FRESHWATER AQUACULTURE:

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Introduction

Freshwater aquaculture is a rapidly growing agricultural food production practice that often involves rearing fish in cages suspended within a lake. Each year in Ontario alone, the freshwater cage aquaculture industry produces 4,510 tonnes of rainbow trout, which has an estimated economic contribution of $80 million (Moccia & Bevan, 2016). Increased demand for fish protein to meet the needs on an ever growing population highlights the need for aquaculture policy that effectively protects the environment but enables industry growth. However, a lack of functional government regulations and guidelines prevent the cage culture industry from expanding existing sites and accessing new sites (Fisheries and Oceans Canada, 2006; Moccia & Bevan, 2016). Therefore, a better understanding of how freshwater cage aquaculture facilities affect lake ecosystems is required.

The environmental impact of waste from the fish culture industry, notably from cage culture operations, is increasingly a matter of close scrutiny. There are many environmental implications associated with cage aquaculture as waste feed and fecal matter are directly released into the natural system. These environmental issues are categorized into water quality, sediment alteration and effects on native fish populations (Fisheries and Oceans Canada, 2006; Kullman et al., 2009) and have been primarily studied in marine systems. Research has been conducted on water quality changes due to high levels of dissolved nitrogen and phosphorus causing eutrophication, algae blooms, and decreased oxygen (Folke et al., 1994; Fernandez-Jover et al., 2007; Sara, 2007, Guo et al., 2009). The the potential for nutrient loading and oxygen depletion have been mediated by developing high density, low phosphorus feed and by establishing farm sites that have improved water circulation (Cho and Bureau 1997). Cage aquaculture has also been shown to alter the habitat in which it is situated by increasing sedimentation and organic matter concentrations, in sediment close to the cages (Cho & Bureau, 2001; Carroll et al., 2003).When waste settles under the cages, it is degraded by bacteria who consume oxygen in the process. This degradation process by bacteria can lead to significant reduction in dissolved oxygen and create anoxic conditions (Cho & Bureau, 2001). Sediment changes are often found in shallow lake areas that are likely not suitable for long term sustainable aquaculture sites due to their already high nutrient levels and low flushing abilities. The technique of moving the cages (fallowing) is a mechanism used to mitigate sedimentation because the area where the cages once were, is able to recover when the cage location is changed (Carroll et al., 2003, Cho & Bureau, 2001, Guo et al, 2009). Although decreased water quality and habitat alteration have associated implications for native organisms, with current Canadian policy regarding the establishment of aquaculture it seems less likely to occur.

With a growing population and demand for fish protein, the expansion of the aquaculture industry seems like a likely avenue. This review provides a background on the research that has been conducted with regards to the environmental impacts of freshwater net-pen aquaculture and suggests future directions for research.

Waste Production

Understanding factors influencing waste production in freshwater net-pen aquaculture is of great importance in order to reduce environmental impacts and have the industry grow in a sustainable manner (Cho and Bureau 2001; Bureau and Hua 2010). The discharge of solid wastes is mainly a function of the digestibility of dietary components, whereas the discharge of dissolved wastes is mainly a function of the metabolism of nutrients by farmed fish (Cho and Bureau 2001).

Solid Waste

Solid waste forms the majority of waste from net-pen aquaculture with feces being the main component and a small amount of waste feed. In Ontario, total solid wastes are estimated to be between 240 and 318 kg/ metric ton of fish produced with the majority of waste coming from fish faecal waste (Bureau et al. 2003; Reid et al. 2009). It is estimated that 15-30% of applied feed is released as fecal waste (Bureau et al., 2003; Osuchowski, 2013). Waste feed includes both uneaten feed pellets and fines (small dust-like particles of feed) however feed wastage is well managed as feed presents a substantial cost to the operator. The amount of waste feed varies, however with common feeding methodologies, the average is 2-5% of feed applied (Bureau et al., 2003; Osuchowski, 2013). Factors affecting waste production include amount of feed applied, fish size, fish species, water temperature, feeding method and diet composition. However the most important factors that affect waste output according to Cho and Bureau 2001, are the digestibility of ingredients used in commercial feed applied as well as nutrient content and how closely it matches the nutrient requirements of the farmed fish species (Ackefors and Enell 1994; Cho and Bureau 1997). The ideal feed is well suited to the nutritional needs of the fish so that maximum growth can be achieved with minimum waste, particularly phosphorus and nitrogen (Cho and Bureau 2001).

Dissolved Waste

Dissolved nutrients are released through the gill and urinary excretions of cultured fish, are leached from faeces and feed as they fall through the water column, and are released from the sediments as solid wastes deposited under the cages decompose (Kelly 1992, 1993; Bureau and Cho 1999; Fernandez-Jover et al. 2007). The release of dissolved nutrients is a direct function of feed consumption, metabolism and retention of nutrients by farmed fish. (Azevedo et al. 1998; Bureau and Hua 2010). Nutrients from feed are absorbed by the fish and can either be used for metabolic processes or are retained for tissue components. The nutrients that are not retained, are used to support bodily processes and the end products from metabolism are eliminated through excretion (Bureau and Hua 2010). Nutritional strategies offer a direct way of managing waste released from net-pen aquaculture operations. Modification of feed composition has proven to be a very effective tool at reducing waste (Cho and Bureau 1997). It is important to understand how factors such as fish species, size and age affect waste output in order to minimize waste output (Bureau and Hua 2010).

Nitrogenous Waste

Nitrogenous waste appears in mostly in dissolved form from net-pen aquaculture practices. Dissolved nitrogen (N) is the largest component of dissolved waste from net-pen aquaculture operations and it is estimated that over 70% of nitrogenous wastes are in the form of dissolved ammonia (Ackefors and Enell 1990; Enell and Ackefors 1991; Enell 1995). The majority of dissolved N comes from ammonia and urea which are metabolic by products of amino acid metabolism and are released through gills and through fish urine (Weston et al. 1996). Ammonia production is affected by temperature, feed type and fish size. The highest production of ammonia and urea occurs in warmer temperatures and at high feeding rates (i.e. high metabolic rates). N is also released from settled waste. N contributes to primary production however it is not a limiting nutrient in freshwater systems therefore it is of less of a concern in comparison to dissolved P.

Phosphorus Waste

Another main contributor to waste released from aquaculture activities is phosphorus (P). Phosphorus is an essential mineral in diets fed to fish but P released in aquaculture effluent is considered a point source of pollution by many regulatory agencies. Uneaten food and unavailable dietary P in feces are the two primary contributors in fish farm effluents. The majority of waste P is lost to the environment in particulate matter (Ackefors and Enell 1990; Enell and Ackefors 1991). Phosphorus is the most concerning waste from an environmental perspective as it is a limiting nutrient for freshwater. The concern arises when excess amounts of phosphorus are available which can result in significant algal blooms and eutrophication. Sources of P are urinary excretions, solubilisation of feed and faeces and release from waste accumulated in the sediment (Azevedo et al. 1998; Bureau and Cho 1999). P released from aquaculture waste is very dependent on feed composition for leaching from feed and faeces therefor feed containing the required dietary content of digestible P will excrete only small amounts dissolved P (Cho and Bureau 2001).

P leaching from feed is estimated at 0.3% of the soluble P excreted by cultured fish at a feed loss rate of 20% of all feed applied. Since the feed lost to the environment is estimated at a maximum of 5% in Ontario, P leaching is very insignificant source of soluble P relative to leaching from feces (Garcia-Ruiz and Hall 1996). Faeces present a greater proportion of labile P with 43% of total P content in faeces being labile (Garcia-Ruiz and Hall 1996). This isn't surprising as faeces are a large source of waste, sink more slowly than pellets and break apart easily (Phillips et al. 1993). It is also noted by researchers that anthropogenic activities such as industrial and agricultural activities are much greater sources of P input to freshwater than aquaculture. Input from agricultural areas contributes to 33-44% of the P (Robertson and Saad, 2011), thus contributing significantly to P loading in aquatic systems.

Water Quality

Dissolved Oxygen Concentrations

Dissolved oxygen (DO) in the water column is essential for successful fish rearing. Fish respiration and the microbial metabolism are both processes that consume dissolved oxygen in the water column near farm operations. In addition, indirect effects on oxygen consumption may occur due to nutrient-related increases in microbial, phytoplankton, and zooplankton biomass and its respiration and eventual decomposition (Weston et al. 1996).

The effects of aquaculture on dissolved oxygen (DO) concentrations in the scientific literature are inconsistent. The greatest concern for decreased dissolved oxygen is in the hypolimnion. The hypolimnion has less capacity to regenerate oxygen content thus making it the most sensitive to changes in DO (Gowan et al. 1994). During stratification, the hypolimnetic oxygen pool is static and consumption of oxygen by fish and decomposition processes can reduce the quantity of DO (Gowan et al. 1994). Hypolimnetic anoxia has been reported as a result of organic enrichment from experimental aquaculture in small, deep mine-pit lakes (Axler et al. 1996). However, the application of the results from this study to the Canadian industry is limited due to the very unique environment presented in mine-pit lakes. These lakes have little or no water renewal, which is not the case for commercial net-pen aquaculture sites in Ontario. Another study conducted in Quebec by Cornel and Whoriskey (1993), found that there was an average DO reduction of 4 mg·L-1 and was restricted to the depths occupied by the cages. However the aquaculture operation had a FCR of 3.7, therefore producing much more waste than current practices which may be why they saw a reduction in DO levels. With sufficient water exchange, DO concentrations are held fairly constant and when they do drop, it is usually minor and only drop for short periods of time (Demir et al. 2001; Cho and Bureau 2001).

Several studies in marine systems have reported no significant effects of marine cage culture on dissolved oxygen. Sarà 2007 conducted a meta-analysis of 30 peer-reviewed articles and concluded that dissolved oxygen was generally not affected by aquaculture operations. Modelling has also been used to predict whether fish farming is likely to have effects on dissolved oxygen. Reid et al. 2006, used modelling to assess the risk of oxygen depletion in 135 deep water loch basins and their results suggested that farming was unlikely to contribute significantly to hypoxic events. Lake Huron, might be more comparable to DO studies conducted in marine environments due to its high flushing capacity compared to smaller freshwater lakes where much of the water quality studies have been conducted.

An examination of the literature suggests that findings are fairly inconsistent and that there are few freshwater studies that make any clear conclusions regarding net-pen aquaculture effects on DO concentrations. In general, changes in dissolved oxygen are not detected or are negligible in and around aquaculture operations (Price et al. 2015). And it is important to note that in Ontario the operators of fish farms are required to monitor and report DO concentrations, and marked reductions would result in action to bring the levels back to appropriate standards. Proper site choice that avoids placing cages in areas of poor water circulation, proper husbandry, and controlling farm production at levels that do not result in significant accumulation of organic wastes are important management tools to minimize or eliminate dissolved oxygen depletion.

Nutrient Concentrations

The primary environmental concern associated with net-pen aquaculture waste is the potential for nutrient induced stimulation of algae blooms and the creation of hypoxic waters. Because P is a limiting nutrient in freshwater, it is possible that elevated phosphorus could contribute to increases in phytoplankton and macroalgae production. Few studies document clear trends of increasing nutrient levels in either marine or freshwater cage aquaculture and the literature regarding nutrient levels in the water column in the vicinity of aquaculture operations have inconsistent findings (Cloern 2001). However, even with popular concern over increasing nutrient concentrations, no studies in Canadian freshwater have reported eutrophication caused by net-pen aquaculture waste. It is difficult to link such effects specifically to aquaculture since dissolved nitrogen and phosphorus discharge from fish farms is negligible compared to other sources and often secondary impacts resulting from nutrient enrichment are of greater concern. Nutrient levels in the water column are not only affected by waste from the aquaculture operation but also by, lake morphometry, flushing rate, water chemistry, biological activity within the lake, and land-use patterns in the watershed.

Hamblin and Gale 2002, conducted a study in Lake Wolsey, a restricted embayment along the northwestern shoreline of Manitoulin Island that drains into the North Channel of Lake Huron. They found that total phosphorus concentrations in Lake Wolsey during autumn turnover doubled since the establishment of the net-pen aquaculture facility. However, this studies methods were questionable and water column data was collected within a 50 m radius of the cages, and compared with spring samples collected at a “deep station” that was an undisclosed distance from the cage farm. It is difficult to determine whether they were single point measures or averages, as little information for sample size or variability is provided, and there were no data available from autumn sampling at the deep station. In contrast, MacIsaac and Stockner (1995) reported no change in water column nutrients at two cage sites in British Columbia lakes. Veenstra et al. (2003) reported no significant increases in water column N or P as a result of trout cages in Lake Texoma, Oklahoma and Demir et al. (2001) showed only small and seasonal differences nutrient concentrations downstream of rainbow trout net pens in a Turkish reservoir. Similarly, Cornel and Whoriskey (1993) found no effect of a small cage operation on water column nutrient concentrations in Lac du Passage, Quebec, even though the FCR for the operation was high.

Ammonia is released by fish and from the decomposition of wastes. Ammonia can be present as the ammonium ion and as un-ionized ammonia. Un-ionized ammonia is the more toxic form of ammonia however it is present in very small concentrations compared to ammonium. It is unlikely that ammonia discharges from fish culture will result in toxicity to wild fish (NCC 1990, Weston et al. 1996) however, toxicity to benthic invertebrates directly under cages is possible. This is an area of research that has not been studied in freshwater.

A change in the ratio of nutrient availability can also have significant effects on algal populations. Demir et al. (2001) reported no significant change in chlorophyll a or species composition downstream of culture pens, and Veenstra et al. (2003) could detect no significant difference in chlorophyll a concentrations between their control sites and a net pen operation. Cornel and Whoriskey (1993) reported no differences in chlorophyll a concentrations between a control site and a farm site in a lake containing a small rainbow trout cage farm in Quebec, but suggested that long-term monitoring might be more successful in detecting effects. Older literature has reported enhanced primary production rates, increased algal biomass, and changes in algal species composition (Trojanowski et al. 1985a; Kelly 1993). For example, fish farm nutrient loading resulted in significant increases in chlorophyll a and primary productivity, and a change in species composition of phytoplankton during the open water season in Lake Konnevesi, Finland (Eloranta and Palomaki 1986). Many of these observations are, however, almost 20 years old and may not be representative of present day effects. There is currently no published information about the effects of cage culture operations on the species composition of phytoplankton communities or production of harmful algal blooms in North American ecosystems.

Studies that find significant increases in nutrient concentrations associated with net-pen aquaculture are usually found in literature where there was high FCRs or in literature concerning fish farming in shallow basins or small basins with reduced flushing rates (e.g., Stirling and Dey 1990; Axler et al. 1996). It is also important to note that while aquaculture can cause significant increases in lake water total phosphorus (TP) levels, many older studies use mass balance models that may substantially overestimate the contributions of cage farms to TP concentrations (Yan 2005). In general, the reviewed literature supports the view that modern cage farms with good husbandry that are located in well-flushed, deep basins do not show significant, long-term effects on water column nutrient concentrations.

Sedimentation

Solid wastes from net-pen aquaculture settle and may form accumulations on the lake sediments in the vicinity of fish-pens. The environmental impacts of salmon cage aquaculture resulting from deposition of organic waste to the sediment are thought to be a function of the local environmental conditions and management practices and are often localized to only a few meters away from the pen area. There is high variability of sedimentation accumulation throughout the production cycle at aquaculture sites. A study on salmon farming in Norway found that waste accumulations were typically localized around farms (Caroll et al. 2003) and the greatest accumulations were found directly under cages with lesser amounts extending less that 50m from the facility and this is consistent with other findings in Scottish lakes (Enell and Lof 1983a). The dispersion of waste and accumulation of sediment under farms depends on current speed, depth, rate of decomposition by invertebrates and assimilation of waste by native organisms (Kullman et al. 2009).

The main concern regarding accumulation of solid waste in the sediment is that the degradation of solid waste accumulations can result in the release of labile P to the water column (Kelly 1992, 1993). In southern Sweden, Enell and Lof (1983b) reported that anaerobic sediments under farms showed phosphate release rates 30 to 550 times that of control sediments. Temporetti and Pedrozo (2000) reported that P release from the sediments ranged from 8 to 125 mg $Pm^{-2}\cdot d^{-1}$ depending on aerobic and anaerobic conditions in two lakes in Patagonia, Argentina. These observations are similar to the findings of Enell (1983) who measured the proportion of P from farm wastes that could be released into the water column ranged between 7% and 64%. Although these findings are similar in that there is a large range of release of P, the factors affecting the rate and total proportion of P that is recycled from sediment into the water column have not been well studied in Ontario or with current feed formulations and practices. Since P is the nutrient limiting primary production in lakes, and that the solid waste portion of P is the largest component of P lost to the environment, this knowledge gap significantly hinders our ability to predict the effects of aquaculture activities on lake productivity (Temporetti and pPedrozo, 2000).

Fallowing is a technique which greatly reduces the accumulation of waste below the fish pens. The technique involves moving the pens seasonally to different locations within the lake. Guo et al. 2009 found that after 3 months of fallowing, water N and P concentrations decreased to background levels but the sediment nutrient content remained high. This was a shallow lake, and the FCR at the farm was 3.7 which is very high compared to today's average approaching 1 in Ontario farms. Caroll et al. 2003 reviewed 138 studies and reported that recovery of sites by fallowing is one of the best management tools for sustainable salmon farming in cold-water environments. Therefore, fallowing should be used as a viable recovery strategy for sediments and attention should be paid to where fish farming operations are established (Guo et al. 2009).

Native Species Effects

Fish

The primary mechanisms through which cage aquaculture has the potential to affect wild fish populations are: direct, by an energetic subsidy in the form of faecal matter and waste feed consumed by wild fish; indirect, through food web changes mediated by waste inputs to the ecosystem; and, through the ecological and genetic interactions that may occur between escapees and indigenous species. There are very few studies that examine the effect of freshwater net-pen aquaculture operations on native fish in Canada. Research on the effects of aquaculture in freshwater has not evolved with the expansion of this industry, resulting in few advances in our understanding of how current practices affect native fish populations.

Net-pen aquaculture operations provide a continuous point source of organic matter through the release of excess feed and fecal matter that can be utilized either directly or indirectly by native fish populations (Ackefors & Enell, 1990, Kullman et al., 2009). Excreted waste and uneaten food are released directly into the surrounding environment and thereby introduce an allocthonous source of limiting nutrients and organic solids that alter resource abundances within the system (Yan, 2005; Johnston et al., 2010; Oksanen, 2013). This organic material can act as a food source for invertebrate and fish species, and studies have shown that natural fish populations surrounding cage culture operations exhibit a shift in diet towards that of the released cage culture feed and waste (Fernandez-Jover et al., 2007a; Fernandez-Jover et al., 2011). Although this research comes mainly from marine environments, Kullman et al. (2009) set up an experimental study in a freshwater lake where they established a cage aquaculture operation and monitored the effects of aquaculture for several years. They found the effects of waste from cage aquaculture on native organisms included, increased abundances of benthic organisms, increased growth, reproduction and densities of invertebrates and small fish. While informative, the results of this study are limited; Kullman et al. 2009's study was conducted in a small lake where effects would arguably be more pronounced than in the larger lakes typically chosen by the aquaculture industry. There is a clear need for a natural experiment done at a spatial scale that is more consistent with the lakes commonly chosen for aquaculture. However, this research faces the significant challenge of designing such natural experiments in a way that the energy and nutrient flux in open systems can be quantified.

Invertebrates

Macroinvertebrates are a pillar within the food web as they can illicit bottom-up effects through the entirety of the food web. Macroinvertebrates are a good bio-indicator of potential exogenous inputs as they integrate external inputs over a larger timescale compared to the temporal snapshot attained by chemical sampling. Aquaculture effects on macroinvertebrate communities as biomarkers have been widely researched throughout river systems but currently there is a need for further research in lake systems. The community composition of macroinvertebrates along with biomass proportions are used to infer the amount of anthropogenic stress that is accumulating in a specific area. Coupled with a proper comparable control site it allows for any changes to be quantified. Previous research has looked at anthropogenic inputs via waste water treatment effluent on rivers and the subsequent change in macroinvertebrate community downstream of the input. Researchers have found higher densities of oligochaetes and chironomids, in close vicinity to anthropogenic input which are both pollutant tolerant species. Chironomini larvae feed on organic detritus and typically benefit from moderate increases in organic loading. These effects re still yet to be studied in large freshwater bodies where aquaculture in Canada is present.

Conclusion

If the net-pen aquaculture industry is to continue and expand in The Great Lakes, there needs to be improvement to policy regarding the establishment of cage aquaculture operation and a better understanding of how freshwater cage culture affects lake ecosystems is required to meet this objective. As well, a sustainable approach needs to achieve balance between ecological, economic and societal requirements and desires. To date, the biggest challenges that serve as barriers to growth of the cage culture industry in Georgian Bay are: 1) establishing framework for licenses that ensures the safety of the environment and 2) the management of implementing policy.

There has been a great deal of research conducted to identify and understand the implications of aquaculture in marine ecosystems, however the implications for freshwater aquaculture is still an area that needs attention. There has been considerable effort in the literature on the study of waste loading under varying husbandry practices in Canada. Scientific knowledge of the effects of this waste loading on Canadian freshwater ecosystems is, however, almost completely lacking. Another issue with the research on freshwater aquaculture is that many studies are outdated due to advances in the aquaculture industry. With a growing human population and demand for high quality protein, global aquaculture production is likely to increase. If it is to increase, it is necessary to balance the benefits that this industry brings (i.e. a consistent supply of fish, jobs and economic opportunity) with a commitment to aquatic stewardship. What follows is a list of areas that require further research to adequately understand the implications of net-pen aquaculture on freshwater aquatic environments:

- One of the research needs that relates to all aspects of the environmental implications of net-pen aquaculture is that much of the research done thus far has been generated under experimental rather than commercial operating conditions. Studies on large freshwater bodies would be extremely useful because many experimental studies are on shallow lakes where commercial sites would not be allowed under current Canadian policy thus making the results of these studies a good starting point that requires further investigation.
- To date, there are few published data regarding sedimentation rates or benthic accumulations at Canadian farms.
- There is a lack of research on scientific literature on the effects of freshwater aquaculture activities on benthic habitats. Since this is the habitat most likely affected the most by net-pen aquaculture, it is an important research need. Research is needed to quantify the extent of accumulations under commercial farms in Ontario and an understanding of the factors that affect the rate of accumulation. Research is also needed to understand the implications of sedimentation on benthic invertebrate communities.
- Understanding how Integrated Multi-Trophic Aquaculture and fallowing practices could be used in The Great Lakes to mitigate the environmental effects of waste.
- There is restricted research on combining other non-point sources of anthropogenic nutrient input to mass-balance models that determine nutrient loading for policy decisions. Research is needed to develop an understanding of how phosphorus, nitrogen, and carbon from aquaculture facilities

cycle in the freshwater environment especially given current feed practices and feed formulations.

- There are very few studies documenting the effects of assimilation of waste by native organisms and what this might mean in terms of food web dynamics and stability.

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