PATHWAYS OF EFFECTS FOR FINFISH AND SHELLFISH AQUACULTURE

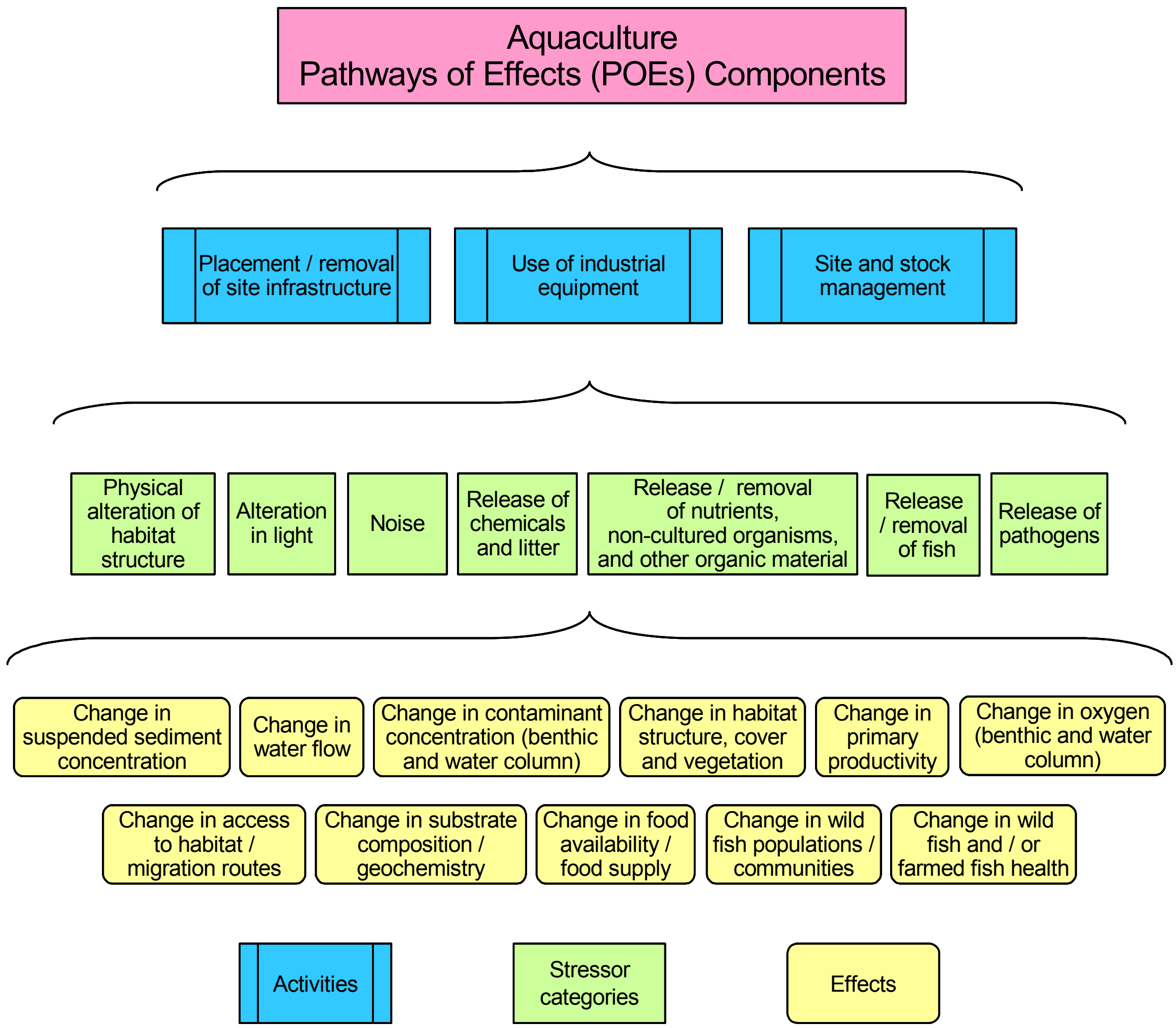

Figure 1: Aquaculture Pathways of Effects components: activities, stressor categories and effects.

Context

A Federal-Provincial/Territorial (F-P/T) Working Group (supported by the Canadian Council of Fisheries and Aquaculture Ministers and the Aquaculture Task Group) is developing a national Framework for Aquaculture Environmental Management (FAEM) to provide the basis for a coherent national approach to the regulation of the aquaculture sector (suspended and bottom culture of finfish and shellfish in freshwater and marine environments) in Canada. This same framework is also expected to provide the baseline for demonstrating how Canadian regulation responds to emerging market-driven sustainability certification expectations as they relate to aquaculture.

The FAEM uses a Pathways of Effects (POEs) approach to address the environmental effects of aquaculture. Four aquatic ecosystem components are considered: fish habitat; water quality; fish health;

and fish communities and populations.

The F-P/T WG desires scientific peer-review of its POEs to help ensure they are underpinned and informed by science. Draft POE diagrams and accompanying risk descriptions were developed to outline potential linkages between aquaculture activities and environmental stressors and effects; they were based on the professional and technical knowledge of federal, provincial and other experts. The POE diagrams and descriptions were provided to science for the review process and were structured to identify the aquaculture risks related to the four ecosystem components that were relevant to government regulators.

The DFO Canadian Science Advisory Secretariat (CSAS) process was identified by the F-P/T Working Group as the best approach for peer-reviewing these POEs and identifying areas of uncertainty or knowledge gaps. The scientific review focused on the stressor-effect linkages provided by the F-P/T WG. It will inform the development of the overall FAEM and will also help regulators in carrying out their responsibilities. It should be noted that while this review could be generalized to all forms of finfish aquaculture in net pens, both marine and freshwater; the same could not be said for shellfish. This review did not examine all types of shellfish aquaculture and was focused entirely on the culture of marine bivalves, which comprise almost all of the current Canadian industry. Further CSAS processes are expected to be undertaken in support of various components of the FAEM, including indicators, level of risk (likelihood) and risk response (mitigation) associated with these POEs. It is important to note that this CSAS process excluded consideration of mitigation measures and the potential to reduce or eliminate stressors or effects. Mitigation measures, their effects and potential side-effects will be assessed in a future process.

SUMMARY

1. The science review was provided with proposed activity – stressor – effect linkages for each of seven categories of stressors: chemicals, escapes, light, noise, nutrients, pathogens and structure. The linkages identified in the provided draft Pathways of Effects (POEs) were determined to be comprehensive but relatively simplistic representations, as they did not communicate the full complexity of all relationships and feedbacks that may occur. There is reasonable evidence that cumulative and/or cascading effects occur across pathways, and vary geographically and temporally and by level of activity. An appreciation of these complexities is essential to understanding the linkages. It was also noted that the provided POEs did not directly identify large-scale synergistic ecological functions and yet they are recognised by science as being important. The supporting scientific papers provide charts to complement the POE diagrams.

2. Chemicals enter the aquatic environment during normal aquaculture practices. They are released directly into the water column (pesticides, antifoulants and disinfectants) or in faeces and constituents of medicated food (drugs). Hazards have been determined for most of these compounds but field data on exposure and effects is limited. While data are collected on use patterns of therapeutants, access to these data is limited, which greatly hinders the characterization of pathways and of effects.

3. Potential hazards to wild populations posed by aquaculture escapes have been identified, but the probabilities and magnitudes of effects for such are not well known. Targeted in-depth investigations are needed in well-defined ecological systems where escapes and interactions are known to be occurring.

4. There is evidence that light used for aquaculture operations would have only a local effect.

5. Apart from acoustic deterrents, the effects of noise associated with aquaculture are generally short-term and localized and insufficient to cause injury.

6. Overall there is scientific evidence that bivalve and finfish aquaculture can affect nutrient flow in both pelagic and benthic environments. There is strong empirical and modeling evidence that increased deposition of organic matter from cultured and non-cultured/fouling organisms has the potential to alter local benthic habitat. Linkages between bivalve filtration and nutrient removal are well known. Some of the effects of release of nutrients from aquaculture to the water column are less well understood.

7. The extent to which pathogens released from aquaculture sites are stressors requires knowledge of infection and disease in wild aquatic populations. In Canada and other jurisdictions, pathogen surveillance of wild animal populations is virtually non-existent and should be established. Without this knowledge the extent to which pathogens are stressors cannot be assessed. There is scientific evidence that pathogens present in wild populations are the source of initial infections in aquaculture animals and some evidence that aquaculture animals release pathogens in their environment. However, evidence of pathogen transfer from aquaculture animals and/or products to wild populations is very limited.

8. Considerable physical structure is added or removed as part of all types of aquaculture activity. This includes both non-living (ropes, buoys, anchors, etc.) and living (fish, bivalves) components. Diverse biological assemblages may colonize this structure and affect the ecosystem both locally and at larger spatial scales.

9. There is substantial evidence and understanding from a broad range of environments that the major factors influencing the Pathways of Effects include i) water column characteristics (e.g., current flow, stratification, temperature, salinity, dissolved oxygen concentration); ii) bathymetry (e.g., depth, bottom topography); iii) operational practices (e.g., cultured species, non-cultured/fouling organisms, feed characteristics, stocking density); and, iv) the biological, chemical and physical characteristics of the receiving environment.

10. Significant knowledge gaps exist for some of the key stressor-effect linkages that make it difficult to complete Pathways of Effects diagrams. The research required to address these knowledge gaps is identified within each of the stressor categories.

INTRODUCTION

A Federal-Provincial/Territorial working group developed the draft POE diagrams and accompanying descriptions to outline potential linkages between aquaculture activities and environmental stressors and effects. The POE diagrams and descriptions were structured to identify environmental effects related to the four ecosystem components identified as relevant to government regulators: fish health, fish habitat, water quality and fish communities and populations. In initiating this review of the POEs, the Department organized a steering committee that comprised academia, government, industry, non-governmental organizations and First Nations.

The Steering Committee organized this CSAS workshop to review and discuss the prepared scientific papers with the following questions as a framework:

- **1a.** Is there evidence in the literature that supports or challenges the existence of the stressor-effect linkages identified in the draft Pathways of Effects?

- Elaborate as to evidence that supports or challenges the existence of the stressor-effect linkages, and where further information/knowledge could lead to a more complete understanding of the stressor-effect linkages.

- Qualify the strength of evidence that supports or challenges the existence of the stressor-effect linkages.

1b. Are the Pathways of Effects diagrams comprehensive? If not, identify missing stressor-effect linkages.

2a. Describe state of knowledge with respect to each stressor-effect linkage, including:

- A description of each effect and its associated ecological outcomes (effect profile).

- The factors and conditions that influence the expression of an effect (including exposure profile, receiving environment profile, etc.).

2b. For each stressor-effect linkage with scientific evidence described above, describe the documented biological implications of the effects on overall ecosystem function.

3a. Identify specific areas of uncertainty and knowledge gaps respecting the stressor-effect linkages.

- Which of the uncertainties or knowledge gaps hinder us most in terms of gaining a more holistic understanding of the effect profiles and the biological implications on overall ecosystem function?

The following assessments, which appear in alphabetical order, are derived from the discussions and reviews of the Research Documents and the input of workshop participants.

ASSESSMENT, ADVICE AND RECOMMENDATIONS

1. Chemicals

Pathway of Effects

Chemicals enter the aquatic environment during the normal operation of aquaculture sites. Chemical inputs can be intentional or incidental. Intentional inputs come from treatment of fish for bacterial infection and infestations of parasites and of mussels for biofouling. In addition antifouling compounds are applied to nets and disinfectants are routinely used to enhance biosecurity at aquaculture sites. Incidental inputs include litter, fuel and oil from boat traffic and constituents of food.

State of Knowledge of Stressor-Effect Linkages

Antibiotics and some antiparasitics enter the aquatic environment as constituents of medicated fish food and eventually may be incorporated into sediment where they can remain for long periods of time, depending on the compound. Use of these compounds is regulated and data are collected on use patterns of most of these compounds. Access to these data is lacking.

Antifoulants, disinfectants and some antiparasitics are released directly into the water column by leaching from treated nets and from direct release from bath treatments or disinfecting activities. While use of antiparasitics and antifoulants is regulated, use of disinfectants is not. Data on use of regulated compounds are collected but access to these data is lacking.

Bacteria resistant to antibiotics occur naturally in the aquatic environment. Studies indicate that antibiotic-resistant bacteria occur at higher frequencies in the vicinity of marine finfish aquaculture sites, likely related to antibiotic use at those sites. There is very little information available regarding use of antibiotics in freshwater aquaculture, the presence of antibiotic residues in receiving environments or the incidence of antibiotic resistant bacteria correlated with aquaculture activity in freshwater.

There is considerable laboratory-based data available on the hazard of chemical therapeutants to many kinds of aquatic organisms. Lethal effects of anti-sea lice treatments on non-target organisms (e.g., crustaceans) are well established and sub-lethal effects have been identified for some species. There are few data regarding effects on microflora and sediment microorganisms. The potential for exposure and effects in field situations is not well known. Where field studies have been conducted, data and conclusions are inconsistent, some suggesting high risk, others no risk to sensitive non-target species.

Exposures and effects of therapeutants at aquaculture sites depend on application practices. Bath treatments result in a direct release of chemical into the water column. In-feed compounds enter the environment bound to food and faeces. The persistence of therapeutants depends on physical and chemical factors which are generally well documented. The subsequent bioavailability of persistent compounds can be predicted based on these characteristics but confirmational data from the field are lacking.

Copper is the active ingredient in antifoulant paints that are routinely applied to nets used in finfish aquaculture. It leaches from treated nets and is bound in sediments and has been measured at concentrations in excess of Canadian Council of Ministers of the Environment interim sediment quality guidelines. Lethal and sub-lethal effects of copper on marine organisms are well established. Effects of copper in sediments at aquaculture sites are dependent on bioavailability and exposure. Factors such as the oxic condition of sediments, for example, greatly influence bioavailability.

Knowledge Gaps

- With regard to antibiotic resistant bacteria, the magnitude of single and multiple resistance occurrences and the potential impact on animal and human health is unknown for marine and freshwater aquaculture.

- Toxicity tests need to be conducted for all potentially toxic compounds to determine hazards at the sublethal level (e.g., behaviour, crustacean moulting, reproduction and growth). In addition, research needs to be conducted to investigate non-traditional endpoints that take into account modes of action of chemical compounds. These studies must be conducted at environmentally relevant concentrations and over realistic exposure periods.

- Research is needed to improve characterization of exposure-magnitude, duration, spatial extent, and frequency in both water and sediments.
- Research is needed to ensure that hazards are determined in studies designed to match exposure conditions such as method of application, duration of exposure and frequency.
- Field research on effects is needed to better characterize environmental risk.
- Research is needed to identify and characterize cumulative effects. Cumulative impacts may occur from repeated use of single compounds (or class of compounds), from coincident or sequential exposure to a number of chemicals or from exposure to chemicals under varying environmental conditions, such as dissolved oxygen or temperature.

2. Escapes

Pathway of Effects

There is evidence that escaped cultured finfish and shellfish may interact with wild populations and other ecosystem components in a variety of ways (e.g., direct competition, reproduction). For species studied extensively to date, such as Atlantic salmon in their indigenous range, effects of escapees on ecosystems (e.g., levels of prey species, effects on genetic constitution and phenotype of population or species, population and/or species viability) are anticipated in some cases. The potential for and magnitude of effects will be influenced by numerous factors including health of ecosystem components affected, species, life-stage and numbers released, etc. Effects are expected to range from negligible or very small short-term impacts (e.g., consumption of a small number of prey) to very large and long-acting impacts (e.g., multi-generational disruption of population structure and viability of populations). For less-well studied organisms like marine finfish and other salmonids, a high degree of uncertainty currently exists on potential effects due to insufficient empirical data, and uncertainty regarding extrapolation of existing information from other species and ecosystems. For shellfish, information from outside of Canada suggests that release of cultured bivalves can cause ecological disruptions in ecosystems where they are non-indigenous.

State of Knowledge of Stressor-Effect Linkages

Effects are expected to be very context-specific and can be influenced by geography (e.g., receiving environment, proximity to aquaculture activity), species, strain phenotypes and genetics (e.g., degree of domestication or divergence from recipient wild populations), climate, life stages released and interacting with wild fish, and health of the receiving ecosystem. Some laboratory and limited field data, as well as modeling, have suggested that Atlantic salmon escapees within their indigenous range could affect conspecific populations, most notably through competition at the juvenile freshwater stage and by reproductive interactions with small populations to affect their adaptive genetic structure. For other species of escapees, a higher degree of uncertainty regarding the Pathways of Effects exists.

Widespread ecological consequences have not been identified from the purposeful introduction of non-indigenous bivalves in Canada. However, information from outside of Canada indicates that escaped non-indigenous bivalves established beyond the aquaculture site could, in some cases, result in far-field alterations in fish habitat and water quality, as well as trophic interactions with native species occupying similar habitats. Such effects may be minimal where local, indigenous, wild-caught animals are used for culture.

Quantifiable endpoints (e.g., population size, species distribution and genetics, ecosystem biodiversity) have not yet been specified to allow for determination of harm/hazard or benefits arising from effects of escaped aquaculture organisms.

Knowledge Gaps

- Research is needed in Canadian ecosystems on escapes from a wider variety of cultured species such as bivalves, marine finfish and salmonids other than Atlantic salmon. These studies would examine the interactions with conspecifics, other species, and ecosystem components to assess whether generalizations can be made between species/ecosystems.

- Targeted in-depth investigations need to be continued in well-defined ecological systems where escapes and interactions are known to be occurring. Studies must be of sufficient temporal and spatial scale to reduce uncertainty and provide clear outcomes useful for management decisions. There also needs to be follow-up on existing POE natural experiments, such as the discovery in the wild of feral rainbow trout in Newfoundland, and Atlantic salmon and Pacific oysters in British Columbia.

- Research is needed to identify critical variables that influence the reliability of laboratory-to-field and field-to-field extrapolations. These studies would determine uncertainty, allowing it to be incorporated into the POE process.

- Research is needed to improve our understanding of the vulnerability and resilience of ecosystems being exposed to escapes.

- Research is needed to improve understanding of the relative effect of escapes from local versus non-local populations, and the degree of selection from wild type (domestication) on effects of escapes.

3. Light

Pathway of Effects

Artificial illumination of marine finfish net cages is currently widespread in the evening during late fall to early spring, a common practice to improve fish productivity by delaying maturation. Significantly less illumination is deployed for net cages holding Atlantic salmon compared to Atlantic cod.

State of Knowledge of Stressor-Effect Linkages

Above-ambient light levels are observed outside the cage periphery, though the variability in this intensity is a function of number and placement of light fixtures, their intensity and light spectrum, as well as water clarity and net biofouling. Studies have shown that illumination within the visible light spectrum deployed in cages does not penetrate more than a few metres below the bottom of the cage. While there is a lot of evidence to indicate that marine organisms are attracted or avoid light at night, there is very little information existing on the attraction or aversion of marine biota to illumination of net cages at night.

Knowledge Gaps

- Conduct measurements of light intensity beyond edge of net cages for different lighting arrays and water clarity to assess level of light decay.
- Conduct a biological survey of the presence and abundance of various pelagic and benthic species (primary and secondary producers) around lit and unlit net cages in different aquaculture regions during day, night and different seasons. Assess the threshold light intensity / spectrum or distance of a near-field effect for key biota.
- Conduct laboratory and field research to develop a knowledge base of the threshold behavioural responses (attraction/aversion) of key aquatic organisms to artificial light deployed in night conditions.

4. Noise

Pathway of Effects

Noise is generated from aquaculture by day-to-day activities related to site operations and by acoustic predator deterrents. The latter, which include acoustic harassment devices (AHDs), seal bombs and cracker shells, propagate efficiently through water and may be perceptible to marine mammals many kilometres from their source. Based on research in other mammals, these acoustic deterrents may cause hearing injury to marine mammals at very close range.

State of Knowledge of Stressor-Effect Linkages

Field observations indicate that seals appear to habituate to AHDs. Extrapolations from studies on other mammals indicate that this may be due to hearing impairment, but the mechanism(s) of habituation have not been assessed in seals. Consequently, these devices are generally ineffective at deterring predators over the long-term though the specific mechanism(s) of their ineffectiveness is not clear.

There are no empirical data or literature to indicate that fish or invertebrates are affected by AHDs, but our understanding of the hearing and use of sound in these taxa is less complete than in marine mammals. Cetaceans such as harbour porpoise and killer whale appear to be sensitive to AHDs and field studies have shown they are displaced from large areas when AHDs are in use.

Based on our knowledge of sounds generated by the types of vessels, equipment and machinery used by aquaculture during routine operations, these sounds may have short-term, localized effects on aquatic animals (e.g., avoidance, masking communication and echolocation sounds) but do not appear sufficient to cause injury to, or permanent displacement of, aquatic animals.

Knowledge Gaps / Research Priorities

- Additional research is needed on hearing capabilities and the effects of sound on fish, invertebrates and sea turtles.
- Additional research is needed on the longer term health implications of noise exposure in marine mammals and other aquatic animals.
- There is a need for a systematic survey of noise sources and current use of acoustic deterrents in the aquaculture industry.

5. Nutrients

Pathway of Effects

For the purposes of this Pathway of Effects, nutrients were defined as including both particulate and dissolved organics and inorganics such as nitrogen and phosphorous (see Glossary for definitions). The stressor-effect linkages identified in the Pathways of Effects descriptions are simplistically comprehensive but rudimentary and do not communicate the complexity of relationships and feedbacks. An appreciation of these complexities is essential to understand the linkages. Synergistic and cumulative effects on a range of scales are recognised as being important but are not directly identified in the POE aquaculture effect categories.

Table 1. Availability of evidence supporting the existence of a linkage between the stressor and effect components. Note that the table i) does not recognize the direction or severity of stressor-effect linkage; and, ii) it is not a stand-alone product and it must be considered together with the supporting text and research documents to better understand the complexity of the various potential feedbacks.

	Stressors						
Ecosystem components	**Release of fouling organisms**	**Removal of food and oxygen (as a result of increase in biomass of cultured organisms)**				**Release of harvest waste and mortalities**	**Release of excretory waste and excess feed**
		Removal of food		**Removal of oxygen**			
		Shellfish	**Finfish**	**Shellfish**	**Finfish**		
Fish Health							
Wild/farmed fish health							Substantial peer-reviewed evidence
Fish Habitat							
Habitat structure, cover and vegetation							Substantial peer-reviewed evidence
Substrate composition	Direct peer-review evidence for bivalves; limited evidence for finfish					Not supported in literature	Substantial peer-reviewed evidence
Water Quality							
Food availability/food supply	Limited peer-reviewed evidence	Substantial peer-reviewed evidence	Not supported in literature	Limited peer-reviewed evidence	Some peer-reviewed evidence	Not supported in literature	Some peer-reviewed evidence
Primary productivity	Not supported in literature	Some peer-reviewed evidence	Not supported in literature	Not supported in literature	Not supported in literature	Not supported in literature	Some peer-reviewed evidence
Oxygen (water column, benthos)	Direct peer-reviewed evidence for bivalves; limited evidence for finfish	Not supported in literature	Not supported in literature	Limited peer-reviewed evidence	Substantial peer reviewed evidence	Not supported in literature	Substantial peer-reviewed evidence
Fish communities							
Wild fish populations and communities	Limited peer-reviewed evidence	Some peer-reviewed evidence	Not supported in literature	Limited peer-reviewed evidence	Some peer-reviewed evidence	Not supported in literature	Substantial peer-reviewed evidence

Key to table

A simple qualitative ranking scheme is used in this table to categorize into four components the availability of evidence supporting the existence of a linkage between stressor and effect.

- Substantial peer-reviewed evidence – this area has been studied in detail.
- Some peer-reviewed evidence – this area has been the subject of a number of studies.
- Limited peer-reviewed evidence – this area has received only minor attention.
- Not supported in literature – the area was not identified as having been studied in any detail.
- Empty cells indicate that the pathway was not considered in this section.

State of Knowledge of Stressor-Effect Linkages

Bivalve and finfish aquaculture activities can modify nutrient dynamics through the release of waste materials from the feeding and excretory processes of cultured and associated non-cultured/fouling organisms. In the case of freshwater and marine finfish activities, the release of waste by-products and unconsumed feed results in a net input of nutrients to the environment.

Bivalves

The major pathways are removal of seston (suspended particulate matter) from the water column and release of organic matter and nutrients to the water column and benthos by both the cultured bivalves and non-cultured/fouling organisms. There is substantial evidence that bivalve farms may alter the pelagic environment by removing seston. In certain situations bivalve filtration can change the quantity and composition of the seston at the scale of the bay or inlet. The magnitude and spatial extent of water column effects depend largely on the nature and total biomass of cultured and non-cultured/fouling organisms and the assimilative and carrying capacity of the water body. Depletion of the seston can be predicted using relatively simple calculations of bivalve population filtration capacity and estimates of phytoplankton supply. More complex ecosystem modeling approaches can provide estimates of the effects of bivalve filtration on broader ecosystem functioning. General principles suggest in certain situations that changes in the quantity and composition of the seston at the scale of bay or inlet have the potential for effects at higher trophic levels.

There is substantial evidence that increased deposition of organic matter from cultured and non-cultured/fouling organisms has the potential to alter local benthic habitat and community structure. The magnitude and spatial extent of benthic effects from bivalve culture depend largely on the nature and total biomass per unit area and flux of seston to the cultured and non-cultured/fouling organisms. Release of nutrient from excretion and the microbial recycling of deposited fecal organic matter (occurring both within and on aquaculture structures and the seabed) can alter ecological functions such as recycling rates, trophic relationships and productivity. Bottom culture generally has a lower potential for impacts than suspended culture due to the greater limitations on biomass per area and access to the water column.

Marine and Freshwater Finfish

Stressor-effects pathway categories and linkages are similar in marine and freshwater environments, although some of the details are different (e.g., limiting nutrients such as phosphorus in fresh water and nitrogen at sea, geochemical cycling, and hydrodynamics).

There is substantial evidence that nutrients are released to the environment through fish excretory processes and waste feed. There is substantial empirical and modeling evidence that support a linkage between the release of organic materials in the form of waste feed and fish faeces and resulting alterations to the physical, chemical and biological composition and structure of soft sedimentary marine benthic habitats in close proximity to the finfish net pens. There is evidence that drop-off of fouling organisms does contribute organic material to the benthos as well as create physical structure in the near-field seabed of marine environments.

The effects and magnitude of nutrient releases to the marine pelagic environment (through dissolved, suspended and water-surface pathways) are not well known. The effects of nutrients released to the freshwater pelagic environment are reasonably well known. However, in relation to finfish farming in fresh water, physical and biological processes depending on local environmental conditions and the size and number of finfish farms will determine the actual levels of increases of these nutrients.

Knowledge Gaps

- Research is needed to develop and improve predictive and diagnostic assessment tools for bivalve and finfish (both freshwater and marine) culture. This should include far-field effects and ecological consequences including secondary impacts from direct modification of physical, chemical and biological domains and processes.
- Research is needed on interactions of bivalve culture and broad-scale ecological functions such as nutrient recycling rates, trophic relationships and productivity.
- The far-field effects of nutrient flow in the pelagic environment are not well known for bivalve and finfish aquaculture. There is a need to better understand and quantify losses and fates of feed and excretory wastes along suspended, dissolved and water-surface pathways (for example the role of micro-monolayers), from finfish farms across the full scale of aquaculture settings in Canada in order to establish general applicability.
- There is a need to better characterize the impacts and consequences of ecological feedbacks from nutrient and organic matter released from marine bivalve culture and freshwater finfish culture in Canadian lakes.
- There is limited peer-reviewed knowledge describing the alterations that occur to hard bottom marine environments and all types of substrates in freshwater environments as a result of increased deposition of waste materials. Standards and monitoring procedures need to be developed for effects on these environments.

6. Pathogens

Pathway of Effects

There is substantial evidence that pathogens are an important constraint in finfish and bivalve culture. Pathogens occur naturally in wild populations and can be amplified, diluted or modified in cultured populations. Most scientific evidence focuses on pathogen transfer from wild to farmed populations and among farmed populations. The POE paper provides a background to the general principles of pathogen transfer then discusses four pathogens that exemplify specific modes of biology or transfer in bivalves and finfish: infectious salmon anaemia virus, *Renibacterium salmoninarum*, *Haplosporidium nelsoni*, and *Aeromonas salmonicida* sub *salmonicida*. Pathogens such as sea lice and many others, while not discussed here in detail, are well described in scientific literature and references to these are made in the document as necessary. There is limited evidence for pathogen transmission between susceptible farm and susceptible wild populations.

It is noted that a measurable outcome of infection can be disease and that disease is not synonymous with infection, but also requires the confluence of environmental or host factors. Disease can be lethal or sub-lethal (e.g., affecting growth, reproduction).

Table 2. Examples of factors influencing bi-directional transmission of pathogens and disease outcomes in wild and farmed populations.

Host	Pathogen	Environment
Species (stock, age)	Strain (pathogenicity, virulence, infectivity)	Temperature
Immunity (acquired, natural)	Concentration, dose	Salinity
Stress (e.g., husbandry)	Bioavailability	Water quality (turbidity, plankton, chemistry
Density		Contamination (natural, anthropogenic)
Nutrition		Currents
Health status (e.g., co-infection)		Intermediate hosts, carriers

Understanding the potential of a pathogen to cause an infection in a population requires an understanding of the importance of the modulating factors, such as those listed in Table 2 for that particular pathogen, which can be more or less important, in determining the potential for transmission and disease in a population. For example, survival of MSX-infected oysters depends on salinity; and the survivability of *R. salmoninarum* outside a host (fish) may depend on the amount of organic matter in the water and water hardness.

State of Knowledge of Stressor-Effect Linkages

There is good evidence that some pathogens can be spread by human-induced activities (e.g., boats, nets, fish or their products, escapes) and natural processes (e.g., currents). There is a good base of knowledge of the factors that generally influence transmissibility, viability and virulence of several pathogens present in cultured salmonids and bivalves.

Knowledge Gaps

- Factors influencing the bi-directional transmission of pathogens and disease outcomes are not equally well known for all pathogens, particularly for pathogens of bivalves.
- Some pathogens are difficult to detect and treat (e.g., *Renibacterium salmoninarum*, the causative agent of bacterial kidney disease in salmonids). Hence it is difficult to demonstrate the extent with which they are transferred from broodstock to farms, from farm to farm and from farm to wild.

- Some pathogens (e.g., infectious salmon anaemia virus) occasionally occur as non-virulent infections in farmed and wild salmonids, but the mechanism leading from avirulent to virulent forms of the virus are unknown.

- Pathogen effects in wild populations may be detected by measuring changes in pathogen prevalence, intensity or by changes in the demographics of affected individuals within the target population. Therefore a pathogen reference baseline is required for the target population, which may be obtained by systematic surveillance or other epidemiological methods. In Canada, however, pathogen surveillance of wild aquatic animal populations is virtually non-existent and should be established.

- Current diagnostic methods focus on pathogens only and are not able to determine if host populations have been previously infected by a pathogen. Seroprevalence, a non-lethal assay that detects antibodies against the pathogen, would provide that information. Seroprevalence, and other non-lethal assays (e.g., mucus swab, kidney punctures), should be explored.

7. Structure

Pathway of Effects

Considerable physical structure is added or removed in all types of aquaculture, this includes both non-living (ropes, buoys, anchors, etc.) and living (fish, bivalves) components. This may directly affect the bottom and act as a settlement surface for a variety of organisms which may have numerous effects on both water column and benthic processes.

Table 3. Availability of evidence supporting the existence of a linkage between the stressor and effect components. Note that the table i) does not recognize the direction or severity of stressor-effect linkage; and, ii) must be considered together with the supporting text and research documents to better understand the complexity of the various potential feedbacks.

	Stressors				
Ecosystem components	**Shading**	**Release of fouling organisms**	**Shoreline / bottom structure**	**Vertical structure**	**Resuspension / entrainment**
Fish Health					
Wild/farmed fish health					
Fish Habitat					
Suspended sediment concentration					Not supported in literature
Habitat structure, cover, and vegetation	Limited peer-reviewed evidence		Limited peer-reviewed evidence	Substantial peer-reviewed evidence	
Access to habitat / migration routes			Substantial peer-reviewed evidence[1]		
Substrate composition		Some peer-reviewed evidence for bivalves; indirect evidence for finfish	Limited peer-reviewed evidence	Substantial peer-reviewed evidence	Substantial peer-reviewed evidence
Water Quality					
Food availability / Food supply	Not supported in literature	Not supported in literature		Direct peer-reviewed evidence for bivalves; indirect evidence for finfish	
Primary productivity	Not supported in literature	Not supported in literature	Not supported in literature	Direct peer-reviewed evidence for bivalves; indirect evidence for finfish	
Water Flow				Substantial peer-reviewed evidence	
Oxygen (water column, benthos)		Not supported in literature;			Not supported in literature
Contaminant concentration					Limited evidence for bivalves, unknown for finfish
Fish Communities					
Wild fish communities and populations		Some peer-reviewed evidence for bivalves; indirect evidence for finfish	Limited peer-reviewed evidence	Substantial peer-reviewed evidence	

[1] for structure placed to limit access to predators in on/in bottom bivalve culture; otherwise, few documented effects.

Key to table

A simple qualitative ranking scheme is used in this table to categorize into four components the availability of evidence supporting the existence of a linkage between stressor and effect.

- Substantial peer-reviewed evidence – this area has been studied in detail.
- Some peer-reviewed evidence – this area has been the subject of a number of studies.
- Limited peer-reviewed evidence – this area has received only minor attention.
- Not supported in literature – the area was not identified as having been studied in any detail.
- Empty cells indicate that the pathway was not considered in this section.

State of Knowledge of Stressor-Effect Linkages

Information on environmental effects due to structure is of variable quality and quantity, and is often confounded with other factors, particularly biodeposition. As a result much extrapolation is needed from non-aquaculture related studies to predict pathways of potential effects. The addition, removal, and modification of physical benthic structure may directly influence bottom sediments and communities although this has only been shown for in-faunal clam culture. The addition of vertical structure has been shown to influence hydrodynamics at a variety of spatial scales.

Research has shown that both benthic and vertical structure added for aquaculture serve as fouling substrates for hard-bottom species and associated soft-bottom species and may attract mobile species. Fouling has a variety of cascading effects on the structure, diversity and productivity of benthic and pelagic communities; although they have not been well-studied directly. Shellfish harvesting and other operations have been shown to impact both the physical and biological components of the benthic environment.

Limited work has shown that some structures and associated debris, particularly those that are lost or abandoned, entrap organisms and modify sedimentation processes, such as deposition, accretion and erosion.

Seals, sea lions, whales, porpoises, and other aquatic animals can become entangled or entrapped in anti-predator nets and other aquaculture-associated structure. Reporting of these incidents has been too sporadic and incomplete to assess their ecological impact.

Knowledge Gaps

- The biomass of associated organisms in bivalve culture may be as great as or greater than that of the farmed animals. Ecosystem models need to be developed that take this factor into account as these organisms have the potential of creating at least as great an impact as those being cultured. Validation of these models must be done using targeted descriptive studies.

- Appropriate indices must be developed/evaluated to identify effects.

- Empirical information and predictive understanding of flow patterns within and near farm structures needs to be determined.

- Improved data on the number and nature of entanglements of marine mammals and other animals at aquaculture sites is required, and an assessment of factors (e.g., net design, proximity to seal and sea lion haulouts, husbandry practices) affecting entanglement rates.

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Appendix 1: Glossary

Term	Definition
Activity	The actions undertaken by the site operator to establish, operate and close operations.
Acoustic deterrent	A pyrotechnic or electronic device that produces sound to deter seal or sea lion attacks at salmon farms.
AHD - Acoustic Harassment Device	A type of acoustic deterrent that generates intense sounds electronically that is intended to be uncomfortable or painful to seals and sea lions.
Anthropogenic	Caused or produced by humans.
Antibiotic	A substance designed to inhibit the growth of and kill pathogenic microorganisms.
Antifoulant	Agents that are added to paints and coatings or otherwise used to restrict growth of aquatic fouling pest organisms such as algae, tunicates and bivalves on nets or mussel socks.
Antiparasitic	A substance designed to inhibit the growth of and/or kill parasitic organisms.
Arthropod	Animals of the Phylum Arthropoda, including the Subphylum Crustacea. Invertebrate that has an exoskeleton, segmented body and jointed appendages.
Benthic habitat	Bottom environments with distinct physical, geochemical, and biological characteristics that vary widely depending upon their location and depth, and are often characterized by dominant structural features and biological communities.
Benthos	The assemblage of organisms inhabiting the bottom environment.
Bio-available	A substance that can be incorporated into living tissue.
Biodeposition	Deposition of biological material from living organisms.
Bivalve	An aquatic mollusc (class Bivalvia) that has a compressed body enclosed within two hinged shells, including oysters, clams, mussels, and scallops.
Cascading effects	Chain of events due to an act on a system.
Chronic	Marked by long duration or frequent recurrence.
Crustacean	Subphylum of invertebrates in the phylum Arthropoda, such as crabs, lobsters, barnacles.

CSAS	Canadian Science Advisory Secretariat – provides coordination of the peer review of scientific issues for Fisheries and Oceans Canada.
Disease	Clinical signs that are observable, repeatable and attributable to an etiological agent including parasites, viruses and / or bacteria, and result in a significant deviation in the natural status of an animal.
Disinfectant	Antimicrobial agents that are applied to non-living objects to destroy microorganisms.
Effect	A change in a particular component of the ecosystem as a result the occurrence of a stressor.
Empirical	Information gained by means of observation, experience, or experiment.
Endpoint, measurable endpoint, sub-effect	These terms are used to indicate specific aspects of effects that can be measured.
Escapes	Escape of cultured organisms into Canadian waters can be direct through accidental release of organisms from holding facilities or movement away from areas of introduction, or indirect through release of reproductive material resulting in feral offspring of contained cultured organisms.
Exposure period	Realistic timeframe during which an organism may be exposed to a stressor.
FAEM	Framework for Aquaculture Environmental Management
Far-field	A spatial point within an ecosystem that is outside of the immediate farm site footprint.
Feedback	The use of part of the output of a system to control its performance. In positive feedback, the output is used to enhance the input; in negative feedback, the output is used to reduce the input.
Finfish	Vertebrate organisms of the class Pisces.
Fish	*Fisheries Act* definition plus US EOA Tech guidelines: *Fisheries Act* includes parts of fish, shellfish, crustaceans, marine animals and any parts of shellfish, crustaceans or marine animals, and the eggs, sperm, spawn, larvae, spat and juvenile stages of fish, shellfish, crustaceans and marine animals, plus (US EOA Tech Guidelines) which adds: planktonic species (bacterioplankton, phyto- and zooplankton, ichthyoplankton), and benthic species (microalgae (epiphytes), macrophytes, infauna).
Fouling organism	Organisms that grow on submersed aquaculture equipment, often to the detriment of the equipment and culture organisms. Includes organisms such as algae, tunicates and bivalves on nets or mussel socks.

Habitat structure	Physical (e.g., crevices) and biological (e.g., plants) structures that organisms depend on to avoid predation (Oceans HMP Practioner's Guide).
Hard bottom/sediment	Bottom environment composed of rock, shell or similar hard materials that cannot be sampled by sediment grab devices.
Hydrodynamic	The study of fluids in motion.
Infection	Colonization of a host organism by a foreign species.
Lethal	Causing death.
Microflora	Populations of microorganisms including bacteria, viruses, protozoa, algae and fungi inhabiting a determined environment. Colony of microorganisms including bacteria, viruses, protozoa, fungi.
Multiple resistance occurrence	A change in frequency of resistant bacteria (or parasites) to multiple antibiotics (or antiparasitics). In the case of bacteria, resistance can be acquired by the transfer of DNA material (plasmid or cassette) from one bacterium to another. In parasites, the mechanisms of resistance are poorly understood.
Near-field	A spatial point within an ecosystem that is within the immediate farm site footprint.
Nutrient	Substance that provides energy or building material for the survival and growth of a living organism.
Nutrients (flux and budgets)	Three major nutrients found in seawater are nitrates, phosphate and silicate. Nitrate is most abundant, but nitrate, ammonia and organic compounds also contribute to organic build-up. When nutrient levels are deficient in the surface waters they can limit primary productivity.
Pathogen	An organism able to produce disease in a living host. The pathogens chosen for this review are representative of parasite, bacterial and viral agents, in addition to residing in both intra- and intercellular host locations.
Pelagic	Relating to or occurring or living in or frequenting the open ocean.
Phytoplankton	Phytoplankton are the main primary producers in oceans converting inorganic carbon into organic compounds through photosynthesis; they constitute the basic source of energy. The level of photosynthesis is affected by three major nutrients - nitrates, phosphate and silicate. In seawater, nitrite is usually the limiting factor while in freshwater it is phosphates.
POE	Pathways of Effects
Receiving environment	The spatial and temporal domain of the bottom and water column found outside the net pens used to contain cultured fish on finfish farms and outside the suspended nets, bags, cages and the immediate biological

	matrix associated with socks used to contain the shellfish being cultured.
Sea cage	Aquaculture net cage as used in marine settings.
Sea lice	Several species of parasitic copepods that are commonly found on fish in the marine environment.
Sediment	The term sediment is used to refer to all consolidated particles transported and deposited by water, wind, glaciers, and gravity.
Seroprevalence	Number of individuals in a population who test positive for a specific disease based on the presence of antibodies in blood serum specimens.
Seston	Minute living organisms and particles of nonliving matter which float in water and contribute to turbidity.
Single resistance occurrence	A change in frequency of resistant bacteria (or parasites) to a single antibiotic (or antiparasitic); resistance is acquired by the transfer of DNA material (plasmid or cassette) from another bacteria (or parasite) or by mutations of the genetic material.
Soft bottom/sediment	Seabed composed of gravel, sand, mud or other similar materials that can be sampled with sediment grab devices.
Species	Includes populations, species and sub-species.
Stressor	Factors that affect the aquatic environment. In the ecological sense, the term stressor is neutral – it is not meant to imply positive or negative connotations. While some Risk Management processes and their Risk Assessment stages specifically state that only negative stressors and effects are to be described, the FAEM principles commit to examining and considering both positive and negative effects in the final Risk Assessment.
Stressor-effect linkage	Cause and effect relationship between the identified stressors and the identified effects.
Structure	Physical surfaces providing potential additional habitat for non-culture species. Includes on-bottom structures such as anchoring devices, and vertical structures such as ropes, cage structures, buoys, etc.
Sub-lethal	Causing harm, but not to the point of death; sub-lethal effects may be as detrimental to populations as lethal effects on a population-scale.
Sulphide	A chemical compound containing sulphur in its lowest oxidation number of −2.
Therapeutant	A product used in the treatment of diseases. When delivered via medicated feed or by injection, it is considered a drug (Health Canada's Veterinary Drug Directorate) and can only be acquired by prescription from a licensed veterinarian. Therapeutants used in bath treatments are considered pesticides (Health Canada Pesticide Management Regulatory

	Agency) and are also only available by prescription from a licensed veterinarian.
Toxicity	Degree to which a substance can cause harm to animals or environment.
Trophic level	Stage within ecological food web (e.g., primary producers, primary consumers, predators, etc.).

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