Fisheries and Oceans Canada Pêches et Océans Canada
Ecosystems and Oceans Science Sciences des écosystèmes et des océans

Central and Arctic Region

Canadian Science Advisory Secretariat
Science Advisory Report 2015/051

FRESHWATER CAGE AQUACULTURE: ECOSYSTEMS IMPACTS FROM DISSOLVED AND PARTICULATE WASTE PHOSPHORUS

*Figure 1. A freshwater cage aquaculture facility raising Rainbow Trout (*Oncorhynchus mykiss *Walbaum). (photo by Cynthia A. Wlasichuk, 2012)*

Context:

There is public and industry interest in understanding the potential environmental impacts of phosphorus (P) released from freshwater aquaculture operations. As a result, Fisheries and Oceans Canada's (DFO) Fisheries and Aquaculture Management Directorate requested science advice on the risks to freshwater lake ecosystems from the release of dissolved and particulate waste P from freshwater cage aquaculture operations. Although there are other issues which may be associated with freshwater cage aquaculture facilities (e.g., organic enrichment, other nutrients, habitat alteration, genetic and ecological interactions with wild fish populations), this assessment focused on P. This assessment includes a review of the current scientific literature on P in freshwater environments (fate and cycling), as well as, information on freshwater aquaculture, particularly P assimilation and release by Rainbow Trout aquaculture operations. Although the ecosystem response to P loading added as aquaculture waste is not well understood, this review attempts to gather, assess, and synthesize the available information. The focus of this assessment is on the existing industry in Lake Huron (Ontario)*, Saskatchewan, British Columbia and work done at the Experimental Lakes Area. This is the first Canadian Science Advisory Secretariat (CSAS) focused specifically on freshwater cage aquaculture.*

This Science Advisory Report is from the June 17-19, 2014 regional peer review of Freshwater Cage Aquaculture: Ecosystems Impacts from Dissolved and Particulate Waste Phosphorus. Additional publications from this meeting will be posted on the [DFO Science Advisory Schedule](#) as they become available.

SUMMARY

- Phosphorus (P) is biologically significant and both naturally and anthropogenically sourced. Naturally, P is found in low but variable concentrations in water bodies and tends to be the growth-limiting nutrient for primary production. P concentration in lakes is significantly correlated with changes in lake productivity and water quality. Anthropogenic change to P loading to a lake ecosystem therefore should be considered in the process of managing activities that can contribute to total P loading.
- To accurately predict and manage potential effects of P additions to lake ecosystems from aquaculture, it will be necessary to develop an understanding of the factors that can influence P cycling on an ecosystem-specific basis. In particular, further work needs to be done to understand the factors influencing release/retention of P from sedimented waste material and how food web structure may influence P cycling between the water column and the sediments.
- Introduction of invasive species and changes to landscape use have the potential to alter P cycling within a lake ecosystem. A change in landscape use can significantly alter not only total P loading but also the ratio of dissolved to particulate P loading. Therefore, continued monitoring of catchment P loading and alterations to trophic structure within the water body are needed in ecosystems that are being managed to accommodate aquaculture in order to understand the total P loads.
- P excretion by aquaculture fish is directly linked to amount and digestibility of P in the diet.
- P loading from aquaculture can be minimized through the use of low content, highly digestible-P in feeds.
- Nutritional modelling of feed and husbandry data provides an accurate estimate of the contribution of P that is not quantifiable by sampling the receiving water because of rapid dispersion, settling, and transformations that occur to waste P once it enters the environment.
- Management of the potential effects of aquaculture-related P inputs to lake ecosystems would be improved by employing nutritional modelling to characterize the amount, form, and timing of P loading.
- Total farm P output is not an accurate measure of potential eutrophication risk of P addition to the ecosystem. The timing of delivery and the fate of the P loading can significantly modify that risk.
- Ecosystem-specific differences in limnology, geochemistry, and trophic structure can modify P cycling, therefore further science is needed to determine the fate of aquaculture P in ecosystems supporting commercial cage culture.
- The low level of monitoring of tributary P inputs is a significant source of uncertainty in the estimation of the total P loads to the North Channel of Lake Huron. There is a need to significantly improve spatial monitoring of P sources to ecosystems that are being managed to accommodate for aquaculture. The accurate estimation of P loading is necessary to determine P budgets.
- Natural variability in annual precipitation can significantly affect watershed P loading to lake ecosystems. It would be advisable to manage all anthropogenic P loading such that there is room to accommodate the natural range of variation in watershed loading and still prevent deterioration of water quality.
- Although the aquaculture industry is currently only contributing approximately 5% of the P load to the North Channel of Lake Huron, the biological importance of P to lake productivity and the need to meet International Joint Commission (IJC) P load targets suggest that P loading needs to be

considered in the management of future industry expansion or other activities known to contribute to P loading.

- Development of future P load targets would be improved by consideration of nearshore versus offshore responses to P loading and consideration of particulate versus dissolved forms of loading. Development of separate load limits for nearshore versus offshore and for dissolved P versus particulate P would improve management of the North Channel ecosystem.
- A watershed management strategy that considers not only aquaculture but also other activities within the watershed and their potential contribution to P loads would be of benefit to all stakeholders.
- A significant portion of the P waste (dissolved and particulate) added to a temperate lake by aquaculture operations is sequestered to the sediments, as would be the case for ‘natural’ P coming from tributaries. Therefore, the total P loading is not necessarily an accurate predictor of the eutrophication potential of the P loading. It is the amount of P that remains in the water column and that which is released from sediments that needs to be considered.
- Data, however limited, exists which indicates that the forms of P found in sediments under and around fish cages differs in relative quantities from those found in sediment at reference sites.
- The form of P, as well as the quantity, needs to be understood to properly characterize the potential for remobilization and thereby the development of internal loading. Internal P loading releases P that was sequestered in the sediments and makes it bioavailable. This release is undesirable as it contributes to eutrophication potential.
- Additional sampling for P fractionation at commercial cage aquaculture sites and reference sites, as well as measures of P release from the sediments (i.e., becomes soluble), would improve the ability to characterize the risk that this P accumulation in sediments poses to eutrophication potential.
- The ability to manage the cumulative impacts of freshwater aquaculture in Canada may be improved by using European models that have specifically incorporated aquaculture in predicting the response of whole lake ecosystems to P loads.
- These models need to be verified in Canadian ecosystems because the structure of the foodweb and sediment chemistry may vary.
- Nutritional strategies can be a direct and effective means to manage P release from fish culture.
- Development of feed that is more efficiently utilized by fish could be a means to reduce feed usage and waste outputs.
- In Ontario, licensing requirements that incorporate the use of feed quotas and the requirement for low P feed use have proven effective at mitigating the eutrophication potential of P waste from fish culture operations.
- Cage siting requirements that minimize the potential to develop internal P loading (e.g., sites with sufficient flushing) and routine environmental monitoring are currently used to mitigate the risks of P loading.
- Additional refinements in siting criteria such as fallowing or placement in offshore areas could be developed to further mitigate risks of aquaculture P loading in nearshore freshwater areas. Fallowing is not currently carried out for freshwater cage aquaculture. Movement of operations to the offshore could take advantage of higher P loading targets and would also benefit from greater water depths resulting in greater waste dispersion.

- The likelihood of P inputs from the cage aquaculture industry resulting in eutrophication of Canadian freshwater environments, under the current level of industry production and practices, can generally be characterized as 'low'.
- Future growth of the industry or expansion of any other anthropogenic activity that contributes to the P loading requires careful consideration of the P input from all sources.

INTRODUCTION

In Canada, freshwater cage culture (Figure 1) currently occurs in Ontario (Lake Huron), Saskatchewan (Lake Diefenbaker) and in British Columbia (Lois Lake and Lake Georgie). Most (57% of production) of this industry is currently based in Ontario. Since 2000, the commercial aquaculture industry has experienced modest growth in production of Rainbow Trout (*Oncorhynchus mykiss*) reared in freshwater cages. In Ontario, the Rainbow Trout industry shifted from initially land-based production to 88% cage production by 2010. In Canada, the growth of the industry has been very limited and future growth is uncertain due to regulatory and environmental challenges.

Waste materials are released directly from cage (i.e., net pen) aquaculture operations in freshwaters into aquatic environments. These wastes may be in the form of particulate matter (e.g., faeces and uneaten feed) that typically settles to the benthic environment beneath the cage arrays, or they may be in the form of dissolved wastes that are released directly into the water column from feed, faeces and metabolic excretions of fish. Fish size, water temperature, and aquaculture practices (e.g., feed composition, ration, and feeding methods) are some of the factors that can affect the level of waste production. The release of Phosphorus (P) in the freshwater environment is of particular concern because P is generally the most limiting element for algal growth in freshwater ecosystems. Excessive inputs of P into lakes could increase algal biomass and lead to harmful or nuisance blooms, fouling of the shoreline with attached algae and decreased oxygen concentrations in deep water.

There has been little research into the cycling of P between aquaculture wastes and the water column, and it is not known what proportion of P released from aquaculture operations will eventually be available for primary production. Based on a review of the current scientific knowledge of the release of P (dissolved and particulate) from freshwater cage aquaculture operations and research done at the Experimental Lakes Areas and elsewhere, the objective of this scientific review process was to provide advice on the potential impacts that might be associated with P enrichment by the freshwater cage aquaculture industry. A research document (Otu et al. in prep.) that provides the technical details and the full list of cited material, was reviewed during the meeting.

ASSESSMENT

Phosphorus in the Freshwater Environment

P is ubiquitous in the environment; the Earth's lithosphere contains, on average, a relatively high concentration of P (about 1000 ppm).

P in the environment is often present as part of a phosphate molecule (PO_4^{-3}, PO_4^{2-}, PO_4^{-}); it is rare in its elemental form.

In lakes, P is found in low but variable concentrations. The productivity of water bodies is often characterized by their total P concentration: oligotrophic (4-10 $\mu g\ L^{-1}$), mesotrophic (10-30 $\mu g\ L^{-1}$), and eutrophic (30-100 $\mu g\ L^{-1}$).

In the aquatic environment, phosphates are typically measured as total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), and particulate phosphorus (PP).

Particulate P can be further divided into a number of different chemical forms through analytical fractionation techniques.

In biological systems, P occurs as organic and inorganic phosphates. Organic phosphates include phospholipids, coenzymes, and nucleotides (deoxyribonucleic acid (DNA), and ribonucleic acid (RNA)). Inorganic phosphate includes orthophosphate ions, pyrophosphate, polyphosphates, and phosphate minerals such as apatite found in bones or shells.

There are a number of naturally occurring and anthropogenically driven processes that contribute P to lakes (Figure 2). Dissolved phosphate (PO_4) is released naturally through chemical weathering of rocks and particulate P through physical weathering of rocks. Decay of terrestrial organic matter results in the release of dissolved P in the form of inorganic phosphates and organic compounds and/or release of particulate P in the form of iron hydroxides, carbonates, and cellular components. Human sources of P include sewage effluent, animal husbandry wastes, fertilizer application, dust pollution, and industrial outfalls. Natural or human sources of P enter lakes via rivers, directly as precipitation, ground water and runoff, or via wet or dry atmospheric deposition; the relative contribution of each varies greatly depending on the catchment characteristics.

Transformations of P in lakes include: physical abiotic translocations of P, for example mixing, flushing, and exchange between the sediment and water boundary layer; chemical reactions such as redox reactions, acid/base reaction, and adsorption; and biotic transformations, including uptake and release by microbes, algae, and other components of the food web.

Phosphate is cycled between its different forms in lakes both within the water column and in the sediments. Several processes (abiotic and biotic) affect the concentration of P in lakes. P in temperate, dimictic lakes follows a seasonal cycle of transformations that dictate water P concentrations, with typically high P concentrations during spring as a result of lake turnover (mixing), and progressively lower concentrations through the open water season as P taken up into the food web is gradually removed from the water column by sedimentation. Transport to and burial in sediments is the fate of much of the P in lakes (typically more than 80% of the total P).

P is important in the freshwater environment because it is often the growth-limiting nutrient for primary producers. The high biotic demand for P in lakes generally means that soluble P does not build up over time in the water column, but instead tends to be barely detectable. P is in greatest demand in the euphotic zone (boundary defined as depth to which there is penetration of 1% of surface light intensity) where primary producers such as phytoplankton can access light energy to effectively photosynthesize. P recycling times in the epilimnion (the top-most layer in a thermally stratified lake) of low nutrient lakes can occur on the order of minutes.

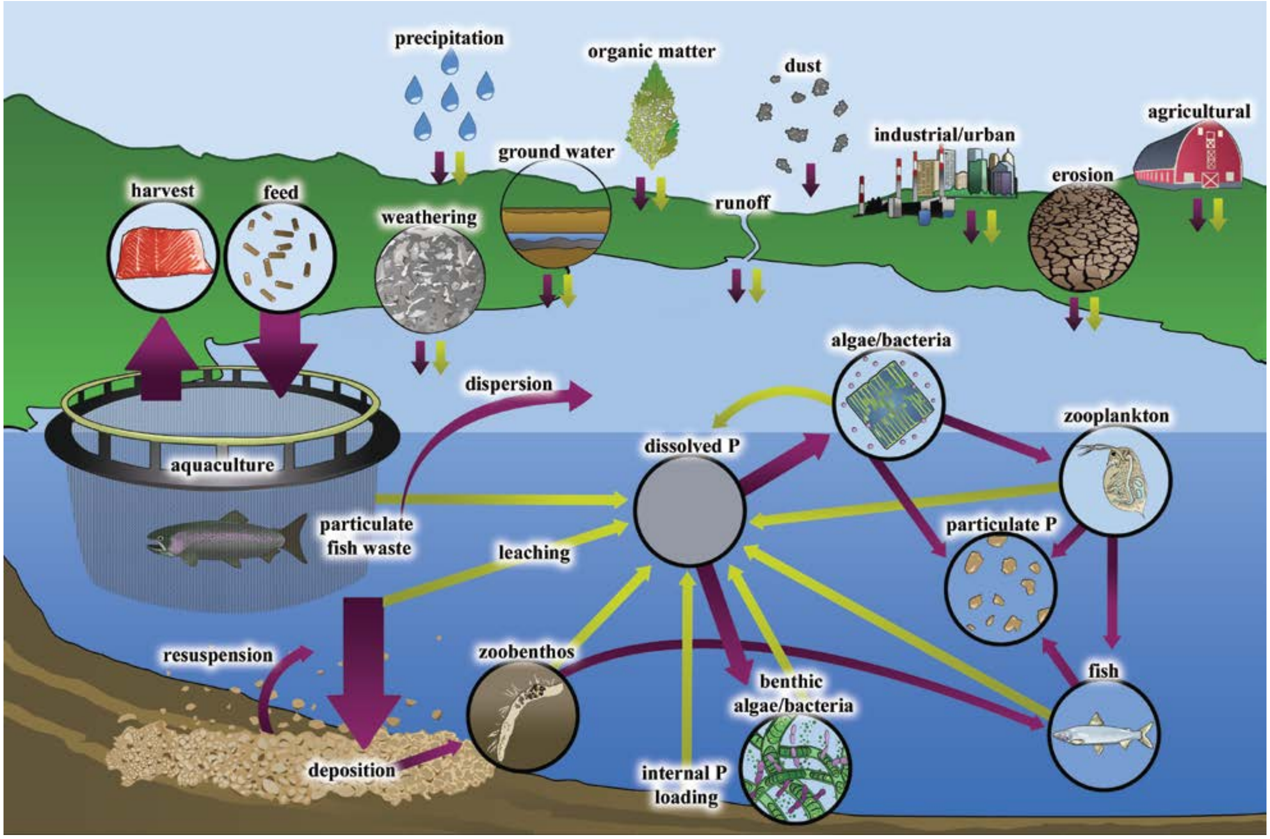

Figure 2. Diagram of potential phosphorus loads from aquaculture and other sources of phosphorus from the surrounding catchment of a lake basin (Otu et al. in prep.).

The ecosystem response to P is affected by the food web. Water column P concentrations may not be a direct function of the total nutrient loading but rather the response by consumers of the nutrients. The efficiency of P cycling in lakes can be affected by trophic transfer up the food web with varying proportions of phytoplankton, zooplankton, and fishes. In the Laurentian Great Lakes, major changes affecting the food web and P cycling have been reported over the past 30 years. These include changes in P loading from point and non-point sources, the introduction of dreissenid mussels, and consequential reengineering of the nearshore topography, sequestering of P in the nearshore sediments, and increased water transparency. This has resulted in a spatial change to the P cycle with the primary consequence being a decoupling of nearshore and offshore P cycles with resulting P sequestration and eutrophication[1] in the nearshore while offshore areas are experiencing oligotrophication[2].

Lake Diefenbaker (Saskatchewan) and Lakes Lois and Georgie (British Columbia) differ from the Laurentian Great Lakes in size, depth, geology, terrestrial landscape use, limnological characteristics, and other factors which may affect P cycling. Little has been published on these aquatic ecosystems. Lake Diefenbaker is the focus of an upcoming special issue in Journal of Great Lakes Research and

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[1] Eutrophication is the ecosystem response to the addition of excessive nutrients (mainly phosphates) through detergents, fertilizers, or sewage in a lake or other body of water which causes a dense growth of plant life. The decomposition of the plants depletes the supply of oxygen.

[2] Oligotrophication is the reduction of nutrients in a lake or other mass of water reducing the lake's ability to support the growth of aerobic plants and microorganisms, and contain abundant dissolved oxygen at all depths.

results indicate that internal P loading (i.e., P released from the sediments to the water column) in this large reservoir may play an important role in the P cycle.

P utilization by fish and the release of P waste by fish culture operations have been the focus of numerous research efforts and are relatively well understood and characterized. Principles of nutrition can be used to describe or predict the excretion of P wastes by fish and, by extension, fish culture operations.

Fish ingest P as part of various compounds/nutrients in their diets. These compounds are digested, absorbed, metabolized, partly retained in the body, and partly excreted by the animals. The quantity and digestibility of the P fed and the P requirement of the animal will determine the amount and types of P wastes excreted by fish and, by extension, fish culture operations.

Digested and absorbed P is used by the animal to sustain life processes and form body tissue components (hydroxyapatite in bones and scales, phospholipids, nucleic acids, etc.). Rainbow Trout require around 0.6% digestible P in their diet. Fish receiving only the digestible P amount needed to meet their growth requirements excrete only small amounts of dissolved P (~ 5 mg P kg body weight^{-1} day^{-1}).

The amount of particulate P waste output of aquaculture operations is mainly a function of the amount (concentration) and digestibility of various P forms present in the diet consumed by the animal. Undigested P-containing compounds are egested as faecal material by the animal and particulate P in faecal waste will settle to the sediments. The digestible fraction of P that exceeds fish digestible P requirement is excreted through urine as orthophosphates and represents most of the dissolved P waste of fish culture operations. The dissolved P will enter the water column.

The amount and type of P waste outputs of fish culture operations can be estimated from the amount of feed used, the total P concentration of the feed, the digestibility of P in the feed, the whole body P concentration of the fish, and the feed conversion ratio, as well as the feed wastage by fish culture operations. The amount and types of P waste output of fish culture operations can be quite variable across fish culture operations, seasons, years, fish size, and production cycles.

Fish muscle tissue P concentrations are stable and evolve slightly with change in body size in Rainbow Trout. The evolution of the body P concentration is well described by mathematical models. Whole body P concentrations of Rainbow Trout vary between 0.3 to 0.45%. The concentration of P of commercial Rainbow Trout feeds used in Canada typically varies between 0.9 and 1.4%. Digestibility of P in commercial Rainbow Trout feeds used in Canada typically varies between 40 and 60%.

Feed conversion ratio (FCR), which is the weight of dry feed relative to the wet weight of animal produced, is a metric used in animal husbandry to measure an animal's efficiency in converting feed mass into increases of the desired output (i.e., fish biomass). FCRs at commercial fish culture operations in Canada are largely dependent on the weight of fish, the quality (mainly nutritional composition) of feed used, as well as environmental factors (temperature, seasons) and husbandry practices (feeding practices, production management, etc.). FCRs for commercial Rainbow Trout culture operations in Ontario vary between 1.15 and 1.35 for the entire production cycle (from a typical stocking weight of 30 g to a typical harvest weight of 1.1 kg).

Feeding is generally well-managed on modern commercial fish culture operations and feed wastage is very limited (less than 1% of the feed used). Consequently, most (> 97%) of particulate P wastes released by fish culture operations is of faecal origin.

"Typical" total P waste output of Rainbow Trout culture operations in Canada is estimated to vary between 7 and 15 kg of P (3 to 9 kg of particulate P and 4 to 6 kg of dissolved P) per tonne of fish biomass produced for Rainbow Trout grown from about 30 g to 1,100 g harvest weight under commercial conditions.

Accurate estimation of the amount and type of P waste released by cage culture operations can be achieved through analysis of production data and feed (amounts and direct measure of digestibility or estimation from detailed information of formulation) used by the fish culture operations. Methods to estimate the quantities of P inputs include a simple mass balance approach, various nutritional models (e.g., Fish-PrFEQ model), and direct measures (i.e., sampling under cages with sediment traps). Sampling of the receiving environment is not an accurate method to estimate waste outputs because of the rapid dispersion and uptake of P in the environment. Nutritional models and mass balance methods are the most practical methods. The nutritional model has been shown to generate highly accurate estimates of waste outputs from cage aquaculture.

Hua et al. (2008) integrated information on P nutrition of fish into a factorial model that can be used to estimate P digestibility, retention, and waste outputs of salmonid fish culture operations. This model operates within the framework of the Fish-PrFEQ bioenergetics model (Cho and Bureau 1998, Bureau et al. 2003) and has been shown to generate accurate estimates of waste outputs of Rainbow Trout culture operations to allow theoretical estimation of the different types of P wastes.

Cycling and fate of the chemical forms of P

A whole-lake aquaculture experiment was conducted in Lake 375 at the Experimental Lakes Area (ELA) from 2002-2009. The L375 experiment was a highly detailed scientific study of ecosystem impacts of aquaculture and it provides the most precise mass balance model of a freshwater aquaculture site available. The mass balance showed that sedimentation was the primary fate of P (84–93% of inputs) (Figure 3), therefore, the majority of the P addition from aquaculture was transported to sediments and was not immediately available for biological processes.

While the experiment used commercial methods as much as possible, it did not attempt to simulate commercial aquaculture loading rates in this small lake; a comparison of water volume, biomass of fish produced, and residence time of the water body suggest that the P loading in the experiment was approximately two orders of magnitude greater than what would occur in a commercial setting. Therefore, any observed impacts would be a “worst case” scenario. The P loading delivered by the experimental aquaculture farm (0.27-0.41 g P m^{-2}) to Lake 375 was designed to be comparable to previous fertilization studies conducted at the ELA (0.34 and 0.34-0.48 g P m^{-2} for L226 and L227, respectively). This allowed researchers to compare the ecosystem response to P delivered as aquaculture waste (primarily settleable particulates) with the ecosystem response to P delivered in dissolved form to the epilimnion of a lake. While the aquaculture P inputs did result in measureable changes in water quality and increased algal production; the extent of the changes was considerably less that that observed in L226 and L227, and L375 remained oligotrophic, unlike L226 and L227.

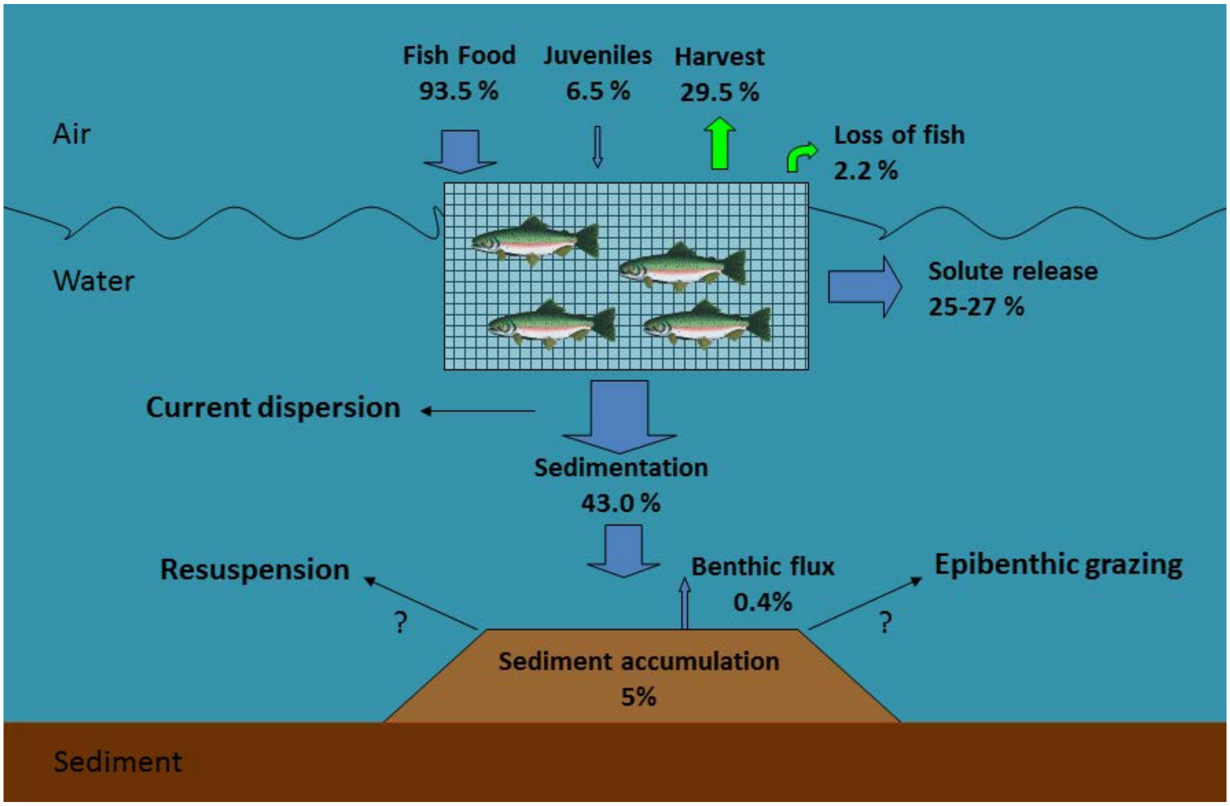

Figure 3. Phosphorus mass balance for Lake 375, ELA experimental aquaculture production in 2005.

The International Joint Commission (IJC) sets P loading targets for the Great Lakes as a means to manage P levels to maintain oligotrophic conditions and reduce the probability of development of nuisance algae. The target total P load to the North Channel of Lake Huron, where most commercial freshwater cage aquaculture in Canada is situated, is 520 metric tonnes per annum (MTA). Dolan and Chapra (2012) calculated P loads for the period of 1994-2008 and reported that P loads to the North Channel exceeded target levels four times during the study period. Years in which the P load exceeded the IJC P target typically occurred during wet years, with the higher loading attributed to diffuse (watershed) P loading sources. However, Dolan and Chapra (2012) included all flows from both the St. Mary and the Les Cheneaux River complex in the North Channel budget and there is some question as to whether this was accurate. Approximately 30% of the St Mary’s flow is estimated to go to the North Channel (David Schwab, NOAA, pers. comm.), while Zhao et al. (2012) estimated only 0.7% connectivity between the Les Cheneaux and the North Channel. The relative lack of data to accurately apportion flow and P loading from these two sources and the limited monitoring of other P inputs to the North Channel remain areas of uncertainty in the North Channel P budget.

Based on 2006 production and watershed P loading values, aquaculture is contributing an estimated 14.1 MTA TP (5.1 MTA dissolved P) to the North Channel (Table 1) which is approximately 5% of the annual total P loads. This is roughly one third the amount that enters the North Channel through precipitation annually.

Table 1. Total phosphorus loads to the North Channel in 2006 (data from Dolan and Chapra 2012) including an estimate of total cage Rainbow Trout aquaculture P loading. Due to uncertainty in the allocation of flows from the Les Cheneaux complex and the St Mary's River to the North Channel, P loading resulting from the lowest suggested allocation and the highest water allocation are provided. Aquaculture waste loading was estimate using the range of P in dissolved /particulate produced per tonne of production at Canadian farms. Note: current IJC North Channel TP load target is 520 MTA.

North Channel TP Sources 2006	**TP load Low (High) (MTA)**	**TP/Total Low (High) (%)**	**TDP load[6] (MTA)**	**TDP/Total Low (High) (%)**
Aquaculture Production (1,660 tonnes)[1]	11.70 (24.98)	4.4 (7.6)	6.72 (10.04)	57.4 (40.2)
Industrial point sources (St. Mary's River)[2]	8.7 (29)	3.2 (8.8)	6.2 (21)	71.3 (72.4)
Municipal point sources (Saulte St. Marie WWTP)	5.1	1.9 (1.5)	3.6	70.6
Direct to North Channel (other municipal waste)	1	0.37 (0.30)	1	100
Unmonitored Indirect source	16	6.0 (4.8)	3	18.8
Atmospheric Wet Deposition	48	17.9 (14.5)	33	68.8
Atmospheric Dry Deposition	48	17.9 (14.5)	0	-
Lake Wolsey [3]	0.18	0.07 (0.05)	0.18	100
Spanish River [4]	98	36.6 (29.7)	32	32.7
Mississagi River	20	7.5 (6.1)	2	10.0
Les Cheneaux Delta Complex[5]	0.9 (30)	0.3 (9.1)	0.2 (7)	22.2 (23.3)
Serpent River	2	0.7 (0.6)	0.4	20.0
Blind River	2	0.7 (0.6)	0.3	15.0
Garden River	2	0.7 (0.6)	0.3	15.0
Thessalon River	2	0.7 (0.6)	0.2	10.0
Root River	2	0.7 (0.6)	0.1	5.0
Big Carp River	0.1	0.04 (0.3)	0.01	10.0
East Davignon Creek	0.04	0 (0.01)	0.005	12.5
TOTAL	**267.72 (330.38)**	**100**	**87.7 (109.3)**	**33.2 (34.5)**

[1] Aquaculture production in 2006 was 1,660 tonnes of fish from all Lake Huron cage farm operations excluding one operation in Georgian Bay and one in Lake Wolsey (data provided by Moccia and Bevan, Aquaculture Centre, University of Guelph).

[2] St. Mary's River flows both into Main Lake Huron and the North Channel and only 30% of the industrial point sources (29 MTA) may contribute to the North Channel budget (Bai et al. 2013).

[3] Lake Wolsey has a man-made channel that connects with the North Channel and directly exchanges water. TP load from Lake Wolsey to Lake Huron was calculated to be 262 kg/year outflow, all of which we have attributed to the TDP load estimate and a proportion (32% or 83.84 kg/year) of that loading was assumed to originate from the Lake Wolsey operation (Milne 2012).

[4] Spanish River loading was composed of 40 MTA TP (28 MTA TDP) from point sources and 58 MTA TP (4 MTA TDP) from non-point sources.

[5] Les Cheneaux Delta complex is a series of inflows that primarily enter main Lake Huron. We estimated that only 3% of Les Cheneaux loading (29 MTA TP or 7 MTA TDP) flows to North Channel (Zhao et al. 2012). High load estimations included 100% of measured TP and TDP loads without consideration of splitting water flow.

[6] Calculation of TDP loads was based on measured values for industrial and municipal point sources, Milne (2012) measured values for monitored rivers (Mississagi, Root and Spanish Rivers) while all others were estimated based on neighbouring catchments.

Dissolved P loading is of greatest concern in nearshore areas of the Great Lakes, where sequestration to the nearshore and rapid turnover of P can create conditions of algal fouling and eutrophication. Dolan and Chapra's (2012) work clearly implicated precipitation as one factor driving interannual variation in P loads and thus the influence of cage aquaculture on nearshore conditions would be expected to be greatest in years when the water inputs and watershed loading are least as was the case in 2006.

P abatement plans put into place in response to IJC target setting, focused on the reduction of point source P loading through the implementation of wastewater treatment and effluent limits, while reduction in nonpoint source P focused on reduction of soil erosion and thereby reduced particulate P loads. Long-term monitoring of P loading to Lake Erie by the National Centre for Water Quality Research at Heidelberg University (Ohio) has identified that since the 1990s there has been a significant increase in the portion of tributary P loads that are in the form of highly bioavailable soluble reactive P (Joosse and Baker 2011, LaBeau et al. 2014) which is believed to have been caused primarily by changes in agricultural practices. In 2011 there was a record-setting algal bloom in Lake Erie (Michalak et al. 2013). The land-use patterns in the North Channel area are not highly agricultural and therefore a similar increase in the ratio of DP:TP may not be occurring; however, the level of tributary monitoring in the North Channel area is insufficient to support any conclusions.

Aquaculture P waste in the form of dissolved P (which generally comprises about 30% of the total P discharge by these operations) is readily available for biotic uptake by bacteria and primary producers. In the receiving environment, dissolved P is further diluted in the water column and rapidly assimilated into the food chain. These processes occur rapidly enough that monitoring programs in Lake Huron typically do not detect elevated TP in the water column downstream of farms (Podemski and Kshymensky in prep.). The fraction of the added P that that is assimilated into nuisance algae will depend in large part on the form of P added, the availability of other essential nutrients, where the P is delivered to and characteristics of the food web and the water body, availability of other essential nutrients, and the amount of P added.

Particulate P waste, primarily in the form of faeces, falls to the sediment rapidly. The depth of water will affect the extent to which particulate waste is distributed and transformed (consumed by wild fishes or leached) as it settles. Under hydrodynamic conditions at Canadian sites that have been studied, this waste is not widely distributed but rather accumulates directly under the cages thereby limiting the area affected.

Sedimentation of P that is assimilated into biota (e.g., algae), as well as sedimentation of particulate P waste is the primary fate of P added to the lake ecosystem by aquaculture. This is similar to the fate of P from tributaries which is also primarily transported to and sequestered in the sediments.

Remobilization of P from sediments can be the result of resuspension of deposited material or chemical release of P from the sediments. The former is the result of water movement at speeds in excess of the resuspension threshold, while the latter is a chemical process dependent upon the form of P and the environmental conditions within and above the sediments.

The release of P from waste settled on the lake bottom can increase the risk of eutrophication of the waterbody, thus, an understanding of the factors that affect the amount and timing of release of P is necessary. Particulate phosphorus occurs in many chemical forms and the environmental conditions necessary for conversion from particulate to dissolved P and then release from sediment differ. P fractionation, in which extraction techniques are used to partition the total P into loosely sorbed P, P bound by Iron (Fe), Aluminum (Al), or calcium (Ca), organic-P, and residual P, contributes to understanding the sediment chemistry (e.g., availability of Fe and SO4) and can help us to understand the potential for mobilization of P load from sediment to water. For example, if Fe:P ratio is low or large areas of the lake bottom becomes anoxic, loosely sorbed P and Fe P fractions may rapidly become soluble. Other forms are not as readily available. Ca-bound P (calcium hydroxyapatite, sourced from bone in the fish feed) requires acidic conditions for dissolution (Andrieux and Aminot 1997), in bioassays this form of P has not sustained algal growth (Williams et al. 1980), and apatite is viewed by many authors as having low bioavailability (e.g., Sonzogni et al. 1982, Li and Brett 2013). Fractionation of particulate P in sediments under aquaculture cages differs from that at reference sites in Lake Huron (Table 2). For example, the rapidly mobilized P (loosely sorbed and Fe P) is 13% of TP under cages, as compared to 4.1% at reference sites, whereas the less soluble fraction of Ca-bound P under cages is 65% and 32% of TP under cages and at reference sites, respectively. The fraction of TP that is potentially rapidly dissolved is greater under cages than at reference sites, but the surface area affected is generally restricted to < 30 m distance from cages, which may help to mitigate risks of internal P loading. Future P fractionation analyses may aid in the prediction of the potential for internal P loading from aquaculture waste deposited to the sediment.

Table 2. The percent and standard deviation of total P concentrations measured by P fractionation analyses from surface sediments at three sites: under fish cages, 30 m distance away and at reference sites (> 1,000 m away) from two freshwater commercial Rainbow Trout farms in Lake Huron (Podemski unpubl. data).

Fraction	Under Cage	30 m from Cage	Reference Site	Mobility
Loosely sorbed-P (NH_4Cl-P)	7.8 ± 1.4	1.5 ± 0.8	0.9 ± 0.9	Labile (anoxia)
Fe-P (BD-P)	5.1 ± 0.1	4.6 ± 1.3	3.2 ± 2.0	Labile (anoxia)
Organic-P (NaOH-nrP)	2.0 ± 0.6	5.2 ± 3.8	16.8 ± 3.1	Portion labile (anoxia)
Al-P (NaOH-rP)	5.5 ± 0.7	12.6 ± 8.3	9.2 ± 5.3	
Ca-P (HCl-P)	65.0 ± 3.9	50.2 ± 23.5	32.4 ± 13.9	Refractory
Res-P (Residual-P)	7.0 ± 0.1	8.1 ± 1.1	11.6 ± 1.7	Refractory

Methods to predict, manage, and mitigate cage aquaculture P effects

The response of a lake to added P can be predicted by models ranging from simple empirical models relating P loading to chlorophyll a concentrations, to simple dynamic models that treat the lake as a single compartment, to complex dynamic models that divide the lake into many compartments and include a complexity of hydrodynamic and ecological processes.

Currently in Ontario, the Lake Shore Capacity model, an empirical, Vollenweider-based model relating changes in P loading from watershed activities to changes in chlorophyll a concentrations, is the approach most often applied to make decisions on the capacity of small lakes to assimilate P additions from changing lakeshore development. It is not routinely applied to the regulation of aquaculture activities (Milne 2012).

P loading from the experimental aquaculture facility in L 375 enhanced phytoplankton productivity and biomass but to a lesser extent than predicted by Vollenweider-based models (Bristow et al. 2008). A similar overestimation by Vollenweider modelling of the response to P loading from aquaculture was observed by Håkanson and Carlsson (1998). Two more sophisticated models that have been tested in Europe to predict the response of a whole lake environment to P loads, including effects of freshwater cage aquaculture, are the LEEDS (Håkanson and Carlsson 1998) and LakeWeb (Håkanson 2005) and they have provided more accurate predictions of chlorophyll response to P loading. These two related models (LEEDS is a modified version of LakeWeb) include P in both dissolved and particulate forms and incorporate the processes of: direct consumption of waste P by wild fish, sedimentation, mineralization, resuspension/advection, diffusion, burial, biotic uptake, P released from biota, and mixing between strata. Neither version has been tested for applicability to Canadian ecosystems.

Because the P wastes (particulate and dissolved) produced by fish find their origins in the intake, digestion, and metabolism of dietary P compounds, nutritional strategies offer a direct way of managing and mitigating the release of P waste of fish culture operations. The modification of feed composition has been demonstrated to be a highly effective way of minimizing P waste outputs by fish culture operations (Cho et al. 1994, Cho and Bureau 1997, Hua et al. 2008). Dietary manipulations have been used to improve the digestibility of dietary P. The formulation of diets that have reduced total P levels, and are adequately meeting the nutritional requirements of the fish, have reduced the amounts of P waste output from fish culture operations. In Ontario, aquaculture licensing requirements have set upper limits on the P content of feeds but the *Canada Feeds Act* has imposed a minimum 1% P content of feed, so further reductions may not be feasible. Annual feed quotas (amount of feed a farm can use) have proved effective at reducing P waste from fish culture operations. Additional developments could include improved composition of the feed to improve efficiency of feed utilization thereby reducing the amount of feed required and reducing solid/particulate outputs.

Ensuring proper siting of aquaculture operations is an effective strategy to mitigate the effects of P loading. In Ontario, the licensing process limits sites to areas with sufficient hypolimnetic flushing as a means to limit the likelihood of developing anoxia and hence internal P loading.

Siting criteria could be further developed to mitigate risks of P loading. The P levels in the Great Lakes are not spatially homogeneous; there is greater concern about P loading in the nearshore due to the potential for algal fouling of shorelines, whereas in the offshore, P is limited so loading is of less concern. Moving cages offshore is a mitigation strategy that could be considered to reduce P loading in the nearshore.

Although no scientific information is currently available from freshwater and only limited information from marine, fallowing strategies could also be considered as a mitigation measure against exceeding P loading limits in nearshore aquaculture sites.

Ongoing environmental monitoring at freshwater aquaculture sites in Canada ensures impacts to the environment are reported. In Ontario and Saskatchewan, license conditions require ongoing water chemistry (total P concentrations, dissolved O_2 concentrations) and sediment chemistry be monitored. In Ontario, adverse impacts trigger a requirement for additional sampling and may also result in a requirement for on-site mitigation strategies such as reduced feed quotas.

Risk characterization of P from freshwater cage aquaculture

This review does not provide a formal risk assessment but rather characterizes some of the risks associated with P inputs from freshwater aquaculture.

The likelihood of P inputs from the cage aquaculture industry resulting in eutrophication to Canadian freshwater environments, under the current level of industry production and practice, can generally be characterized as ‘low’. In Ontario, legislation permits regulation of the industry and monitoring agreements enable provincial bodies to identify non-compliance. Current mitigation measures include water and sediment quality monitoring, limits of P content in feeds, the use of feed quotas, and siting criteria. The aquaculture industry currently accounts for approximately 5% of the total P input to the North Channel and routine environmental monitoring has failed to detect any significant non-compliance with water quality standards.

In the late 1990s, the area around one freshwater aquaculture site in the LaCloche Channel, near Manitoulin Island, experienced problems with low dissolved oxygen and algal blooms (Gale 1999). It was determined that this site was poorly sited due to low water flushing rates in the area and the site was decommissioned in 1998. Since this time, farms in Lake Huron have been sited in areas with better hypolimnetic flushing and problems with excessive algae or low dissolved oxygen have not been reported. Total P concentrations are routinely monitored at cage aquaculture sites licensed in Ontario and P concentrations do not exceed provincial water quality guidelines.

P inputs from licensed sites can be characterized with a high degree of certainty through the use of nutritional modelling. There is, however, uncertainty in the level of P loading from fish farm operations that are currently not reporting production, feed use, or monitoring information to provincial and/or federal authorities.

Although the freshwater cage aquaculture industry is currently sustainable in Lake Huron, as evidenced by the small contribution to total P load and the lack of elevated P in receiving waters downstream of the operations, the growth of the industry (or expansion of any activity that contributes to the P loading) requires careful consideration of the total amount of P loading (from all sources not just aquaculture) and the location, so as not to exceed an area’s total loading limits. There is a high level of uncertainty surrounding the magnitude of watershed P loading to lakes due to insufficient monitoring of all input sources, and little is known of inter-annual variation in P loading. Given the uncertainty surrounding other sources of P, it is determined that the well quantified inputs of P from aquaculture sources at current levels of production and using current industry practices shows little evidence of contribution to eutrophication of the receiving water.

Furthermore, confounding variables like the introduction of invasive species, changes in land use practices, and climate change will challenge our current understanding of the influence of P from freshwater cage operations on the eutrophication potential.

Under current environmental conditions, concern for P levels in the Great Lakes is related to the spatial distribution of P loads. In the nearshore, there is a greater need to mitigate P loads due to the occurrence of algal fouling of shorelines, whereas in the offshore, P loading is of less concern and higher P loads may be considered advisable as a means to address concerns regarding low productivity of forage fish and poor condition of sport and commercial fish species. The IJC is in the process of revising P target loads (currently 520 MTA) in the North Channel); they are anticipated to distinguish for the first time between nearshore and offshore and may also include dissolved versus particulate load targets. It is anticipated that the redistribution of P loading targets will result in some nearshore areas being identified with lower targets for dissolved P in particular, whereas higher P loading targets may be identified for the offshore.

Sources of Uncertainty

Data Uncertainties

While the knowledge of P content in feeds and the use of feed quotas can be used together to estimate P loading, in Ontario there is uncertainty in the level of P loading from fish farm operations that are currently not reporting monitoring information to provincial and/or federal authorities.

Improved knowledge is required of the primary biological, limnological, and geochemical factors that can influence the specifics of P cycling on an ecosystem-specific basis. In particular, there is a need to better understand the physical (e.g., climate, depth, temperature), chemical (e.g., redox, Fe, sulfate), and biological (e.g., invertebrate interactions and decomposition) processes acting on the aquaculture wastes deposited under freshwater cages to better understand P remobilization from deposited wastes.

Primary biological, limnological, and geochemical factors that influence P cycling and how these differ across the lake ecosystems in Canada that currently support, or may be suitable for aquaculture production in the future, are not well understood.

Measurement of all sources of external P loadings (particularly non-point sources of P) needs to be improved to capture P loading variability. Measurements should include both dissolved and particulate P fractions on a year-round scale and event basis. Current monitoring excludes a number of sources of P including some rivers, dry deposition, adequate spatial assessment of atmospheric deposition, event-based P measures from tributaries, and dissolved P concentrations. The paucity of tributary monitoring data, in particular, compromises the ability to calculate accurate P loading.

Modelling Uncertainties

How different lakes will respond to P loading from aquaculture waste is uncertain. Existing models may overestimate P concentrations and algal blooms. There is a need to develop and improve P models for prediction, management, and mitigation of aquaculture P waste. The applicability of European whole lake models that have specifically incorporated aquaculture in predicting the response of lake ecosystems to P loads should be investigated in Canada.

Unknowns in Mitigation Strategies

There is a need to identify and understand the P assimilative capacity of freshwater aquaculture sites in order to be able to assess potential cumulative effects associated with the addition of aquaculture P loads and to determine the maximum allowable aquaculture production yield in an area in advance of adverse water quality or food web changes.

There is uncertainty whether aquaculture cage siting is best characterized by the Type 1-3[3] classification scheme used in Ontario given the number of limnological tools currently available. There is an interest in identifying site characteristics, other than flushing, that could be considered during the site licensing process, such as sulfate concentrations, sediment grain size, and sulfide:iron:phosphate ratios.

Should fallowing be implemented as a mitigation strategy against the effects of P loading, there is a need to better understand the timeframes for P remediation at sites. Given that aquaculture waste is largely deposited below cages and results in P being exported to the sediments, an effective fallowing strategy requires further knowledge of sediment recovery times, P burial, and recycling.

Offshore freshwater cage operations are anticipated to become a viable means of industry expansion in the coming years with advances in remote feeding and cage design. Due primarily to the deeper waters, there is a need to better understand how particulate aquaculture wastes would be distributed during sedimentation and how the potential for internal P loading may change in offshore areas.

CONCLUSIONS AND ADVICE

The importance of P to the freshwater environment and in particular to those Canadian ecosystems where cage aquaculture is prevalent

P is naturally found in the environment although rarely in its elemental form. It is naturally present in variable concentrations in the water column of freshwater aquatic environments, often in the form of phosphates (PO_4^{-3}, PO_4^{2-}, PO_4^{-}).

Sources of P to lakes include geologic (e.g., weathering of rock), biologic (e.g., leaf litter), and anthropogenic (e.g., sewage effluent). The relative contribution of natural and anthropogenic sources varies greatly with catchment characteristics.

P is the growth limiting nutrient for primary producers in most lakes and lake productivity is therefore related to P availability. Water bodies are often categorized by their total P concentration: oligotrophic (4-10 $\mu g\ L^{-1}$), mesotrophic (10-30 $\mu g\ L^{-1}$), eutrophic (30-100 $\mu g\ L^{-1}$).

Phosphate is cycled between its different forms in lakes within the water column and the sediments with many biotic and abiotic factors influencing the distribution and form of P in the ecosystem. The high biotic demand for P in lakes generally means that soluble P does not build up over time in the water

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[3] As defined by Boyd (Ontario Ministry of the Environment unpubl. rep.), a Type 1 site is an enclosed basin with limited flushing; Type 2 is a partially exposed site with good epi/metalimnetic flushing but limited or no hypolimnetic exchange; and Type 3 is an exposed location where the entire water column is well flushed.

column, but rather tends to be barely detectable. Transport to and burial in the sediments is the normal fate for most (typically more than 80%) of total P that enters a lake.

> *Advice:* Phosphorus (P) is biologically significant and both naturally and anthropogenically sourced. Naturally, P is found in low but variable concentrations in water bodies and tends to be the growth-limiting nutrient for primary production. P concentration in lakes is significantly correlated with changes in lake productivity and water quality. Anthropogenic change to P loading to a lake ecosystem therefore should be considered in the process of management activities that can contribute to total P loading.

To accurately predict the effect of P additions to a lake ecosystem, it is necessary to understand how the biotic (e.g., food web structure) and abiotic characteristics (e.g., sediment chemistry, limnology) of that ecosystem will affect P cycling.

Major changes in the Laurentian Great Lakes over the past 30 years with respect to food web structure and the amount and character of P loading have had profound effects on P cycling. This has resulted in a spatial change to the P cycles with increasing eutrophication reported in many areas of the nearshore and oligotrophication occurring more widely in the offshore environment.

In Canada, freshwater cage culture currently occurs in lakes that differ in size, depth, geology, terrestrial landscape use, limnological characteristics, and other factors which may affect P cycling; however, little information is available on the significance of P from aquaculture to these lakes.

> *Advice:* To accurately predict and manage potential effects of P additions to lake ecosystems from aquaculture, it will be necessary to develop an understanding of the factors that can influence P cycling on an ecosystem-specific basis. In particular, further work needs to be done to understand the factors influencing release/retention of P from sedimented waste material and how food web structure may influence P cycling between the water column and the sediments.
>
> *Advice:* Introduction of invasive species and changes to landscape use have the potential to alter P cycling within the lake ecosystem. The extent to which an invasive species may impact P cycling will be dependent upon characteristics of that species; for example, zebra mussels have been particularly influential because of their filter feeding habit coupled with high filtration rates. A change in landscape use can significantly alter not only total P loading but also the ratio of dissolved to particulate P loading. Therefore, continued monitoring of catchment P loading and alterations to trophic structure are needed in ecosystems that are being managed to accommodate aquaculture in order to understand the total P loads.

P inputs from freshwater cage farms and methods for estimating inputs

The amount of P waste output attributable to aquaculture operations is mainly a function of the amount of P (concentration) and digestibility of various P forms present in the diet. Undigested P is excreted in faeces. The digested fraction of P that exceeds fish growth requirements is excreted through urine as orthophosphates and represents most of the dissolved P waste of fish culture operations.

P released from freshwater cage aquaculture operations is primarily in the form of particulate P waste from faeces and to a lesser extent as dissolved P waste from urine and gills.

- P excretion by aquaculture fish is directly linked to amount and digestibility of P in the diet.
- P loading from aquaculture is minimized through the use of low-P, highly digestible feeds.

P concentration in commercial Rainbow Trout feeds used in Canada currently ranges between 0.9 and 1.4%; P digestibility typically varies between 40 and 60%.

Feed waste is generally low (less than 1%) and is managed closely by farms to minimize feed costs.

Feed conversion ratio (FCR) is dependent on the life stage or size of the fish and on animal husbandry practices but typically ranges from 0.8–1.6. Over a production cycle typical FCRs for Rainbow Trout in Canada range from 1.15-1.35.

Nutritional models are the most practical method to accurately estimate P release from farms. P waste is currently modelled with high precision for Rainbow Trout using models such as FISH-PrFEQ which are based on knowledge of fish species bioenergetics and nutrient modelling.

P waste outputs of Rainbow Trout culture operations in Canada are estimated to vary between 3 to 9 kg of particulate P and 4 to 6 kg of dissolved P per tonne of fish biomass produced.

Modelled P waste from aquaculture operations is an accurate estimate of the contribution of P that is not directly quantifiable by sampling the receiving water because of sediment dispersion and alterations (e.g., uptake, sediment focusing, and resuspension) that can occur.

- Nutritional modelling of feed and husbandry data provides an accurate estimate of the contribution of P that is not quantifiable by sampling the receiving water because of rapid dispersion, settling, and transformations that occur to waste P once it enters the environment.

  Advice: Management of the potential effects of aquaculture-related P inputs to lake ecosystems would be improved by employing nutritional modelling to characterize the amount, form, and timing of P loading.

Cycling and fate of the chemical forms of phosphorus in the freshwater environment

The ELA L375 experiment demonstrated that P loading in the form of aquaculture waste (i.e., primarily settleable particulate faeces) resulted in a smaller ecosystem response than a similar loading of P delivered in a soluble form to the epilimnion of two other lakes (L226 and L227) at the ELA. Lake 375 remained oligotrophic after 5 years of aquaculture while L226 and L227 became eutrophic within months.

The form and timing of P loading and where P loading is delivered to a lake ecosystem affects the ecosystem response. Therefore, not all forms of P loading can necessarily be assumed to pose equal risk.

The ELA L375 experiment provides the most precise mass balance model of a freshwater aquaculture site available. This mass balance showed that sedimentation was the primary fate of P (Figure 3), consequently a large proportion of P release by farms ends up being removed from the water column. Total P output is not an accurate measure of a farm's potential impact on water quality.

Aquaculture contributed approximately 5% of the TP loads to the North Channel in 2006. This was a low precipitation year and therefore the contribution of aquaculture to the total load is proportionally higher.

The North Channel may exceed IJC target P loads in wet years; however, limitations in the availability of data used to calculate the P loading creates uncertainty in this conclusion.

- Total farm P output is not an accurate measure of potential eutrophication risk of P addition to the ecosystem. The timing of delivery and the fate of the P loading can significantly modify this risk.

  Advice: Ecosystem-specific differences in limnology, geochemistry, and trophic structure can modify P cycling, therefore, further science is needed to determine the fate of aquaculture P in ecosystems supporting commercial cage culture.

  Advice: The low level of monitoring of tributary P inputs is a significant source of uncertainty in the estimation of the total P loads to the North Channel. There is a need to significantly improve

> spatial monitoring of P sources to ecosystems that are being managed to accommodate for aquaculture. The accurate estimation of P loading is necessary to determine P budgets.
>
> *Advice:* Natural variability in annual precipitation can significantly affect watershed P loading to lake ecosystems. It would be advisable to manage all anthropogenic P loading such that there is room to accommodate the natural range of variation in watershed loading and still prevent deterioration of water quality.
>
> *Advice:* Although the aquaculture industry is currently only contributing approximately 5% of the P load to the North Channel, the biological importance of P to lake productivity and the need meet IJC P load targets suggest that P loading needs to be considered in the management of future industry expansion or other activities known to contribute to P loading.
>
> *Advice:* Development of future P load targets would be improved by consideration of nearshore versus offshore responses to P loading and consideration of particulate versus dissolved forms of loading. Development of separate load limits for nearshore versus offshore and for dissolved P versus particulate P would improve management of the North Channel ecosystem.
>
> *Advice:* A watershed management strategy that considers not only aquaculture but also other activities within the watershed and their potential contribution to P loads would be of benefit to all stakeholders.

In the receiving water, dissolved P waste is diluted and is rapidly assimilated into the foodchain. Monitoring programs at Lake Huron farms typically do not detect increased TP in the water column.

Whether or not dissolved P contributes to nuisance algal growth will depend in large part on the amount and form of P added, availability of other essential nutrients, where the P is delivered to and characteristics of the water body and the food web.

Particulate P waste, primarily as faeces, falls to the sediment rapidly. The depth of water will affect the extent to which particulate waste is distributed and transformed (i.e., consumed by wild fishes or leached) as it settles. Under hydrodynamic conditions at monitored Canadian sites, fish waste was not observed to be widely distributed but instead accumulated under the cages.

Mass balance models have demonstrated that a significant portion of the P waste (dissolved and particulate) in temperate lakes ends up in the sediment. In the ELA experiment, 85% or more of P added through aquaculture was sequestered to the sediments.

> Advice: A significant portion of the P waste (dissolved and particulate) added to a temperate lake by aquaculture operations is sequestered to the sediments, as would be the case for ‘natural’ P coming from tributaries. Therefore, the total P loading is not necessarily an accurate predictor of the eutrophication potential of the P loading. It is the amount of P that remains in the water column and that which is released from sediments that needs to be considered.

P in sediments can be found in a variety of different fractions, for example, bound by Fe, Al, or Ca.

Under the right conditions, some fractions of P in sediments may become soluble, known as internal P loading, and thus available to enter the food web. The most commonly understood mobilization is the release of P bound to Fe under conditions of anoxia. Some fractions are essentially nonmobile because the conditions required to mobilize P from this form are highly unlikely to occur or because the rate of mobilization is extremely low.

Particulate P fractionation techniques can be used to understand the form of P binding in sediments and thereby better understand the potential for dissolved P leaching from the sediment.

Limited data from P fractionation analysis exists from two commercial Rainbow Trout sites in Lake Huron. Fractionations of particulate P in sediments under cages differed from reference site P composition (Table 2). For example, Ca-bound P, particularly bone meal from fish food found, occurred in higher proportions under cages than at reference sites. The Ca-bound P is believed to be less mobile and only liberated under acidified conditions.

- Data, however limited, exists which indicates that the forms of P found in sediments under and around fish cages differs in relative quantities from those found in sediment at reference sites.
- The form of P, as well as the quantity, needs to be understood to properly characterize the potential for remobilization and thereby the development of internal loading. Internal P loading releases P that was sequestered in the sediments and makes it bioavailable. This release is undesirable as it increases the proportion of the P loading that contributes to eutrophication potential.

  Advice: Additional sampling for P fractionation at commercial cage aquaculture sites and reference sites, as well as measures of P release from the sediments (i.e., becomes soluble), would improve the ability to characterize the risk that this P accumulation in sediments poses to eutrophication potential.

Methods to predict, manage, and mitigate effects of cage aquaculture phosphorus in the freshwater environment (i.e., water, sediment, biota)

There are modelling tools of varying levels of complexity that could be used for the prediction and management of impacts associated with the addition of P to systems from freshwater aquaculture: the applicability of these models to Canadian waters has not been tested.

> *Advice:* The ability to manage the cumulative impacts of freshwater aquaculture in Canada may be improved by using European models that have specifically incorporated aquaculture in predicting the response of whole lake ecosystems to P loads.
>
> *Advice:* These models need to be verified in Canadian ecosystems because the structure of the foodweb and sediment chemistry may vary.

Nutritional strategies offer a direct way of managing and mitigating the release of P waste of fish culture operations.

The modification of feed composition to improve digestibility and closely meet dietary requirements has been demonstrated to be an effective means of reducing P waste outputs by fish culture operations.

These formulated low P feeds are used widely in the commercial cage industry.

In Ontario, licensing requirements set limits on the P content of feeds and these combined with annual feed quotas (amount of feed a farm can use) and have proved effective at reducing P output from farms.

Additional feed development could focus on improving efficiency of utilization which would reduce feed usage and waste outputs.

> *Advice:* Nutritional strategies can be a direct and effective means to manage P release from fish culture.
>
> *Advice:* Development of feed that is more efficiently utilized by fish could be a means to reduce feed usage and waste outputs.

- In Ontario, licensing requirements that incorporate the use of feed quotas and the requirement for low P feed use have proven effective at mitigating the eutrophication potential of P waste from fish culture operations.

Ensuring proper siting of aquaculture operations is the current method for mitigating the risks of P loading. In Ontario, the licensing process limits sites to areas with sufficient hypolimnetic flushing to limit the probability of anoxia and hence internal P loading developing.

Moving cages offshore and fallowing at nearshore sites are potential strategies to mitigate risks of P loading, but there is currently no scientific information to support the development of advice.

Ongoing environmental monitoring at established freshwater aquaculture sites ensures impacts to the environment are reported. In Ontario and Saskatchewan, license conditions require ongoing monitoring of total P, dissolved O_2, and sediment quality. Adverse impacts trigger additional monitoring and may result in a requirement for reduced feed quotas.

- Cage siting requirements that minimize the potential to develop internal P loading (e.g., sites with sufficient flushing) and routine environmental monitoring are currently used to mitigate the risks of P loading.

  Advice: Additional refinements in siting criteria such as fallowing or placement in offshore areas could be developed to further mitigate risks of aquaculture P loading in nearshore freshwater areas. Fallowing is not currently carried out for freshwater cage aquaculture. Movement of operations to the offshore could take advantage of higher P loading targets and would also benefit from greater water depths resulting in greater waste dispersion.

Assess risk of phosphorus inputs from the cage aquaculture industry to Canadian freshwater environments

This review is not a formal risk assessment but rather characterizes some of the risks associated with P inputs from freshwater aquaculture.

The likelihood of P inputs from the cage aquaculture industry resulting in eutrophication to Canadian freshwater environments, under the current level of industry production and practices, can generally be characterized as ‘low’. In Ontario, legislation permits regulation of the industry and monitoring agreements enable provincial bodies to identify non-compliance. Current mitigation measures include water and sediment quality monitoring, limits to P content in feeds, the use of feed quotas, and siting criteria.

Although the freshwater cage aquaculture industry is currently sustainable in Lake Huron, the growth of the industry (or expansion of any activity that contributes to the P loading) requires careful consideration of the total amount of P loadings (from all sources not just aquaculture) and the location so as not to exceed an area’s total loading limits.

- The likelihood of P inputs from the cage aquaculture industry resulting in eutrophication of Canadian freshwater environments, under the current level of industry production and practices, can generally be characterized as ‘low’.

  Advice: Future growth of the industry or expansion of any other anthropogenic activity that contributes to the P loading requires careful consideration of the P input from all sources.

Under current environmental conditions, concern for P levels in the Great Lakes is spatially heterogeneous. In the nearshore, there is a greater need to mitigate P loads due to the occurrence of algal fouling of shorelines whereas in the offshore, P loading is of less concern.

The IJC is in the process of revising P target loads (currently 520 MTA North Channel) and will include future nearshore and offshore limits as well as distinction between dissolved and particulate loads. It is anticipated that redistribution of P loading targets will result in areas of concern in the nearshore that will be identified for lower P targets (dissolved phosphorus (DP) loadings in particular), and potentially higher P loading targets in the offshore.

- Revised IJC target P loads are expected to distinguish between dissolved versus particulate forms of P and nearshore and offshore (i.e., spatial distribution of P loads). Management of future development of the industry should combine nutritional modelling with whole lake modelling to provide accurate estimations of P outputs along with siting criteria to best accommodate spatial load targets.

OTHER CONSIDERATIONS

The release of P, C, and N in farm wastes are intrinsically related and although the subject of this review was P, this was due to the nature of the CSAS request and was not intended to imply that the sole concern associated with waste release is P loading. Aquaculture waste contains not only P but also can represent a significant nitrogen and carbon load to the receiving waters. Organic carbon for example, has the potential to significantly alter benthic habitats and to reduce dissolved oxygen concentrations in sediments and the overlaying water column and multiple pathways of effect need to be considered in managing and mitigating the potential risks to aquatic ecosystems.

SOURCES OF INFORMATION

This Science Advisory Report is from the June 17-19, 2014 regional peer review of Freshwater Cage Aquaculture: Ecosystems Impacts from Dissolved and Particulate Waste Phosphorus. Additional publications from this meeting will be posted on the DFO Science Advisory Schedule as they become available.

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ISSN 1919-5087

Correct Citation for this Publication:

DFO. 2015. Freshwater cage aquaculture: ecosystems impacts from dissolved and particulate waste phosphorus. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/051.

Aussi disponible en français :

MPO. 2015. Aquaculture en cage en eau douce : impacts écosystémiques des déchets de phosphore dissous et sous forme de particules. Secr. can. de consult. sci. du MPO, Avis sci. 2015/051.