Great Lakes
Net-Pen Commercial Aquaculture:
A Short Summary of the Science

A report submitted to the Michigan Quality of Life group, including the departments of Agriculture and Rural
Development, Environmental Quality and Natural Resources Quality
By 1
The Science Advisory Panel 1
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I am scientist and physical oceanographer with the NOAA Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, MI. Since 2007, my research program has explored the hydrodynamics of the Great Lakes, including development of the Great Lakes Coastal Forecasting System, which is a suite of real-time nowcast/forecast models that predict the physical conditions in the lakes and connecting channels such as currents, water temperature, waves, and water level fluctuations. These efforts have also extended to ecological investigations of harmful algal bloom (HAB) transport and the development of real-time ecological forecast products, as well as provided support of drinking water safety, beach quality, and contaminant spill response. Before coming to NOAA, I was a research scientist at the University of Michigan and fellow with the National Research Council. I earned my Bachelor's Degree (2003) and Ph.D. (2007) from Case Western Reserve University.

Dr. John M. Dettmers, Fishery Management Program Director, Great Lakes Fishery Commission, 2100 Commonwealth Boulevard, Ann Arbor, MI 48105.
I earned my Bachelor's Degree from the University of Wisconsin-Madison (1986), MS from The Ohio State University (1991), and Ph.D. from The Ohio State University (1995). I worked for the Illinois Natural History Survey during 1995-2005, serving as Director of its Lake Michigan Biological Station during 1997-2005. Since 2005, I have been employed by the Great Lakes Fishery Commission, where I work to facilitate coordinated fishery management across all five Great Lakes. I also am an adjunct professor at Michigan State University, Loyola University – Chicago, University of Illinois-Champaign, and Carleton University. My research interests include early life history of fish, the feeding ecology of fish, effects of invasive species on Great Lakes foodwebs, and fish movement and behavior.

Dr. James S. Diana, Professor of Fisheries and Aquaculture, School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109-1041.
I have served as a professor of fisheries and aquaculture at the University of Michigan since 1979; I am also the director of the Michigan Sea Grant College Program, and a faculty associate in the Center for East and Southeast Asian Studies. I earned my BS and MS from California State University, Long Beach in 1974 and 1975, respectively, and a Ph.D. in 1979 from the University of Alberta. One area of my research focuses on the interaction between aquaculture practices and environmental impacts and seeks to find solutions for more sustainable production in the future. My fish ecology research is on the management, restoration, and rehabilitation of wild populations that have been inevitably influenced by human disturbance. I have been active throughout the world in fisheries science and aquaculture. I served as the president of the North Central Division of the American Fisheries Society and received a Lifetime Achievement Award from the World Aquaculture Society and AquaFish CRSP. I have conducted extensive aquaculture research throughout the Great Lakes region, as well as in Egypt, Thailand, Kenya, Bangladesh, China, and Nepal.

Mr. Keith D. McCormack, P.E. Hubbell, Roth & Clark, Inc., Bloomfield Hills, Michigan.
I am a civil engineer at Hubbell, Roth & Clark, Inc., (HRC) where I specialize in municipal and industrial wastewater treatment as well as storm water management issues. I received my Bachelor's Degree from Purdue University (1978). After my graduation, I worked in Indianapolis for HNTB where I was involved in the planning, design and construction of Water Resource Recovery Facilities (WRRF) throughout Indiana during the last phases of the EPA Construction Grants Program. I served on the board of the Indiana Water Environment Association. Upon returning to Michigan and working at HRC, I have continued to work on WRRF projects for Michigan communities but have also participated in many MS4 and water quality issues related to storm water runoff. I was President of the Michigan Water Environment Association and am the current chair of the MWEA-MDEQ Coordination Committee. I am participating on the Great Lakes Water Quality Agreement Annex 4 sub-committee, which is developing the Lake Erie nutrient reduction strategy.

Dr. James A. Morris, Jr., NOAA National Ocean Service, National Centers for Coastal Ocean Science, Coastal Aquaculture Planning and Environmental Sustainability Program 101 Pivers Island Rd. Beaufort, NC 28516.
Dr. James Morris is an ecologist with NOAA National Ocean Service's National Centers for Coastal Ocean Science where his research focuses on coastal marine ecology, aquaculture, and invasive species. Dr. Morris leads the Coastal Aquaculture Planning and Environmental Sustainability program (CAPES) which works to provide tools and services for coastal managers empowering them to maintain healthy resilient ecosystems while supporting aquaculture development in the coastal zone. Dr. Morris's past research include an array of multidisciplinary investigations of aquaculture and environmental interactions, biology and ecology of invasive lionfish, and propagation mechanisms of invasive colonial tunicates. In addition, Dr. Morris has cultured dozens of species of marine fish and shellfish for both laboratory experiments and seafood production and has decades of experience in commercial fishing and aquaculture industries.

Dr. A. David Scarfe, Aquatic Veterinary Associates, LLC / OVA-CAP Veterinary & Consulting Services (CEO) and USDA-APHIS-VS (Veterinary Medical Officer), 365 Monarch Birch Ct., Bartlett, IL 60103.
After 15 years as Assistant Director of Scientific Activities with the American Veterinary Medical Association, overseeing all national and international aquatic veterinary issues and programs, Dr Scarfe recently returned to private veterinary practice to service aquaculture and livestock producers and industries, and to assist the USDA-APHIS National Animal Health Response Corps respond to outbreaks of nationally important diseases. Since earning a PhD (fish physiology & ecology, 1979) and DVM (1987) from Texas A&M, prior to joining AVMA in 2001, Dr. Scarfe was a University Professor (1979-1994) at West Florida University, Texas A&M University, Langston University and Tuskegee University. He has also developed and operated several veterinary practices in several states, developed disease-free aquaculture hatcheries in Chesapeake Bay, and has served as a consultant to governmental agencies, NGOs and industries in the U.S., Europe, S. America and Asia on numerous aquaculture, livestock and animal health/disease issues.

Dr. Craig A. Stow, Scientist, NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI 48108.
I am a limnologist at the NOAA Great Lakes Lab where my research focus is the development of probabilistically-based models to guide decision-making. I earned my Bachelor's Degree from Cornell University (1977), and my MS from Louisiana State University (1981). After completing the MS I worked in the Louisiana Department of Environmental Quality, drafting NPDES permits, before completing a PhD at Duke University (1992). My research in the Great Lakes began as a post-doctoral researcher at the University of Wisconsin (1992-96) where my focus was on contaminant dynamics in the fishery. More recently, my colleagues and I have been constructing nutrient models for Saginaw Bay and western Lake Erie. Additionally, I currently serve on the Great Lakes Water Quality Agreement Annex 4 sub-committee, which is developing the Lake Erie nutrient reduction strategy.

Dr. Roy A. Stein (chair), Professor Emeritus, Aquatic Ecology Lab, Department of Evolution, Ecology, and Organismal Biology, The Ohio State University, Columbus, OH 43212-1156.
I am a professor emeritus of Evolution, Ecology, and Organismal Biology at The Ohio State University where I served as professor (1976-2008) and established the Aquatic Ecology Lab under the auspices of an enduring OSU-Ohio DNR partnership. I earned my Bachelor's Degree from the University of Michigan (1969), my MS from Oregon State University (1971), and my PhD from the University of Wisconsin (1975). In concert with colleagues and students, my research program has provided insights into stocking terminal predators, reservoir ecosystem functioning, and the role of exotics in the Great Lakes. I served as a commissioner at the Great Lakes Fishery Commission (1998-2004 and beyond as secretariat staff), where rigorous science informs sea lamprey control and fishery management.

INTRODUCTION

The State of Michigan has received concept proposals from proponents to establish privately owned net-pen operations in public waters of the Laurentian Great Lakes. To determine an appropriate response to these proposals, Michigan's Quality of Life (QOL, agencies) group, i.e., the departments of Agriculture and Rural Development, Environmental Quality, and Natural Resources, established a Scientific Advisory Panel (our panel, we) to provide scientific insight into aquaculture and its impact on lake ecosystems. The QOL group seeks to evaluate these and other requests so as to manage the public waters of the State of Michigan in an ecologically sound manner, while also fostering economic development where practical.

The Panel Process

As the Scientific Advisory Panel (panel), we considered the environmental/ecological issues and concerns surrounding potential nearshore net-pen and offshore cage aquaculture in Michigan's jurisdictional waters of the Great Lakes. We reviewed the science related to net-pen and cage aquaculture to inform Michigan about risks that aquaculture poses, as well as provided insight into science-based policies and practices that safeguard Great Lakes ecosystems. With a series of questions (Appendix A), the agencies specifically asked the panel to evaluate the following topics: **Operations, Fish Health, Ecosystem Interactions (including Effluents),** and **Siting,** which we have slightly re-organized for the purposes of this report. As a panel, we sought to understand what is known about these topics, the uncertainty surrounding this scientific knowledge, and what might be quickly learned to help fill science gaps. In addition to these topics, we also agreed to include information about personnel needs and special considerations for the Great Lakes for all topics.

The panel worked independently from the agencies and sought input on program area information from agency staff, academic researchers, industry operators, and the public. The panel met twice in-person in Lansing and Ann Arbor during June and August, 2015, participated in three conference calls of >2 hours, multiple e-mail exchanges, and one-on-one phone calls. A public meeting was held on June 25, 2015 to allow interested parties to provide the panel with any information that might not be readily available to them. Additional specific information was requested by the panel and provided by agency staff, academic researchers, and industry operations through teleconferences. Based on expertise, each member was assigned to write specific sections based on the peer-reviewed scientific literature and an agreed-upon outline. All sections were critiqued by all panel members who provided written reviews. Three complete report drafts then were reviewed by all panel members; comments were discussed, text modified and agreed upon, and then incorporated into revisions, which were reviewed yet again. Agency input was then sought regarding accuracy in description of programs and regulations and to provide input about the degree to which the panel addressed agency-provided questions (Appendix A). At each step, all panel members were directly encouraged to voice their opinions in conversations, reviews, and text approvals. Each panel member's thoughts, ideas, and perspectives were expressed such that we could incorporate all concerns into our emerging report. All final decisions were consensus based, with this report enjoying the explicit approval of all members.

The Report

We developed this report based on general aquaculture principles and information for finfish culture, recognizing that the specifics, i.e., a fish species in a particular Great Lake, would not be available, though information will be included if available. A complete list of the species permitted for aquaculture is included in the Michigan Aquaculture Development Act, Act 199 of 1996. Of the species permitted for aquaculture by Michigan, those likely to be of greatest interest to aquaculture proponents in the Great Lakes are Rainbow Trout (*Onchorhynchus mykiss*), Atlantic Salmon (*Salmo salar*), Lake Whitefish (*Coregonus clupeaformis*), Walleye (*Sander vitreus*), and Yellow Perch (*Perca flavescens*). Of this group of fishes, Lake Whitefish, Walleye, and Yellow Perch are native to the Great Lakes; Rainbow Trout have been naturalized in these systems. As a panel, we developed our report with these species in mind.

We concluded that climate change must be considered among the possible ecosystem effects related to net-pen aquaculture, for it could have important future ramifications on any commercial industry (though specific impacts are difficult to anticipate). We specifically reflected on how 1) climate warming might affect the suitability of water temperatures for cultured species, 2) changing ice cover might influence aquaculture operations, and 3) climate change may increase the frequency of severe storms with ramifications for catastrophic net-pen failure. We also fully recognize

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[1] As a matter of convention herein, net pen was not hyphenated when used as a stand-alone noun but was hyphenated when used as a compound modifier, as in net-pen aquaculture.

that the Great Lakes are undergoing rapid ecological change owing to invasive species and shifts in nutrient loading and hatchery-driven abundance of top predators, especially in lakes Michigan and Huron (Bunnell et al. 2014). Both ecosystem and climate changes may make it difficult to interpret the environmental effects of net-pen aquaculture within an adaptive management framework against the background of potentially large and rapid ecosystem shifts.

We organized this report to provide an introduction to the issue of net-pen aquaculture that includes considerations for the use of adaptive management principles and sound statistical design to quantify any effects of net pens (See Overarching Management Approach). We first explored the operational aspects of net pens, seeking to understand both opportunities and risks for the Great Lakes as they relate to their normal operations. Next, we considered the threat of fish diseases to aquaculture. This segment of the report begins to explore possible links between aquaculture operations themselves and the ecosystem beyond them. Moving on to ecosystems, we then considered many possible ecosystem effects of net-pen aquaculture to the Great Lakes. These impacts ranged from net-pen effluents to possible effects on sensitive species. Lastly, we evaluated possible siting considerations for net pens, based on our understanding of the physical and biological processes at play in the Great Lakes. We also explored specific considerations for the Great Lakes, as compared to marine systems, and considerations for the types of personnel who will be required to operate and evaluate the potential impacts of net pens. We ended the report with a series of management implications based on the management partnerships currently applicable to the Great Lakes, followed by a succinct set of summary panel recommendations for consideration by the Quality of Life agencies within Michigan.

OVERARCHING MANAGEMENT APPROACH

We strongly recommend that if Michigan were to allow commercial net-pen aquaculture in the Great Lakes, all commercial ventures should be directed to participate in an adaptive management approach (Walters 1986) to maximize the ability of Michigan to make scientifically informed management decisions that account for unexpected ecosystem changes through time (Box 1). The principles of adaptive management for natural resources include experimentation at the relevant management scale, intensive monitoring, and stakeholder involvement (Walters 1986). Thus, the ability to determine the existing ecosystem conditions, monitoring in locations both with and without a perturbation (in this case net-pen aquaculture), understanding the magnitude of change resulting from the perturbation, evaluating the effects of the perturbation (which would necessarily include a rigorous statistical analysis of the data), and then determining appropriate next steps in consultation with stakeholders, thus completing the adaptive management cycle. This cycle should be led and coordinated by a single group for greatest effectiveness; the QOL group may be best positioned to be this body. A useful approach to evaluation of commercial net-pen aquaculture is an experimental design termed

Box 1.

Adaptive management is the use of deliberate management action as experimentation (Hilborn et al. 1995). Such active management experimentation is essential to provide a sustainable harvest, given the many biological unknowns in a particular ecosystem, the behavior of exploiters of the resource, and the inability of humans to predict how the production potential of the ecosystem may change through time. To embrace an active adaptive management approach, some key elements must be implemented:

- A strong experimental design must be in place to allow for maximum learning about sustainability in a changing ecosystem.
  - ◊ Modeling can be a very helpful tool to synthesize knowledge and provide groundwork for management hypotheses to be tested.
- Long-term and large-scale monitoring must occur in both perturbed and unperturbed areas.
  - ◊ These areas should be ecologically similar.
  - ◊ Monitoring must occur both well before and well after a perturbation has been implemented.
- Understanding of long-term and cumulative impacts is essential to wise management.
- Research to support management decision making in this context should be interdisciplinary, nonlinear, and should focus on cross-scale phenomena that tease apart fast-acting processes from those that act at scales of a decade or longer (Hillborn et al. 1995).
- Understanding the ability of a system to return toward an unexploited state after perturbation is important to guide wise management decisions.
  - ◊ Some perturbations may push the local ecosystem past a wise end point, for the purpose of learning whether and/or how quickly the ecosystem will recover from the perturbation.
- A single group must lead and coordinate any adaptive management effort.
- Adaptive management is an ongoing process that includes involvement of stakeholders.
- A cycle of adaptive management that includes the steps above may take five or more years to complete.
- Coordinating the permitting schedule with the adaptive management cycle may be useful to provide maximum ability to implement learned insights.

the BACI design (Stewart-Oaten and Bence 2001; Box 2). Evaluation of possible effects using a BACI approach should include monitoring **before** an **intervention** (net-pen aquaculture) is introduced, intensive monitoring during a period of operation at both aquaculture sites and similar **control** sites, and additional monitoring **after** a period of operation to determine how quickly, or whether, a return to original ecosystem conditions occurs. Choosing an appropriate length of time to monitor after operation can be tricky because of the time lag often required to measure biological responses. For instance, numerous examples document the importance of time lag and the ability to measure an outcome of either a restoration activity or a detrimental introduction (Meals et al. 2010). The most well-known example in the Great Lakes is the long time lag between the beginning of the invasion of zebra and quagga mussels and their ultimate altering of the physical environment and water quality at a large scale which has been detrimental to native Unionids and the food web for native fishes (Ricciardi 2003). Both the state and the industry will need to be cognizant of these time lags as experimental manipulations are planned and carried out.

Box 2.
The Before-After Control-Impact (BACI) study design for monitoring is used to detect effects of aperturbation or management action in the context of a changing ecosystem, if certain design principles are upheld (Stewart-Oaten and Bence 2001). Key elements of this design include:

- Monitoring at an ecologically relevant scale of similar sites **before** any planned perturbation occurs.
    ◊ Ideally one must know where a perturbation will occur, where similar sites are, and to monitor for multiple years before beginning the perturbation, so as to account for natural variation in ecosystem responses across years.
- Monitoring at an ecologically relevant scale of similar sites both **after** the perturbation begins (i.e., during net-pen operations) and ends.
    ◊ The design expects the perturbation to end after some period of time so as to allow evaluation of long-term ecological change as a result of the perturbation.
    ◊ Monitoring for multiple years after the perturbation ends is likely necessary to tease apart effects of any perturbation from ongoing ecological change, especially in the rapidly changing Great Lakes. The temporal scale of monitoring may be determined by the life history of organisms, or the persistence of compounds to determine the appropriate amount of time needed to monitor after a perturbation has ended.
- Monitoring of ecologically similar control sites before, during, and after the perturbation.
    ◊ Control in this sense does not mean a traditional experimental control, but rather is used to tease apart natural, ongoing changes in the ecosystem, either within or across **control** sites, from changes caused by the intervention (Stewart-Oaten and Bence 2001).
- Choosing an **intervention** effect that is likely to be detected in the face of ongoing ecological change, which we believe would certainly include commercial net-pen aquaculture.
    ◊ It is important to know the magnitude of an effect one is seeking to detect at the beginning of any adaptive management cycle, so as to inform the frequency and spatial scale of monitoring to determine possible effects.

Incorporating an adaptive management approach using a BACI design for monitoring to inform decision making means that both operators and the state must provide resources to ensure that data are collected and analyzed properly. Although the division of responsibilities would need to be decided between the state and industry, we strongly believe that such a monitoring effort must be overseen and coordinated by the state. As such, whereas industry would be conventionally required to provide the resources for their assessment and monitoring efforts, it will be important to ensure that necessary fiscal and personnel resources are available within appropriate state agencies to accomplish any additional monitoring design, field sampling, sample processing, and statistical analysis to implement the adaptive management approach with a BACI design.

OPERATIONS

The Ontario Experience

We first reviewed what net-pen systems might be used in the Great Lakes and then recommended specific management options associated with them. Information specific to net-pen aquaculture in the Great Lakes exists from Ontario waters of Lake Huron where net-pen aquaculture has been permitted since 1988. At present, Ontario licenses six operations at seven facilities; a request for an additional five licenses is under review. Three other aquaculture operations are conducted by First Nations, which are not licensed by Ontario. Facilities are leased from the province under a land-use permit. Estimated annual production from unlicensed and licensed operations approaches 8,000 metric tons of Rainbow Trout annually;

about 3,500 metric tons is produced by the licensed facilities (Masser and Bridger 2007). This production from licensed operations is similar to the annual harvest by Ontario's commercial fishery in Lake Huron. At present, the province does not have specific provisions of responsibility for licensees related to closure or decommissioning. We interviewed operators, as well as state hatchery personnel who have visited these sites, and were comfortable describing the most common types of systems in place (D. Sampson, Michigan DNR, Oden, Michigan, personal communication, 2015; D. Jordison, Coldwater Fisheries, Little Current, Ontario, personal communication, 2015).

All Ontario operations are floating net pens in the nearshore zone, most attached to shore by a pier, but some require boat access. These pens operate year-round, so ice cover and ice buildup from spray can be a problem, depending on location. Some use heaters and bubblers to reduce ice formation; others submerge their cages to avoid ice damage during winter ice-in and spring ice-out. Submerged cages and pens are monitored by divers for mortalities, pen integrity, and excess food. Based on our interviews with operators, mortalities are rarely collected in winter, pens remain robust, and most feed (amount fed dependent on temperature) is consumed.

Net-Pen Descriptions

Successful net-pen aquaculture critically depends on location (see Siting). Nearshore pens are usually located in moderately shallow water (< 30 m) with protection nearby and easy access to shore, yet with sufficient currents and wave action to allow flushing. Most nearshore net pens are square with rigid collars to support the net pens and are anchored to the bottom or to a pier-mooring system (Fredheim and Langan 2009). Because these areas are protected, difficulties with large waves and ice scour should be less than offshore. Most likely, benthic modification by net-pen operations will be higher in nearshore than offshore locations (see Ecosystem Interactions), simply because net bottoms will be close to the lake bottom (Price and Morris 2013). If net pens are used beyond the 30-m boundary, circular plastic, collared pens could be used with a commensurate reduction in wave resistance owing to reduced surface area (Fredheim and Langan 2009). Aquaculture can be conducted throughout the year within the nearshore zone, although greater efforts are required there with regard to ice management, as compared to offshore. Nearshore net pens are more easily monitored than offshore ones for disease, mortalities, feeding rates, and environmental impacts.

Offshore (i.e., >10 km beyond the coast) aquaculture may well be feasible in the Great Lakes, although no proof of concept has been completed. Large submersible cages, such as SeaStation cages (designed by Ocean Spar LLC), are commonly used in offshore aquaculture and have been successfully deployed in marine systems with large waves and vessel traffic, but not in locations with significant ice conditions (Fredheim and Langan 2009). Management of offshore cages requires boat or snow vehicle access to provide feed, clean cages, and monitor conditions (a list of monitoring categories is presented in Box 3). During open water, storms may preclude access for short periods, but insufficiently to preclude offshore use. During ice in winter, long time spans exist with no opportunity to visit and manage cage systems in many offshore locations. Monitoring and managing offshore cages will add significant costs to culture operations. There may be good reasons to reduce monitoring efforts in winter, due to lower fish metabolism, lower feeding rates, and likely much lower incidence of disease and mortality. Offshore aquaculture would minimize sedimentation impacts on the benthos, because material settling from cages would be more highly dispersed and either decomposed or consumed before accumulating on the lake floor.

Net-pen operations have two limits on production: 1) size and density of fish stocked into a single net pen and 2) number of net pens in a circumscribed area. Both influence water quality, as well as other ecosystem components, all of which could be addressed by regulation. Because cage size and stocking density interact to allow for commercial success, efficient marketing, and economic gain, we believe these features of a farm are less of a regulatory concern than they are the purview of business management. However, total production should be limited in a specific location, to assure that impacts are localized and do not affect ecosystem structure and function. We are concerned that small-scale aquaculture, such as bait fish holding during summer in Great Lakes net pens, has the potential to be damaging by introducing invasive species, as well as disease, to nearshore waters. Large-scale commercial monoculture would have different issues (i.e., effluent, disease, escapes, sedimentation, etc.) but they could more effectively use Better Management Practices

(BMPs) developed for commercial-scale culture to limit these impacts. We recommend that if aquaculture permits are granted, operators begin with pilot projects with monoculture at a commercial scale to develop data on ecological and economic outcomes; quantifying these impacts with an adaptive management plus BACI design (see Management Approach). Small-scale operations, such as multispecies baitfish culture, should be left for later evaluation. Economics also may drive the large size of commercial enterprises, as the cost of permitting, site evaluation prior to permitting, and infrastructure will make small operations untenable.

Net-Pen Operations

Net-pen operations require sufficient water flow (current, waves, and diffusion) to produce rapid water turnover to allow removal of metabolites, waste materials, and excess food (see Siting). Operations must focus on large fish, which means small individuals of cultured species would be grown at inland operations with net pens stocked with fish sufficiently large to allow for large net mesh while minimizing escapes. In Ontario's waters of Lake Huron, rainbow trout are stocked at about 5 g in 1 to 3 net pens, then later apportioned across more pens as they grow. We do not have specific recommendations on mesh size or strength, as this depends on species, fish size, and location. Net pens should be covered to reduce predation (mainly by birds). Cage covers are double-edged swords, as they prevent birds, such as cormorants (*Phalacrocorax auritus*), from entering cages, but simultaneously, they may serve to entangle other fish-eating species, including diving birds. Therefore, we recommend that net pens be covered with predator-prevention netting, designed to reduce predation and minimize bird mortalities.

As with all methods of containment, net pens must withstand rare extreme events, such as large waves of short wavelength (typical of the Great Lakes), ice scouring, and collision with floating ice and other debris. Most escapes from net pens occur during catastrophic failures, when pens or sets of pens are compromised and most fish are lost. Only 3-4 catastrophic failures have occurred since 1988 in the Great Lakes, mainly due to extreme storms, with the subsequent release of thousands of fish per event; even so, numbers can be large, as in one event after Hurricane Sandy during which 200,000 fish escaped fish. Escapes in other contexts, such as during stocking, routine operations, or harvesting of net pens, at least in the marine environment, are far less common, with early estimates at 3%, and recently (since 2000), about 0.3% of the fish originally stocked (Rust et al. 2014). Field releases and experimental work in Norway with Atlantic Salmon (Flemming et al. 2000) reinforce literature reviews (Hindar et al. 1991) that escaped salmon may have wide-ranging negative genetic effects on native salmon populations. Genetic change due to escapes have not yet been identified in the Great Lakes, but we would expect impacts similar to Norway. Thus, we support use of triploid or other infertile fishes. Triploids exist for many salmonids, with success rates exceeding 94% and fertility greatly reduced (Johnson et al. 2004). Similar options are not yet available for Yellow Perch, Walleye, Lake Whitefish, or Lake Trout (*Salvelinus namaycush*). An alternative to genetic manipulation to produce infertility would be to stock pens with fish genetically similar to wild populations, but reduced growth rates in culture may make this economically impractical. We recommend that the permit process for any net-pen operation consider the potential genetic impact of catastrophic escape on natural populations and provide evidence for using the most reasonable, recent method for reducing reproductive capacity of the cultured species.

Concentrating fish in net pens, coupled with poor management can increase stress, thus increasing disease or parasites within the pen and amplifying the spread to wild populations (see Fish Health and Disease). To manage these issues, monitoring culture operations is critical and should include determination of appropriate feeding level (as measured by such metrics as % body weight per day) and assessment of mortality. These activities add difficulty to offshore culture, where daily monitoring is challenging. Remote monitoring may be feasible using video technology, but of course it would still be difficult to remove mortalities from a remotely sensed offshore system in winter. Overfeeding can be monitored by visual assessment, sediment traps below cages, or video cameras mounted within the system (Rust et al. 2014).

Net-Pen Decommissioning

Aquaculture systems may close prematurely due to economic issues, environmental concerns, weather, or other catastrophic events. Because pens are located in public waters, decommissioning must be considered at the time of permit application. Upon closure, owner/operators should be held responsible for returning the modified ecosystem to its original structure and function, as closely as possible. To ensure successful decommissioning, we recommend that performance and payment bonds be required as part of permitting, to cover decommissioning costs. Insurance also could provide decommissioning funds, although it is unlikely that any insurance companies will be willing to undertake these risks in a new and rather controversial industry. At a minimum, all built structures should be removed and a monitoring program completed that would include all ecosystem features influenced by the farm (see Ecological Interactions).

Personnel

Developing successful and sustainable commercial aquaculture in the Great Lakes will require professionally trained personnel. These personnel should not only be experts in raising fish, but also in engineering of aquaculture facilities, understanding water chemistry and quality, appreciation (if not expertise) for ecosystem services, and a deep understanding of cutting-edge technology. These professionals are likely not currently available for immediate aquaculture expansion, so more training programs must be developed to allow for any expansion of aquaculture throughout Michigan. While programs exist in neighboring states and provinces, as well as at Lake Superior State University and some community colleges, an unmet demand will exist for trained personnel if aquaculture production reaches its potential in Michigan. Whereas this training applies to the owner/operator, professional needs for ecologically sound aquaculture runs deep and must be part of any permitting process. Technology experts also are needed as computers, robotic cleaning devices, and video monitoring are commonly used in net-pen culture. Dissolved oxygen and other water quality parameters also are monitored in aquaculture systems with provisions for alarms to notify personnel when problems occur. Finally, biosecurity concerns can only be alleviated by specialized systems and personnel. A plan for a sophisticated surveillance system, which would provide security against human intervention, also should be required by the permitting process. To accomplish these objectives, the Quality of Life agencies should consider an operator-certification program similar to those for wastewater treatment and water- treatment/distribution operators.

Special Great Lakes Considerations

Given limited experience with aquaculture in the Great Lakes, we provide a list of what "special considerations" might apply uniquely to the Great Lakes.

Fish feed availability. Fish feed is not produced in Michigan at present. In our view, any permitted aquaculture should be required to use the best available feed source with lowest available P level (i.e., <1%), therefore minimizing both waste and surplus phosphorus and nitrogen fed to fish (Cho and Bureau 2001). Historically, using fish meal in fish feed contributed more fishing pressure to over-fished stocks of forage fishes (Naylor et al. 2005), although high costs of fish meal in recent years has reduced reliance on it (Tacon et al. 2006). Alternative protein sources for feed include soy, meat processing by-products, etc. Because feed is costly, economics will complement regulatory strategies to reduce fish meal. Even so, we recommend the use of high-quality feeds (as evaluated by the MDARD Laboratory), minimizing fish meal without increasing unassimilated P excreted, and monitoring of food fed to curtail wastage. Finally, a feed industry may develop in Michigan if aquaculture expands, which would be a welcome addition to Michigan's economy.

Fouling agents. As water clarity has increased due to dreissend invasion, *Cladophora*, a native alga, is increasing in the Great Lakes (Auer et al. 2010), fouling beaches with algal debris or "muck". *Cladophora* can quickly colonize trap and gill nets in parts of the Great Lakes, affecting commercial fishing operations. Existing aquaculture in Ontario has not had problems with *Cladophora* fouling net pens, but we believe *Cladophora*, by colonizing nets, would reduce flushing rates, perhaps collapse net pens, and severely compromise aquaculture operations. Mitigation could include power-washing, hand or machine scrubbing, or lifting nets to dry, then shaking them — a method commonly used in current Great Lakes fisheries. We believe *Cladophora* will be a significant fouling agent, which should be monitored closely.

Zebra (*Dreissena polymorpha*) and quagga (*D. rostiformis*) mussels colonize substrates, rocky areas in shallow depths, soft sediments in deep water, and nets near the surface. Because mussel growth is rapid, they also could foul net pens quickly. As filter feeders, they readily will remove suspended solids from aquaculture operations. In marine culture systems, integrated multi-trophic aquaculture (IMTA) uses mollusks, such as oysters (e.g., *Ostrea* spp.) and scallops (Family: Pectinidae), to remove suspended solids near pens creating a valuable crop (Neori et al. 2004). Unfortunately, zebra mussel populations will not produce an economic return, but nonetheless, they will have a food source near culture operations and likely interfere with net-pen culture.

Ice issues. Ice issues are a special Great Lakes concern related to aquaculture, as most marine aquaculture occurs in areas with no ice, and freshwater aquaculture in cages largely occurs in warm climes. Net-pen culture could avoid ice problems by developing a grow-out that would use 6 months of open water for production, then fallowing locations during winter ice. We have no specific recommendations on this issue, but operators applying for a permit should clearly indicate how they plan to deal with ice conditions if they intend to continue their operations through winter.

Best Practices. Whereas well-defined methods exist to manage net-pen impacts on benthic conditions (Price and Morris 2013, also see Ecological Interactions), these methods have not been well tested in the Great Lakes. If organic waste accumulation beneath and around farms is substantial, we recommend use of fallowing to counter it. By using an experimental design, including BACI in the context of adaptive management (see Management Approach), the usefulness of fallowing can be rigorously tested and included or not depending on quantitative results (Price and Morris 2013).

Integrated multi-trophic aquaculture (IMTA) can reduce sedimentation and nutrient enrichment in marine systems. In marine coastal IMTA systems, seaweeds remove dissolved nutrients, mollusks remove suspended solids, and detritivores, e.g., sea cucumbers (Class: Holothuroidea), can remove settled solids (Neori et al. 2004). If these added organisms have market value, this becomes a win-win situation, with reduced ecological burdens and increased value. At present, IMTA would not be feasible to improve environmental and economic performance of net-pen culture in the Great Lakes simply because organisms associated with net pens are unlikely to have market value.

Box 3. Better Management Practices. A number of groups have proposed criteria to gauge performance of aquaculture operations. The Monterey Bay Aquarium (MBA) criteria fit into 10 categories that focus on environmental performance: 1) data; 2) effluent; 3) habitat; 4) chemical use; 5) feed; 6) escapes and introduced species; 7) disease, pathogen, and parasite interaction; 8) source of stock — independence from wild fish stocks; 9) predator and wildlife mortalities; and 10) escape of unintentionally introduced species (MBA 2015). Additionally, the Northern Ontario Aquaculture Association (2006) developed *Best Management Practices for Sustainable Aquaculture in Ontario*, which also focused on environmental and social aspects of potential impacts. Their categories include: 1) guiding principles, 2) legislation and regulations, 3) integrating with the environment, 4) site selection, 5) facility design and infrastructure, 6) fish containment, 7) predator management, 8) fish health, 9) harvest and post-harvest practices, 10) feed management, 11) effluent/nutrient management, 12) other organic waste management, 13) general farm and human waste management, 14) chemical handling and storage, 15) human health and safety, 16) information and data management, 17) integrating with the public, and 18) compliance and enforcement.

Many groups currently are evaluating aquaculture operations, developing best management practices to regulate the industry (Box 3) and certifying culture systems for their environmental, social, and economic performance. These groups include organizations that certify specific operations, such as the Aquaculture Stewardship Council or Global Aquaculture Alliance, as well as ones evaluating whole industries, such as the Monterey Bay Aquarium (MBA). Each produces specific criteria that serve as best practices, determining compliance with these practices to evaluate ecosystem impacts (Box 3, See Ecological Interactions). We strongly recommend that specific freshwater metrics be developed for each of these categories in any permitting process for net-pen use. In so doing and in combination with a rigorous experimental design (BACI), operation performance can be objectively assessed. Coupled with adaptive management, net-pen operations in the Great Lakes will improve, thus reducing their environmental impact and increasing their efficiency. We have given more general guidance in this document to each category, as our goal was to offer policy considerations, not specific regulations or permitting requirements. But the documents cited in this report — and many others — offer excellent advice on BMPs that should be developed for the industry. These considerations combined with appropriate evaluation techniques will allow the industry, in collaboration with the state, to most quickly develop guiding principles, specific metrics, and ultimately best management practices for net-pen aquaculture.

Recommendations

If net-pen culture is implemented in Michigan's jurisdictional waters of the Great Lakes, we recommend that commercial aquaculture operators:

- Begin with pilot projects on monoculture at a commercial scale to develop data on ecological outcomes that can be used for further adaptive management.
- Cover net pens with netting, designed to reduce predation and minimize bird mortalities.
- Consider carefully the potential genetic impact of catastrophic escapes on natural populations by using triploid/sterile fish, where possible and present evidence for using the best method for controlling reproduction of the fish species being grown.
- Provide performance and payment bonds to cover decommissioning costs.
- Use high-quality, low P (<1%) feeds, along with monitoring of feed consumed such that wastage is minimized.
- Describe clearly how they will deal with ice if operations continue through winter.
- Evaluate densities of native mussels near proposed net-pen sites, taking care to accommodate these populations.
- Monitor net-pen operations. Throughout this analysis, it has become clear that certain set areas of operations should be monitored regularly in any net-pen operation, including at least:
  ◊ 1 disease incidence and outbreak;
  ◊ 1 numbers and removal of moribund fish;
  ◊ 1 feed management and overfeeding;
  ◊ 1 water quality in surrounding waters;
  ◊ 1 benthic sedimentation below and in proximity to cages;
  ◊ ice damage to nets or supporting structures; and 1
  ◊ overall integrity of the pen system. 1

FISH HEALTH AND DISEASE

Minimizing infectious and contagious (transmissible) diseases in Great Lakes aquaculture will positively influence fish health, public (human) health, and environmental health. This conclusion applies to all aquaculture in the Great Lakes or its watershed, irrespective of whether the operation is a private/commercial enterprise, or a public state/federal hatchery. Non-infectious diseases (e.g., toxicoses, nutrition, trauma, etc.) typically can be corrected through management (Roberts 2012), with few ecosystem effects; hence, they will not be discussed.

Infectious and contagious fish diseases in the Great Lakes and its watershed have received attention by the Great Lakes Fishery Commission (GLFC) for a number of years (e.g., Meyer et al. 1983, Hnath 1993, Horner and Eshenroder 1993, Tulen 1999). With input from the GLFC-sponsored Great Lakes Fish Health Committee (GLFHC), early approaches and recommendations for evaluating risk and minimizing impact of disease have been refined over time (GLFHC 2014, 2015), including developing a process to evaluate and mitigate environmental effects of aquaculture throughout the Great Lakes (Brister and Kapuscinski 2009).

Disease Surveillance and Monitoring

Managing fish diseases will require disease surveillance and monitoring throughout the Great Lakes. With important diseases identified, any changes in distribution can then be pursued with ongoing monitoring focusing on specific areas. Although both surveillance and monitoring programs may require some complicated epidemiological procedures (Salman 2003, Cameron 2004, Peeler and Taylor 2011), several tools (e.g., Cameron 2002) and software applications (e.g., "AquaPathogen X", Emmenegger and Kurath 2012) can simplify tasks, allow change to be monitored, and determine epidemiology of disease outbreaks. In addition, although disease surveillance and monitoring appear daunting, all Great Lakes states/provinces, and both APHIS (Animal and Plant Health Inspection Service) and CFIA (Canadian Food Inspection Agency) already report many disease outbreaks, and the GLFHC plus other agencies have monitored fish diseases in the Great Lakes for a number of years (e.g., Faisal et al. 2012, GLFHC 2015).

Many transmissible fish diseases occur in the Great Lakes, its watershed, and in private and public aquaculture facilities (Plumb 2002, Faisal et al. 2012). However, for a variety of reasons, not all transmissible diseases create problems for wild fish or aquaculture operations. Infection with a pathogen is not always expressed as mortality, morbidity, or other signs of clinical disease. Early in the progression of a disease, subclinical infections occur without overt signs while the pathogens replicate in the host. In some fish diseases, clinical disease and pathology may only be triggered when water and fish body temperatures reach certain critical points, or fish are stressed (Stene et al. 2014). Indeed, some pathogens remain "latent" in immunocompetent fish after recovering from natural infections or immunization against, for example koi herpesvirus, and may be shed when fish are stressed (Eide et al. 2011). This is further complicated as some strains of a transmissible agent do not cause any pathogenic effects (e.g., infectious salmon anemia HPRO) associated with infection (Christiansen et al. 2011).

Wild fish populations are reservoirs for diseases endemic in the Great Lakes. Without large fish kills, determining which diseases or pathogens occur in wild fish populations is extremely difficult. Although disease outbreaks can cause mass mortality (epizootics) of wild fish, their impact on ecosystem structure and function is difficult to fully determine (Ward and Lafferty 2004). However, should U.S. Fish and Wildlife Service's disease surveillance efforts with wild fish (Heil 2009, USFWS 2015) be expanded into the Great Lakes and its watershed, valuable epidemiological information could be collected. In turn, if aquaculture operations used only certified specific disease or pathogen-free (SPF) fish, naive to diseases of concern, and operations were required to report disease outbreaks, net-pen aquaculture could serve as valuable sentinels for several diseases (Baldock et al. 2008). Although disease outbreaks can cause mass mortality (epizootics) of wild fish, their impact on ecosystem structure and function is difficult to fully determine (Ward and Lafferty, 2004).

Diseases of Concern

Transmissible diseases in fish, particularly those priority diseases that cause significant fish morbidity or mortality, are highly regulated at the federal (CFIA 2014, USDA-APHIS 2014b), international, and state/provincial levels. To adhere to the World Trade Organization Sanitary and Phytosanitary agreements (OIE 2015c), outbreaks of OIE listed diseases are required to be reported to OIE (World Organization of Animal Health). As the international animal health and diseases standards-setting body, OIE publishes standard approaches for detecting, preventing, controlling, and eradicating diseases in the Aquatic Animal Health Code (OIE Code), and Manual of Diagnostic Tests for Aquatic Animals (OIE

Manual; OIE 2015a, 2015b). As OIE-member countries, both the United States and Canada incorporate OIE Code and Manual standards and principles into their National Aquatic Animal Health programs (NAAHPTF 2008, DFO 2005). State and provincial fish health and disease regulations and programs generally align with federal and OIE approaches; those regulations pertaining specifically to Michigan and Great Lakes states are covered by Weeks (2009).

Detection or outbreaks of certain priority diseases (CFIA 2014, USDA-APHIS 2014a) in wild or farmed fish elicit strong regulatory responses. For example, fish kills in Great Lakes wild fish from a new strain of viral hemorrhagic septicemia (VHS strain IVb; CFSPH, 2007), affecting a large number of finfish species (MI Sea Grant, 2007), resulted in U.S. and Canadian federal regulatory action that prevented the movement of both wild and farmed fish from, and to, Great Lakes states and provinces, unless they were tested to be free of VHS (USDA-APHIS, 2008). State and provincial regulations implemented to accommodate the U.S. Federal Order were equally applied to farmed fish, despite no evidence of the disease from any aquaculture operation in either country. Once regulations were subsequently implemented at the state level, the Federal Order was lifted (USDA-APHIS 2014c).

Recently, to supplement and build on the U.S. National Aquatic Animal Plan (NAAHTF 2008), USDA-APHIS and the aquaculture industry have developed a new approach by considering "industry standards" that incorporate both animal health regulations and best management standards for the U.S. aquaculture industry (APHIS 2015a).
The GLFHC has identified the following diseases as important to aquaculture and wild fish in the Great Lakes (Phillips et al. 2014), with the following priorities:

1. **Emergency diseases/pathogens** are not yet detected in the Great Lakes basin, but do cause epizootic events; if discovered in an aquaculture operation, containment and eradication must then occur. These include (*=OIE listed): *Ceratomyxa shasta*; infectious hematopoietic necrosis virus*; infectious salmon anemia virus*; *Tetracapsuloides bryosalmonae* (causes proliferative kidney disease); viral hemorrhagic septicemia (all strains except IVb- although Michigan law does not differentiate between strains)*; white sturgeon (*Acipenser transmontanu*) herpesvirus; and white sturgeon iridovirus.
2. **Restricted fish diseases/pathogens** may be detected in the Great Lakes basin and cause epizootic events in hatcheries or in the wild; responses to minimize their effects vary depend on the disease or pathogen, but when detected, fish should not be transferred to other aquaculture facilities, but may, or may not, be released into the Great Lakes, depending on a number of factors (Table 1). These include: *Aeromonas salmonicida* (causing furunculosis); largemouth bass virus; *Renibacterium salmoninarum* (causing bacterial kidney disease); *Yersinia ruckeri* (causing enteric redmouth disease); *Heterosporosis sp.;* infectious pancreatic necrosis virus; koi herpesvirus; *Myxobolus cerebralis* (causing whirling disease); spring viremia of carp virus, and viral hemorrhagic septicemia virus. 1
3. **Provisional fish diseases/pathogens** include possible emerging diseases that might negatively affect fish in the Great Lakes, but their pathobiology, epidemiology, and/or etiology, are not fully understood. These include: *Bothriocephalus acheilognathi* (an Asian tapeworm), *Nucleospora salmonis* (an intra-nuclear microsporidian parasite), epizootic epitheliotropic disease virus, *Piscirickettsia*-like organism, and lymphosarcoma virus (a tumor¬-causing virus).

Table 1. Optimal approaches for reducing the spread of "restricted fish diseases/pathogens" and options for reducing their spread in the Great Lakes (modified after Philips et al. 2014, *=OIE listed). The Great Lakes Fish Health Committee (GLFHC) considers Level 1 diseases/pathogens to pose lower threats to wild fish than Level 2 and that fish infected with Level 1 pathogens might be moved to areas where the pathogen occurs and where its effect is predicted to be negligible. The GLFHC's risk-assessment tool is useful to determine the likelihood of a disease entering or leaving a location or epidemiological unit. Level 2 restricted pathogens are untreatable, difficult to manage, and transmission continues throughout the life of infected fish; therefore, infected stock should be depopulated. We believe that this approach is useful for stocking net pens; however, the risk of introducing or spreading disease can be substantially reduced, or eliminated, if only certified disease or pathogen-free fish were used and strict biosecurity protocols were followed (see Disease Prevention and Disease Control below).

Level Pathogen	**Recommended Actions for all Aquaculture**
1. *Aeromonas salmonicida salmonicida* Largemouth Bass Virus *Renibacterium salmoninarum* *Yersinia ruckeri*	• Use only certified, specific pathogen-free (SPF) fingerlings • Implement biosecurity programs (Figure 1) using the GLFHC risk-assessment tool. • In the event of a disease outbreak, utilize vaccination or therapeutic treatments as appropriate.
2. *Heterosporis* sp. Infectious Pancreatic Necrosis Virus Koi Herpesvirus* *Myxobolus cerebralis* Spring Viremia of Carp Virus* Viral Hemorrhagic Septicemia	• Use only certified, specific pathogen-free (SPF) fingerlings • Implement biosecurity programs (Figure 1) using the GLFHC risk-assessment tool. • Depopulate infected fish

Interestingly, only columnaris (caused by *Flavobacterium columnare*) and coldwater disease (caused by *Flavobacterium psychrophilum*) have been encountered in net-pen aquaculture in Canadian Great Lakes waters (Dan Sampson, MDNR, Lansing, personal communication, D. Jordison, Coldwater Fisheries, Little Current, Ontario, personal communication, 2015).

Disease Prevention

Managing diseases in farmed fish in the Great Lakes must focus on prevention, control, and the eradication of any infectious disease or disease-causing agent (pathogen). However, for a variety of reasons, the prevention and control of diseases in wild populations is typically extremely difficult or impractical, as wild fish serve as reservoirs for pathogens, without infected fish showing recognizable signs of disease. Because animals are concentrated in aquaculture operations, an outbreak of a disease can be amplified, frequently with recognizable increases in mortality, morbidity, or reduced

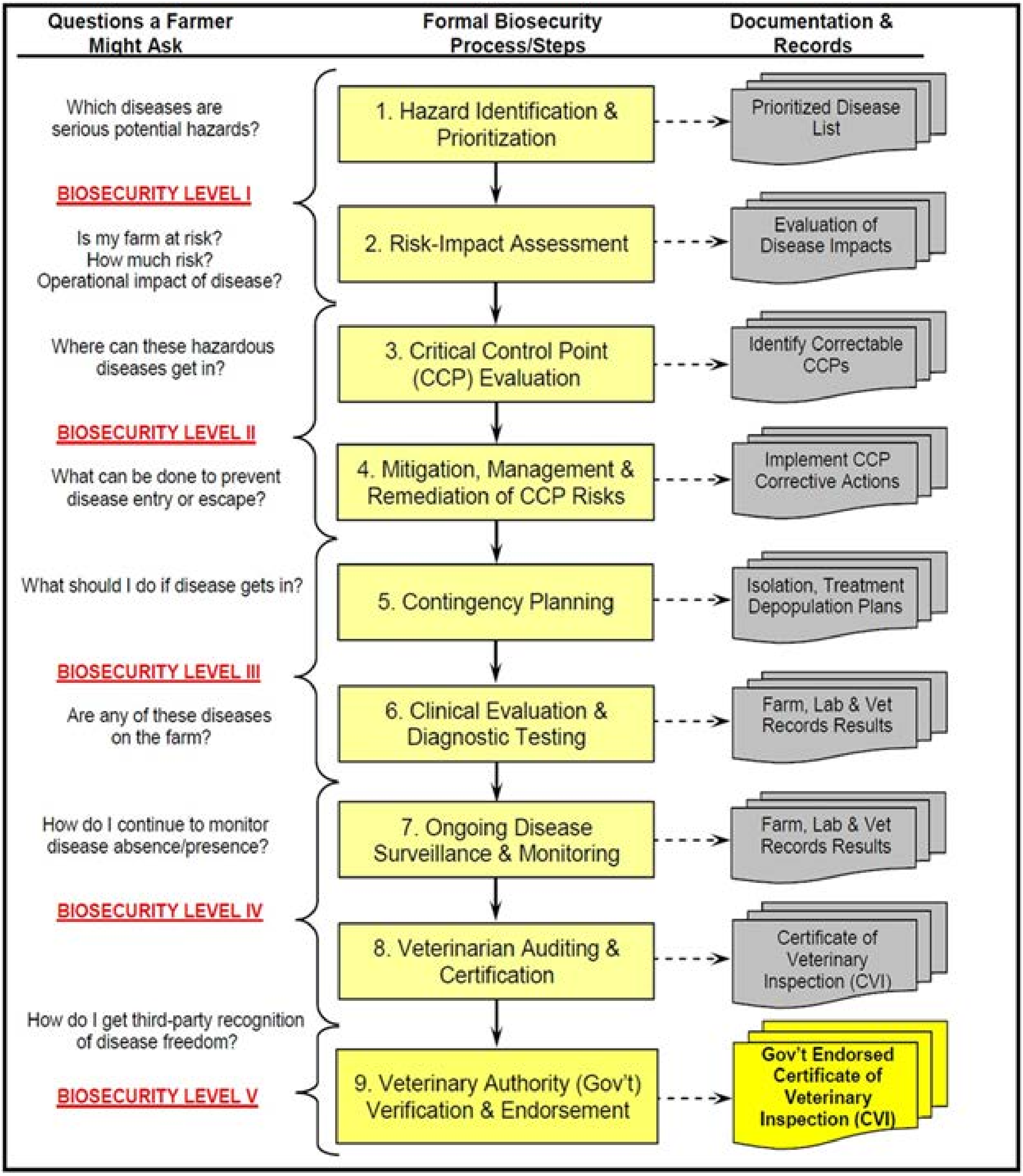


Figure 1. Steps for developing, implementing, auditing and certifying an effective biosecurity program intended to prevent, control and possibly eradicate disease in any epidemiological unit – a tank/pond, farm, state/province, zone, region or country (after Palić et al. 2015).

growth or production. When appropriate biosecurity practices for infectious diseases are diligently implemented, they must include: 1) specific measures to prevent disease introduction, 2) contingency plans to control a disease outbreak, and 3) plans to prevent or minimize any disease/pathogen spread.

Fish "health management" (preferably termed biosecurity) options need therefore to specifically focus on the prevention as well as control and eradication of infectious and transmissible diseases or their pathogens on individual epidemiological units (EpiUnit, Box 4). EpiUnits can be one or more contiguous fish ponds, tanks, net pens, or aquaculture operations. Treating diseases in this context is the most viable way to "manage" a disease and avoid potential ecological damage from any disease outbreak (Palić et al. 2015). Indeed, when sound veterinary epidemiological principles are applied for prevention and control, most diseases/pathogens can be contained and eradicated from an EpiUnit (Salman 2003, Cameron 2004, Peeler and Taylor 2011, Jones 2015).

Implementing effective and efficient biosecurity to meet both commercial producers' economic goal and regulatory requirements can be complex (see Operations). However, earlier attempts to provide practical and economical biosecurity approaches that meet OIE and regulatory requirements (e.g., Scarfe 2003a, Scarfe et al. 2006, Håstein et al. 2008, and Oidtmann et al. 2011) have now been refined (Palić et.al. 2015) and are outlined in Figure 1.

Box 4. The OIE Aquatic Code (2015a) defines an epidemiologic unit (EpiUnit) as "*a group of animals that share approximately the same risk of exposure to a pathogenic agent with a defined location. This may be because they share a common aquatic environment (e.g. fish in a pond, caged fish in a lake), or because management practices make it likely that a pathogenic agent in one group of animals would quickly spread to other animals (e.g. all the ponds on a farm, all the ponds in a village system).*" Within an EpiUnit disease transmission between individuals is relatively easy. However, the population of animals within an EpiUnit is separated in some way (often geographic, physical, or temporal) to reduce the contact with other populations, and affords some level of protection against disease spread in or out of the EpiUnit. EpiUnits might be a small as a farm, or encompass larger areas including states/provinces, whole countries, or larger geopolitical areas.

Disease Control

The old idiom attributed to Benjamin Franklin, that "an ounce of prevention is worth a pound of cure," aptly applies to all fish diseases. In aquaculture operations, where animals are confined, the use of therapeutic agents is often an option. However, when these options are unavailable, or the risk of a regulated disease is high, quarantine and depopulation are more effective. Therapeutic agents include antibiotic drugs (effective for bacteria only), biologics (bacterins: bacterial diseases; vaccines: viral diseases), or parasiticides. Few drugs and biologics are approved or licensed for fish diseases in the U.S. by, respectively, the U.S. Food and Drug Administration, Center for Veterinary Medicine (FDA-CVM 2014), or USDA, Center for Veterinary Biologics (USDA-CVB 2015). However, extralabel use of other animal or human drugs is only permitted under the direction of a veterinarian and other strict requirements (FDA-CVM 2015a). Whereas vaccines and bacterins might increase the immunocompetency of the host, reducing clinical expression (usually by reducing pathogen replication and load), they do not guarantee that animals become infection free. Vaccination as a disease control strategy is only effective if the majority of the population of fish is immunocompetent (from vaccination or natural infection); naïve fish may serve as disease reservoirs and shed pathogens.

Drugs and biologics can be administered to fish through injection (generally infeasible for large populations in net pens), immersion, or through feed. When administered properly, and with safeguards to prevent dispersion (AFS-FCS, American Fisheries Society, Fish Culture Section 2011), drug immersion may be feasible. However, drugs delivered through feed will be preferred by most producers. In marine systems, cameras monitor feed consumed by net-pen fish, thus allowing quantitative monitoring of medicated feed delivery (Belle and Nash 2009). Recent veterinary feed directive (VFD) regulations (FDA-CVM 2015b) will further optimize the judicious use of medicated feed as all medicated feed will require a VFD (similar to a prescription for restricted drugs) to be issued by a licensed veterinarian who has inspected ill fish before medicated feed can be used.

Several existing guidance documents can assist aquaculture producers regarding the appropriate and legal uses of drugs (AFS-FCS 2011, AVMA 2013, FDA-CVM 2014), and avoidance of drug residues (Reimschuessel 2014) to ensure safe seafood. Further, veterinary pharmacologists with the Food Animal Drug Residue Avoidance Databank (FARAD 2015) are available to advise veterinarians on the risks and withdrawal times necessary for any drug, chemical, or biotoxin (e.g., mycrocystin from toxic/harmful algal blooms) encountered by fish.

Some disease outbreaks will require an aquaculture unit be quarantined and that the fish be depopulated, typically for exotic or foreign animal diseases that are required to be reported to Federal authorities or OIE (e.g., USDA-APHIS 2014a, CFIA 2014, OIE 2015). For outbreaks of non-zoonotic diseases or those not resulting in food-borne illness, fish may be slaughtered and processed as seafood, as is the case with infectious salmon anemia (USDA-APHIS 2010). In cases where processing infected fish as seafood would be inappropriate, composting provides a safe means of disposal.

Public/Human Health and Seafood Safety

Animal health, public (human) health and environmental health are closely intertwined in the "One Health" concept. Although developed in the 1800s (CDC 2013), this concept was recently rejuvenated under the One Health Commission (OHC 2009, Mackenzie et al. 2009), as a worldwide strategy for expanding interdisciplinary collaborations and communications (see One Health Initiative, http://www.onehealthinitiative.com/about.php).

Fortunately, few bacterial or viral diseases in fish are zoonotic, i.e., transferable to humans (Haenen et al. 2013). While having no direct impact on aquaculture production, some parasites, bacteria, and viruses can cause food-borne illness (e.g., Chai et al. 2005) when sanitary conditions during seafood processing are suboptimal. However, when Hazard Analysis Critical Control Point (HACCP) procedures for seafood processing are in place (FDA-CFSAN 2011), seafood contamination is eliminated.

Antimicrobial resistance of important human drugs is now a global issues (WHO, World Health Organization 2014), and the use of antibiotics in animals, including aquaculture, is receiving a great deal of attention (Buschmann et al. 2012). However, FDA-CVM has announced plans to restrict the availability of antibiotics, requiring all to be used under the direction of a veterinarian, and made available to producers through a prescription (parenteral delivery) or, in the case of medicated feed, through a veterinary feed directive (FDA-CVM 2015b).

Bioaccumulation of heavy metals or polychlorinated biphenyls (PCBs) in farmed and wild fish are frequently food safety concerns (Schmitt et al. 1999). Because fish are in net pens for only 12-24 months, feeding on contaminant-free food, the likelihood for bioaccumulation of heavy metals or polychlorinated biphenyls (PCBs) would be quite low. In addition, state agencies continually monitor residues of heavy metals and PCBs accumulated in fish from the Great Lakes fish, and issue guidelines for consuming seafood (e.g., MDHHS 2015). Consequently, we believe that contaminants should pose little or no risk in net-pen reared fish.

Personnel

Prevention, control, and eradication of disease requires cooperation and collaboration of producers, aquatic veterinarians, other fish health professionals, diagnostic laboratory resources, and regulatory officials all with knowledge and understanding of biosecurity principles. Michigan and other Great Lakes states have a number of veterinarians and diagnostic laboratories already servicing the aquaculture industries (see www.AquaVetMed.info).
Furthermore the USDA-APHIS National Veterinary Accreditation Program (NAVP), which allows private veterinarians to perform some regulatory functions on behalf of government agencies (such as issue Certificates of Veterinary Inspection that document animals are free of specific diseases), has expanded its training/accreditation to include farmed fish (USDA-APHIS 2015b). The NAVP, together with aquatic veterinarians and diagnostic laboratories listed in the online AquaVetMed directories, should provide adequate personnel and resources to help with fish health issues in the Great Lakes.

Special Great Lakes Considerations

When comparing Great Lakes aquaculture to net-pen aquaculture in marine waters of the Northeast and Northwest U.S. few, if any animal health, public health, or seafood-safety issues are viewed as unique. However, emerging diseases not yet known in the Great Lakes may require attention in the future.

Recommendations

If net-pen culture is implemented in Michigan's jurisdictional waters of the Great Lakes, we recommend that commercial aquaculture operators:

- Only certified, disease- and specific pathogen free (SPF) fish should be used.
- Adoption of biosecurity plans that focus on disease prevention, control and eradication, and meet OIE standards and governmental regulations should be a high priority.
- Disease surveillance, monitoring and reporting programs in the Great Lakes should be improved and involve federal, state and provincial producer collaboration.
- Licensed and USDA accredited veterinarians should be used to ensure the most appropriate responses, to diseases, and the legal use of therapeutic agents.

ECOLOGICAL INTERACTIONS

Given the global rise of aquaculture, concerns exist about how aquaculture interacts with and performs in the environment. In some areas, coastal managers focus to maintain environmental quality *for* aquaculture while others work to protect the environment *from* aquaculture. In many parts of the world, including the United States, aquaculture development is restricted not by environmental, but by social capacity. Substantial advancements in siting and management practices in the past two decades now provide coastal managers with higher confidence when managing aquaculture industries (Price and Morris 2013). Poor practices in the past have furnished many "lessons learned" to guide future development and improved environmental regulations (e.g., the EPA's Clean Water Act, 1972) now provide greater protections for water quality, habitat, and food webs than previously existed.

Despite increasing experience, enhanced technology, and deeper understanding of ecosystems, managers still should remain cautious about ecological interactions when siting and managing net-pen aquaculture. Without being exhaustive, possible interactions include organic effluent discharge, sedimentation and accumulation, modifications of benthic communities and habitats, sediment recovery and fallowing processes, biodiversity, escapes, and invasive species. Environmental change caused by aquaculture can be both positive and negative depending on the interaction and system. Some interactions, commonly perceived as positive, include increased secondary production from nutrient loading, increased biodiversity, and the aggregation of fish and other marine life (Rensel and Forster 2007). Negative interactions are typically described as effects that cause disturbance at local or ecosystem levels and include such effects as reduced biodiversity, increased nutrient loading which drives environmental degradation, and harm to sensitive habitats or species (Price and Morris 2013). As with most environmental issues, quantifying disturbance and comparing its effects with other environmental stressors is difficult and subject to much debate.

Each coastal environment has its own set of environmental challenges. Within the Great Lakes, interactions between net pens and the environment should be carefully evaluated. Decisions based on best available science will provide managers and the public with the confidence needed to assess the relative potential for a sustainable net-pen industry. In the sections below, we provide a synthesis of key environmental concerns and special considerations for the Great Lakes.

Effluent Considerations

Eutrophication symptoms, including nuisance and harmful algal blooms (HABs), hypolimnetic hypoxia, and resultant drinking water problems, have plagued areas of the Great Lakes for decades. In the 1960s-1970s, the Great Lakes served as the epicenter for a vigorous debate regarding whether nitrogen or phosphorus limited algal growth in freshwater. Resolution of this controversy led to the establishment of target phosphorus loads for each lake under the 1978 amendments to the Great Lakes Water Quality Agreement (GLWQA) (EPA 2013). These target loads set a precedent for Total Maximum Daily Load (TMDL) development under the EPA's Clean Water Act (1972) and were largely achieved by regulating point-source inputs. Initially, this approach was effective, i.e., through the late 1990s, eutrophication management in the Great Lakes appeared quite successful. However, since then invasive dreissenid mussels have complicated the nutrient situation in lakes Michigan, Huron, Erie, and Ontario. These mussels are hypothesized to sequester nutrients in the nearshore, especially near tributary mouths, inhibiting nutrient transport offshore (Hecky et al. 2004, Cha et al. 2011). Additionally, by preferentially feeding on desirable phytoplankton while "selectively rejecting" undesirable cyanobacteria such as *Microcystis* (Vanderploeg et al. 2001), dreissenids likely promote HABs.

Consequently, some nearshore areas are experiencing severe HABs or beach fouling caused by benthic algae such as *Cladophora*, while other areas have become nutrient and phytoplankton depauperate, straining offshore fisheries (Evans et al. 2011, Vanderploeg et al. 2012, Bunnell et al. 2014). Recently, seasonal nitrogen limitation in several Lake Erie embayments has been reported (Chaffin et al. 2013, Chaffin et al. 2014), and developing evidence suggests that some nitrogen forms may increase HAB toxicity (Davis et al. 2010, Horst et al. 2014).

Net pens generate effluents (which increase biological oxygen demand) containing organic wastes (such as total suspended solids), nutrients (N, P), and some metals combined with chemicals applied to treat fish and maintain associated equipment. Literature estimates suggest 3 - 10 kg of phosphorus and 39 - 55 kg of nitrogen are released to the environment for every metric ton of fish produced in freshwater aquaculture (Podemski 2006, Weir 2006). Organic waste and nutrients, produced by fish fecal waste and uneaten food, can promote eutrophication, leading to HABs which, in turn, may contribute to anoxia, thereby modifying the benthic community within and near net pens. The extent of impact of organic and nutrient loadings depends on conditions surrounding net pens (see Siting). In the western basin of Lake Erie, seasonal eutrophy, due in large part to abundant nutrients from farm fields during storm-water runoff occurs; net-pen effluents could exacerbate those conditions. Other areas of the Great Lakes are oligotrophic and may not experience detectable nutrient increases with facilities of a size similar to those operated in the Canadian jurisdictional waters of Lake Huron in Georgian Bay.

Net-pen effluents contribute measurable levels of organic wastes and nutrients but these substances can dissipate within relatively short distances from net pens (C.L. Podemski, DFO, Winnipeg, Manitoba, personal communication, 2015).

Though the benthic community is modified underneath net pens, it recovers within as little as 100 m away from net pens in a small Canadian lake (Rooney and Podemski 2009). Phosphorus, measured in the water column between 1 and 2 km downstream of net pens, differed little from background levels (C.L. Podemski, DFO, Winnipeg, Manitoba, personal communication, 2015). Distribution of these nutrient and organic inputs greatly depends on the local conditions of the net-pen site (see Siting).

Regulatory Authority

The Michigan Department of Environmental Quality (MDEQ) is responsible for regulating water quality. Part 31 Rules grant MDEQ broad authority to control discharges that

> "*…may become injurious to… livestock, wild animals, birds, fish, aquatic life, or plants…*" (R324.3109).

This authority applies to both *point sources*, such wastewater treatment plants and storm water runoff, and non-point sources, such as agricultural runoff or overland flow.

Net pens meeting certain requirements are considered concentrated aquatic animal production (CAAP) facilities and are defined as point source discharges subject to regulation under the federal National Pollutant Discharge Elimination System (NPDES) Program (40 CFR 122.24). A net pen containing cold-water fish species is classified as a CAAP facility if it produces >20,000 pounds per year of harvest weight and feeds more than 5,000 pounds of food during the calendar month of maximum feeding (Appendix C to Part 122)

MDEQ authorizes point source discharges by issuing NPDES permits which include both technology-based and water quality-based requirements. MDEQ can apply state-wide, technology-based effluent standards using its best professional judgment (BPJ). Part 324.3106 and 40CFR 125.3 enable MDEQ to issue case-by-case technology-based effluent limits (TBEL) to industrial dischargers. The Department also may set site-specific, water quality-based effluent limitations in the Great Lakes to protect the dissolved oxygen standard (R 323.1064), limit nutrients (R 323.1060), or protect designated uses (R 323.1100). Michigan has set a BPJ-based TBEL for Total Suspended Solids (TSS) limit of 6 mg/l for permitted aquaculture facilities using recirculating or flow-through technology. This precedent demonstrates how MDEQ can issue standards protective of designated uses.

The USEPA-promulgated national effluent limitation guidelines (ELGs) for the Concentrated Aquatic Animal Production (CAAP) Point Source Category (CFR Part 451 Subpart B, Net-pen Subcategory) applies to discharges from net-pen facilities that harvest > 100,000 pounds per year of aquatic animals. 40 CFR Part 451.21 establishes effluent limitations attainable by the application of the Best Practicable control Technology (BPT) currently available. The limitations, expressed as narrative standards, include the following practices: feed management, waste control and disposal (feed bags, packaging materials, waste rope, and netting), transport or harvest discharge, carcass removal, materials storage, maintenance, recordkeeping, and training. In addition, the permit includes the requirements of Part 451.3 that the permittee shall develop, implement, and certify a Best Management Practices (BMP) Plan to document these practices into an operational plan for the facility which is maintained and updated as needed to comply with the requirements of the rule. The permit also contains a condition to comply with the reporting requirements for the use of and spillage of investigational new animal drugs or any extralabel drug, and any failure or damage to the structure of an aquatic animal containment system resulting in a discharge of pollutants into the waters of the state.

In addition to federal and state regulations applicable to nutrient control, Annex 4 of the updated 2012 GLWQA includes the following lake ecosystem objectives developed specifically to guide decision-making regarding Great Lakes nutrient inputs:

1. 1 minimize the extent of hypoxic zones in the Waters of the Great Lakes associated with excessive phosphorus loading, with particular emphasis on Lake Erie;
2. 1 maintain the levels of algal biomass below the level constituting a nuisance condition;
3. 1 maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the Great Lakes;
4. 1 maintain cyanobacteria biomass at levels that do not produce concentrations of toxins that pose a threat to human or ecosystem health in the waters of the Great Lakes;
5. 1 maintain an oligotrophic state, relative algal biomass, and algal species consistent with healthy aquatic ecosystems in the open waters of lakes Superior, Michigan, Huron, and Ontario; and 1
6. 1 maintain mesotrophic conditions in the open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie. 1

Effluent Control

The three main approaches for controlling net-pen effluents include capture and remove solids, limit and modify the feed applied, and locate net pens where effluents can be most easily assimilated.

Capture and remove solids. Land-based, flow-through aquatic operations can capture and remove solids that accumulate in fixed raceways, owing to their accessibility by maintenance personnel. Net pens cannot be cleaned in this manner, even though attempts have been made. Alternatives for collecting solids have been reviewed with the result that collection is not currently economically viable (Belle and Nash 2008). Efforts continue, however, around the world to evaluate effluent containment technologies and we encourage industry to vigorously pursue cost-effective technology that protects the environment as the USEPA effluent guidelines include the possibility of requiring "capture of waste feed and feces" (40 CFR 451.21).

Limit and modify feed. USEPA effluent guidelines provides the following best management practice for feed management:

> *Employ efficient feed management and feeding strategies that limit feed input to the minimum amount reasonably necessary to achieve production goals and sustain targeted rates of aquatic animal growth. These strategies must minimize the accumulation of uneaten food beneath the pens through the use of active feed monitoring and management practices (40CFR451.21).*

This is one part in a set of best management practices that meet the Best Practical control Technology (BPT) standard. Implicit is that feed management is the most effective means for reducing net-pen effluent. We encourage industry to use low-phosphorus feeds to further reduce nutrient input. Additionally, USEPA effluent limitations guideline call for real-time feed monitoring:

> *Use of real-time feed monitoring, including devices such as video cameras, digital scanning sonar, and upweller systems; monitoring of sediment quality beneath the pens; monitoring of benthic community quality beneath the pens."*

Locate net pens where effluents can be most easily assimilated or flushed. Locating a facility in an appropriate site should minimize its impact on the environment (see Management Approach and Siting). The basic premise of this approach is that the receiving waters may be capable of assimilating a limited amount of pollutant loadings without negatively impacting the ecosystem. Examples would include nutrient-deficient waters and/or locations with natural currents sufficient to disperse discharged pollutants. Careful siting must be used in combination with techniques discussed above. At a minimum, applicants for net-pen facilities should build a hydraulic and environmental model of the site and its surrounding environment to predict the potential impact of organic and nutrient loadings from a new operation (see Siting). Many states require or request environmental modeling as part of the permitting process to build confidence in the amount and fate of effluents near the operation. These models use input parameters such as hydrology, fish physiology, feed rates, and species composition to predict effluent discharge and sedimentation rates. Using these models, specific environmental concerns at local and regional scales can be evaluated and addressed.

To make informed decisions about the likely contributions of phosphorus (P) and nitrogen (N) to any waters in which net-pens are proposed to be sited, and the potential impact to the overall contribution of these nutrients to the lake, we urge the QOL group to assemble a Technical Working Group comprised of experts regarding net-pen operations, feed formulation, nutrient modeling, fish bioenergetics, etc. A mass-balance approach to estimate relevant forms of P and N produced by net-pen fish seems appropriate for it would require collecting such relevant information as amount of feed fed, amount consumed by fish, proximate composition of feed, fish, breakdown products of feed, etc. (Bureau et al. 2003). For each input used in the modeling effort, supporting assumptions should be articulated and appropriate uncertainty analyses performed to bound the estimates of nutrient production. This effort would provide an understanding of the relative contributions of net pens to the nutrient loadings, relative to established recommended loading limits for a given Great Lake.

Despite localized areas assimilating organic and nutrient loadings from a new facility without significant negative impacts, the Great Lakes have a limited capacity for absorbing these pollutants. Allowing net pens to discharge these pollutants may compromise use by others, of equal or higher value. In addition, land-based aquaculture operations are at a competitive disadvantage simply because they must install, operate, and maintain capture/treatment facilities for fecal waste and excess food.

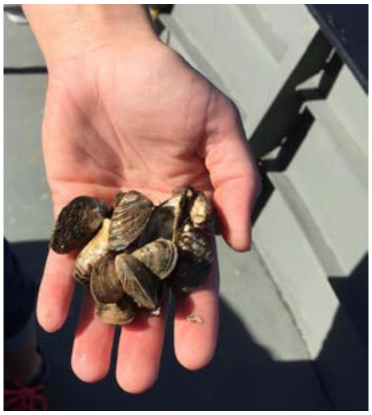
Assessing the success of siting a facility (and thereby its continuing use) relies on an adaptive management approach which would include a rigorous experimental design, i.e., BACI, designating and monitoring intensely Before, After, Control, and Impact sites (See Management Approach for a more complete description). By using this approach, commercial aquaculture operators can evaluate the wisdom of specific net-pen locations through time, thus continually improving and reducing their environmental footprint.

Sensitive Habitats

The Great Lakes ecosystem contains many sensitive habitats including bird sanctuaries, fish spawning grounds, native mussel habitat, reefs, and expansive coastal wetlands. Net-pen aquaculture interactions with sensitive habitats are typically related to benthic deposition which can impact the area directly under the net pen. Operational activities such as increased boat or vehicle traffic also can influence bird nesting areas. The siting of net-pen operations in areas that are critical spawning habitats for species such as Lake Whitefish poses one of the highest habitat concerns. Best practices include avoiding sensitive habitats at the onset. Advance mapping technologies now provide easy access to spatial maps that can guide the site-selection process (see Siting).

Threatened Species

Native mussels in the Great Lakes have been threatened and have become endangered. In fact, native mussels are among the most endangered species throughout the United States (Wilcove and Master 2005). These mussels colonize benthic habitats and could be damaged by sedimentation, aquaculture operations, and vessel traffic around net pens. We recommend thoroughly evaluating densities of native mussels near proposed net pens for impacts of net pens could be quite complex. By adding a new food source, net pens could potentially enhance native mussel populations. The nature of impacts will differ with the amount of suspended solids and sedimentation from an operation, as excessive sedimentation also could smother native mussels. We would recommend not siting net pens near native mussel populations, at least initially.



Invasive species

Invasive species have significantly altered the ecosystems of the Great Lakes during the past two centuries (Mills et al. 1994). With at least 25 non-native fishes, zebra and quagga mussels, spiny and fish hook water fleas (*Bythotrephes longimanus* and *Cercopagis pengoi*), and a number of invasive plants, the Great Lakes ecosystem presents a challenge to managers working to maintain environmental integrity. Introductions occur from many pathways including shipping, the pet trade, and transfers from other water bodies. Due to aquaculture releases of Asian carp in river systems ultimately connecting to Lake Michigan, the possibility of an invasion into the Great Lakes remains. Thus, we advise that managers remain cautious when considering the risk of invasive species.
The invasiveness of aquatic species is difficult to predict especially under rapidly changing environmental conditions. Net-pen aquaculture is a documented source of introductions when non-native species are cultured. We recommend that policies continue to limit aquaculture to only native or naturalized species to avoid risk of future introductions. We also recommend that comprehensive biosecurity plans be required to ensure that non-native species are not introduced or spread as part of aquaculture operations. Possibilities exist for non-native species introduction and spread from activities such as the transport of fry from hatcheries and routine movement of fish and gear among farm sites (e.g., net fouling). Biosecurity plans could include requirements for cleaning gear, inspections of farm sites, and other precautions similar to those in place for zebra mussels.

The interactions between existing invasive species and net-pen aquaculture in the Great Lakes present challenging scenarios. Invasive zebra and quagga mussels that colonize on and near aquaculture operations could serve a beneficial ecological role by assimilating nutrients from net-pen operations. Coupling net pens and extractive species (e.g., bivalves and algae) is a common technique being tested around the world to mitigate poor water quality by assimilating and storing P, N, and C, around fish farms. Interestingly, invasive zebra and quagga mussels may provide similar benefits in freshwater, generating an integrated multi-trophic (IMTA) type response. However, dense mussel populations near net pens in response to elevated nutrients and structural habitat could provide propagules to new areas previously unaffected.

Escapes

Given the potential for aquaculture species to interact with wild stocks, managers should make every effort to contain cultured species. Fish escape from aquaculture operations for many reasons including human error, extreme weather events (e.g., ice sheet movement, storms, etc.), damage to nets, catastrophic gear failure, and even vandalism. The magnitude of escape events can vary from small releases resulting from a tear in a net to large releases resulting from storms or other large-scale impacts. Large-scale releases are typically realized immediately; conversely, small-scale releases may go undetected for some time.

While some research has documented the risk of aquaculture escapes, uncertainty remains. Rust et al. (2014) summarized research over the past 5 years and concluded that risk of escape depends on 1) number and survival of escapes relative to wild conspecifics, 2) difference in genetic makeup between escapees and wild fish, 3) reproductive fitness of escapees, and 4) opportunity for reproduction with wild fish. When considering decades of interactions between wild and domesticated species provided by salmon restoration activities, general propagation of marine species, salmon aquaculture, general hatchery practices, and agriculture, the following key principles were provided by Waples et al. 2012 (adapted slightly):

1. 1 Long-term sustainability depends on conserving a diverse array of natural populations.
2. 1 Domestication of aquaculture species may result in some genetic change; however, these changes may, but will not necessarily have substantial genetic effects on wild populations.
3. 1 Escapes cannot be avoided, particularly when production is scaled to allow profitability; therefore, risk assessments should account for reality and the potential effects on wild populations.
4. 1 To make a genetic impact, escapes must survive and reproduce successfully in the wild. The capability of escapees to do this can vary widely, depending on a variety of factors. In general, fitness in the wild of captively reared individuals declines with number of generations in captivity.
5. 1 Some genetic risks are inversely correlated, such that reducing one risk simultaneously increases another. For example, creating a genetically divergent aquaculture population might reduce the chances that escapes can survive and reproduce, but those that do can pass on maladapted genes to the wild population.
6. 1 An effective monitoring component is important but cannot compensate for failure to implement risk-averse strategies. Even ambitious monitoring programs might have low power to detect adverse effects before serious harm occurs.

Owing to the fact that escapes can and will occur, we believe it critical that risk of genetic impact be assessed at a level that provides confidence to the coastal manager and the public. In general, two strategies can minimize risk. The first strategy is the “make-them-different strategy” where cultured animals are selectively bred to be much different than wild counterparts. In this strategy, fitness in the wild is drastically reduced; thus, the risk of genetic interaction is minimized. The second strategy is the “keep-them-similar strategy” where genetic similarity of broodstock to wild stocks is managed in the hatchery to reduce genetic impact should there be an escape. The appropriate strategy can be situation-specific depending on the species involved, length of domestication, trade-offs between culture practices and escape risks (Lorenzen et al. 2012).

To better understand and predict the risk of escapes and the trade-offs, net-pen operators and researchers have developed models capable of simulating how hatchery practices can affect the genetic enhancement of aquaculture species and their fitness if released into the wild. Models such as the Offshore Mariculture Escapes Genetics Assessment (OMEGA) model uses the size and growth characteristics of cultured fish, survival rates of escapees in the wild, probability of escaped fish entering wild conspecific populations and interbreeding, and the dynamics of the wild population to predict the impact escapes may have on survival and genetic fitness of the wild population (NOAA 2014). Tools such as these can be an effective way to understand and bolster confidence regarding the potential for genetic impacts from escapes.

Prevention of escapes is, however, the best approach to minimize interactions (see Operations). Briefly, net-pen managers can prevent or minimize the risk of escape events by using appropriately designed net-pen technology for local conditions, use of predator nets to prevent birds and other predator interactions, land-based culture for appropriate stages of the grow-out, and carefully designed handling practices that minimize losses; use of sterile fish when appropriate also reduces negative consequences of escape (Rust et al. 2014).

An escape event was simulated in Canadian waters to track tagged rainbow trout from two commercial operations in the North Channel of Lake Huron (Patterson and Blanchfield 2013). From telemetry and external tags, fish exhibited quite variable site fidelity, i.e., returning to within 500 m of the farm. Fidelity to two farms using two different telemetry tags varied from 2% to 40% 3 months after release. Released fish often were detected in nearshore areas or near neighboring commercial operations. Finally, fish occurred > 350 km from their release site in rivers, open water, and in an adjacent Great Lake. Survival was about 50% after 3 months with some fish recaptured > 2.5 years later. Avian predators and anglers accounted for most of the mortality. Thus, escapees can survive long periods and move considerable distances from released sites.

Given that escapes will occur, we recommend that an Aquaculture Genetic Management Plan (AGMP) be used to asses risk and reduce potential for negative interactions (Waples et al. 2012). With this plan, performance standards can be met, including minimizing opportunities for interaction with wild fish through proper broodstock management and marking, maintaining stock integrity and genetic diversity, minimizing interactions with wild fish through effective containment, maximizing in-culture survival of broodstock and progeny, and limiting the impact of pathogens on wild fish (Brasket et al. 2013; Waples et al. 2012).

Mammals and Birds

Aquaculture interactions with protected species including mammals and birds and some fish species has been a global concern. Fortunately, we anticipate no negative interactions with mammals in the Great Lakes. However, a number of protected bird species as well as those species considered a nuisance (double crested cormorants) could interact with aquaculture operations. Nets covering net pens are commonly used to exclude birds. We recommend that management agencies work with net-pen operators to ensure that these nets are of the appropriate design to prevent bird entry while avoiding entanglement (see Operations).

Personnel

To adequately assess ecological interactions, expertise across the entire ecosystem will be needed. Experts capable of assessing water quality changes, benthic impacts, and interactions with wildlife are available from local, state, and federal management agencies. Environmental consulting firms and university staff also can provide similar expertise. Sampling for the BACI design will require this expertise from the beginning to the end of any aquaculture operation in the Great Lakes (See Operations).

Special Great Lakes Considerations

There are a number of ecological interactions that require special consideration when siting and managing net-pen aquaculture in the Great Lakes. Monitoring and controlling nutrients and organic wastes by regulators are both critical for proposed net-pen operations in the Great Lakes. The potential for net pens to promote eutrophication highly depends on their scope and location. While some areas are currently experiencing extreme nutrient impacts, such as algal blooms including HABs, other areas (offshore, most typically) have low background nutrient levels and are less likely to be strongly influenced by well-regulated aquaculture activities. Current state and federal regulations, as well as the provisions of the 2012 GLWQA, provide regulators with both the mandate and tools for appropriate regulation.

The potential for interactions between commercial and recreational fisheries exist in any aquaculture industry. In the Great Lakes, interactions are likely with commercial fisheries, especially conflicts related to space and resources (see Siting). Potential net-pen sites that occur near tribal commercial fisheries would require considerations for co-management decisions as called for in the Great Lakes Consent Decree (U.S. v. Michigan 2000). The greatest interaction, however, may be with recreational fishing. As observed in Canadian waters, anglers treat aquaculture operations as fish aggregating devices (FADs). This interaction is generally seen as positive for both the aquaculture industry and the recreational angler. In some instances, however, vandalism occurs for the purpose of releasing aquaculture fish for the benefit of the recreational angler (Steve Naylor, Ontario Ministry of Agriculture, Food and Rural Affairs, Guelph, personal communication).

Recognizing the congruence between net-pen aquaculture and invasive zebra/quagga mussels, these invasive mussels may colonize underneath, around, and on net-pen structures and mooring systems. Nutrient releases from the net pens may intensify recruitment leading to dense local populations around net pens and thus providing propagules to areas not previously colonized. Conceivably, invasive mussels could serve a beneficial role by assimilating and sequestering nutrients released from net-pen operations.

Net-pen aquaculture also may influence endangered species of native mussels. Considerations for these impacts are necessary to ensure that aquaculture operations do not affect species recovery. Pre-installation monitoring surveys should include threatened species.

Recommendations

If net-pen culture is implemented in Michigan’s jurisdictional waters of the Great Lakes, we recommend that commercial aquaculture operators:

- Endorse Annex 4 of the 2012 GLWQA, working to assure their operations do not hamper achievement of lake ecosystem objectives.
- Vigorously pursue all available and possibly future practices to minimize net-pen effluents.
- Locate net-pen operations to minimize impacts on sensitive environments, ecosystems, food webs, species (especially native mussels), etc.
- Use only native or naturalized fish species.
- Follow closely key principles adapted from Waples (2012) dealing with genetic interactions between farmed and wild fish.
- Follow a rigorous biosecurity program.

SITING

Aquaculture site selection in the Great Lakes is critical to ensuring water quality and limiting ecological impacts, and directly influences net-pen operations, fish-health considerations, and ecological interactions such as impacts to nutrients, algae, benthic communities, higher trophic levels, and even escapes. Indeed, proper siting provides the most comprehensive approach to regulate net-pen implementation in the Great Lakes. To choose sites wisely, we require data dealing with physical conditions at various spatial- and temporal-scales, including site-specific information such as depth, current speed, water-level oscillations, wave height and period, and substrate. Specifically, flushing rate and depth at the net-pen site are critical to limiting ecological impacts (Price and Morris 2013); yet, information available through operational models, online tools, scientific literature, and other sources varies across these scales. Essentially we are able to quantify variables at the lake-wide or regional-scale quite well whereas, we have far less ability to quantify similar physical variables at the site-specific scale. As a result, we recommend supplementing these site-specific data sources with preliminary monitoring at all potential site locations. For example, ambient longshore current, as a function of month or season, is well characterized at the regional scale for most reaches of the Great Lakes; however, site-scale (e.g., beach) circulation patterns vary with greater uncertainty, requiring supplemental observations and modeling (Beletsky et al. 1999). Even so, information across these spatial- and temporal-scales, with particular emphasis on water exchange and depth, is crucial for proper site selection. Therefore, in the following sections, we describe siting considerations as a function of spatial-scale, from lake-wide to regional-, and site-specific characteristics along with the level of uncertainty associated with each component. This information will provide a baseline understanding of the physical processes in the lakes and the suite of conditions that should be quantified and modeled to ensure optimal net-pen siting.

Lake-wide Considerations (>300 km)

In general, uncertainty associated with hydrodynamic processes increases with finer resolution, such that the conditions (e.g., current) at a specific time and location are less understood than the regional seasonal conditions (e.g., lake summer circulation patterns). On a lake-wide scale, seasonal variations in meteorological conditions dominate water temperature, ice dynamics, circulation patterns, and water quantity in the lakes. Conversely, short-term changes in weather (e.g., hourly) affect lake-scale water level oscillations, commonly referred to as *seiche* modes, which are lake-scale standing waves. With seasonal variation, spring thaw and precipitation increase tributary flows and nutrient loads to the lakes, which in turn can increase nearshore hydraulic flow, alter water quality, and introduce floating debris, all of which would influence net-pen placement. As the lake surface warms in spring and early summer, the lake undergoes thermal stratification (thermocline often in the upper 30 m; Rao and Schwab 2007), which induces inertial current oscillations in the lakes, where high surface current speeds (~50 cm/s) rotate in an anticyclonic (clockwise) fashion at a period near 17 h. These currents, which exist > 5 km offshore, are often more dispersive than nearshore flow patterns and would contribute to optimization of flushing for net pens. In terms of water quantity, spring flows and fall evaporation contribute to natural lake level variability on the order of 0.3-0.6 m within 1 yr, where the historical range of lake level fluctuations is > 2 m (Gronewold and Stow 2014; recent lake level changes in Lake Michigan-Huron have surged over 1 m in 2 yrs; Gronewold et al. 2015). Short-term water level fluctuations caused by hourly wind conditions affect regional- and local-scales, but they are caused in part by lake-scale, water-level fluctuations (e.g., seiches). These lake-scale standing waves develop when wind blows across the lake stacking up water on the downwind end, which then releases and sloshes, similar to water motion in a bathtub, with the passing of the inducing weather system. The magnitude of these short-term, water-level oscillations depends on the strength of the weather condition; however, its period depends on the lake's size and depth, and therefore can be predetermined. For example, the first mode of free oscillation is 9.1 h in Lake Michigan and 6.7 h in Lake Huron (Mortimer and Fee 1976). Overall, these water-level fluctuations can substantially influence site depth at any given time and play an important role in flushing, both of which influence net-pen placement.

Regional-scale Considerations (50-100 km)

At the regional scale, circulation patterns drive ambient flow, and although current speeds and patterns respond to wind conditions, seasonal circulation patterns develop in each lake. Based on observations and computer modeling, these patterns have been documented providing an understanding of dominant flow directions in any region with reasonable confidence (Beletsky et al. 1999). Short-term water fluctuations such as seiches, as noted above, also play a role on a regional scale, where semi-enclosed bays can have their own natural resonance. Because of their region-specific oscillation modes, siting of net pens must be made with care, ensuring an understanding of regional-scale flushing. In addition, both wind conditions and internal waves also can induce changes in regional thermal structures, (e.g., upwellings or downwellings). Water quality varies regionally due to differences in nutrient loading concentrations, land-use, flushing, and depth. Finally, ice formation occurs throughout the Great Lakes, though regional differences exist in ice thickness, type, concentration, and transport. The majority of regional differences in ice characteristics are driven by exposure to the open lake (versus protection in embayments or other sheltering topographical features), latitude, and depth (areas of greater depth tend to freeze last). Therefore, net pens located in sheltered bays will experience minimal ice movement and risk to operations. Offshore sites located in deeper waters may experience less ice; however, site access will be greatly restricted due to dynamic ice conditions, especially during periods of ice-in and ice-out, in the nearshore region.

Site-specific Considerations (1-10 km)

Site-specific physical conditions are most critical to successful site selection, but contain the most uncertainty and risk, compared to the lake- or regional-scale. For net-pen placement, a suite of key parameters should be evaluated at this scale to minimize ecological and social impacts, including distance from shore, depth, water temperature, dissolved oxygen, current speed, substrate, sediment, habitat, wind and waves, recreational and commercial fishing, and other recreational activities (Ross et al. 2013, Riley and Wickliffe 2015). Even if lake- and regional-scale investigations identify promising sites, pre-install observations and modeling are required at the scale of the site. Specifically, survey design should include hourly measurement of waves and profiles of water temperature, currents, conductivity, and turbidity over several days or weeks and across seasons at the site and at least one nearby adjacent location (Belle and Nas, 2008). Both range of wave conditions using maximum fetch calculations and dominant meteorological conditions should be documented (e.g., maximum wind speed, direction, and duration; Beveridge 2004). Hydrodynamic, sediment, and water quality models will provide a three-dimensional depiction of key physical processes, where simulation periods should cover hours to months at spatial scales on the order of pen size (0 ~ 10 - 100 m) (Wu et al. 2014). These models should be calibrated/validated with field data and used to evaluate the ecological impacts across time-scales. Effluent transport can be highly variable across time-scales from episodic (storm) events to seasons. Thus, the monitoring plan and modeling efforts should be designed to capture the range of these conditions to ensure that net-pen sites will meet minimum flushing and depth requirements at all times for an acceptable level of ecological impact.

In particular, flushing of a net-pen site will require sufficient current patterns to remove effluents from the site; however, currents will vary with wind conditions, nearby tributary inputs, water-level oscillations, and seasonal weather and lake conditions. Low mean currents at a site may not correlate with poor flushing, as episodic (e.g., storms) or periodic (e.g., seiche) conditions can provide sufficient effluent removal, resulting in low ecological impacts. Similarly, a high mean current speed may not always correlate with sufficient flushing if the imposed circulation pattern in the immediate area causes effluents to collect in certain locations. Although the production capacity of a site depends on flushing rate, no simple relationship exists between capacity and water exchange, and therefore each site must be evaluated through adequate monitoring and modeling as described above. High current speeds also can induce stress in cultured species when the current exceeds the swimming speed of the species (Carrol et al. 2003; Belle and Nash 2008).

Water depth plays an equally critical role in net-pen siting (Price and Morris, 2013) for shallow water can lead to lower flushing rates and the interaction between nets and substrate can lead to tearing and escapes. In marine environments it has been noted that water depth should be >2X net pen depth (Belle and Nash 2008), though in the Great Lakes this limit should ultimately be set to achieve adequate flushing and access to the hypolimnion (cold subsurface waters) for caged fish. Additionally, with increased depth comes increased wave heights and ice flows, compromising net-pen operations. Overall, net-pen siting should balance the required depth, flushing rates (no effluent detection beyond a few hundred meters per C.L. Podemski, DFO, Winnipeg, Manitoba, personal communication, 2015), while minimizing exposure to destructive waves and ice conditions.

Nearshore Zone and the Coastal Boundary Layer

In terms of physical processes, the Great Lakes can be characterized by distance from shore and divided into the surf zone, coastal boundary layer (CBL), and the offshore or open lake zone. In the surf zone, currents are extremely complex and driven by a balance between water transport driven by breaking waves, parallel (longshore) transport, and return flows along the coast. Erosion of bottom substrate is maximized in this zone as a result of wave action; overall, this region is not a viable candidate for net-pen installation. However, beyond the surf zone, the CBL can be more amenable to nearshore net-pen siting.

The CBL is often defined by depth contour (up to 30 m) or by distance (out to 5 or 10 km). The shoreline itself provides a boundary that directs flow in the longshore direction (e.g., parallel to the coastline), and as a result of the shallow depths, bottom currents in this region are much higher (causing greater resuspension) than in the offshore zone (Rao and Schwab 2007). At this boundary, the circulation patterns transition from the offshore conditions (e.g., inertial current oscillations in summer) to nearshore processes. This region experiences the greatest range of temperature fluctuations as a result of upwelling/downwelling and thermocline impingement, which occur over hours to days. The magnitude of the longshore transport (parallel current) in the CBL increases with distance from the shoreline, peaking near 3 km from shore, and then declines as it transitions into the open lake (offshore). Cross-shore currents (perpendicular to shoreline) also exist in this region, but tend to be nearly 5x smaller than the longshore currents and peak ~5 km offshore. These length scales define regions critical to flushing, i.e., wastes generated > 3 – 5 km offshore have a greater chance of being dispersed. Conversely, effluent within ~3 km nearshore can be trapped in poor recirculating waters though still potentially transported along the shore and away from the site. With nearshore siting, flushing can be optimized by locating pens near points of highest longshore and cross-shore transport.

River inputs provide hydraulically driven currents in the nearshore, sediment, and runoff from the watershed. During heavy spring precipitation, river inputs increase turbidity in the nearshore that extend several kilometers into the lake. Whereas this may increase flushing, this can adversely affect water quality and fish production as well as increase floating debris that can damage net pens.

In winter, nearshore ice is the first to form in the lakes and occurs nearly every year, a pattern which may differ with climate change. Depending on weather and shoreline topography, ice flows can be compacted along the shoreline, be transported in the longshore direction, or be pushed from the shoreline. In embayments and protected areas, ice conditions likely are more static. Nearshore complexities and model limitations make understanding ice conditions at a site difficult. Net-pen installation may be best suited for ice-free periods or in deeper waters where pens can be submerged.

Offshore Zone and the Open Lake

The offshore region of the lakes begins transition at the edge of the CBL, ~5 to 10 km offshore, and extending to mid-lake. Though water conditions in the offshore may be less complex, our understanding of the offshore meteorological conditions that drive currents/waves is limited. Circulation in the offshore zone is still driven by episodic wind events (storms) and seasonal current patterns and gyres. Inertial current oscillations during stratification yield high current velocities with substantial dispersion in all directions. With greater dispersion in the offshore (than nearshore), offshore-farm effluent often cannot be detected > 30 m from net pens (Rust et al. 2014).

Wave conditions in the offshore region are better understood and modeled than in nearshore zones (Schwab et al. 1984). Although offshore wave heights can be large, improved predictive capability (through NOAA NDBC buoys, modeling techniques, and fetch-driven wave calculation) provides a better understanding of net-pen risks.

Ice formation in offshore regions occurs less often than in the nearshore zone, with reduced concentration and thickness in deeper waters and high interannual variability. In each year, ice formation begins in the nearshore zone and extends outward to the center of the lakes, with the deepest areas of the lake freezing last if at all. Operating net pens in winter can be hazardous, with offshore sites experiencing potential cover and ice flows, icing conditions which can sink structures, as well as the inability to reach and maintain sites due to ice conditions in the nearshore.

Sensitive Habitats and Other Restrictions

Sites should be selected after carefully surveying species presence, distribution, and diversity, including endangered species and benthic fauna and flora (Belle and Nash 2008). These data should be supplemented by the literature and other data sources while accounting for seasonal variation in species presence. Assessing potential impacts to these communities due to effluent discharge, interbreeding via escapes, disease, and deposition should all be evaluated. Finally, site selection should include a survey of other restricted zones such as heritage sites, National Marine Sanctuaries, commercial shipping lanes, and routine monitoring sites.

Personnel

Proper site selection and evaluation will require an in-depth survey of the proposed sites with regard to a suite of biological, physical, chemical, and geological variables. Expertise in physical processes, water quality, and ecological impacts will be required to develop survey plans, carry out pre-installation monitoring and modeling, and evaluate the results. Site selection efforts that neglect one or more of the areas or substitute them with employment of uncalibrated computer models should re-evaluated. To aid in this process, quite a number of data sources, management tools, and literature exist to supplement site-selection decisions.

Table 2. Relevant data sets, source, and web access for assessing siting conditions in the Great Lakes.

Data	Source	Link
Meteorological conditions	NOAA National Center for Environmental Information (NCEI)	https://www.ncei.noaa.gov/
Oceanographic conditions	NOAA National Ocean Service (NOS)	http://tidesandcurrents.noaa.gov/
	NOAA Great Lakes Environmental Research Laboratory (GLERL)	http://www.glerl.noaa.gov/res/glcfs/
	Great Lakes Observing System (GLOS)	http://www.glos.us/
Bathymetric data	NOAA National Center for Environmental Information (NCEI)	https://www.ncei.noaa.gov/
	U.S. Army Corps of Engineers	http://www.usace.army.mil/
Lakebed Alteration Tool	University of Michigan	http://www.glgis.org/ladst/
Ecological Data	EPA	http://www.epa.gov/glnpo/
General Information	NOAA/GLERL	http://www.glerl.noaa.gov

Special Great Lakes Considerations
Because the Great Lakes experience processes similar to coastal oceans, the literature on aquaculture implementation and best management practices apply. Major differences include (1) freshwater, (2) enclosed basins uncoupled from the deep ocean, (3) different ecological interactions, and (4) annual ice formation. Due to their enclosed nature, aquaculture in the Great Lakes must avoid overlap with recreational areas, commercial fisheries, drinking water intakes, and commercial navigation, presenting a set of best management practices that may not differ greatly from ocean-based aquaculture. Given these similarities, Great Lakes siting must rely on quantitative, well-documented, site-specific information. Important characteristics such as current- and seiche-driven flushing need to be understood at fine spatial- and temporal-scales. Given the mismatch between what we know at lake- and regional-scales and what we don't know at nearshore and site-specific locations, pre-installation monitoring and modeling should be completed at potential net-pen sites.
With regard to key site selection parameters (identified in Riley and Wickliffe 2015), physical processes within coastal-marine systems and the Great Lakes are quite similar. Great Lakes offshore regions provide roughly the same set of challenges as the coastal ocean, save for ice formation in the lakes, though with differing magnitudes of spatial- and temporal-scale. Nearshore and coastal conditions experience similar mixing processes, but without tides and with shorter wave periods in the Great Lakes. As a result, periods of water level oscillations, frequency and type of episodic events, and their seasonal variation should be carefully monitored to accurately estimate flushing. Seasonal variation in temperature and currents including annual overturn, stratification, and ice formation, have significant impacts to the physical, biological, and chemical processes in the lakes, thereby substantially influencing net-pen siting.

Recommendations
If net-pen culture is implemented in Michigan's jurisdictional waters of the Great Lakes, we recommend that commercial aquaculture operators:

- Recognize and respond appropriately (re modeling, data collection, etc.) to differences in our depth of knowledge for lake-, region-, and site-wide physical processes.
- Supplement site-specific data sources with on-site monitoring to confirm critical metrics, e.g., flushing rate, circulations patterns, longshore currents, etc.
- Use rigorous data-driven modeling to evaluate site-specific characteristics vital to site choice.

PANEL REFLECTIONS ON NET-PEN AQUACULTURE IN THE GREAT LAKES

Below, we reflect on the fishery management implications of our work by first considering relevant legal considerations and agreements (to which Michigan is subject). We then review the precautionary principle and how it interacts with our recommended adaptive management approach to assist the Quality of Life group as they explore the notion of commercial aquaculture within the Great Lakes.

In addition to the Michigan's own regulations and authorities relevant to net-pen aquaculture (see Ecological Interactions), we must fully recognize the complex suite of partnerships and both legal and nonbinding agreements that Michigan has agreed to work within.

Michigan is party to a Consent Decree (U.S. v Michigan 2000) with five tribal nations regarding fishing rights in the 1836 Treaty-ceded waters of the Great Lakes, including parts of eastern Lake Superior, Lake Michigan, and Lake Huron. Through the 2000 Consent Decree, Michigan has specific obligations to uphold with respect to tribal fishing rights in these waters. These obligations may, at times, be in conflict with development of net-pen aquaculture.

The Michigan Department of Natural Resources is signatory to *A Joint Strategic Plan for Management of Great Lakes Fisheries* (GLFC 2007). This document outlines the strategic procedures by which fishery management agencies throughout the Great Lakes have agreed to cooperatively manage fishery resources. As such, each lake is managed by a lake committee comprised of senior fishery managers from each jurisdiction with management authority on that lake. When decisions in one jurisdiction may affect fisheries in the lake, all jurisdictions must come to consensus about a proposed management action before any decision is implemented. This cooperative process is facilitated by the Great Lakes Fishery Commission.

The Michigan Department of Environmental Quality, through its Office of the Great Lakes, works within the structure established by Canada and the United States in the *Great Lakes Water Quality Agreement* (GLWQA 2012) to regulate nutrient loading and in-lake nutrient concentrations. Two key parts of this process include 1) Annex 4 of the GLWQA, which sets nutrient loading targets for each lake and, in some cases, specific locations in each lake and 2) the Lakewide Action and Management Plan (LAMP) process. Cooperators on each lake develop an action plan to assess, restore, protect, and monitor the ecosystem function of each lake. Lake partnerships coordinate the work of federal, state, provincial, tribal, and non-governmental partners to improve the status of each lake ecosystem with respect to chemical, biological, and physical goals established by the LAMP document. A public consultation process ensures that each LAMP addresses public concerns (www.http://epa.gov/greatlakes/lamp/index.html).

After our review of the agreements to which Michigan is a party, we turned our attention to how more general perspectives might be developed, ones which would aid the Quality of Life group place commercial aquaculture into a broader context. In our view, at least one such context consists of balancing stewardship of public trust resources for the benefit of all society with development of economic opportunities through net-pen aquaculture in the Great Lakes.

In our search for context, we reflected on net-pen aquaculture via two major approaches, one that provides overall philosophical guidance (Precautionary Principle) and one that provides for measurable learning by doing (active Adaptive Management). Embracing the precautionary principle would slow the development of the net-pen aquaculture industry simply because its ultimate effects on lake ecosystems are poorly known, as demonstrated by our report. Because unknowns are currently paramount, i.e., we don't know what we don't know, we should use a historically successful management process, adaptive management, in combination with a BACI design (Before, After, Control, Intervention or Impact), to provide robust, quantitative insight into the ecosystem effects of inshore net-pen or offshore cage aquaculture (see Overarching Management Approach). In cooperation with ongoing commercial aquaculture, state agency scientists and managers can collect data from industry activities that can truly evaluate impacts. The cycle of adaptive management provides insight about the impacts of industry activities, even though lake ecosystems are changing in response to other elements, such as climate change, water-level fluctuations, human population growth, etc. Such active management experimentation provides an ecologically sound harvest, "given the many biological unknowns in a given ecosystem, the behavior of exploiters of the resource, and the inability of humans to predict how the production potential of the ecosystem may change through time" (from Hilborn et al. 1995, Stewart-Oaten and Bence 2001).

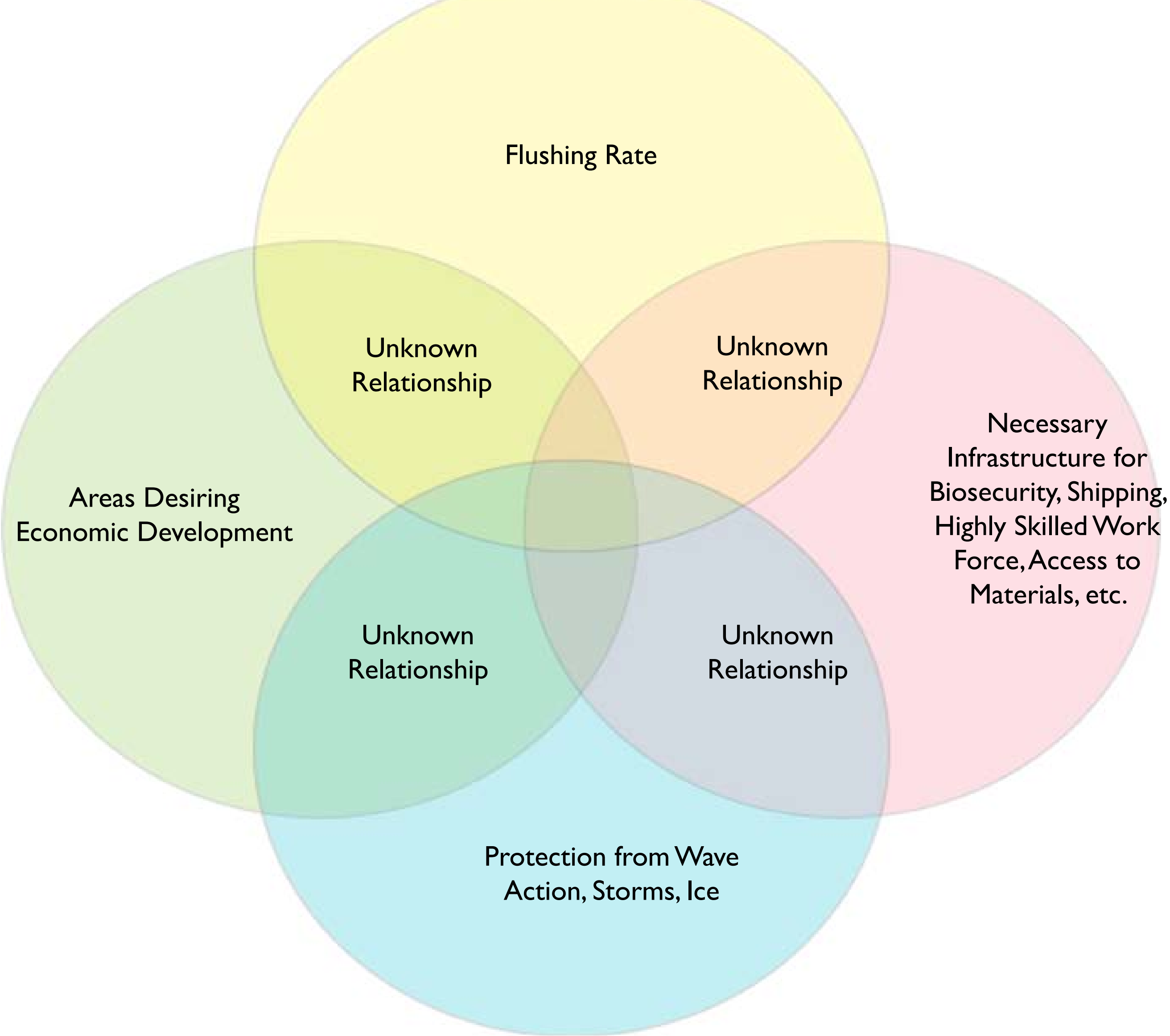
As a panel, we cannot recommend a rate at which the industry should develop, only that the rate should allow for the intricacies of adaptive management to provide new understanding of how the industry can be organized to minimize its impact on lake ecosystems. Throughout this process, we believe that if your goal is to preserve ecosystem structure, function, and nutrient status, managers and regulators must err on the side of caution (Hilborn et al. 1995), if commercial aquaculture develops in the Great Lakes.

Explicitly considering nutrient status within the Great Lakes, each lake has specific targets which are to be met as part of the Great Lakes Water Quality Agreement (GLWQA, 2012), an agreement hard fought which brought nutrient limits to the Great Lakes. Both nearshore net pens and offshore cages contribute nutrients and organic matter to the nutrient pool within the lake simply because these organic materials cannot be collected, treated, or removed. These nutrient contributions could challenge the very goals of the GLWQA (2012), if net-pen aquaculture were expanded to the level suggested by the Michigan Aquaculture Plan. With the GLWQA, an individual lake's nutrient status or water quality has been formally set and this status must be maintained, leading one to conclude that organic loading capacity, as a measurable entity, must be limited, i.e., only so many metric tons of P can be dumped into the lake before these targets are exceeded. Thus, as in any competitive interaction for a limited resource (here it is how much organic loading can occur), tradeoffs will exist. Individual facilities will generate phosphorus loading, contributing to the annual limit. This phosphorus would not be entering the system without an aquaculture facility present.

Would Michigan citizens prefer to use an allocated loading amount to permit new building or a manufacturing facility in the watershed or to allow commercial aquaculture operations to develop? And, if the answer is commercial aquaculture, because loadings are finite, the number of commercial operations also must be finite, thus leading to limited entry, by a set number of licenses determined by an overall P loading limitation. For commercial net-pen aquaculture in the Great Lakes, allowing for too many facilities could result in overexploitation of the nutrient status of a lake, with resultant ecosystem effects including, but not limited to, eutrophication, HABs, *Cladophora* fouling, hypoxia in the bottom waters, compromised ecosystem structure and function, etc. (see Ecological Interactions). Based on these arguments, we conclude that the net-pen aquaculture industry in the Great Lakes, if permitted, may require a limited entry approach to allow for other competing uses of organic loading in the lake and fairness amongst those competitors.

Clearly, siting drives the success or failure of a net-pen or cage operation. To begin to visualize how we reflected on all the factors influencing site choice, we generated a hypothetical Venn diagram with four variables (Figure 2), including flushing rate paired against protection from wave action, storms, etc. and need for economic development paired with access to necessary infrastructure. Metrics in these two pairings are inversely related, i.e., as flushing rate increases, protection declines; as need for rural development increases, infrastructure support declines. Hence, as indicated by the small space where all four factors overlap, finding suitable net-pen sites clearly will require a thoughtful and deliberative spatial analysis, especially when considering all of the other parameters (critical spawning grounds, reefs, threated species, proximity to rivers, sensitive habitats, etc.) described in our review and the potential for finding specific, low-impact, high-yield locations may be challenging, even given the size of the Great Lakes.

Figure 2. A hypothetical Venn diagram incorporating only four constraints and demonstrating conceptually the challenge of finding net-pen sites with low-impact (re ecosystem structure and function), high-yield (re fish production) locations. Size of the circles and the amount of overlap is unknown without additional spatial analysis and stakeholder involvement. "Unknown Relationship" simply refers to our lack of knowledge of how, for example, protection and infrastructure are related, if at all.



Sites, such as the western basin of Lake Erie, likely can be eliminated from consideration by just one variable, such as phosphorous, given the status of the current blue-green algal bloom situation and state prioritization in reducing P loading through better agricultural and wastewater treatment. In other cases, such as bays that serve as critical spawning locations for valuable fishes, including Lake Whitefish, Walleye, and Yellow Perch, all species commercially fished by tribal groups as well as recreational anglers may be inappropriate for net-pen aquaculture. Our point here is that even if other elements of the aquatic environment made it ideal for net-pen aquaculture, social factors may present a significant enough challenge to preclude activity. The panel recommends that a multi-faceted, stakeholder-shared, spatial decision support tool be developed to work through technical, legal, and social issues of siting. A similar support tool was successfully developed during discussions regarding siting of windpower turbines in the Great Lakes (Lakebed Alteration Decision Support Tool, http://www.glgis.org/ladst/, accessed September 27, 2015). Yet another example, in a much earlier stage of development, provides tools to inform restoration priorities in the Great Lakes (Allan et al. 2015). Following the approach of these decision tools, siting of aquaculture net pens can becomes quantitatively defensible and in the public's best interest.

SUMMARY OF PANEL RECOMMENDATIONS

From the specific recommendations provided in our report, we have chosen to summarize the most critical to present here. For each recommendation, we make every attempt to provide rigorous scientific reasoning to justify including it here.

Operations
Because excess pelletized food contributes to nutrient and organic materials produced by net-pen aquaculture, regulatory agencies must require the industry to both monitor and adjust, as necessary, feed provided cultured fishes so as to minimize wastage (rather than maximize growth). Producers must use high-quality feeds (as evaluated by the MDARD Laboratory). To further reduce nutrient input, we urge regulators to require that the industry to use low-phosphorus feeds. USEPA effluent guidelines call for real-time feed monitoring, using devices such as video cameras, digital scanning sonar, and upweller systems.

Because rearing fish through the winter is now technologically possible, regulatory agencies should require nearshore net-pen and offshore cage operators to fully explain how they will cope with ice, whether it be by submerging pen walls or using compressed air to reduce ice encroachment on pen walls. Though we often think of summer storms as the most destructive to nearshore net pens, we believe ice-in and ice-out periods (coupled with strong winds) could be just as lethal. Protection procedures during these periods would be especially critical to the permitting process.

If individual operations end prematurely, the industry must be held accountable for modifications (both physical and biological) to the environment via decommissioning. To ensure success, we urge regulatory agencies to require performance and payment bonds to fund decommissioning; insurance also could provide these resources. At a minimum, decommissioning must 1) remove all constructed structures (see Operations); 2) monitor all ecosystem features until they return (as close as possible) to pre-installation levels (see Ecological Interactions, and 3) rehabilitate those ecosystem characteristics unresponsive to simply the removal of the net pens or cages (see Ecological Interactions). Industry only can accomplish these goals by having robust pre-installation data (as required by the active adaptive management approach) by which to compare data from decommissioned sites.

Fish Health and Disease
We recommend intensifying fish disease surveillance and monitoring throughout the Great Lakes, with federal, state/provincial, and industry all collaborating to anticipate and report disease outbreaks. We urge that the epidemiological interpretation of these activities, including occurrence and distribution of priority diseases, be provided to all stakeholders. Because some pathogens do not cause overt signs of disease, regulatory agencies must surveil and monitor all types of fishes, including those apparently uninfected.

All aquaculture operations must implement biosecurity measures to prevent, control, and eradicate diseases, and only use certified, disease-free (specific pathogen free -- SPF) fish. With just these measures, disease incidence and their impacts will be minimized, and production will increase. In particular, **we emphasize disease-prevention over control,** with prevention strategies vigorously pursued by the aquaculture industry. Should the approach for implementing and certifying biosecurity practices, as explained in the Fish Health and Disease section, become standard practice for aquaculture, training for veterinarians, government officials and aquaculture producers will be necessary.

All drugs, vaccines/bacterins and medicated feed must be used under the direct supervision, or written prescription/veterinary feed directive, of a Michigan-licensed veterinarian. Further, vaccines and bacterins should be used to control clinical disease, providing fish are confined and isolated from healthy populations; The Great Lakes Fish Health Committee provides recommendations that may be useful in its *Model Program for Fish Health in the Great Lakes (http://www.glfc.org/pubs/SpecialPubs/Sp14_02.pdf).*

Approaches for regulating diseases in Great Lakes commercial aquaculture should be harmonized with OIE standards, and existing/future federal and state policies to encourage both adherence and enforcement. We recommend that all nearshore net-pen and offshore cage operations adhere to these regulatory guidelines.

Ecological Interactions
How nutrient and organic inputs influence ecosystem structure and function highly depends on local conditions of the net-pen site (see Siting). With high-profile international agreements, such as the Great Lakes Water Quality Act (2012), the federal governments of Canada and the United States, along with their state, tribal, and provincial partners, seek to limit P loadings into the lakes. Interestingly, P loads will occur with net-pen aquaculture, regardless of where in the Great Lakes pens or cages may be located. In Lake Michigan, P loading is limited to 5,600 metric tons annually; however, as aquaculture grows, P loading will increase accordingly. If the industry builds to 250 facilities by 2025 (as

some projections suggest, G. Whelan and E. Eisch, Michigan Department of Natural Resources, Lansing, Michigan, personal communication 2015), and if all were built in Lake Michigan, this single source of P loading could be important. Clearly, aquaculture in the Great Lakes, if allowed, will need to be accounted for in any calculations of future loadings, recognizing that these loadings are limited. As a limited resource, P loading use by aquaculture could compromise how much P loading could be used by another industry or development (see Management Implications).

Considered a point source discharge, net pens are regulated under the federal National Pollutant Discharge Elimination System (NPDES) Program (40CFR451). Effluents must be limited the application of the Best Practicable control Technology (BPT). By requiring "capture of waste feed and feces" (40 CFR 451.21) per USEPA regulations, the industry must make a good-faith effort to control effluents. However, at present, no aquaculture facility (marine or freshwater) using nearshore net pens or offshore cages takes any action to capture excess feed and feces. Realistically, the panel does not see how Michigan commercial net-pen aquaculture facilities could capture these wastes with the technologies currently available. Hence, net-pen effluents exploit a portion of the limited loadings permitted by the Great Lakes Water Quality Agreement (GLWQA, 2012), making it unavailable to alternative development. Any opportunity lost is, of course, borne by the public as nutrient control costs are externalized to the waters of the Great Lakes. One way of preventing this externalization of costs is to develop technology that would allow net-pen operators to collect and treat wastes onsite and dump treated waters into the lake. Our advice is that the industry should work to develop such technology, with net-pen and cage operations limited until this option is available.

Before installing net pens, operators should be required to quantify native mussel density and any other aquatic or terrestrial species that may be considered at risk. Net-pen impacts will differ, possibly substantially, as suspended solids and sedimentation vary. Indeed, excessive sedimentation could smother native mussels. Net pens should not be sited near native mussel populations.

Net pens cannot be sited in critical spawning habitats for species such as Yellow Perch, Walleye, and Lake Whitefish. Best practices include avoiding sensitive habitats at the onset, which can be accomplished through advance mapping technologies (see Siting).

Escapes from the Georgian Bay industry can survive for multiple years, move 100s of kilometers, even into other lakes, and likely reproductively interact with extant populations. Thus, the permit process for any net-pen operation must include an assessment of the potential genetic impact of catastrophic escapes (as well as the continuing low frequency escapes from any net-pen operation) on natural populations, using the most effective method for reducing reproductive capacity of the cultured species. To assess risk, we strongly urge operators to use an Aquaculture Genetic Management Plan (AGMP, Waples et al. 2012). With this plan, performance standards can be set, including 1) minimizing opportunities for interaction with wild fish through broodstock management and marking and effective containment, 2) maintaining stock integrity and genetic diversity, 3) maximizing in-culture survival of broodstock and progeny, and 4) limiting the impact of pathogens on wild fish (Brasket et al. 2013; Waples et al. 2012, also see Fish Health and Disease). Models such as the Offshore Mariculture Escapes Genetics Assessment (OMEGA) model uses the size and growth characteristics of cultured fish, survival rates of escapees in the wild, probability of escaped fish entering wild conspecific populations and interbreeding, and the dynamics of the wild population to predict the impact escapes may have on survival and genetic fitness of the wild population (NOAA 2014).

Great Lakes aquaculture must be limited to native or naturalized species to avoid future introductions. Comprehensive biosecurity plans should be required to ensure that non-native species are not introduced or spread as part of aquaculture operations (See Ecological Interactions).

Siting

In our view, a critical first step in any process associated with siting should include a multi-faceted, stakeholder-shared, spatial decision support tool. Though this tool must be developed specifically for siting aquaculture facilities, it will allow managers to work through technical, legal, and social issues of siting. Similar tools have been developed re siting windpower turbines (Lakebed Alteration Decision Support Tool, http://www.glgis.org/ladst/, accessed September 27, 2015) and generating insight into restoration priorities in the Great Lakes (Allan et al. 2015). Use of these decision tools should allow siting aquaculture net pens where fish production can reach its potential, the environment can be protected, and the public well served.

Given the mismatch between what we know at lake- and regional-scales and what we don't know at nearshore and site-specific locations, extensive pre-installation monitoring and modeling must be completed at potential net-pen sites. These data would be captured through the recommended active adaptive management plan which incorporates a Before, After, Control, Impact (BACI) design. In addition, the monitoring plan and modeling efforts (see Siting) should be designed to capture the range of physical conditions (water-level fluctuations, seasonal currents, etc.) to ensure that net-pen sites will meet minimum flushing and depth requirements at all times for an acceptable level of ecological impact. Net-pen siting should balance the required depth (>2X the depth of the cage, per the marine experience), flushing rates (no effluent detection beyond a few hundred meters), while minimizing exposure to destructive waves and ice conditions.

Operating net pens in winter can be hazardous, with offshore sites experiencing potential cover and ice flows, icing conditions which can sink structures, as well as the inability to reach and maintain sites due to ice conditions in the nearshore. Net pens located in sheltered bays will experience minimal ice movement and risk to operations. Offshore sites located in deeper waters may experience less ice; however, site access will be greatly restricted due to dynamic ice conditions, especially during periods of ice-in and ice-out, in the nearshore region.
Finally, site selection should include a survey of other restricted zones such as heritage sites, National Marine Sanctuaries, commercial shipping lanes, and routine monitoring sites.

Personnel

As has been obvious, the need for specialized personnel in support of a net-pen or offshore cage aquaculture is considerable. Skills required include specialized training (including perhaps advanced degrees) in particular disciplines including aquaculture, technology, ecology (including systematics of all trophic levels), fish disease, hydrology, modeling, and statistics. Clearly, some expertise can come from universities, federal and state laboratories, and private consulting companies. Even so, onsite need for sophisticated expertise in aquaculture, technology, and perhaps fish disease, will be required. State certification of certain levels of operator proficiency may be considered.

Great Lakes Special Considerations

Throughout our deliberations, we sought to keep those aquaculture characteristics unique to the Great Lakes uppermost in our discussions. Even though reviewed in our report, features unique to aquaculture in the Great Lakes are listed below.

Both dreissenid mussels and *Cladophora*, through rapid colonization of nets and associated structures will be a genuine nuisance to nearshore net pens and offshore cages, perhaps even compromising operations. Most marine aquaculture occurs in ice-free regions. If operators maintain operations through winter, multiple precautions must be taken, including, but not limited to, choosing quite protected sites; a willingness, at times, to forego access; submerging net walls, etc. Overall, ice can challenge the most resourceful operator (see Operations). One feature of the nearshore ocean, not present in the Great Lakes, is tides. Where ocean net pens would be regularly flushed, twice per day, Great Lakes net pens would not experience these tides, thus requiring operators to choose sites with greater continual flushing rates to assure dispersal of wastes. One other factor unique to the Great Lakes is the multitude of agreements that influence decisions of single jurisdictions. Michigan must comply with conditions of the 2000 Consent Decree when considering tribal fishing rights, and Michigan chooses to participate in the Great Lakes Water Quality Agreement Process (thus directly limiting nutrient loading from nearshore net pens or offshore cages), as well as in cooperative fishery management decision-making facilitated by the Great Lakes Fishery Commission. While these agreements might constrain Michigan's autonomy, they function to enhance cooperation among multiple jurisdictions, all with legitimate management authority.

Lastly, implementing an adaptive management program will require additional monitoring and assessment. Some requirements will undoubtedly be upon industry to provide pre-, during, and post installation assessment and monitoring. However, true implementation of a formal adaptive management approach will require coordination of the adaptive management framework as well as additional field monitoring and assessment activities, not currently conducted by the Quality of Life agencies. Careful assessment of these needs should be conducted to secure programmatic resources and funding that would be required to implement the adaptive management process effectively while providing service to the industry and protecting the waters of the state.

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APPENDIX A
CONTEXT AND QUESTIONS FOR THE SCIENCE ADVISORY PANEL ON COMMERCIAL AQUACULTURE IN THE GREAT LAKES

Context

The Departments of Agriculture and Rural Development, Environmental Quality, and Natural Resources have been approached with two proposals for establishing commercial aquaculture net-pen operations in northern Lakes Huron and Michigan. While Ontario has established net-pen operations in the North Channel and Georgian Bay in Lake Huron, there are no commercial aquaculture operations in Michigan's open waters of the Great Lakes.

The Departments are on public record stating full support for development of recirculating, closed, or flow through aquaculture operations inland. We recognize the aquaculture industry as a valuable and potential growth area of Michigan's economy.

Before considering the development of these activities, the Directors have asked the internal Agency Aquaculture workgroup to develop an ecosystem approach to evaluating the: 1) legal circumstances regarding the establishment of net pens such as permitting (water quality, bottomlands, and stocking), recognition of Great Lakes Consent Decree issues recognizing tribal nation rights; 2) economic aspects (product demand, processing, distribution, etc.), and 3) environmental/ecological considerations. After this information is compiled, evaluated, and synthesized, the Agencies envision a public forum to present the information and take public input regarding the social aspects (conflicts, fishing, etc.) and desires. The role of the Scientific Advisory Panel (Panel) is to consider the environmental/ecological issues and concerns and recognize that the policy issues will be addressed in consideration of the legal, economic, social, and biological information in whole.

To help frame the work of the Panel the agency Aquaculture Workgroup developed a list of questions, categorized by larger theme areas. The role of the panel is to provide information regarding the risks and uncertainties associated with each of these theme areas and recommendations for moving forward. While the two proposals presented are for rainbow trout, the Panel's insight on other coldwater species would be welcomed. Other questions or areas may also be addressed by the Panel as they find appropriate.

General Questions for Consideration by the Panel Followed by Specific Issues

I. 1 Effluent Discharge and Nutrient Loading

a. 1 What are the discharge and nutrient loading effects from net-pen operations, both local, regional, and lakewide?

b. 1 Is pre-installation ambient monitoring needed? If so, what protocol is recommended?

c. 1 What are the impacts on dissolved oxygen levels (considering sediment oxygen demand)?

d. 1 What is recommended for waste control, removal, and treatment? Can waste be effectively collected and removed for treatment on land?

e. 1 What is recommended for nutrient control? Should standards be set for the nutrient content of feed?

f. 1 What requirements are recommended for potential chemical usage?

g. 1 What is recommended for potential antibiotic usage?

h. 1 What are the recommended parameters to be monitored, sampling methods, and monitoring frequencies?

i. 1 Are there any other effluent considerations?

II. 1Fish Health

a. 1 Is there a significant concern that aquaculture will introduce new aquatic invasive species, including diseases and antibiotic-resistant bacteria, into the lake environment?

b. 1 Is there a concern that aquaculture will have a significant impact on fish disease in the existing fishery?

c. 1 Should fish placed into the pens be triploid? If they are not 100% triploid, would escape from the pens have a negative effect on local fish populations?

III. Operations

a. 1 What operational controls are recommended (e.g., minimum gauge of netting)?

b. 1 Are there any recommended limitations on maximum production levels?

c. Is it necessary to include operational controls specific to existing Great Lakes aquatic invasive species (e.g., quagga mussels), predation, or the prevention of either escaped fish or spread of fish diseases?

d. What best management practices are recommended for monitoring, management, and response to fish health issues that may occur in net pens?

e. 1 If a net-pen operation goes out of business, what is recommended for decommissioning the operation, is post-operational monitoring necessary, and if so, for what length of time?

f. 1 What amounts of escaped fish can be expected? Does it vary with net-pen density or size? What are the factors that contribute to fish escaping from net pens?

IV. Human Health

a. Fish consumption advisories: Are there significant concerns on the consumption of fish raised in net pens in the Great Lakes? If there is a significant concern, what are the concerns and how do they compare to the wild native and non-native fisheries?

V. Ecosystem Effects

a. 1 Are there any potential conflicts of commercial net pens with the existing commercial and recreational fisheries?

b. 1 Are there any concerns about net pens specific to existing Great Lakes aquatic invasive species (e.g., quagga mussels), fish diseases, or predators?

c. 1 Are there any recommendations for routine monitoring of the sediment, comparing near-field vs. far-field samples, or the lakes in general specific to ecosystem concerns?

d. 1 Are there any concerns about the reversibility of sediment quality following the cessation of net-pen activities? Is post-operational monitoring recommended? If so, for what length of time?

e. 1 If a net-pen operation experiences a catastrophic event (e.g., results in a significant release of a disease) that requires action by the State, what is recommended for decommissioning the operation, is post-operational monitoring necessary, and if so, for what length of time?

VI. Siting

a. 1 What are the recommended lake-wide, region-specific, and site-specific conditions related to siting cage operations?

b. 1 Are standards recommended for lake currents, water depth, mixing conditions, distance from shore, or distance from commercial or recreational fisheries?

c. 1 Are there any recommendations for limiting the size of individual or aggregate net-pen rearing areas, setting minimum distances from the bottom of net pens to the lake floor, or requiring secondary containment nets?

d. 1 What current or flow patterns need to be considered for the Great Lakes for siting net pens?

e. 1 Are there ecologic concerns involving siting and proximity to other jurisdictions?