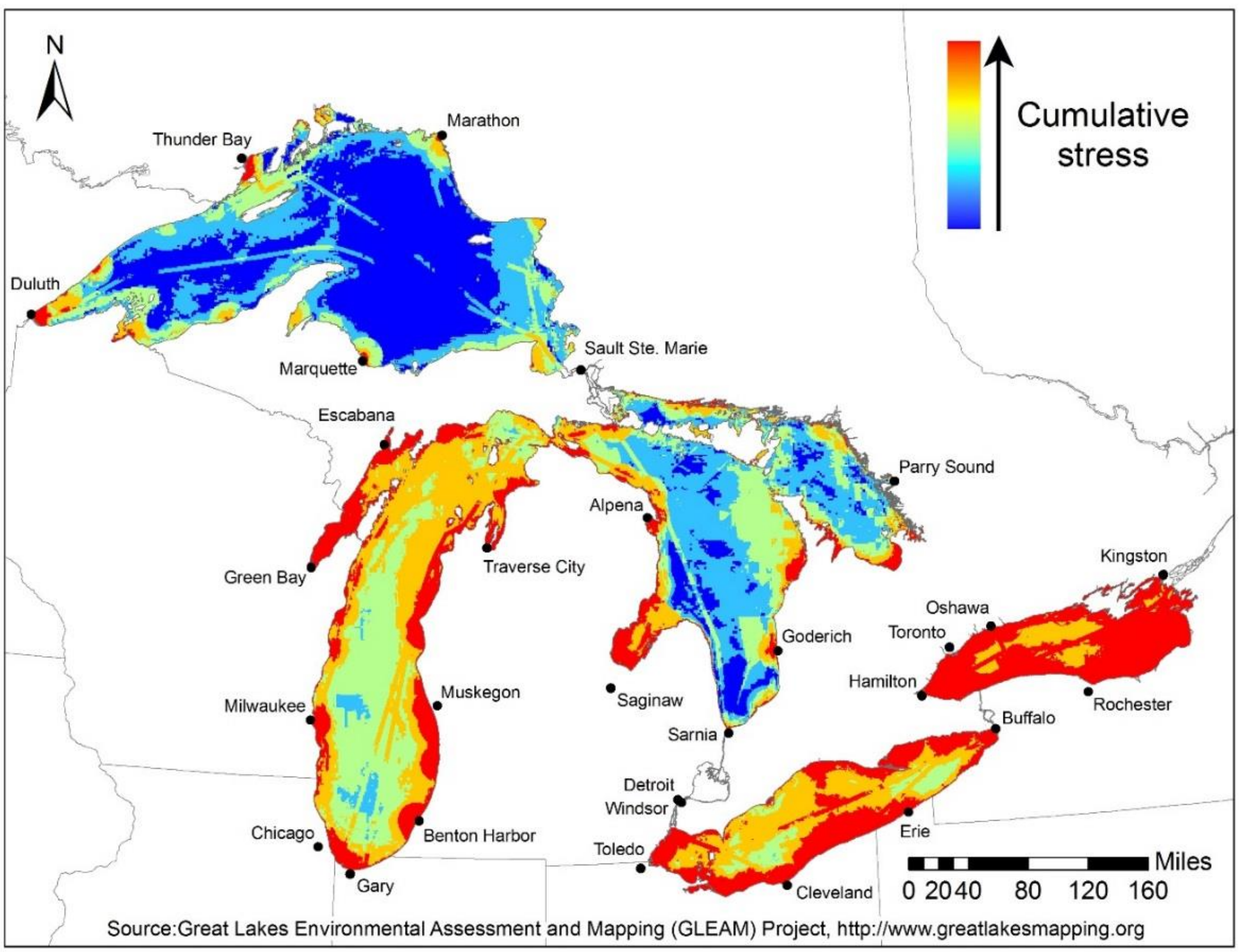
Stressor Interactions in the Great Lakes

SUBMITTED TO:

U.S. Department of State
International Joint Commission
Science Advisory Board
Stressor Interactions Work Group

February 4, 2020



LimnoTech

Water Environment | Scientists Engineers

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 EXECUTIVE SUMMARY

This report was prepared to support the work of the International Joint Commission's Science Advisory Board. The Stressor Interactions Work Group initiated this study because it recognized the lack of understanding of the potential for nonlinear effects and unanticipated and possibly sudden ecological changes that may result from the additive impact and non-additive interaction of several stressors. The group recognized that the degree of synergistic interaction among Great Lakes stressors is difficult to predict, and that the net impacts of two or more stressors on the same ecosystem are not routinely considered in ecosystem management and restoration decisions.

The goal of the project was to characterize stressor interactions in the Laurentian Great Lakes, with emphasis on a set of priority pairs of stressors. The report includes a high-level summary of multi-stressor literature both within and outside the Great Lakes, an overview of seven priority stressors in the lakes, and consideration of the best documented and most important stressor interactions among these priority stressors.

Findings:

- Aquatic stressor interaction studies have yielded variable results that do not support generalization across ecosystems and geographies. For example, a recent review of stressor interactions within the Great Lakes showed that synergistic and antagonistic interactions were dominant whereas a large river multi-stressor study in European freshwater systems found two-thirds of the effects were additive (no interactive effects). All of these studies find some evidence of a greater impact when stressors co-occur, but vary as to whether the effective is additive, antagonistic, or synergistic. As a consequence, even if individual stressors can be measured, cumulative stress is difficult to assess.
- Priority interacting stressors in the Great Lakes region include the following: invasive species, toxic chemicals, excess nutrients, habitat loss, climate change, pathogens, and fish harvest. Although each of these categories can be further sub-divided, and the list is not exhaustive, these priority stressors provide a restricted subset for further consideration.
- Based on the above list of priority interacting stressors and considering feedback from experts on important potential interactions of these stressors, the following 11 stressor pairs were examined in detail:
  - invasives and climate change,
  - invasives and nutrients,
  - toxics and climate change,
  - toxics and nutrients,
  - toxics and habitat loss,
  - climate change and nutrients,
  - climate change and habitat loss,
  - nutrients and habitat loss,

- climate change and pathogens,
- fish harvest and invasives, and
- invasives and habitat loss.

- The potential exists for the environmental consequences of one stressor to be modulated by the presence of a second stressor. For example dreissenid mussels can increase light penetration and trap nutrients in sediment, promoting *Cladophora* growth. Climate change can increase the intensity and frequency of rain events, and subsequently the amount of runoff leading to higher levels of nutrients and pathogens delivered from watershed.

- As part of the expert workshop three pairs were evaluated further (nutrients-toxics; nutrients-invasives; and invasives-habitat loss) to provide more informative tests of the application of stressor interaction to management approaches. These workshop case studies highlighted the importance of considering spatial and temporal variability when evaluating the intensity of the interaction in the Great Lakes region. Because the majority of stressors originate on land where agricultural and urban activities are most pronounced, the intensity of many stressors is likely to be greatest in near-shore waters, and decrease with distance from shore.

- Other contextual considerations appear to be important. As for example, stressor frequency and duration as well as the sensitivity and vulnerability of the impacted resource value can vary with weather extremes, ecosystem conditions and drivers of human activity. In some cases the analysis of interactions may be required at a relatively fine spatial scale.

- Trends in stressor interactions are likely linked to trends in stressors themselves, as well as the intensity of their management through time. For example, loading from point sources of toxics and nutrients has been substantially reduced over time, and invasive lampreys are effectively managed with lampricide application and other measures. Climate change, emerging contaminants of concern, and many invasive species are not effectively managed.

Key Knowledge Gaps:

- Spatial resolution and temporal resolution of data on stressors often are insufficient to determine their status and trends, and their interactions, in order to facilitate informed management decisions. Important gaps identified by workshop participants include better data on nearshore nutrient cycling and speciation, abundance of invasive fish, seasonality of stressors, primary productivity and upper food web linkages, emerging and understudied contaminants, river plume dynamics, fish pathogens, fish toxins that drive consumption advisories, and response of ecosystems to management actions.

- Gaps in process understanding of stressor interactions are common. Robust studies of interactions are rare, and often limited to controlled laboratory settings or mesocosms and single species or life stages. These limitations can make it difficult to translate results to natural environments across a range of contextual considerations and meaningful management scales.

Recommendations:

- Although active monitoring and research programs are addressing some questions related to stressor intensity and interactions, continued investment in two particular areas is a priority: (1) improved management and integration of data that reduce latency and efficiently put information on stressor and affected ecosystem status in forms that support management decisions, and (2) creation and maintenance of operational models that accurately simulate ecosystem processes and states under multiple interacting stressors, as well as likely or possible future stressor scenarios. .
- Although process understanding of stressor interactions is relatively limited, continued investment in programs which manage multiple stressors within a system in a coordinated way will likely be more effective than programs managing individual stressors. Particular examples that address multiple stressors include Areas of Concern and fisheries management programs. Within these programs, consideration of interactions may be important to incorporate as our understanding of stressors interactions improves.
- Great Lakes policies that regulate, support, and incentivize sustainable reduction of individual stressors, should be better integrated across jurisdictions to avoid gaps in mitigation and should target resources toward stressor interactions that are either best understood, most urgent to address, or most amenable to management.

2 INTRODUCTION

There is substantial uncertainty in scientific understanding of the synergistic role of multiple stressors in ecosystem health and resilience, and a corresponding lack of clarity in terms of prioritizing management actions to reduce stressors that will be most effective in restoring ecosystem functions and services. Most stressors are the result of either past or ongoing human activities, so as we seek to live more sustainably, we need to understand which changes in behavior and management of Great Lakes ecosystems will result in the greatest and most durable improvements.

The International Joint Commission (IJC) has responsibility for regular reporting on progress in the Great Lakes and other boundary waters, as well as for investigating the risk to ecosystems that may result from current or future stressors. The Laurentian Great Lakes are subjected to a wide range of stressors, including climate change, invasive species and toxic chemicals, but the interaction between these stressors remains understudied. Recent studies highlight the relevance of cumulative impacts of multiple stressors and the potential for significant and adverse impacts on the lakes (e.g., Danz et al. (2007), Morrice et al. (2008), Allan et al. (2013), Smith et al. (2015)). IJC has determined the importance of characterizing stressor interactions in the Great Lakes, building on the results of this project, with particular emphasis on assessing up to 10 pairs of priority interacting stressors, and of identifying additional research, surveillance, and monitoring activities that are required to fill associated knowledge gaps. IJC has also expressed the desire for an evaluation of ways in which they can understand and communicate the potential of nonlinear effects to result in ecological damage from the additive impact of several stressors. A Great Lakes multiple stressor framework (e.g., Stow and Hook 2013; European MARS project, Hering et al. 2015) is clearly needed to guide ecosystem status tracking by IJC and others, as well as for decision-making about restoration actions. This study has attempted to continue to advance current synthesis and understanding of stressor interactions with that goal in mind.

Definitions:

Stressor – external driver of a degraded condition in ecosystem state, function or service provision

Anthropogenic – human-produced or mediated

Antagonism – partial or complete cancellation of individual stresses caused by the combined interaction of two or more stressors

Synergy – stressor interactions that produce greater impacts than the sum of individual stressors

Additive– combined stressor impacts that are equal to the sum of the individual impacts

Multiplicative – stressor impacts that are similar to synergy (greater than additive)

Non-additive - stressor impacts that result in synergy or antagonism (less than or greater than additive)

Cumulative - the influence of all stressors together, often estimated as an additive summation

In this report, the term "stressor" focuses exclusively on anthropogenic disturbances, including human-mediated introductions of nonindigenous aquatic species to the Great Lakes and human-induced climate change. This is to distinguish it from natural disturbances such as a large flood or a volcanic eruption, which may have disastrous environmental impacts, but which still cannot be considered stressors under this definition.

Ecosystems are inherently complex, often making it difficult to forecast a particular response to an environmental stressor. This is further complicated by nonlinear responses as well as complex interactions among multiple stressors. For example, natural loading of chemical species such as nutrients or trace metals may enhance a lake community or provide a net ecological "benefit", but when levels exceed a critical threshold the system responds nonlinearly and becomes stressed. Additionally, some communities which are metal-tolerant have been shown to become more susceptible to other stressors such as acidification, ultraviolet radiation, or predation as they approach the upper end of their tolerance range (Courtney and Clements 2000). Acclimating to one set of stressors may increase an organism's sensitivity to another. This sensitivity to stressors can also differ widely among organisms or locations, which makes studying and predicting responses to multiple stressors very difficult. It is therefore useful to attempt to understand the interactions among stressors, in order to predict the combined impact, rather than simply managing each in isolation.

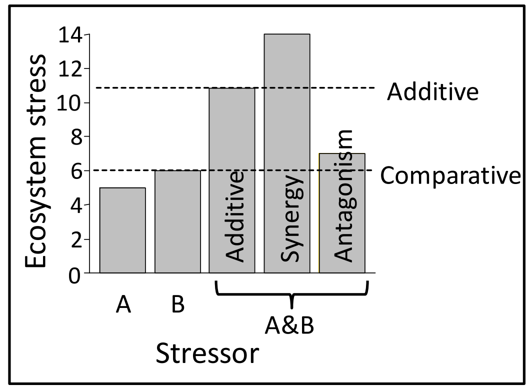


Figure 1. Conceptualization of interactions among stressors (from Smith et al. 2019)

Folt et al. (1999) described three key modes for stressor interactions: additive, multiplicative, or non-additive. In this model, both synergism and antagonism could derive from both additive and multiplicative models, whereas the non-additive model described situations where the net effect of the combined stressors was less than the sum of their individual effects. Folt et al. (1999) compared this to Liebig's law of the minimum, where the effect of nutrients depends on the concentration of the one, most-limiting nutrient. Additionally, the direction of the interaction can be important. Smith et al. (2019) presented a conceptualization of three possible stressor interaction outcomes in the context of two individual stressors, A and B (Figure 2Figure 1). Stressor A and B may decrease or increase an ecological response or process compared to a control, but the combined effect of A and B may occur in the same or the opposite direction as that predicted for the individual stressor effect (Crain et al. 2008, Piggot et al. 2015).

For the purposes of this report, additive or cumulative effects are considered to be the direct sum of two individual stressor effects with no net interaction, while synergistic effects (larger net effect than additive) and antagonistic effects (smaller net effect than additive) are considered to be significant interactions. An applicable example was described by Gennings et al. (2005), in reviewing toxicological interactions, where they defined an interaction between two chemicals as occurring when the dose–response relationship for one chemical is affected by the dose of the other chemical. If the shape of the dose–response relationship of one stressor does not change in the presence of another stressor, then these stressors do not interact, and the responses are said to combine additively. These definitions are also consistent with others who have presented a conceptual representation of multiple stressors effects (e.g., Gunderson et al. 2016, MARS 2018, Smith et al. 2019).

3 APPROACH

This assessment project was divided into four tasks, which were described by the IJC Work Group as shown in Table 1, in slightly modified form. Initial work consisted of discussions with IJC staff and Work Group leadership, followed by the initial literature review, conference calls with the Work Group, and selection of preliminary priority stressors and stressor pairings for analysis. Attention then shifted to development of a report outline and preparations for the expert workshop. The workshop was conducted and a workshop report was prepared to capture the discussions and conclusions. Subsequently, a full report draft was prepared for review by Work Group members and review comments were incorporated into a final draft.

Table 1. Project Task Descriptions

Task	Description
1	Literature Review: Review existing literature that considers stressor interactions, including marine and other literature from outside the Great Lakes, to develop a working vocabulary of stressor interaction terms, summarize the state of knowledge, and generate an annotated list of key references. The review will include at least 50 articles from peer-reviewed and grey literature, agency and other reports, internet resources, and interviews with subject matter experts. The work of academic entities, agencies (e.g., Great Lakes Water Quality Agreement Annex Committees), Indigenous nations, and non-government organizations will be considered, as required.
2	Identify Priority Interacting Stressors: Develop a list of a subset of stressors where (a) the impact of at least one of the stressors is thought to be important and potentially modified by the presence of a second stressor, and (b) information exists to either assess interactions directly, or (c) develop conceptual models and hypotheses that identify mechanistic pathways to clarify how pairs of stressors may interact. A deeper understanding of stressor interactions will require detailed consideration of the mechanistic pathways linking stressors to biological and ecosystem impacts.
3	Workshop: The output from Tasks 1 and 2 will be reviewed and evaluated through an expert workshop. A key goal of the workshop will be to confirm a list of priority interacting stressors and their associated information, e.g., spatial extent, severity, etc. The workshop will also include a discussion related to management implications and options to communicate and mitigate identified stressor interactions. The results of the two-day binational expert workshop (participants from academic, government, and non-government, sectors) will be compiled and reported. Workshop participants will be identified by the Work Group in consultation with IJC staff and the contractor.
4	Reporting: Prepare a project report that addresses the state of knowledge of stressor interactions in the Great Lakes, identifies and describes up to 10 pairs of ‘priority’ interacting stressors, including their spatial variability and severity across the lakes, identifies key knowledge gaps and recommends science and policy priorities to address or further evaluate the importance of stressor interactions in the Great Lakes. The contractor will provide report drafts, which will be reviewed by Work Group members and IJC staff, and prepare a final report of approximately 70-100 pages. The IJC Work Group, in consultation with IJC staff, will utilize the contractor’s report as a basis for its reporting to the IJC.

4 STRESSORS LITERATURE BACKGROUND

The purpose of this section is to briefly provide information on multiple stressors both in a broader context and within the Great Lakes ecosystems. We reviewed a broader set of literature, both from within and beyond the Great Lakes basin, in order to:

- examine stressor combinations that are commonly documented in scientific literature;
- describe how common non-additive effects are;
- identify priority stressor combinations for the Great Lakes;
- characterize the strength of stressor interactions across different environments and scales;
- assess underlying data quality and strength of evidence for non-additive stressor interactions; and
- identify corresponding research and monitoring needs.

LimnoTech further coordinated with the IJC Stressor Interactions Work Group, and with invited experts at a project workshop, to refine the collective current understanding of the topic and to build consensus about important ways to prioritize future research and management directions. As discussed above (Section 2), there are multiple modes of interactions among stressors, with varying definitions across the literature. While non-additive effects of stressors have been hypothesized, synergistic stressor interactions and their occurrence in nature are still not well understood. Crain et al. (2008) synthesized 171 marine studies and found that synergistic interactions were just as common as antagonistic interactions. The prevalence of synergies in stressor interactions in freshwater ecosystems, however, appears to be variable.

A meta-analysis of stressor interactions in freshwater ecosystems found that the net effect of stressors pairs was most frequently antagonistic (Jackson et al. 2016; see Figure 2 below), in contrast with the findings of Crain et al. (2008) for marine systems. Yet, a recently published literature review of Great Lakes stressor interactions by Smith et al. (2019) found synergies accounted for 49% of the total interactions. Finally, Darling and Côté (2008) performed a meta-analysis of 112 studies of multiple stressors in freshwater, marine and terrestrial communities. They found that less than one-third of experiments were additive, while more than 75% showed non-additive effects (i.e., synergies or antagonisms).

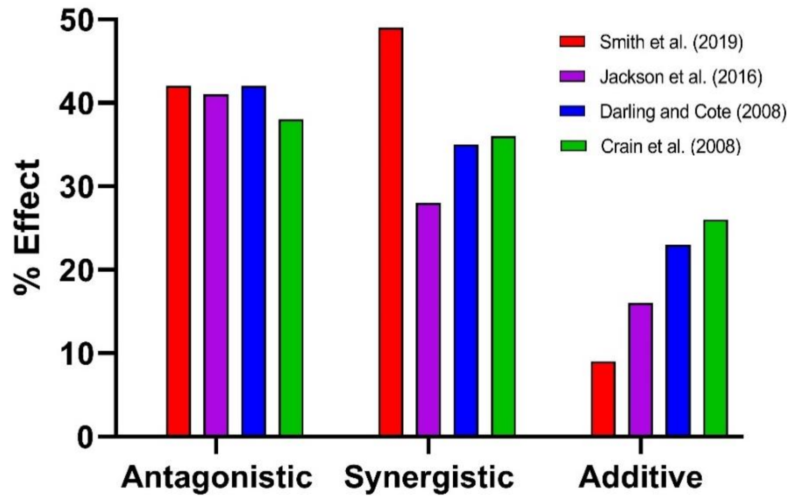


Figure 2. Results from four peer-reviewed literature compilations that identify the number of studies that found antagonistic, synergistic, and additive effects.

Interestingly, among the four articles ranging from 2008-2019 in which each reviewed the literature for interactions among stressors, there was a remarkable consistency with respect to the percent of antagonistic interactions (~40%; Figure 2). However, there was significant variation in the percent of synergistic (28-49%) vs. additive effects (9-26%). The biggest difference was in the Smith et al. (2019) Great Lakes synthesis which suggested the high number of synergistic interactions compared to additive effects (49% vs, 9%) possibly was due to a potential publication bias or the lower sample size included. It should also be noted that the relatively low number of additive effects (9-26%) reported in these reviews is contrary to a major European multi-stressor project (discussed below in section 4.2), where they found two-thirds of the stressor pairs were additive and only a third were interactive (synergistic or antagonistic).

4.1 Great Lakes stressors

The Great Lakes hold a significant portion of the world's surficial fresh water (~18%) and cover a total area of 244,000 km^2 with over 16,000 km of coastline. Over 40 million people depend on the Great Lakes for their drinking water supply and the Great Lakes region generates billions each year economically. As such, clean water in the Great Lakes is fundamental to sustain both its human and ecological health and its economic value in the bi-national region. The Great Lakes ecosystems are subjected to multiple co-occurring stressors and interactions among these stressors can elicit unexpected impacts. These stressors and interactions can also differ temporally and spatially within and across the lakes (Allan et al. 2013, 2017). Allan et al. (2013) mapped 34 human-induced stressors which ranged from pollution to climate change to provide an overview of cumulative ecosystem stress across the Great Lakes (Figure 3).

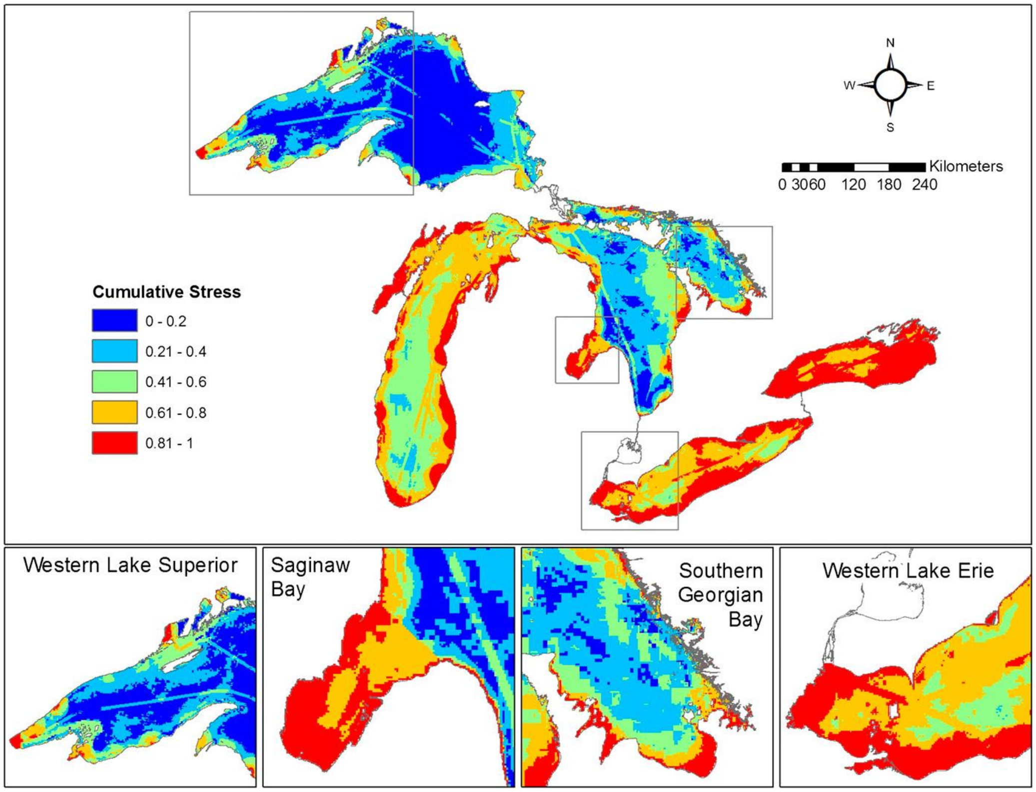


Figure 3. Map of 34 unique stressors within the Great Lakes (taken from Allan et al. 2013).

While this map provides an excellent representation of areas which are the most heavily stressed, the index was based on additive impacts, given the lack of knowledge on interactions among stressors (Allan et al. 2013). While the potential for these stressors to overlap in the Great Lakes has been identified by many, and indicators for individual stressors (IJC 2014) have been widely used, a gap still exists in understanding interactions among stressors (S. Smith et al. 2015, 2019).

Smith et al. (2019) performed an extensive systematic literature review of interacting stressors in the Great Lakes. They used the review and expert elicitation to identify priority pairs of likely or potentially important interactions in the Great Lakes. Figure 4 shows the results of the literature findings, whereby the most studied was nutrient loading and invasive species, followed by invasive mussels and invasive fish. Expert elicitation frequently identified synergy as the probable form of interaction, and often was inconsistent with the systematic literature review.

Stressor pair	Elicitation findings	No. (lit.)	Systematic lit. review findings		
Nutrient loading x invasive mussels	Synergy	14	50% Synergy	50% Ant.	
Climate change impacts x nutrient loading	Synergy	5	60% Synergy	40% Ant.	
Invasive mussels x invasive fish	N/A	13	23% Syn.	31% Add.	46% Ant.
Toxic organics x nutrient loading	N/A	3	100% Antagonism		
Toxics with each other	N/A	4	25% Add.	75% Antagonism	
Coastal dev. x nutrient loading	Synergy	1	100% Synergy		
Climate warming water temperature x hypoxia	Synergy	2	50% Syn.	50% Ant.	

Figure 4. Systematic literature review of potential interactions in the Great Lakes (taken from Smith et al. 2019).

The review showed that while there are many potential interactions in the Great Lakes, studies among co-occurring stressors were limited and few measurements of both individual and joint effects of stressors had been published (Smith et al. 2019; Figure 4 above). This was also noted in a summary of the challenges for research in the Great Lakes, by Sterner and colleagues (2017), where they articulated the importance of focusing attention on developing a more comprehensive approach to understanding human-induced stress than simply examining single stressors on a case-by-case basis. They also highlighted a need to better understand whether the response of the Great Lakes to multiple stressors is "simply additive, or involves synergistic or antagonistic effects". Sterner et al. (2017) also stressed that while understanding interactions is important, we also need to understand the resiliency of the Great Lakes to multiple stressors. Indeed, while the concept of resiliency is not discussed in depth in the current report, it remains an important consideration in understanding how the Great Lakes ecosystems will respond to additional stress. Knowing the potential capacity for the ecosystem to absorb change may help to better predict what changes (both structurally and functionally) within an ecosystem are expected.

While direct studies of stressor interactions in the Great Lakes are few, and there is only partial agreement about the frequency of non-additive versus additive effects, there is ample evidence that system responses to an individual stressor can be modulated by one or more additional stressors. For example, Collingsworth et al. (2017) aimed to improve our understanding of responses of Great Lakes fisheries to climate change both alone and among other human-induced stressors (e.g., invasive species, nutrients, fish stocking). They forecasted that warmer temperatures and altered precipitation patterns would interact with other stressors and lead to additional stress on fisheries from longer stratification leading to increased bottom hypoxia, expanded invasive species distribution from warmer temperatures in northern lakes (Whitney et al. 2016), as well as intensified competition from higher consumption rates (Yurista et al. 2010).

In another example, Auer et al. (2010) applied numerical models and historical water quality data to determine the impact of changes in phosphorus loading in combination with mussel-driven changes in water clarity on *Cladophora* distribution and biomass. They concluded that *Cladophora* declines in the 1970s and early 1980s, driven by phosphorus loading reductions (single stressor management), were largely offset by greater water clarity and light penetration due to filter feeding by invasive mussels that increased the depth of Cladophora occurrence, and consequently the amount of total production.

4.2 Beyond the Great Lakes

A recent effort in the European Union, the Managing Aquatic ecosystems and water Resources under multiple Stress (MARS) Project, has dealt with multi-stressor effects on European freshwater systems (Birk and Hering 2018). Expected products include >200 publications (see: http://www.mars-project.eu/). As reported in the MARS recommendations, "Out of 156 single results of pair-wise stressor combinations analyzed within studies of MARS, two-thirds were additive (i.e. had no significant interactions), while one third showed significant interactions." It should be noted that MARS considered significant interactions to be non-additive (e.g., synergism or antagonistic), where the effect of the two stressors was greater than or less than their sum. The most consistent non-additive interactions with nutrients and a secondary stressor as identified in MARS are shown in Table 2.

Table 2. Managing Aquatic Ecosystems and Water Resources Under Multiple Stress (MARS) interactions across stressors. The tabular subset is taken from the MARS report and highlights nutrients interactions with other stressors (BQE=Biological Quality Elements, Browning - an increase in the yellow-brown color of lake/river water, caused mainly by dissolved organic matter).

No.	Stressor 1	Stressor 2	BQE	Water Cat.	Type of water body	Type of interaction
1	Nutrients	Temperature	Phytoplankton	Lakes Rivers	Nutrient limited lakes & rivers	Synergistic
2	Nutrients	Temperature	Phytoplankton	Lakes	Nutrient-saturated lakes	Antagonistic
3	Nutrients	Browning	Phytoplankton Cyanobacteria	Lakes	Nutrient limited Northern, stratified lakes	Antagonistic
4	Nutrients	High flow	Phytoplankton	Lakes Rivers	Large stratified lakes with long retention time (incl. large rivers, impounded)	Synergistic, but see addendum in text.
5	Nutrients	High flow/ Hydropeaking	Phytobenthos	Rivers	Nutrient limited upland rivers	Antagonistic (up to dominating 2nd stressor)
6	Nutrients	Channelization	Benthic invertebrates and Fish	Rivers	Rivers	Antagonistic, but small interaction effect

The MARS results suggest that in European aquatic systems (mostly rivers [42% of 130 total water bodies studied] and some lakes [24%] and coastal waters [34%] impacted by non-point pollution and hydrologic alteration), stressor interactions (beyond simple additivity) are less common. In other words, the influence of stressor A and B is most often A+B (see Figure 1), but not less than or greater than their sum. Additionally, using a stream ecosystem in Japan as a model, Fausch et al. (2010) found that the strong negative effects of individual stressors, reduced or eliminated the impact of more subtle stressors. In cases when individual stressors have very large effects, synergism or antagonism may be less relevant; that is, the combined influence of the two stressors is no greater than that of the most severe stressor acting alone.

Several broad literature reviews, mentioned earlier, that attempted to determine the generality of stressor interactions in aquatic ecosystems, yielded differing conclusions. Crain et al. (2008), in a highly-cited paper, "synthesized 171 studies that manipulated two or more stressors in marine and coastal systems and found that effects in individual studies were additive (26%), synergistic (36%), and antagonistic (38%)." Jackson et al. (2016) "analysed data from 88 papers including 286 responses of freshwater ecosystems to paired stressors and discovered…that the net effects of stressor pairs were frequently more antagonistic (41%) than synergistic (28%), additive (16%) or reversed (15%)." In contrast, Geiswein et al. (2017), assessed 1095 sites within a mountainous catchment, using 12 stressor variables covering three different stressor groups. They concluded that "additive stressor effects dominated, while significant and meaningful stressor interactions were generally rare and weak."

Some of the apparent discrepancies between these studies, but not all, can be attributed to differences in terminology and methods. One aspect that currently is not well understood is how habitat-specific these findings are. That is, should broad general principles regarding stressor interactions emerge from studies in similar ecosystems around the world, or are watersheds, species assemblages, or ecoregions idiosyncratic? Should marine and freshwater systems be expected to behave similarly? This was discussed in Johnston et al. (2017), where they highlighted a need for two types of contrasting but complementary scales of environmental assessments. The first being an overall characterization of condition for the entire region of interest (e.g., Allan et al. [2013] for the Laurentian Great Lakes) and the second, a more spatially and temporally refined assessment at prioritized locations (e.g., Areas of Concern or other hotspots). The authors described an integrated ecological modeling system for assessing impacts of multiple stressors on river ecosystem services by forecasting water quality and quantity, habitat suitability for aquatic biota, fish biomasses, population densities, productivities, and contamination by methylmercury across head-water watersheds (Johnston et al. 2017). They concluded that an integrated ecological modeling system may be very useful for the assessment of multiple impacts (e.g., land use and climate change) to enable forecasting of alternative futures and filling data gaps where monitoring data may be unavailable. They state "the ultimate goal is to support environmental decisions with quantifiable estimates of uncertainty and variability, as a necessary evolution of quantitative process-based modeling for prediction and long term forecasting of alternative future scenarios".

Uncertainty is also highlighted in Côté et al. (2016), where the authors provided a comprehensive and well-illustrated conceptual review that emphasizes application of stressor interactions to conservation management, including the consideration of uncertainty. This component is not always addressed in interaction studies, but is essential when defining gaps in process understanding; as additional experiments are performed and monitoring periods are lengthened, uncertainty is reduced.

5 EXPERT WORKSHOP

As part of this project, a workshop was conducted in Windsor, Ontario on April 9-10, 2019 (see agenda and attendee list in Appendix A; photo in Figure 6). The workshop included an invited list of subject matter experts from Canada and the United States who were also known to be collaborative "big thinkers" and effective synthesizers. Many of them had worked together on previous related projects and publications. The group represented a diversity of geographic and technical expertise. There was common overall specialization in the areas of freshwater ecology and ecosystem management among the majority of participants. Summaries of the presentations and details of workshop discussions are included in a separate workshop report. A brief summary of results is included here.

Figure 5. Project workshop in March 2019.

The workshop began with a welcome and introductory comments by the hosts, organizers, and facilitators. This group outlined the objectives and approach, and reviewed the materials that were sent to the group in advance, as well as printed material and forms that were available on tables during the workshop. Some background information on the project progress to date was provided by the contractor team, and the broader workshop discussion was initiated by five panelists who spoke briefly on each of five stressor categories nutrients and their potential interactions. The five main stressor categories were as follows:

- Chemicals - Mike Murray, National Wildlife Federation
- Invasive Species - Bob Hecky, Univ. of Minnesota - Duluth
- Climate - Craig Stow, NOAA GLERL
- Nutrients - Bob Sterner, Univ. of Minnesota – Duluth
- Habitat Loss - Lucinda Johnson, Univ. of Minnesota – Duluth

Each panelist provided general thoughts on these major categories. Mike Murray summarized prior studies of chemical interactions and potentially productive approaches that could be adapted from other applications (e.g., human health). Bob Hecky was skeptical of the importance of stressor interactions, which he illustrated through the history of invasive species impacts. This was an important counter to an emphasis on interactions, although that there are notably direct (reduced food base) and indirect (greater water clarity) effects of dreissenids. Bob Sterner's emphasis on spatial overlap was important. He agreed that many stressors are likely congruent, yet the key issue of spatial context (nearshore vs. offshore, individual lakes, embayments) remains important. Lucinda Johnson made important points about habitat being both a stressor and a response, identifying the complexities of habitat. Craig Stow emphasized uncertainties and the end of stationarity as a result of changing climate. Consideration of uncertainty applies broadly, but non-stationarity is especially relevant to hydrology.

A key goal of the workshop was to confirm a list of priority interacting stressors and their associated information (e.g., spatial extent, severity), building from an initial draft matrix that was prepared in advance (Table 3). Stressor pairs were selected based on the following criteria:

- At least one of the stressors is thought to be important and potentially modified by the presence of a second stressor, and
- Information exists to either assess interactions directly, or
- Sufficient understanding exists to develop conceptual models and hypotheses that identify mechanistic pathways to clarify how pairs of stressors may interact.

Note that the reality of interactions in natural settings among three or more stressors was recognized by workshop attendees and discussed briefly, but was eliminated as too complex for further productive consideration in this venue.

Table 3. Initial stressor pair matrix. Potentially every pair may interact, but each X indicates an interaction that is likely to be of higher concern based on published information and professional judgment.

	Mussels	Gobies	PCBs	Mercury	Pathogens	Warming	Phosphorus
Mussels							
Gobies	X						
PCBs	X						
Mercury		X	X				
Pathogens	X						
Warming	X	X		X	X		
Phosphorus	X		X			X	
Habitat		X		X	X	X	X

5.1 Day One Breakout Session Overview

The Day One breakout session was an initial screening of stressor pairs considered likely to result in significant interactions. For each stressor pair in the above matrix (Table 3), each breakout group was tasked with the following: (a) describe the interaction in one-two sentences, (b) assess whether the interaction likely to be important enough for further consideration, and (c) assess whether the interaction is likely to be synergistic or antagonistic. Specifically, the first breakout session focused on the following two questions:

- Are the identified stressor pairs of greatest concern in the Great Lakes ecosystems and, if not, what other pairs should be considered?
- For each pairing, are the effects additive, synergistic, antagonistic, or not yet known?

Workshop participants generally agreed that the initial stressor matrix included important stressors that should be part of a definitive list of those considered most important. However, there was discussion about the merits of higher level (e.g., climate, nutrients, toxics) categories versus more specific sub-categories (e.g., warming, phosphorus, mercury). Climate change was recognized as an “overlying” stressor that affects most, if not all others. A number of workshop participants believed additional stressors should be added to the original list, including fishing pressure or exploitation, and pathogens. A revised listing was not finalized, but the Work Group later agreed on a consensus seven stressor categories which form the basis of Section 6 of this report (below). Of these seven stressor categories, 11 stressor-pairs were selected for further consideration.

Participants noted that an analysis and characterization of stressor pairs is highly location-specific (e.g., lake-specific, nearshore/offshore), and their opportunity for interactions may vary from one location to the next. Although context also includes the many environmental variables (e.g., temperature, DO) that differ among locations and these considerations may all be important when defining stressor pair impacts. This can also include a social dimension (e.g., the perceptions of a "user" of the Great Lakes system). For example, if you like fishing for brown trout in the nearshore you might like the presence of gobies.

As the IJC is most interested in management-relevant recommendations, as opposed to those that are limited to a call for more research, this aspect was considered in review of potential stressors for analysis. Management recommendations were considered to be best suited for stressor pairs where data, information, and understanding of interactions are sufficient to offer recommendations with confidence.

5.2 Day Two Breakout Session Overview

Given the importance of spatial considerations with respect to stressor pairs, three case-studies were developed from workshop participant suggestions. To the extent possible, stressor pairs/locations were selected to represent different categories of stressor interactions (e.g., additive, synergistic, or antagonistic), with a focus on those where sufficient data and information exist to allow for meaningful management recommendations.

The three case studies were as follows:

- Interactions of Nutrient and Toxic Stressors in the Western Basin of Lake Erie
- Interactions of Invasive Mussel and Nutrient Stressors in Lake Michigan
- Interactions of Invasive and Habitat Loss Stressors in the Lake Ontario Basin

Methodical attention to several questions associated with each of three case studies was important to address such matters as the nature of the stressor interaction, key mechanisms, contextual considerations, management recommendations, monitoring/surveillance recommendations, and research recommendations. The results of the case studies and associated discussions are incorporated into the larger set of pairwise comparisons of stressor interactions discussed below (Section 6.2).

6 PRIORITY STRESSOR INTERACTIONS IN THE GREAT LAKES

A combination of the literature review, Work Group and workshop interactions, and subsequent analysis resulted in a final list of priority Great Lakes stressors that are described below. We then consider the binary interactions of a subset of the possible stressor pairs.

6.1 Stressor selection

Seven priority stressor categories were selected based on existing literature, prior IJC projects including the Great Lakes Early Warning System study and workshop, IJC Work Group discussions, IJC workshop discussions, and professional judgment. The selection of stressors involved several iterations, but ultimately a larger list of the key stressors was decided upon to better capture the breadth of stressors within the Great Lakes. The selected stressors consist of the following:

- Invasive species
- Toxic chemicals
- Excess nutrients
- Habitat loss
- Climate change
- Pathogens
- Fish harvest

A brief description of each stressor category is below, followed by discussions of the interactions between 11 representative stressor pairings.

6.1.1 *Invasives*

Invasive species are among the greatest threats to the Great Lakes basin. The abundance of non-native species can dramatically alter the structure and function of these aquatic communities. Researchers have identified the Great Lakes as one of the most invaded freshwater systems across the world (Ricciardi and MacIsaac 2000, Ricciardi 2006). At present, over 180 species have been identified as nonindigenous to the region (Sturtevant et al. 2019). Figure 6, provides a representation of the number of known invaders on the US side of the Great Lakes watershed. A comparable Canadian watershed figure or data source was not identified.

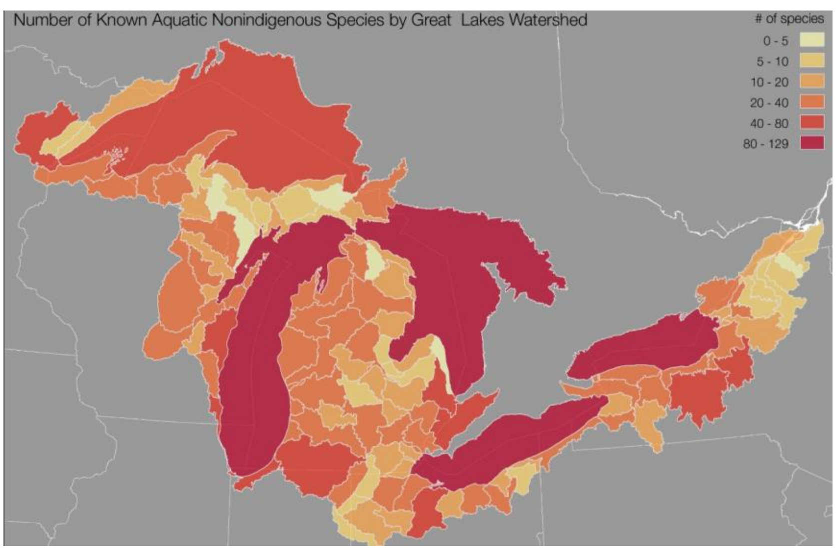


Figure 6. Aquatic nonindigenous species in the Great Lakes (taken from GLANSIS 2018 report) and nearby US communities. Comparable Canadian watershed data were not identified.

While there are over 180 invaders in the Great Lakes, in recent years sea lampreys, dreissenid mussels, and round gobies have received significant attention. The dreissenid mussel invasion, first by zebra mussels (*Dreissena polymorpha*) and then by quagga mussels (*Dreissena rostriformis bugensis*), caused major changes in the waters and sediments of the Great Lakes. Zebra mussels were first detected in Lake Erie in the late 1980s, but eventually were able to

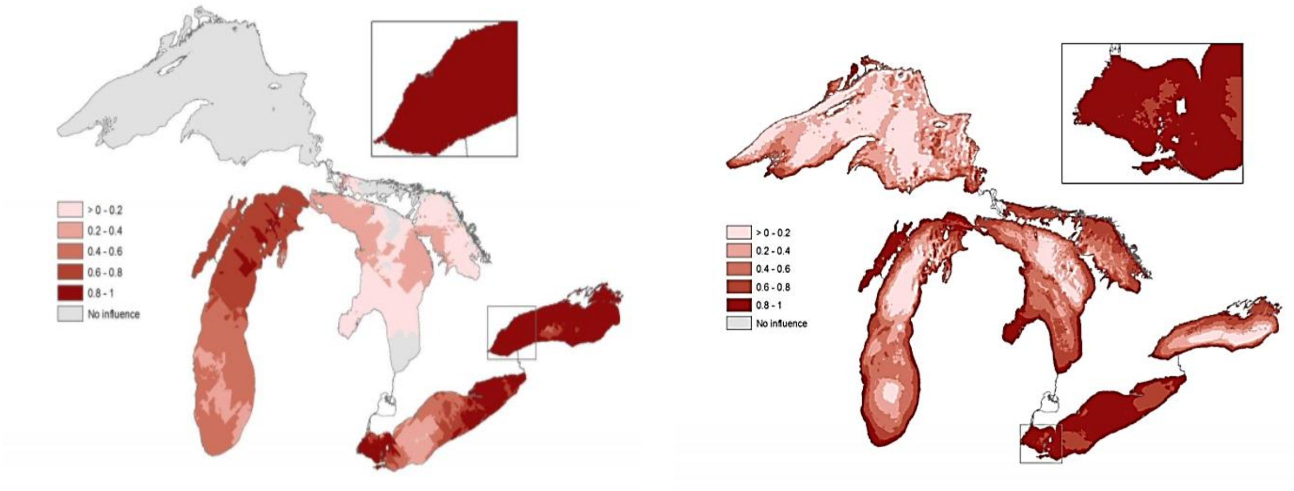


Figure 7. The spatial distribution of zebra and quagga mussels (LEFT) and round gobies (RIGHT) in the Laurentian Great Lakes normalized to a scale from zero to one (from GLEAM).

spread and become established in all of the Great Lakes, except for offshore areas of Lake Superior (Dove and Chapra 2015). Like the dreissenid mussels, the round goby is one of the most successful invaders in the Great Lakes, reaching densities of 1-14 individuals per square meter in some areas, with maximum densities over 130 per square meter. Round gobies are present in all lakes and Figure 7 clearly shows significant overlap with the dreissenids. Many studies have suggested that gobies could be (or have already been) effective at reducing dreissenid populations by predation (Lederer et al., 2008, Wilson et al., 2006, Naddafi and Rudstam, 2014, Foley et al. 2017). Research has shown that gobies can consume up to ~ 80 zebra mussels/day, but they generally prefer smaller mussels. A number of researchers have shown a shift in dreissenid mussel length-frequency distributions due to this preferential consumption of smaller mussels (Ray and Corkum 1997, Wilson et al. 2006). Though this predation may contribute to a reduction in mussels, it is unlikely that gobies would significantly reduce recruitment because small mussels survive beneath rocks or wedged between larger mussels (Djuricich and Janssen 2001, Wilson et al. 2006).

Given their expansive range across both nearshore and offshore Great Lakes environments, they are likely to interact with most other types of stressors as well as other invasive species. However, the extent and severity of these interactions can vary across time and space. For example, within Lakes Huron and Michigan, mussels appear to trap and retain phosphorus nearshore (nearshore shunt hypothesis; Hecky et al. 2004) enhancing nearshore nuisance blooms but also reducing offshore productivity (Bunnell et al. 2014). Within the eutrophic western basin of Lake Erie, habitat is less suitable for mussels and shallow water depths make sediment resuspension common, so the influence of mussels there is less important.

Additionally, there are several other potentially harmful invaders including the sea lamprey, a primitive jawless fish, which parasitizes a number of economically and ecologically important fish; and the wetland plant, *Phragmites*, both of which interact to varying degrees with other major Great Lakes stressors.

6.1.2 *Toxics*

A number of anthropogenic chemicals can be found within the Great Lakes watershed including persistent organic pollutants (POPs) as exemplified by p,p'-DDT, polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (dioxins) and dibenzofurans, per- and polyfluoroalkyl substances (PFAS) and many other emerging chemicals (e.g., pharmaceuticals, personal care products). For the purposes of this report the focus will primarily be on POPs (mainly PCBs), and the metal, mercury. These chemicals have a long history and widespread occurrence within the Great Lakes watershed. Though there has been a significant decrease across all lakes since their ban in the 1970s, most restrictive fish consumption advisories are still driven primarily by PCBs and secondarily by mercury (Gandhi et al. 2016, 2017, OMOECC 2015). Figure 8 presents the trends in whole lake trout and walleye PCB concentration across the Great Lakes over the last several decades, showing a significant decline across all Great Lakes.

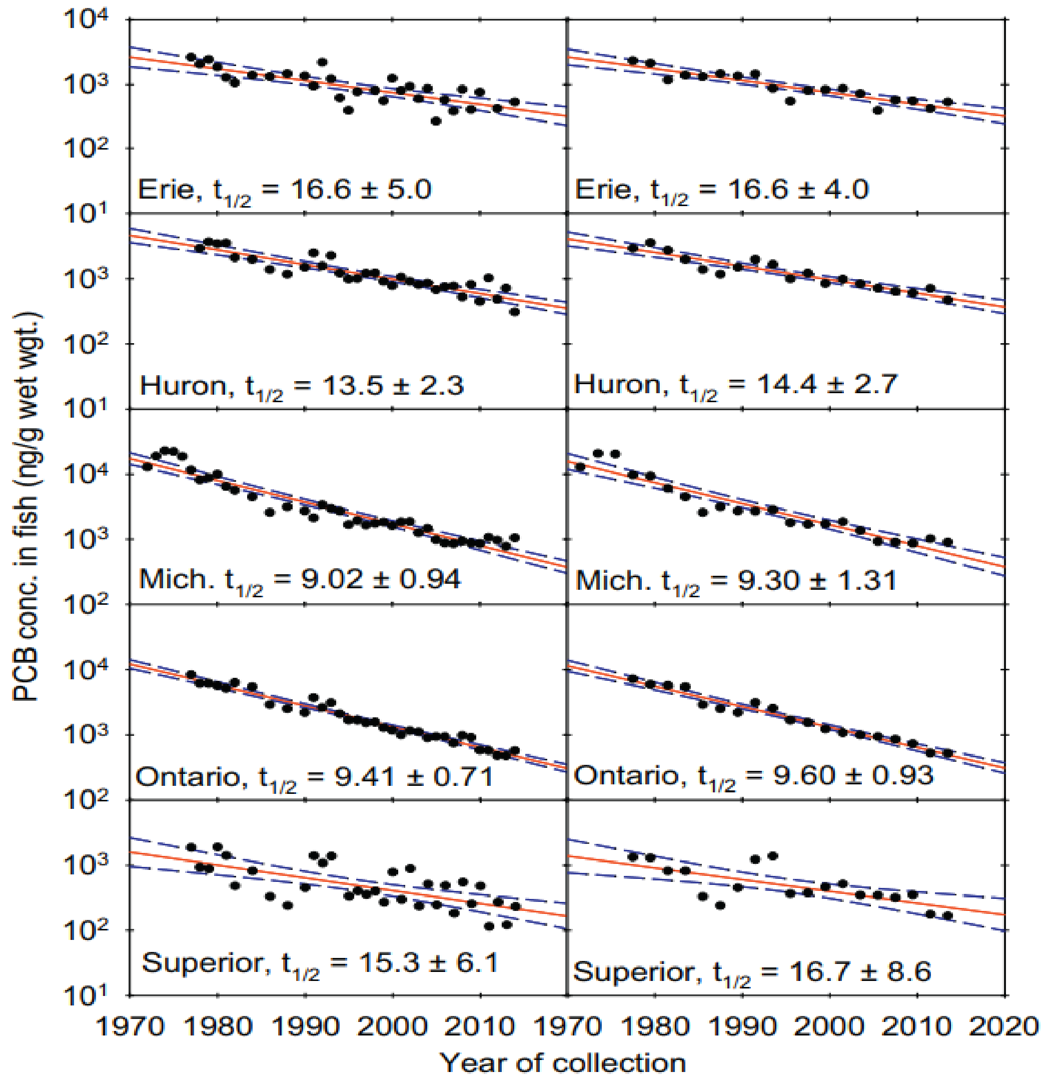


Figure 8. Concentration of PCBs over time in walleye and lake trout (from Hites and Holsen 2019).

Similarly, a general pattern across the Great Lakes has been a declining trend from the elevated mercury concentrations of the 1970s, followed by a gradual stabilization (Visha et al. 2018a). The declining trend was most significant with top predators (e.g., lake trout, walleye), whereas benthivorous fish declined to a lesser extent. More recently, some species show an increasing trend that may be attributed to shifts in energy trophodynamics and food web changes induced from the introduction of invaders, and the fluxes from the atmosphere (Visha et al. 2018a). While the focus of the discussion herein will be on the interaction of single toxic compounds or classes with stressors other than different toxics, the reality of a potential within-category interaction should not be forgotten. Individual contaminants, in the presence of many other contaminants, can induce a variety of interactions including additive and synergistic effects.

Thus, toxics can be considered as individual stressors interacting with stressors other than contaminants, or as pairs, triads, or larger groupings of toxic stressors alone.

6.1.3 *Nutrients*

Nutrients, such as phosphorus, nitrogen, and silica are essential components of phytoplankton growth and are essential to the proper functioning of the base of the Great Lakes food web. However, when excess loads of nutrients (mainly phosphorus) from point and non-point sources enter surface waters, at concentrations beyond the system's ability to incorporate the excess into normal biogeochemical cycles, this can lead to significant algal growth and ecological and human health concerns. While nitrogen and silica will be mentioned here, the focus of this report will be on phosphorus and how its impacts interact with those of other Great Lakes stressors. Phosphorus has been recognized for decades as the primary limiting nutrient for primary productivity in most freshwater systems, including the Great Lakes. Concerns about the impacts of excess nutrient loading on the lakes, including algal blooms and oxygen depletion of bottom waters, led to regulation and mitigation of total phosphorus (TP) loading to the lakes from the United States and Canada beginning in the 1970s, and accelerating through the 1990s and early 2000s (Dove and Chapra 2015). The reappearance of large algal blooms and continuing hypoxia in parts of Lake Erie and other parts of the Great Lakes in the mid-2000s has been attributed to factors including a rise in loading of dissolved P, much of which originates from agricultural tile drains (D. Smith et al. 2015), and higher runoff in recent years (Stow et al. 2015) attributed by some to changing climate.

As previously mentioned, (6.1.1) the synergistic interaction between phosphorus and mussels is one of the best studied within the Great Lakes. And while synergistic interactions or additive effects are most commonly reported, nutrients may also interact antagonistically with invasives. For example, in areas where productivity leads to seasonal bottom hypoxia, mussels may be limited. This has been observed in the offshore dead zone in the central basin of Lake Erie where the bottom substrate is nearly void of mussels.

6.1.4 *Habitat Loss*

For the purposes of this report, the focus of this stressor will be on habitat loss or alteration within coastal wetlands, given the primary human role and the widespread impacts and interactions with other co-located stressors. A significant portion of the biological productivity and diversity within the Great Lakes is concentrated in the coastal wetlands. Anthropogenic activities, however, such as land-clearing and drainage for agriculture, and filling of wetlands to permit coastal development, have resulted in the historical loss of significant portions of Great Lakes wetlands. Some experts have estimated that nearly 50% of the pre-settlement Great Lakes coastal wetlands have been lost and in some areas such as Saginaw Bay in Lake Huron, up to 95% have been lost. Additionally, invasive plants such as *Phragmites* and *Typha* have replaced a significant portion of native wetland plants. These factors continue to threaten the quality of existing wetlands (Trebitz et al. 2009). Figure 9 presents data from the period of 1996-2010 showing losses and gains in both development and wetlands. Clearly, wetland loss is a continuing problem in the Great Lakes. Other direct alterations of habitat which are important include dredging/filling, hardening of shorelines, and construction of dams and other barriers that restrict fish passage in tributaries and modify flows.

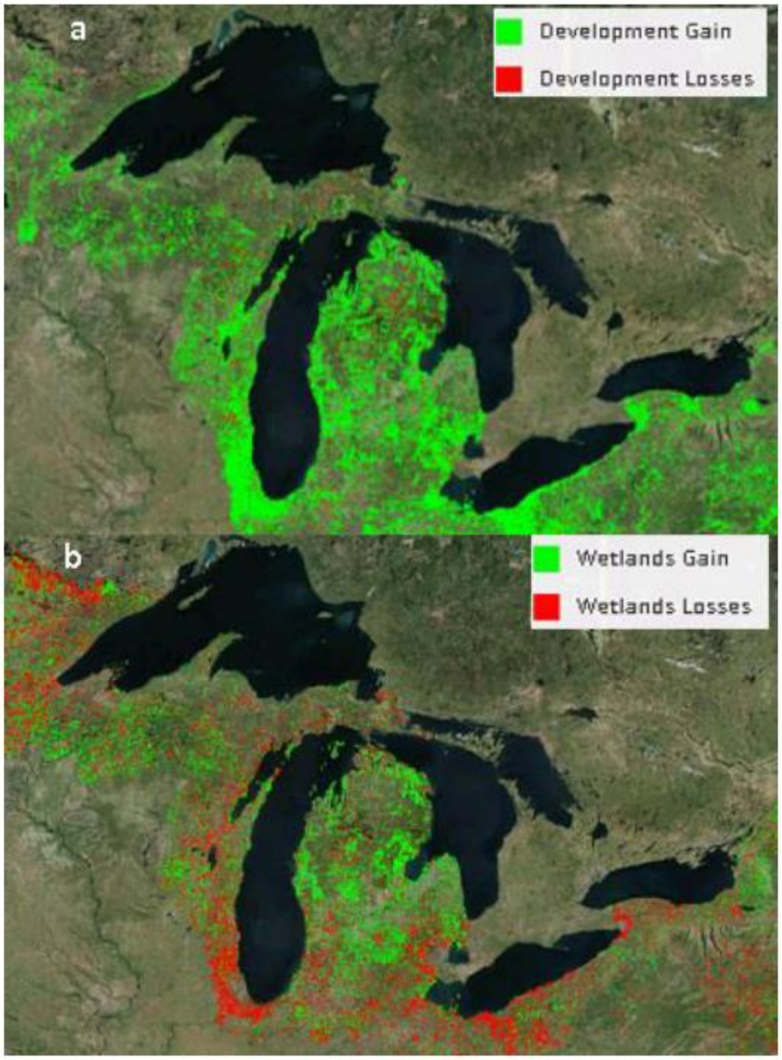


Figure 9. Gains and losses are shown for the period of 1996-2010 for A) Development and B) Wetlands. Data were summarized from NOAA C-CAP land cover atlas database (taken from Shuchman et al. 2017). Note that no comparable Canadian data are included.

The loss of wetlands can interact directly with other Great Lakes stressors, including climate change, nutrients and toxics. For example, wetlands can sequester toxics and trap nutrients from entering the main waterbody such that the loss of wetlands leads to additional contaminant loads in the main water bodies.

6.1.5 *Climate Change*

Climate change is causing significant impacts on the Great Lakes basin, affecting multiple aspects of the aquatic ecosystem as well as human activities (ELPC 2019). To focus the discussion of climate change impacts in this project, the primary stressors considered were warming and precipitation. According to the ELPC report, "Between 1901-1960 and 1985- 2016, the Great Lakes basin has warmed 1.6°F in annual mean temperature, exceeding average changes of 1.2°F for the rest of the contiguous United States. By the end of the 21st century, global average temperatures are expected to rise an additional 2.7°F to 7.2°F." These changes in climate are impacting several components in the Great Lakes including air temperature, precipitation intensity and timing, length of growing season, and lake ecology and indigenous wildlife distributions. Figure 10, from ELPC (2019) based on work reported in Mason et al. (2016), shows multi-decadal trends in ice cover and surface water temperature across the Great Lakes.

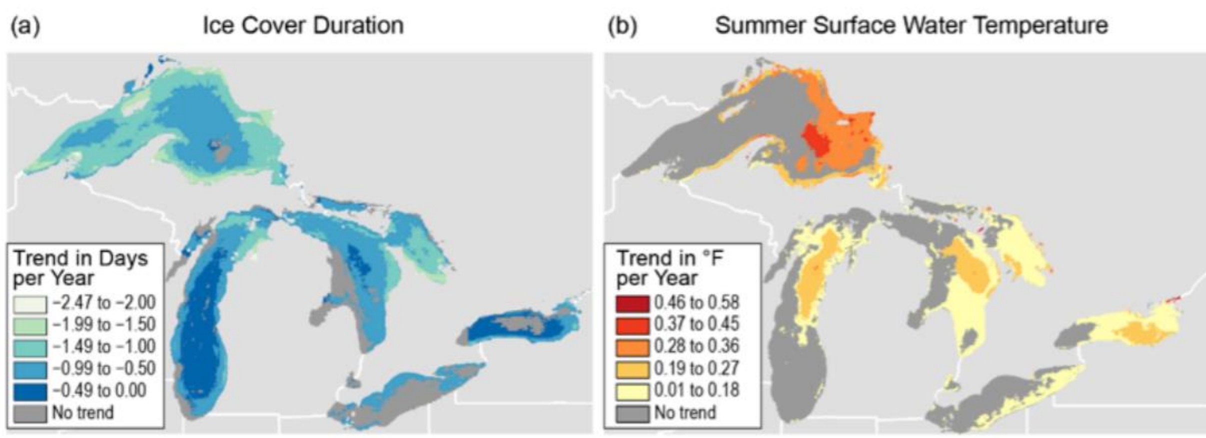


Figure 10. The maps show the duration of seasonal ice cover (left) decrease in most areas of the Great Lakes between 1973 and 2013, and summer surface water temperature (right) increases from 1994 and 2013 (Mason et al. 2016).

With regard to precipitation, the Great Lakes region saw an almost 10% increase from 1901 to 2015 (U.S. increased just 4%), with more of this precipitation coming as unusually large events (ELPC 2019). Scientists expect wetter winters and springs, while summer precipitation should decrease by 5-15% for most of Great Lake states by 2100.

Given the widespread impact that climate has on the Great Lakes region, it is not surprising that climate can closely interact with other co-occurring stressors. However, the interaction type and strength can vary both seasonally and temporally. For example, increased temperatures can both provide new refuge for some invaders (e.g., mussels invade Lake Superior) yet reduce the densities of cooler water invaders in the southern Great Lakes. Warmer water temperatures can enhance the mobility of toxics but may also increase microbial breakdown of some contaminant groups. Likewise, warmer temperatures may intensify algal blooms but reduced spring snow melt may also reduce runoff. It is clear that while the interactions of other stressors with climate change are complex, they are increasingly important to understand.

6.1.6 *Pathogens*

Pathogens in the Great Lakes are an ongoing management concern. This section encompasses both beach advisories and closings often based on fecal indicator bacteria (FIB), as well as fish disease such as viral hemorrhagic septicemia (VHS). Disease transmission through the contamination of recreational and drinking water sources is a significant public health concern in the Great Lakes (Corsi et al. 2015, Lenaker et al. 2017). Extensive work done in the Great Lakes has shown that *E. coli* can persist in a wide variety of secondary habitats, such as water, beach sand, sediment, and periphyton (references within Mathai et al. 2019). While FIB are the prominent measure of contamination, recent research has demonstrated that FIB can be poor surrogates for pathogens (Ishii et al. 2014, Corsi et al. 2015). It has been suggested that viruses are responsible for a significant portion of illness resulting from recreational water exposure. Indeed, there are over 500 waterborne pathogens of potential concern in drinking waters, identified by the U.S. Environmental Protection Agency (EPA).

Pathogenic organisms can closely interact with other stressors, including toxics, warming, habitat loss, and fishery overharvest. For example, VHS, an invasive virus caused by an aquatic rhabdovirus, has had an impact on the Great Lakes fish community and fish harvest (Figure 11), including in areas that are already stressed by invasive species.

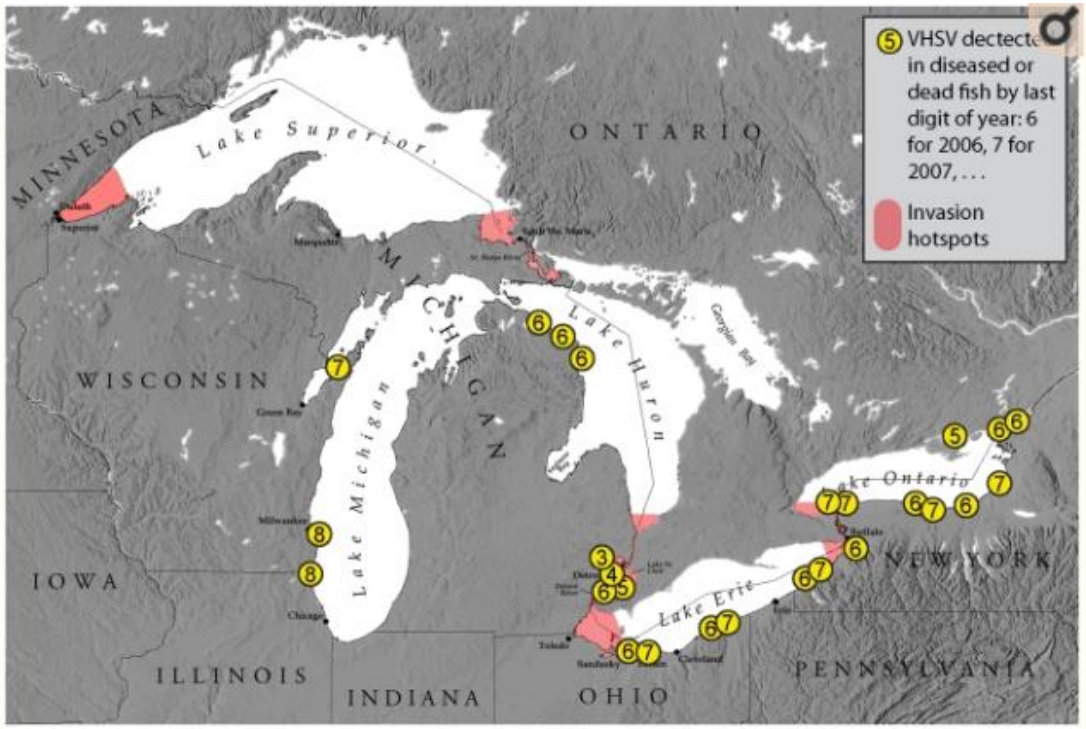


Figure 11. Map showing VHS detections across the great lakes from 2003-2008.

Until the late 1980's the VHS virus was considered to be a pathogen limited to Western Europe. However, following its discovery in Lake Ontario in 2005, after a significant fish die off, it was identified in archived fish samples from Lake St. Clair as early as 2003. The virus has affected many different fish species from different families in the Great Lakes (Elsayed et al. 2006) and is responsible for significant fish mortality. Pathogenic organisms also interact with climate change, where increases in precipitation can lead to higher bacteria and virus loads in nearshore Great Lakes environments.

6.1.7 *Fish Harvest*

Improperly managed fishery exploitation can be an important threat to sustainable fish populations and healthy ecosystems in the Great Lakes and elsewhere. Historically, a number of examples in the Great Lakes basin demonstrate how overharvesting can functionally extirpate a species, such as the lake sturgeon (Sweka et al. 2018) and/or significantly reduce others (cisco, lake whitefish and walleye; Ebener et al. 2008, Brenden et al. 2010, Haponski et al. 2016, Hansen et al. 2019). The Great Lakes Fishery Commission now facilitates binational stock assessments and harvest decisions to ensure a well-balanced and productive fish population that supports recreational, commercial, or subsistence fisheries, as well as healthy ecosystems.

This cooperative fishery management has been critical as management of stocks requires an understanding of other stressors such as invasive species, habitat loss, and climate change that will impact sustainable harvest quantities (de Kerckhove et al. 2015). For example, while lake trout were also subjected to overfishing, the invasive sea lamprey has caused the most damage to this species (Elrod et al. 1995) and warming from climate change is expected to have a significant effect on the distribution and abundance of Great Lakes fish (Lynch et al. 2010, Minns 2014, Collingsworth et al. 2017). Understanding how these stressors interact remains an important component of regional fisheries management strategies.

6.2 Stressor pair selection

The selected stressor pairs are shown in the following table (Table 4), with consideration of their interactions and mechanisms. The table is followed by more detailed discussion of each pair, including a case study and references.

As noted above (section 5), three cases studies were discussed in depth at the workshop[1]. These included toxics and nutrients, invasive species and nutrients, and habitat loss and invasives (Sections 6.2.1-6.2.3). The workshop identified the difficulty in selecting important stressor pairs without contextual considerations. As for example, toxics and nutrients may be an important interaction in the western basin of Lake Erie but may not be an issue in upper Lake Superior. Given these considerations, participants focused on a select stressor pair within a specific lake or basin. In the following three case studies the general stressor pair is introduced followed by a summary of the workshop discussion of the pair at a specific location. This is followed by less comprehensive treatments of the other selected stressor pairs that were not considered in detail at the workshop (Sections 6.2.4-6.2.11).

---

[1] Each group responded to the following questions in discussing their case studies:

1. *Identify and describe the stressor combinations that are commonly documented in scientific literature;*
2. *Describe how common non-additive effects are, i.e., synergistic and antagonistic effects;*
3. *Identify the stressor combinations that are thought to be of greatest concern in the Great Lakes ecosystem;*
4. *Characterize the strength of stressor interactions across different aquatic environments and across different scales, including scale of measurement, spatial scale from local embayment to whole lake, and temporal scale, and the ability of existing indicators to capture such interactions;*
5. *Assess the underlying data quality and strength of evidence of the identified stressor interactions;*
6. *Identify and describe the additional research, surveillance, and monitoring activities that are needed to fill knowledge gaps and better address an assessment of interacting stressors in the Great Lakes.*

Table 4. Potential additive/synergistic or antagonistic relationships of stressor pairs.

Stressor Pair	Additive or Synergistic	Antagonistic*	Most Probable Interaction
Toxics and Nutrients	Nutrient induced hypoxia could enhance mobility and microbial transformation of some toxics (e.g., methylation of Hg), and possibly bioavailability	Increased organic matter burial due to higher productivity could sorb and sequester toxics in sediment; productivity increases due to increased P loads, biomass dilution effect increases with trophic status; nutrient induced hypoxia could make redox-sensitive metals less bioavailable	Antagonistic
Invasives and Nutrients	Nearshore shunt traps nutrients, reducing offshore productivity (Hecky et al. 2004) and fish biomass; mussel feeding increases light penetration and traps nutrients in sediment, which promotes macroalgae growth; selective feeding of mussels on diatoms vs. cyanobacteria may be a factor in HABs, but magnitude of effect is unclear; scale of impact on HABs of nearshore nutrient shunt (antagonism) is also unclear	Seasonal hypoxia limits mussels in central basin of Lake Erie; mussel feeding may sequester nutrients in sediment, reducing HABs; *Phragmites* may also take up and trap nutrients in coastal areas	Additive or Synergistic
Invasives and Habitat Loss	Mussels can enhance light penetration and promote growth of nuisance macroalgae; this is further enhanced by nutrient runoff in areas with decreased wetlands for nutrient trapping; some invasives like gobies, who favor rocky rip rap	Wetland filling, and particularly complete wetland destruction, may fragment habitat, slowing the geographic spread of some invaders.	Additive or Synergistic

Stressor Pair	**Additive or Synergistic**	**Antagonistic***	**Most Probable Interaction**
	shoreline habitat, do better in areas without wetlands.		
Invasives and Climate Change	Warming allows range expansion within lakes, particularly into Lake Superior (mussels), increases potential Asian carp habitat, and increases lamprey growth rates and fecundity (Hansen et al., 2016); warmer winters allow subtropical invaders to survive	Warming may create temperatures that are unfavorable for some invasives in shallow water or at southern limits in the Great Lakes; sequestration of carbon in peat by *Phragmites* can offset some atmospheric carbon fluxes, creating a negative feedback on climate change	Additive or Synergistic
Toxics and Climate Change	Warmer temperatures enhance mobility and microbial transformation of some toxics (e.g., methylation of Hg), and possibly bioavailability	Warming may accelerate microbial degradation rates and annual duration of higher activity impacting some organic pollutants	Both
Toxics and Habitat Loss	Wetland loss reduces filtration and area of potential sink in organic-rich sediments prior to lake loading of toxic effluent	Filling of coastal wetlands caps toxics in some industrial areas such as river mouths and harbors (e.g., Muskegon Lake); loss of wetlands can reduce production of some contaminants (e.g., methyl mercury)	Both
Climate Change and Nutrients	Warmer and longer summer seasons may favor more intense algal blooms, stratification and hypoxia; more sediment P mobilization by longer and more widespread hypoxia; higher	Warming may cause early algal blooms to consume available nutrients that would otherwise fuel blooms later in the season, as in Lake Erie in 2018; Warmer winters may	Additive or Synergistic

Stressor Pair	Additive or Synergistic	Antagonistic*	Most Probable Interaction
	precipitation and increased river discharges may further increase loadings	result in less snowmelt for spring runoff and associated loading	
Climate Change and Habitat Loss	Warming may favor invasives such as *Phragmites* and decrease the amount of wetland area with native vegetation	Warming without corresponding increases in precipitation would decrease water levels, increase growing season, and potentially increase wetland area	Additive or Synergistic
Nutrients and Habitat Loss	Less watershed and coastal nutrient trapping by wetlands, and corresponding increase in impervious surface in filled urban wetland areas increases lake loading; higher nutrient loads in smaller wetlands may favor establishment and rapid growth of invasives (*Phragmites*)	In the absence of invasives, moderate increases in nutrient loading to coastal wetlands can enhance growth of native wetland vegetation, which can in turn trap more nutrients	Additive or Synergistic
Climate Change and Pathogens	Increase in intensity and frequency of rain events increases levels of pathogens delivered from watersheds; increase in beach closings and human health advisories	Some pathogens do not replicate or survive at higher temperatures (e.g., most VHS outbreaks occur when water temperatures are 39- 57°F, fish rarely die above 59 °F).	Additive or Synergistic
Invasives and Fish Harvest	Invasives (e.g., sea lamprey) can reduce native fish populations thereby impacting harvest fish populations	Invader can improve conditions for a local fishery (zebra mussels improved water clarity, supporting visual predators like Lake Ontario salmon)	Additive or Synergistic

*(note: “antagonistic” does not necessarily mean a negative net outcome)

6.2.1 *Toxics and Nutrients: Organic Pollutants and Phosphorus*

The concentration of persistent organic pollutants such as PCBs and methyl mercury (MeHg) in biota is driven by a number of physicochemical properties, but there is also growing recognition of the roles of physiological and ecological characteristics in modifying concentrations and bioaccumulation potential (Borga et al. 2012, Lavoie et al. 2013). A number of studies have shown how increased productivity can decrease the concentration of POPs in higher trophic level organisms by biodilution (e.g., Larsson et al. 1992, Berglund et al. 2001, Pickhardt et al. 2002, Kidd et al. 1999, Clayden et al. 2013). An example is shown in Figure 12 where the authors compared the concentration of methyl mercury in *Daphnia* with increased phosphorus inputs and showed a significant decline.

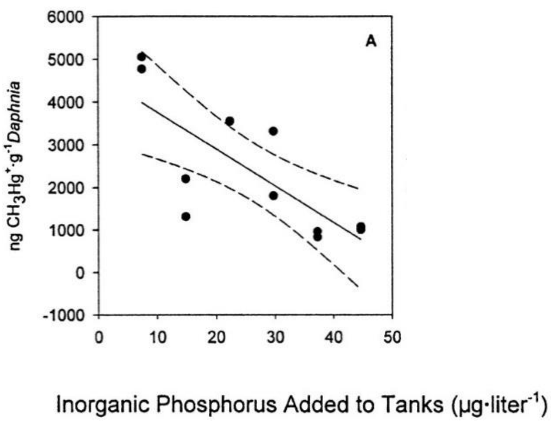


Figure 12. Mean concentration of methyl mercury in *Daphnia* against added phosphorus (panel A shown from Pickhardt et al. 2002).

In this case the contaminant pool is diluted by several factors including a larger amount of biomass making up the base of the food web, more effective transport of contaminants to sediment via algae sinking (higher rates of sedimentation), and more efficient growth of fish from increased food abundance and/or food quality (Guildford et al. 2008).

6.2.1.1 Workshop Case Study: Interactions of Nutrients and Toxic Stressors in the Western Basin of Lake Erie

Defining ‘nutrients’ and ‘toxics’ was necessary to contextualize the discussion. Nutrients were defined as phosphorus loadings, toxics as the concentration of persistent bioaccumulative toxics (PBTs) (e.g., PCBs, Hg, PFAS) in fish. As described above, phosphorus load reductions have the potential for increased toxics mobilization and/or higher toxics concentrations in organisms due to lower growth rates and less biomass dilution. From a risk-benefit perspective, however, the need to reduce P may outweighs concerns about potential toxics liberation or increased concentrations in organisms, particularly given parallel efforts to remove legacy contaminants in sediment and to reduce toxics loading in the Great Lakes.

The group focused narrowly on the case study topic; there was little discussion of other stressor combinations. There was strong consensus that – as reported in the literature – stressors vary temporally and spatially and thus their interactions do too. Although the persistent nature of toxics means that the chemicals are less influenced by temporal considerations, those come into play through life stage and migration considerations. For example, larval feeding by fish on diatoms may influence toxics uptake, and seasonal temperature patterns can influence primary productivity and fish metabolism/growth rates.

The group generally agreed with prevailing literature that toxics decline with increasing nutrients in the system based on biomass dilution due to higher growth rates and other factors, and thus the effects are antagonistic. Notwithstanding the complexity of the nutrient load and fish productivity relationship, mechanisms were discussed. As productivity increases due to increased P loads, increased growth rates in fish dilute PBT concentrations in tissue. The biomass dilution effect increases with trophic level. Increased primary production also results in more rapid burial of PBTs not bound in tissue. Nutrient increases can also lead to increased bacterial growth rates and enhanced bacterial degradation of PCBs.

Conversely, as P loads are reduced, PBT concentrations tend to increase in fish tissue and burial is also reduced. PCBs in particular may re-enter the water column through diffusion, bioturbation and dredging or other disturbances. The group also briefly considered the influence of toxics on nutrients, for example P content in glyphosate.

In the context of the case study, mechanisms of interactions between nutrients and toxics vary between Lake Erie basins: the western basin is broadly representative of other shallow productive 'embayments' where the mechanisms described above are relatively strong. The east basin sees lower prey fish biomass, predator growth rates, and limited burial – and may be broadly representative of interactions in mesotrophic and especially oligotrophic compartments elsewhere in the Great Lakes basin. Indicators were not discussed, although there was an acknowledgement that endpoints should be considered. The fishable/drinkable/swimmable objectives in the Great Lakes Water Quality Agreement may be instructive.

The breakout group did not address the question of underlying data quality and strength of evidence specifically. It was suggested that the mechanisms by which phosphorus leads to reduced toxics concentrations in fish is reasonably well studied. As noted earlier from a risk-benefit perspective the relationship should not deter continued focus on phosphorus load reductions to Lake Erie, although there is a need to carefully communicate and manage expectations of the implications of P load reductions on PBT trends.

As a general sentiment, the group felt that the importance of monitoring and surveillance needs to be elevated. A 'marketing plan' to promote the need for long-term monitoring could emphasize education and citizen science, affordable deployable sensors, and reinforce the connection between the lakes and people. More specifically, enhanced monitoring of primary productivity is required, supplemented with fish age and growth rate monitoring. Monitoring coordination opportunities exist e.g., potential for improved utilization of data associated with fish consumption advisory programs.

Additional research may be required to understand response times between P load reductions and PBT trends in fish tissue. Additional research is needed on chemical classes other than PBTs giving consideration to the chemical classes that are most likely to lead to ecological perturbations, temporal variability (e.g., ice cover season), spatial variability (e.g., position in water column), and mechanistic pathways (e.g., glyphosate impacts on algal growth, particularly eukaryotes). As knowledge of stressor interactions improves it should be applied through the adaptive management process. The Annex structure under the Agreement provides an appropriate institutional home and funding source for applying those understandings over time.

Brief Summary of Stressor Pair

Overall, the main relationship between toxics and nutrients is antagonistic. This is due to a number of potential mechanisms including increased organic matter burial due to higher productivity sorbing and sequestering toxics in sediment, as well as biomass dilution due to higher growth rates in fish and other organisms, among other factors.

6.2.2 *Invasives and Nutrients (Dreissenid Mussels and Phosphorus)*

Mussels have dramatically changed the ecosystem and driven oligotrophication in the Great Lakes where they have become strongly established (Barbiero et al. 2012). Mussels likely trap and retain phosphorus in nearshore areas, thereby increasing benthic nutrient levels in shallow-water locations (Hecky et al. 2004). As mussels increase water transparency and convert particulate phosphorus to soluble reactive phosphorus, they are also causing declines in offshore primary production and nutrient concentrations (Hecky et al. 2004; Cha et al. 2011; Stow et al. 2014). The long-term trend toward more intense oligotrophy in Lake Michigan, Lake Huron, and Lake Ontario appears to be related to the aforementioned reduction in phosphorus concentrations in offshore waters (Dove and Chapra 2015). This low offshore productivity may be impacting the upper food web, where prey fish biomass has declined (Bunnell et al. 2014). Figure 13 shows a side by side comparison of relative Lake Michigan prey fish biomass compared to spring total phosphorus concentration.

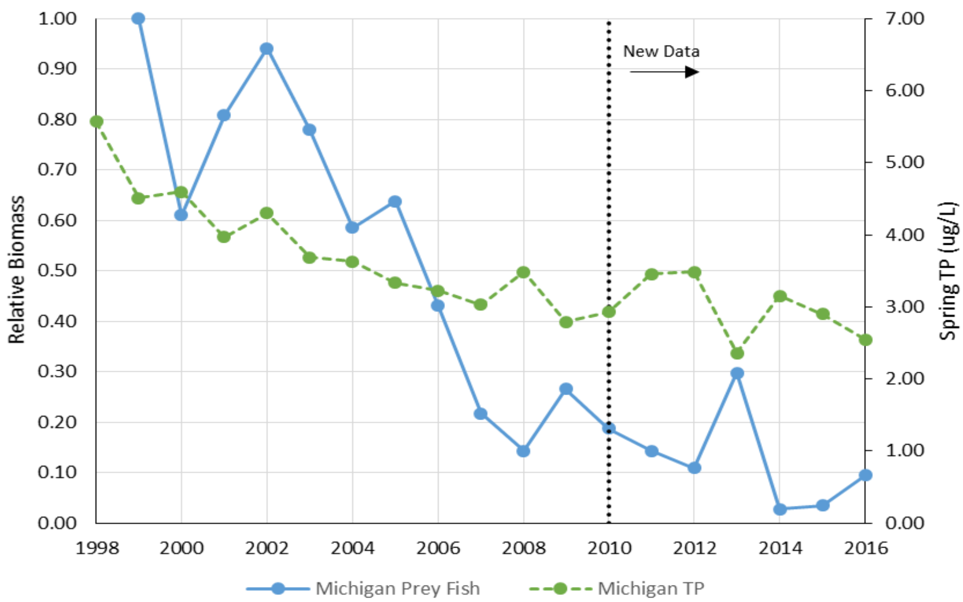


Figure 13. Lake Michigan prey fish relative biomass estimates compared with spring TP (taken from the Declining Offshore Lake Productivity contractor report prepared for IJC).

Phosphorus is an essential nutrient for the growth of plants and animals, yet the levels in these lakes are generally below target levels. The total offshore impacts of this nutrient trapping or "shunting" remain unclear, and are often difficult to distinguish from reductions in nutrient loading from tributaries. Additionally, quagga mussels are able to colonize soft sediments in deeper waters which could represent a permanent trapping mechanism for phosphorus, termed the "mid-depth sink" hypothesis by Vanderploeg et al. (2010). The redistribution of bioavailable phosphorus to the nearshore benthos (Ozersky et al. 2009), along with increased water clarity and light penetration due to mussel filtration, has also contributed to the expansion of macroalgae, particularly filamentous *Cladophora*, in some nearshore areas of Lake Michigan, Lake Huron, eastern Lake Erie, and Lake Ontario (Howell 2018). The net long-term impact of nearshore changes driven by mussels on offshore nutrient delivery and primary productivity, and the subsequent impacts to fisheries, is an area of active research in the Great Lakes. The interaction of nutrient loading and invasive mussels is generally antagonistic. The interaction results in an enhancement of conditions for some species (nearshore macroalgae) and a degradation of conditions for others (offshore fish), which creates a complex management environment when nutrient load reductions are considered in some settings.

6.2.2.1 Workshop Case Study: Interactions of Invasive Mussel and Nutrient Stressors in Lake Michigan

There is a need to consider nearshore and offshore habitats separately when examining nutrient and mussel interactions, as the nature of the interaction effect will vary. The end points need to be specified regarding desired nutrient concentrations and impacts of mussels, given that nutrients can be both too high and too low for particular endpoints (e.g., fish diversity and productivity objectives). The need to examine effects seasonally as well as spatially was highlighted in group discussions, with special consideration of the variable paths of river plumes in three dimensions, to more fully understand interactions. Other factors that are important in understanding nutrient and mussel interactions are predation on mussels by round gobies, and mussel effects on water clarity and concentration of nutrients in sediments via pseudofeces production that promote nuisance algae.

Management implications include consideration of the fact that localized mussel control approaches are needed; lake-wide control is not realistic. The nutrient ratios of P and N are an important consideration that goes beyond nutrient reduction alone. Mussels have also changed the trophic status in the lakes. In some lakes, specifically Michigan and Huron, the nearshore nutrient trap (or shunt) has led to significant oligotrophy in offshore regions. This has potentially impacted fisheries, whereby the limited productivity offshore leads to a reduction in fish biomass (Bunnell et al. 2014). Given this, we may need to manage differently than in the past, or even take an entirely new approach. For example, it may be appropriate to manage the system to enhance alewife production (alewife populations are in decline, likely due to in part to decreases in plankton) to increase prey biomass, which would be a complete reversal of prior alewife objectives.

A major need for improved monitoring and surveillance in the near-shore areas was identified. Data trends need to be analyzed to re-calibrate/validate models. Tracking of dissolved vs. particulate phosphorous is needed in order to better assess bioavailability. Research needs include examining social conditions and understanding values placed on the system; the end goals must be identified.

The group concentrated on the case study topic, but did mention other related stressors or responses such as excess macroalgae due to benthification and greater light penetration, food web impacts, invasive species impacts beyond mussels (e.g., round gobies), climate change influences on loading, and impacts on the fishery and associated management decisions.

The group highlighted the importance of examining spatial congruence related to interactions, given that mussel-nutrient interaction produces opposite results in nearshore versus offshore waters (enhanced productivity nearshore, reduced productivity offshore). Patterns such as these may be common with other stressor pairs.

The group agreed that mussels and nutrients were among the most important stressors in many parts of the Great Lakes. The group self-selected for this case study on Day 2, which likely indicated their disciplinary expertise and potential bias in evaluating the relative importance of a broader set of stressors.

The strength of mussel-nutrient interaction across different aquatic environments and across different scales was discussed extensively, with special emphasis on nearshore to offshore gradients, river plume dynamics, and seasonality of nutrient loading and mussel metabolism. The spectrum of interactions from Lake Superior (limited mussels, low nutrients) to Lake Erie (more eutrophic, variable mussel colonization by basin) was also discussed.

The breakout group felt that the overall data quality and strength of evidence were sufficient to broadly characterize the nature of the stressor pair interaction, especially in offshore areas. The group stated that there was a need to improve nearshore research and monitoring to understand important process questions and to track impacts of management actions on the interaction of mussels and nutrients, as well as their food web and fishery impacts. More sophisticated analysis of nutrient ratios, of phosphorus and nitrogen speciation, and of three dimensional and seasonal dynamics of nutrient delivery around river plumes were also identified as areas that need research and monitoring attention.

Brief Summary of Stressor Pair

The relationship between mussels and phosphorus is one of the more widely researched interactions, and in general it is thought to be synergistic or additive (more phosphorus can produce more food for mussels). However, antagonistic interactions are also possible in some locations, where nutrient-induced seasonal hypoxia limits mussel abundance (e.g., the central basin of Lake Erie). Additionally, mussel feeding may sequester nutrients in sediment, reducing productivity and HABs, and the invasive *Phragmites* may also take up and trap nutrients in coastal areas.

6.2.3 *Habitat Loss and Invasives: (Round Gobies and Wetland Loss)*

The invasion of gobies into the Great Lakes has been well studied but there are a still a number of uncertainties regarding its spatial distribution and intensity. Wetlands have long been considered more resistant to invasions due to their unique physico-chemical properties as well as their structural complexity (Chapman et al. 1996; Jude et al. 2006; Cooper et al. 2007). This is thought to be particularly true with respect to round gobies, who prefer rocky and gravel substances including artificial riprap (Ray and Corkum 2001). Uzarksi et al. (2005) studied 62 coastal Great Lakes wetlands and found relatively few gobies (22 of 15,263 total fish) within the wetlands. A follow-on study was completed by Cooper et al. (2007), which examined round goby abundance within eastern Lake Michigan tributaries. The authors provided further evidence that wetland habitats are more resistant to goby invasion than lake habitat. The potential for the synergistic interaction between wetland loss and round goby invasion may be further exacerbated by the preference of gobies for riprap structures. Riprap has long been used in development projects to provide shoreline protection by dissipating wave energy. Therefore, coastal development (wetland loss) results in reduced native fish spawning habitat, and may also provide enhanced round goby habitat.

6.2.3.1 Workshop Case Study: Interactions of Invasives and Habitat Loss Stressors in the Lake Ontario Basin

Many specific habitats, invasive species, and locations could be examined to explore the nature of this type of stressor interaction in the Great Lakes. Habitat can include aspects of tributary condition (dams, sedimentation, channelization), near-shore habitat (*Cladophora* abundance, sediment burial of natural coarse substrate, alteration of natural water level variability), deep-water reefs (alewife predation at spawning sites), and more. However, Great Lakes wetland loss/degradation is among the most important concerns. In this context, stressor interactions may involve invasive plants such as *Typha* and *Phragmites*, and habitat modification may be due to water level change and shoreline hardening. Interactions likely vary spatially, among lakes and between wetland types such as lacustrine and river mouth wetlands, open shorelines vs. embayments, etc. Spatial variation strongly influences the context of any interaction between invasive species and habitat degradation. Wetland types vary spatially as do abundances of invasive species. Historical wetland loss also varies spatially. Water level stabilization is most pronounced in Lake Ontario. Shoreline hardening/ urbanization varies across wetland locations. Climate and possible climate change also are important to context.

A literature review can establish which combinations of invasive species with habitat degradation are best documented. The breakout group identified a number of invasive species that may interact with habitat degradation, including plants (*Typha*, *Phragmites*) and fish (gobies, non-native salmonids, alewives). Invasion by infectious microbes was suggested as an under-appreciated category. A number of habitat types experiencing degradation were mentioned, including nearshore benthos, deepwater reefs, and shorelines, but wetlands (of various types) were considered of particular concern. Principal stressors causing wetland degradation were considered to be water level fluctuations (or stabilization) and shoreline hardening. The breakout group mentioned both large-scale water level fluctuations (as influenced by lake hydrological fluctuations) and local water level influences such as dikes and pumping.

The breakout group pointed to the importance of establishing endpoints and identifying mechanisms to address this question. Endpoints should be measurable and something we care about. They may be population measures of any of the biota, or functional metrics, and at different levels of granularity (healthy fish assemblages vs. walleye harvest). Discussion did not resolve whether the effect on wetland habitat is synergistic or antagonistic between invasive species and habitat stressors such as water level change or shoreline hardening. Both were considered to have negative effects. Water level change was thought to exacerbate the influence of invasive species (so an interaction occurs), but not vice versa.

The higher-level question of which stressor combinations are thought to be of greatest concern in the Great Lakes was not addressed in the breakout group, except within the narrower context of habitat X invasives, where a focus on wetlands (the endpoint), emphasizes invasive plants and water levels.

The breakout group did not address the question of the strength of stressor interaction across different environments and scales directly, but recognized that, even when narrowed to two stressor categories – invasive species and stressors causing habitat degradation – there are many possible individual combinations. Further narrowing to consider wetland habitats affected by invasive plants and water level fluctuations reinforces the importance of spatial and temporal considerations, and the difficulty of generalizing. Wetland types, the extent of historical loss, and exposure to threats vary within and among lakes. Water level fluctuations have basin-wide drivers (natural hydrologic variation and further influence of climate change) and local drivers (diking, pumping, shoreline hardening). Invasive plant spread is influenced by near-shore bathymetry and substrate. The short answer may well be that the question needs to be considered for any specific case, but lacks a general answer. The breakout group did not address scale of measurement.

The breakout group did not address the question of underlying data quality and strength of evidence specifically. It was suggested that the mechanisms by which invasive plants and water level change influence wetland habitats is well studied. In addition, the breakout group felt that management actions were reasonably well understood. Water level management can be accomplished by allowing or creating natural fluctuations. Invasive plants can be managed by mechanical removal, chemical treatment, or burning. However, barriers to management exist, including homeowner and shipping concerns, and management of water levels is difficult in extreme years.

Surveillance can be accomplished with existing methods for determining wetland plant composition using satellite data, assessing other community elements using fish surveys, and tracking water levels at monitoring sites. However, new surveillance techniques may be needed, as well as novel and more effective control techniques for invasive plants. There is a need to understand effectiveness of management and its societal acceptance, by context (wetland type, climate). Fish pathogens and their potential for magnification are under-studied. Management would also benefit from better understanding of how stressor impacts and interactions vary over space and time, affecting the frequency and context in which stressors potentially interact.

Brief Summary of Stressor Pair

As noted in the workshop breakout group, the interaction between habitat loss and invasive species is complex. In some instances, (e.g., gobies and wetland loss), it appears to be a synergistic interaction but in other instances the relationship may vary. Therefore, it important to consider context with respect to these two stressors, including the spatial and temporal variability among each individual stressor.

6.2.4 *Invasives and Climate Change (Mussels and Warming)*

The interaction between warming from climate change and invasive mussels has been a primary concern since the 1990s. Thorp et al. (1998), studied the survival and growth of mussels at three different temperatures to determine potential effects of warming. The authors concluded that, at lower latitudes, increases in temperature will lead to a reduction in dreissenids from increased stress and decreased growth potential (Figure 14). However, they surmised that more northern populations will benefit from the predicted climatic change and may extend their range to appropriate habitats in higher latitudes (Thorp et al. 1998).

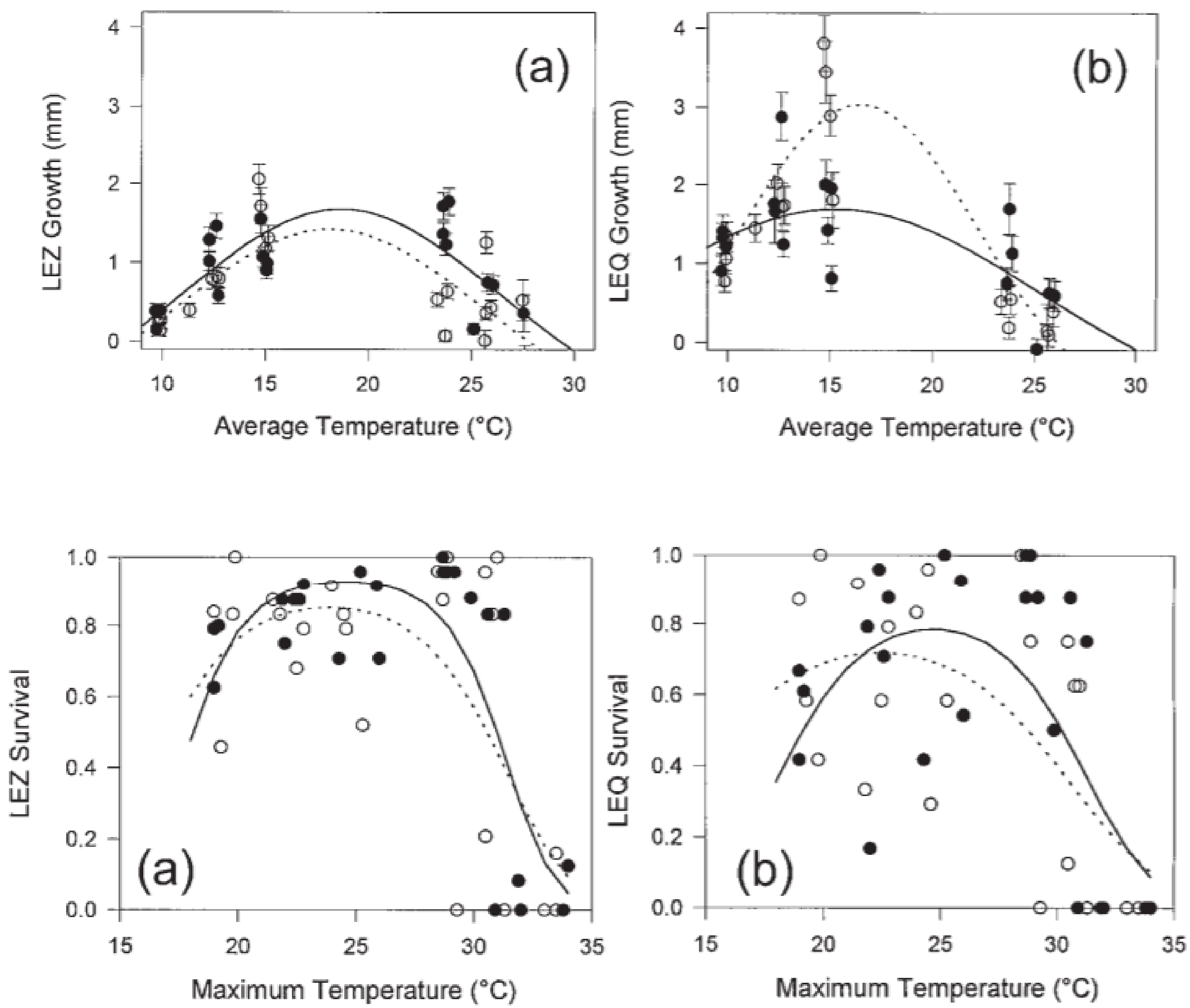


Figure 14. Average and maximum temperature for optimal growth and survival in quagga (LEQ) and zebra (LEZ) mussels (taken from Thorp et al. 1998)

While zebra and quagga mussels have successfully colonized most of the Great Lakes watershed, offshore Lake Superior remains relatively unimpacted. Further, dreissenid densities continue to be minimal across most of Lake Superior (ECCC & USEPA 2017). The colder temperatures and limited nutrients have limited the widespread occurrence of dreissenids in Lake Superior (Figure 7). However, higher water temperatures could permit increases in the populations of zebra and quagga mussels (Moy et al. 2010, Huff and Thomas 2014). Changing water chemistry can also be important and may actually reduce the competitive advantage of some invasives. For example, as pH lowers, the saturation state of two forms of calcium carbonate will decrease, which is more energetically costly for calcifying animals such as dreissenids (Gregg et al. 2012).

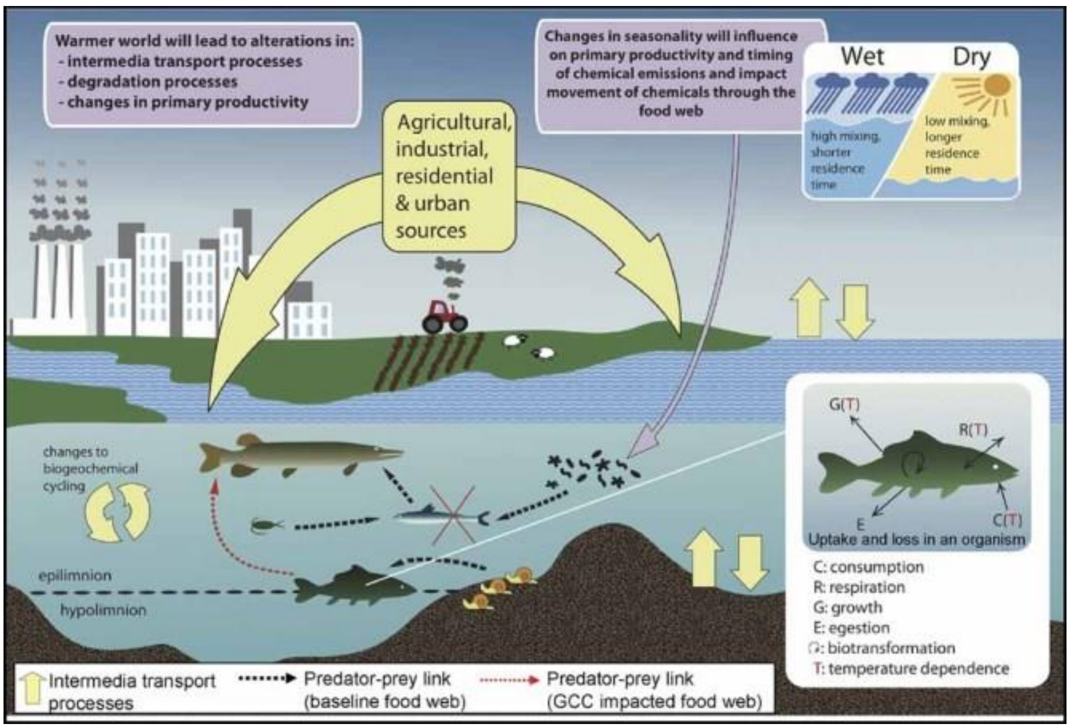
In addition to the potential greater presence of mussels in Lake Superior, warming potentially will increase the range of available habitat to other invasives of concern, including Asian carp, and may increase lamprey growth rates and fecundity (Hansen et al., 2016). Kramer et al. (2017) recently mapped the suitability for potential invasive species in the Great Lakes. Suitability was higher in the lower lakes for the northern snakehead and golden mussel and increasing temperatures may further increase their potential for invasion in the southern limits. However, warming may also create temperatures that are unfavorable for some invasives in shallow water or at southern limits in the Great Lakes. For example, the invasive spiny waterflea, prefers cooler waters and may be limited by increasing temperatures (Pagnucco et al. 2015).

Brief Summary of Stressor Pair

In most cases, the addition of a warming climate to invasive species effects suggests at least an additive if not a synergistic relationship. Warming is likely to increase mussel growth rates and metabolism. While this is likely true in many scenarios, warming can also create temperatures that are unfavorable for some invaders, especially in shallow waters or at the southern limits in the Great Lakes, while expanding ranges to the north for cold-limited species. Further, the sequestration of carbon in peat by *Phragmites* can offset some atmospheric carbon fluxes (antagonism between warming and effects of invader), although this potential asset may be offset by an increased production of methane by invasive *Phragmites* (additive or synergistic interaction).

6.2.5 *Toxics and Climate Change (Organic Pollutants and Warming)*

The interaction of climate with POPs is complex, and climate warming may influence POPs in several ways. Climate change alters a number of environmental factors such as temperature, solar radiation, wind, and precipitation that can also alter the fate, transport, distribution and effects of POPs (Hooper et al. 2013, Balbus et al. 2013). For example, warming climate may increase microbial decomposition and the subsequent release of POPs from bottom sediments, increasing bioavailability for uptake (Yediler and Jacobs 1995) but in some cases it may increase the degradation of contaminants to less toxic more easily degraded molecules. Further, altered biotransformation of contaminants may lead to more bioactive metabolites although this is contaminant dependent. Warming temperatures may produce a minor reduction in POP exposure to aquatic biota because of enhanced partitioning from water to the atmosphere but can also increase bioaccumulation potential (Noyes et al. 2009). Figure 15 presents a representation of the



influence of climate change on bioaccumulation at different scales. Temperature can affect several key fish processes including consumption, growth and respiration. It can also affect other

Figure 15. Global climate change scenarios on bioaccumulation and uptake in fishes (from Gouin et al. 2013)

key bioaccumulation processes including environmental (changing concentrations in media) and dietary exposure (changing predator-prey relationships) (Gouin et al. 2013).

Ng and Gray (2011) forecasted the effects of climate change on bioaccumulation in three Great Lakes fish species that were adapted to three different thermal regimes. Fish are commonly grouped into thermal guilds, where each guild represents a different temperature preference for optimal growth. Warm-water fish generally do well in waters up to 30°C, cool-water fish up to

the mid-20°Cs and cold-water fish below 20° (Eaton and Scheller 1996). The Great Lakes is unique in that it is host to fish across all three temperature guilds and it's not uncommon for fish in the Great Lakes to live at the edge of their thermal range at sub-optimal temperatures (Lynch et al. 2010). As expected, warmer temperatures tended to limit growth potential for cold water species, whereas cold water limited growth for the warm water species. The impact of climate warming on growth depended on both the winter lows/duration and the summer highs in combination with the species' thermal limits. While changes in consumption, respiration and growth will all impact bioaccumulation, understanding thermal sensitivities will be important to understanding implications of bioaccumulation from warming (Ng and Gray 2011).
In general, the strength of the interaction between climate and toxics may depend on more than just the exposure to the contaminant but also the susceptibility of the individual or population which is being exposed (Schiedek et al. 2007). In addition, as mentioned above, with many Great Lakes species living at the edge of their thermal range, any additional climate enhanced exposures to toxics may further hinder the ability of organisms to acclimate to their environment (Noyes et al. 2009).

Brief Summary of Stressor Pair

A number of changing climate variables (precipitation, temperature, ice and snow cover) can also alter the fate and behavior of toxics (Macdonald et al. 2005). However, the complexity of this relationship is due not only to these abiotic processes but also a wide range of potential biotic responses. The interaction type and intensity may vary across toxics and geographic ranges.

6.2.6 *Toxics and Habitat Loss (Mercury and Wetland Loss)*

Biological productivity and diversity in the Great Lakes are generally known to be concentrated in the coastal zones, particularly within wetlands. They provide sites for many critical life history needs for species inhabiting or migrating through the basin (Pearsall et al. 2012, 2013, Vadeboncoeur et al. 2011). Macrophytes which make up the base of the wetland biomass play important roles in the biogeochemistry of contaminants (Weis and Weis 2004). They actively take up elements into plant tissue which can lead to the immobilization of particular contaminants (e.g., metals). For this reason wetlands are often considered "sinks" and are frequently constructed to prevent pollutants from moving into nearby water bodies. However, anthropogenic activities, such as land-clearing and drainage for agriculture, and the filling of wetlands to permit coastal development, have resulted in the historical loss of Great Lakes wetlands (Trebitz et al. 2009). The removal of these wetlands often re-mobilizes the stored contaminants and leads to a substantial inputs of contaminants to the water body.

While wetlands can play a beneficial role in sequestering contaminants, they can also be sources of methylmercury production and export. Wetlands, especially those rich in organic matter, are important sites of methylmercury (MeHg) production as the biogeochemical conditions common to wetlands facilitate methylation (Selvendiran et al. 2008; Figure 16).

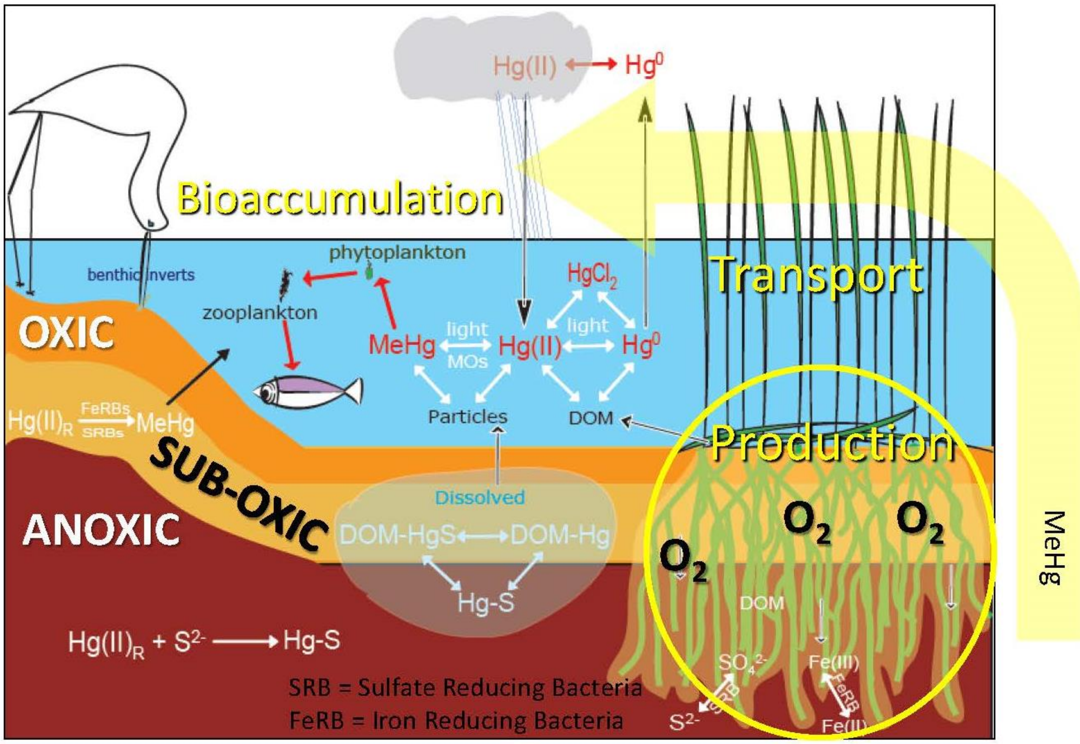


Figure 16. Mercury methylation in wetlands (from USGS lecture by Lisamartie Widham-Myers, June 30 2016)

Under certain conditions mercury is converted from a relatively inert form to a potentially more toxic and bioaccumulative form. A number of studies have identified wetlands as a sink for total mercury (THg) but a net source of MeHg (Driscoll et al. 1998, Grigal et al. 2000; Brahmstedt et al. 2019).

Brief Summary of Stressor Pair

The above example highlighted how the most common interaction between toxics and wetland loss is likely additive/synergistic, but it can also be antagonistic. Wetlands are a net source for MeHg and in some cases filling of coastal wetlands can cap toxics in industrial areas such as river mouths and harbors, an antagonistic interaction.

6.2.7 *Climate Change and Nutrients (Precipitation and Phosphorus)*

Harmful algae blooms, a widespread concern in the Great Lakes, are primarily driven by nutrient loadings. Given that this loading is a product of both river flow and concentrations in river water, climate change is predicted to have a significant impact on this loading, both recently and into the future (Stow et al. 2015). Given that the most dramatic climate alterations (e.g., increase in precipitation and runoff) will happen during periods characterized by intensive agricultural activities (e.g., tillage and application of fertilizer and manure in the spring), climate may play a significant role in increased nutrient loadings. Figure 17 shows a significant increase in extreme precipitation events from 1970 through 2010, closely matching an increase in overall dissolved reactive phosphorus loads to the Lake Erie watershed (see also Stow et al. 2015). The conclusion that climate change may intensify the negative impacts of eutrophication was also the finding of a national study of harmful algal blooms (Chapra et al. 2017).

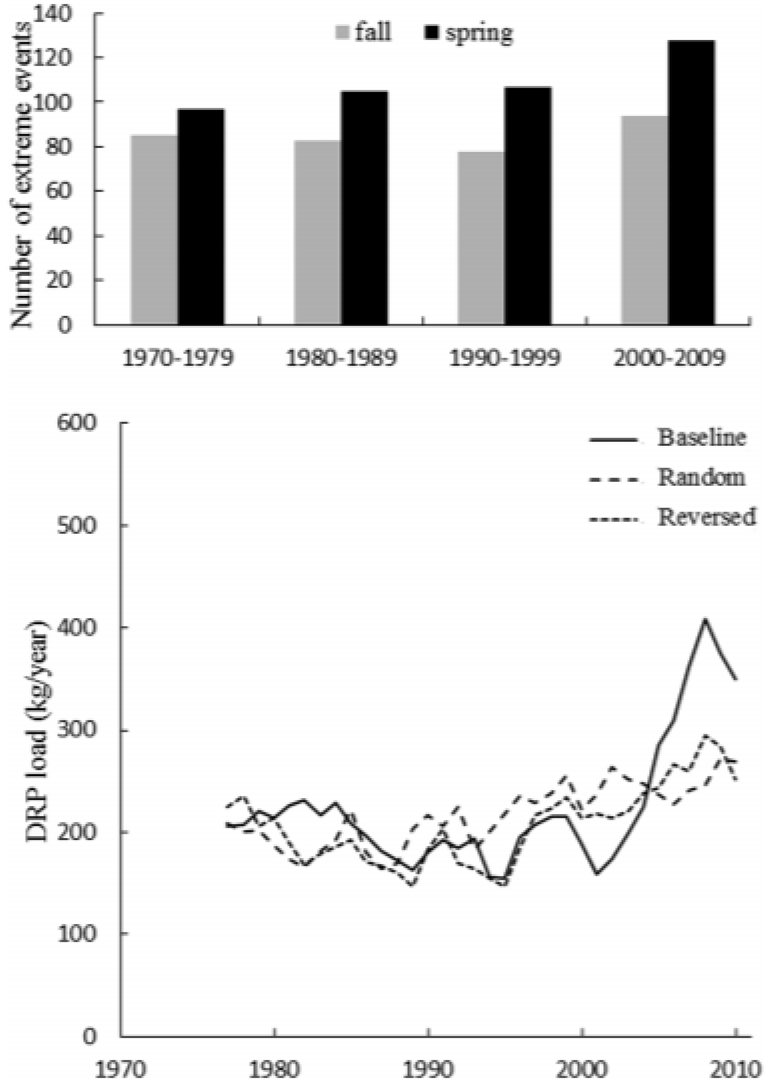


Figure 17. The upper panel shows the number of extreme weather events over four decades and the bottom shows three dissolve reactive phosphorus load scenarios in the same Lake Erie watershed (taken from Daloglu et al. 2012).

Brief Summary of Stressor Pair

In general, it is expected that wetter springs, greater nutrient loading, and warmer and longer summer seasons will favor more intense algal blooms, stratification and hypoxia. These are likely examples of a synergistic interaction, however antagonism is also plausible. For example, warmer winters could lead to less snowmelt and spring discharge, thereby reducing nutrient loads.

6.2.8 *Climate Change and Habitat Loss (Warming and Wetland Loss)*

As summer temperatures continue to warm and the length of the growing season and ice-free periods increases, conditions in wetlands may favor invasives such as *Phragmites* (Mazur et al. 2014), and further decrease the amount of coastal wetland area with native vegetation in the Great Lakes. Warming without corresponding increases in precipitation would decrease water levels, increase growing season, and potentially increase wetland area. The most opportunistic species, however, such as *Phragmites*, are likely to colonize bare sediment exposed during low water periods (lower edge) or shortly after high water periods (upper edge) more rapidly than native plants. This has been simulated for the St. Lawrence River wetlands (Tougas-Tellier et al. 2015) with potentially dire consequences for native wetlands. This also presents a challenge for wetland restoration,

The tolerance of *Phragmites* for harsher and more variable conditions than many native wetland plants gives them an advantage under climatic conditions that are more extreme in terms of temperature, hydroperiod, and other factors (Pagter et al. 2005). The loss of native wetland area by physical alteration places more remaining wetland closer to the limit of its viability. As environmental conditions become increasingly extreme due to climate change, coastal wetlands have less margin to respond to stresses. Coastal wetlands that may have become fragmented and isolated by alteration could become reconnected briefly by high or low water, or pumping and water diversion, allowing seeds and propagules of invasives to move to new areas while these climate-induced invasion pathways are open.

Brief Summary of Stressor Pair

In general, it is expected that climate change will further stress native wetlands in the Great Lakes that have already been reduced in area by human alteration and invasive species. More variable and extreme climate and water level conditions favor opportunistic invaders, which may be able to colonize new habitats during brief intervals of favorable and extreme conditions. Great Lakes coastal wetlands have become quite well monitored and the focus of extensive restoration efforts under the Great Lakes Restoration Initiative (https://greatlakeswetlands.org/Home.vbhtml).

6.2.9 *Nutrients and Habitat Loss (Phosphorus and Wetland Loss)*

A number of studies have shown that most wetlands retain sediment, nutrients, and toxic contaminants or transform the nutrients and toxins into less bioavailable or less harmful forms. In particular, wetlands have a high capacity to retain nutrients (e.g., phosphorus) helping to limit excessive P concentrations in surface waters (Zedler 2003; Dunne et al. 2015). A recent review by Currier et al (2017) examined the highly effective utilization of wetlands for phosphorus reduction in the Great Lakes. Phosphorus cycling in wetlands is complex and inorganic and organic P forms cycle through wetlands in different ways (Reddy and DeLaune 2008). Figure 18 shows key processes (abiotic and biotic) involved in the phosphorus cycle, including the incorporation of P into plant biomass, as well as sedimentation and accretion (Currie et al. 2017).

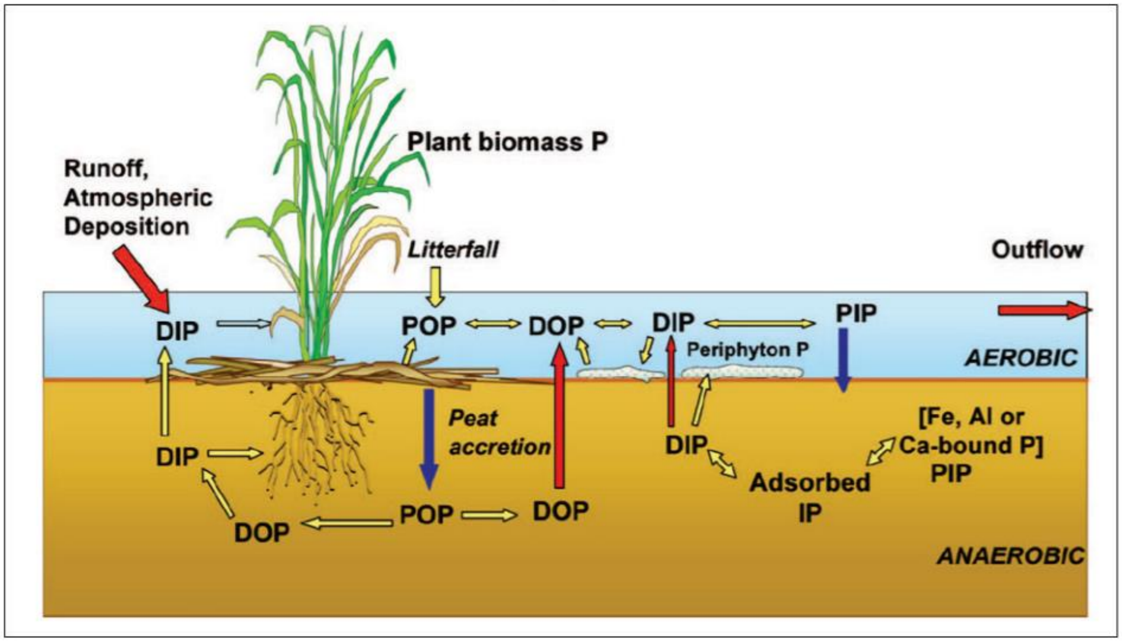


Figure 18. Phosphorus cycling in wetlands (taken from DeLuane and Reddy 2008). P = phosphorus, IP = inorganic phosphorus, DIP = dissolved inorganic phosphorus, DOP = dissolved organic phosphorus, PIP = particulate inorganic phosphorus, POP = particulate organic phosphorus.

Within Lake Erie, wetlands often act as partial sinks or transformers of nutrients and could be an important factor in mitigating eutrophication in the western basin of Lake Erie. However, the loss of wetlands mobilizes these nutrients back into the surface waters. Research has shown that creating or restoring wetlands can be an effective tool in minimizing nutrient inputs to the water body. A recent review by Lan et al. (2016) examining 203 freshwater wetlands found that on average, new and/or restored wetlands significantly reduced the transport of nutrients (total phosphorus and total nitrogen) and could be an effective tool in counteracting eutrophication. Although the effectiveness did vary depending on a number of variables such as wetland area, loading rates, and temperature among others.

Brief Summary of Stressor Pair

Wetlands can be highly effective at trapping excess nutrients and decreasing excessive loads to water bodies. However, reduction in wetlands can potentially lead to enhancement of harmful algal blooms and bottom hypoxia due to reduction in nutrient trapping. Studies on this stressor pair interaction in the Great Lakes remain limited, but it is anticipated that the relationship is synergistic, with wetland loss exacerbating the negative effects of excessive nutrient loads.

6.2.10 *Climate Change and Pathogens (Precipitation and Pathogens)*

There is a strong connection between rain events and the amount of pollutants entering the Great Lakes via tributary runoff and conveyance infrastructure (Patz et al. 2008). Urban stormwater and sewer overflows introduce significant contaminant loads each year and are considered major sources of impairment in the U.S. (Marsalek and Rochfort 2004). Many of these contaminants have been linked to adverse public health effects including exposure to fecal indicator bacteria (e.g., *E. coli*), pesticides, and viruses (Haile et al. 1999). Animal wastes from agricultural sources are another important source of pathogens in surface water. The impact of stressor interactions on human health was not a focus of this study, but the IJC Health Professionals Advisory Board commissioned a separate contractor study that examined this topic in more detail (LimnoTech 2019; see also McLellan et al. 2018). The fish pathogen, VHS, is discussed in Sections 6.1.6 and 6.2.6 above.

Elevated levels of bacteria are one of the most common causes of water quality impairments in the Great Lakes watersheds (USEPA 2004). This is because stormwater contaminated with sewage can increase the levels of presence of human bacteria and viruses in surface waters (Dila et al. 2018) and within the Great Lakes tributaries storms have been shown to increase pathogens by several orders of magnitude (Templar et al. 2016, McLellan et al. 2018).

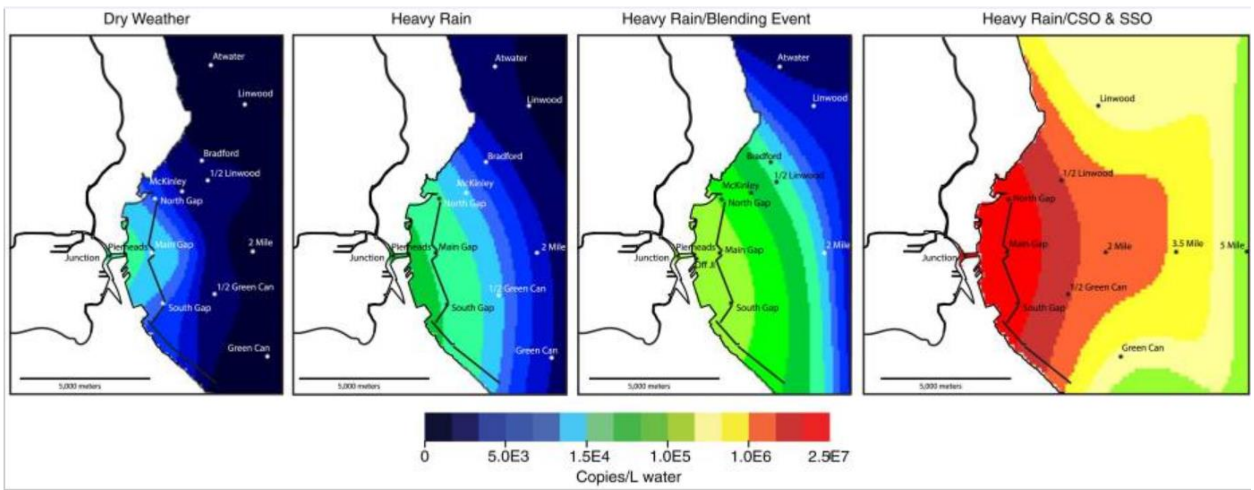


Figure 19. A map showing the transect from Milwaukee, WI, USA waterways into nearshore Lake Michigan. The colors represent changing signals of human fecal indicators during different weather periods (taken from Newton et al. 2013).

While many of these pathogens die or are heavily diluted by the time they reach the open waters of the Great Lakes, Newton et al. (2013) tracked the contamination up to 3 km offshore following heavy rains and up to 8 km offshore after a sewage overflows (Dila et al. 2018) (Figure 19). Increases in heavy rainfall, warmer lake water and lowered levels are all expected to contribute to increased contamination by overwhelming the combined sewer systems and increased storm runoff.

Brief Summary of Stressor Pair

In most cases it is expected that climate change induced impacts (e.g., increased rain events) will contribute to additional negative effects (e.g., increased pathogens). Whether this is an additive or synergistic interactions remains uncertain, as research specific to this stressor interaction is limited. While less common, antagonistic interactions are probable. For example, some pathogens do not survive at increased temperatures (e.g., VHS) and so climate induced warming could contribute to a decline in the negative consequences to fish.

6.2.11 *Invasives and Fish Harvest (VHS and Fish Harvest)*

Invasives can reduce native fish populations thereby further impacting fish harvest regulations. While lake trout have been historically subjected to overfishing, the invasive sea lamprey has also caused significant damage to this species (Elrod et al. 1995). While non-native lamprey impacts are among the best studied examples that impact Great Lakes fisheries, viral hemorrhagic septicemia (VHS) also presents an interesting case study. VHS was first diagnosed in the Great Lakes as a cause for fish kills in 2005, but has since been detected across all lakes. While a wide range of fishes have been impacted by VHS (Figure 20), the susceptibility varies across species. For example, Kim and Faisal (2010) found that, in general, cool-water fish species (e.g., muskellunge, largemouth bass, yellow perch) are likely more susceptible to the virus than are cold-water salmonids.

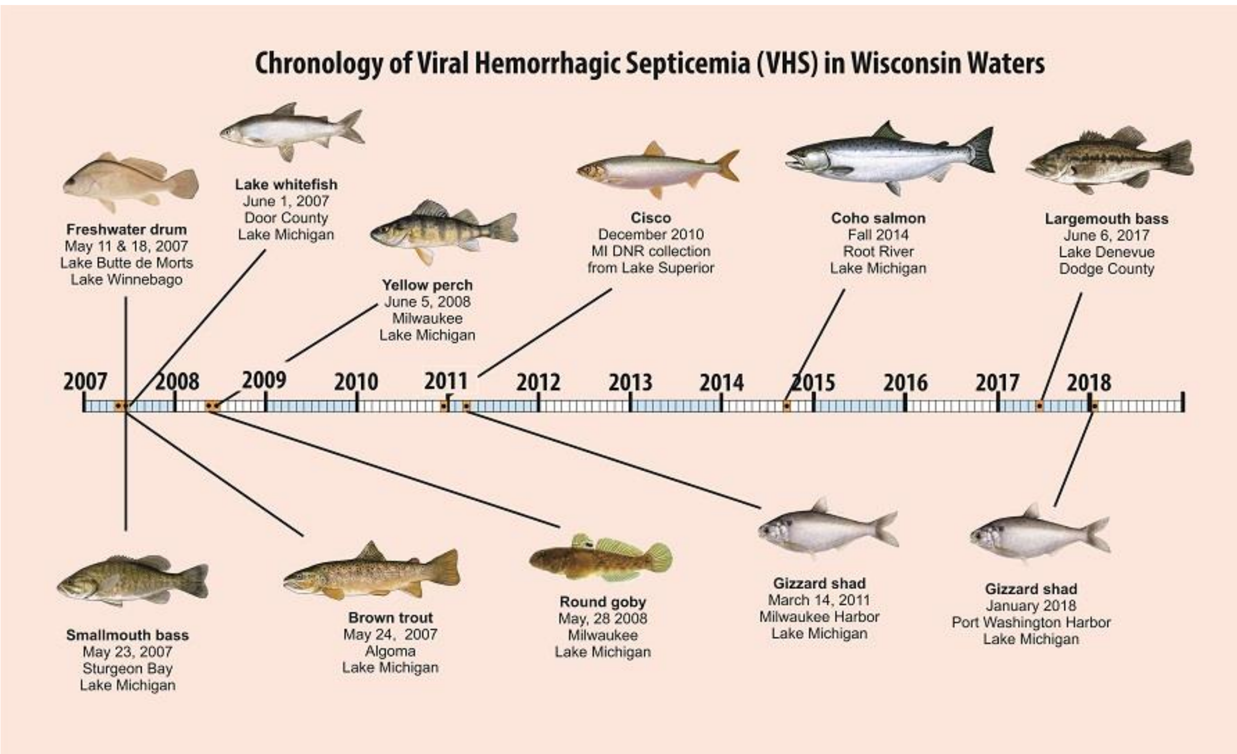


Figure 20. Timeline of VHS detected in multiple fishes in Wisconsin waters https://dnr.wi.gov

Muskellunge have historically been in decline within the Great Lakes, attributed to overharvest and environmental degradation (Farrell et al. 2007). While improved habitat and stricter regulations have improved muskellunge population health (Turnquist et al. 2017), exploitation can still be high in some populations. For example, Michigan DNR noted that there was a 36%

exploitation rate in Elk and Skegemog lakes (inland lakes in Michigan) over a one year period.

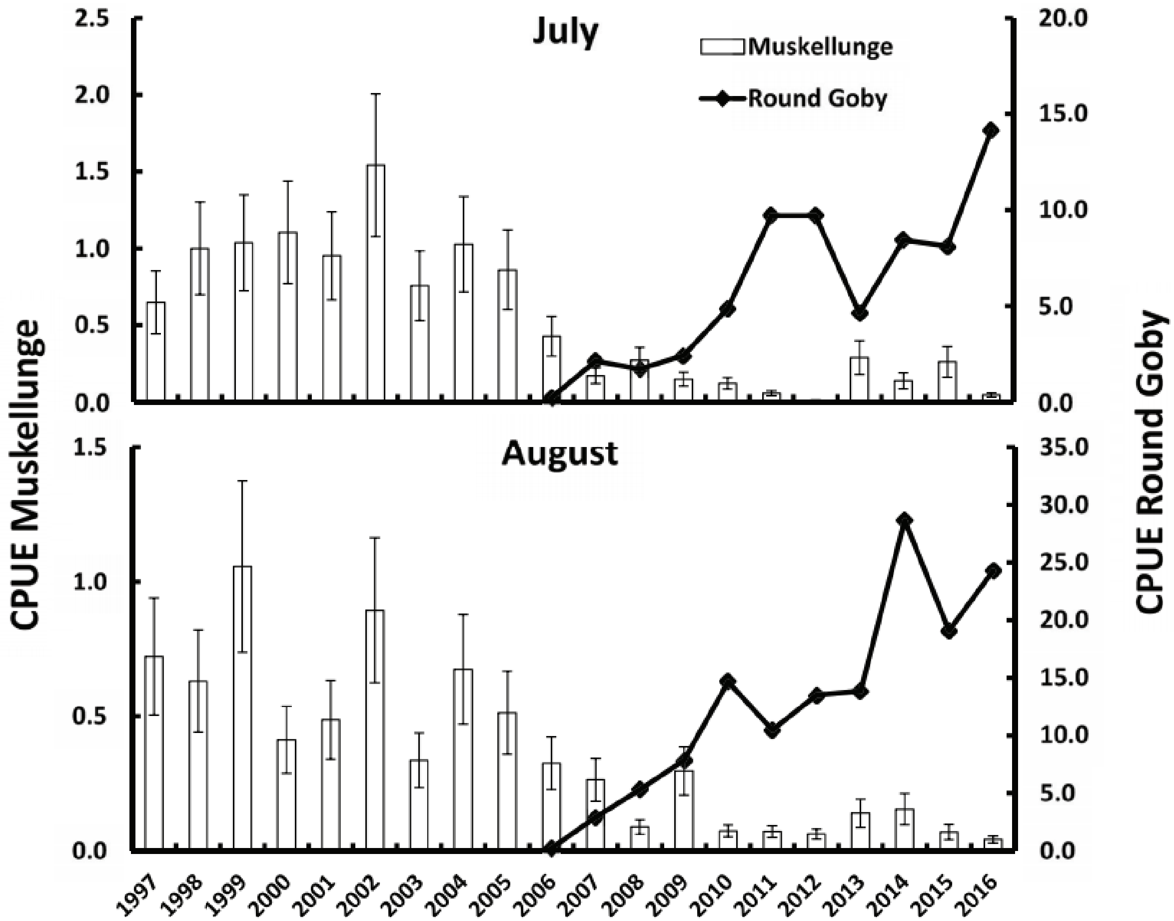


Figure 21. Catch per unit effort of Muskellunge over a 20-year period in the St. Lawrence River.

In the St. Lawrence River from 2005-2008, a significant die-off of muskellunge occurred concomitant with an outbreak of VHS. Interestingly, another invader, the round goby, also increased during this time period. Both perturbations have been strongly correlated with a significant decline in muskellunge population (Figure 21) (Farrell et al. 2017). Muskellunge are apex predators and a highly sought sports fish, subject to several stressors, and VHS likely exacerbates harm to this species via a synergistic interaction.

Brief Summary of Stressor Pair

Fish harvest can be impacted by a number of variables, including other stressors like invasives, climate and habitat loss. The above example highlighted a likely synergistic interaction but antagonistic interactions are also possible. For example, in some instances an invader can improve a local fishery or lead to a reduction in fishing pressure (e.g., zebra mussels leading to

HABs). Still, synergistic interactions or additive effects are the most likely when considering overfishing and other stressors.

7 INTEGRATION AND MANAGEMENT IMPLICATIONS

Here we attempt to integrate some of the information contained in the case studies above and to explore implications for management in light of insights gained about interactions. The discussion considers variability and trends in stressor pair interactions, science needs, management implications and actions, and policy priorities. Given the relatively small number of research studies on stressor interactions in the Great Lakes that have been conducted to date (Smith et al. 2019), this synthesis necessarily requires some extrapolation and hypothesizing beyond what is well constrained by the existing published literature.

7.1 Spatial and temporal variability in stressor pair interaction

When considering interactions of stressors, an important factor to evaluate is the variation in their occurrence that dictates (1) the possibility, and (2) the intensity of their interactions; spatial and temporal variability are both important. Although not well studied, it is expected that localized interactions follow the intensity of each individual stressor. The intensity of many stressors appears to drop off with distance from the shore and distance from urban areas (Allan et

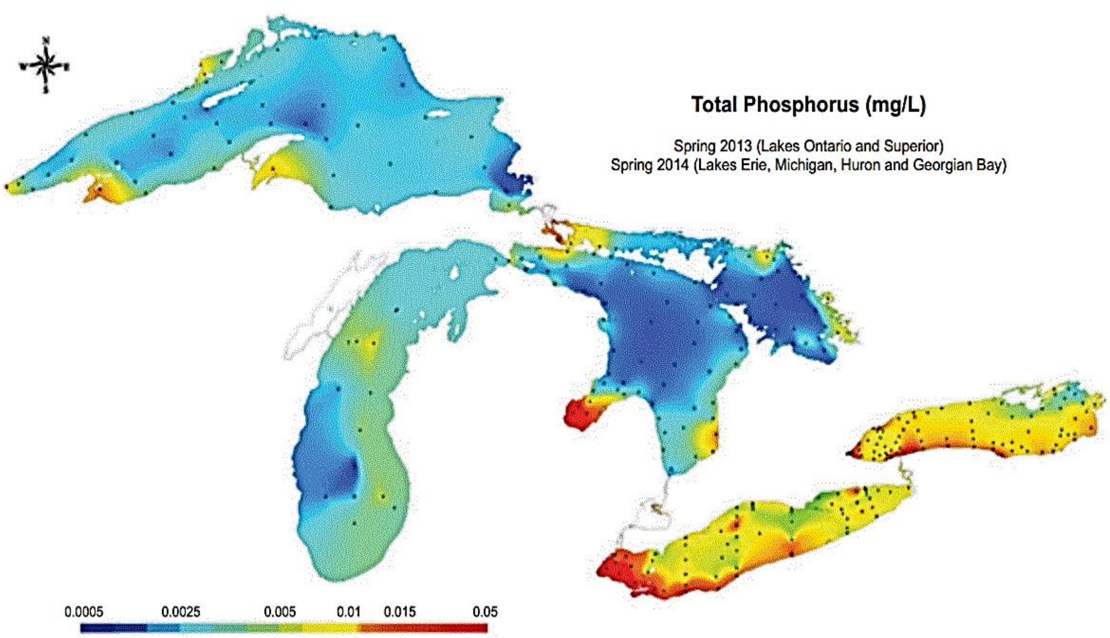


Figure 22. Spring total phosphorus concentrations for the Great Lakes, showing elevated areas in several embayments, including Saginaw Bay, as well as in western Lake Erie, and along northwestern and southern shorelines of Lake Ontario. Note that data for Green Bay are not collected or reported from these sources. Reproduced from ECCC and USEPA (2017), incorporating 2013 and 2014 data from ECCC (Dove and Howell) and USEPA (Osantowski).

al. 2013; Figure 22 and Figure 23), or distance from the mouths of larger tributaries (Robertson et al. 2018; Host et al. 2019). For example, increased precipitation leads to higher loadings of nutrients, pathogens, and toxics at outlets of agricultural and urban watersheds, and where urban storm drains and combined sewer outfalls occur. Further, most nonpoint-source loading occurs during large runoff events, which are more common during the spring and early summer.

Because individual stressors vary both temporally and spatially, their interactions will likely vary across both scales. It is reasonable to assume that many stressors would have the greatest opportunity to interact in nearshore areas and shallow embayments, such as Maumee Bay or Sandusky Bay in Lake Erie, with long water residence times and elevated summer temperatures (Verhamme et al. 2016; Salk et al. 2018). In addition, many stressor interactions, and potentially their impacts, could be seasonally amplified, whether by warm summer temperatures and lake stratification, by interaction with organisms during particular life cycle stages (e.g., nesting, spawning), or during vulnerable periods (e.g., end of winter, or during migration). Temporal coincidence of stressor occurrence and potential interactions could reasonably be expected to be greatest in spring and summer during periods of high river flow and high water temperature. The GLEAM additive stress map (Figure 23) shows the spatial intersection of multiple stressors (orange and red colors). The color scale is based on an assumption of additive interactions and normalized stressor values.

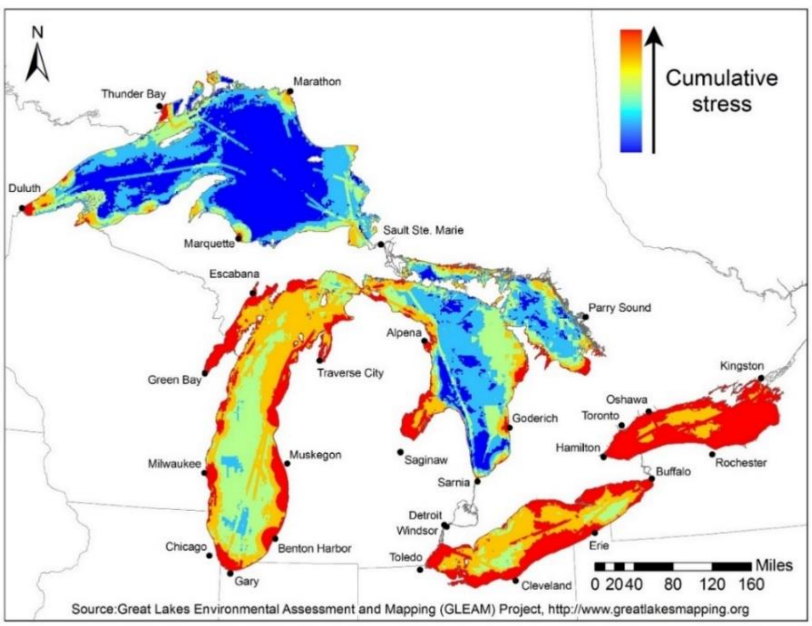


Figure 23. Cumulative stress map from multiple stressors.

Based on our understanding of the spatial variability of stressors within the Great Lakes region, Table 5 lays out ideas about where we would most expect each stressor pair to interact (or not interact), along with notes and related data sources or references. The interactions themselves could be in either direction. Note that research to demonstrate the reality or magnitude of these interaction hypotheses is lacking in most cases. Particular stressor pairs would be expected to interact differently in each lake, and the within-lake patterns would reflect the spatial complexity of driver distribution. For example, the nearshore–offshore trend applies to both Lake Erie and Lake Superior (Figure 23), but because additive stress is much greater in Erie and the lake itself is smaller, the gradient is less distinguishable. These proposed interaction patterns may merit further research.

Table 5. Hypothetical spatial variability of stressor pair interactions across the Great Lakes region.

Stressor Pair	Greatest Potential Spatial Interaction	Least Potential Spatial Interaction	Notes and References
Habitat Loss and Invasives	Near developed land and natural coastal wetland areas, especially near boat launches	Where natural climate, geomorphology, native plant allelopathy (e.g., *Typha*) or other conditions are unfavorable for colonization by invasives	Mazur et al. 2014, GLANSIS Information portal
Invasives and Climate Change	Connecting channels, river mouths, shallow bays and nearshore in lower lakes	Where annual variability is lowest and productivity is lowest (deep water, oligotrophic L. Superior and offshore waters of Michigan, Huron, E. Erie, Ontario)	Collingsworth et al. (2017); GLANSIS watch list
Invasives and Nutrients	Near ports in embayments and nearshore areas of lower lakes	Least direct effect in offshore areas and most of Lake Superior (but indirect effect of nearshore shunt), also see bloom impacts of recent extreme rainfall events in L. Superior; hypoxic area of L. Erie (no mussels)	Main effect is from dreissenid mussels, Rowe et al. (2015); Karatayev et al. (2017)
Toxics and Climate Change	Urban areas, ports, connecting channels, and tributaries	Least developed areas and in deep water, except where atmospheric sources exist (Hg)	This interaction is complex and dependent on which toxics are being considered, the biota involved, and the timescale of interest, as both

Stressor Pair	Greatest Potential Spatial Interaction	Least Potential Spatial Interaction	Notes and References
			positive and negative interactions exist
Toxics and Nutrients	AOCs and areas impacted by agricultural and urban runoff, and wastewater	Least developed areas with little input of toxics or nutrients (open Lake Superior and Lake Huron)	NOAA Mussel Watch Program (ftp://ftp.library.noaa.gov/noaa_documents.lib/NOS/NCCOS/TM_NOS_NCCOS/nos_nccos_180.pdf)
Toxics and Habitat Loss	AOCs and wetlands around shallow bays and connecting channels	Least developed lakeshore areas outside of embayments and river mouths, especially with forested watersheds	NOAA Restoration Center https://www.fisheries.noaa.gov/tags/great-lakes-restoration-initiative
Climate Change and Nutrients	Eutrophic embayments and basins impacted by agricultural runoff	Offshore and least developed lake areas (e.g., Lake Superior, although Superior is warming rapidly)	GLWQA Annex 4 and Domestic Action Plans https://binational.net/annexes/a4/
Climate Change and Habitat Loss	Urban areas and around river mouths with agricultural watersheds	Least developed nearshore lake areas with steep shorelines (i.e., least horizonatl variation in shoreline position and coastal habitat area with water level change, even with bluff or dune erosion)	Coastal Wetland Monitoring https://www.greatlakeswetlands.org/Home.vbhtml
Nutrients and Habitat Loss	Urban areas and around river mouths with agricultural watersheds	Oligotrophic lake basins and least developed nearshore lake areas	Cooper et al. (2016)
Climate Change and Pathogens	Urban areas and at river mouths of agricultural watersheds with large numbers of livestock	Undeveloped and offshore areas, especially in upper Great Lakes	IJC Centennial Study bacteria Work Group report (LimnoTech, 2019)

Stressor Pair	Greatest Potential Spatial Interaction	Least Potential Spatial Interaction	Notes and References
Fish Harvest and Invasives	Offshore areas of deeper lakes or basins (impacts on fish food supply) subject to commercial and charter boat harvest, vulnerable to nearshore nutrient shunt from mussels and offshore lamprey pressure	Remote nearshore areas where harvest is less intense and mostly recreational, total biomass is greater than offshore, and round gobies serve as prey fish but avoid nursery wetlands; nearshore fishery is overall more resilient	Managed by fish stocking, catch limits, and lampricide treatments in tributaries, Bunnell et al. 2014

7.2 Trends in priority stressors that may influence interactions

Changes over time have been observed in many Great Lakes stressors, which, in turn, would be expected to influence their interactions as well. Many stressors have been stabilized or put into a declining state by human actions. Examples of mostly stable, declining, or prevented stressors include several invasive species (e.g., lamprey, mussels, Asian carp); fish overharvesting; point source and particulate phosphorus nutrient loading (but not dissolved phosphorus); pathogens in treated wastewater, mitigated CSOs, and drinking water; wetland habitat destruction; and toxics in sediment and biota.

Stressors or undesirable conditions that may not fit the description of stable or declining include *Phragmites* occurrence, climate change, and dissolved phosphorus loading in some embayments, *Cladophora* areal coverage (maybe), and emerging contaminants. Many of the stressors that are stable or declining require continuing investment to maintain that status (e.g., lamprey control) or to prevent the appearance of new stressors (e.g., new invasives), including ongoing investment in monitoring programs and in enhancement of policy frameworks, development of effective regulations, and synchronization of regulations across state, provincial, and international boundaries.

Others stressors have declined but remain concerns, and full understanding of the rates and processes involved is lacking. This includes drivers of fish consumption advisories due to the presence of persistent organic pollutants (e.g., PCBs, PDBE, PFAS; Figure 24) as well as mercury. Visha et al. (2018b) assessed PCB trends in 11 species of Great Lakes fish and concluded that invasive mussels, round gobies, nutrient loading, and climate change may play important roles in PCB cycling trends.

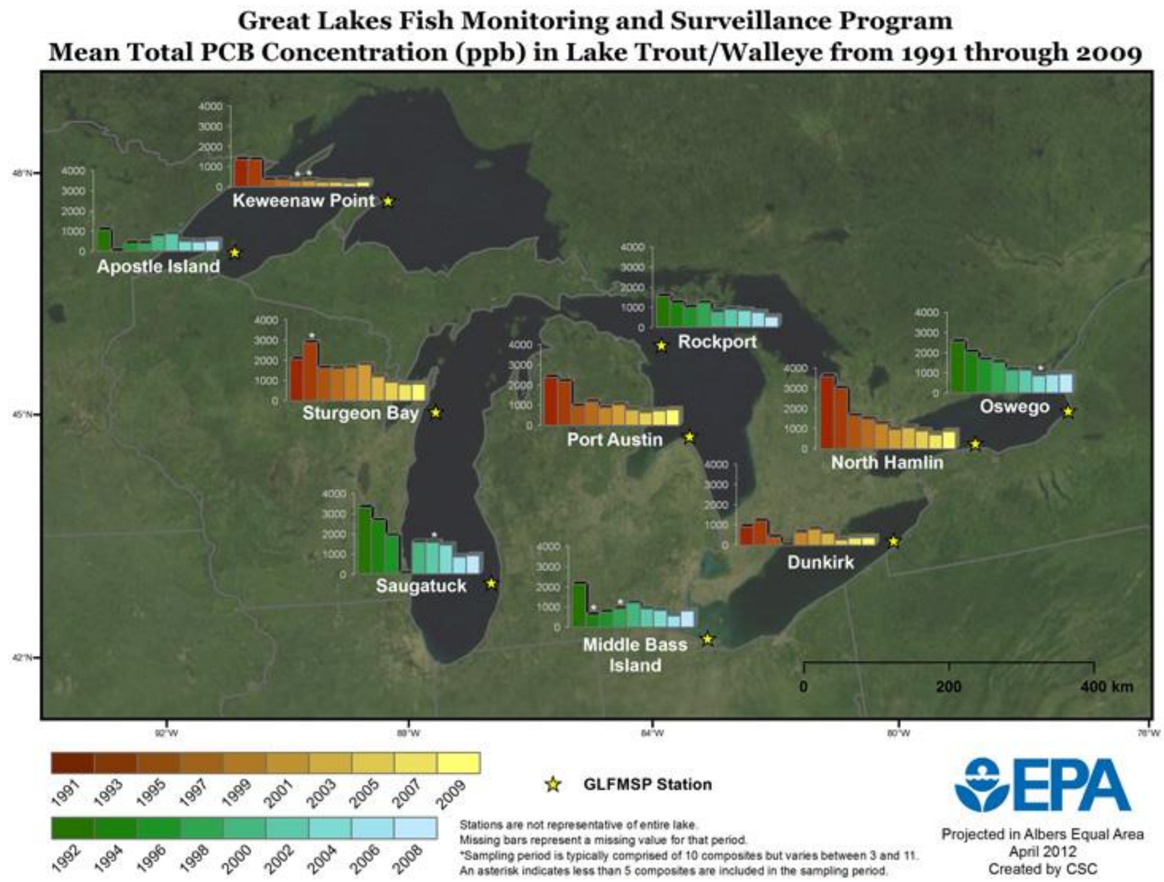


Figure 24. PCB trends in Great Lakes fish.

7.3 Management and policy implications of stressor interactions

Although generalizing about stressor interactions and management is challenging, there are still practical applications of the concept at finer levels of detail. Because of the relative paucity of data on stressor interactions in the Great Lakes and the scarcity of information regarding explicit management consideration of stressor interactions, it may be premature to quantitatively consider stressor interactions separately from management of individual stressors in achieving the broad goals of ecosystem protection and restoration. Most of the research described previously suggests that non-additive stressor interactions (synergistic or antagonistic) may be collectively more common than additive interactions. Therefore, there may be an advantage to treating stressors more holistically in many cases, even if the exact nature of their interactions is unclear.

Because of the co-occurrence of stressors in developed areas that also commonly host Areas of Concern, multiple stressors are already being managed simultaneously in these settings, and within a beneficial use or ecosystem services context that integrates stressors in terms of their ecosystem impacts. Multiple components of the Great Lakes fishery that interact are already carefully managed including lamprey control, fish stocking, and regulation of harvest seasons, species-specific fish quantity and size, and geographic location of harvest (e.g., Bunnell et al. 2014), with some explicit consideration of their interaction.

The stressor pair case studies examined in the project workshop provide informative tests of the application of stressor interaction to management approaches. The workshop group that discussed the nutrients-toxics pair highlighted a widely antagonistic interaction whereby increased nutrients can reduce contaminant concentrations in upper trophic levels due to higher growth rates of fish and biomass dilution of toxins. This demonstrated the importance of considering secondary impacts of management of a single tressor. The nutrients-invasives pair is one of the more thoroughly studied interactions in the Great Lakes. The associated workshop group highlighted the importance of spatial and temporal considerations when examining stressor interactions, which has obvious management impacts. The invasive-habitat loss pair group also discussed the importance of contextual considerations, whereby even when narrowed to two stressor categories – invasive species and stressors causing habitat degradation – there are many possible individual combinations. Further narrowing these stressors to consider wetland habitats affected by invasive plants and water level fluctuations reinforces the importance of spatial and temporal considerations of stressor interactions in management decisions, and the difficulty of generalizing about interactions across stressor subcategories and scales.

Although not developed extensively in the pairwise consideration of stressor interactions in this study, an argument in favor of intensified investment in research on stressor interactions, and on development of management approaches that explicitly consider interactions, is the recognition that ecosystem responses to both individual stressors and interacting stressors may be non-linear (e.g., Horan et al. 2011; http://www.tippingpointplanner.org/). That is, ecosystems can be pushed beyond tipping points, which are often not known in advance and even potentially unknowable or at least difficult to predict. Beyond the tipping points, decline may accelerate due to feedback loops and reversal may be substantially more difficult than prior to passing the tipping point, or even impossible, due to hysteresis effects (Bails et al. 2005).

The rate of ecosystem recovery as a result of restoration activities may also be non-linear in some cases, with potentially positive consequences (e.g., Olds et al. 2012). Recent attention in ecosystem management discussions has highlighted the goal of enhancing ecosystem resilience in light of ongoing threats from multiple stressors (Glick et al. 2011), and enhancing ecosystem services (Steinman et al. 2017). This approach does not ignore stressors, but considers them in light of an ecosystem's ability to withstand them, with growing employment of an explicit learning framework required by active adaptive management (e.g., U.S. Action Plan for Lake Erie, https://www.epa.gov/sites/production/files/2018-03/documents/us_dap_final_march_1.pdf).

At this point in our understanding of stressor interactions in the Great Lakes, it is unclear whether traditional stressor-by-stressor management versus more holistic and complex management of stressors within an explicit interacting framework will be more beneficial. The underpinnings of the holistic approach, even if theoretically more desirable, are not currently adequate for practical implementation, so there may be no real choice available at present. This situation may shift in the future as the results of further related research become available.

7.4 Programmatic needs to support science priorities

In order to continue to improve understanding of the status of Great Lakes ecosystem stressors and the processes that drive their interaction, it will be necessary to continue to monitor these systems closely and to perform research to understand system function. Continued support or expansion of associated laboratory and field experimentation, monitoring, data management, and modeling programs, including both conceptual and numerical modeling, are necessary to advance informed adaptive management of Great Lakes ecosystems in the face of multiple stressors. A variety of federal, Indigenous, state, provincial, academic, non-governmental, and other organizations perform this monitoring and research. These organizations need stable or increased funding to support their monitoring and research programs, including shore-based and vessel-based facilities, and the staff to carry out their work. Continued investment in training the next generation of Great Lakes field and laboratory scientists, engineers, and data managers is also essential. This may take the form of enhancement of existing strong programs and organizations, as well as development of new centers of excellence where emerging technologies can be adapted to Great Lakes applications (e.g., drones, autonomous underwater vehicles, and other new surveying platforms).

Some specific research questions and monitoring priorities identified in or derived from stressor pair case studies above (Section 6) include the following:

- What is the extent of dreissenid mussel and round goby colonization in the Great Lakes, how are these changing, and how important is mussel predation by gobies in their mutual occurrence and spread?
- What are the seasonal nutrient loads from major Great Lakes tributaries, how are they changing, and what are the most important factors driving the changes?
- How is removal or isolation of legacy toxics from Great Lakes sediments impacting benthic communities and the upper food web?
- Can climate change impacts on pollutant loading, invasive species colonization and range expansion, and coastal wetland habitat be predicted? How can future impacts be mitigated in ecosystem management?
- Is coastal wetland protection and restoration having quantifiable effects on related ecosystem health, including fish recruitment and wetland biodiversity?
- How can broader ecosystem understanding, including growing information on nutrient and toxics loading and cycling, be better incorporated into fishery management?
- How are human and fish pathogens influenced by other stressors including climate

change and nutrient loading?

Although active monitoring and research programs are addressing some of these questions, continued investment in two particular areas is a priority: (1) improved management and integration of data that efficiently and timely puts information on stressor and affected ecosystem status in forms that support management decisions, and (2) creation and maintenance of operational models that accurately simulate ecosystem processes and states under multiple interacting stressors, as well as likely or possible future stressor scenarios.

7.5 Management actions needed to mitigate impacts of priority stressor interactions in the Great Lakes

Management actions needed to mitigate impacts of priority stressor interactions in the Great Lakes include investments to prevent or rapidly respond to new occurrences of invasive species, continued programs to reduce sources of chemicals and remediate legacy toxins, sustained and targeted investment in non-point nutrient control, coastal habitat restoration, surveillance of fish and bird pathogens, and integrated management of fish stocking and harvest. Programs to address multiple stressors that occur in the same locations, such as remediation of Areas of Concern, are likely to reduce stressor interactions as well. This is particularly true when such areas (e.g., connecting channel reefs and islands) are also occupied during critical times, such as spawning periods for fish or nesting seasons for birds. Resources should be targeted toward interactions that are either best understood, most urgent to address, or most amenable to management. Adaptive management will require ongoing assessment of how understanding of stressor interactions has changed with additional research and practical knowledge gained from management actions that have produced unexpected results, either positive or negative.

7.6 Summary and discussion

This study finds evidence that multiple stressors often co-occur, and may interact in ways that can enhance or offset the impact of a primary stressor on valued components of the Great Lakes ecosystem. Cumulative stress is important, but is not easily determined due to the complexity of interactions when they occur, and the spatial and temporal variability in stressor co-occurrence. The potential for stressor interactions to influence ecosystem status merits consideration in research, monitoring, management, and policy decisions regarding the Great Lakes. However, this recommendation simply highlights the need for attention to this issue, and does not indicate a need for special programs or investments beyond the existing infrastructure, organizations, and governance systems that exist in the Great Lakes. Although existing reviews indicate that a majority of stressor interactions may be non-additive (see Figure 2 above), process understanding is insufficient in many cases to quantitatively inform management decisions or policies. Fishery management is among the most sophisticated spheres of human intervention in Great Lakes ecosystems, and it already incorporates some consideration of stressor interactions.

The most pervasive stressor that may merit more specific consideration in terms of its interaction with other stressors is climate change in all its manifestations: ice cover, warming, stratification, wind patterns, and precipitation locations and intensity. A special challenge here is that natural variability in the region is so great that climate change signals are difficult to extract from even fairly long-term datasets, and the resulting stressors are difficult to mitigate even where the trends can be extracted. Climate change is expected to manifest more strongly over time, which may increase the intensity of that signal in the future. Given the global nature of climate change drivers, regional management of climate change per se is not a viable option to ameliorate impacts in the region, despite the incremental value that actions to reduce regional contributions to global climate change may have. The best approach may be to explicitly consider how climate change may impact the natural variability in lake levels, storms, droughts, and heat waves over time, and to manage wherever possible with an eye toward enhancing resilience in the face of these stresses (e.g., Collingsworth et al. 2017).

8 FINDINGS, GAPS, AND RECOMMENDATIONS

Here we summarize the results of this study of the importance of stressor interactions in the Great Lakes.

Findings:

- Aquatic stressor interaction studies have yielded variable results that do not support generalization across ecosystems and geographies. For example, a recent review of stressor interactions within the Great Lakes showed that synergistic and antagonistic interactions were dominant whereas a large river multi-stressor study in European freshwater systems found two-thirds of the effects were additive (no interactive effects). All of these studies find some evidence of a greater impact when stressors co-occur, but vary as to whether the effective is additive, antagonistic, or synergistic. As a consequence, even if individual stressors can be measured, cumulative stress is difficult to assess.
- Priority interacting stressors in the Great Lakes region include the following: invasive species, toxic chemicals, excess nutrients, habitat loss, climate change, pathogens, and fish harvest. Although each of these categories can be further sub-divided, and the list is not exhaustive, these priority stressors provide a restricted subset for further consideration.
- Based on the above list of priority interacting stressors and considering feedback from experts on important potential interactions of these stressors, the following 11 stressor pairs were examined in detail:
    - invasives and climate change,
    - invasives and nutrients,
    - toxics and climate change,
    - toxics and nutrients,
    - toxics and habitat loss,
    - climate change and nutrients,
    - climate change and habitat loss,
    - nutrients and habitat loss,
    - climate change and pathogens,
    - fish harvest and invasives, and
    - invasives and habitat loss.
- The potential exists for the environmental consequences of one stressor to be modulated by the presence of a second stressor. For example dreissenid mussels can increase light penetration and trap nutrients in sediment, promoting *Cladophora* growth. Climate change can increase the intensity and frequency of rain events, and subsequently the amount of runoff leading to higher levels of nutrients and pathogens delivered from watershed.
- As part of the expert workshop three pairs were evaluated further (nutrients-toxics; nutrients-invasives; and invasives-habitat loss) to provide more informative tests of the application of stressor interaction to management approaches. These workshop case studies highlighted the

importance of considering spatial and temporal variability when evaluating the intensity of the interaction in the Great Lakes region. Because the majority of stressors originate on land where agricultural and urban activities are most pronounced, the intensity of many stressors is likely to be greatest in near-shore waters, and decrease with distance from shore.

- Other contextual considerations appear to be important. As for example, stressor frequency and duration as well as the sensitivity and vulnerability of the impacted resource value can vary with weather extremes, ecosystem conditions and drivers of human activity. In some cases the analysis of interactions may be required at a relatively fine spatial scale.
- Trends in stressor interactions are likely linked to trends in stressors themselves, as well as the intensity of their management through time. For example, loading from point sources of toxics and nutrients has been substantially reduced over time, and invasive lampreys are effectively managed with lampricide application and other measures. Climate change, emerging contaminants of concern, and many invasive species are not effectively managed.

Key Knowledge Gaps:

- Spatial resolution and temporal resolution of data on stressors often are insufficient to determine their status and trends, and their interactions, in order to facilitate informed management decisions. Important gaps identified by workshop participants include better data on nearshore nutrient cycling and speciation, abundance of invasive fish, seasonality of stressors, primary productivity and upper food web linkages, emerging and understudied contaminants, river plume dynamics, fish pathogens, fish toxins that drive consumption advisories, and response of ecosystems to management actions.
- Gaps in process understanding of stressor interactions are common. Robust studies of interactions are rare, and often limited to controlled laboratory settings or mesocosms and single species or life stages. These limitations can make it difficult to translate results to natural environments across a range of contextual considerations and meaningful management scales.

Recommendations:

- Although active monitoring and research programs are addressing some questions related to stressor intensity and interactions, continued investment in two particular areas is a priority: (1) improved management and integration of data that efficiently and timely puts information on stressor and affected ecosystem status in forms that support management decisions, and (2) creation and maintenance of operational models that accurately simulate ecosystem processes and states under multiple interacting stressors, as well as likely or possible future stressor scenarios. .
- Although process understanding of stressor interactions is relatively limited, continued investment in programs which manage multiple stressors within a system in a coordinated way will likely be more effective than programs managing individual stressors. Particular examples that address multiple stressors include Areas of Concern and fisheries management

programs. Within these programs, consideration of interactions may be important to incorporate as our understanding of stressors interactions improves.

- Great Lakes policies that regulate, support, and incentivize sustainable reduction of individual stressors, should be better integrated across jurisdictions to avoid gaps in mitigation and should target resources toward stressor interactions that are either best understood, most urgent to address, or most amenable to management.

9 REFERENCES

Allan, J.D., McIntyre, P.B., Smith, S.D.P., et al. 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. Proc Natl Acad Sci, 110, pp. 372–77.

Allan, J.D., Smith, S.D., McIntyre, P.B., Joseph, C.A., Dickinson, C.E., Marino, A.L., Biel, R.G., Olson, J.C., Doran, P.J., Rutherford, E.S. and Adkins, J.E., 2015. Using cultural ecosystem services to inform restoration priorities in the Laurentian Great Lakes. Frontiers in Ecology and the Environment, 13(8), pp. 418-424.

Allan, J.D., Manning, N.F., Smith, S.D., Dickinson, C.E., Joseph, C.A. and Pearsall, D.R., 2017. Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services. Journal of Great Lakes Research, 43(4), pp. 678-688.

Auer, M.T., Tomlinson, L.M., Higgins, S.N., Malkin, S.Y., Howell, E.T. and Bootsma, H.A., 2010. Great Lakes Cladophora in the 21st century: same algae—different ecosystem. Journal of Great Lakes Research, 36(2), pp. 248-255.

Bails, J., Beeton, A., Bulkley, J., DePhilip, M., Gannon, J., Murray, M., Regier, H., and Scavia, D. 2005. Prescription for Great Lakes ecosystem protection and restoration. http://miseagrant.umich.edu/downloads/habitat/Prescription-for-the-Great-Lakes-08-2006.pdf

Balbus, J.M., Boxall, A.B., Fenske, R.A., McKone, T.E. and Zeise, L., 2013. Implications of global climate change for the assessment and management of human health risks of chemicals in the natural environment. Environmental Toxicology and Chemistry, 32(1), pp. 62-78.

Barbiero, R.P., Lesht, B.M. and Warren, G.J., 2012. Convergence of trophic state and the lower food web in Lakes Huron, Michigan and Superior. Journal of Great Lakes Research, 38(2), pp. 368-380.

Berglund, O., Larsson, P., Ewald, G. and Okla, L., 2001. The effect of lake trophy on lipid content and PCB concentrations in planktonic food webs. Ecology, 82(4), pp. 1078-1088.

Birk S, Hering D. (eds) 2018. Managing Aquatic Ecosystems and Water Resources under Multiple Stress. Retrieved from: http://www.mars-project.eu/files/download/final_report/MARS_FinalReport_April2018.pdf

Brenden, T.O., Ebener, M.P., Sutton, T.M., Jones, M.L., Arts, M.T., Johnson, T.B., Koops, M.A., Wright, G.M. and Faisal, M., 2010. Assessing the health of lake whitefish populations in the Laurentian Great Lakes: lessons learned and research recommendations. Journal of Great Lakes Research, 36, pp. 135-139.

Borgå, K., Kidd, K.A., Muir, D.C., Berglund, O., Conder, J.M., Gobas, F.A., Kucklick, J., Malm, O. and Powell, D.E., 2012. Trophic magnification factors: considerations of ecology, ecosystems, and study design. Integrated Environmental Assessment and Management, 8(1), pp. 64-84.

Brahmstedt, E.S., Zhou, H., Eggleston, E.M., Holsen, T.M. and Twiss, M.R., 2019. Assessment of mercury mobilization potential in Upper St. Lawrence River riparian wetlands under new water level regulation management. Journal of Great Lakes Research, 45(4), pp. 735-741.

Bunnell, D.B., Barbiero, R.P., Ludsin, S.A., Madenjian, C.P., Warren, G.J., Dolan, D.M., Brenden, T.O., Briland, R., Gorman, O.T., He, J.X. and Johengen, T.H., 2013. Changing ecosystem dynamics in the Laurentian Great Lakes: bottom-up and top-down regulation. BioScience, 64(1), pp. 26-39.

Cha, Y., Stow, C.A., Nalepa, T.F. and Reckhow, K.H., 2011. Do invasive mussels restrict offshore phosphorus transport in Lake Huron? Environmental Science & Technology, 45(17), pp. 7226-7231.

Chapman, L.J., Chapman, C.A. and Chandler, M., 1996. Wetland ecotones as refugia for endangered fishes. Biological Conservation, 78(3), pp. 263-270.

Chapra, S.C., Boehlert, B., Fant, C., Bierman Jr, V.J., Henderson, J., Mills, D., Mas, D.M., Rennels, L., Jantarasami, L., Martinich, J. and Strzepek, K.M., 2017. Climate change impacts on harmful algal blooms in US freshwaters: a screening-level assessment. Environmental Science & Technology, 51(16), pp. 8933-8943.

Clayden, M.G., Kidd, K.A., Wyn, B., Kirk, J.L., Muir, D.C. and O'Driscoll, N.J., 2013. Mercury biomagnification through food webs is affected by physical and chemical characteristics of lakes. Environmental Science & Technology, 47(21), pp. 12047-12053.

Collingsworth, P.D., Bunnell, D.B., Murray, M.W., Kao, Y.C., Feiner, Z.S., Claramunt, R.M., Lofgren, B.M., Höök, T.O. and Ludsin, S.A., 2017. Climate change as a long-term stressor for the fisheries of the Laurentian Great Lakes of North America. Reviews in Fish Biology and Fisheries, 27(2), pp. 363-391.

Cooper, M.J., Ruetz III, C.R., Uzarski, D.G. and Burton, T.M., 2007. Distribution of round gobies in coastal areas of Lake Michigan: are wetlands resistant to invasion? Journal of Great Lakes Research, 33(2), pp. 303-313.

Cooper, M.J., Costello, G.M., Francoeur, S.N. and Lamberti, G.A., 2016. Nitrogen limitation of algal biofilms in coastal wetlands of Lakes Michigan and Huron. Freshwater Science, 35(1), pp. 25-40

Courtney, L.A. and Clements, W.H., 2000. Sensitivity to acidic pH in benthic invertebrate assemblages with different histories of exposure to metals. Journal of the North American Benthological Society, 19(1), pp. 112-127.

Côté, I.M., Darling, E.S. and Brown, C.J., 2016. Interactions among ecosystem stressors and their importance in conservation. Proceedings of the Royal Society B: Biological Sciences, 283(1824), p.20152592.

Crain, C.M., Kristy Kroeker, Benjamin S. Halpern. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecology Letters, 11(12), pp. 1304-1315. DOI: 10.1111/j.1461-0248.2008.01253

Corsi, S.R., Borchardt, M.A., Carvin, R.B., Burch, T.R., Spencer, S.K., Lutz, M.A., McDermott, C.M., Busse, K.M., Kleinheinz, G.T., Feng, X. and Zhu, J., 2015. Human and bovine viruses and bacteria at three Great Lakes beaches: Environmental variable associations and health risk. Environmental Science & Technology, 50(2), pp. 987-995.

Currie, S.J., VanZomeren, C.M. and Berkowitz, J.F., 2017. Utilizing wetlands for phosphorus reduction in great lakes watersheds: a review of available literature examining soil properties and phosphorus removal efficiency (No. ERDC/EL-SR-17-4). U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi, United States.

Danz, N.P., Niemi, G.J., Regal, R.R., Hollenhorst, T., Johnson, L.B., Hanowski, J.M., Axler, R.P., Ciborowski, J.J., Hrabik, T., Brady, V.J. and Kelly, J.R., 2007. Integrated measures of anthropogenic stress in the US Great Lakes basin. Environmental Management, 39(5), pp.631-647.

Darling, E.S. and Côté, I.M., 2008. Quantifying the evidence for ecological synergies. Ecology Letters, 11(12), pp. 1278-1286.

de Kerckhove, D.T., Minns, C.K. and Chu, C., 2015. Estimating fish exploitation and aquatic habitat loss across diffuse inland recreational fisheries. PloS One, 10(4), p.e0121895.

DeLaune, R.D. and Reddy, K.R., 2008. Biogeochemistry of wetlands: science and applications. CRC press.

Dila, D.K., Corsi, S.R., Lenaker, P.L., Baldwin, A.K., Bootsma, M.J. and McLellan, S.L., 2018. Patterns of host-associated fecal indicators driven by hydrology, precipitation, and land use attributes in Great Lakes watersheds. Environmental Science & Technology, 52(20), pp. 11500-11509.

Djuricich, P. and Janssen, J., 2001. Impact of round goby predation on zebra mussel size distribution at Calumet Harbor, Lake Michigan. Journal of Great Lakes Research, 27(3), pp. 312-318.

Driscoll, C.T., Holsapple, J., Schofield, C.L. and Munson, R., 1998. The chemistry and transport of mercury in a small wetland in the Adirondack region of New York, USA. Biogeochemistry, 40(2-3), pp. 137-146.

Dove, A. and Chapra, S.C., 2015. Long-term trends of nutrients and trophic response variables for the Great Lakes. Limnology & Oceanography, 60(2), pp. 696-721.

Dunne, E.J., Coveney, M.F., Hoge, V.R., Conrow, R., Naleway, R., Lowe, E.F., Battoe, L.E. and Wang, Y., 2015. Phosphorus removal performance of a large-scale constructed treatment wetland receiving eutrophic lake water. Ecological Engineering, 79, pp. 132-142.

Eaton, J.G. and Scheller, R.M., 1996. Effects of climate warming on fish thermal habitat in streams of the United States. Limnology & Oceanography, 41(5), pp. 1109-1115.

Ebener, M.P., Kinnunen, R.E., Schneeberger, P.J., Mohr, L.C., Hoyle, J.A. and Peeters, P., 2008. Management of commercial fisheries for lake whitefish in the Laurentian Great Lakes of North America. International governance of fisheries ecosystems: learning from the past, finding solutions for the future. American Fisheries Society, Bethesda, Maryland, pp. 99-143.

ECCC and USEPA (Environment and Climate Change Canada and the U.S. Environmental Protection Agency). 2017. State of the Great Lakes 2017 Technical Report. Cat No. En161- 3/1E-PDF. EPA 905-R-17-001. Available at binational.net

Elrod, J.H., O'Gorman, R., Schneider, C.P., Eckert, T.H., Schaner, T., Bowlby, J.N. and Schleen, L.P., 1995. Lake trout rehabilitation in Lake Ontario. Journal of Great Lakes Research, 21, pp. 83-107.

Elsayed, E., Faisal, M., Thomas, M., Whelan, G., Batts, W. and Winton, J., 2006. Isolation of viral haemorrhagic septicaemia virus from muskellunge, *Esox masquinongy* (Mitchill), in Lake St Clair, Michigan, USA reveals a new sublineage of the North American genotype. Journal of Fish Diseases, 29(10), pp. 611-619.

Environmental Law & Policy Center (ELPC). 2019. An Assessment of the Impacts of Climate Change on the Great Lakes. Chicago, IL. 71 pp. http://elpc.org/wp-content/uploads/2019/03/Great-Lakes-Climate-Change-Report.pdf

Farrell, J.M., Klindt, R.M., Casselman, J.M., LaPan, S.R., Werner, R.G. and Schiavone, A., 2007. Development, implementation, and evaluation of an international muskellunge management strategy for the upper St Lawrence River. Environmental Biology of Fishes, 79(1-2), pp.111-123.

Farrell, J.M., Getchell, G., Kapuscinski, K. and LaPan, S.R., 2017. Long-term trends of St. Lawrence River muskellunge: Effects of viral hemorrhagic septicemia and round goby proliferation creates uncertainty for population sustainability. In American Fisheries Society Symposium 85, pp. 275-301.

Foley, C.J., Andree, S.R., Pothoven, S.A., Nalepa, T.F. and Höök, T.O., 2017. Quantifying the predatory effect of round goby on Saginaw Bay dreissenids. Journal of Great Lakes Research, 43(1), pp. 121-131.

Folt, C.L., Chen, C.Y., Moore, M.V. and Burnaford, J., 1999. Synergism and antagonism among multiple stressors. Limnology & Oceanography, 44(3part2), pp. 864-877.

Gieswein, A., Hering, D. and Feld, C.K., 2017. Additive effects prevail: the response of biota to multiple stressors in an intensively monitored watershed. Science of the Total Environment, 593, pp. 27-35.

Gennings, C., Carter Jr, W.H., Carchman, R.A., Teuschler, L.K., Simmons, J.E. and Carney, E.W., 2005. A unifying concept for assessing toxicological interactions: changes in slope. Toxicological Sciences, 88(2), pp. 287-297.

Gandhi, N., Drouillard, K.G., Arhonditsis, G.B., Gewurtz, S.B. and Bhavsar, S.P., 2016. Are fish consumption advisories for the Great Lakes adequately protective against chemical mixtures? Environmental Health Perspectives, 125(4), pp. 586-593.

Gandhi, N., Gewurtz, S.B., Drouillard, K.G., Kolic, T., MacPherson, K., Reiner, E.J. and Bhavsar, S.P., 2017. Polybrominated diphenyl ethers (PBDEs) in Great Lakes fish: Levels, patterns, trends and implications for human exposure. Science of the Total Environment, 576, pp. 907-916.

Glick, P., J. Hoffman, M. Koslow, A. Kane, and D. Inkley. 2011. Restoring the Great Lakes' Coastal Future: Technical Guidance for the Design and Implementation of Climate-Smart Restoration Projects. National Wildlife Federation, Ann Arbor, MI, 66 pp. https://www.nwf.org/~/media/PDFs/Global-Warming/Climate-Smart-Conservation/NWF_Restoring_the_Great_Lakes_Coastal_Future_090211.ashx

Gouin, T., Armitage, J.M., Cousins, I.T., Muir, D.C., Ng, C.A., Reid, L. and Tao, S., 2013. Influence of global climate change on chemical fate and bioaccumulation: The role of multimedia models. Environmental Toxicology and Chemistry, 32(1), pp. 20-31.

Farrell, J.M., Klindt, R.M., Casselman, J.M., LaPan, S.R., Werner, R.G. and Schiavone, A., 2007. Development, implementation, and evaluation of an international muskellunge management strategy for the upper St Lawrence River. Environmental Biology of Fishes, 79(1-2), pp.111-123.

Farrell, J.M., Getchell, G., Kapuscinski, K. and LaPan, S.R., 2017. Long-term trends of St. Lawrence River muskellunge: Effects of viral hemorrhagic septicemia and round goby proliferation creates uncertainty for population sustainability. In American Fisheries Society Symposium 85, pp. 275-301.

Gregg, R. M., K. M. Feifel, J. M. Kershner, and J. L. Hitt. 2012. The State of Climate Change Adaptation in the Great Lakes Region. EcoAdapt, Bainbridge Island, WA.

Grigal, D.F., Kolka, R.K., Fleck, J.A. and Nater, E.A., 2000. Mercury budget of an upland-peatland watershed. Biogeochemistry, 50(1), pp. 95-109.

Guildford, S.J., Muir, D.C.G., Houde, M., Evans, M.S., Kidd, K.A., Whittle, D.M., Drouillard, K., Wang, X., Anderson, M.R., Bronte, C.R. and Devault, D.S., 2008. PCB concentrations in lake trout (*Salvelinus namaycush*) are correlated to habitat use and lake characteristics. Environmental Science & Technology, 42(22), pp. 8239-8244.

Gunderson, A.R., Armstrong, E.J. and Stillman, J.H., 2016. Multiple stressors in a changing world: the need for an improved perspective on physiological responses to the dynamic marine environment. Annual review of marine science, 8, pp. 357-378.

Haile, R.W., Witte, J.S., Gold, M., Cressey, R., McGee, C., Millikan, R.C., Glasser, A., Harawa, N., Ervin, C., Harmon, P. and Harper, J., 1999. The health effects of swimming in ocean water contaminated by storm drain runoff. Epidemiology, pp. 355-363.

Hansen, M.J., Madenjian, C.P., Slade, J.W., Steeves, T.B., Almeida, P.R. and Quintella, B.R., 2016. Population ecology of the sea lamprey (Petromyzon marinus) as an invasive species in the Laurentian Great Lakes and an imperiled species in Europe. Reviews in fish biology and fisheries, 26(3), pp.509-535.

Hansen, M.J., Krueger, C.C., Muir, A.M., Klemetsen, A. and Power, M., 2019. Assessing the impact of charr research past, present, and future. Hydrobiologia, 840(1), pp. 1-10.

Haponski, A.E. and Stepien, C.A., 2016. Two decades of genetic consistency in a reproductive population in the face of exploitation: patterns of adult and larval walleye (*Sander vitreus*) from Lake Erie's Maumee River. Conservation Genetics, 17(6), pp. 1345-1362.

Hecky, R.E., Smith, R.E., Barton, D.R., Guildford, S.J., Taylor, W.D., Charlton, M.N. and Howell, T., 2004. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. Canadian Journal of Fisheries and Aquatic Sciences, 61(7), pp. 1285-1293.

Hering, D., et al. 2015. Managing aquatic ecosystems and water resources under multiple stress: An introduction to the MARS project. Science of the Total Environment, 503-504(2015), pp. 10–21.

Hites, R.A. and Holsen, T.M., 2019. Temporal trends of PCBs and DDTs in Great Lakes fish compared to those in air. Science of the Total Environment, 646, pp. 1413-1418.

Hooper, M.J., Ankley, G.T., Cristol, D.A., Maryoung, L.A., Noyes, P.D. and Pinkerton, K.E., 2013. Interactions between chemical and climate stressors: A role for mechanistic toxicology in assessing climate change risks. Environmental Toxicology and Chemistry, 32(1), pp. 32-48.

Horan, R.D., Fenichel, E.P., Drury, K.L. and Lodge, D.M., 2011. Managing ecological thresholds in coupled environmental–human systems. Proceedings of the National Academy of Sciences, 108(18), pp. 7333-7338.

Host, G.E., Kovalenko, K.E., Brown, T.N., Ciborowski, J.J. and Johnson, L.B., 2019. Risk-based classification and interactive map of watersheds contributing anthropogenic stress to Laurentian Great Lakes coastal ecosystems. Journal of Great Lakes Research, 45(3), pp. 609-618.

Howell, E.T., 2018. *Cladophora* (green algae) and dreissenid mussels over a nutrient loading gradient on the north shore of Lake Ontario. Journal of Great Lakes Research, 44(1), pp. 86-104.

Huff, A. and Thomas, A., 2014. Lake Superior climate change impacts and adaptation. Battelle. https://www.epa.gov/sites/production/files/2015-11/documents/lake-superior-climate-change-impacts-report-201401-139pp.pdf

Ishii, S., Nakamura, T., Ozawa, S., Kobayashi, A., Sano, D. and Okabe, S., 2014. Water quality monitoring and risk assessment by simultaneous multipathogen quantification. Environmental Science & Technology, 48(9), pp. 4744-4749.

Jackson, M.C., Charlie J. G. Loewen, Rolf D. Vinebrooke, Christian T. Chimimba. 2015. Net effects of multiple stressors in freshwater ecosystems: A meta-analysis. Global Change Biology DOI: 10.1111/gcb.13028

Johnston, J.M., Barber, M.C., Wolfe, K., Galvin, M., Cyterski, M. and Parmar, R., 2017. An integrated ecological modeling system for assessing impacts of multiple stressors on stream and riverine ecosystem services within river basins. Ecological Modelling, 354, pp. 104-114

Jude, D.J., Janssen, J., Hensler, S.R. and Mangan, M., 2006. Wetlands as refugia from invasion by round gobies. In, Annual Conference on Great Lakes Research (abs.) (Vol. 49), Windsor, Ontario, May 22 -26. International Association for Great Lakes Research.

Karatayev, A.Y., Burlakova, L.E., Mehler, K., Bocaniov, S.A., Collingsworth, P.D., Warren, G., Kraus, R.T. and Hinchey, E.K., 2018. Biomonitoring using invasive species in a large Lake: *Dreissena* distribution maps hypoxic zones. Journal of Great Lakes Research, 44(4), pp. 639-649.

Kidd, K.A., Paterson, M.J., Hesslein, R.H., Muir, D.C. and Hecky, R.E., 1999. Effects of northern pike (*Esox lucius*) additions on pollutant accumulation and food web structure, as determined by δ13 C and δ15 N, in a eutrophic and an oligotrophic lake. Canadian Journal of Fisheries and Aquatic Sciences, 56(11), pp. 2193-2202.

Kim, R. and Faisal, M., 2010. Comparative susceptibility of representative Great Lakes fish species to the North American viral hemorrhagic septicemia virus sublineage IVb. Diseases of Aquatic Organisms, 91(1), pp. 23-34.

Kramer, A.M., Annis, G., Wittmann, M.E., Chadderton, W.L., Rutherford, E.S., Lodge, D.M., Mason, L., Beletsky, D., Riseng, C. and Drake, J.M., 2017. Suitability of Laurentian Great Lakes for invasive species based on global species distribution models and local habitat. Ecosphere, 8(7), p.e01883.

Land, M., Granéli, W., Grimvall, A., Hoffmann, C.C., Mitsch, W.J., Tonderski, K.S. and Verhoeven, J.T., 2016. How effective are created or restored freshwater wetlands for nitrogen and phosphorus removal? A systematic review. Environmental Evidence, 5(1), p.9.

Larsson, P., Collvin, L., Okla, L. and Meyer, G., 1992. Lake productivity and water chemistry as governors of the uptake of persistent pollutants in fish. Environmental Science & Technology, 26(2), pp. 346-352.

Lavoie, R.A., Jardine, T.D., Chumchal, M.M., Kidd, K.A. and Campbell, L.M., 2013. Biomagnification of mercury in aquatic food webs: a worldwide meta-analysis. Environmental Science & Technology, 47(23), pp. 13385-13394.

Lederer, A.M., Janssen, J., Reed, T. and Wolf, A., 2008. Impacts of the introduced round goby (*Apollonia melanostoma*) on dreissenids (*Dreissena polymorpha* and *Dreissena bugensis*) and on macroinvertebrate community between 2003 and 2006 in the littoral zone of Green Bay, Lake Michigan. Journal of Great Lakes Research, 34(4), pp. 690-697.

Lenaker, P.L., Corsi, S.R., Borchardt, M.A., Spencer, S.K., Baldwin, A.K. and Lutz, M.A., 2017. Hydrologic, land cover, and seasonal patterns of waterborne pathogens in Great Lakes tributaries. Water Research, 113, pp. 11-21.

LimnoTech, 2019. The Great Lakes Water Quality Centennial Study: Final Report. Prepared for Health Professionals Advisory Board, International Joint Commission, under contract to U.S. Department of State, 118 pp.

Lynch, A.J., Taylor, W.W. and Smith, K.D., 2010. The influence of changing climate on the ecology and management of selected Laurentian Great Lakes fisheries. Journal of Fish Biology, 77(8), pp. 1764-1782.

Macdonald, R.W., Harner, T. and Fyfe, J., 2005. Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. Science of the Total Environment, 342(1-3), pp. 5-86.

Marsalek, J. and Rochfort, Q., 2004. Urban wet-weather flows: sources of fecal contamination impacting on recreational waters and threatening drinking-water sources. Journal of Toxicology and Environmental Health, Part A, 67(20-22), pp. 1765-1777.

Mason, L.A., Riseng, C.M., Gronewold, A.D., Rutherford, E.S., Wang, J., Clites, A., Smith, S.D. and McIntyre, P.B., 2016. Fine-scale spatial variation in ice cover and surface temperature trends across the surface of the Laurentian Great Lakes. Climatic Change, 138(1-2), pp. 71-83.

Mathai, P.P., Dunn, H.M., Magnone, P., Zhang, Q., Ishii, S., Chun, C.L. and Sadowsky, M.J., 2019. Association between submerged aquatic vegetation and elevated levels of Escherichia coli and potential bacterial pathogens in freshwater lakes. Science of the Total Environment, 657, pp. 319-324.

Mazur, M.C., Kowalski, K.P. and Galbraith, D., 2014. Assessment of suitable habitat for *Phragmites australis* (common reed) in the Great Lakes coastal zone. Aquatic Invasions, 9(1), pp. 1-19.

McLellan, S.L., Sauer, E.P., Corsi, S.R., Bootsma, M.J., Boehm, A.B., Spencer, S.K. and Borchardt, M.A., 2018. Sewage loading and microbial risk in urban waters of the Great Lakes. Elementa (Washington, DC), 6.

Minns, C.K., 2014. Management of Great Lakes fisheries: Progressions and lessons. Aquatic Ecosystem Health & Management, 17(4), pp. 382-393.

Morrice, J.A., Danz, N.P., Regal, R.R., Kelly, J.R., Niemi, G.J., Reavie, E.D., Hollenhorst, T., Axler, R.P., Trebitz, A.S., Cotter, A.M. and Peterson, G.S., 2008. Human influences on water quality in Great Lakes coastal wetlands. Environmental Management, 41(3), pp.347-357.

Moy, P., G. Clark, D. Hart, D. Mickelson, A. Luloff, K. Angel, K. Barrett, C. Wu, and S. Boldt. 2010. Coastal Communities Working Group Report. Wisconsin Initiative on Climate Change Impacts.

Nadal, M., Marquès, M., Mari, M. and Domingo, J.L., 2015. Climate change and environmental concentrations of POPs: a review. Environmental Research, 143, pp. 177-185.

Naddafi, R. and Rudstam, L.G., 2014. Predation on invasive zebra mussel, *Dreissena polymorpha*, by pumpkinseed sunfish, rusty crayfish, and round goby. Hydrobiologia, 721(1), pp. 107-115.

Newton, R.J., Bootsma, M.J., Morrison, H.G., Sogin, M.L. and McLellan, S.L., 2013. A microbial signature approach to identify fecal pollution in the waters off an urbanized coast of Lake Michigan. Microbial Ecology, 65(4), pp. 1011-1023.

Ng, C.A. and Gray, K.A., 2011. Forecasting the effects of global change scenarios on bioaccumulation patterns in great lakes species. Global Change Biology, 17(2), pp. 720-733.

Noyes, P.D., McElwee, M.K., Miller, H.D., Clark, B.W., Van Tiem, L.A., Walcott, K.C., Erwin, K.N. and Levin, E.D., 2009. The toxicology of climate change: environmental contaminants in a warming world. Environment International, 35(6), pp. 971-986.

Olds, A.D., Pitt, K.A., Maxwell, P.S. and Connolly, R.M., 2012. Synergistic effects of reserves and connectivity on ecological resilience. Journal of Applied Ecology, 49(6), pp. 1195-1203.

Ontario Ministry of the Environment and Climate Change. 2015. 2015–2016 Guide to Eating Ontario Fish. Toronto, Ontario, Canada, 236 p. https://dr6j45jk9xcmk.cloudfront.net/documents/4460/fishguide2015-final-aoda-en-final.pdf

Ozersky, T., Malkin, S.Y., Barton, D.R. and Hecky, R.E., 2009. Dreissenid phosphorus excretion can sustain *C. glomerata* growth along a portion of Lake Ontario shoreline. Journal of Great Lakes Research, 35(3), pp. 321-328.

Pagnucco, K.S., Maynard, G.A., Fera, S.A., Yan, N.D., Nalepa, T.F. and Ricciardi, A., 2015. The future of species invasions in the Great Lakes-St. Lawrence River basin. Journal of Great Lakes Research, 41, pp.96-107.

Pagter, M., Bragato, C. and Brix, H., 2005. Tolerance and physiological responses of *Phragmites australis* to water deficit. Aquatic Botany, 81(4), pp. 285-299.

Patz, J.A., Vavrus, S.J., Uejio, C.K. and McLellan, S.L., 2008. Climate change and waterborne disease risk in the Great Lakes region of the US. American Journal of Preventive Medicine, 35(5), pp. 451-458.

Pearsall, D., P. Carton de Grammont, C. Cavalieri , C. Chu, P. Doran, L. Elbing, D. Ewert, K. Hall, M. Herbert, M. Khoury, D. Kraus, S. Mysorekar, J. Paskus and A. Sasson 2013. Returning to a healthy lake: Lake Erie biodiversity conservation strategy. Technical Report. A joint publication of The Nature Conservancy, Nature Conservancy of Canada, and Michigan Natural Features Inventory. 340 pp. with Appendices.

Pearsall, D.R., Khoury, M.L., Paskus, J., Kraus, D., Doran, P.J., Sowa, S.P., Taylor, R.F. and Elbing, L.K. 2013. "Make no little plans": Developing biodiversity conservation strategies for the Great Lakes. Environmental Practice: Environmental Reviews and Case Studies, 15(4), pp. 462-480.

Pickhardt, P.C., Folt, C.L., Chen, C.Y., Klaue, B. and Blum, J.D., 2002. Algal blooms reduce the uptake of toxic methylmercury in freshwater food webs. Proceedings of the National Academy of Sciences, 99(7), pp. 4419-4423.

Piggott, J.J., Colin R. Townsend, Christoph D. Matthaei. 2015. Reconceptualizing synergism and antagonism among multiple stressors. Ecology and Evolution, 5(7), pp. 1538-1547, DOI: 10.1002/ece3.1465.

Ray, W.J. and Corkum, L.D., 2001. Habitat and site affinity of the round goby. Journal of Great Lakes Research, 27(3), pp. 329-334.

Ricciardi, A. and MacIsaac, H.J., 2000. Recent mass invasion of the North American Great Lakes by Ponto–Caspian species. Trends in Ecology & Evolution, 15(2), pp. 62-65.

Ricciardi, A., 2006. Patterns of invasion in the Laurentian Great Lakes in relation to changes in vector activity. Diversity and Distributions, 12(4), pp. 425-433.

Robertson, D.M., Hubbard, L.E., Lorenz, D.L. and Sullivan, D.J., 2018. A surrogate regression approach for computing continuous loads for the tributary nutrient and sediment monitoring program on the Great Lakes. Journal of Great Lakes Research, 44(1), pp. 26-42.

Rowe, M.T. and Zanatta, D.T., 2015. Investigating the genetic variation and structure of a native unionid mussel in the Laurentian Great Lakes following an invasion of dreissenid mussels. Biological Invasions, 17(1), pp. 351-364.

Salk, K.R., Bullerjahn, G.S., McKay, R.M.L., Chaffin, J.D. and Ostrom, N.E., 2018. Nitrogen cycling in Sandusky Bay, Lake Erie: oscillations between strong and weak export and implications for harmful algal blooms. Biogeosciences, 15(9), pp. 2891-2907.

Selvendiran, P., Driscoll, C.T., Bushey, J.T. and Montesdeoca, M.R., 2008. Wetland influence on mercury fate and transport in a temperate forested watershed. Environmental Pollution, 154(1), pp. 46-55.

Schiedek, D., Sundelin, B., Readman, J.W. and Macdonald, R.W., 2007. Interactions between climate change and contaminants. Marine Pollution Bulletin, 54(12), pp. 1845-1856.

Shuchman, R. A., Bosse, K., Sayers, M. J., Fahnenstiel, G. L., & Leshkevich, G. (2017). Satellite observed water quality changes in the Laurentian Great Lakes due to invasive species, anthropogenic forcing, and climate change. 37th International Symposium on Remote Sensing of Environment, 42(3).

Smith, Sigrid D P, Peter B McIntyre, Benjamin S Halpern, Roger M Cooke, Adrienne L Marino, Gregory L Boyer, Andy Buchsbaum, G A Burton Jr, Linda M Campbell, and Jan J H Ciborowski. 2015. Rating impacts in a multi-stressor world: A quantitative assessment of 50 stressors affecting the Great Lakes. Ecological Applications 25 (3):717–28.

Smith, S.D., Bunnell, D.B., Burton Jr, G.A., Ciborowski, J.J., Davidson, A.D., Dickinson, C.E., Eaton, L.A., Esselman, P.C., Evans, M.A., Kashian, D.R. and Manning, N.F., 2019. Evidence for interactions among environmental stressors in the Laurentian Great Lakes. Ecological Indicators, 101, pp. 203-211.

Smith, D.R., King, K.W., Johnson, L., Francesconi, W., Richards, P., Baker, D. and Sharpley, A.N., 2015. Surface runoff and tile drainage transport of phosphorus in the midwestern United States. Journal of Environmental Quality, 44(2), pp. 495-502.

Smith, B.R., and J.J. Tibbles, 1980. Sea lamprey (*Petromyzon marinus*) in lakes Huron, Michigan, and Superior: history of invasion and control 1936-78. Canadian Journal of Fisheries and Aquatic Sciences, 37, pp. 1780-1801.

Steinman, A.D., Cardinale, B.J., Munns Jr, W.R., Ogdahl, M.E., Allan, J.D., Angadi, T., Bartlett, S., Brauman, K., Byappanahalli, M., Doss, M. and Dupont, D., 2017. Ecosystem services in the Great Lakes. Journal of Great Lakes Research, 43(3), pp. 161-168.

Sterner, R.W., Ostrom, P., Ostrom, N.E., Klump, J.V., Steinman, A.D., Dreelin, E.A., Vander Zanden, M.J. and Fisk, A.T., 2017. Grand challenges for research in the Laurentian Great Lakes. Limnology and Oceanography, 62(6), pp. 2510-2523.

Stow, C. and T. Hook (Editors) 2013. Saginaw Bay Multiple Stressors Summary Report. NOAA Technical Memorandum GLERL-160.

Stow, C.A., Cha, Y., Johnson, L.T., Confesor, R. and Richards, R.P., 2015. Long-term and seasonal trend decomposition of Maumee River nutrient inputs to western Lake Erie. Environmental Science & Technology, 49(6), pp. 3392-3400.

Stow, C.A., Dyble, J., Kashian, D.R., Johengen, T.H., Winslow, K.P., Peacor, S.D., Francoeur, S.N., Burtner, A.M., Palladino, D., Morehead, N. and Gossiaux, D., 2014. Phosphorus targets and eutrophication objectives in Saginaw Bay: A 35 year assessment. Journal of Great Lakes Research, 40(Supplement 1), pp. 4-10.

Sturtevant, R.A., Mason, D.M., Rutherford, E.S., Elgin, A., Lower, E. and Martinez, F., 2019. Recent history of nonindigenous species in the Laurentian Great Lakes; An update to Mills et al., 1993 (25 years later). Journal of Great Lakes Research, 45(6), pp. 1011-1035.

Sweka, J.A., Neuenhoff, R., Withers, J. and Davis, L., 2018. Application of a depletion-based stock reduction analysis (DB-SRA) to Lake Sturgeon in Lake Erie. Journal of Great Lakes Research, 44(2), pp. 311-318.

Templar, H.A., Dila, D.K., Bootsma, M.J., Corsi, S.R. and McLellan, S.L., 2016. Quantification of human-associated fecal indicators reveal sewage from urban watersheds as a source of pollution to Lake Michigan. Water Research, 100, pp. 556-567.

Tougas-Tellier, M.A., Morin, J., Hatin, D. and Lavoie, C., 2015. Freshwater wetlands: fertile grounds for the invasive *Phragmites australis* in a climate change context. Ecology and Evolution, 5(16), pp. 3421-3435.

Trebitz, A.S., Brazner, J.C., Pearson, M.S., Peterson, G.S., Tanner, D.K. and Taylor, D.L., 2009. Patterns in habitat and fish assemblages within Great Lakes coastal wetlands and implications for sampling design. Canadian Journal of Fisheries and Aquatic Sciences, 66(8), pp. 1343-1354.

Turnquist, K.N., Larson, W.A., Farrell, J.M., Hanchin, P.A., Kapuscinski, K.L., Miller, L.M., Scribner, K.T., Wilson, C.C. and Sloss, B.L., 2017. Genetic structure of muskellunge in the Great Lakes region and the effects of supplementation on genetic integrity of wild populations. Journal of Great Lakes Research, 43(6), pp. 1141-1152.

Thorp, J.H., Delong, M.D. and Casper, A.A.F., 1998. In situ experiments on predatory regulation of a bivalve mollusc (*Dreissena polymorpha*) in the Mississippi and Ohio Rivers. Freshwater Biology, 39(4), pp. 649-661.

USEPA. 2004. National Water Quality Inventory: Report to Congress 2004 Reporting Cycle. United States Environmental Protection Agency Office of Water Washington, DC 20460 EPA 841-R-08-001

Uzarski, D.G., Burton, T.M., Cooper, M.J., Ingram, J.W. and Timmermans, S.T., 2005. Fish habitat use within and across wetland classes in coastal wetlands of the five Great Lakes: development of a fish-based index of biotic integrity. Journal of Great Lakes Research, 31, pp. 171-187.

Vadeboncoeur, Y., McIntyre, P.B. and Vander Zanden, M.J., 2011. Borders of biodiversity: life at the edge of the world's large lakes. BioScience, 61(7), 526-537.

Vanderploeg, H.A., Liebig, J.R., Nalepa, T.F., Fahnenstiel, G.L. and Pothoven, S.A., 2010. Dreissena and the disappearance of the spring phytoplankton bloom in Lake Michigan. Journal of Great Lakes Research, 36, pp. 50-59.

Verhamme, E.M., Redder, T.M., Schlea, D.A., Grush, J., Bratton, J.F. and DePinto, J.V., 2016. Development of the Western Lake Erie Ecosystem Model (WLEEM): Application to connect phosphorus loads to cyanobacteria biomass. Journal of Great Lakes Research, 42(6), pp. 1193-1205.

Visha, A., Gandhi, N., Bhavsar, S.P. and Arhonditsis, G.B., 2018a. Assessing mercury contamination patterns of fish communities in the Laurentian Great Lakes: A Bayesian perspective. Environmental Pollution, 243, pp. 777-789.

Visha, A., Gandhi, N., Bhavsar, S.P. and Arhonditsis, G.B., 2018b. A Bayesian assessment of polychlorinated biphenyl contamination of fish communities in the Laurentian Great Lakes. Chemosphere, 210, pp. 1193-1206.

Walsh, M.G., Dittman, D.E. and O'Gorman, R., 2007. Occurrence and food habits of the round goby in the profundal zone of southwestern Lake Ontario. Journal of Great Lakes Research, 33(1), pp. 83-92.

Weis, J.S. and Weis, P., 2004. Metal uptake, transport and release by wetland plants: implications for phytoremediation and restoration. Environment International, 30(5), pp. 685-700.

Whitney, J.E., Al-Chokhachy, R., Bunnell, D.B., Caldwell, C.A., Cooke, S.J., Eliason, E.J., Rogers, M., Lynch, A.J. and Paukert, C.P., 2016. Physiological basis of climate change impacts on North American inland fishes. Fisheries, 41(7), pp. 332-345.

Wilson, K.A., Howell, E.T. and Jackson, D.A., 2006. Replacement of zebra mussels by quagga mussels in the Canadian nearshore of Lake Ontario: the importance of substrate, round goby abundance, and upwelling frequency. Journal of Great Lakes Research, 32(1), pp. 11-28.

Yediler, A. and Jacobs, J., 1995. Synergistic effects of temperature; oxygen and water flow on the accumulation and tissue distribution of mercury in carp (*Cyprinus carpio* L.). Chemosphere, 31(11-12), pp. 4437-4453.

Yurista, P.M., Vanderploeg, H.A., Liebig, J.R. and Cavaletto, J.F., 2010. Lake Michigan Bythotrephes prey consumption estimates for 1994–2003 using a temperature and size corrected bioenergetic model. Journal of Great Lakes Research, 36, pp. 74-82.

Zedler, J.B., 2003. Wetlands at your service: reducing impacts of agriculture at the watershed scale. Frontiers in Ecology and the Environment, 1(2), pp.65-72.

10 ATTACHMENT A

10.1 Workshop agenda

WORKSHOP AGENDA

Holiday Inn and Suites
1855 Huron Church Road
Windsor, Ontario, Canada

IJC Workshop – Evaluation of Stressor Interactions
April 9-10, 2019

Purpose:

- Confirm stressor pairs thought to be most important in the Great Lakes;
- Characterize their effects (i.e., additive, synergistic or antagonistic) and variability across the Great Lakes; and
- Assess the underlying data quality associated with priority stressor pairs.

Desired Outcomes:

- Make the case for the importance of stressor interactions as a means to better understand and address ecological challenges through science and management programs;
- Reveal data and knowledge gaps related to stressor interactions to be used by the SAB to develop recommendations for improved monitoring and surveillance, research, and management; and
- Facilitate the development of conceptual models and hypotheses that identify mechanistic

pathways to clarify how pairs of stressors may interact.

Tuesday, April 9

1:00 pm	Welcome and Introductions	David Burden, IJC GLRO Director Dave Allan, SAB Work Group Chair Workshop Participants
1:10 pm	Project Purpose and Background	Dave Allan
1:15 pm	Workshop Approach	Mike Donahue, AECOM
1:20 pm	Review of Progress to Date • Project background • Vocabulary • Literature review highlights • Preliminary list of stressor pairs	John Bratton, LimnoTech
1:50 pm	Panel Session: Perspectives on Stressor Interactions in the Great Lakes - Case Study Emphasis (8-10 minutes each) • Chemicals • Invasive Species • Nutrients • Habitat Loss • Climate	Moderator: Mike Donahue Mike Murray, Nat'l Wildlife Federation Bob Hecky, U of MN-Duluth Bob Sterner, U of MN-Duluth Lucinda Johnson, U of MN-Duluth Craig Stow, NOAA-GLERL
2:50 pm	Break	
3:05 pm	Charge to Breakout Groups	Mike Donahue
3:10 pm	Facilitated Small Group Discussions Each of three small groups will address the following: • Are the identified stressor pairs of greatest concern in the Great Lakes ecosystems and, if not, what other pairs should be considered? • For each pairing, are the effects additive, synergistic, antagonistic, or not yet known?	Each small group will have an assigned facilitator and recorder, and a volunteer reporter. Participants should review background material (see attached) for guidance.

4:10 pm	Plenary Session - Reporting Out and Discussion	Reporters from Small Group Workshop Participants
5:15 pm	Summary and Preview of Day 2	Mike Donahue, John Bratton
5:30 pm	Adjourn	
6:30 pm	Dinner at Rock Bottom Bar & Grill (offsite)	3236 Sandwich Street, Windsor

Day 2, Wednesday, April 10

Note - The Day 2 agenda was modified to build on Day 1 outcomes and to provide for development of findings and recommendations to the SAB and IJC. Participants self-selected one of three breakout groups, each focusing on a specific stressor pair and lake. Participants were encouraged to discuss their pairings at a basin-wide scale to the extent possible. If contextual considerations made generalizable discussion difficult, participants were directed to focus their analysis on the geographic scale noted. Case studies were drawn from workshop participant suggestions, with a focus on those where sufficient data and information exist to allow for development of meaningful management recommendations.

8:30 am	Day 1 Recap and Day 2 Focus	Mike Donahue
8:35 am	Review of Progress to Date (Part 2) • Spatial variability of stressor pairs • Underlying data quality, deficiencies, etc.	John Bratton
9:00 am	Charge to Breakout Groups	Mike Donahue and Facilitators
9:10 am	Facilitated Small Group Discussions	
	Group 1 Case Study: Interactions of Nutrient and Toxic Stressors in the Western Basin of Lake Erie	Matthew Child, Facilitator
	Group 2 Case Study: Interactions of Invasive Mussel and Nutrient Stressors in Lake Michigan	John Bratton, Facilitator
	Group 3 Case Study: Interactions of Invasives and Habitat Loss Stressors in the Lake Ontario Basin	Dave Allan, Facilitator
	Each Group will address the following: • Are the stressor interactions additive, synergistic, antagonistic, or unknown? • What are the key mechanisms of stressor pair interactions (narrative description)? • What are the contextual considerations (e.g., location, time of year, event frequency)? • What are the key management recommendations? • What are the key monitoring/surveillance and research needs?	
10:45 am	Break	
11:00 am	Plenary Session – Reporting Out and Open	Reporters and All
12:15 pm	Discussion	Participants
12:25 pm	Summary and Next Steps	Mike Donahue, John Bratton
12:30 pm	Closing Remarks	Dave Allan
	Adjourn	

10.2 Workshop attendees

Attendee	Organization	Breakout Groups (Day 1, Day 2)
David Allan	U. Michigan (Work Group Chair)	1, Invasives/Habitat
Tracie Baker	Wayne State U.	3, Toxics/Nutrients
Harvey Bootsma	U. Wisconsin - Milwaukee	3
Mary Anne Evans	USGS	3
Kurt Fausch	Colorado State U.	1
Lauren Fry	USACE	1
Bob Hecky	U. Minnesota - Duluth	2, Toxics/Nutrients
Tomas Höök	Purdue	1
John Jackson	Citizen activist	2, Toxics/Nutrients
Lucinda Johnson	U. Minnesota - Duluth	3, Habitat
Donna Kashian (Day 2)	Wayne State U.	NA, Toxics/Nutrients
Karen Kidd	McMaster U.	2, Toxics/Nutrients
Marten Koops	DFO-GLLFAS	3
Thomas Loch	Michigan State U.	1
Mike McKay	U. Windsor	2, Toxics/Nutrients
Carol Miller	Wayne State U.	2
Mike Murray	National Wildlife Federation	1, Toxics/Nutrients
Jeff Schaeffer	USGS	1
Christina Semeniuk	U. Windsor	3
Sigrid Smith	Delaware State U.	2
Bob Sterner	U. Minnesota - Duluth	2
Craig Stow	NOAA-GLERL	3, Toxics/Nutrients
Don Uzarski	Central Michigan U.	2
Matthew Child	IJC (SPC Secretary)	3, Toxics/Nutrients
David Burden	IJC (GLRO Director)	NA
Ryan Graydon	IJC (Sea Grant Fellow)	2, Nutrients/Mussels
John Bratton	LimnoTech (Contract Proj. Mgr.)	2, Nutrients/Mussels
Jennifer Daley	LimnoTech (Contract Scientist)	3, Toxics/Nutrients
Mike Donahue	AECOM (Contract Facilitator)	Circulator