or sensitivity at greater risk of disturbance. Farm design can also influence the degree of physical and acoustic disturbance, and monitoring results can guide design refinements to minimize impacts.

Optimize Timing of Operations: Understanding patterns of wildlife presence and sensitivity allows farmers to adjust timing of maintenance or harvest activities to reduce disturbance during critical periods such as breeding, molting, or migration. Temporal adjustments can be an effective mitigation strategy with relatively low operational cost.

Existing Data and Monitoring Efforts: Habitat disturbance by farms or harvest is not directly monitored in AK or BC.

In AK: Mariculture Research and Restoration Consortium (Mar ReCon) collects data on the presence of fish, birds, and mammals at farm sites to generate baseline data and make inferences about how farms may affect wildlife.

In BC: During the permitting process, applicants must complete a habitat survey and avoid sensitive ecosystems and at-risk species.

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BIODIVERSITY – Epibiota

Rationale: The organisms that live and grow on seaweed, epibiota, include microorganisms like algae as well as sessile and mobile animals including hydroids, amphipods, gastropods, and bryozoans. Monitoring epibiota on farmed seaweed provides information about how farms are used as habitat and whether mitigation steps should be taken by farmers to avoid issues with biofouling of seaweed. Biofouling can deteriorate crop quality by inhibiting photosynthesis and growth, causing damage to blades from grazing, increasing disease susceptibility, or contributing to crop loss. In addition, seaweed farms may facilitate the spread of invasive epibionts between farms and wild seaweed beds. For example, farmers have reported the non-native Japanese skeleton shrimp (*Caprella mutica*) on sugar kelp farms in Norway.

Indicator Scoring: Epibiota was identified as a **Group A** variable due to literature support and relevance to management for monitoring. There is also significant community concern on biofouling impacts to crop quality and the risk of introducing or spreading invasive species.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	2
Sensitivity and Responsiveness	2
Robustness	2
Feasibility	2
Cost-effectiveness	2
Reliability for Predicting Causality	3
Likelihood of Interaction	3
Community Interest / Concern	3
Total Score (Max = 27)	**22**

Key Metrics	Definition
Sessile Epibiont Coverage	% of blade surface occupied by bryozoans, hydroids, algae, etc.
Mobile Epibiont Coverage	Counts of fauna loosely attached to blades.
Taxa Richness & Diversity	Counts of distinct taxa or community indices.
Epibiont Biomass	Wet mass of organisms on blades.

Methods and Protocols:

Direct Observation and Destructive Sampling: Monitoring for epibiota might include direct observations of epibiota, collecting samples (e.g., by rising seaweed into a fine sieve), and/or microscopic examination.

Invertebrate Collector Devices: Epibiota can also be sampled using fauna traps or settlement plates which are deployed and collected after colonization. These methods provide a way to assess diversity, percent coverage, and detection of non-native species.

Environmental DNA (eDNA) Sampling: Epibiota can also be identified by eDNA from water samples. Passive eDNA collection methods, such as subsurface automated samplers (SASe), are also available and can capture genetic material over a longer time and enhance detection probability.

Decision-relevance:

Pest Management: Data on epibiota provide the foundation for a Marine Integrated Pest Management (MIPM) approach. MIPM uses monitoring data to identify dominant pests and grazers, determine the accepted level of pests, understand target and non-target species life cycles, develop pest or disease forecasting techniques, and identify environmental risks to crops. For example, data on the presence of nuisance organisms such as the snail *Lacuna vincta*, which consumes kelp, advises farmers on optimal site location to minimize potential impacts before leases are finalized.

Site Selection and Design: Understanding how environmental drivers (e.g., wave exposure, currents) influence epibiont larval supply and settlement informs farm site selection and infrastructure.

Farm Operations and Harvest Timing: Monitoring epibionts and biofouling provides farmers with a means of early detection, allowing for adjustments to farm operations and harvest timing to prevent crop loss. Mussel biofouling, for instance, can sink culture lines, warranting in-season adjustments.

Economic Assessment and Management: Monitoring data is necessary to calculate both direct and indirect costs caused by pests, providing a complete picture to support decision-making.

Biosecurity and Policy: Data on epibionts are crucial for assessing potential pathogen and non-native species infestation and supporting robust biosecurity measures. This data is also necessary to guide potential regulatory changes like amending invasive species and environmental protection acts.

Existing Data and Monitoring Efforts:

AK: Epibiota is assessed by the Mariculture Research and Restoration Consortium (Mar ReCon) program as part of the benthic component through imagery of kelp blades taken by farmers and submitted to researchers. These images are used to estimate % coverage of epiphytes. Blade samples are also collected by farmers, frozen, and transported for later processing for species identification.

BC: Since 2005, Fisheries and Oceans Canada has deployed settlement plates (data archived in the Ocean Biodiversity Information System), and more recently used eDNA, to monitor invasive species and develop distribution models. In addition, biodiversity eDNA data collected in 2017 identified 1477 unique species ranging from zooplankton to marine mammals which may provide baseline species presence data relevant to seaweed farming (see Jacquemot et al. 2024). University, government and First Nation Partners have been studying kelp-encrusting bryozoan populations in BC since 2014/15 through targeted research and the Marine Plan Partnership's (MaPP) regional kelp monitoring project.

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Photo: NOAA

BIODIVERSITY – Fish

Rationale: Monitoring fish presence and diversity helps to establish the potential ecological benefits of seaweed farms to fish. Farms may serve as refugia, nursery areas, or feeding grounds. Monitoring aims to establish fish presence and biodiversity in seaweed farms and may include behavioral or residency metrics. Fish monitoring is also relevant for site selection, farm design, and harvest timing to avoid impacts to ecologically important species or sensitive life stages. For example, it may be of interest to farmers to deter herring from spawning on farmed seaweed.

Indicator Scoring: Fish presence was identified as **Group A** indicator due to its relevance to management, literature support, and community concern. Monitoring should consider that data quality relies heavily on appropriate experimental design and methods needed to overcome high variability. Measuring sensitivity, responsiveness, and robustness is challenging due to the high mobility and variability inherent in fish populations.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	3
Sensitivity and Responsiveness	1
Robustness	1
Feasibility	3
Cost-effectiveness	2
Reliability for Predicting Causality	1
Likelihood of Interaction	3
Community Interest / Concern	3
Total Score (Max = 27)	20

Key Metrics	Definition
Richness	Number of distinct fish or taxonomic groups per site
Diversity Index	Measure of species richness and evenness
Community Composition	Relative proportions of species by site
Abundance	Number of individuals per space

Methods and Protocols:

Direct Observation and Destructive Sampling: Observation of fish can be done through underwater visual census, and in some cases destructive sampling through fishing around kelp farms. However, visual surveys can be limited by visibility and do not account for diurnal movements.

Underwater Video: This technique involves deploying stationary or remote cameras, baited or unbaited, to survey mobile fish assemblages over longer timeframes than is possible via diving. Video systems, such as "FishCams" built on open-source Raspberry Pi computers, have been successfully used to monitor pelagic fauna at seaweed farms in the Northeast Pacific. Processing visual data is increasingly augmented by computer vision algorithms (e.g., YOLOv8), which can automatically identify and count common fish taxa.

Acoustic Monitoring (Imaging Sonar): Sonar systems are suitable for surveying mobile fauna, particularly schooling forage fish. Sonar surveys record variables like location, depth, and speed, providing data to estimate fish biomass, density, and behavior. Sonar videos must be processed through manual annotation and can be paired with underwater video methods.

Environmental DNA (eDNA) Metabarcoding: Fish can also be sampled by eDNA, or the detection of genetic material in water samples. New technology like sub-surface automated eDNA samplers (SASe) can be used as a low-cost tool to take more complete eDNA profiles from sites compared to manual eDNA collections.

Associated with: Tamburello, N., Gillies, E., Gutzmann, S., Cypher, A., Hollarsmith, J., and Theuerkauf, K. 2026. Cultivating with Care -Environmental Effects and monitoring Indicators for the Seaweed Farming Sector in Alaska and British Columbia. Volume I - Science Synthesis. Report prepared for The Pew Charitable Trusts. 63 p + Appendices.

Decision-relevance:

Farm Site Selection and Design: Monitoring can help inform farm infrastructure design, for example, adjusting the depth of lines to either avoid or maximize habitat provision.

Timing of Operations for Outplanting and Harvest: Fish abundance and diversity fluctuate seasonally, and monitoring can provide temporal data to determine how harvesting affects the temporary habitat provided by the seaweed farm.

Conservation and Policy Support: Quantifying fish use helps managers assess whether farms are acting as fish habitat. If monitoring shows that farms provide habitat for important species, this may support financial mechanisms like biodiversity credits.

Existing Data and Monitoring Efforts:

AK: In Alaska, monitoring of fish in kelp farms is being conducted in Prince William Sound (PWS) through the Pelagic Fish Component of the Mariculture Research and Restoration Consortium (Mar ReCon) project and in Southeast Alaska by NOAA Alaska Fisheries Science Center. In PWS, methods for imaging sonar sampling have been tested at several farm and control sites and indicate that fish and fish school encounters are common and dominated by smaller fish species like Pacific herring. In Southeast Alaska, eDNA metabarcoding is being used to detect the presence, diversity, and abundance of fish, with results indicating strong seasonality and depth stratification of fish communities and little influence of the farm presence. The Nearshore Fish Atlas used by the NOAA Habitat Conservation Division for Essential Fish Habitat might be relevant for baseline information on species distributions.

BC: Cameras deployed by Cascadia at their farms have collected over 9,000 hours of video footage across two kelp farms and adjacent reference sites over 16 months. In addition, biodiversity eDNA data from 2017 has identified 1477 unique species ranging from zooplankton to marine mammals which may provide baseline species presence data relevant to seaweed farming (see Jacquemot et al. 2024). Several data sources from Fisheries and Oceans Canada exist that provide a baseline for local fish biodiversity, including rockfish, juvenile salmon, and subtidal surveys, and, groundfish species distribution models. The Marine Life Sanctuaries Society runs a citizen science rockfish monitoring program.

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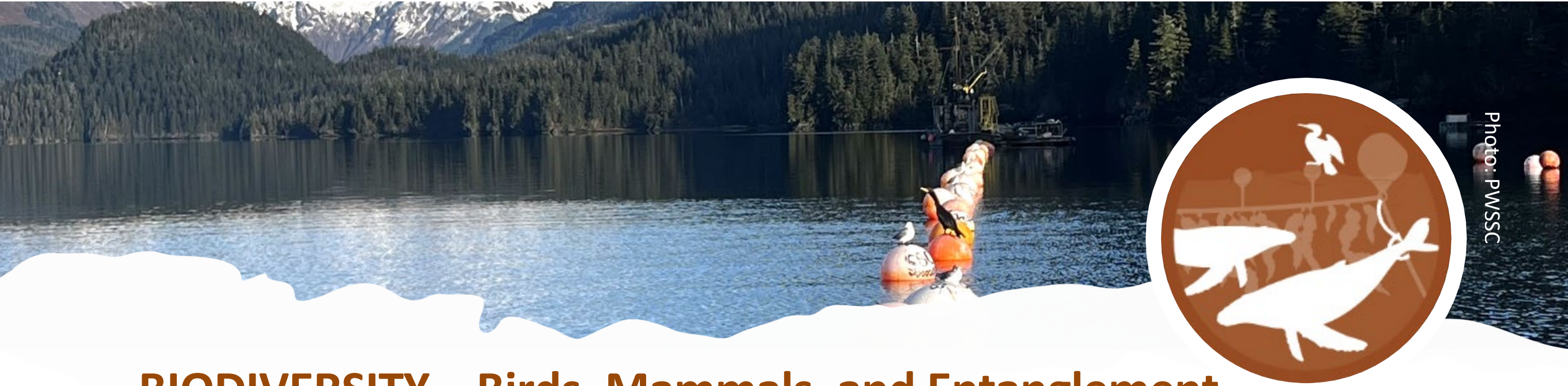

BIODIVERSITY – Birds, Mammals, and Entanglement

Rationale: Seaweed farms modify habitat and have the potential to interact with wildlife. This may include attractants such as providing structures for perching, enhancing prey availability for fish-eating birds and mammals, or negative effects such as enhanced entanglement risk. Bird and mammal presence can also influence seaweed farms through organic enrichment. Federal laws protect marine mammals and birds in the US and Canada from negative interactions with human activities, which would include seaweed farming. In both countries, legal frameworks and their permitting process include measures, impact assessments, and reporting to minimize negative interactions. Many seabirds use specialized habitats on stops along long migration routes and are thought to be particularly susceptible to habitat alteration. Gear loss from seaweed farms may also lead to later entanglement in ghost gear.

Indicator Scoring: Birds were identified as a **Group B** indicator that is feasible to incorporate into monitoring with moderate concern by the farming community and literature for monitoring. Mammals were identified as a **Group C** primarily due to minimal documentation of mammal interactions with farms. Entanglement was identified as a **Group B** variable, primarily due to its relevance to management as reporting is required by regulatory agencies. However, the likelihood of interaction was deemed low as cases of entanglement have not been reported in AK or BC.

Indicator Selection Criteria Scores (0-3)	Birds	Mammals	Entanglement
Relevance to Management	1	3	3
Literature Support	2	1	1
Sensitivity and Responsiveness	1	1	2
Robustness	1	1	2
Feasibility	3	3	2
Cost-effectiveness	2	2	2
Reliability for Predicting Causality	1	0	2
Likelihood of Interaction	2	0	1
Community Interest / Concern	2	2	2
Total Score (Max = 27)	15	13	17

Key Metrics	Definition
Counts	Number of birds and mammals
Species	Identification
Behavior	Interactions with farms (e.g., perching)
Occurrence	Entanglement observation
Injury/ Mortality	Injury or signs of mortality are evident

Methods and Protocols:

Direct Observation and Surveys: Conducting vessel-based surveys at or near farms can involve counting birds or mammals, haulout events by mammals, foraging behavior, and time spent at farms. If entanglement is suspected, observers should report cases and locations immediately to the relevant agency.

Remote Video: The deployment of stationary or remote cameras in and around seaweed farms can provide remote observations of marine birds and mammals.

Acoustic Monitoring: Hydrophones or recording devices can remotely monitor bird or mammal vocalizations.

Decision-relevance:

Inform Site Selection and Design: Prior and ongoing data collection on marine bird and mammal interactions with farms can inform decision-making about farm site selection and potential for conflicts during farming operations. Careful siting will lower the risk of negative wildlife interactions with the farm and its operations.

Optimize Timing of Operations: Where possible and within the constraints of processing and market timelines, understanding when specific species are engaging in critical life stages can allow farm managers to adjust harvest schedules to reduce disturbance to marine birds and mammals.

Adaptive Management and Mitigation: Monitoring provides feedback for changes if wildlife conflicts arise, such as damage to farms or restrictions on farm operations due to the presence of and interactions with wildlife. This can inform adaptive mitigation strategies to avoid negative interactions, such as adjustments to the farm gear or design, operations, or location.

MSC Certification: Requires consideration of wildlife interactions, especially endangered, threatened or protected species.

Existing Data and Monitoring Efforts:

AK: The Mariculture Research and Restoration Consortium monitors marine birds and mammals in and around seaweed farms in Prince William Sound, Kachemak Bay, and Kodiak Island. Reports and data are available through DataONE and the Exxon Valdez Oil Spill Trustee Council. In addition, the Gulf Watch Alaska program monitors whales and marine birds in the Northern Gulf of Alaska in areas impacted by the *Exxon Valdez* oil spill. Data is available through AOOS. Reporting of marine mammal entanglements, injuries, or mortalities is a legal requirement through NOAA and the Alaska Department of Fish and Game.

BC: Fisheries and Oceans Canada (DFO) uses a combination of acoustic methods and vessel surveys to track marine mammals with data available upon request. Whale and sea turtle sightings are also crowdsourced by reporting networks such as the Ocean Wise Sightings Network. Additional information is collected by hydrophone networks across the Northeast Pacific, particularly for species of conservation concern such as orca (killer whales), and coastal waterbird surveys done by Birds Canada. Reporting of marine mammal entanglements, injuries, or mortalities is a legal requirement through DFO. DFO also provides sea lion and harbor seal haulout baseline data in the Coastal Environmental Baseline database.

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Photo: PWSSC

BIODIVERSITY – Benthic

Rationale: Benthic invertebrates and autotrophs include infauna (in sediment), mobile macrofauna, mobile and sessile organisms, and seagrass and seaweed communities. The composition of the benthic community may be affected by seaweed farming due to organic enrichment from dissolved and particulate matter originating from the farm and reduced light penetration due to farm shading.

Indicator Scoring: Benthic communities were identified as a **Group B** variable that was well supported in the literature as relevant to management of seaweed farming with high concern by the farming community, but methodology and cost was found to be limiting. The need for technical diving and identification requires a higher degree of financial and scientific support for monitoring. For monitoring benthic communities, appropriate control sites are needed to attribute effects to a seaweed farm. Researchers should also be careful about assigning positive and negative impacts to benthic communities based on species richness or diversity as variables like trophic linkages, habitat provisioning, and ecosystem service provision should also be considered. Current research suggests that seaweed farming has a relatively benign effect in comparison to other forms of aquaculture.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	2
Sensitivity and Responsiveness	2
Robustness	2
Feasibility	1
Cost-effectiveness	1
Reliability for Predicting Causality	2
Likelihood of Interaction	1
Community Interest / Concern	3
Total Score (Max = 27)	**17**

Key Metrics	Definition
Taxa Richness	Number of distinct taxa per site
Diversity Index	Measure of species richness and evenness[4]
Community Composition	Relative proportions of species by site[4]
Abundance	Number of individuals per space
Infaunal/Benthic Quality Index	Indices of community health[3,4,5]

Methods and Protocols:

Direct Observation and Destructive Sampling: Grab samplers can be used to collect sediment samples to collect infauna for later assessment. Bottom trawling provides a means to collect larger benthic organisms but typically damages the seafloor and would be very difficult to do under a farm. Visual surveys by divers provide direct observation, usually along transects or quadrants.

Underwater Video: Deployment of stationary or remote cameras in and around seaweed farms provide a means to remotely observe benthic communities.

Remote Sensing: Sonar systems (e.g., side-scan, multibeam) provide a means to map the seafloor in terms of bottom texture, substrate, and vegetation but provide little information about infaunal, sessile, or mobile benthic species.

Environmental DNA (eDNA) Metabarcoding: Benthic communities can also be assessed by eDNA, or the detection of genetic material in water or sediment samples. New technology like sub-surface automated eDNA samplers (SASe) can be used as a low-cost tool to take more complete eDNA profiles from sites compared to manual eDNA collections.

Decision-relevance:

Inform Site Selection and Design: Baseline surveys are essential prior to farm operation to avoid impacts to sensitive or unique benthic habitats. This information guides decisions about the optimal location, extent, and density of cultivation gear.

Optimize Timing of Operations: Understanding when specific species are engaging in critical life stages allows farm managers to adjust harvest schedules to reduce disturbance to benthic communities.

MSC Certification: Requires third party auditors to report on endangered species and effects on ecosystem structure and function.

Existing Data and Monitoring Efforts:

AK: The Mariculture Research and Restoration Consortium is assessing biodiversity and habitat benefits of several kelp farms in Southcentral Alaska. Interim results show more encounters with fish in fall and a prevalence of smaller fish, possibly Pacific Herring, supporting the use of farms as refugia. NOAA Alaska Fisheries Science Center research on kelp farms in Southeast Alaska found no change in the benthic macroinvertebrate community inside and outside of farms.

BC: In BC, there are several monitoring programs which collect data on benthic invertebrates, including the Sentinels of Change Project (Hakai Institute), DFO dive surveys on algae and substrate between 1996 and 2021, DFO Benthic Habitat Mapping, and DFO Coastal Environmental Baseline Program. Although not specific to seaweed farming, these programs may aid in providing baseline data. During the permitting process, applicants must complete a habitat survey and avoid sensitive ecosystems and at-risk species. In addition, biodiversity eDNA data was collected in 2017 and identified 1477 unique species ranging from zooplankton to marine mammals which may provide baseline species presence data relevant to seaweed farming (see Jacquemot et al. 2024).

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BIODIVERSITY – Phytoplankton, Zooplankton, and Chlorophyll α

Rationale: Plankton are microscopic or small macroscopic organisms that drift through the water column including autotrophic phytoplankton and heterotrophic zooplankton. Chlorophyll α (Chl a), used in photosynthesis, can serve as a proxy for primary production (i.e., the amount of algae present in seawater samples). Chl a is influenced by contextual factors such as nutrients, oxygen, and light. Because seaweed farms can alter these factors, they may have an indirect effect on plankton abundance and community composition.

Indicator Scoring: Plankton was identified as a **Group C** indicator with moderate relevance to management with some community concern. However, data can be highly variable due to either natural or farm conditions, limiting the ability of monitoring to detect change after a seaweed farm is established. While species identification requires advanced technical experience, farmers can assist with sample collection for later analysis. Chl a was also identified as a **Group C** indicator but scored much lower due to poor data quality in terms of detecting measurable differences with the establishment of seaweed farms and a poor likelihood for establishing causality. While it is inexpensive to incorporate Chl a into monitoring efforts, its usefulness for assessing the ecological effects of seaweed farms was the lowest of any indicator evaluated during the formation of this science synthesis.

Indicator Selection Criteria Scores (0-3)	Phyto/ Zoop	Chl a
Relevance to Management	2	1
Literature Support	2	2
Sensitivity and Responsiveness	1	0
Robustness	1	0
Feasibility	2	2
Cost-effectiveness	2	3
Reliability for Predicting Causality	1	0
Likelihood of Interaction	1	0
Community Interest / Concern	2	0
Total Score (Max = 27)	14	8

Key Metrics	Definition
Taxa abundance	Counts by taxonomic group
Diversity	Measure of species richness and evenness
Community Composition	Relative proportions of species
Chl a	Estimates algal growth in seawater

Methods and Protocols:

Plankton Tows: Farmers or scientists can sample using plankton tows with different mesh sizes for targeting phytoplankton or zooplankton. Samples require technical expertise to identify species and estimate abundance using microscopy. Chl a samples, collected in Niskin bottles at standard depths, can be measured using standard fluorometric techniques.

Continuous Environmental Monitoring: Moored fluorometers (e.g., WETLabs) can be deployed to continuously estimate Chl a fluorescence.

Decision-relevance:

Site Selection and Design: Baseline data on plankton abundance and Chl a can provide farmers with insights on how productive a prospective site is for seaweed farming.

Farm Operations and Harvest Timing: Monitoring plankton abundance and Chl a fluorescence, particularly in combination with nutrient data, can inform farmers about harvest times and the onset of bloom events that can lead to biofouling on farmed seaweed.

Existing Data and Monitoring Efforts:

AK: In AK, the Continuous Plankton Recorder Survey, a global monitoring program, uses commercial shipping as a platform to automatically sample along trans-Pacific transects. Data are available through AOOS. Coastal plankton monitoring is conducted by plankton tows at multiple stations in bays across the sound, two of which have multiple seaweed farms. In addition, there is an oceanographic profiler, fit with a plankton camera, that surveys across a range of depths and has collected millions of images of individual plankton. This work is part of the Gulf Watch Alaska and The Mariculture Research and Restoration Consortium programs funded by the Exxon Valdez Oil Spill Trustee Council.

BC: Fisheries and Oceans Canada (DFO) performs oceanographic monitoring in BC to collect baseline data that includes plankton abundance in different survey regions, such as Southern Canadian Continental Shelf (since 1978), Coastal inlets (annually since 2022), Quatsino Sound (annually since 2021), and Clayoquot Sound (annually since 2023). The global Continuous Plankton Recorder also operates in BC. Emerging in-situ imaging methods may speed up monitoring compared to traditional plankton tows and supplement more manual efforts. In addition, biodiversity eDNA data was collected in 2017 and identified 1477 unique species ranging from zooplankton to marine mammals which may provide baseline species presence data relevant to seaweed farming (see Jacquemot et al. 2024).

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ECOLOGICAL HEALTH – Genetic Diversity

Rationale: Genetic diversity is important to ecosystem health and the sustainability of the seaweed farming industry. Seaweed farming sources reproductive material from wild stocks or hatchery-propagated lines. Maintaining genetic variation within and among cultivated and wild seaweed populations supports adaptive capacity to environmental change, disease resistance, and overall productivity. Inadequate genetic diversity can increase the susceptibility of crops to disease and/or pests, warming waters, ocean acidification, pathogens, and extreme events. Nearby wild populations may be affected by the genetics of farmed seaweeds if farmed seaweeds are on the farm throughout their reproductive cycle.

Indicator Scoring: Genetic diversity was identified as a **Group B** indictor due to its relevance to management, moderate support from the literature, and the concern expressed by the farming community. Methodologies are currently being developed to enhance sampling and better understand the genetics of seaweeds to inform monitoring. Until more information is available, the likelihood of interaction was designated as a low as there is little evidence at this time that seaweed farming affects genetics of farmed or wild seaweed.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	2
Sensitivity and Responsiveness	1
Robustness	2
Feasibility	2
Cost-effectiveness	2
Reliability for Predicting Causality	2
Likelihood of Interaction	1
Community Interest / Concern	2
Total Score (Max = 27)	**17**

Key Metrics	Definition
Population Structure	Allele frequencies between groups
Adaptive Variation	Mutations, gene flow
Variation-Hatchery vs. Out-planted	Genetic variation between farm stages
Wild beds genetic relatedness	Relatedness between wild beds

Methods and Protocols:

Standardized Sample Collection and Processing: Farmed or wild seaweed samples can be collected by farmers, hatchery operators, or researchers and dried, frozen, or preserved for later analysis.

Genotyping: Genotyping methods may include microsatellites, single nucleotide polymorphisms (SNPs), or other molecular markers appropriate to the target species. These tools allow assessment of genetic diversity, population structure, relatedness, and gene flow.

Decision-relevance:

Site selection: In AK and BC, precautionary permitting requirements are in place that restrict farmers to sourcing broodstock from at least 30 (in BC) to 50 (in AK) wild individuals within 50 km of the farm site, and do not permit the use of cultured seed stock. Additional information on genetic impacts and diversity may be used to revise this protocol in the future.

MSC Certification and Policy Compliance: Certification requires third party auditors to report on genetic impact on wild populations. Periodic genetic monitoring could be used to verify compliance and assess effectiveness of the 30/50 by 50 policy directives.

Existing Data and Monitoring Efforts:

AK: The ADF&G Gene Conservation Laboratory leads a Seaweed Population Genetics program that relies upon sampling from farmers and hatchery operators from across the state. The goal of this program has been to identify methods to better preserve genetic material, assess population structure and adaptive variation, and develop rapid and cost-effective genotyping tools. Maps of genetic collection sites are available. The only two established genetic seed banks for seaweeds in the U.S. are Bigelow Laboratory's National Center for Marine Algae and Microbiota in Maine and Kelp Ark in California, with the latter recently securing funding to study kelp genetics and carry out gametophyte seed banking for Alaskan strains of sugar, ribbon, and bull kelp in collaboration with the University of Alaska Fairbanks (UAF). While several other permitted nursery facilities maintain gametophyte collections, most are not officially considered gene banks.

BC: Several organizations maintain gametophyte collections, including Kelp Rescue Initiative (KRI), North Island College, Hakai Institute, Bisgrove Lab (Simon Fraser University), West Coast Kelp, and Cascadia. Efforts to secure funding for maintaining a coordinated decentralized biobank network for kelp in BC are ongoing (J Schuster, KRI, Pers. Comm.) Independent academic research has been and is being done to catalogue wild kelp genetic diversity.

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ECOLOGICAL HEALTH – Biofouling

Rationale: Biofouling (the settlement of marine organisms onto seaweed tissue or farm infrastructure), is a concern for farmers. Biofouling can reduce growth by restricting nutrient uptake and light availability. It can also add weight to the lines and may lead to crop detachment from farm lines. For food-grade seaweed, it also reduces product quality and value. Biofouling varies greatly between years, farm sites, bays, and regions. There is concern that biofouled material from farms can be a vector for invasive species, as many marine invasives are fouling species.

Indicator Scoring: Biofouling was identified as a **Group B** indicator due to practitioners' high level of concern and moderate literature support as well as its relevance to management. This indicator would benefit from an experimental design that incorporates early season evaluation of biofouling organisms and re-examination over the growing season, coupled with contextual environmental monitoring.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	2
Literature Support	2
Sensitivity and Responsiveness	2
Robustness	1
Feasibility	2
Cost-effectiveness	2
Reliability for Predicting Causality	1
Likelihood of Interaction	2
Community Interest / Concern	3
Total Score (Max = 27)	**17**

Key Metrics	Definition
Species presence	Detection of unwanted species
% Coverage	Coverage of species on blades

Methods and Protocols:

Direct Observation and Destructive Sampling: Visual monitoring for biofouling organisms using underwater observation, collecting kelp blades or line material, or identifying species microscopic examination.

Invertebrate Collector Devices: Biofouling organisms can also be sampled using fauna traps or settlement plates which are deployed and collected after colonization over a timeframe of interest to assess presence, species diversity, and percent cover.

Decision-relevance:

Farm Operations and Harvest Timing: Biofouling can be ubiquitous on farm sites and is a major operational concern for farm integrity (e.g., sinking due to weight) and product quality. Monitoring biofouling provides farmers with a means to detect issues early, allowing for adjustments to farm operations and harvest timing to prevent crop loss.

MSC certification: Certification requires third party auditors to report on pest and disease management.

Existing Data and Monitoring Efforts:

AK: Biofouling is included in data collection efforts to assess epibiota associated with seaweed farms. Epibiota is assessed by the Mariculture Research and Restoration Consortium program as part of the benthic component through imagery of kelp blades taken by farmers and submitted to researchers. These images are used to estimate percent coverage of epiphytes. Blade samples are also collected by farmers, frozen, and transported for later processing for species identification.

BC: There currently are no dedicated monitoring efforts for biofouling of seaweed farms in BC. Fisheries and Oceans Canada's broader aquatic invasive species monitoring program may provide some baseline knowledge for seaweed farmers on the potential for biofouling organisms. These can also be invasive, particularly near high-risk areas such as ports and marinas. The SPECTRAL Lab (University of Victora) and partners are engaged in regional research and monitoring for kelp-encrusting bryozoans in on wild kelps. BC seaweed farmers have used reported using plankton tows to detect mussel larvae early in the season and temporarily adjust the depth of lines to prevent colonization.

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ECOLOGICAL HEALTH – Invasive Species and Disease

Rationale: Seaweed farms are inherently at risk for disease transmission. High stocking densities, shared infrastructure, and repeated use of genetically similar material can increase susceptibility to pathogens and facilitate spread within and between farms. Because seaweed farming is a new industry in AK and BC, there is minimal information about disease etiology. The incidence of disease is expected to grow with the scale of the sector and the influence of climate change. Seaweed farms may also increase the potential for introduction or further distribution of invasive species. Aquaculture generally is a documented vector of invasive species, but the role of seaweed farming is relatively understudied. However, in AK, one Prince William Sound farmer reported an abundance of invasive Japanese skeleton shrimp (*Caprella mutica*) on kelp lines late into the growing season.

Indicator Scoring: Invasive species was identified as a **Group B** that has high relevance to management and is of moderate concern to the farming community. Disease and Infection was identified as a **Group C** indicator that has high relevance to management and moderate is of concern to the farming community. However, data quality for diseases and invasive species scored low due to a lack of region-specific information.

Indicator Selection Criteria Scores (0-3)	Invasive Species	Disease
Relevance to Management	3	3
Literature Support	2	1
Sensitivity and Responsiveness	1	1
Robustness	1	2
Feasibility	2	1
Cost-effectiveness	2	1
Reliability for Predicting Causality	1	0
Likelihood of Interaction	2	0
Community Interest / Concern	2	2
Total Score (Max = 27)	**16**	**11**

Key Metrics	Definition
Presence	Observation of invasive species or pathogen
Abundance	Number of individuals present
Distribution	Spatial area species is observed
% coverage	% of blade area occupied by epiphytic species or pathogens
Transmission rates	Spread of pathogen within or between species

Methods and Protocols:

Direct Observation and Sampling: Visual inspections of farm infrastructure, cultured seaweeds, and surrounding substrates are the most common and accessible methods for invasive species and disease monitoring. Photographic documentation and simple abundance or coverage estimates can support trend tracking over time. When abnormalities are observed, tissue samples may be collected for laboratory analysis to identify pathogens.

Invertebrate Collector Devices: Biofouling organisms can also be sampled using fauna traps or settlement plates which are deployed and collected after colonization over a timeframe of interest to assess presence, species diversity, and percent cover.

Decision-relevance:

Site Selection and Design: Disease and infection considerations are relevant to site selection and farm layout and design, particularly as the industry scales. Locations with strong water exchange, appropriate depth, and lower environmental stress may reduce the likelihood of disease transmission. Thus, farmers may want to design farms, in terms of line spacing, cultivation depth, and orientation to water flow to reduce transmission potential. Monitoring disease can inform future permitting and expansion decisions, where avoiding known invasion hotspots can lower long-term management costs and ecological risk.

Farm Operations and Harvest Timing: Monitoring invasive species abundance and coverage supports decisions related to cleaning frequency, harvest timing, and biofouling management. Early detection supports operational decision-making by allowing farmers to respond to early signs of invasive species and/or infection before crop loss. Observations can inform adjustments to maintenance, cleaning frequency, or partial harvests to reduce biomass density and limit spread. In some cases, early or accelerated harvest of affected lines may reduce losses and prevent further transmission. While predictive capacity is currently limited in AK and BC, routine documentation improves situational awareness and supports adaptive management as knowledge increases.

MSC certification: Certification requires third party auditors to report on invasive species, pest, and disease management.

Existing Data and Monitoring Efforts:

AK: The University of Alaska Anchorage (UAA)'s Alaska Center for Conservation Science maintains the Alaska Aquatic Invasive Species Clearinghouse, a database that houses temporal and geospatial information for invasive species along AK coastlines. NOAA Fisheries also works with other federal agencies, the State of Alaska, academic institutions, and local communities to educate, monitor, and detect invasive species.

BC: DFO aquatic invasive species monitoring data (since 2005) has been used to model invasive species hotspots. DFO also hosts data collected for specific studies on the geolocations and movement patterns for static maritime structures (e.g., barges, dry docks, oil platforms) which can serve as vectors for invasive species. These data sources may serve as baseline data to understand invasive species colonization and transfer risks.

There are currently no dedicated seaweed disease monitoring programs in AK and BC due to a lack of incidents reported. Observations by farmers at farm sites when assessing crop quality are the only current data being collected.

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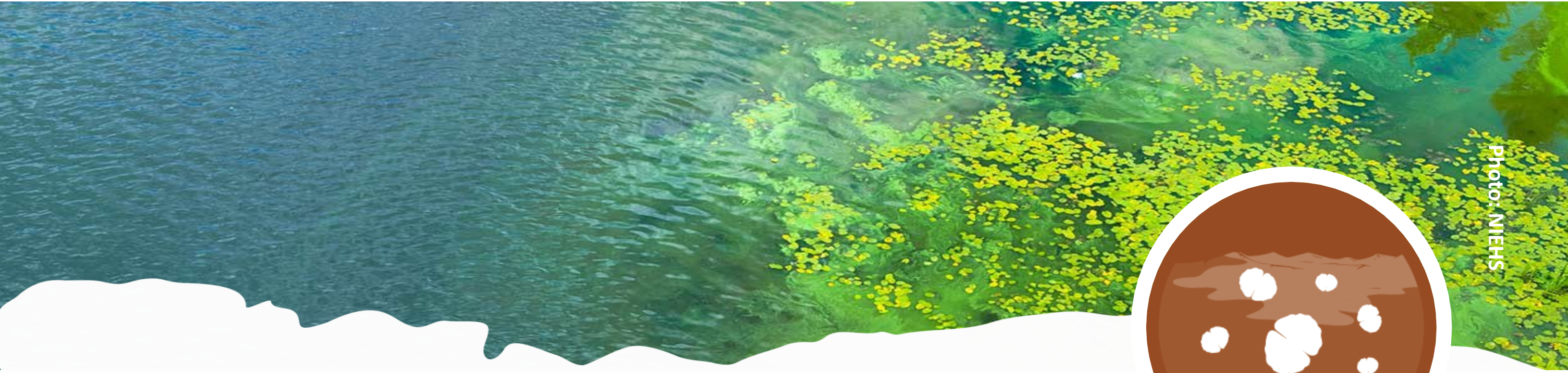

ECOLOGICAL HEALTH – Harmful Algal Blooms

Rationale: Harmful algae blooms (HABs) occur when certain species of phytoplankton experience excessive growth. Species of special concern in coastal Alaska are those that produce toxins that are harmful to human and animal health. HABs can impact mariculture operations but are a greater factor for shellfish farms than seaweeds currently. In AK and BC, saxitoxins (produced by dinoflagellate *Alexandrium catenella*), domoic acid (produced by diatom *Pseudo-nitzschia*), and fish-killing algal species including *Heterosigma akashiwo* and *Chaetoceros spp.* are major concerns.

Indicator Scoring: HABs was identified as a **Group C** indicator with moderate relevance to management and support from the literature, but little research links benefits or impacts by HABs to seaweed farms or from seaweed farms to HABs and much of the literature is theoretical.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	2
Literature Support	2
Sensitivity and Responsiveness	2
Robustness	1
Feasibility	1
Cost-effectiveness	2
Reliability for Predicting Causality	2
Likelihood of Interaction	0
Community Interest / Concern	1
Total Score (Max = 27)	**13**

Key Metrics	Definition
Event incidence	Observation or detection of a HAB
Event severity	Toxicity or mortality observations

Methods and Protocols:

Direct Observation and Sampling: Methods include monitoring for HAB pre-requisites like algal cells, spores, or cysts and HAB-risk factors like high organic and inorganic nutrients, temperature, and stratification.

Decision-relevance:

Food Safety and Harvest Timing: Similar to shellfish, monitoring and testing for HAB toxins may be required for seaweed designated for food products but is not currently required.

Existing Data and Monitoring Efforts:

AK: Monitoring for HABs is ongoing in Alaska through the Alaska Harmful Algal Bloom Network which collects phytoplankton and shellfish data, provides valuable information to citizens, and provides data to the public through AOOS.

BC: DFO conducts a Marine Biotoxin Monitoring through recent Fieldnotes programs to better understand dynamics and drivers of HABs and associated biotoxins. There is also the We All Take Care of the Harvest (WATCH) community-based HAB monitoring program.

Prior global modelling studies have developed species distribution models for the current and future distributions of biotoxin-producing algae with global climate change, forecasting that harmful algal blooms are predicted to contract in lower latitudes but expand in higher latitudes, including BC and AK (Borges et al. 2022, data available on request).

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Photo: Schery Umanzor

BIOGEOCHEMISTRY – Nutrients in Seaweed Tissues

Rationale: Monitoring nutrient content in cultivated seaweed tissues serves multiple critical purposes related to product quality, decision-making in farm management, and ecological benefits. Seaweed absorbs nutrients directly from the surrounding seawater, and environmental nitrogen availability is a crucial factor for site selection and growth. Monitoring tissue composition allows farmers to determine the optimal timing for harvest to secure high biomass yield and nutritional quality, as tissue nitrogen (N) concentrations generally decrease later in the growing season. Cultivation of seaweed may mitigate eutrophication by removing nutrients including N, phosphorus (P), and carbon (C), from the marine environment. This may provide a route for developing nutrient trading credit programs.

Indicator Scoring: Nutrients in seaweed tissue was identified as a **Group A** indicator due to its high relevance to management and community concern, particularly for mitigating eutrophication, and high likelihood of effect.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	3
Sensitivity and Responsiveness	2
Robustness	2
Feasibility	2
Cost-effectiveness	2
Reliability for Predicting Causality	1
Likelihood of Interaction	2
Community Interest / Concern	3
Total Score (Max = 27)	**20**

Key Metrics	Definition
Tissue Nitrogen	% N of dried mass
Tissue Carbon	% C of dried mass
Carbon-to-Nitrogen ratio	Metric for nutritional status
Tissue Phosphorus	% P of dried mass
Stable Isotope ($\delta^{15}N$ and $\delta^{13}C$)	Difference relative to standards

Methods and Protocols:

Nutrient Extraction Toolkit: A validated, cost-effective, and durable toolkit developed and implemented in AK specifically to guide kelp farmers in the standardized collection of both tissue and seawater samples.

Standardized Sample Collection and Processing: Standardized tissue samples taken from the tip, mid-section, and base of the seaweed frond in the field can be shipped to a receiving lab for analysis.

Elemental and Stable Isotope Analysis: For C and N content, ground seaweed tissue is analyzed by combustion using an elemental analyzer and/or continuous-flow isotope-ratio mass spectrometer (CF-IRMS).

Dry Mass and Ash Determination: Inorganic salts, metals, and minerals found in seaweed can be analyzed by drying and combusting samples into ash. The relative content of these compounds is obtained by considering their mass as a fraction of overall sample mass.

Decision-relevance:

Optimizing Farm Design: Monitoring links tissue composition and yield to physical parameters, informing farm design choices such as line spacing. Increased spacing is desirable in nitrogen-limited environments to maximize water flow and nutrient transfer.

Adjusting Harvest Timing: Tissue N content and C:N ratios are key indicators for setting the optimal harvest window. Because tissue N content generally decreases later in the growing season, monitoring helps ensure harvesting occurs when nutrient quality and biomass are maximized. Monitoring has shown that optimal harvest timing varies by species; ribbon kelp (*Alaria marginata*) reaches peak nitrogen content earlier (April) than sugar kelp (*S. latissima*). Harvested biomass also correlates strongest with total nitrogen concentration in the seawater during the harvest month.

Monetizing Bioextraction and Nutrient Trading Credits: The nutrient removal capacity of seaweed, particularly for N and P, can be quantified and assigned a monetary value. For example, *S. latissima* bioextractive yields in Long Island Sound demonstrated the potential to generate upwards of $1600 per hectare of additional revenue from the sale of nitrogen credits through Connecticut's Nitrogen Credit Trading Program. Seaweed aquaculture is recognized as a potentially ideal trading partner in Water Quality Trading (WQT) programs, where polluted sources may purchase offsets from farms, potentially making seaweed cultivation more cost-effective than terrestrial remediation methods. However, realizing this potential requires thorough development of Monitoring, Reporting, and Verification (MRV) standards.

Existing Data and Monitoring Efforts:

AK: Mariculture Research and Restoration Consortium has conducted nutrient analysis (%C and N) in seaweed tissue at multiple sites throughout AK (Kodiak, Prince William Sound, and southeast AK). 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 (see Serin 2026).

BC: While not directly related to seaweed farming but useful as a baseline study, researchers at Hakai Institute have measured mean percentage of nitrogen per gram of blade tissue in seaweeds (kelp) in response to environmental conditions at three sites in the Central Coast of BC (see Pontier et al. 2024).

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BIOGEOCHEMISTRY – Nutrients in Seawater

Rationale: Monitoring seawater nutrients is relevant for optimizing seaweed growth and for understanding the restorative potential of seaweed farming. Productivity in inner shelf regions of the Northeast Pacific is typically high from March to May and decreases into summer. The uptake of nitrogen (N), phosphorus (P), and carbon (C) drives seaweed biomass and farm productivity. Monitoring supports understanding the relationship between ambient nutrient levels and kelp tissue chemistry (e.g., C:N, tissue %N). This helps assess nutritional quality and suitability for different end markets. Monitoring also helps quantify the effectiveness of the removal of excess N and P through farming and harvest, which may mitigate site-specific eutrophication.

Indicator Scoring: Nutrients in seawater was identified as a **Group A** indicator due to its relevance to management of seaweed farming, significant concern by the farming community, and moderate data quality.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	2
Literature Support	3
Sensitivity and Responsiveness	2
Robustness	2
Feasibility	3
Cost-effectiveness	3
Reliability for Predicting Causality	2
Likelihood of Interaction	2
Community Interest / Concern	2
Total Score (Max = 27)	**21**

Key Metrics	Definition
Dissolved Inorganic Nitrogen (DIN)	Concentration of nitrate, nitrite, and ammonium in seawater
Total Dissolved Inorganic Nitrogen	Total nitrogen (nitrate, nitrite, ammonium)
Orthophosphate $[PO_4]^{3-}$	Dissolved concentration of inorganic phosphate

Methods and Protocols:

Standardized Field Sampling and Processing: To ensure consistent data collection across geographically dispersed farms, AK researchers developed the Nutrient Extraction Toolkit and protocol for standardized water and kelp tissue sampling.

Laboratory Analysis: Filtered seawater samples are analyzed for dissolved inorganic nutrients, primarily nitrate, nitrite, ammonium, DIN, and orthophosphate. Samples are typically processed at specialized facilities.

Continuous Environmental Monitoring: Continuous monitoring of seawater nutrients can be achieved via smart buoys, equipped with sensors for *in situ* nitrate and phosphate measurements.

Decision-relevance:

Informing Site Selection and Baseline Yields: Nutrient data is useful for assessing site suitability, biomass yields, and nutrient content of harvested crops, especially considering the significant spatial and temporal heterogeneity of nutrient availability across regions.

Informing Farm Design and Density: Integrating nutrient monitoring with hydrodynamic data can inform farm design decisions. For example, optimal yield depends on managing the interaction between nutrient concentration and physical parameters like line spacing, often necessitating wider spacing in low-flow or nitrogen-limited sites.

Optimizing Harvest Timing and Quality: Monitoring seasonal trends in N helps determine species-specific harvest timing to maximize biomass quality.

Supporting Modeling and Regional Management Strategy: Nutrient data helps parameterize and validate ecological site-selection and cumulative effect models. These models integrate regional nutrient and flow data to predict seaweed biomass yield and nutrient budgets over larger regions that might host multiple farm sites.

Existing Data and Monitoring Efforts:

AK: Nutrient data has been modeled through the Gulf of Alaska Regional Oceanic Model System - Carbon, Ocean Biogeochemistry and Lower Trophic Hindcast Simulation V2 (1993–2023), accessible via AOOS Data Portal. Ongoing marine water quality monitoring in AK occurs as part of oceanographic research cruises by NOAA Fisheries and the Alaska Department of Environmental Conservation in harbors and shipping lanes. The AOOS Mariculture Map shows the locations of permitted sewage outfalls and seafood processing discharge locations, which could introduce nutrients into the marine environment. These are usually avoided by farms but could be opportunities for bioremediation.

BC: DFO's Institute of Ocean Sciences (IOS) collects water samples on oceanographic cruises which analyze water quality parameters. Point data from these samples are compiled under the 'IOS Rosette Bottle Data' entry in the Canadian Integrated Ocean Observing System Data Portal (CIOOS).

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BIOGEOCHEMISTRY – Carbon Cycling

Rationale: Seaweed farming contributes to ecological carbon (C) cycling through uptake and redistribution of C in the ecosystem through fragmentation and drift. Although seaweed farming has received attention for its potential role in C capture, only a fraction of this C may be sequestered over climatically relevant timescales. Thus, rather than through seaweed farming directly, potential climate change benefits include long-term storage in harvested products or replacement of more carbon-intensive products. However, quantifying these C pathways remains scientifically complex and highly context dependent. Monitoring efforts therefore focus on measuring carbon uptake, standing biomass, and carbon removal through harvest.

Indicator Scoring: Carbon cycling was identified as a **Group C** indicator with moderate relevance to management, support by the literature, and interest by the farming community. However, interpretation is limited by complex, poorly understood pathways.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	2
Literature Support	2
Sensitivity and Responsiveness	1
Robustness	1
Feasibility	1
Cost-effectiveness	2
Reliability for Predicting Causality	1
Likelihood of Interaction	1
Community Interest / Concern	2
Total Score (Max = 27)	**13**

Key Metrics	Definition
C	Total carbon
CO_2 equivalent	Tons CO2e/hectare/year

Methods and Protocols:

Standardized Sample Collection: Sampling depends on the metric and time frame of interest. Farmers or researchers can collect samples from farm sites at periodic intervals to assess growth rates which are a proxy for carbon uptake. The wet or dry weight of seaweed per line can be used to estimate total farm biomass. Biomass carbon can be used to estimate carbon and carbon dioxide removal to calculate carbon dioxide equivalent if sampled over a long-time frame.

Elemental Analysis: C content from tissue is weighed and analyzed by combustion using an elemental analyzer or continuous-flow isotope-ratio mass spectrometer. Species-specific carbon fractions can then be applied to total harvested biomass to estimate the amount of carbon removed from the water column through harvest.

Decision-relevance:

Optimizing Farm Design: Carbon monitoring can inform farm design decisions by identifying cultivation practices that maximize biomass production and carbon uptake per unit area. Line density, depth, species selection, and harvest timing all influence total carbon captured in biomass.

Monetization: Carbon capture data may support claims related to bioextraction, ecosystem services, or participation in emerging carbon or sustainability markets. However, only carbon that can be credibly shown to be stored or offset over long timescales can be considered for monetization. Monitoring provides the empirical foundation needed to engage responsibly with markets and policy discussions related to monetization.

Existing Data and Monitoring Efforts:

Carbon cycling is not yet routinely monitored at seaweed farm sites in AK and BC. While there is ongoing research working to better understand how to quantify carbon cycling by seaweed farms, most of this work is performed by academic institutions; for instance, two farms in BC were sampled as part of a global study to quantify carbon sequestration by seaweed farms (see Duarte et al. 2025). The global Modern Ocean Sediment Archive and Inventory of Carbon provides sediment core data including for AK and to a lesser extent BC, with an emphasis on carbon content.

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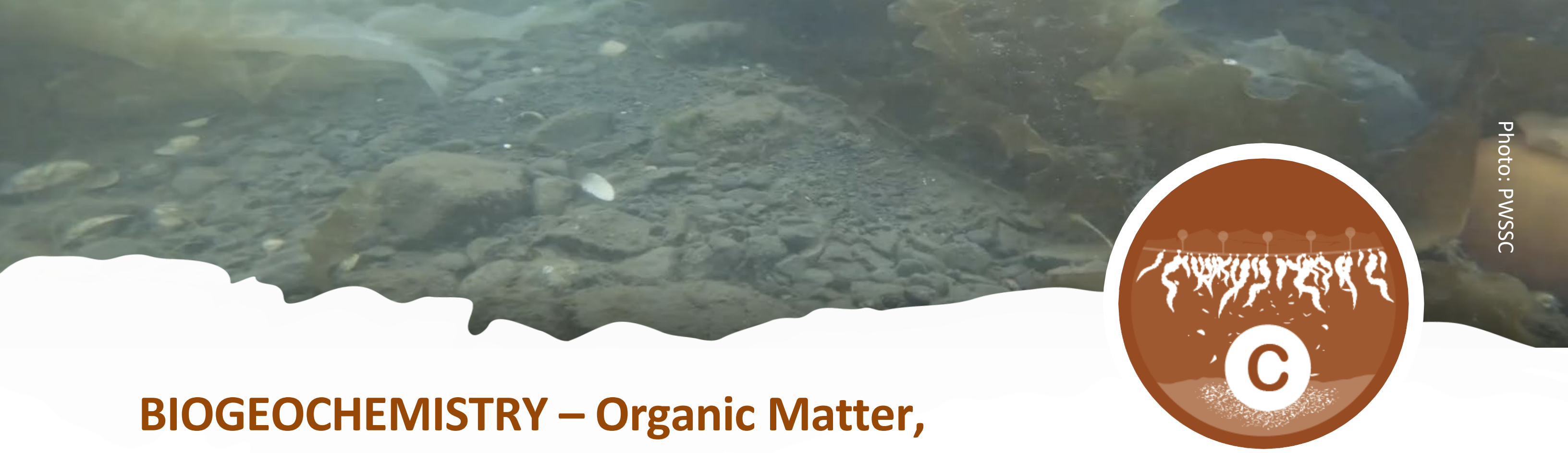

BIOGEOCHEMISTRY – Organic Matter, Organic Enrichment, and Sedimentation

Rationale: Seaweed farming can influence local organic matter dynamics through the production, release, and removal of particulate organic matter (POM) through blade erosion, as well as dissolved organic matter (DOM) through tissue decay. This organic matter may lead to increased organic matter in the water column or sediments, particularly in environments with limited flushing. Organic enrichment can alter sediment chemistry, oxygen demand, and benthic community structure. Organic inputs from seaweed farms are generally lower than other forms of aquaculture, but site flow, fine sediments, and farm density may increase loadings. Sedimentation processes mediate how organic material is deposited, transported, or resuspended. Understanding organic matter pathways and sediment responses is therefore important for evaluating benthic effects, cumulative impacts, and compatibility of seaweed farming with sensitive habitats. While organic matter, organic enrichment, and sedimentation are closely linked, they describe different pathways and cannot be reliably inferred from one another. Treating them as separate indicators improves diagnostic power, reduces misinterpretation, and supports targeted management actions.

Indicator Scoring: Organic matter, organic enrichment, and sedimentation were all designated as **Group C** variables with relatively low relevance for management, low community concern, and moderate support from the literature for monitoring the effects of seaweed farms. Existing data quality can be variable due to either natural or farm conditions, making attribution difficult.

Indicator Selection Criteria Scores (0-3)	OM	OE	S
Relevance to Management	1	2	1
Literature Support	2	2	2
Sensitivity and Responsiveness	2	2	2
Robustness	2	1	1
Feasibility	1	2	1
Cost-effectiveness	2	1	1
Reliability for Predicting Causality	2	2	2
Likelihood of Interaction	1	1	1
Community Interest / Concern	1	1	1
Total Score (Max = 27)	**14**	**14**	**12**

Key Metrics	Definition
POM	Particulate organic matter
DOM	Dissolved organic matter
DOC	Dissolved organic carbon
Sediment C	Carbon in sediment
SOM	Sediment organic matter

Methods and Protocols:

Standardized Sample Collection: Monitoring organic matter, organic enrichment, and sedimentation relies on water and sediment sample collection, paired with laboratory-based elemental analysis. Water column samples are collected

Associated with: Tamburello, N., Gillies, E., Gutzmann, S., Cypher, A., Hollarsmith, J., and Theuerkauf, K. 2026. Cultivating with Care -Environmental Effects and monitoring Indicators for the Seaweed Farming Sector in Alaska and British Columbia. Volume I - Science Synthesis. Report prepared for The Pew Charitable Trusts. 63 p + Appendices.

periodically within and adjacent to farm footprints to quantify POM and DOM. Sediment samples are collected beneath farms and at reference sites outside the influence of farm infrastructure to assess sediment organic matter. Core or grab samples are processed using consistent protocols for depth, handling, and preservation. Laboratory elemental analysis is used to characterize organic enrichment relative to baseline conditions.

Elemental Analysis: C content from tissue is weighed and analyzed by combustion using an elemental analyzer or continuous-flow isotope-ratio mass spectrometer.

Decision-relevance:

Site Selection and Design: Data on organic matter accumulation and sedimentation inform site selection by identifying areas where organic material is more likely to accumulate. Sites with higher flushing and coarser substrates generally have lower potential for organic enrichment. Monitoring results can guide farm layout, spacing, and density decisions to minimize localized accumulation and benthic disturbance.

Farm Operations and Harvest Timing: Monitoring organic matter and sediment conditions supports adaptive farm management by identifying periods or practices associated with increased organic inputs. While seaweed farms generally have lower organic loading than fed aquaculture, periodic assessment helps ensure that operational practices remain compatible with local environmental capacity.

Economic Assessment and Management: Although organic enrichment impacts are not expected to be a dominant potential effect of seaweed farming, monitoring provides assurance that farms are operating within acceptable environmental bounds. This reduces regulatory uncertainty and supports efficient permitting and expansion decisions. From an economic perspective, proactive monitoring of organic matter and sedimentation can help avoid costly remediation, operational restrictions, or delays associated with environmental concerns.

Existing Data and Monitoring Efforts:

AK: There are no dedicated monitoring programs evaluating organic matter, enrichment, or sedimentation in AK. However, dedicated studies have evaluated sediment quality assessment in Alaska (see Walinsky et al. 2009 and Apeti & Hartwell, 2016). The global Modern Ocean Sediment Archive and Inventory of Carbon provides sediment core data including for AK (and to a lesser extent, BC).

BC: Fisheries and Oceans Canada (DFO) evaluates sediments at soft bottom finfish aquaculture sites as part of the Aquaculture Monitoring Program.

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Photo: PWSSC

WATER QUALITY – Temperature, Salinity, Acidification, and Dissolved Oxygen

Rationale: Temperature, salinity, ocean acidification, and dissolved oxygen (DO) are drivers of seaweed growth and influence the biomass produced by farms. While seaweed farms could potentially influence local temperature or salinity through alterations to local current patterns, it is more strongly hypothesized that farms can reduce local acidification and increase dissolved oxygen. Monitoring programs for these water quality variables will also add to the broader understanding of local and regional ecosystem change. These water quality variables are among the most measurable and transferable indicators across farms and regions, making them a core component of ecological and operational monitoring frameworks.

Indicator Scoring: Temperature and salinity were identified as **Group C** indicators because they are efficient to monitor, but their usefulness in determining the environmental impacts of seaweed farming is limited. Acidification and DO were identified as **Group B** indicators with moderate relevance to management and concern by the farming community. While it is easy to incorporate DO measurements into monitoring, acidification monitoring requires more expensive equipment and expertise. Data can be highly variable due to either natural or farm conditions, making attribution difficult.

Indicator Selection Criteria Scores (0-3)	T	S	Acid	DO
Relevance to Management	1	1	2	2
Literature Support	1	1	2	2
Sensitivity and Responsiveness	1	1	2	2
Robustness	1	1	1	1
Feasibility	3	3	2	3
Cost-effectiveness	3	3	2	3
Reliability for Predicting Causality	0	0	1	1
Likelihood of Interaction	0	0	2	0
Community Interest / Concern	1	1	2	2
Total Score (Max = 27)	**11**	**11**	**16**	**16**

Key Metrics	Definition
SST	°C or °F
Salinity	ppt
pH	Acidity
pCO_2	Dissolved CO_2
DO	Dissolved O_2

Methods and Protocols:

Standardized Field Sampling and Processing: Temperature, salinity, pH, and DO can be collected during farm visits by taking water samples and using field probes. Standardized protocols for timing, depth, and calibration improve comparability across sites and seasons. For acidification metrics, laboratory analysis is typically required.

Continuous Environmental Monitoring: Continuous monitoring using deployed sensors or data loggers provides high-resolution temporal data, capturing short-term variability and extreme events that may be missed by discrete sampling. Temperature and DO are commonly monitored continuously due to sensor availability and reliability, while long-term pH monitoring is increasingly feasible as technology improves.

Decision-relevance:

Informing Site Selection: Long-term temperature, salinity, acidification, and DO data inform site selection by identifying areas with suitable environmental ranges and lower exposure to extreme or stressful conditions. Sites with stable conditions and adequate water exchange may reduce cumulative stress on cultivated seaweeds and improve consistency of production.

Optimizing Harvest Timing and Quality: Water quality monitoring supports decisions about harvest timing, particularly during periods of thermal stress, low oxygen events, or extreme freshwater influence. Understanding environmental conditions can help farmers avoid harvesting during periods that may compromise blade quality, shelf life, or processing outcomes.

Environmental Monitoring with other Indicators: Water quality data provides essential context for interpreting biological indicators such as disease prevalence, invasive species interactions, and genetic performance. Integrating environmental and biological monitoring improves attribution of observed changes and supports adaptive management under changing climate conditions.

Existing Data and Monitoring Efforts:

AK: Temperature and salinity data is widely available, for example, through state, the Gulf Watch Alaska (e.g., GAK1, Seward Line, Prince William Sound, etc.), Mariculture Research and Restoration Consortium, and Alaska Ocean Acidification Network. The University of Alaska Fairbanks Ocean Acidification Research Center monitors marine carbonate. The Alaska Ocean Observing System tracks carbon variability with the AK Marine Highway System CO2 Monitoring Program. The Gulf of Alaska Ecosystem Observatory also includes water quality data at stations and transects across the state.

BC: Numerous monitoring programs and studies collect water quality data in BC. Some of the more comprehensive programs include Fisheries and Oceans Canada's Weather Buoys, Southern BC Coastal Waters monitoring, and archival data, Marine Plan Partnership's Regional Kelp Monitoring Program, Hakai Institute oceanographic monitoring, as well as daily temperature and salinity measurements collected across 12 light stations. Data is also available on the Canadian Integrated Ocean Observing System and Ocean Networks Canada platforms.

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WATER QUALITY – Light and Turbidity

Rationale: Light availability is a limiting factor for seaweed photosynthesis and growth, making it a fundamental environmental factor for seaweed farming. Turbidity, commonly measured through water clarity or suspended sediment concentration, affects light penetration and thus indirectly influences seaweed productivity. AK and BC coasts are often influenced by glacial melt, river discharge, and plankton blooms, all of which can increase turbidity and reduce light availability. While seaweed is generally adapted to variable conditions, prolonged periods of low light can reduce growth rates and alter tissue quality. Seaweed farms can influence light penetration to the benthos, and farm maintenance or gear deployment could increase turbidity in and around farm sites.

Indicator Scoring: Light and turbidity were both identified as **Group B** indicators that are easy and cost-effective to incorporate into monitoring with moderate data quality. Neither was a significant concern for the farming community due to a lack of information that seaweed farms, at their currently operational size, would significantly impact light and turbidity in farming areas.

Indicator Selection Criteria Scores (0-3)	Light	Turbidity
Relevance to Management	2	1
Literature Support	1	2
Sensitivity and Responsiveness	2	2
Robustness	2	1
Feasibility	3	3
Cost-effectiveness	3	3
Reliability for Predicting Causality	1	2
Likelihood of Interaction	1	1
Community Interest / Concern	1	1
Total Score (Max = 27)	**16**	**16**

Key Metrics	Definition
PAR	Photosynthetically Active Radiation
SSC	Suspended Sediment Concentration
Clarity	Transparency of water

Methods and Protocols:

Standardized Field Sampling: Discrete measurements of light and turbidity are commonly collected during routine farm visits. Light availability is typically measured as PAR at the cultivation depth using handheld sensors or underwater light meters. Turbidity may be assessed through water clarity measurements (e.g., Secchi depth) or grab samples for suspended sediment concentration. Sampling should occur along consistent depths, time intervals, and tidal stages to improve comparability across sites and seasons.

Continuous Environmental Monitoring: Deployable PAR sensors and turbidity loggers are available and provide high-resolution data that captures short-term variability, particularly during storm or other weather events.

Decision-relevance:

Informing Site Selection: Light and turbidity data support site selection by identifying areas with sufficient light penetration throughout the growing season. Sites with persistently high turbidity or limited light at cultivation depth may constrain productivity, particularly for species with higher light requirements.

Associated with: Tamburello, N., Gillies, E., Gutzmann, S., Cypher, A., Hollarsmith, J., and Theuerkauf, K. 2026. Cultivating with Care -Environmental Effects and monitoring Indicators for the Seaweed Farming Sector in Alaska and British Columbia. Volume I - Science Synthesis. Report prepared for The Pew Charitable Trusts. 63 p + Appendices.

Optimizing Harvest Timing and Quality: Monitoring light availability can inform harvest timing, as prolonged low-light conditions may reduce growth rates or affect blade quality. Turbidity data can also help interpret short-term declines in productivity associated with freshwater pulses, sediment resuspension, or bloom events.

Environmental Monitoring with other Indicators: Light and turbidity measurements provide essential context for interpreting other indicators such as growth performance, disease occurrence, and nutrient dynamics. Integrating indicators improves understanding of environmental drivers and supports adaptive management under variable coastal conditions.

Existing Data and Monitoring Efforts:

AK: Data collection for light and turbidity is less common in comparison to temperature and salinity. Some farmers collect data at farm sites (e.g., Seagrove Kelp Company, Native Conservancy in Kake and Metlakatla). An autonomous profiler deployed in Prince William Sound collects turbidity data between the surface and 60-m depth. The Alaska Department of Environmental Conservation Division of Water collects turbidity data at multiple stations in ports and along shipping lanes. The Alaska Center for Conservation Science (University of Alaska Anchorage) also includes turbidity at stations in Kachemak Bay to monitor water quality.

BC: The DFO Coastal Environmental Baseline Program and Marine Plan Partnership (MaPP) Regional Kelp Monitoring Program collect light data. Data is available on the Canadian Integrated Ocean Observing System and Ocean Networks Canada platforms.

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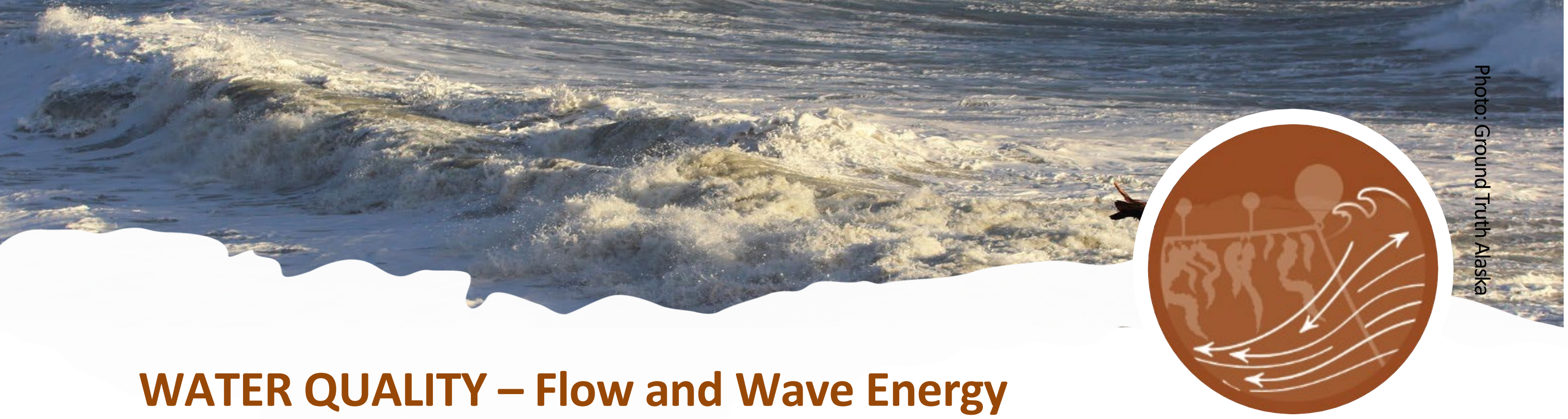

Photo: Ground Truth Alaska

WATER QUALITY – Flow and Wave Energy

Rationale: Seaweed farms may dissipate wave energy, influence water velocity, disrupt currents, alter water stratifications, and change tidal drag and turbulence. These changes to water movement can alter oxygen conditions as well as nutrients and food supply to surrounding waters. The dense crop of fully grown farmed seaweed could also reduce flow within the farm, with effects on pH (increase or reduce acidification risk), oxygen concentration (increase), and nutrient availability (reduce). Most farmed kelp grow best in high flow environments. On the other hand, it is proposed that dense seaweed can protect coastlines by reducing erosion; however, it is important to note that peak biomass occurs during a short period of time for this seasonal crop.

Indicator Scoring: Flow and wave energy were each designated as **Group B** indicators as both are concerns for the farming community. Wave energy scored higher due to greater relevance to management and greater support in the literature for monitoring the effects of seaweed farming. Both had moderate data quality with detectable differences possible if experimental design incorporates baseline data prior to farm establishment.

Indicator Selection Criteria Scores (0-3)	Flow	Wave Energy
Relevance to Management	1	2
Literature Support	2	3
Sensitivity and Responsiveness	3	3
Robustness	1	1
Feasibility	2	2
Cost-effectiveness	2	2
Reliability for Predicting Causality	2	1
Likelihood of Interaction	1	3
Community Interest / Concern	2	2
Total Score (Max = 27)	16	19

Key Metrics	Definition
Velocity	Speed of current
Flow diffusivity	Rate of pressure change
Current direction	Direction of flows
Wave energy flux	Rate of energy transport
Wave height and period	Trough to crest distance and time

Methods and Protocols:

Standardized Field Sampling: Discrete measurements of flow and wave conditions may be collected during site assessments and routine farm visits. Flow is commonly characterized using handheld current meters, or drogues. Wave exposure may be estimated using fetch-based indices, visual observations, or short-term deployment of pressure sensors.

Continuous Environmental Monitoring: Acoustic Doppler Current Profilers (ADCP) can be deployed for continuous monitoring of current speeds and directionality and to characterize flow patterns. Wave action can be continuously monitored using spotter buoys (e.g., SoFar) that are deployed at farm sites. In many cases, farm data can be supplemented with modeled or nearby observational datasets to contextualize local conditions within broader hydrodynamic regimes.

Decision-relevance:

Informing Site Selection: Flow and wave energy data help identify locations that balance sufficient water movement for nutrient delivery with acceptable mechanical stress on crops and infrastructure. Sites with excessive exposure may require considerations for long-term gear stability, while overly sheltered sites may experience reduced growth or increased fouling.

Optimizing Harvest Timing and Quality: Monitoring flow and waves supports operational planning by identifying safe weather windows for maintenance and harvest. High-energy events can increase seaweed breakage and biomass loss, while calmer periods may be better suited for harvesting to maximize yield and product quality.

Environmental Monitoring with other Indicators: Flow and wave energy strongly interact with other indicators, including nutrient availability, temperature, turbidity, and disease dynamics. Integrating physical and biological monitoring improves interpretation of observed changes in growth, health, and farm performance. Modeling for flow effects on substrate (e.g., resuspension) requires knowledge of the substrate type and sediment grain size beneath the farm. Potential wave attenuation benefits from seaweed farms may be assessed via information on shoreline type, sensitivity, and history of erosion based on local or remote sensing studies.

Existing Data and Monitoring Efforts:

AK: ADCPs have been deployed at several farm sites in Prince William Sound (University of Alaska Fairbanks) and Kodiak (Kalsin Bay). In addition, a subset of buoys operated by the National Data Buoy Center include sensors for wave energy with data collection in AK and BC. NOAA (Jenkins 2025) has more comprehensively characterized seabed properties in Alaska and may provide a baseline to model flow effects from AK farms. ShoreZone provides data on shoreline type.

BC: DFO's Coastal Environmental Baseline and Oceanographic Monitoring programs record hydrodynamic data, and additional data may be found on the Canadian Integrated Ocean Observing System and Ocean Networks Canada hubs. DFO has also mapped seafloor substrate and associated public dataset of substrate types. ShoreZone provides data on shoreline type, and BC Parks also has a Shoreline Sensitivity Model.

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POLLUTANTS – Contaminants in Seaweed Tissues

Rationale: Several areas of interest to seaweed farming in AK and BC may be influenced by legacy or ongoing contaminants from urban runoff, mines or pulp mills, and routine discharges from maritime shipping, all of which are known to contribute contaminants like heavy metals into the environment. Seaweeds are known to accumulate pollutants including inorganic arsenic, iodine, and heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), and copper (Cu). Commercially, monitoring such contaminants is critical to prevent adverse human health effects. Ecologically, contaminants bioaccumulated by kelp exert negative effects through trophic transfer. Trophic transfer has been documented in grazing sea urchins and filter-feeding shellfish in Integrated Multi-Trophic Aquaculture (IMTA) systems consuming organic matter from farmed kelp.

Indicator Scoring: Contaminants in seaweed tissue was identified as a **Group A** indicator due to its extensive support in the literature and significant community concern for food safety and bioremediation. There is documented bioconcentration of pollutants, heavy metals and polycyclic aromatic hydrocarbons (PAHs), in both wild and farmed kelp in the Northeast Pacific.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	3
Literature Support	3
Sensitivity and Responsiveness	2
Robustness	2
Feasibility	2
Cost-effectiveness	2
Reliability for Predicting Causality	2
Likelihood of Interaction	2
Community Interest / Concern	3
Total Score (Max = 27)	**21**

Key Metrics	Definition
Cadmium (Cd) Concentration	Milligrams per kilogram of dry weight
Total Arsenic (AsT) Concentration	Milligrams per kilogram of dry weight
Inorganic AsT Concentration	Milligrams per kilogram of dry weight
Lead (Pb) Concentration	Milligrams per kilogram of dry weight
Mercury (Hg) Concentration	Milligrams per kilogram of dry weight

Methods and Protocols:

Sample Collection and Preparation: Seaweed tissue samples are collected, rinsed in seawater, weighed, and packed in plastic bags on ice. It is important to avoid contamination with metals during the sampling process, for example, by using a ceramic-bladed knife in the collection of tissue samples.

Chemical Analysis: Tissue samples are analyzed for contaminant contents using analytical chemistry tools such as with gas chromatography/mass spectrometry. Some contaminants may require specialized approaches.

Decision-relevance:

Site Selection and Planning: Ambient contaminant monitoring can minimize the potential for impacts by selecting farm sites away from areas with known high contaminant inputs.

Harvest Practices and Food Safety Protocols: Data on contamination levels are used to calculate site-specific, species-based maximum consumption rates to protect human health. If concentrations exceed screening levels, farmers may need to limit harvest or consumption from that area, or selectively use specific parts of the seaweed to mitigate health hazards.

Existing Data and Monitoring Efforts:

AK: The NOAA National Mussel Watch Program monitors chemical contaminants in marine environments, focusing primarily on blue mussels (*Mytilus trossulus*). Compared to national monitoring data, cadmium, copper, and nickel concentrations were relatively high in AK, which may be due to natural rock weathering, alongside anthropogenic sources. Monitoring of kelp (*Alaria nana)* on Adak Island, AK found that cadmium, lead, and selenium were present at levels that suggested potential effects on human consumers. In addition, AK 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.

BC: Several initiatives in BC have collected information on environmental contaminant concentrations that are relevant for evaluating potential effects to farms during site selection. In the Salish Sea, contaminants have been measured in various edible seaweeds, including *Nereocystis luetkeana* and *Fucus* species, across 43 sites (Hahn et al. 2022 study in reference list below). Ocean Wise's PollutionTracker program tested marine sediments and mussel tissue for the presence of contaminants and microplastics between 2015 and 2023. The resulting data provide baseline information on the distribution and potential for biological uptake of contaminants across the BC coast, and data is available upon request.

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POLLUTANTS – Marine Debris and Plastics

Rationale: The use of plastic-based gear, such as ropes, longlines, buoyant balls, and nets, in seaweed farming can lead to the production and release of macroplastics (e.g., ghost gear) and secondary microplastics (particles smaller than 5 mm; MPs). MPs less than 150 μm and nanoplastics (1-100 nm) are of particular concern due to their ability to penetrate cells. MPs can be ingested by a wide array of marine organisms, leading to reduced feeding capacity, poor body condition, and decreased reproductive success. MPs can also absorb toxic contaminants, such as Persistent Organic Pollutants (POPs) and Persistent, Bioaccumulative, and Toxic compounds (PBTs). Seaweed can act as an accumulator or vehicle for MPs, which are then transferred into marine food webs upon consumption.

Indicator Scoring: Marine Debris and Plastics was identified as a **Group A** indicator as it is well-supported in literature as a concern for monitoring of seaweed farms. Data can be variable, depending on location, confounding factors such as currents, and type of microplastic.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	2
Literature Support	3
Sensitivity and Responsiveness	2
Robustness	3
Feasibility	3
Cost-effectiveness	2
Reliability for Predicting Causality	2
Likelihood of Interaction	3
Community Interest / Concern	3
Total Score (Max = 27)	**23**

Key Metrics	Definition
Microplastic in Biota	Abundance of particles per organism number or area
Microplastics in Seawater	Particles per cubic meter
Particle Size and Shape	Size and shape (fibers, fragments, etc.)
Polymer Composition	Molecular composition of plastic
Plastic Mass	The total weight of plastic used at farm
Recyclability Rank	A scoring system for how difficult it is to recycle

Methods and Protocols:

Discrete Filtration for Water Sampling: Sampling for biologically relevant MPs involves small-volume water samples or towed manta nets to capture particles, followed by separation and analysis in a lab.

Biota Sample Collection and Digestion: Biological samples on which microplastics may adhere or be embedded (e.g., seaweed) require extraction protocols using chemical or enzymatic digestion, followed by filtering and analysis steps.

Spectroscopic Analysis: Identification of the type and source of plastic can be done using spectroscopic techniques like Fourier Transform Infrared Spectroscopy to verify chemical identity and polymer type.

Nanoplastic Methodological Development: There is an urgent need to develop and standardize analytical methods for detecting and quantifying nanoplastics (<100 nm) in environmental matrices and food, as current methods are lacking relative to existing methodologies for MPs.

Decision-relevance:

Marine Debris Release and Recovery: Data can inform gear marking standards to enhance traceability, prevent illegal dumping, and support Extended Producer Responsibility strategies. Visual inspection and documentation of gear damage at farm visits can inform debris prevention. Reporting missing gear, in addition to marking gear so it is attributable to a location, can assist gear recovery efforts. However, these measures address debris loss rather than the ongoing microplastic shedding from gear still in use.

Informing Material Choice: Monitoring clarifies the environmental cost of conventional gear, providing the necessary incentive for policymakers to mandate a shift towards materials like natural fibers or biodegradable polymers that can reduce or eliminate microplastic shedding at the source.

Risk Assessment: Quantifying accumulation in harvested kelp allows for human dietary risk assessments of MP exposure.

Existing Data and Monitoring Efforts:

AK: NOAA and the National Centers for Environmental Information (NCEI) have managed a data repository for aggregated MP data. While there are efforts to establish a baseline for the extent and nature of MPs in Alaska, there has not been an assessment of how seaweed farming may contribute to plastic pollution.

BC: Several initiatives in BC have collected information on the baseline environmental presence and concentration of microplastics, although attribution to farms is not possible without dedicated sampling at farm sites. Ocean Wise's Pollution Tracker program tested marine sediments and mussel tissue for the presence of MPs between 2015 and 2023. The NOAA/NCEI microplastics database also includes some entries for sampling that has taken place in BC waters.

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POLLUTION – Aqueous and Airborne Pollutants

Rationale: Aqueous and airborne pollutants from seaweed farming activities may affect local ecosystems, even though seaweed farms are generally considered low emission compared to other forms of aquaculture. Aqueous pollutants include contaminants present in the water column or sediments, such as hydrocarbons, trace metals, and other anthropogenic compounds that may originate from vessels, gear, or surrounding coastal activities. Airborne pollutants primarily relate to emissions associated with vessel operations, on-site processing, and nearby industrial or transportation sources. Seaweed farms do not apply chemical treatments, feeds, or therapeutants, which substantially limits direct pollutant inputs. However, farm-related vessel traffic can introduce fuel residues, lubricants, and combustion byproducts into both air and water. Monitoring aqueous and airborne pollutants provides contextual information to distinguish farm-derived contributions from background contamination associated with ports, shipping lanes, urban runoff, or industrial sources.

Indicator Scoring: Aqueous and airborne pollutants were both identified as **Group B** indicators. Aqueous pollutants were considered more relevant to management of seaweed farming and of greater concern by the farming community than airborne pollutants. Airborne pollutants, however, were considered more likely to be directly linked to seaweed farming if monitored. For both indicators, existing data quality is moderate.

Indicator Selection Criteria Scores (0-3)	Aqueous	Air
Relevance to Management	3	1
Literature Support	2	1
Sensitivity and Responsiveness	2	3
Robustness	2	2
Feasibility	2	2
Cost-effectiveness	2	2
Reliability for Predicting Causality	2	3
Likelihood of Interaction	1	3
Community Interest / Concern	3	1
Total Score (Max = 27)	19	18

Key Metrics	Definition
Concentration	ng/L or ng/g
Particulate Matter	$\mu g/m^3$

Methods and Protocols:

Sample Collection: Water samples can be collected to assess aqueous pollutants. Airborne pollutants can be monitored using passive or active air sampling. Given the generally small spatial footprint of seaweed farms, airborne sampling is often limited to areas with regular vessel activity.

Laboratory Analysis: Laboratory analysis is used to quantify pollutant concentrations using established analytical techniques such as gas or liquid chromatography and mass spectrometry.

Continuous Environmental Monitoring: Continuous monitoring is less common for aqueous pollutants due to cost and complexity but is feasible for monitoring airborne pollutants.

Decision-relevance:

Site Selection and Design: Pollutant monitoring can inform site selection by identifying and avoiding areas with elevated background contamination.

Farm Operations and Harvest Timing: Monitoring aqueous and airborne pollutants supports refinement of operational practices, including vessel maintenance, fuel handling practices, gear materials, and timing of farming activities. While pollutant inputs from seaweed farms are typically low, documentation of conditions during peak operational periods provides transparency and supports best management practices.

Economic Assessment and Management: From an economic perspective, pollutant monitoring supports product quality assurance, regulatory compliance, and market confidence. Demonstrating low levels of contamination reduces potential impacts on processors and buyers and supports access to premium or sustainability-focused markets.

Existing Data and Monitoring Efforts:

AK: The Alaska Department of Environmental Conservation's Fish Monitoring Program tracks contaminants in fish tissue across the state, particularly heavy metals. The National Park Service monitors contaminants across Southeast Alaska, and NOAA's Mussel Watch Program monitors contaminants in bivalve tissue. Many research projects have evaluated aqueous contaminants in coastal waters across AK, but few dedicated monitoring programs exist.

BC: Ocean Wise's PollutionTracker program tested marine sediments and mussel tissue for the presence of contaminants and microplastics between 2015 and 2023. Other programs which may be used to compare a seaweed farm's impacts against include Transport Canada's National Aerial Surveillance Program for oil spills and the Environment and Climate Change Canada Marine Emissions Inventory Tool that shows estimated levels of emissions based on vessel traffic data.

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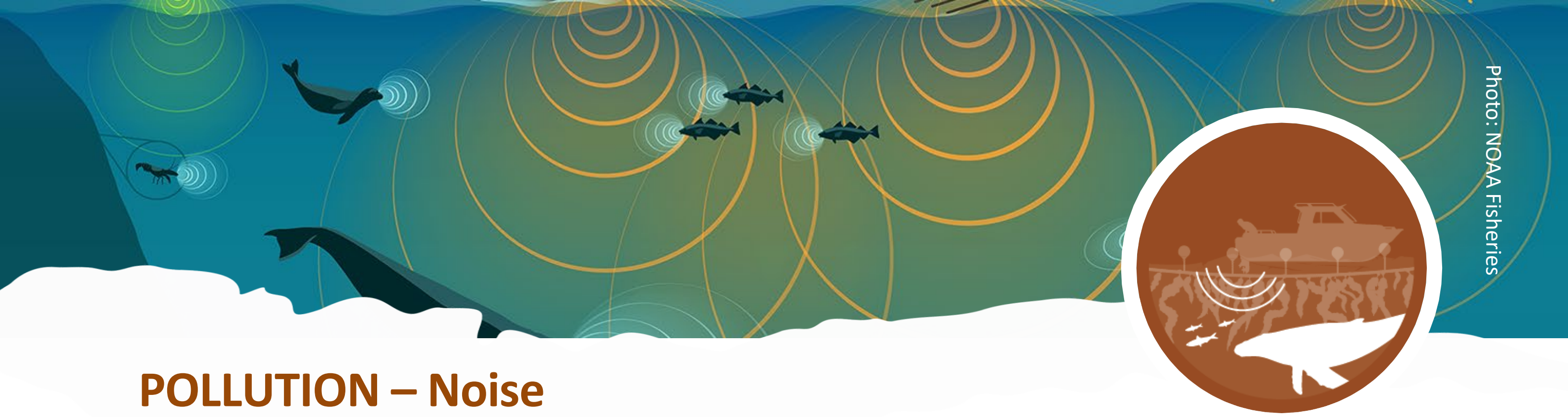

Photo: NOAA Fisheries

POLLUTION – Noise

Rationale: Noise generated by seaweed farming activities represents a potential ecological stressor in coastal environments, particularly for acoustically sensitive species such as marine mammals, fish, and some invertebrates. Noise associated with seaweed farming primarily originates from vessel traffic, engines, winches, hydraulic systems, and other mechanical equipment used during farm deployment, maintenance, and harvest. While seaweed farms are generally less noise-intensive than other marine industries, repeated or localized noise exposure may still influence animal behavior and habitat use.

Indicator Scoring: Noise was identified as a **Group B** indicator but had moderate support from literature and relevance to management with lower concern by the farming community. Data quality is moderate to good with a moderate likelihood of establishing a direct or cumulative effect to noise pollution by seaweed farming.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	2
Literature Support	2
Sensitivity and Responsiveness	3
Robustness	2
Feasibility	2
Cost-effectiveness	1
Reliability for Predicting Causality	2
Likelihood of Interaction	2
Community Interest / Concern	1
Total Score (Max = 27)	**17**

Key Metrics	Definition
Decibels	Sound Intensity
Frequency (Hz)	Pitch of sound
Occurrence	How often sounds occur

Methods and Protocols:

Acoustic Monitoring: Noise monitoring typically involves passive acoustic monitoring (PAM) using hydrophones deployed near farms to record underwater sound levels over time. Measurements may include sound pressure levels (decibels), frequency spectra (Hz), and temporal patterns of noise occurrence. Monitoring designs may range from short-term deployments during specific activities (e.g., harvest) to longer-term deployments to characterize baseline and operational conditions. Acoustic data is often paired with activity logs documenting vessel presence, maintenance, or harvest operations to support interpretation and attribution. Where feasible, reference sites outside farm influence are included to distinguish farm-related noise from background levels, but attribution may be challenging in areas with high levels of other vessel traffic. Because vessel traffic and acoustic environments are highly variable due to ambient conditions, weather windows for vessel travel, and distance from harbor infrastructure, monitoring efforts prioritize characterization of relative changes rather than absolute thresholds.

Decision-relevance:

Site Selection and Design: Noise data can inform site selection by identifying areas with high baseline acoustic sensitivity, such as proximity to marine mammal haulouts, migration corridors, or known feeding areas. Siting farms away from acoustically sensitive habitats reduces the likelihood of disturbance and cumulative impacts. Monitoring results may support farm design modifications that reduce noise intensity or propagation.

Farm Operations and Harvest Timing: Noise monitoring supports operational decisions related to timing and duration of activities. Scheduling maintenance or harvest during periods of lower wildlife presence or higher ambient noise can reduce relative disturbance. Monitoring can also identify activities that generate disproportionate noise, informing targeted mitigation such as vessel speed reductions.

Economic Assessment and Management: From an economic perspective, proactive noise monitoring helps reduce potential regulatory and reputational impacts, particularly in regions with strong protections for marine mammals and other sensitive species. Demonstrating low or well-managed noise impacts supports efficient permitting, operational continuity, and social license. Monitoring data can also inform cost–benefit analyses of noise-reduction measures, helping farmers balance operational efficiency with environmental stewardship.

Existing Data and Monitoring Efforts:

AK: Baseline noise data is collected in Cook Inlet, Glacier Bay National Park, the Bering Strait, and other coastal AK waters by entities like NOAA Fisheries, the National Park Service, and the Defenders of Wildlife. Underwater noise is monitored by several organizations in Alaska, including government agencies, academic institutions and non-governmental organizations.

BC: Underwater noise is monitored in BC by several organizations including federal government agencies, First Nations, non-governmental organizations and academic institutions, for example, by the Raincoast Conservation Foundation's Noise Tracker and Ocean Networks Canada. There is also an underwater listening station in the Salish Sea operated by JASCO Applied Sciences. Individual vessel noise from seaweed farms may be modeled using similar techniques as those used in regional studies on noise pollution's impacts to killer whales have been done for multiple regions across the BC coast.

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Photo: Marine Conservation Society

POLLUTION – Sewage

Rationale: Sewage represents a potential source of nutrients, organic matter, pathogens, and chemical contaminants that may affect coastal ecosystems and interact with seaweed farming. Seaweed farming may mitigate pollution from such sources and is not likely to contribute to sewage contamination, as farm vessels are not allowed to dump sewage close to shore. However, there could be potential future effects in the instance of offshore seaweed farming.

Indicator Scoring: Sewage was designated as a **Group C** indicator due to its lack of relevance for management, low support in literature, moderate concern by the farming community, and the likelihood that sewage introduction by farming operations was low. This indicator may become relevant if the seaweed industry increases in size.

Indicator Selection Criteria Scores (0-3)	
Relevance to Management	1
Literature Support	1
Sensitivity and Responsiveness	2
Robustness	2
Feasibility	2
Cost-effectiveness	2
Reliability for Predicting Causality	1
Likelihood of Interaction	1
Community Interest / Concern	2
Total Score (Max = 27)	**14**

Key Metrics	Definition
Suspended Solids (SS)	Fine particles that cloud water
Chemical profile	Concentrations of pollutants

Methods and Protocols:

Sample Collection: Sewage-related monitoring typically involves periodic collection of water samples at farm sites and reference locations to assess indicators such as suspended solids, nutrients, and chemical tracers associated with wastewater inputs. Sampling locations are selected to represent areas of farm activity, vessel presence, and background conditions.

Laboratory Analysis: Laboratory analyses are used to characterize bacterial or chemical profiles indicative of sewage influence, including presence of bacteria (e.g., enzymatic tests, qPCR) or wastewater-associated compounds (e.g., chromatography, spectroscopy). Analysis of suspended solids (e.g., gravimetric analysis, turbidity measurements) provides information on particulate loading that may influence light availability, sedimentation, and benthic conditions. Where appropriate, laboratory results are compared to regional baseline data or water quality guidelines.

Decision-relevance:

Site Selection and Design: Sewage monitoring informs site selection by identifying areas with elevated background wastewater influence, such as proximity to outfalls, anchorages, or heavily trafficked waterways. Avoiding sites with chronic sewage inputs minimizes confounding factors when assessing farm-related effects.

Farm Operations and Harvest Timing: Monitoring supports best management practices related to vessel sanitation, waste disposal, and operational planning. While sewage inputs from seaweed farming are expected to be minimal, documenting conditions during periods of increased vessel activity or harvest provides transparency and helps ensure compliance with applicable regulations.

Economic Assessment and Management: Sewage monitoring supports product quality assurance, regulatory compliance, and public confidence. Demonstrating that farms are not contributing to sewage-related pollution reduces the potential impacts of market restrictions, reputational impacts, and regulatory delays. Proactive monitoring can also help avoid future costs associated with remediation or operational changes should concerns arise.

Existing Data and Monitoring Efforts:

AK: Monitoring in AK is primarily focused on human health at popular recreation areas. The BEACH Program, operated by the Alaska Department of Environmental Conservation, collects water samples at recreation beaches across the state to assess fecal coliforms and enterococci bacteria that may indicate fecal contamination.

BC: Sewage monitoring in BC is more extensive due to proximity of highly populated areas. The Capital Regional District conducts environmental monitoring at beaches. Metro Vancouver also conducts wastewater testing and environmental monitoring to confirm the efficacy of wastewater treatment plants with outfalls to the Fraser River or the ocean.

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