Environmental Effects of Open-Cage Salmonid Aquaculture in Ontario and Recommendations for Future Research

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Introduction

Aquaculture, or the farming of aquatic organisms, is the fastest-growing agricultural enterprise globally as it strives to close the ever-widening “seafood gap” between the static wild capture fisheries and the increasing global demand for fishery products (Trushenski 2019). Freshwater open-cage aquaculture of salmonid fishes in Canada is found mostly in Canadian waters of the Great Lakes, specifically the North Channel of Lake Huron around Manitoulin Island and the Parry Sound area of eastern Georgian Bay. This region of Lake Huron contains the only commercial net-pen activities in the entire Great Lakes (Lennox et al. 2023) and represents the largest concentration of freshwater open-cage salmonid aquaculture in the country. The commercial production of Rainbow Trout (*Oncorhynchus mykiss*) in Ontario has grown from less than 2,000 tonnes (metric tons) in 1988, which was primarily land-based at that time (Moccia and Bevan 2004), to more than 5,000 tonnes annually since 2019. Open-cage aquaculture in Georgian Bay and the North Channel now accounts for nearly 99% of the province’s production (Moccia and Burke 2022).

The Georgian Bay Association (GBA) in its submissions to Fisheries and Oceans Canada (DFO) and to Ontario’s Ministry of Natural Resources and Forestry (OMNRF) and Ministry of Environment, Conservation and Parks (OMECP) has identified several areas of concern regarding open net-pen or cage culture of salmonid fishes, particularly Rainbow Trout. These concerns are consistent with the findings of a literature review conducted several years ago for the Ontario Ministry of the Environment (now OMECP) to examine the environmental effects of cage aquaculture waste products in Ontario (Cantox Environmental 2006), which pose significant threats to water quality and aquatic communities in Georgian Bay, including (but not limited to):

- effects of nutrient loading and sedimentation, particularly phosphorus loading, on reduction in water quality, hypoxic events, water transparency and algae production, and on the benthic invertebrate community, its species diversity, and its natural habitat;

- effects on native, wild fish stocks by the inevitable escapements of domesticated Rainbow Trout or other new introduced species, and disease pathogens they may carry, and by the loss of fish habitat due to anoxic conditions caused by the farms; and,

- possible effects of introducing chemotherapeutants, such as antibiotics, and/or other contaminants into the environment from medicated or contaminated feed sources.

Background

The following report is not meant to be a comprehensive or exhaustive review, but is intended as a synthesis of pertinent information on the environmental effects of open-cage culture of salmonid fishes in temperate freshwaters, with a particular focus on the Great Lakes in Ontario, as well as to provide a general background underlying relevant issues associated with open-cage or net-pen aquaculture. Several scientific studies, reports, and reviews have been published both in the primary and the “gray” literature over many years that describe the environmental effects of marine salmonid net-pen or cage aquaculture (e.g., reviews of Gowen and Bradbury 1987; Weston et al. 1996; Brooks et al. 2002; Wildish et al. 2004; Reid 2007; Sepúlveda et al. 2013; Rust et al. 2014; and others). While general findings and concepts from marine studies can relate to the freshwater environment, the results cannot be directly comparable to freshwater systems. Factors such as differences in water chemistry and biota between fresh and salt water environments and tidal flushing and marine coastal currents not present in freshwaters preclude direct comparisons.

Fewer studies have documented the ecological impact of cage culture production of salmonids in temperate freshwaters on nutrient loading, water chemistry and primary production, and on the surrounding aquatic communities and their habitat (e.g., reviews of Phillips et al. 1985; Weston et al. 1996; Davies 2000; Podemski and Blanchfield 2006; Wetton 2012; Sepúlveda et al. 2013; Johnson and McCann 2017; Otu et al. 2017a; and others), specifically in Georgian Bay and the North Channel (e.g., Gale 1999; Hamblin and Gale 2002; Bureau et al. 2003; Clerk et al. 2004; Hille 2008; Milne 2008; Johnston et al. 2010; Patterson and Blanchfield 2013; Johnston and Wilson 2015; Diep and Boyd 2016a, 2016b; Milne et al. 2017). These investigations and reviews generally agree that nutrient loading into surrounding waters and sediments ranks as the most significant environmental problem related to open-cage or net-pen aquaculture in these waters.

Rainbow Trout, the principal salmonid reared in temperate, freshwater, open-cage culture, is a member of the Pacific salmon genus (*Oncorhynchus*) and is native to mostly coastal drainages in North America west of the Continental Divide (Scott and Crossman 1973; Behnke 2002). It is one of the most widely introduced fish species throughout the world (MacCrimmon 1971) and one of the most popular for freshwater fish culture, the primary producing areas being Europe, North America, Chile, Japan, and Australia (FAO 2005). Rainbow Trout from western stocks, including the coastal, larger, faster-growing steelhead variant, were first introduced into Canadian waters of the Great Lakes possibly as early as 1883 (Scott and Crossman 1973; Kerr 2010) and first appeared in Lake Huron in 1904

(Kerr 2010). Rainbow Trout are now naturalized throughout Ontario and the Great Lakes including Georgian Bay (Kerr and Grant 2000) and are not only highly valued as a sport fish and marketable food item, but also readily adaptable to temperate, freshwater aquaculture.

The Rainbow Trout stock used for fish culture programs throughout North America likely originated from a mixture of both stream-resident and anadromous (sea-run) strains from the McCloud River, northern California, in the late 1800s (Behnke 2002). A Rainbow Trout broodstock program in Ontario for government stocking was initiated in about 1917 (Moccia and Bevan 1991). Ontario legislation passed in 1962 allowed for the commercial culture and sale of Rainbow Trout (Kerr 2010). Rainbow Trout for cage culture grow-out are typically supplied as fingerlings from land-based hatchery operations within the province, and certified pathogen-free eggs are now obtained mostly from domestic-strain broodstock. Domestic Rainbow Trout broodstock are selected for their rapid growth for commercial value and have been isolated by several decades of artificial selection from their ancestral western North American wild stocks.

Part I. Effects of Cage Aquaculture on Water Quality, Nutrient Release and Primary Production

Nutrient Release from Cage Culture into Freshwaters

Many investigations have documented and reviewed the release of nutrients, notably phosphorus (P), originating from freshwater cage culture of salmonids into the surrounding environment; these have been reviewed extensively (e.g., EC 2004; Cantox Environmental 2006; Wetton 2012; Otu et al. 2017a) and discussed (GLFC-HAB & IJC-GLWQB 1999; Yan 2005). Most of the P input is from solid wastes and ends up in the sediments underlying the cage. Organic solid wastes consist of mainly fish faeces, or manure, which contains about 2.5% P (Naylor et al. 1999), but also of uneaten feed, which contains about 1.2-1.3% P. Up to 50% of the total waste from freshwater aquaculture may end up in the sediments, and most of the excess and nondigestible P is bound within the faeces (Reid 2007; EC 2009; Figure 1). The eventual accumulation of P in lake sediments can be more than 80% of the TP released into the water (DFO 2015).

In freshwater systems with a history of nutrient pollution, sediments become a reservoir of previously deposited P, which can be then recycled or released (internal loading) into the water column to stimulate algal growth (Orihel et al. 2017). Various dynamic, diagenetic (chemical, physical, and/or biological) processes are responsible for releasing P from the sediments and involve other ions of iron, aluminum, and calcium, depending on both sediment and water conditions (Markovic et al. 2019). The zone of highest sediment deposition is naturally directly beneath the cage, but the “zone of influence” (dispersal distance) can be relatively small within 5 m (Rooney and Podemski 2010) or spread out with diminishing concentration for up to 50 m (Brooks et al. 2003) depending on both the depth of water and current velocity below the cage site, and on the settling velocities of faecal waste and uneaten food (Gowen et al. 1989).

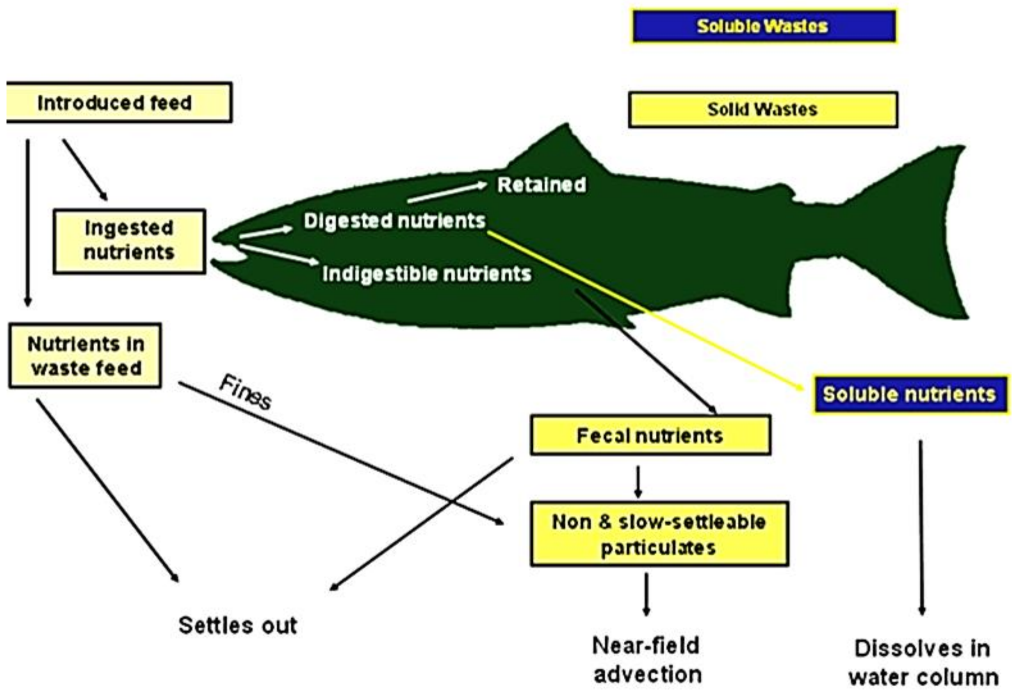

Figure 1. Source and fate of nutrients (e.g., P) in open-cage salmonid aquaculture systems (diagram from Reid 2007).

It is well established that P is the main nutrient factor limiting primary production in freshwaters (OECD 1982; Guildford and Hecky 2000; DFO 2015), provided nitrogen (N) is also available and in a favourable ratio with P for aquatic plant growth (see Downing and McCauley 1992). Thus, the major concern of nutrient loading from freshwater cage culture is the release of P from solid wastes, which can result in increased eutrophication, the effects of which can lead to: (1) a decrease in biodiversity and changes in biota, (2) a decrease in sensitive species and increase in tolerant (facultative) species, (3) an increase in plant (e.g., algae) and animal biomass, (4) an increase in turbidity, (5) an increase in organic matter leading to high sedimentation, and (6) development of hypoxic or anoxic conditions (EC 2004).

Algal production in freshwater is limited mostly by the amount of P available, which in turn is influenced by the geophysical, limnological and biological nature of the aquatic environment and underlying sediments. Phosphorus occurs in lake sediments in solid and aqueous phases in a variety of organic and inorganic molecular forms, or “species” (Orihel et al. 2017). Phosphorus exists in dynamic flux in many forms and phases in the water, but only soluble inorganic P, or soluble reactive P, as orthophosphate (PO_4^{3-}) is available for algae growth (EC 2004). Organic soluble P and undifferentiated organic phosphates are also present in natural waters. The total P (TP) is differentiated into soluble phosphate-P (filtrable or soluble orthophosphate), organic soluble P, and sestonic P (seston is considered as the living organisms and non-living matter in the water column) (Kutty 1987).

The various pools of P in water and sediments, the physio-chemical and biotic factors that affect the relationships among them, and the mechanisms involved in the internal loading process are complex (Orihel et al. 2017) and beyond the scope of this review. For practical purposes, however, the forms of concern can be grouped as inorganic P (particulate and soluble), particulate organic P, and dissolved (soluble) organic P, all of which cycle in the environment (EC 2004). Several studies have calculated the amount of P, or TP, released to the freshwater environment based on actual measurements or estimates of feed applied and faecal matter (manure) produced, or estimated from mass-balance equations using feed data or actual fish production.

Seventeen separate published studies cited in the review of Yan (2005) indicated that the TP losses into the environment from salmonid cage culture using historical rearing practices ranged from 4.8 to 40.2 kg P/tonne fish, averaging roughly 18 kg/tonne. A cage culture operation in Lake Glebokie, a small, mesotrophic lake in Poland, was followed for over a year from the time Rainbow Trout were stocked into cages until they were 1 kg for market (Penczak et al. 1982). The investigators determined that for every kilogram of trout produced, the lake was enriched by 0.023 kg P, or 0.84 g/m^2 per year, which translated to 23 kg/tonne. The level of eutrophication predicted was expected to cause the loss of the natural populations of native whitefishes (*Coregonus albula* and *C. lavaretus*).

Proximate analysis of 28 samples of cage-cultured Rainbow Trout from two cage farms in Georgian Bay (n = 14 per farm) were analyzed to predict waste output including P from 1-kg fish (Bureau et al. 2003). Solid wastes were estimated to be 240-318 kg/tonne of fish produced based on 5% feed wastage, depending on the feed used, and TP released (solid plus dissolved) was 7.5-15.2 kg/tonne (solid P, 5.8-9.8 kg; dissolved P, 1.7-5.5 kg); food conversion ratios (FCRs) ranged from 1.15 to 1.29 (Bureau et al. 2003). Total P waste was estimated to be ≤8 kg/tonne for the two most widely used feeds. However, the investigators cautioned that results should be considered as preliminary.

The dietary requirement of P for grower-size Rainbow Trout is about 0.6% (Halver 1996; Flimlin 2003; FAO 2023). Modern feed formulations contain more P than required because not all P incorporated into the feed is digestible, thus it is not bioavailable to the fish (Hardy 2002; Flimlin 2003) and is eliminated. Major manufacturers have reduced the P content in commercial formulations for grower-size trout to about 1.2% (FAO 2023) while still meeting the nutritional requirement of 0.6%.

A simple mass-balance "feed input – production output" approach can be used to estimate TP released where either of the variables, feed input or production output, is entered into the equation and the other variable is calculated in the formula by adjusting it accordingly with the FCR, i.e.:

$$\text{TP released} = (\text{feed input} \times \%P_{feed}) - (\text{production} \times \%P_{fish})$$

(simplified from: Ronsholdt 1995 and OSPAR 1999). In Table 1, the theoretical feed input needed to balance the equation was determined by multiplying the actual production value by the FCR, assuming the latter remains constant and all feed applied is consumed.

Assuming an FCR for grower-size Rainbow Trout of 1.25 (e.g., 1.2-1.4: Ronsholdt 1995; FAO 2023), and a P content in feed ($\%P_{feed}$) of 1.2% (FAO 2023) and in salmonid tissue ($\%P_{fish}$) of 0.45% (OSPAR 1999), respectively, the estimated TP released from the 5,791 tonnes of Rainbow Trout produced from open-cage culture in Georgian Bay/North Channel in 2021 (Moccia and Burke 2022) hypothetically would have been about 61 tonnes (Table 1). This equates to 10.5 kg/tonne of fish, which is within the range of TP released determined in the laboratory analysis by Bureau et al. (2003).

Table 1. Rainbow Trout (RBT) production in Ontario 2016–2021, and estimated release of TP from open-cage aquaculture in Georgian Bay/North Channel (GB/NC) from the formula: TP released = (theoretical feed input [i.e., production × FCR] × $\%P_{feed}$) – (production × $\%P_{fish}$). Actual production data was from Aquastats, Aquaculture Centre, University of Guelph.

Year	Total RBT produced In Ontario (tonnes)	% of total raised in GB/NC	RBT produced in GB/NC cages (tonnes)	Estimate of TP released (tonnes)	% Change from previous year
2016	5,060	85	4,301	45.2	-
2017	5,530	89	4,922	51.7	14.4
2018	5,416	90	4,874	51.2	−1.0
2019	5,583	96	5,360	56.3	10.0
2020	5,318	97	5,158	54.2	−3.8
2021	5,873	98.6	5,791	60.8	12.3

By comparison, several years earlier in 1998, nine open-cage farms in Georgian Bay and the North Channel were estimated to release 15 tonnes of TP per year, with a predicted increase of up to 30 tonnes in the following decade (Gale 1999). In their source-loading assessment study, Diep and Boyd (2016b) determined that the single fish farming operation in Lake Wolsey, North Channel, discharged 2.4 tonnes of TP annually into the lake, although the majority of this was expected to settle out of the water column and not be available for primary production unless conditions favoured resuspension or internal loading (e.g., bottom-water anoxia). This was similar but slightly higher than the discharge of 2.2 tonnes of TP estimated by Milne et al. (2017). Generally, while most of the TP coming from faecal material, uneaten feed and feed dust from a typical cage aquaculture operation will be deposited and accumulate in the sediment (Yan 2005), up to 60% of the P loading could still be bioavailable for primary production (Perrson 1991).

The equation used in Table 1 is overly simplistic, however, in that the FCR could vary depending on (1) feed quality and ingredients and (2) feeding habits, size and life stage, and growth rates of the fish. Moreover, a certain amount of feed applied may not be eaten and settle out as waste (e.g., 5-6%). More importantly, the estimate of the amount of TP directly released into the environment does not necessarily reflect the measurable concentration of TP in the water column. To get a more realistic assessment of the TP released, additional data are needed, such as receiving water volume and water retention time, for example (Håkanson et al. 1998).

The fate and bioavailability of additional P, and what effect it will have on overall water quality, primary production leading to eutrophication, and the aquatic community in general depend on several other factors such as (1) the physical and chemical conditions of the water and sediments affecting the solubility and form of P, (2) the underlying currents and water exchange rate around the cage site, and (3) the dynamics of P exchange between sediments and the water column (DFO 2015). Ideally, waste output estimates of P from cage farms should account for the different forms of particulate and dissolved P excreted, not just the TP waste output (Bureau and Hua 2006). In the laboratory experiment of Bureau et al. (2003), dissolved P represented 23-36% of TP. However, TP in the water column, which is more easily and typically measured, can serve as a useful proxy for bioavailable P. It has been suggested that an increase of 50% over the baseline TP level could result in observable changes in the biotic community (EC 2004).

The TP in natural waters can be high (e.g., up to 100 µg/L for eutrophic systems), but oligotrophic waters such as Georgian Bay typically would have TP concentrations of 4-10 µg/L (EC 2004). In Georgian Bay TP levels offshore were about 5 µg/L in the mid-1980-1990s but by 2014 had declined to as low as about 2 µg/L (Bywater and Clark 2018). Georgian Bay spring TP levels offshore in 2017 were 2.2 µg/L, the low concentrations here and some other Great Lakes possibly as a result of the filter-feeding behaviour of the invasive dreissenid mussels intercepting the phosphorus (EEEC 2020).

These TP levels are similar to spring offshore levels in Lake Huron proper, which were 2.0 µg/L in the 2005-2010 sampling period but increased to 2.7 µg/L over the 2011-2017 sampling period (Rudstam et al. 2020), although were 2.1 µg/L in 2017 (EEEC 2020). Nearshore levels of TP tend to be higher than those offshore, and at Canada's Lake Huron nearshore sampling sites, half of which are in eastern and southern Georgian Bay plus one at Manitoulin Island, average spring TP levels ranged from 4.1 to 4.4 µg/L for the 2005-2017 period (Rudstam et al. 2020).

Before 2000, however, one cage culture site in the LaCloche Channel, Georgian Bay, recorded TP concentrations of 16-40 µg/L, and in summer, the water column below the farm was essentially anoxic; dissolved oxygen (DO) was absent at 30 m depth (Gale 1999). Historically, TP levels at the site before that operation were 3 to 7 µg/L, and hypolimnetic DO levels were 6-9 mg/L (Hamblin and Gale 2002). Data from Ontario Ministry of Environment and Climate Change (now OMECP; cited in Diep and Boyd 2016a) for Lake Wolsey from the time an open-cage culture operation began in 1986 up to 2014 indicated average annual levels of TP between 6.7 and 16.4 µg/L, ranging from 3.0 to 24.0 µg/L over that period; average and median levels were similar. Average TP levels were higher during the 1986-2000 period than those during 2008-2014, although there was a 10-year gap from 1989 to 1998 in the first dataset (Diep and Boyd 2016a).

A TP budget model developed for Lake Wolsey based on a TP loading of 1,350 kg from the open-cage fish farm and water exchange rates for the lake, predicted an increase of 5 µg/L over the background level of 8 µg/L for an estimate of 13 µg/L, which was similar to the average measured level of 12 µg/L (Hamblin and Gale 2002). The current Ontario guideline of maximum allowance for TP is an average concentration of 10 µg/L during the ice-free period, and a proposed operation would be considered ineligible if, upon assessment, the predicted median TP exceeded 10 µg/L 30 m from the cage site (OMNRF 2017). Chow-Fraser (2006) measured water quality in wetlands at aquaculture cage sites, but at least 30 m away, in the vicinity of High and Eastern Islands (North Channel). Concentrations of TP in the vicinity of the cages ranged between 12.8 and 26.5 µg/L, which did not differ from those measured at unrelated sites in the region (11.7-37.4 µg/L) at the time, but sample numbers and frequency were not described. However, high levels of total ammonia-N (10-40 µg/L) associated with the cages were found compared with other areas (<1-20 µg/L), which were suggestive of aquaculture activity (ammonia is a soluble waste product of fish metabolism excreted via the gills).

Levels of TP typically are not consistent throughout the year and will show considerable variation, particularly relative to fish farm activity (summer versus winter) and during the periods of spring and fall turnover when sediments are disturbed and TP is released into the water column (Hamblin and Gale 2002). For example, during the time of spring and fall turnover in Lake Wolsey, TP concentrations in 1998-1999 were 9 and 20 µg/L, respectively (Gale 2000, as cited in Clerk 2002). Similarly, levels of TP in Lake Wolsey with active fish farming during 1999-2003 were typically lowest in spring, usually ≤10 µg/L, and increased over summer and fall up to twofold higher into the 10-20 µg/L range, which contrasts with natural waters without anthropogenic input where TP levels are typically higher in spring after ice-out and inflow from spring freshets (Diep and Boyd 2016a). Levels of TP also vary vertically within a season. Concentrations of TP increased twofold vertically from ~12 µg/L at the surface to 24 µg/L at the bottom in a vertical profile sampled at three depths in Lake Wolsey, and internal loading of P from sediments into the water column to levels ranging from 17 to 57 µg/L was observed in the hypolimnion at stratified sites where waters were hypoxic or anoxic (Diep and Boyd 2016a). Severe DO depletion and hypolimnetic anoxia was wide-spread in Lake Wolsey since the mid-2000s (Diep and Boyd 2016a).

Another complicating factor is that TP also enters freshwater systems through several other pathways. A TP mass-balance approach based on collected field data was used to model and compare the relative contributions of TP into Lake Wolsey from the open-cage aquaculture site and from non-point (watershed and tributaries) and other sources (e.g., groundwater, dwellings, etc.) in and around the lake (Milne 2012; Milne et al. 2017). The study found that non-point sources contributed the highest amount of TP (40%) to the lake, which was followed by the fish farm (32%) and lesser contributions from the remaining sources. Diep and Boyd (2016b) found that non-point sources contributed 49% of TP in Lake Wolsey, whereas the fish farm accounted for 45% of TP (both particulate and dissolved) released into the watershed, which was higher than that determined by Milne (2012).

Research studies that describe the recovery of the aquatic environment following closure of cage farm sites in freshwaters are few. After the closure of an open-cage fish farm site that operated for 6 years on Great La Cloche Island near Grassy Bay (North Channel), it took approximately 9 years for the site to recover through dispersion or assimilation of the particulate wastes (Milne 2008). However, fish waste deposits from the operation were confined to within 15 m of the former cage sites. During recovery, the depth of the sediment deposits at the site decreased by approximately 3 cm/year over a 6-year period.

Lac Heney in western Québec experienced a period of eutrophication in the 1990s resulting from a fish farming operation comprising 28 large tanks (not net-pens) raising trout on a tributary of the lake, which discharged directly into a small bay. It was estimated that the fish farm contributed approximately 40% of the annual external P input into the lake; however, because of the low flushing rate, much of the P was retained in the lake and precipitated into the sediments (KAL 2018). After closure of the farm in 1999 by the Québec government, TP levels remained at 22-25 µg/L up to 2007 (Golder 2016). A massive remediation program was undertaken in 2007 by adding iron chloride ($FeCl^3$) to couple the reactive iron (Fe^{3+}) with P into an insoluble, settleable complex. Average TP was reduced in 2008 to 11 µg/L but had increased to 16 µg/L in 2013, and then declined again to 14 and 9 µg/L in 2014 and 2015, respectively (Golder 2016). By 2017, the average TP level was about 11 µg/L (KAL 2018). However, as previously discussed, yearly average values are misleading because TP levels will vary considerably with season and depth (e.g., Clerk 2002; Hamblin and Gale 2002; Golder 2016; KAL 2018).

A paleolimnological approach was used to assess water quality changes in the LaCloche Channel, North Channel, before and after open-cage aquaculture operations (Clerk et al. 2004). Specifically, the investigators assessed the changes in chironomid midge larvae (order: Diptera, family: Chironomidae) and diatoms (class: Bacillariophyceae) within the strata of sediment cores taken from the channel. Clerk et al. (2004) demonstrated taxonomic shifts in both chironomid and diatom assemblages in the sediments and concluded that these shifts indicated significant changes in bottom-water oxygen conditions and open-water nutrient levels, respectively, which are consistent with eutrophication.

In another before-after study, Karakoca and Topçu (2017) found that TP values in the sediments of a Turkish reservoir supporting Rainbow Trout cage culture were 8.8 µg/L and 9.1 µg/L before and after the 7-month fish farming period, whereas soluble reactive P in sediment pore water increased from 3.35 to 11.04 µg/L. The investigators concluded that Rainbow Trout cage culture in the reservoir had no negative effect on sediment quality. However, samples were obtained one time only just before and just after the production period at 110 m depth, and there appeared to be no follow-up assessment.

In Minnesota, Axler et al. (1996) examined water quality parameters over 6 years in two abandoned, freshwater mine pit lakes used for net-pen aquaculture of Rainbow Trout and Chinook Salmon (*Oncorhynchus tshawytscha*). In those lakes the dispersion of fish faecal wastes and uneaten feed into previously oligotrophic lake water resulted in expected increased levels of P and N, increased deposition of sediment, and depletion of DO content compared with pre-aquaculture conditions and unused mine pit lakes. Trophic state indices (a function of means of three components based on TP, chlorophyll *a*, and Secchi disc depth) that Axler et al. (1996) used indicated a clear shift from oligotrophic status to a more eutrophic one in the aquaculture lakes relative to the reference lakes. In that study, TP levels, compiled from existing databases, in the reference lakes remained <10 µg/L, whereas those in the two aquaculture lakes were noticeably higher and occasionally as high as 100 and >200 µg/L, respectively.

Changes in Algae and Algal Communities

Fish farms raising Rainbow Trout are well established in the highlands of Scotland because of the abundance of small lakes (lochs) available; one such cage culture operation in Loch Fad, a 71-ha lake in Scotland with a production of up to 300 tonnes of trout annually, showed many signs of eutrophication, including frequent dense blooms of cyanobacteria (Stirling and Dey 1990). Phosphate levels over 12 months, measured as orthophosphate, were 43-46 µg/L at the control site, which the investigators indicated was 4-5 times higher than levels typical of oligotrophic waters, and 48-56 µg/L at the cage site, a 17% increase. Water quality and algal species showed the lake to be highly eutrophic. Several species of green algae and five species of blue-green algae (cyanobacteria) were documented, but the blue-green alga *Microcystis aeruginosa* dominated the algal assemblage and may have limited other species by light attenuation (Stirling and Dey 1990). Light attenuation at the surface resulting from blue-green algae blooms can reduce the growth of green algae and macrophytes underneath, leading to significant surface accumulation of the cyanobacteria, major die-offs and deoxygenation, and exposure of toxins (e.g., microcystin) and other contaminants to farmed fish that can impair their market quality and saleability.

In Lake 375 in the Experimental Lakes Area (ELA), northwestern Ontario, TP concentrations increased 15-fold over a 4-year study, and phytoplankton biomass increased fourfold annually (Findlay et al. 2009). However, 10% of P remained in the water column; thus, the effective increase in available P was 2.5 times higher than pre-cage levels. The greatest increases in phytoplankton were observed during spring and fall turnover, as would be expected with the mixing of water and sediment during these periods. Phytoplankton blooms were dominated by dinoflagellates and chrysophytes in spring, and biomass remained high. In late summer and fall, biomass shifted to two diatom species and the cyanobacterium *Chroococcus limneticus*. The dominant phytoplankton in the metalimnion in early summer was dominated by *Pseudoanabaena galeata*, another blue-green alga. The investigators concluded that as a result of the experimentally high stocking rate in the cage and the 5-year retention time in the lake, there was a significant impact on water quality, and further suggested that the aquaculture effects will be cumulative with further deterioration in water quality.

Although the TP levels in open waters of Georgian Bay are presently very low (ca. 2 µg/L), nearshore or inshore waters remain at levels more typical for oligotrophic systems (e.g., between 4 and 10 µg/L), and TP inputs from cage farms could still have a profound localized effect on the biota. In Lake Wolsey, for example, TP values have been somewhat higher than Georgian Bay proper, ranging in the mesotrophic zone of 10-20 µg/L (Gale 1999; Hille 2008). Subsequently, Diep and Boyd (2016a) concluded that Lake Wolsey was a moderately productive system with concentrations of chlorophyll *a* ranging from 1.1 to 4.7 µg/L, although interannual variability was evident over the sampling period (chlorophyll *a* is often used as an indicator of phytoplankton standing crop and thus a proxy for primary productivity). Like TP levels, chlorophyll *a* concentrations increased from spring to fall in the lake.

Conditions in Lake Wolsey around the cage site led to a proliferation of filamentous green algae, diatoms, and microcystin-producing cyanobacteria, including a bloom of blue-green algae (dominant species*: Phormidium autumnale*) in a nearshore area of the lake (Hille 2008). Many species of blue-green algae, such as *Microcystis* sp., which is common in the Great Lakes (Paerl and Paul 2012), can be a nuisance or even toxic to cultivated fish, livestock, pets, and humans. Levels of the toxin, microcystin, in general were low in Lake Wolsey compared with those in the ELA lakes monitored (Lakes 239, 373 and 375) (Hille 2008), which may be a function of lake size as Lake Wolsey is 100 times larger than the ELA lakes. However, Hille (2008) concluded that it was difficult to separate the effect of aquaculture on the natural biotic community in Lake Wolsey because of effects from other disturbances such as previous cottage and farm development, the presence of Round Gobies (*Neogobius melanostonus*) and the spiny water flea (*Bythotrephes cederstroemi*), and the existing high densities of zebra mussels (*Dreissena polymorpha*), which colonized most surfaces from ~1 to 10 m depth in the lake. Although the presence of zebra mussels complicated epilithic algae sampling in Lake Wolsey in Hille's (2008) study, a cause-effect relationship was not established between the nutrients from the fish farm and concentrations of zebra mussels in the lake.

Another major open-cage culture enterprise within a large freshwater lake in Canada is in Lake Diefenbaker, Saskatchewan, an artificial impoundment of the South Saskatchewan River. This operation also raises Rainbow Trout (anadromous steelhead variant) for the commercial market and was monitored to determine changes in the reservoir's phytoplankton community in proximity to the cages (Otu et al. 2017b). Spatial trends in diatoms, cryptophytes, and cyanobacteria between upstream and downstream locations in the reservoir were significantly related to distance downstream, but there was no evidence to indicate an effect from the fish farm. Far greater interannual variability than spatial variability in phytoplankton biomass was apparent, possibly related to regional flooding and drought. However, Lake Diefenbaker is an in-river reservoir with a long fetch and an average flow-through of 200-300 m^3/s (Hunter 2018). Moreover, Lake Diefenbaker has soft sandy banks that result in high shoreline erosion rates, which aid in the burial of any P that is not flushed out of the system. Thus, these monitoring results cannot be compared directly with Georgian Bay/North Channel where inshore areas used for fish farm sites have a relatively low flushing rate and correspondingly slower removal of nutrients, and shoreline erosion and resultant sediment deposition rates are much lower. For these reasons Georgian Bay/Lake Huron inshore waters would not be considered particularly well suited for open net-pen aquaculture.

Part II. Effects of Cage Aquaculture on Aquatic Biota and Native Fishes

Attraction of Fish and Changes in the Aquatic Biota around Open-Cage Farms

The extensive review by Callier et al. (2018) documented the attraction of native fishes and invertebrates to open-cage fish farms as a common and well-known outcome of farm presence in both freshwater and marine environments, although most studies reviewed were in the latter. Fish and other organisms will aggregate near cages to take advantage of (1) increased availability of food resources within the trophic web resulting from enhanced input of nutrients, and (2) the increase in habitat complexity (e.g., shelter, substrate, habitat for prey) provided by the floating cages (Callier et al. 2018).

Commercial Cage Culture in Georgian Bay and Lake Huron

Five aquaculture sites on the north side of Manitoulin Island were assessed to determine the relationship between cage culture operations and native fish fauna (Johnston et al. 2010). Catches of native species were higher around cage sites than control reference sites, and catch ratios ranged from 2.10:1 to 2.26:1 for offshore sampling and 1.57:1 for sites sampled inshore. Species captured included Rainbow Smelt (*Osmerus mordax*), Spottail Shiner (*Notropis hudsonius*), Trout-perch (*Percopsis omiscomaycus*), Yellow Perch (*Perca flavescens*), Lake Whitefish (*Coregonus clupeaformis*), White Sucker (*Catostomus commersonii*), and Lake Trout (*Salvelinus namaycush*). Results of Johnston et al. (2010) indicated that open-cage culture altered the distribution of native fishes in the region, with the net effect being the attraction of wild fish to the cages; fish abundance was 1.5 to 2.3 times higher around cage sites than at reference sites.

However, carbon and nitrogen stable isotope signatures (i.e., $\delta^{13}C$ and $\delta^{15}N$; a method for tracking dietary signatures through trophic levels of the food web) did not differ significantly between biota sampled around cage sites and those from reference sites 1-2 km away suggesting that dietary shifts did not occur and that direct consumption of fish farm wastes by native fauna was limited. Johnston et al. (2010) postulated a number of possible reasons for this lack of difference, in contrast to the changes observed in the Lake 375 studies (Kullman et al. 2009) described below, one being the size difference between the two water bodies.

Experimental Cage Culture in Lake 375, Northwestern Ontario

An experimental Rainbow Trout cage culture operation in Lake 375 was carried out to assess the effects of intensive fish farming on native fishes and fish communities in a small, oligotrophic water body (Rennie et al. 2019, and study-related papers therein). Approximately 10,000 Rainbow Trout were reared to market size annually for 5 years in a single aquaculture cage within the 23-ha lake to simulate a commercial cage culture operation, and the effects on water quality and aquatic biota were assessed during and up to 10 years after the experiment.

Minor, statistically detectable changes in zooplankton (crustaceans and rotifers) were evident, but overall, except for the freshwater plankter *Mysis diluviana* (a planktonic crustacean and popular prey for pelagic fishes), zooplankton populations did not display appreciable changes (Paterson et al. 2010). In contrast, phytoplankton biomass increased fourfold every year in response to the increased nutrient input after the initiation of the cage culture operation and was particularly noticeable during spring and fall turnovers when chrysophyte and dinoflagellate algae biomass increased 12-fold (Findlay et al. 2009). Those investigators' findings suggest that the impact of continued cage culture operation could be cumulative and further affect water quality.

Benthic invertebrate abundance was reduced by about 84% under the cage after 2 months compared with samples 45 m distant, and effects of the cage operation were observed beyond the perimeter of the cages to within 5 m after 13 months (Rooney and Podemski 2009). Invertebrate species richness was reduced under the cage, with the dominant taxa being chironomid midge larvae and nematodes (phylum: Nematoda), but beyond 5 m no appreciable difference in the invertebrate community was observed from that before production.

Populations of *Mysis diluviana* rapidly decreased by as much as 93% as a result of depressed hypolimnetic oxygen levels, and their densities remained low for several years (Paterson et al. 2011). Minnow species, i.e., Finescale Dace (*Chrosomus neogaeus*), Northern Redbelly Dace (*Chrosomus eos*), Pearl Dace (*Margariscus margarita*) and Fathead Minnow (*Pimephales promelas*), as well as Slimy Sculpin (*Cottus cognatus*) were observed to increase more than fivefold in numbers during aquaculture operations but decreased by 70-75% after production ceased (Kennedy et al. 2019). The results indicated that cage culture altered the distribution of wild fishes in this region. Shifts in stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) in minnows and invertebrate fauna were more pronounced in the experimental lake with cage aquaculture than in reference lakes, indicating that aquaculture wastes became an increasingly important food source for the minnows over the study span (Kullman et al. 2009).

During the production period, Lake Trout increased nearly twofold in abundance, size-at-age increased, and age of maturity decreased, quite likely in response to increased prey availability, such as increased abundance of the minnows and Slimy Sculpin, associated with increased nutrient loading of the system. The short-term stimulus of growth rates is not surprising given the increased nutrient input and primary production that would be expected to result from the cage culture.

However, Lake Trout numbers rapidly declined post-production, and size-at-age returned to pre-production levels, probably because of food limitations as sculpin and minnow abundance also declined after the operation ceased. Size-at-age of age-classes 2 and 3 declined sharply, annual survival was consistently below 1, and recruitment was consistently low after aquaculture ceased. Similarly, relative weight (W_r, an index of body condition) of Lake Trout increased during culture years, but then decreased again after production to pre-production levels (Kennedy et al. 2019). Based on analysis of stable isotope signatures ($\delta^{13}C$ and $\delta^{15}N$), an apparent food shift to nearshore resources was observed in Lake Trout in the fall after the dramatic decline in *Mysis* populations (Kennedy et al. 2019).

In comparison, White Sucker numbers declined dramatically during the aquaculture operation to their lowest level 2 years post-production, and some population metrics took many years to recover (Rennie et al. 2019). There was a decrease in overwinter survival of young-of-year (age-0) suckers as well as minnows. The precise reasons for the drop in White Sucker abundance was not clear, but one speculation was that competition for resources in nearshore habitats suppressed sucker growth rates to below the threshold necessary to survive over the winter. It was also suggested that the decline in White Suckers could possibly have been due to a limitation in community food availability, namely zooplankton. Although zooplankton densities, other than *Mysis*, remained similar throughout, initial minnow abundance increased.

Overall, the findings of Rennie et al. (2019) and colleagues (cited above) of these aquatic community changes suggest that cage culture operations may increase the carrying capacity for some fishes in the short term as a result of the increased nutrient input into the food web. However, there may be a cost to other members of the fish assemblage and other biota, which could have long-term ecological effects on the aquatic community. As a cautionary note, however, general results from small lakes such as Lake 375 may not be applicable to very large lakes such as the Great Lakes.

Freshwater Salmonid Cage Culture Outside of Ontario

Dual-frequency identification sonar (DIDSON) technology was used to assess the response of the wild fish community in Lake Diefenbaker to the presence of commercial Rainbow Trout cage farms, specifically to determine (1) possible differences in fish abundance before and after aquaculture development, (2) any alteration in habitat use of wild fish, and (3) attraction of wild fish to the fish farm site (Enders et al. 2016). A significant increase in wild fish abundance, determined as DIDSON fish detections per unit effort (DPUE; number of fish$\cdot$10 $m^{-3}\cdot$2 h^{-1}) occurred around the net cages before and after their installation. The average pre-cage DPUE was 0.22 ± 0.41 (mean ± SD) around the cages, and after cage installation the DPUE was 4.63, an approximately 20-fold increase (Enders et al 2016). Fishes captured in gill nets near the cage sites included Cisco (*Coregonus artedi*), the most abundant species, followed in order by Walleye (*Sander vitreus*), Lake Whitefish, Yellow Perch, Goldeye (*Hiodon alosoides*), and a single Rainbow Trout. In a separate study, Lake Whitefish in the area surrounding the aquaculture facility used waste feed from the fish farm as a diet subsidy although other fishes did not (Prestie 2018). Lake Whitefish feeding on the pelleted fish feed were larger in size and in better condition than those that were not; however, the effect was extremely localized and restricted to the immediate vicinity of the cages.

In Québec's first natural lake cage culture site in Lac du Passage, DO levels were depleted in the vicinity of the cages due to respiration of the farmed fish. Zooplankton, most of which were *Daphnia* sp., were less abundant during summer in the area of the cages compared with control sites (Cornel and Whoriskey 1993). Provincial regulations presently prohibit cage aquaculture in lakes in Québec (Seafood Watch 2018). Similarly, in an Iranian freshwater reservoir, oxygen depletion occurred in the vicinity of the farms due to respiration of the caged Rainbow Trout, and decreased densities of *Daphnia* were documented around the farm sites over 4 years of study (Daniali et al. 2017). In either case, no changes in the already-low numbers of benthic invertebrates were detected. In an oligotrophic reservoir in Turkey, zooplankton abundance (>90% rotifers plus cladocerans and copepods) was highest around Rainbow Trout cage sites compared with reference sites in all months of a study (Demir et al. 2001). Also, the abundance of four benthic faunal groups—gastropods, dipterans, oligochaetes, and crustaceans—was also highest below the cages.

Similar to that of Lake Trout in Lake 375, the growth rate of native Brown Trout (*Salmo trutta*) and stocked Rainbow Trout was higher in freshwater lochs in Scotland with Rainbow Trout farm cages than in those without, and the growth of Roach (*Rutilus rutilus*) assessed before and after the establishment of the cages also showed a significant increase after trout farming began. The observed stimulation of growth after the introduction of cages was attributed to fertilization of the water body, thereby increasing eutrophication leading to greater production of food resources and/or fish feeding on uneaten waste food pellets from the cages (Phillips et al. 1985).

However, like Rennie et al. (2019) and colleagues' experimental studies in Lake 375, Phillips et al. (1985) stressed the importance of gaining more scientific information to understand the relationships and behavioural interactions between farmed Rainbow Trout and native Brown Trout to assess possible long-term effects relative to food availability, and the environmental impacts of salmonid cage culture in general for proper development of the Scottish industry.

Interaction of Cage Fish Farms with Mussels

Published studies that demonstrate interactions specifically between salmonid cage farms and dreissenid mussels in temperate freshwaters of Ontario or elsewhere are lacking. But the interaction of non-dreissenid mussels and fish farms has been investigated in several other environments and with other species (e.g., Soto and Mena 1999; Cook et al. 2006; Tiemann et al. 2011; Musig et al. 2013; Callier et al. 2018; Sicuro et al. 2020). Certain mussels can create problems at fish farms by physically fouling the cages and altering benthic biodiversity, but as filter-feeders they have been found to also help reduce P levels in the water column.

Attraction of golden mussels (*Limnoperna fortunei*), an unrelated invasive mollusc, to freshwater cage fish farms was documented in Brazil, possibly in response to the greater food availability at the farm site (Ayroza et al. 2019). Although the farm reared warmwater Nile Tilapia (*Oreochromis niloticus*), not salmonids, Ayrozo et al. (2019) cautioned that other molluscs may be favoured by aquaculture activities in aquatic environments. The inadvertent introductions of the golden mussel, which has a similar filter-feeding behaviour and life history as the zebra mussel and quagga mussel (*Dreissena bugensis*), have caused widespread devastating ecological impacts in freshwater systems in South America (Moutinho 2021). Although the risk of this highly invasive species becoming established in the Great Lakes is presently deemed low (Mackie and Brinsmead 2017), it is prohibited in Ontario under the Invasive Species Act (OFAH/OMNRF 2021).

Adult dreissenid mussels are basically sessile organisms, but the mussel larvae, or veligers, are microscopic (typically 70-200 µm: Benson et al. 2023a) and free-floating, and therefore are easily transported by currents. They can rapidly colonize new stable substrates where they settle as juveniles and filter-feed primarily on algae (Benson et al. 2023a, 2023b). Thus, it follows that rapid post-settlement mussel growth will be favoured by enhanced nutrient input, such as from open-cage fish farms, that stimulate proliferation in algae production.

Fish Escapes from Open-Cage Fish Farms

The impacts of both intentional and inadvertent fish introductions on wild fishes have been well known for decades and include the decline and extirpation, reduced growth and survival, and changes in community structure of native fish populations through mechanisms of: (1) competition, (2) predation, (3) inhibition of reproduction, (4) environmental modification, (5) transfer of pathogens, and (6) hybridization (Moyle et al. 1986). More specifically, the possible effects of introduced Rainbow Trout on native fishes in Ontario and elsewhere was reviewed extensively (Kerr and Grant 2000), with the major perceived threat being on native Brook Trout (*Salvelinus fontinalis*) and feral Brown Trout through competition for food and habitat. Unfortunately, fish escapes from cage farm operations are common and inevitable. Data provided to OMNRF by operators indicate that approximately 1.37-1.38 million Rainbow Trout of various sizes have escaped from net pens in aquaculture operations in Georgian Bay and the North Channel between 1996 and 2020 (OMNRF, unpublished data). Most of the escapes were the result of storm damage to the cages.

An experimental release of cage-reared Rainbow Trout into Lake 375 was monitored using telemetry of radio-tagged fish (Blanchfield et al. 2009) to assess the behaviour of escapees. Fish dispersed quickly and lateral movements were extensive, initially covering most of the lake. However, significant numbers of escapees stayed in nearshore waters <25 m from shore and in the upper few metres, and many were found in close proximity to the cages during operations. The released trout did not appear to survive beyond 3 years.

A follow-up study in Lake 375 examined the movements of radio-tagged Rainbow Trout post-release to simulate escapes from cages after aquaculture operations had ceased (Charles et al. 2017). Native Lake Trout were also radio-tagged to determine behavioural interactions between the two species. During the aquaculture production phase, Rainbow Trout escapees lingered around the cages (23%), but were not observed often (2%) after production ceased. Lake Trout, however, did not appear to be attracted to the cages during either period (~1%). Presumably, Rainbow Trout remained around the cages during operations to take advantage of the waste feed and then dispersed to nearshore regions in search of prey afterwards. Thus, farmed, domestic-strain Rainbow Trout and native Lake Trout interactions in Lake 375 appeared to be limited.

A study similar to that in Lake 375 to mimic post-release behaviour of escapees was conducted later to monitor Rainbow Trout released around fish farms in the North Channel using ~1-kg fish either radio-tagged or marked with external tags (Patterson and Blanchfield 2013). As in the Lake 375 study, the trout dispersed quickly, and released fish were detected in nearshore waters. But after the initial dispersal the majority returned to the general area of the release site, although some returned after more than 3 months away and some never returned. Survival appeared to be about 50% after 3 months, with mortality apparently due to bird predation and angling.

Patterson and Blanchfield (2013) determined that 9.7% of the tagged, cage-farmed Rainbow Trout in the North Channel were caught by anglers within 31 months. Angled fish were caught mainly in nearshore areas or around cage sites, but some were occasionally found in tributary rivers as far away as Lakes Huron and Michigan. For example, escapees from the Lake Wolsey aquaculture site travelled as far as 360 km (Patterson 2010). The findings indicate that, like their naturalized conspecifics, escaped Rainbow

Trout are able to undertake long migrations and move into lake and river habitats occupied by native fishes.

The studies of Blanchfield et al. (2009) and Patterson and Blanchfield (2013) suggest that Rainbow Trout escapees can adapt quickly to the natural prey found in higher abundance around cage sites. A higher growth rate of escaped fish and their proximity to nearshore habitats could have a negative impact on food resources and fish communities in those habitats. Mature, adult, domestic-strain Rainbow Trout escapees from North Channel aquaculture sites were subsequently sampled from spawning tributaries (Johnston and Wilson 2015). Domestic Rainbow Trout comprised around 80% of the trout sampled from tributaries near cage sites but <20% of Rainbow Trout from distant spawning sites. Domestic-strain Rainbow Trout were in spawning condition (e.g., ripe gametes) in both spring and fall. Growth rates of female trout were similar to their naturalized counterparts, but domestic males grew more slowly. Based on $\delta^{13}C$ and $\delta^{15}N$ analysis, both strains were inferred to be similar in their food selections. Johnston and Wilson (2015) concluded that “domestic-strain Rainbow Trout of cage culture origin can survive, grow and attempt to spawn in northern Lake Huron and have the potential to compete for food, mates and spawning habitat with naturalized Rainbow Trout.”

Two lakes on Vancouver Island, Lois Lake and Georgie Lake, have supported open-cage salmonid aquaculture operations. Although technically freshwater lakes, both had access to the marine environment via coastal streams. Concerns in British Columbia on the possible effect of introduced Atlantic Salmon (*Salmo salar*) escapees on wild fish communities prompted field surveys to assess the presence and distribution of this introduced species in these lakes and coastal streams (Lough et al. 1997). In Georgie Lake, juvenile Atlantic Salmon comprised 11% of their samples, whereas the remaining 89% of the samples consisted of native Coastal Cutthroat Trout (*Oncorhynchus clarkii*) and Dolly Varden (*Salvelinus malma*). Their assessment indicated that the escaped Atlantic Salmon were capable of surviving and successfully feeding in Georgie Lake (Lough et al. 1997). In Lois Lake, 78% of the fish sampled were Coho Salmon (*Oncorhynchus kisutch*) and Atlantic Salmon that escaped from the fish farm facilities; most (76%) were Coho Salmon and 2% were Atlantic Salmon. Lough et al.’s (1997) results suggested that the escapees profoundly altered the Lois Lake ecosystem.

Studies in Scotland have reported numbers of Rainbow Trout escaped from cages of up to 5% of the total aquaculture production in lochs and, as a result, a sport fishery for Rainbow Trout is now well established. Like those in Ontario, tagging studies of stocked trout in Scotland suggest that Rainbow Trout escapees disperse widely and rapidly after release, but their eventual distribution is limited to the vicinity of the cages in order to either congregate around the physical structure or take advantage of nutrient-enhanced benthic and zooplankton resources (Phillips et al. 1985). Similarly, Carss (1990) found in a fisheries survey adjacent to fish farm sites in a freshwater loch that most fish captured were Rainbow Trout, presumably escapees from the cages since many of the captured trout had pelleted feed in their stomachs. Despite the widespread occurrence of Rainbow Trout in these systems, there was little evidence of populations becoming self-sustaining and no evidence of escapees having an adverse effect on native Brown Trout, although the data appear scant.

Several studies conducted in southern Chile where marine and freshwater culture of introduced salmonids is widespread have shown a strong positive relationship between the magnitude of salmonid production in freshwater facilities and the relative abundance of free-living escapees, including Coho Salmon, Atlantic Salmon, Rainbow Trout, and Chinook Salmon, in lakes (five references in Sepúlveda et al. 2013). Collectively, the evidence reviewed by the investigators suggests that the introduced salmonids have had detrimental impacts on native fishes in lakes as well as other ecosystems and stated that "more research is needed to identify and develop reliable indicators to estimate the impact of escapees at the ecosystem level in both marine and freshwater systems" (Sepúlveda et al. 2013).

Transfer of Pathogens from Fish Farms to Native Fishes

In their review of pathogen transmission from fish farm escapees to wild fish stocks, Arechavala-Lopez et al. (2013) described six possible pathways in their "transmission triangle" by which pathogens (i.e., viruses, bacteria, and parasites) from cage-farmed fish could be transferred and/or interact with native fishes. Two pathways of concern to Georgian Bay fish stocks are: (1) pathogens from farmed fish infecting native fish directly, and (2) dispersion of infected farmed fish to native fish habitats including food webs.

Many review papers have documented and/or discussed the transmission of pathogens from aquaculture facilities to native fish stocks (e.g., Peeler and Murray 2004; Johansen et al. 2011; Gardner et al. 2014; Bouwmeester et al. 2021) and methods for their detection and control (e.g., Bruno and Ellis 1996), but most studies in temperate waters have focused on marine operations. In most aquaculture operations, fish are held in confined spaces at high densities, sorted and graded, handled routinely, and often transported, all of which are physiologically stressful to the fish, which can compromise their immune systems and thus render them susceptible to disease (Barton and Iwama 1991; Barton 2000). Disease outbreaks typically require three major factors to occur—presence of both (1) the pathogen and (2) a suitable host, but also (3) environmental conditions conducive to the host's susceptibility to the pathogen; e.g., high density, poor water quality, stress. A simple Venn diagram has been used often in the literature to illustrate the overlapping of these three factors needed to ultimately result in the occurrence of disease (Figure 2).

Disease problems can arise when fish reared in artificial environments become infected with a pathogen, possibly from wild origin, and are then released back into the wild to potentially infect native fishes (Peeler and Murray 2004).

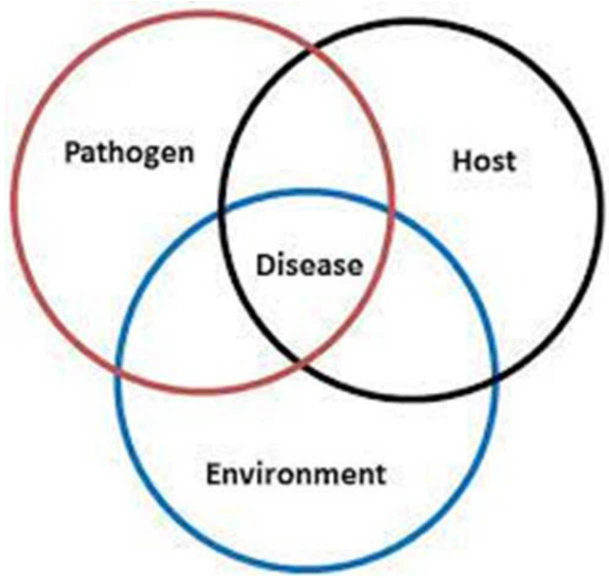

Figure 2. Venn diagram illustrating the relationship between host, pathogen, and environment conducive to a disease outbreak.

Several viral, bacterial, and parasitic pathogens that cause disease are present in Great Lakes waters, and more than 200 pathogens have been isolated from Great Lakes fish populations (Riley et al. 2004). Some fish diseases (and their causative agents) of concern to Great Lakes salmonids, including in Georgian Bay and North Channel, that could possibly transfer from salmonid aquaculture are: (1) viral hemorrhagic septicemia (VHS; VHS virus), (2) infectious pancreatic necrosis (IPN; IPN virus), (3) bacterial coldwater disease (BCD; *Flavobacterium psychrophilum*), (4) columnaris (*Flavobacterium columnare*), (5) bacterial gill disease (BGD; *Flavobacterium branchiophilum*), (6) furunculosis (*Aeromonas salmonicida*), (7) bacterial kidney disease (BKD; *Renibacterium salmoninarum*), (8) enteric redmouth disease (ERM; *Yersinia ruckeri*), (9) whirling disease (*Myxobolus cerebralis*, a protozoan parasite) (Anderson et al. 2015), (10) lake trout herpesvirus (salmonid herpesvirus-3) (Shavalier et al. 2020), and recently (11) lactococcosis (*Lactococcus garvieae*) (Snyman et al. 2020).

Previously BCD, BGD and columnaris have been diagnosed in Ontario aquaculture (OAHN 2017a, 2019). Although not stated, these diagnoses do not appear to have been from cage-reared fish. Bacterial isolates from 55 fish (species not mentioned) surveyed from commercial aquaculture facilities and provincial hatcheries in Ontario detected mainly *Flavobacterium* spp. (54.5% of specimens) and *Aeromonas* spp. (29.1%, mostly *A. salmonicida* and *A. hydrophila*), as well as lesser frequencies of other bacterial pathogens including *Edwardsiella* spp., *Streptococcus* spp., *Vibrio* spp. and *Yersinia* spp. (OAHN 2017b). Outbreaks of both BGD and nodular gill disease (NGD; putatively *Cochliopodium* sp.), a parasitic infection, have occurred in Rainbow Trout recently in commercial aquaculture in Ontario, but these were in fingerlings from hatchery raceways and not from open cages (Snyman et al. 2019).

In late summer 2020 lactococcosis was detected and diagnosed in Rainbow Trout from an open-cage fish farm in Georgian Bay and is the first documented outbreak of this disease in Ontario farmed fish (Snyman et al. 2020). In the last few years, outbreaks of lactococcosis in Rainbow Trout have occurred elsewhere internationally, in which *L. garvieae* has been isolated and characterized as the causative agent (Shahi et al. 2018; Karami et al. 2019; Ortega et al. 2020; Radosavljević et al. 2020). The origin of this bacterium in the USA and Canada is not clear, but a lactococcosis outbreak occurred recently at a commercial Rainbow Trout farm in the Pacific Northwest, USA, from which the genome sequence of *L. garvieae* was described (Nelson et al. 2016). Lactococcosis can cause significant losses in farmed freshwater salmonids, particularly Rainbow Trout, as well as in marine fishes when water temperatures rise above 15°C. The pathogen is resistant or only moderately susceptible to antibiotics such as oxytetracycline (Vendrell et al. 2006; Meyburgh et al. 2017), and managers are turning to vaccination by injection or immersion to control the disease.

Studies that demonstrate the potential transfer of *L. garvieae* from hatchery or cultured fish to wild fish stocks are very limited. When native fishes in the UK were experimentally exposed to the pathogen via effluent water from tanks that held infected Rainbow Trout, Grayling (*Thymallus thymallus*) experienced 37% mortality, but other salmonids and cyprinids (minnows) were less susceptible (Algöet et al. 2009). However, wild fish in their native habitat are not subjected to the same stressors associated with high-density confinement, which are conducive to infection, as are farmed fish. Thus, the probability of transmission of this pathogen to wild stocks may be low.

Presently VHS is the only fish disease listed as one of major concern by the province of Ontario (OMNRF 2022); it is highly infectious and often lethal to several Great Lakes fish species (Bain et al. 2010). At this point, evidence to indicate horizontal transmission of any pathogens in open-cage fish stocks to native wild fishes in freshwaters is lacking.

Release of Antibiotics and Other Chemicals from Fish Farms

The release, fate and environmental effects of antibiotics and other chemicals, i.e., disinfectants, anesthetics, and hormones, used in Canada was reviewed very thoroughly by Scott (2004). Scott (2004) covered 16 databases and reviewed 121 studies pertaining to Canada published since 1990; thus, those findings do not need to be reiterated. Most of the literature reviewed by Scott (2004) involved marine aquaculture systems. Unfortunately, studies examining chemical usage in freshwater open-cage aquaculture were limited, and only two reports were specific to Canadian freshwater aquaculture; however, that review was conducted nearly 20 years ago. As Scott (2004) stated, differences in the physical and chemical characteristics of the water and bottom substrates preclude the ability to make direct comparisons of freshwater systems with their marine counterparts.

A survey of drug use in Ontario fish farms by Thorburn and Moccia (1993) indicated that many trout farmers appeared to use chemotherapeutants on their fish only rarely, although 26% of farmers felt that disease had important economic consequences for production. However, the survey found that only a few farms were completely therapeutant-free, and a few farms apparently used chemotherapeutants frequently. Thorburn and Moccia's (1993) survey was conducted at a time before open-cage fish culture became prevalent in the mid-1990s (Moccia and Bevan 2017), so would have been restricted to land-based operators; thus, it is unlikely that any cage farm operators were included in the survey.

Only four antibiotics are currently approved for use in food fish in Ontario: oxytetracycline, florfenicol, sulphadimethoxine, and sulphathiazole; the two latter sulpha drugs have been or are being phased out (OAHN 2017b). Similarly, oxytetracycline, florfenicol and sulphadimethoxine/ormetoprim are the only antibiotic medications approved for aquaculture in the USA (Trushenski 2019). Other chemicals, such as fungicides (e.g., formalin, hydrogen peroxide), disinfectants and anaesthetics, frequently used in hatcheries are not likely to be used on fish in a freshwater open-cage environment.

Oxytetracycline is one of the most commonly used antibiotics in fish farms and hatcheries globally and is generally applied via medicated feed. This drug is the most widely used antibiotic in Canadian aquaculture (Sheppard 2000). Rasul and Majumdar (2017) indicated that oxytetracycline is poorly absorbed through the intestinal tract of fish and thus should be administered at a relatively high dosage rate to be effective (e.g., 100-150 mg/kg fish per day for 10-15 days). In Canada, a prescription is required for oral administration of oxytetracycline for dosages above 75 mg/kg fish per day.

There are three pathways by which a therapeutant, such as oxytetracycline, can get into the environment: (1) medicated feed presented to fish may not be eaten and end up in the water column or on the bottom; (2) the therapeutant may leach from the feed before the feed is eaten or reaches the bottom; or (3) the feed may be eaten but unabsorbed therapeutant is released via faeces or urinary waste (Scott 2004).

At that point, the chemical can be ingested by other fishes or invertebrates and enter the food web, or can accumulate and persist in the sediments. Several studies cited in Scott (2004) suggest that the majority of antibiotic used for treatment passes through the gastrointestinal tract of fish unabsorbed and enters the environment (e.g., sediments) in an active form and may represent a significant, longer-term exposure risk. If the pathogen is persistent, overuse of therapeutants can lead to resistance (Scott 2004; Miranda et al. 2018), making future control or management of the pathogen problematic (Watts et al. 2017). Because of the high cost, however, fish farmers are likely to be prudent and conservative in their use of antibiotics or other chemotherapeutants.

Since Scott's (2004) review, there have been several reviews published on the use and fate of chemotherapeutants in aquaculture, chiefly oxytetracycline and other antibiotics. Again, these reviews focus on marine aquaculture, such as sea-cage operations with salmon. There still remains little research information for temperate, freshwater cage-culture systems on this topic and a paucity of such information in Canada. Axler et al. (1996) measured concentrations of therapeutants and other chemicals in abandoned mine pit lakes used for salmonid cage culture in Minnesota in the context of suitability for a public drinking water supply. Maximum whole-lake concentrations of oxytetracycline, the most widely used therapeutant in the fish farms, remained <0.2 mg/L over the 5-year study period, which were two to three orders of magnitude below state drinking water guidelines (Axler et al. 1996). The authors concluded that the use of the chemicals at the fish farms were "unlikely to result in unacceptable levels of these additives" for human health.

Suggested Future Research Topics

In summary, there are several pathways and mechanisms by which water quality and the native aquatic community can be affected by open-cage culture of salmonids in temperate freshwaters. As discussed previously, the major of these is the release of nutrients, specifically P, into the aquatic environment. Although extensive for marine systems, research on the following topics is still limited for cage culture in freshwaters. Future research focused on environmental effects from aquaculture in Georgian Bay and the North Channel could address any of these suggested topics (*not* in order of priority):

Water Quality, Nutrient Loading and Primary Production

- Extent of water exchange and/or movement under nearshore floating cages.
- Horizontal distribution, fluctuations, and seasonal changes of nutrients, especially phosphorus, at and around cage sites.

- Seasonal assessment of vertical profiles of phosphorus concentrations during ice-free conditions, including during spring and fall turnovers.
- Water quality and algal monitoring at past and existing cage farm sites using underwater autonomous vehicle (AUV) technology.
- Seasonal extent of oxygen depletion and incidents of hypoxia and anoxia in the water column throughout the year.
- Internal loading of P into the water column from sediments underlying recently decommissioned open-cage fish farm sites using modern observational and mathematical techniques.
- Time course of recovery of sediments, sediment chemistry and sediment biota around cage farm operations to pre-cage natural levels after cessation of operations.
- Evaluation of lake remediation efforts (e.g., aeration, ferric chloride addition, dredging, capping) following recent closure and abandonment of cage farm facilities.

Algae and Invertebrate Aquatic Biota

- Thorough quantification and identification of planktonic and epilithic green algae and cyanobacteria (blue-green algae) under and around cage sites.
- Water sampling where blue-green algae are present to detect possible presence of microcystins or other toxic substances.
- Thorough quantification of benthic fauna around fish farm sites and their recovery after cessation of operations.
- Short-term and long-term changes in the zooplankton community at and around fish farms.
- Potential attraction of dreissenid mussels to nutrient-enhanced increased primary productivity around cage farm sites.

Fish and Fish Communities

- Spatial distribution of native fish assemblages attracted to cages by means of dual-frequency identification sonar (DIDSON) technology.
- Effect of fish farm wastes on food habits and diets of native fishes and other biota using stable isotope analysis.
- Distribution and persistence of Rainbow Trout escapees from fish farms in the natural environment.

- Escaped Rainbow Trout predation on native species and competition with native fishes for food resources at various life stages (e.g., eggs, young).
- Habitat overlap and other behavioural interactions between escaped Rainbow Trout and native fishes.
- Possible long-term impact of escapees on genetic variability and integrity of native fish stocks (e.g., feral Rainbow Trout) using DNA sampling techniques and analysis.
- Potential transfer of fish pathogens (viruses, bacteria, parasites) from domesticated fish to native fish populations during or after a disease outbreak.
- Inventory of usage of antibiotics and other chemotherapeutants in open-cage fish farms to document what is used, where, and in what amounts.
- Fate of antibiotics and other chemotherapeutants following recent applications at fish farms in the natural environment and effects on native flora and fauna.

Possible Research Study Initiatives

Not surprisingly, GBA's concerns regarding open-cage salmonid aquaculture are consistent with those expressed in previous reviews on the effects of this industry in temperate freshwaters of Canada, particularly the release of phosphates (TP) into the environment (e.g., Wildish et al. 2004; Yan 2005; Cantox Environmental 2006; Podemski and Blanchfield 2006; EC 2009; Otu et al. 2017a). Yan (2005) posed several questions related to the many concerns and perceptions about this industry in freshwaters that need to be addressed with research with respect to (among others):

- the influence of cage fish farms on TP concentrations and the role of associated operational and limnological conditions,
- the rate and extent of water quality recovery where degradation has occurred but where cage fish farming has ceased,
- the appropriateness of mass-balance models to make predictions about the effect of increased loading of dissolved and particulate P on average TP concentrations in receiving waters,
- the effect of intensive cage fish farms on dissolved oxygen concentrations and the principal sources of biological oxygen demand.

The GBA Aquaculture Committee determined the most important of the suggested research topics emerging from the current review and established priority needs for research in Georgian Bay, which are grouped into three separate research initiatives.

Initiative 1: Water Quality, Nutrient Loading, and Primary and Secondary Production

Objective: Assess the effect of open-cage fish farms on the dynamics of nutrients released into the environment and their impacts on water quality and on primary and secondary production.

Studies:

- Horizontal distribution, vertical profiles, fluctuations, and seasonal changes of nutrients (i.e., N and P) at and around cage sites.
- Quantification and identification of planktonic and epilithic green algae and cyanobacteria at and around cage sites.
- Quantification and identification of zooplankton at and around cage sites.
- Seasonal extent of oxygen depletion and incidents of hypoxia and anoxia in the water column throughout the year.

Depending on study design, aspects of these could incorporate AUV technology.

Initiative 2: Sediment Chemistry and Benthic Invertebrate Communities

Objective: Determine the extent of accumulated P release into the water (loading) from sediments at former fish farm sites, and the rate of recovery of sediments and the associated benthic invertebrate community.

Studies:

- Internal loading of P into the water column from sediments underlying recently decommissioned fish farm sites using modern observational and mathematical techniques.
- Time course of recovery of sediments, sediment chemistry, and benthic invertebrate communities around cage farm sites after cessation of operations.

Initiative 3: Fate of Escaped Fish from Open-Cage Farm Sites

Objective: Determine the effects of farmed fish escapees from cages on native fishes and the aquatic community.

Studies:

- Distribution and persistence of fish-farm Rainbow Trout escapees in the natural environment.

- Escaped Rainbow Trout predation on native species at various life stages and competition with native fishes for food resources.
- Habitat overlap and other behavioural interactions between escaped Rainbow Trout and native fishes.

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