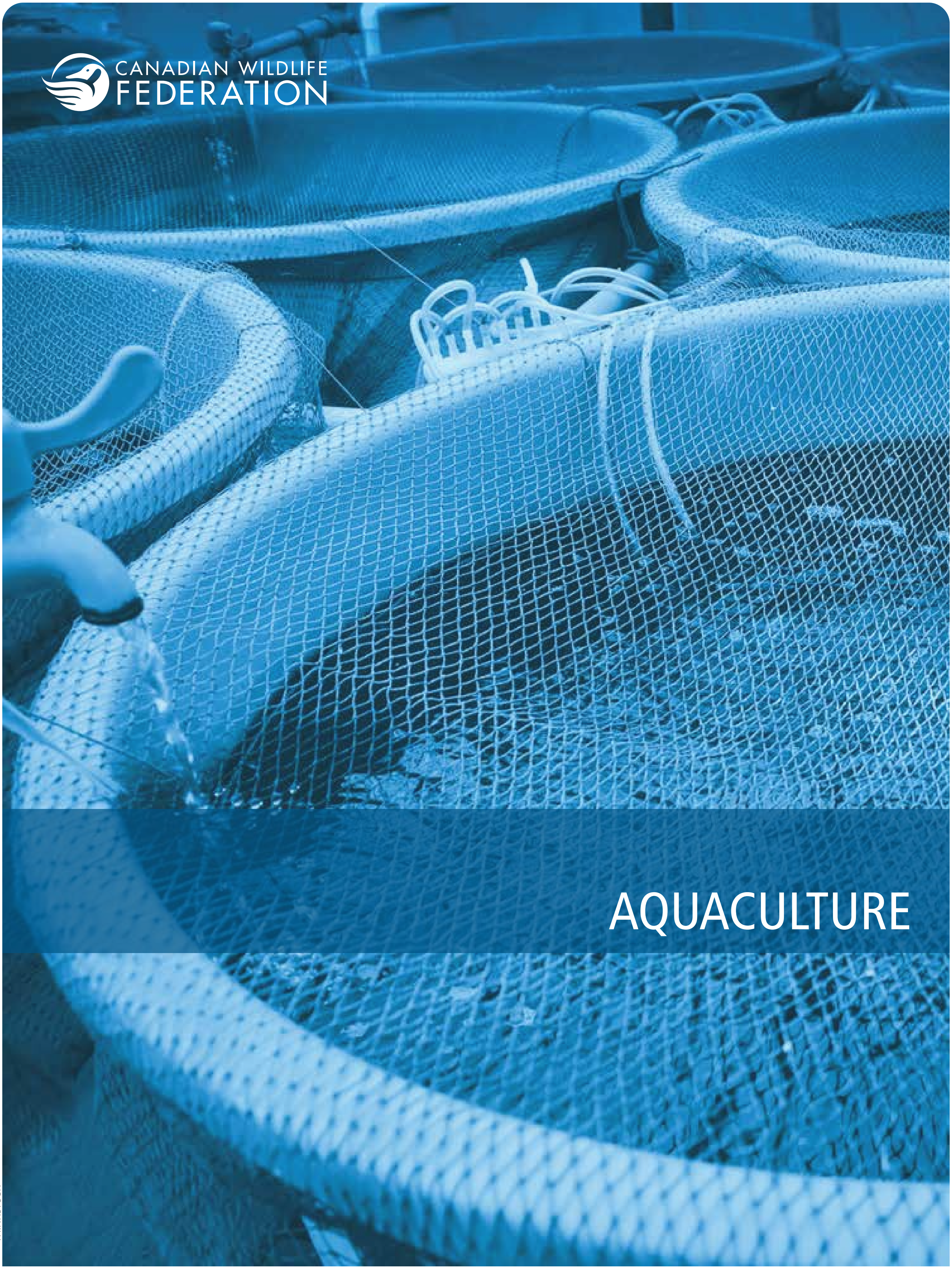

AQUACULTURE

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CANADIAN WILDLIFE FEDERATION

CanadianWildlifeFederation.ca

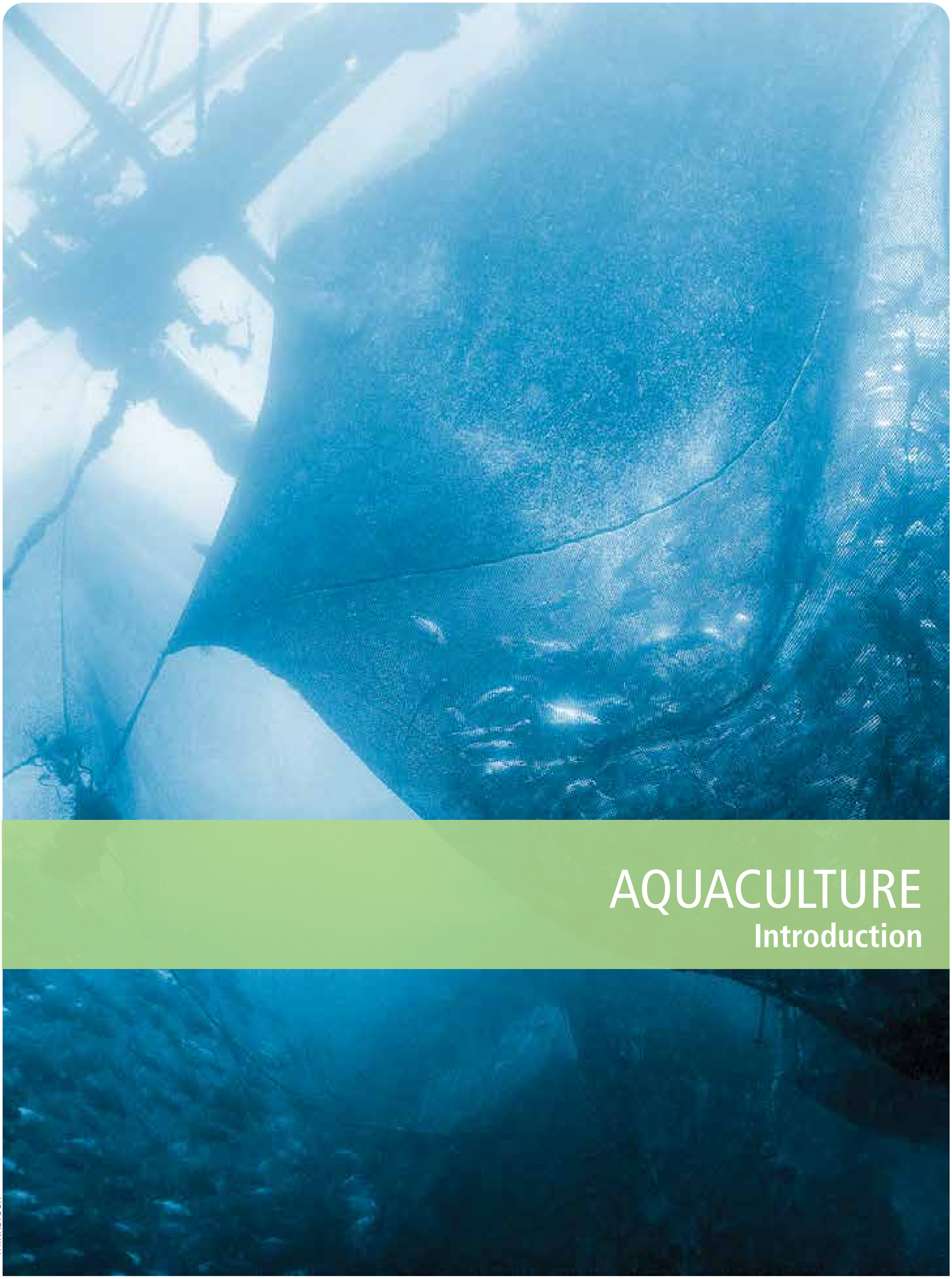
This an update of our 2013 report on the effects of open pen finfish aquaculture (OPFA) on wild fish populations. The purpose of this report remains the same as the original: to clearly establish, and to substantiate the Canadian Wildlife Federation's position on finfish aquaculture, based on a review of the best available knowledge.

This update adds 77 new studies to the report. These were included following a detailed search of scientific literature for studies that examined effects of salmon, finfish or net-pen aquaculture.

The format of this update remains the same as the first report; the first section identifies CWF's position and key messages relating to finfish aquaculture and its effects on wildlife. The second section is an annotated bibliography that provides a brief description of scientific research that investigated the effect of finfish aquaculture on wildlife, and provides the references to this scientific literature, allowing anyone to examine this research themselves.

The 2013 report was compiled and written with Amy Ryan. This 2016 update was done in collaboration with Maddison Scott.

Sean Brillant
Senior Conservation Scientist – Marine Programs
Canadian Wildlife Federation



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AQUACULTURE
Introduction

AQUACULTURE
Introduction

Q What is Aquaculture?

A Aquaculture is the farming of aquatic wildlife like fish, crustaceans, molluscs and aquatic plants. As opposed to commercial fishing, where fish are harvested from the wild, aquaculture grows freshwater and saltwater species in controlled conditions.

This report is focused on two types of finfish aquaculture:

- Closed-containment finfish aquaculture (CCFA)
- Open-pen finfish aquaculture (OPFA)

Q What is Closed-containment Finfish Aquaculture (CCFA)?

A Closed-containment finfish aquaculture (CCFA), is a farming technique that raises fish in a containment system that is a barrier between farms and the natural environment. This technology has varying levels of separation from barriers, such as land-based tanks or floating solid walled tanks in the ocean, to recirculating water systems. CCFA systems have been used successfully for certain species, such as rainbow trout, halibut and tilapia.

There are several challenges for CCFA operations to become a viable means for raising finfish:

- There are additional operational costs and increased fossil fuel requirements;
- The species being raised require different (domestication) traits than those currently used;
- Influent-effluent treatments need to be developed; and
- There are substantial capital costs.


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Although there are some CCFA operations being developed, it is currently viewed as an experimental and developing industry as the challenges listed above are addressed. As it stands, a thorough evaluation of CCFA was done by Chadwick et al in 2010 and the Atlantic Salmon Federation is investing in research to develop CCFA.

The Canadian Wildlife Federation's Position on Closed-containment finfish aquaculture

CWF is supportive of research into CCFA technologies and encourages this method of finfish farming to be developed.

AQUACULTURE
Introduction

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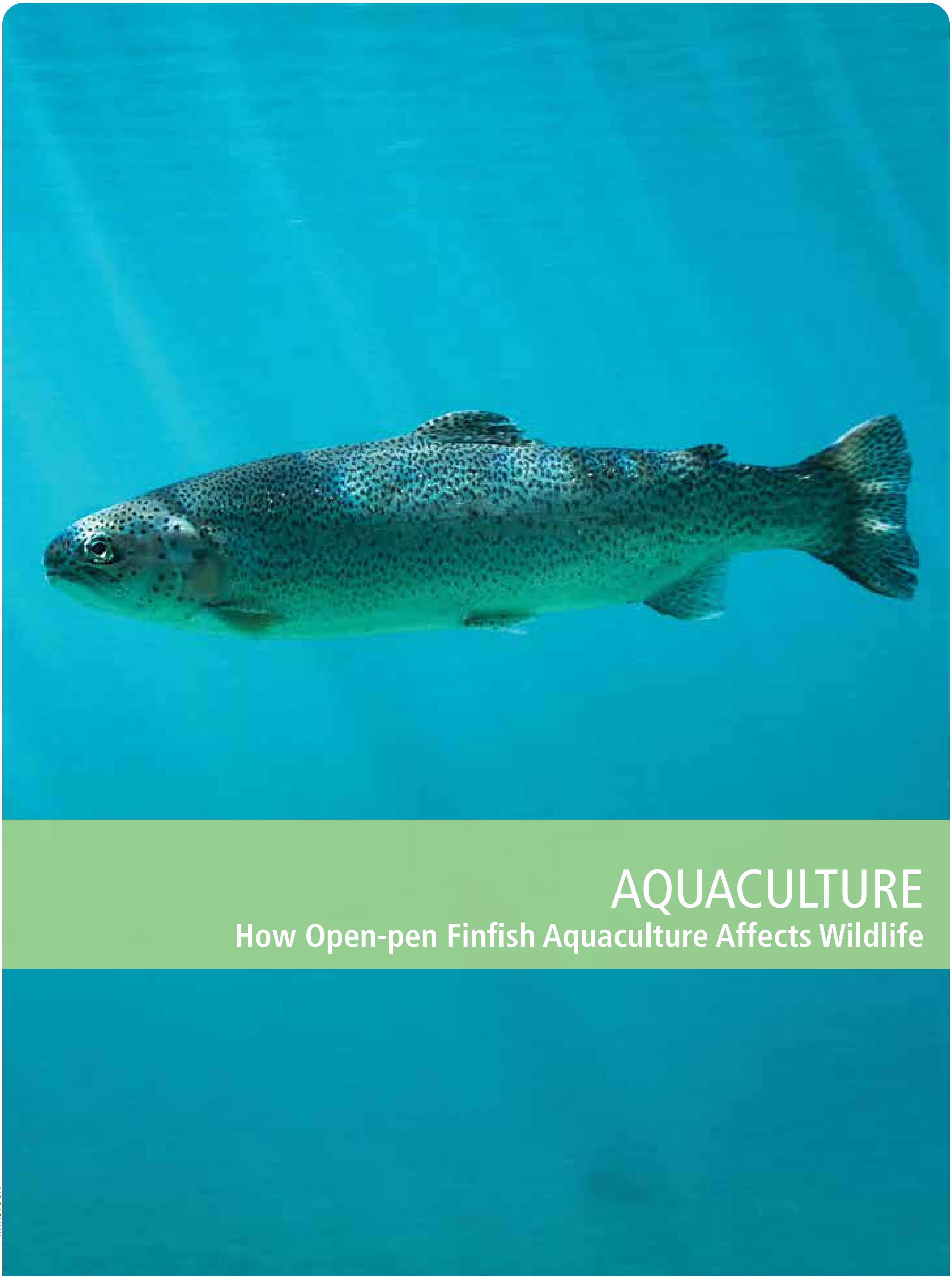
Q What is Open-pen Finfish Aquaculture?

A Open-pen finfish aquaculture (OPFA) is the practice of raising of relatively large numbers of fish in marine or freshwater within net pens or cages that are open to the natural environment. OPFA is common practice within the industry, raising many finfish species, such as salmon. This practice is cost effective for the aquaculture industry, as the open nets take advantage of the already appropriate water temperature, salinity and oxygen from the environment and the currents to disperse the waste from the farmed fish species. Yet, the open nature of OPFA creates a variety of negative implications for the environment.

The Canadian Wildlife Federation's Position on Open-pen Finfish Aquaculture

Open-pen finfish aquaculture alters important aquatic habitats and significantly affects native populations, such as wild salmon and other wildlife. These effects may put the survival of both Pacific and Atlantic salmon species at risk. Although the aquaculture industry creates economic benefits, because of its significant impact on wildlife, CWF would like to see the practice of OPFA in Canada phased out over the next 10 years. In the meantime, CWF believes it imperative that no more OPFA operations be established in Canada.



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AQUACULTURE
How Open-pen Finfish Aquaculture Affects Wildlife

Competitive and Genetic Consequences


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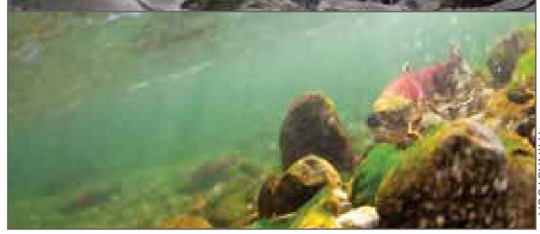
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Large-scale escapes from OPFA operations have occurred on both the east coast and west coast of Canada. When these salmon escape, there are a variety of risks to wild populations. Interbreeding (i.e. introgression) can reduce genetic diversity and reduce fitness in wild populations. Furthermore, when open-pen farmed salmon escape, wild salmon face with new competitors for resources. Increasingly, research shows both of these effects on wild salmon.

Diseases

There are several diseases that salmon held in OPFA operations can contract including:

- Bacterial kidney disease. A chronic bacterial disease that is slowly progressive and frequently fatal.
- Infectious haematopoietic necrosis. An infectious viral disease that may infect salmon of any age but predominately young fish. The virus attacks the blood forming tissues of the fish, as well as its kidney and spleen. To date there is no treatment or cure for the disease.
- Infectious salmon anaemia. A viral disease that causes severe anemia in fish.
- Viral hemorrhagic septicemia. A virus that causes the hemorrhaging of internal organs and tissues.

Although fish in OPFA operations can contract diseases from wild fish, infected fish in OPFA operations are also a source of diseases to local wild fish populations, contributing to the spread, intensity and maintenance of these diseases in wild populations. The latter is of greater risk because the high concentration of fish in OPFA has an increased likelihood of contracting and transmitting disease.

Parasites

Sea lice (parasitic copepods that feed on the skin, mucous and blood of fish) can cause morbidity and even mortality in some populations of salmon. Sea lice are natural parasites and wild populations can have large infections un-associated with OPFA. However, fish in OPFA operations can exacerbate the transmission of parasites, as they are a year-round host population for the parasites that would otherwise be absent. Additionally, the high concentration of salmon in an area year-round is an ideal but unnatural breeding ground for lice. Even juveniles can be infected in OPFA operations because they remain in contact with the adult population. In the wild, juveniles are usually protected from infection because of their separation from the adult population. Sublethal exposure to sea lice at early life stages reduces the growth of individuals, causing negative effects on populations.



PHOTOS: WIKIMEDIA COMMONS

Pharmaceutical pesticides and disinfectants

Finfish in OPFA operations are treated with therapeutants (various compounds to protect their health, including treatment for parasites; see previous section). These treatments are usually regulated, however, emergency treatments are required sometimes, and those treatments can be difficult to regulate. The potential effects of therapeutants being released into the environment are a concern. They can have harmful effects on other species. Crustaceans, for instance, tend to be particularly sensitive to these treatments; more so than other species. Some studies show that, when OPFA therapeutants are used properly, they pose little threat to local populations, but studies have established, experimentally, that therapeutants can cause a variety of lethal and sublethal effects to local, non-target, animals.

The use of antibiotics in OPFA operations also alters local bacterial diversity of the environment, particularly through increased populations of antibiotic-resistant bacteria, and has led to the emergence of new strains of bacteria.

Pollution and habitat alteration

The effect of pollution on the natural environment is dependent on the type of OPFA operation and the depths, tides and currents of local waters (hydrographic conditions). The impacts on the organisms that live on the bottom (benthos) can be large in area, but less acute for OPFA operations in deep water compared to those in shallower water.

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Fish wastes (faeces, uneaten food, mortalities) accumulate beneath cages of OPFA operations, and, in some circumstances, can modify benthic structure, and produce eutrophic (waters rich in nutrients that lead to a boost in plant life, especially algae) and anoxic (low oxygen) conditions. Large-density OPFA operations release quantities of nutrients (nitrogen and phosphorus) comparable to the human sewage production from coastal urban centres.

WIKIMEDIA COMMONS

Heavy metals with toxic properties, particularly copper, can accumulate in the sediments around OPFA operations, often to concentrations well above those predicted to cause ecological effects, though the extent of this contamination varies among locations.

OPFA operations provide novel, varied, and uncolonized surfaces on which organisms may settle, sometimes in unnaturally large numbers (biofouling). This can lead to other problems, such as a boom in invasive species, and particularly in the treatments to prevent fouling.

Effects on distribution and behaviour of wildlife

Attracting wildlife

OPFA operations attract predators such as seals, birds and other fish species; altering their natural behaviour and putting them at risk of becoming injured in nets or equipment, and increasing their vulnerability to predation, fishing and the transmission of diseases. Several studies show wild fish that aggregate around OPFA have different body-forms (e.g. sizes of heads, otoliths), and behaviours compared to those that do not occur near OPFA.

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Light

The lighting used around OPFA operations attracts wild fish to the cages, exacerbating other potential effects, particularly the transmission of disease.

Noise

Operators use noise-makers to deter predators from OPFA cages. While studies show they are ineffective on most target species, like seals and birds, we know they do alter the behaviour and distribution of non-target species, particularly cetaceans (whales, dolphins and porpoises). To date, there is no evidence that these effects on non-target species are long-term or damaging.

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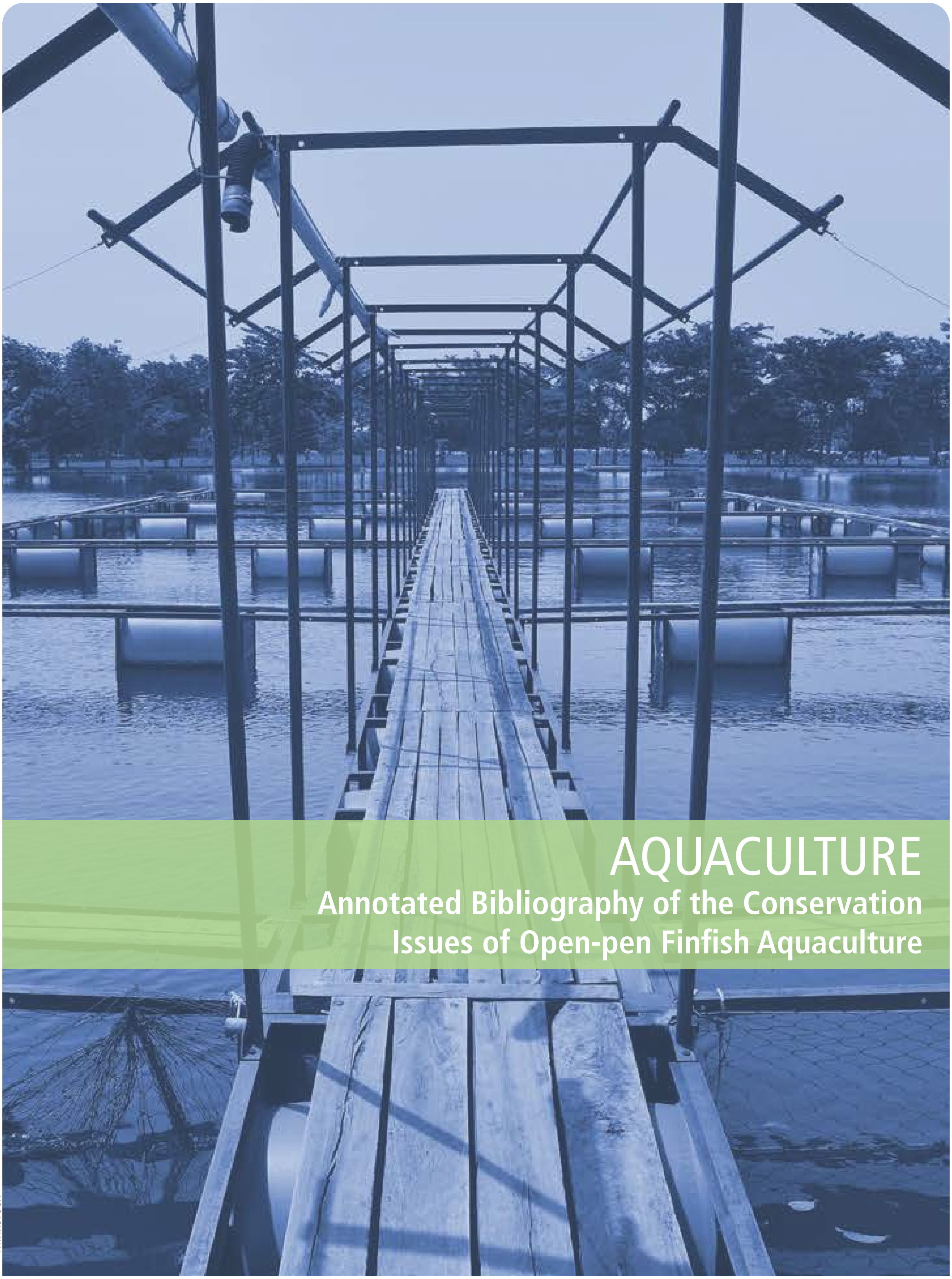
Sustainable use of wild resources

Salmon aquaculture is an added pressure to wild fish stocks. Industry and scientists estimate that it takes between 1.7 Kg to 4.9 Kg of wild forage fish to produce one kilogram of salmon. While this ratio has significantly dropped in the last few decades, it remains that more wild fish are required to produce a given amount of salmon.

Furthermore, more than half of the fishmeal produced by global fisheries for forage fish is used in aquaculture. Some species of finfish, like carp and tilapia, do not need nearly as much fishmeal and fish oil in their diet as do salmon to produce a similar amount of production, leading these farm-raised species to be a potentially more sustainable choice for the consumer in this aspect.



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AQUACULTURE

Annotated Bibliography of the Conservation Issues of Open-pen Finfish Aquaculture

General Impacts

- Salmon farming is conducted almost exclusively in net pens. A number of environmental impacts can be attributed to this type of aquaculture, as cages are open systems that allow for the release of nutrients, pathogens, and chemical inputs to the marine environment.
- Impacts are commonly grouped into four categories: ecological interactions, genetic consequences, disease and parasites, habitat alteration. More specifically: benthic impacts and alteration, chemical inputs (antibiotics, anti-foulants, pesticides), nutrient loading and deterioration of the benthos, attraction of other organisms and predator exclusion, feed sources, effects of escapees and use of exotic species, and exchange of pathogens (sea lice) (Egidius et al. 1991, Waknitz et al. 2003, Cubitt et al. 2008, Hutchings et al. 2012a, Hutchings et al. 2012b, Bergqvist et al. 2015,).
- An analysis of wild salmon mortality in rivers adjacent to salmon farms demonstrated a large reduction in survival and returns in populations exposed to aquaculture. Mortality increased by more than 50 per cent for each generation for wild salmon exposed to aquaculture (Ford and Myers, 2008).
- On the west coast, only pink salmon showed significant declines correlated with aquaculture (Ford & Myers 2008). This was attributed to the genetic impacts from interbreeding with escaped farm salmon, in addition to disease and other impacts described below.

Competitive and Genetic Consequences

- Large-scale escapes are frequent occurrences with open-net pen fish farming and can happen through routine handling, or large-scale episodic events such as storms (McGinnity et al. 2003, Naylor et al. 2005), increasing the risk of interactions between wild and farmed salmon. Farmed fish can also 'escape' when spawning occurs in the pens, and fertilized eggs get released into the surrounding environment (Jorstad et al. 2008, Jensen et al. 2010). Escapes can have severe impacts on the persistence of wild salmon populations (Morris et al. 2008). As salmon farming became more widespread, farmed salmon were found in increasing number in wild populations (Fiske et al. 2006).
- Morris et al. (2008) compiled a series of studies and found that escaped farmed salmon have been reported in 87 per cent of the watersheds that have been investigated since the inception of the salmon aquaculture industry in 1980 (the majority of the investigated rivers were located in primary aquaculture regions, i.e., N.B. and ME).
- Carr & Whoriskey (2006) assessed the occurrence of escapees from freshwater hatcheries and found escapees in streams every year and escapee smolts outnumbered wild smolts in seven out of the eight years studied in the Magaguadavic River. Escapes of juvenile salmon occurred in streams next to at least 75 per cent of the commercial salmon hatcheries in New Brunswick.
- In addition to increased competition for food and habitat, disease transmission, and overall reduced health, there exists the potential of escaped farm salmon to prey on and breed with wild fish (Egidius et al. 1991, Flemming et al. 2000, Jensen et al. 2010). Interactions can also alter the functional response of wild fish to predators (Youngson et al. 2001, Naylor et al. 2005, Tymchuk et al. 2006a, 2006b, Houde et al. 2010), and cause changes to immunity and metabolism in wild populations (Normandeau et al. 2009).
- In contrast to their wild counterparts, farmed salmon are selectively bred for, among other characteristics, faster growth. Due to these genetic differences interbreeding is a major concern. Farmed salmon can outcompete wild salmon at the earliest lifestages (Sundt-Hansen et al. 2015).

- Genetic effects of interbreeding between farmed and wild fish may be direct or indirect. Direct genetic effects include the alteration of the wild genome (introgression) as a result of interbreeding between wild and domesticated fish (Glover et al. 2012, Glover et al. 2013, Heino et al. 2015), or the production of sterile hybrids. Indirect effects include a reduced effective population size or altered selection pressure arising from competition (Tymchuk et al. 2006a, 2006b). In some cases, the added diversity from interbreeding between strains of farmed salmon allow for the successful establishment of new populations (Yanina Di Prinzio et al. 2015).
- Interbreeding can have genetic effects that threaten the reproductive capability and recovery potential of wild populations, a result of the production of fish that are less fit (Vandersteen et al. 2012), as well reduced lifetime success (McGinnity et al. 2003, Thorstad et al. 2008, Hutchings et al. 2012).
- Introgression can eventually lead to genetic homogenization, resulting in an irreversible loss in the genetic variation of wild populations, and subsequently, can alter the genetic integrity of native salmon populations, including loss of local adaptation, or the reduced ability to respond to changing environments (Naylor et al. 2005, Fraser et al. 2010, Bourret et al. 2011). Native cod populations can also suffer from genetic introgression when wild cod breed with escaped farmed cod (Uglem et al. 2008).
- The wild cod populations in Norway were not significantly affected by genetic introgression from escaped farmed cod (Varne et al. 2015) despite interbreeding between the farmed and wild cod (Meager et al. 2010, Skjaeraasen et al. 2010). Male cod cannot breed well with farmed females (Beirao et al. 2014).
- When farmed Atlantic salmon escape during spawning, they travel to the upper portions of rivers, while wild salmon are distributed in the upper, middle, and lower portions. Due to this, interbreeding occurs in the upper portion of the river, unless obstacles prevent travel (Moe et al. 2016).
- Farmed Atlantic salmon (Salmo salar) tend to be competitively and reproductively inferior to their wild counterparts, with less than one-third the reproductive success (Flemming et al. 2000, Naylor 2005, Hindar et al. 2006). However, farmed and wild fish were found to have no significant difference in their tolerance to low temperatures (Solberg et al. 2016). Despite their decreased ability to compete, the farm fishes still were able to compete with the native population. Although breeding performance tends to be inferior to wild salmon, interbreeding does occur successfully resulting in hybridization (Flemming et al. 2000, Naylor 2005, Hindar et al. 2006).
- Hybridization may have contributed to the decline and lack of recovery of many wild Atlantic salmon populations in the Northwest Atlantic because it can change the genetic make-up and life history traits of wild populations (Fraser et al. 2010).
- Hindar et al. (2006) modeled the future of wild salmon populations experiencing invasions of escaped farmed salmon. Results demonstrated that high intrusion could eventually lead to populations that are mixtures of hybrid and farmed descendants within only a few generations and recovery of wild populations in this scenario is not likely.
- Liu et al. (2013) also modeled this showing that increased numbers of escapes reduces the social welfare of the harvest and the wild stocks (recreational).
- McGinnity et al. (2003) demonstrated that interaction of farmed salmon with wild salmon results in lowered fitness, with repeated escapes causing cumulative fitness depression and potentially an extinction vortex in vulnerable populations.
- Most differences appear to result from non-additive gene interactions (rendering effects unpredictable),

which affects traits related to fitness (Roberge et al. 2008). These results suggest that interbreeding of fugitive farmed salmon and wild individuals could substantially modify the genetic control of gene transcription in natural populations exposed to high migration from fish farms, resulting in potentially detrimental effects on the survival of these populations (see also Oke et al. 2013).

- When farmed smolts escape in late summer/early fall, they display reduced or no migratory tendencies, however they do migrate if they escape in late spring/early summer (Skilbrei, 2010).
- Escaped farmed salmon migrate and disperse through the Arctic ocean similar to wild salmon (Jensen et al. 2013).
- The probability that escaped Atlantic salmon will establish populations where the species is exotic seems low, but the possibility cannot be ruled out. Where native populations of salmonids are currently depressed or in decline, conditions for the establishment of Atlantic salmon may be more favourable now than in the past (Thorstad et al. 2008). However, the likelihood of successful hybridization between Atlantic salmon and Pacific salmonid species seems small.
- Escaped farmed rainbow trout can establish self-sustaining populations, which affects local ecosystem (Sepulveda et al. 2013).
- Feral Atlantic salmon were reported in coastal rivers of BC. Volpe et al. (2000) report the first case of successful Atlantic salmon reproduction on the northeast Pacific, which demonstrates the potential for successful colonization, and thus potential for competition for space and food with wild populations of Pacific salmon (in particular *Oncorhynchus spp*.), although these inferences were speculative at best. Currently, farmed Atlantic salmon are found in a majority of salmon supporting rivers in BC, but it is unknown if these are naturalized populations (Fisher et al. 2014). However, farmed salmon have not invaded the Alaskan coast (Piccolo et al. 2012).
- Due to artificial selection of growth in farmed salmon, they tend to have a size advantage over wild salmon (Harvey et al. 2016) and, thus a competitive advantage over wild juveniles (Naylor et al. 2005)
- Stress to wild populations caused by introductions of farmed salmon can affect mortality and growth (Naylor et al. 2005).
- Genetically modified growth hormone (GH) coho salmon are not reproductive, so they do not impact the genepool of the wild populations, and have limited effects on the ecosystem when in small numbers. However, large numbers of GH coho could have impacts on the ecosystem and trophic structure through direct and indirect effects (Li et al. 2015).
- Farmed fish can be genetically modified to limit or prevent genetic impacts from farmed fish. One solution is through the 'sterile feral' gene, which causes sterility outside of controlled conditions (Grewe et al. 2007). Another solution is through the use of triploid salmon, which are sterile, and which also do not migrate to freshwater, further limiting the impacts (Glover et al. 2016, Cotter et al. 2000).

Diseases

- The prevalence of disease is increased with high density of fish in pens commonly observed in salmon aquaculture, and spreads to wild fish, subsequently threatening the persistence of wild fish populations (Hutchings et al. 2012). The open net-pen design for finfish aquaculture allows for the transmission of pathogens from farmed fish to wild populations, and vice versa (Johansen et al. 2011). As well, escaped farmed fish with diseases can transmit those disease to wild populations (Madhun et al. 2015). The Aquaculture industry, through the transportation of fish, can cause long-distance transportation and transmission of diseases (Garseth et al. 2013).

- Bacterial kidney disease (BKD) is an infectious disease of a variety of salmonid species that has been of concern and managed in OPFA in many countries, for many years. It's survival in aquatic environments is poor, so transmission has been associated with the movement of fish and anthropogenic activities (Murray et al. 2012).
- Infectious salmon anaemia (ISA) is one of the most serious infectious diseases facing the economic viability of Atlantic salmon farming (Hammell & Dohoo 2005). It is the most problematic because once infected, there is no treatment (Nylund et al. 1994).
- Characterized by severe anaemia and high mortality, ISA tends to only be diagnosed after fish have been transferred to sea or have been exposed to seawater hatcheries (Nylund et al. 1994).
- While a potential mechanism for spread of disease is passive transmission in seawater, exposure to organic material (i.e., blood) infected with the ISA agent, or to sea lice infected with the ISA virus generated the highest rate of mortality (Nese & Enger 1993, Nylund et al. 1994, Barker et al. 2009). Transfer can occur via skin (mucous membrane, abrasions), urine, and feces.
- Miller et al. (2011) discovered genomic signature in Fraser River Sockeye salmon correlated with survival. They hypothesized that the genomic signal associated with elevated mortality is in response to a virus infecting fish before river entry and that persists to the spawning areas (linkages cited with genes associated with leukemia). Farmed fish are much more susceptible than wild fish to ISA (Aamelfot et al. 2015).
- It's been determined that pathogens can be vertically transmitted or transmitted via infected embryos (transmitted from parent to offspring) (Vike et al. 2009).
- IHN disease (infectious haematopoietic necrosis) is an epidemic in farmed Atlantic salmon in B.C. that is endemic in Pacific wild populations. It causes necrosis of the haematopoietic tissues, and ultimate mortality in fish. Farming practices contributed to its spread. However, waterborne transmission may have played a role between farms located in close proximity to one another (Saksida 2006). Similar to ISA, it spread through feces, urine, and mucous.
- VHS (viral hemorrhagic septicemia) is a virus that causes the hemorrhaging of internal organs and tissue. There are four strains of the virus, which are generally host specific. Herring is a major host to VHS IV, but it can be transmitted from herring to farmed salmon, and potentially from farmed salmon into other salmon (Lovy et al. 2015).

Parasites

- The fishes in sea pens can become infected with pathogens like sea lice by wild populations and in turn become point sources for parasites that multiply in crowded pens and spread to wild fish (Fazer, 2009). Floating sea cages (open-net pen) allows free movement of pathogens between wild and farmed finfish (Costello 2009).
- Sea lice are parasitic copepods, ubiquitous on farmed and wild adult salmonids, particularly adult females, in the oceans of the northern hemisphere, that feed on skin, mucous, and blood and are capable of causing host morbidity and mortality (Costello 2009, Saksida et al. 2007a, 2007b).

- *Caligus clemensi* and *Lepeophtheirus salmonis* are two species of sea lice that are commonly found on farmed salmon (Beamish et al. 2009).
- Natural infection of sea lice, consisting mainly of *C. clemensi*, discovered on juvenile Pacific salmon (all species) of the Gulf Islands, BC. They concluded that this infection was not from a fish farm, as the closest was 100 km from study area (Beamish et al. 2009). This confirms the occurrence of natural infection that could be rapidly transmitted in high-density farm cages.
- Migrating adults are separated from juveniles in early life stages, which acts as a barrier to pathogen transmission between age classes (for a time) (Krkošek et al. 2007). The benefit of this is that juveniles are not subject to pathogens until they are older and less vulnerable.
- Winter treatment of farms with parasiticides prior to out-migration of wild juvenile salmon can reduce parasite loads on the wild fish though it was noted that long-term sustainability of this practice may be affected by the ecological effects of the parasiticide and the potential for resistance in the parasites (Peacock et al. 2013, Rogers et al. 2013).
- Intensive open net-pen salmon aquaculture can undermine this natural barrier to transmission by providing a year-round host population in the near-shore marine environment whose pathogens can spill over to sympatric wild juvenile salmonids (Costello 2009). Sub-lethal exposure to lice during the critical early marine period reduces Coho smolt growth with consequences for Coho population dynamics.
- The creation of large protected areas, where there is no OPFA, can decrease the risk of lice infections in wild fish from aquaculture outbreaks (Bjorn et al. 2011).
- Sea lice transmission from salmon farms may indirectly influence the health of sympatric Coho salmon smolts (Connors et al. 2010), juvenile sockeye salmon (Godwin et al. 2015), and juvenile pink salmon (Brauner et al. 2013, Ashander et al. 2012) via the accumulation of lice from the infected prey. Connors et al. (2010) demonstrated that Coho populations had depressed productivity sevenfold when exposed to louse infestations associated with salmon farms, suggesting that parasite transmission from farmed to wild salmon can propagate up a salmonid food web with negative consequences for predatory salmon populations and the ecosystems in which they are embedded. Brauner et al. (2013) showed increased infection affects swimming ability of pink salmon. Pink salmon populations in British Columbia are severely impacted by the lice infections associated with salmon farms (Krkosek et al. 2007).
- Krkošek et al. (2011a) found that survival was negatively correlated with sea lice abundance on farms in Broughton Archipelago region of B.C. for both pink and Coho salmon. This is a matter up for debate as other studies have reached contradictory conclusions. Marty et al. (2010) did not find a negative correlation between fish farms, or number of sea lice, and pink salmon productivity.
- Wild populations exposed to salmon farms in the Broughton Archipelago, B.C. show a sharp decline in productivity during sea lice infestations relative to pre-infestation years, potentially resulting in declines in pink salmon populations (Krksosek & Hilborn 2011)
- Price et al. (2010) found evidence that salmon farms are a major source of sea lice infestations for wild juvenile pink (*Oncorhynchus gorbuscha*) and chum salmon (*O. keta*) in many aquaculture regions of B.C.
- Krkošek et al. (2011b) examined how sea lice infestation affects predation risk and mortality of juvenile pink and chum salmon and found evidence that lice make juvenile salmon more prone to predation. Infected fish were eaten significantly more often than fish that were not infected, as predators will selectively consume infected prey. Infestation also alters schooling behaviour, as infected fish will occupy peripheral positions in

the school. Conversely, predation on infected fish can serve to reduce sea lice abundance in wild fish.

- Krkošek et al. (2005) studied infections of sea lice on juvenile pink and chum salmon as they passed an isolated salmon farm during their seaward migration down two long and narrow corridors. Results suggested that the infection pressure imposed by the farm was four orders of magnitude greater than ambient levels, resulting in a maximum infection pressure near the farm that was 73 times greater than ambient levels and exceeded ambient levels for 30 kilometres along the two wild salmon migration corridors. Additionally, sea lice already infecting the wild juveniles were able to reproduce during their migration and re-infect the juveniles increasing the range of impact to 75 km. Amplified sea lice infestations due to salmon farms are a potential limiting factor to wild salmonid conservation with potential impacts on wild salmon fisheries, as well (Liu et al. 2011).
- Krkošek et al. (2013) did a meta-analysis of experimental paraciticide treatments on smolts that, lice infection causes 39% loss of adult salmon recruitment (see also Torrissen et al. 2013).
- Krkosek et al. (2009) created a model that showed that during brief exposure to juvenile salmon, sea lice populations rapidly declined. However, when the exposure period was extended, such as when salmon migrate past salmon farms, the sea lice populations increased in abundance and caused severe infections in the salmon. This increased salmon mortality, causing population decline.
- Price et al. (2011) demonstrated a potential role of open net-pen salmon farms in transmission of sea lice to wild juvenile sockeye salmon as they migrate from the Fraser River. They found that juveniles were primarily the fish infected with *C. clemensi*. They concluded that salmon farms are elevating levels of sea lice on Fraser River salmon during their critical early migration.
- Salmon migrating through the Broughton Archipelago are more likely to pick up lice infections, due to the salmon farms present (Morton et al. 2011).
- Juvenile salmon and Pacific herring near the net-pen farms off the Vancouver coast are more likely to be infected by sea lice than those that are not near the farms (Morton et al. 2008).
- Wild sea trout and Arctic char that migrate past salmon farms in Norway are more likely to be infected with higher numbers of sea lice than those that do not migrate past the farms (Bjorn et al. 2001). Net-pen aquaculture is a large cause of the salmon lice infections in the Norwegian fjords (Serra-Llinares et al. 2014).
- Other parasites have also been shown to transmit between cultured and wild fish. Mladineo et al. (2013) showed this using gene-flow of a monogenean.
- Post-smolt salmon and brown trout with severe lice infections did not have significantly different mortality during migration compared to those without infections (Sivertsgard et al. 2007).
- Wild fish around coastal fish farms in the Mediterranean did not have significantly different parasite loads than fish further away from farms (Fernandez-Jover et al. 2010).

Pharmaceutical pesticides and disinfectants

- Although the use of therapeutants is tightly regulated and can only be used if prescribed by a licensed veterinarian, farmers do rely on emergency treatments to combat bacterial infections and ecto-parasites, like sea lice.
- Salmon farmers in Norway, Scotland, Chile, and Canada have used a variety of compounds over the years to treat infected salmon, including amoxicillin, florfenicol, tribrissen, oxytetracycline, erythromycin, pyrethrins,

hydrogen peroxide, azamethiphos, cypermethrin, ivermectin, emamectin benzoate, and teflubenzuron (Burridge et al. 2008, 2010).

- While many of the antibiotics have low toxicity to marine fishes and mammals, crustaceans tend to be more sensitive (McLeese et al. 1980, Davis 1985, Burridge et al. 2004). Therefore, the use of chemicals causes concern among environmentalists and those associated with commercial fisheries. Because anti-lice treatments lack specificity, the effluent released into the marine environment has the potential to cause adverse impacts not only on wild salmon populations, but commercially important species such as the American lobster (*Homarus americanus*) (Johnson et al. 2004, Burridge et al. 2008, 2010, Haya et al. 2001).
- Diflubenzuron (crusticide) can be taken up by Atlantic cod but is rapidly cleared and showed to have small effects (Olsvik et al. 2013).
- Teflubenzuron, a pesticide used to treat lice infections, can enter the surrounding environment and infect the fish and crustaceans, however the concentrations are not high enough to cause major toxic effects (Samuelsen et al. 2015).
- In general, demonstrated effects of the application of therapeutants include alteration of local diversity, increased resistance to antibiotics, and subsequent emergence of new strains of bacteria (Burridge et al. 2010).
- Salmosan® (active ingredient azamethiphos), approved for emergency use in N.B., has lethal and sublethal effects with repeated exposure on lobster at certain concentrations and time of year (Burridge et al. 2008). Organisms were more sensitive to repeated exposure at concentrations of 10 µg/L and during the spring. Field studies have shown that a single treatment with Salmosan® has no negative effect on the survival of non-target organisms except when held within the treatment cage (Burridge 2003).
- Soluble compounds (such as azamethiphos) used for parasite control have potential for widespread dispersion. Other chemicals such as antibiotics (oxytetracycline, Tribrissen and Florfenicol) and zinc, present in feed (particle-bound substances), are more likely to settle and accumulate under and close to farm sites if currents are low (DFO 2003).
- Female lobsters are more sensitive to exposure of anti-lice treatments during spawning and molting season (Burridge et al. 2005).
- SLICE™ (active ingredient emamectin benzoate) is the most common treatment for sea lice and is a fishfeed premix (Burridge et al. 2004).
- The fishing industry is concerned about the use of this pesticide and its impact on lobsters and crabs foraging beneath salmon cages (released in uneaten food, fish feces, urine), as crustaceans, particularly lobster, will eat the feed and are known to be particularly sensitive to the pesticide (Waddy et al. 2002, Willis & Ling 2003, Waddy et al. 2007a). Although, acute toxicity is low (Burridge et al. 2004), it can result in premature molting and loss of eggs by female American lobsters (Waddy et al. 2002). However, the question remains as to whether or not lobsters are likely to ingest enough of the chemical, based on industry concentrations, to cause any observable effect. Feeding studies have confirmed that lobsters ingest less than the amount required to initiate premature molting (Waddy et al. 2007a, 2007b).
- In addition, based on the concentration required to kill a lobster, and the small amount of medicated food consumed, researchers have predicted that chronic exposure is unlikely to result in the death of exposed lobsters (Burridge et al. 2004).
- Emamectin benzoate is also toxic to marine copepods, and causes immobilization and reduced egg production (Willis et al. 2003).

- Alpha Max® (active ingredient Deltamethrin, a pyrethroid insecticide) was approved for emergency use in 2009 and 2010, but is currently not in use. Fairchild et al. (2010) report that "Pyrethroid insecticides are among the most toxic insecticides known" (causing immobility or mortality), and that "among the pyrethroid insecticides, deltamethrin is often the most toxic to crustaceans" (p. iv). In lab conditions, Fairchild et al. (2010) found lobster larvae to be susceptible to deltamethrin at much lower concentrations than the recommended treatment dose.
- Ernst et al. (2001) demonstrated the dispersal capacity of cypermethrin, another widely known highly toxic (particularly for crustaceans) pesticide. Water samples collected from the plume were toxic in a 48 hour lethality test to *Eohaustorius estuarius* (an amphipod) for cypermethrin up to five hours. They concluded that single treatments have the potential to affect non-target invertebrates near cage sites.
- Alternatively, because pyrethroids tend to adsorb onto particulate matter, chronic exposures may not occur other than in laboratory studies. Cypermethrin absorbed by sediment was not acutely toxic to grass shrimp until concentrations in sediment were increased to the point where partitioning into the overlying water resulted in acutely lethal concentrations (Clark et al. 1987).
- The safety of human food can also directly be affected by the presence of residual antibiotics in farmed fish which have been dosed with antibiotics, or from antibiotics that have leached into the surrounding environment and reached wild fish and shellfish collected for consumption (Samuelsen et al. 1992, Coyne et al. 1997, Grave et al. 1999, Cabello 2003, 2006, Fortt et al. 2007, White & McDermott 2009).

Pollution and habitat alteration

- Environmental concerns with cage aquaculture are primarily associated with the release of waste materials into the aquatic environment (Rooney & Podemski 2009).
- Fish waste from cages flows into ocean, adding potentially harmful excess nutrients in the ecosystem; uneaten food and faeces can accumulate on the seabed underneath the pens and degrades, oxygen then becomes depleted, all with significant implications for water quality and species composition (eutrophication, release of noxious gases, etc.) (Dean et al. 2007, Hutchings et al. 2012, Grant, 2010).
- With an annual production of 35,000 tonnes of salmon, approximately 7,200 tonnes of untreated fecal waste, 1,000 tonnes of nitrogen, and 115 tonnes of phosphorus are discharged into coastal waters. In terms of human waste, this equates to an annual equivalent of 93,450 people; the nitrogen discharge is equivalent to that of 437,500 people; and the phosphorus discharge is equal to that of 63,000 people. No other industry is allowed to discharge untreated waste like this into water bodies. Nitrogen and phosphorus are both nutrients that cause algal blooms, which lead to eutrophication, a condition to which very few species are tolerant. Aquaculture has been demonstrated to be by far the largest source of nutrients to the L'Etang - Bliss Harbour – Black's Harbour area of the Bay. It has been shown that a significant number of species have been lost in this area as a result (DFO 2003, Harvey & Milewski 2007).
- Nutrient loading from aquaculture causes an increase in biological activity, which can alter the trophic structure of an ecosystem (Lopez et al. 2008), however, modeling this in the study area around Sardinia suggests that the top predators were not significantly affected.
- Seagrass meadows in Spain, Italy, and Greece are not significantly impacted by aquaculture, due to strong currents in the area, and they remain high in diversity (Apostolaki et al. 2007).

- Metals enter the marine environment from aquaculture activity either from anti-foulant paints or as constituents of fish food. The diet of farmed Atlantic salmon contains trace metals such as copper, zinc, iron, cadmium, manganese, and others (Dean et al. 2007, Burridge et al. 2010).
- Evaluation for toxicity of sediments under salmon cages in the Bay of Fundy, as well as in Scotland, and at various distances away from the cages demonstrate elevated levels of copper (above the threshold effects level), elevated zinc, other metals, ammonia nitrogen, sulfide, total organic carbon, and other organic compounds (Burridge et al. 1999, Dean et al. 2007, Hargrave 2010).
- In Norway, it was found that salmon farms did not increase the concentration of mercury and other elements in wild fish (Bustnes et al. 2011). However, a study done by Debruyn et al. (2006) showed that rockfish near aquaculture farms in British Columbia did have a higher concentration of mercury compared to other rockfish away from farms.
- In the sediments, highest copper concentrations (32–42 mg Cu/kg) are found consistently at the farm site, moderately elevated concentrations at 400 to 2000 metres distance and the lowest concentrations (6–7 mg Cu/kg) are found at a greater distance from the farm site, suggesting that it is plausible for copper, released for purposes of aquaculture and settled in the sediments, to be transferred upward through the water column to the sea surface microlayer. There concentrations are enriched, and can then travel horizontally at relatively high drift speeds due to winds, leading to footprints with scale of one km or more, with the potential for impacts to persist through years of fallow. Observed concentrations of copper in the sediment exceeded optimal threshold levels for the protection of marine life (Loucks et al. 2012).
- Toxicity tests on several species of marine copepods demonstrated reduced survival and reproduction when exposed to metals, such as silver, zinc, and copper in their algal diets and water (Bielmyer et al. 2006, Lauer & Bianchini 2010).
- Copper exposure reduced egg production and hatching rate in male and female copepods (Acartia tonsa). Impacts varied with type of exposure with waterborne eliciting a greater adverse effect on egg production than diet borne (Lauer & Bianchini 2010).
- Sediments enriched in these metals have been linked to decreased production in the clam *Macoma balthica*, due to failed gamete production (Burridge et al. 1999).
- Exposure to copper was linked to chromosomal anomalies in spiny lobster, which increased with exposure to copper, demonstrating adverse impacts at the cellular level, internal organs changed colour, and observed changes in wet weight of muscle, hepatopancreas, and gills (Maharajan et al. 2011). In addition, impacts to the heart were observed, specifically noted was inflammation and cell and tissue damage to inner organs (Maharajan et al. 2012). This could affect vital physiological functions, such as absorption, storage and secretion of the hepatopancreas, digestion of gut and respiration, osmotic and ionic regulations of the gills, which in turn could ultimately affect the survival and growth of *P. homarus* (Maharajan et al. 2012).
- The use of copper treated net-pens did not cause a significant increase in copper concentration of nearby organisms (Solberg et al. 2002).
- Accumulation of fish feces and waste feed enhances aerobic and anaerobic microbial activity, both representing nitrogen-rich organic matter (Giles 2008), as it stimulates phytoplankton production and increases oxygen demand (Hargrave 2003). Eutrophication can cause shifts in phytoplankton species assemblages, although it has been hard to directly link finfish aquaculture to harmful algal blooms (HABS), alters benthic faunal communities, and reduces fish health, which increases the likelihood of parasitism and disease (Hargrave 2003).

- The degree of impact is dependent on local hydrographic conditions, cage depth, uptake by phytoplankton and other organisms, and re-suspension of material (Hargrave 2003, Borja et al. 2009).
- Intermittent hypoxic events from changes in dissolved oxygen (DO) are occurring in cages on the south coast of Newfoundland. These events can be observed for as long as two and a half months and are mostly happening during the summer season. Fish swimming data show that these events do not cause avoidance behavior, and thus fish are negatively impacted as changes in DO can impact fish feeding and growth (Burt et al. 2012).
- Benthic impact from fish farms is a function of site and farm characteristics. Impacts were less intense but further spread in deep areas, whereas impacts in shallow areas appeared more intense but confined to a smaller area around the farm (Giles 2008).
- A study examining the effects of a rainbow trout farm demonstrated a reduction in benthic invertebrate abundance and species richness below the cage due to high levels of organic loading (Rooney & Podemski 2009). However, the impacts dissipated with distance from cage.
- There is potential for far-field effects of waste and nutrient input from salmon farms. Three types of broad-scale changes distant from farm sites include eutrophication, sedimentation and effects on the food web (Hargrave 2003).
- Sea bass farming in the north Adriatic Sea had no effect on water quality, and diversity was higher under the pens due to increased organic material (D'Agaro et al. 2006).
- Bluefin tuna and yellowtail kingfish farming in Australia had little impact on the abundance and assemblage structure of demersal macrofauna (Tanner et al. 2015).
- In addition to the creation of a water surface film from the dust from feed dispensers, uneaten feed and feces contribute to the suspended particulate matter. Potential exists for widespread dispersion and horizontal transport of particulate matter depending on tidal flow, circulation, wind and wave energy, and other physical processes (Hargrave 2003). This can lead to eutrophication events, and in terms of the release of antibiotics and pesticides, can result in inlet-wide scale impacts.
- Aggregation of wild fish around net pens can limit the impact of organic matter leaving the pens, usually by feeding on it (Vita et al. 2004).
- The presence of such large and varied surfaces that accompanies the aquaculture sector provides for a broad diversity of epibiotic organisms including barnacles, bivalves, bryozoans, polychaetes, ascidians, hydroids, sponges and algae to settle and grow. These marine algae and animals, collectively termed biofouling, are severely problematic to culture operations and can have significant economic impacts (Fitridge et al 2012).
- Fitridge et al. (2012) reported three main negative effects of biofouling:
- Restriction of water flow and exchange due to growth of fouling organisms on cages, which reduces water quality and lowers DO
- Disease risk due to fouling organisms acting as reservoirs for pathogens, an impact that is exacerbated by stress induced by reduced water flow that leads to reduced immunity to pathogens
- Cage deformation and structural fatigue due to the weight of fouling organisms, increasing the potential for escapees

Effects on distribution and behaviour of wildlife

- Due to the high abundance of fish in a confined area, sea cages can attract predators, mainly seabirds and marine mammals (Cottee et al. 2009, Jimenez et al. 2013). In addition to increased mortality, stress, and injury to the farmed fish, this can result in predation of other fish species, as well as economic damages incurred by the farmers.
- Predatory animals like seals, sea lions, sharks, birds, and other marine wildlife can become entangled in the fish pens, and deterrents (AHDs) can alter behaviour of predators (Hutchings et al. 2012).
- OPFA attract extensive aggregations of wild fish (Dempster et al. 2002, Goodbrand et al. 2013). These fish aggregate to feed on the excess fish feed (Fernandez-Jover et al. 2008, Izquierdo et al. 2015, Dempster et al. 2009, Bacher et al. 2015) or the farmed fish themselves (Sanchez-Jerez et al. 2008). This aggregation increases vulnerability to fishing, as well as increases pathogen and disease transfer (Dempster et al. 2004).
- Wild saithe (*Pollachius virens*) migrate less, and remain around OPFA pens year-round (Ottera et al. 2014).
- The wild fish that aggregate around OPFA are developing physiological differences from their counterparts not found around OPFA, due to feeding on the excess fish feed, which is more nutritionally balanced (Meruhenda et al. 2015).
- The wild-farm fish are also developing slight phenotypic differences. Two species of sea bream (*Boops boops* and *Sarpa salma*) found around fish farms had a smaller heads, and eyes, and *B. boops* had smaller snout curvature and head depth. Both species also have significantly different otoliths compared to individuals not found around OPFA (Abaad et al. 2016).
- Aggregations of wild fish can limit some of the detrimental effects of aquaculture, for example, by feeding on escaped fish, and feeding on excess fish feed, reducing the addition of organic material into the environment (Uglem et al. 2008)

Light

- Open net-pen salmon farms in British Columbia routinely illuminate their net-pens during the winter and spring, which has been demonstrated to increase the abundance of wild fish larvae, juveniles, and adults around pens, thereby increasing the probability that farmed fish and wild species directly and indirectly interact in coastal marine environments (McConnell et al. 2010).

Noise

- AHDs are generally ineffective at deterring predators, specifically seals, over the long-term, as field observations indicate that seals appear to habituate to AHDs, possibly due to hearing impairment (not yet assessed) (DFO 2010).
- Cetaceans such as harbour porpoises and killer whales appear to be sensitive to AHDs and field studies have shown they are displaced from large areas when AHDs are in use. Yet impacts seem to be short- term and localized (e.g., avoidance, masking communication and echolocation sounds), and do not appear sufficient to cause injury to, or permanent displacement of, aquatic animals (DFO 2010).

Sustainable use of wild resources

- The finfish aquaculture sector is highly dependent on forage fish for dietary input. Forage fish are reduced to fishmeal and fish oil, which threatens the future of wild populations and can impact other wildlife that depends on this food source (Alder et al. 2008, Tacon & Metian 2008, Hutchings et al. 2012). More than 50 per cent of fishmeal produced is used in the aquaculture sector, China being the major fishmeal consumer. China currently consumes more than 1.3 million tons of fishmeal per year.
- The ratio of wild fisheries inputs to farmed fish outputs for Atlantic salmon remains higher than other farmed species. High amounts of forage fish are used in fishmeal and fish oil to sustain this farmed fishery (Naylor et al. 2009).
- Tacon & Metian (2008) reported that, in 2006, the aquaculture sector consumed 3724 thousand tons of fish meal (68.2 per cent of the total global fish meal production in 2006) and 835 thousand tons of fish oil (88.5 per cent of the total reported fish oil production in 2006), or the equivalent of 16.6 million tonnes of small pelagic forage fish (using a wet fish to fish meal processing yield of 22.5 per cent and wet fish to fish oil processing yield of five per cent).
- It takes 4.9 kg of wild fish to produce one kg of salmon (Tacon & Metian 2008), meaning that producing salmon results in a net loss of fish protein for other species that rely on this resource, including human consumption (Harvey & Milewski 2007).
- The International Fishmeal and Fish Oil Organization (IFFO) presented estimates for Fish In – Fish Out (FIFO) ratios for salmon (Jackson 2009) as 2.2 kg wild fish to one kg of salmon. This was further refined to include global pig and poultry production (because they also use fishmeal), reducing the FIFO ratio to 1.68 kg wild fish to one kg of salmon.
- Waagbo et al. (2012) fed Atlantic salmon diets with increasing amounts of vegetable oil and showed they maintained health and product quality, though none of the groups showed net fish production (FIFO ≥ 1.65).

Closed-containment Finfish Aquaculture

- Open-sea net pens have far greater potential and realized negative consequences to marine biodiversity than closed-containment facilities (Hutchings et al. 2012).
- The development of closed-containment systems, a term widely used to describe a range of production systems that employ an impermeable barrier to isolate the culture environment from surrounding ecosystems, has been proposed as a viable alternative to open-pen systems (Ayer & Tyedmers 2009).
- The benefits of closed-containment have been reported as follows (Ayer & Tyedmers 2009):
    - Fish farmers can exert greater control over rearing systems (which, in turn, can improve the quality of fish while minimizing the environmental impact)
    - Minimized escapes
    - Minimized predator interactions
    - Reduced disease transmission
    - Lower feed inputs
    - Higher stocking densities
    - Improved waste management capabilities

- Ayer & Tyedmers (2009) determined that while land-based closed containment systems provide a more environmentally-friendly alternative to the issues associated with open-net pen aquaculture (release of fish waste and other nutrients and chemicals into the marine environment), there are tradeoffs to be considered (it is the poorest environmental performance in this study). This system increased contributions to several other environmental impacts of global concern, including global warming, acidification, and abiotic resource use (non-renewable resources), as it uses more fossil fuels to power electricity driven pumps. A floating bag system demonstrated the highest environmental performance relative to the others due to lower feed input per ton, lower energy demand, and a reliance on hydro-power because it is marine-based. However, performance was related to site location.
- Forster & Slaski (2010) determined that there were no closed-containment systems found globally that is producing exclusively adult Atlantic salmon, and many previous attempts to do this failed. The primary cited reasons include mechanical breakdown, poor fish performance, management failure, declines in market price and inadequate financing.
- Operating and capital cost are among the major factors that prevent viable application of this technology to salmon farming (Chadwick et al. 2010).
- Stechey & Robertson (2010) described and examined five types of aquaculture production systems (including conventional net pen, floating closed-confinement systems both with rigid walls and flexible walls, land-based flow-through systems, and land-based recirculation systems).
- They determined that land-based intensive recirculation facilities demonstrated the highest level of containment; the risk of release of pathogens and parasites was categorized as moderate for all systems; and the risk of escapes was characterized as "low" or "negligible" for all systems except the conventional net pen and floating flexible wall system (Stechey & Robertson 2010).
- Land-based, solid-wall, recirculation and reuse technologies (Recirculating Aquaculture Systems) showed promise for rearing of salmon in fresh or brackish water due to the potential for reduced energy costs compared with those associated with the pumping of seawater (Stechey & Robertson 2010).
- In closed systems there is the potential for increased exposure and the spread of pathogens because fish stocking densities would be higher and water turnover rates lower leading to increased accumulation of waste debris (including pathogens) (Byrne et al. 2010). However, closed systems improve the separation of farmed from wild fish, lowering the risk of spread to wild populations.
- Complete disruption of pathogen exchange between a closed pen facility and the environment is likely only possible in a land-based recirculation system (Byrne et al. 2010).
- Pathogen removal involves the treatment of influent and effluent water flows, the effectiveness of which has yet to be determined (Byrne et al. 2010).

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