# THE STATE OF LAKE MICHIGAN IN 2016

Great Lakes Fishery Commission

**SPECIAL PUBLICATION 2019-01**

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# THE STATE OF LAKE MICHIGAN IN 2016

**Edited by**

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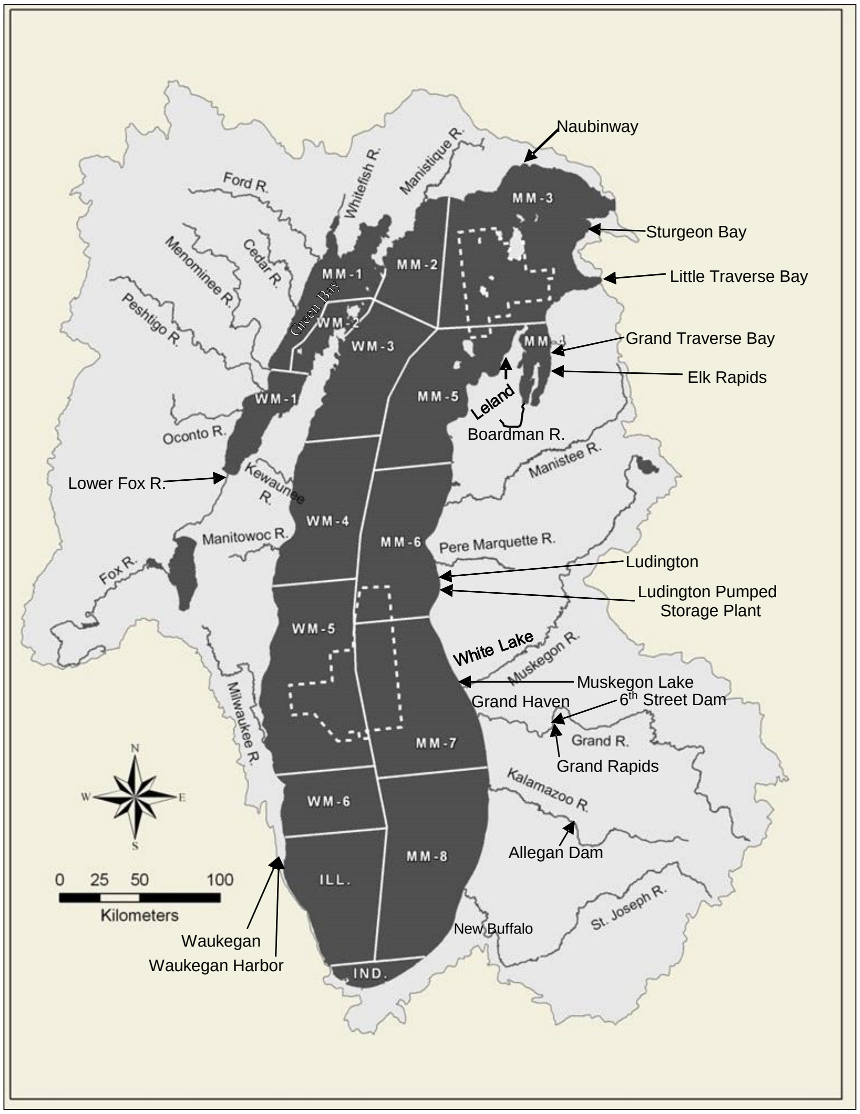
**Frontispiece**. Lake Michigan (dark gray) and its watershed (light gray) depicting statistical districts and locations in this publication. Areas within dashed lines represent the northern and mid-lake refuges for Lake Trout restoration.



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# ABSTRACT[2]

This fourth state of the lake report for Lake Michigan represents an assessment of progress made during 2011-2015 in meeting the fish community objectives (FCOs) established for the lake in 1995. A conference providing more-extensive data than given here was held in March 2016, and this document provides a summary of the presentations. Based on predator-prey modeling, mean lakewide total biomass of pelagic prey fish, including Alewife (*Alosa pseudoharengus*), Rainbow Smelt (*Osmerus mordax*), and Bloater (*Coregonus hoyi*), decreased by 33% between the 2005-2010 and the 2011-2015 periods whereas mean lakewide total biomass of Round Goby (*Neogobius melanostomus*), a non-indigenous benthic prey fish, increased by 8% between the two periods. Slimy Sculpin (*Cottus cognatus*) abundance dramatically declined during 2005-2015, and this decrease was most likely due to increased predation by an expanding population of juvenile Lake Trout (*Salvelinus namaycush*). In 2013, Chinook Salmon (*Oncorhynchus tshawytscha*) population biomass attained its highest level since stocking began in 1967. Chinook Salmon biomass declined substantially between 2013 and 2015. In contrast, Lake Trout biomass continued to increase during the reporting period. Natural reproduction by Lake Trout increased during 2005-2015, and the estimate of the percentage of wild fish in the Lake Trout population exceeded 10% in 2015. Mean annual total harvest of Yellow Perch (*Perca flavescens*) decreased by about 50% between the 2005-2010 and 2011-2015 periods. Adult Yellow Perch abundance during both of these periods has remained well

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[2]Complete publication including map of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp19_01.pdf.

below the peak levels observed in the late 1980s and early 1990s. Abundance of adult wild Lake Sturgeon (*Acipenser fulvescens*) did not change appreciably between the 2005-2010 and 2011-2015 periods. However, based on gillnet surveys along the eastern shore of Lake Michigan, catch-per-unit effort of juvenile Lake Sturgeon increased 10-fold from 2005-2006 to 2015 indicating that the size of the juvenile population has been increasing throughout the reporting period. Average annual commercial yield of Lake Whitefish (*Coregonus clupeaformis*) decreased 12% between the 2005-2010 and 2011-2015 periods. Growth of adult Lake Whitefish remained relatively low during the reporting period, due mostly to reduced *Diporeia* spp. abundance. Lake Whitefish recruitment was also low during 2011-2015, and this low recruitment may be linked to the quagga mussel (*Dreissena rostriformis bugensis*) population expansion. More research is needed to determine if quagga mussels are causing the reduced recruitment and, if so, to identify the underlying mechanisms. During 2011-2015, abundance and spatial distribution of Cisco (*Coregonus artedi*) appeared to expand in northern Lake Michigan, notably in Little Traverse Bay, Grand Traverse Bay, and near Ludington. In response to increased treatment efforts, adult Sea Lamprey (*Petromyzon marinus*) abundance declined during 2011-2015 and remained below the Lake Michigan Committee (LMC) target during 2013-2015 for the first time since 1995. Marking rates on Lake Trout remained slightly above the target level during 2011-2015, but Sea Lamprey-induced mortality rate for Lake Trout dropped below the target level in both the northern and southern sections of the lake in 2015. Progress on habitat and environmental objectives during the reporting period included: (1) development of tools to assess connectivity, (2) construction of a Lake Sturgeon passage facility on the Menominee River, (3) a spawning habitat enhancement project in Grand Traverse Bay for Cisco, Lake Trout, and

Lake Whitefish, and (4) remedial dredging in Waukegan Harbor to reduce environmental concentrations of polychlorinated biphenyls (PCBs). Emerging contaminants of concern included pharmaceutical and personal care products as well as per- and polyfluoroalkyl substances (PFAS). No new introductions of non-indigenous aquatic species were detected in Lake Michigan during 2011-2015. In 2016, the LMC proposed the following action items: (1) research and evaluate factors affecting Lake Whitefish growth and recruitment, (2) examine FCOs with respect to the changing food web of Lake Michigan, (3) develop a native planktivore management strategy for Lake Michigan, (4) balance predator- and prey-fish populations through stocking and harvest management strategies, and (5) support research to better estimate Round Goby biomass.

# INTRODUCTION TO THE STATE OF LAKE MICHIGAN IN 2016[3]

**Charles P. Madenjian[4], Jay K. Wesley, Bradley T. Eggold, Thomas K. Gorenflo, Jeremy Price, and Vic Santucci**

This state of Lake Michigan report provides an evaluation of progress, along with supporting information, toward the achievement of the fish community objectives (FCOs) for Lake Michigan (Eshenroder et al. 1995) during 2011-2015. A state of the lake (SOL) conference and reporting process was initiated by the 1998 revision of *A Joint Strategic Plan for the Management of Great Lakes Fisheries* (Joint Plan) (GLFC 2007).

Previous SOL reports for Lake Michigan were produced following conferences in 2000 (Holey and Trudeau 2005), 2005 (Clapp and Horns 2008), and 2011 (Bunnell 2012). Although the previous reports share a

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[3]Complete publication including map of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp19_01.pdf.

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common goal of evaluating progress toward achievement of the same FCOs, their format and organization differ. The chapters of the 2000 report were structured largely consistent with the themes of the FCOs (e.g., planktivores, salmonine community, Sea Lamprey), but the report also included chapters on lower trophic levels, physical- and chemical-habitat remediation, and fish health. In the 2005 report, the FCOs were covered in five chapters under the heading “Nearshore and Riverine Habitats and Fish Communities” and in seven chapters under the heading “The Salmonine Community and Its Forage Base.” The 2012 report had four chapters focused on the offshore salmonine food web, inshore and benthivore fish communities, Sea Lamprey, and habitat conditions in the Lake Michigan watershed.

The FCOs for this report are similarly integrated within an organization that recognizes the relationship between fish (see Table 1 for an alphabetical list of common fish names and their corresponding scientific names) and their major habitats in similar fashion to the 2012 report. One chapter covers pelagic fish and their prey and includes a brief characterization of lower trophic-level trends. A second chapter focuses on the nearshore and benthic communities in which key species are Yellow Perch, Lake Sturgeon, and Lake Whitefish. These chapters are followed by two shorter chapters on Sea Lamprey and habitat. Each chapter contains a discussion of pertinent FCOs. We have artificially separated the fish community from its habitat for the purposes of the report; we acknowledge that, in reality, these entities do not operate independently of one another and are affected by past and current changes to habitat and productivity, invasive non-indigenous species, and fisheries. This SOL report includes active participation by the Lake Michigan Committee (LMC) in writing the introduction and conclusions and in evaluating the FCOs just as the 2012 report did.

The LMC established FCOs in 1995 (Eshenroder et al. 1995) to provide a unified strategy for inter-jurisdictional fisheries management. These FCOs were derived, in part, from the Great Lakes Water Quality Agreement of 1978 (as amended 1987) and the Joint Plan (GLFC 1981). Eshenroder et al. (1995) describes two overarching goals and then a series of more-specific objectives that primarily address fish assemblages while providing measurable goals by which the productivity, health, and sustainability of a desired fishery can be assessed. Below we restate the overarching goals and specific FCOs and provide a brief commentary on each.

The two overarching goals are

> *To secure fish communities, based on foundations of stable, self-sustaining stocks, supplemented by judicious plantings of hatchery-reared fish, and provide from these communities an optimum contribution of fish, fishing opportunities and associated benefits to meet needs identified by society for: wholesome food, recreation, employment and income, and a healthy human environment.*
>
> *Restore and maintain the biological integrity of the fish community so that production of desirable fish is sustainable and ecologically efficient.*

The first goal relies heavily on self-sustaining fish populations supplemented by stocking of hatchery-reared salmonines and is influenced predominantly by management actions like stocking densities and fishery regulations. Managers continue to seek a balance between stocking levels and prey-fish production (as exemplified by a 25% reduction in Chinook Salmon stocking in 2006) such that societal benefits can be maximized. These efforts, however, continue to be in jeopardy owing to the lack of progress toward the second overarching goal. To introduce the potentially abstract concept of biological integrity, Eshenroder et al. (1995) relied on the description by Kay (1990), whereby an ecosystem with biological integrity is one that could "maintain its organization in the face of changing environmental conditions." Eshenroder et al. (1995) argued that Lake Michigan lost its integrity in the 1960s when the effects of the Sea Lamprey and Alewife invasions had decimated the fish community such that the top piscivore, Lake Trout, was extirpated, and diversity in prey fish was greatly diminished. By the 1980s, however, biological integrity had been substantially improved due to management efforts, including the control of Sea Lamprey and pollutants, the stocking of salmonines, and improved fishery regulations (Eshenroder et al. 1995). Lake Michigan in the 1980s included a diverse salmonine-dominated piscivore community, along with resurging native populations of Bloater, Lake Whitefish, and Burbot. In the 2000s, however, the biological integrity of Lake Michigan was further challenged by non-indigenous dreissenids (*Dreissena polymorpha* and *D. rostriformis bugensis*) and spiny water fleas (*Bythotrephes longimanus*) that proliferated after the late 1980s. These three invasive species have dramatically altered energy pathways through the aquatic ecosystem of Lake Michigan and are linked to declines in abundance of several groups of indigenous zooplankters and benthic macroinvertebrates (Barbiero et al. 2012; Bunnell et al. 2014, 2018; Madenjian et al. 2015a). In addition, these invasions are likely responsible for decreases in growth and condition of several species of fish in Lake Michigan (Madenjian et al. 2015b) and are suspected of causing reduced Lake Whitefish recruitment in Lake Huron (Gobin et al. 2015), which also may be occurring in Lake Michigan.

The salmonine objectives, which address the offshore pelagic fish (trout and salmon) community, are to

> *Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg (6 to 15 million lb), of which 20-25% is lake trout.*
>
> *Establish self-sustaining lake trout populations.*

The salmonine objectives are intended to maintain a diverse fishery for trout and salmon and to foster re-establishment of wild Lake Trout populations. Lake Trout, the purposefully introduced Chinook and Coho Salmon, Brown Trout, and Rainbow Trout serve as the primary piscivores in the Lake Michigan fish community. Lake Trout were extirpated from the lake by the 1950s due primarily to overfishing (Eshenroder and Amatangelo 2002) and Sea Lamprey predation, and the population continues to be sustained primarily through stocking (Hansen et al. 2013; Patterson et al. 2016).

The planktivore objective was designed to match prey production with predator demand in the offshore community and strives to

> *Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands.*

*Expectations are for a lakewide planktivore biomass of 0.5 to 0.8 billion kg (1.2 to 1.7 billion lb).*

Alewife continues to be the primary prey species consumed by piscivores, but high levels of thiaminase in Alewife and the ability of adult Alewife to consume native fish larvae may impede full achievement of the salmonine objectives (Madenjian et al. 2008; Riley et al. 2011). The planktivore prey-fish community also includes Bloater, Rainbow Smelt, Deepwater Sculpin, Slimy Sculpin, and Ninespine Stickleback. The invasive Round Goby was first documented in Lake Michigan in 1993, and, since then its abundance has increased and its distribution has expanded such that it is now considered an important component of the prey-fish community.

The objective for inshore fish addresses a portion of the fish community that has limited influence on salmonine predator-prey dynamics but that has historically supported important sport and commercial fisheries. The dynamics of the inshore fish community are less studied and, thus, less understood than the dynamics between salmonines and their prey. Based on harvest levels in the 1990s, the LMC sought to

*Maintain self-sustaining stocks of yellow perch, walleye, smallmouth bass, pike, catfish, and panfish. Expected annual yields should be 0.9 to 1.8 million kg (2 to 4 million lb) for yellow perch and 0.1 to 0.2 million kg (0.2 to 0.4 million lb) for walleye.*

Lake Whitefish provide the most-important commercial fishery and are a key component of the benthivore objective that seeks to

*Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. Expected annual yield of lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb).*

Re-establishment of self-sustaining Lake Sturgeon populations has been a high priority for the LMC, U.S. Fish and Wildlife Service (FWS), and numerous other organizations (Hay-Chmielewski and Whelan 1997; Elliott 2008; Welsh et al. 2010; Hayes and Caroffino 2012).

Non-indigenous species, such as the Sea Lamprey and dreissenids, have perturbed the fish community and impeded the achievement of several of the FCOs. Since the 1950s, state and tribal fishery-management agencies and the governments of the U.S. and Canada have considered control of Sea Lamprey a high priority, and considerable progress has been made in reducing Sea Lamprey populations throughout the Great Lakes (GLFC 2012). Given the ability of Sea Lamprey to induce substantial mortality on Lake Michigan fish, its predation continues to be an impediment to successful achievement of the salmonine objectives, in particular. The Sea Lamprey objective is less quantitative than the other FCOs, although its inclusion highlights its importance

> *Suppress the sea lamprey to allow the achievement of the other fish-community objectives.*

The other species objective includes fish that have a minimal role in the fishery but are important in maintaining ecosystem function and integrity. Most of these species are indigenous and often overlooked, except when complex food-web dynamics are evaluated. To elicit a stable system, governments should

> *Protect and sustain a diverse community of native fishes, including other species not specifically mentioned earlier (for example, cyprinids, gars (*Lepisosteidus *spp.), bowfin (*Amia calva*), brook trout and sculpins). These species contribute to the biological integrity of the fish community and should be recognized and protected for their ecological significance and cultural and economic values.*

The physical/chemical habitat objective is the most unique of the FCOs in that it addresses physical-habitat and abiotic (non-living) factors that influence achievement of other FCOs. The addition of this objective is a precursor to an acknowledgement that fish communities do not operate independently of their environment. To successfully achieve the other FCOs, two ideas were introduced

> *Protect and enhance fish habitat and rehabilitate degraded habitats.*

> *Achieve no net loss of the productive capacity of habitat supporting Lake Michigan's fish communities. High priority should be given to the restoration and enhancement of historic riverine spawning and nursery areas for anadromous species.*

More recently, the physical-habitat portion of this objective was elucidated with the identification of key habitat improvement and remediation projects in Rutherford et al. (2005).

This SOL report for Lake Michigan provides nominal background information and focuses on changes and progress toward meeting the FCOs during 2011-2015. Chapters were prepared by individuals with an intimate knowledge of assessment data, food-web dynamics, and management actions. Views presented in the chapters, excluding the last chapter, are those of the authors and not necessarily those of the LMC. For further information on historical trends or a broader background on the physical characteristics of Lake Michigan and its fish community, readers are encouraged to review the previous SOL reports for Lake Michigan (Holey and Trudeau 2005; Clapp and Horns 2008; Bunnell 2012).

Table 1. A list of common and scientific fish names used in this publication.

| Common Name | Scientific Name |
|---|---|
| Alewife | *Alosa pseudoharengus* |
| Bloater | *Coregonus hoyi* |
| Brook Trout | *Salvelinus fontinalis* |
| Brown Trout | *Salmo trutta* |
| Burbot | *Lota lota* |
| Chinook Salmon | *Oncorhynchus tshawytscha* |
| Cisco | *Coregonus artedi* |
| Coho Salmon | *Oncorhynchus kisutch* |
| Deepwater Sculpin | *Myoxocephalus thompsoni* |
| Lake Sturgeon | *Acipenser fulvescens* |
| Lake Trout | *Salvelinus namaycush* |
| Lake Whitefish | *Coregonus clupeaformis* |
| Muskellunge | *Esox masquinongy* |
| Northern Pike | *Esox lucius* |
| Ninespine Stickleback | *Pungitius pungitius* |
| Rainbow Smelt | *Osmerus mordax* |
| Rainbow Trout (Steelhead) | *Oncorhynchus mykiss* |
| Round Whitefish | *Prosopium cylindraceum* |
| Round Goby | *Neogobius melanostomus* |
| Salmon | *Oncorhynchus* spp. |
| Sculpins | *Cottidae* spp. |
| Sea Lamprey | *Petromyzon marinus* |
| Slimy Sculpin | *Cottus cognatus* |
| Smallmouth Bass | *Micropterus dolomieu* |
| suckers | *Catostomus* spp. |
| Walleye | *Sander vitreus* |
| Yellow Perch | *Perca flavescens* |

# STATE OF THE LAKE MICHIGAN PELAGIC FISH COMMUNITY IN 2016[5]

**Randall M. Claramunt[6], David M. Warner, Charles P. Madenjian, Matthew S. Kornis, Charles R. Bronte, and Nicholas D. Legler**

## Introduction

The fish community objectives (FCOs) for Lake Michigan seek to restore and maintain the biological integrity of the fish community so that production of desirable fish is sustainable and ecologically efficient (Eshenroder et al. 1995). The ecological efficiency of the Lake Michigan fish community is a function of how energy from pelagic and benthic invertebrates is transferred to planktivorous fish and the predators that consume them (Eshenroder et al. 1995). Fishery managers on Lake Michigan seek to maintain a diverse and balanced salmonine predator and planktivore community in the offshore pelagic zone so that predator demand does not exceed prey-fish production, which would erode the integrity and

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[5]Complete publication including map of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp19_01.pdf.

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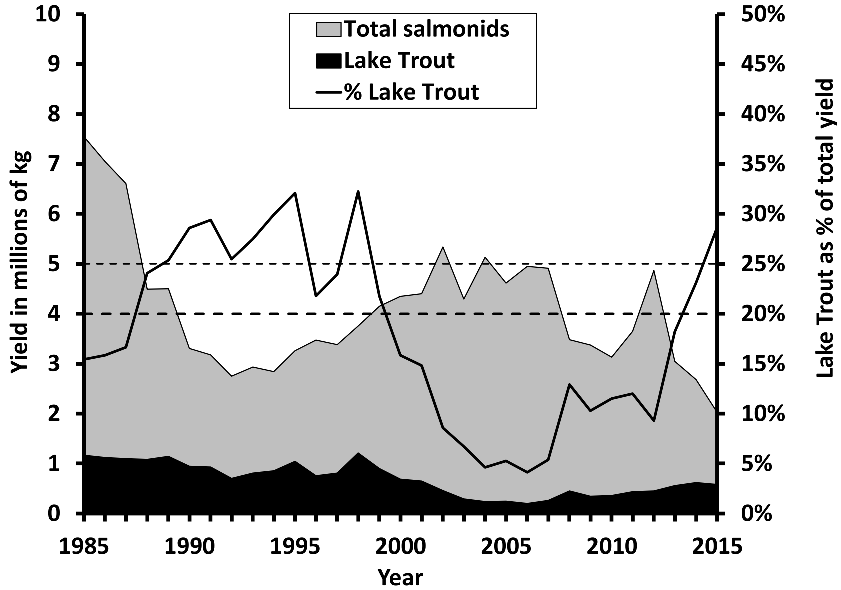
efficiency of the community. Thus, the salmonine and planktivore FCOs for Lake Michigan (Eshenroder et al. 1995) are intrinsically linked and seek to

> *Establish a diverse salmonine community capable of sustaining an annual harvest of 2.7 to 6.8 million kg (6 to 15 million lb), of which 20-25% is lake trout.*
>
> *Establish self-sustaining lake trout populations.*
>
> *Maintain a diversity of planktivore (prey) species at population levels matched to primary production and to predator demands. Expectations are for a lakewide planktivore biomass of 0.5 to 0.8 billion kg (1.2 to 1.7 billion lb).*

The salmonine objectives were only partially met during this (2011-2015) reporting period. Both the salmonine and prey-fish communities were diverse. Lake Trout yield increased over that of the previous reporting period (2005-2010) and exceeded the target yield (Fig. 1), but total salmonine harvest declined below FCO target levels and was only 2.1 million kg (Fig. 1). The ongoing changes in the pelagic zone represent a shift from a Chinook Salmon-Alewife dominated community to a mixed community with increasing importance of Lake Trout and a Lake Trout-Round Goby predator-prey component.

Fig. 1. Recreational- and commercial-fishery yield of salmonine predators (millions of kg) from Lake Michigan during 1985-2015. The dashed horizontal lines represent the target yield range for Lake Trout in kilograms (kg), and the solid line is the percent of the total yield comprising Lake Trout. The target percent for Lake Trout is 25%.

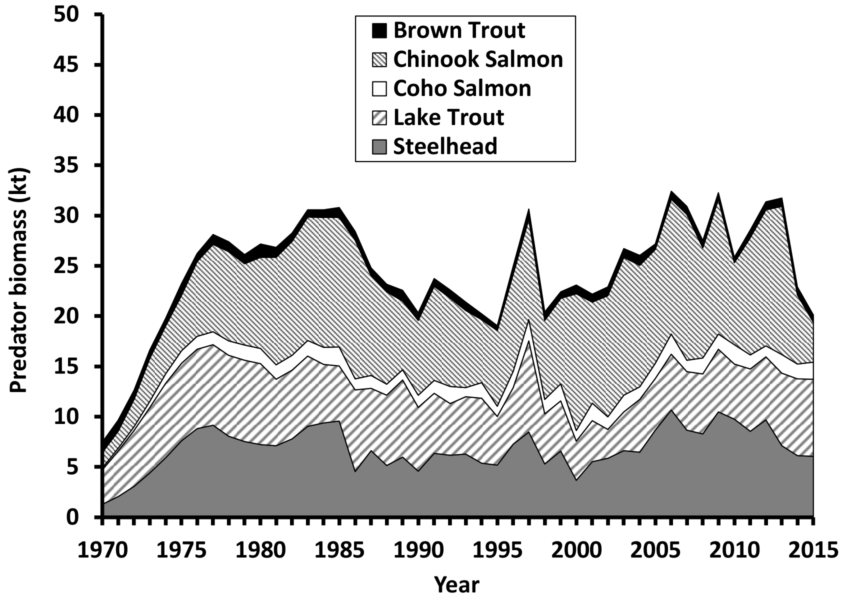



## Present Status

The salmonine community is composed of Chinook and Coho Salmon, Lake Trout, Rainbow Trout (Steelhead), and Brown Trout. Lake Trout is highlighted in the salmonine objective because it is indigenous and the focus of a five-decade-long interagency restoration effort (Holey et al. 2005; Bronte et al. 2008). The Salmonid Working Group (SWG) of the Lake Michigan Technical Committee, which reports to the Lake Michigan Committee (LMC), conducts an annual review of the salmonine community to evaluate the balance between predator demand and prey production and to monitor progress toward achieving the FCOs. Statistical catch-at-age analysis (SCAA) models are used to estimate annual abundance of each predator (Tsehaye et al. 2014a, b) and to assist in the review (Fig. 2).

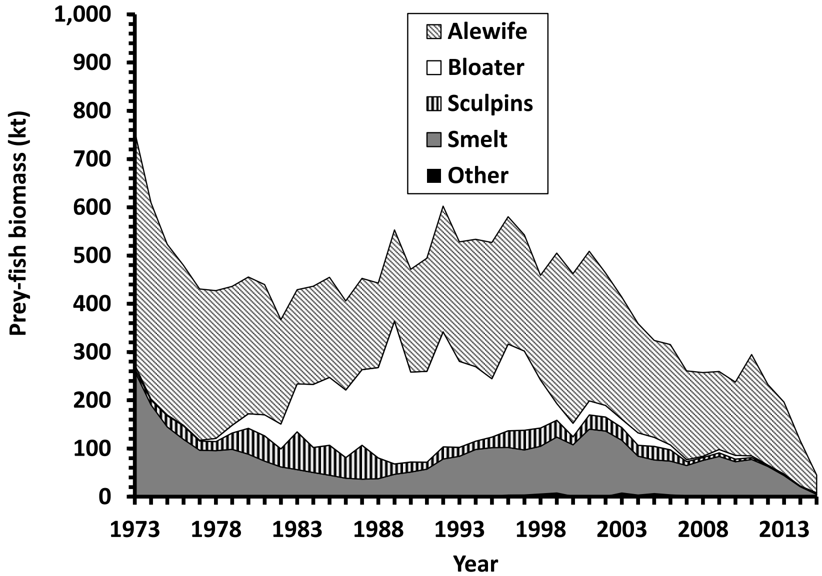
Total salmonine biomass decreased during 2011-2015 from the previous reporting period and was below the long-term average of 24.5 kt during 1970-2015 in both 2014 (22.9 kt) and 2015 (20.1 kt). Much of the decline in predator biomass during the reporting period was due to a decline in Chinook Salmon biomass from 11.6 kt in 2011 to less than 4.0 kt in 2015. The last time Chinook Salmon biomass in Lake Michigan was less than 4.0 kt was in 1972. Biomass of Rainbow Trout (Steelhead) declined from 8.5 kt in 2011 to 6.1 kt in 2015 whereas biomass of Coho Salmon (1.4 to 1.7 kt) and Brown Trout (~0.7 kt) were low but stable during 2011-2015. Lake Trout was the only predator during the reporting period to increase in biomass, which edged up from 6.2 kt (2011) to 7.7 kt (2015).

Fig. 2. Statistical catch-at-age analysis estimates of salmonine predator biomass in kilotonnes in Lake Michigan during 1970-2015.



Biomass of prey fish continued to decline during the reporting period to less than levels observed during all the previous reporting periods (Fig. 3). The average total prey-fish biomass declined by 36% from the previous (2005-2010) reporting period (275.9 kt) to the present (2011-2015) reporting period (177.0 kt).

Fig. 3. Estimated biomass in kilotonnes of prey fish other than Round Goby in Lake Michigan during 1973-2015. Alewife biomass was estimated using a statistical age-structured model that included bottom-trawl and acoustic survey data as well as estimates of predator consumption (Tsehaye et al. 2014b). Bottom-trawl surveys were the basis of all other prey-fish estimates (Bunnell et al. 2015).

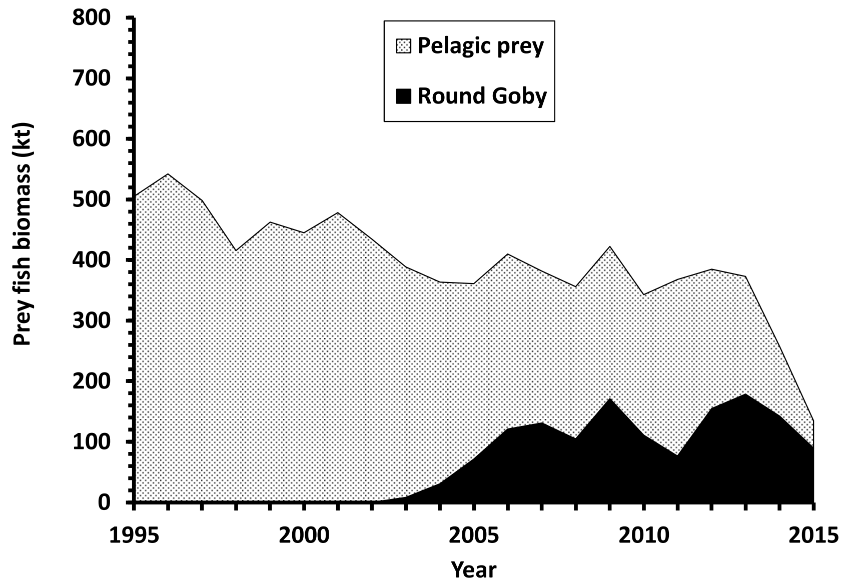


Biomass of Alewife was at an all-time low of only 36.8 kt in 2015 compared to 210.0 kt in 2011, and average biomass declined by 27% from the previous reporting period to the present reporting period. Biomass of Rainbow Smelt averaged 0.05 $kg \cdot ha^{-1}$ and 0.25 $kg \cdot ha^{-1}$ in the bottom-trawl and hydroacoustic surveys, respectively, during the reporting period, and average biomass declined by 42% from the previous reporting period. Bloater biomass averaged 0.5 $kg \cdot ha^{-1}$ and 1.8 $kg \cdot ha^{-1}$ in the bottom-trawl and hydroacoustic surveys, respectively, during the present reporting period, and average biomass declined by 79% from the previous reporting period. Biomass of Deepwater and Slimy Sculpin averaged 0.34 $kg \cdot ha^{-1}$ and 0.18 $kg \cdot ha^{-1}$, respectively, in the bottom-trawl survey during the reporting period, and total sculpin biomass declined by 86% from the previous reporting period.

Changes in the biomass of prey fish likely were due to numerous factors but mostly were due to salmonine predation (Madenjian et al. 2000, 2005b, 2015; Tsehaye et al. 2014a) and reductions in primary production in the pelagic zone due to an expanding abundance of dreissenid mussels (Yousef et al. 2014; Bunnell et al. 2018). The apparent decline in sculpin biomass during 2006-2015 likely was due in part to Deepwater Sculpin shifting its distribution to deeper depths not sampled by the bottom-trawl survey (Madenjian and Bunnell 2008; Madenjian et al. 2012). In addition, abundance of Slimy Sculpin, which is typically found at bottom depths of 50-100 m in Lake Michigan (Madenjian and Bunnell 2008), decreased during this same time period, most likely in response to increased predation by the expanding abundance of juvenile Lake Trout (Madenjian et al. 2005a, 2008, 2015a).

The invasive Round Goby has become a very-important prey for many predators in Lake Michigan (Hensler et al. 2008; Kornis et al. 2012; Happel et al. 2017), since first appearing in bottom-trawl surveys in 2003. Its distribution and abundance have increased since then and exhibit high inter-annual variability. Round Goby biomass increased to an average of 128.3 kt during this reporting period from 118.3 kt during the previous reporting period. Annual estimates of Round Goby biomass ranged from 76 to 178 kt during this reporting period and was similar to annual estimates of 71 to 170 kt during the previous reporting period (Fig. 4). Pelagic prey-fish biomass of Alewife, Rainbow Smelt, and Bloater declined from 260.7 kt during the previous reporting period to 175.1 kt during the current reporting period. Round Goby biomass was 90.0 kt compared to a pelagic prey-fish biomass of 44.6 kt in 2015.

Fig. 4. Biomass in kilotonnes of Round Goby and pelagic prey fish (Alewife, Bloater, and Rainbow Smelt) in Lake Michigan during 1995-2015. Round Goby biomass was estimated by subtracting the biomass of Alewife, Bloater, and sculpins consumed by salmonine predators from the total estimated biomass (Clark 2012; Clark et al. 2014). The approach assumes that Round Goby is the preferred alternative prey to pelagic prey fish (Huo et al. 2014).




### ***Predator-Prey Dynamics and Management***

Previous state of the lake reports recommended moving away from harvest-based management benchmarks for the salmonine FCO, which appeared to be unreachable, to focus more on predator-prey dynamics (Jonas et al. 2005;

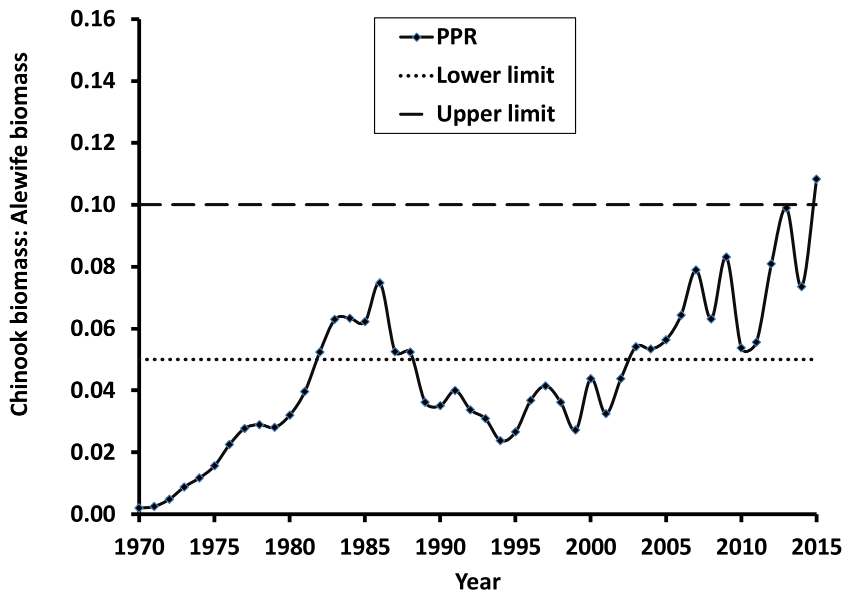
Bronte et al. 2008; Claramunt et al. 2008; Claramunt et al. 2012). Proliferation of dreissenids in combination with large declines in *Diporeia* spp. and prey-fish biomass (Bunnell et al. 2014, 2015) have affected the fish community (Claramunt et al. 2012; Nalepa et al. 2009; Barbiero et al. 2012). These "bottom-up effects" (Bunnell et al. 2014, 2018) have become increasingly influential in shaping predator-prey dynamics in the offshore pelagic zone and have increased their variability.

Total salmonine consumption of prey fish during this reporting period declined from the previous reporting period and was below the 1970-2015 average of 98.3 kt in both 2014 (84.2 kt) and in 2015 (77.8 kt). The decline in Chinook Salmon and Rainbow Trout (Steelhead) abundance during this reporting period (Fig. 2) reduced their prey-fish consumption by 71% and 30%, respectively. Consumption of prey by Coho Salmon declined 24% from 2011 to 2015. Brown Trout consumption of prey fish increased slightly from 2011 to 2015, and Lake Trout consumption of prey fish increased 55% from 2011 to 2015, reflecting an abundance increase in Lake Trout during the reporting period.

Fishery managers reduced stocking levels of Chinook Salmon 50% in 2013 from levels during the previous reporting period to decrease the predatory demand on pelagic prey fish. The reduction in stocking levels was taken in response to prey-fish declines and high salmonine abundance during previous reporting periods (Claramunt et al. 2012; Bunnell 2012). Fishery managers simultaneously implemented a new Lake Trout rehabilitation strategy during this reporting period that increased stocking levels of Lake Trout, especially in northern Lake Michigan. These actions were in response to previous reports by Bronte et al. (2008) and Dexter et al. (2011).

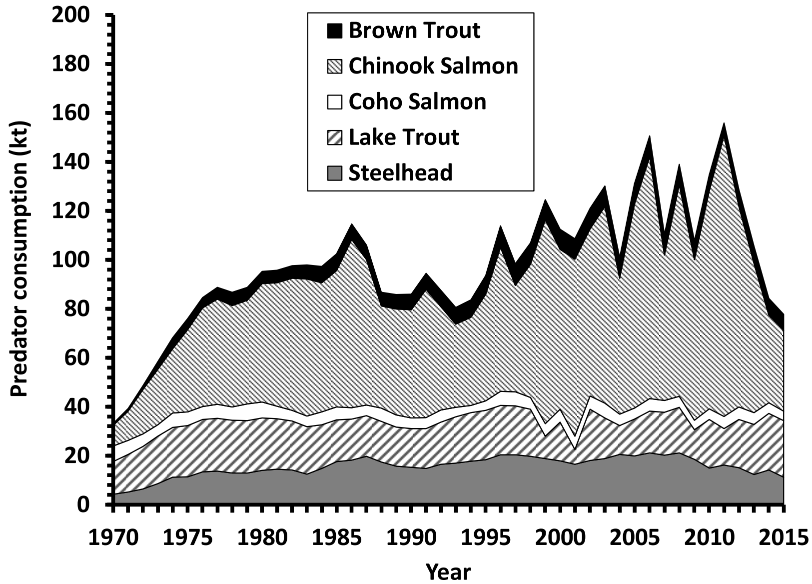
To aid fishery management, a predator-prey ratio (PPR) criterion based on Clark (2012), Clark et al. (2014), and Jones et al. (2014) and further refined by the SWG was developed during this reporting period. The PPR will be the primary indicator of predator-prey balance and was developed using the entire suite of salmonine predators and prey fish (Tsehaye et al. 2014a, b). A red-flag analysis that used fewer biological criteria to trigger stocking adjustments had been used to guide Chinook Salmon stocking decisions during the previous reporting period. The red-flag analysis was replaced by the PPR during this reporting period following a critical review of the red-flag analysis completed during 2012 (Clark 2012; Jones et al. 2014). The PPR incorporates detailed datasets and analytical approaches that better account for complexity in the food web.

Fig. 5. Predator-prey ratio (PPR) defined as the biomass (kt) of age-1 and older Chinook Salmon divided by the biomass of age-1 and older Alewife in Lake Michigan during 1970-2015.



The primary indicator used in the PPR approach is the ratio of total lakewide biomass of age-1 and older Chinook Salmon to total lakewide biomass of age-1 and older Alewife (Fig. 5). Age-specific Chinook Salmon and Alewife abundances are estimated using SCAA models based on data from multiple agencies and surveys. Abundance estimates are then multiplied by species- and age-specific average body weights and summed across ages to generate total lakewide biomass estimates for each species.

Fig. 6. Estimated kilotonnes of prey fish consumed by salmonine predators in Lake Michigan during 1970-2015.



The management objective is to maintain the PPR between 0.05 and 0.10 (Fig. 5). A PPR value less than 0.05 indicates an overabundance of Alewife that will have negative effects on the entire fish community whereas a PPR value greater than 0.10 indicates an overabundance of predators relative to Alewife. The PPR "safe zone" between 0.05 and 0.10 was established based on literature reviews, risk-assessment models presented at previous stakeholder meetings, and comparisons with similar ratios from Lakes Huron and Ontario. In Lake Huron, the Alewife population collapsed in 2003 following a time when the estimated PPR ranged from 0.10 to 0.13 per year and averaged 0.11 during 1998-2002. The Lake Huron Chinook Salmon population had collapsed by 2006 (Bence et al. 2008; He et al. 2008; Riley et al. 2008). In Lake Ontario, the Chinook Salmon population fluctuated but remained relatively stable during 1989-2005 when the PPR averaged 0.065.

### *Auxiliary Indicators of Predator-Prey Balance*

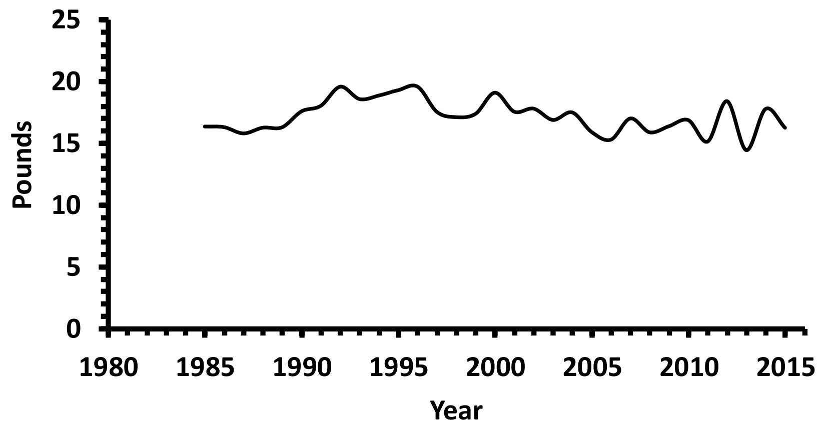
Five "auxiliary indicators" were established to compliment the PPR and provide additional feedback on predator-prey balance in Lake Michigan (Fig. 7). The auxiliary indicators are plotted as individual datasets through time without targets or upper limits and include

- Standard weight of 35-inch angler-caught Chinook Salmon during July 1 to Aug 15
- Average weight of age-3 female Chinook Salmon from fall weir and harbor surveys
- Catch-per-angler hour of Chinook Salmon from charter boats
- Percent composition of total weight harvested by species
- Age structure of the Alewife population

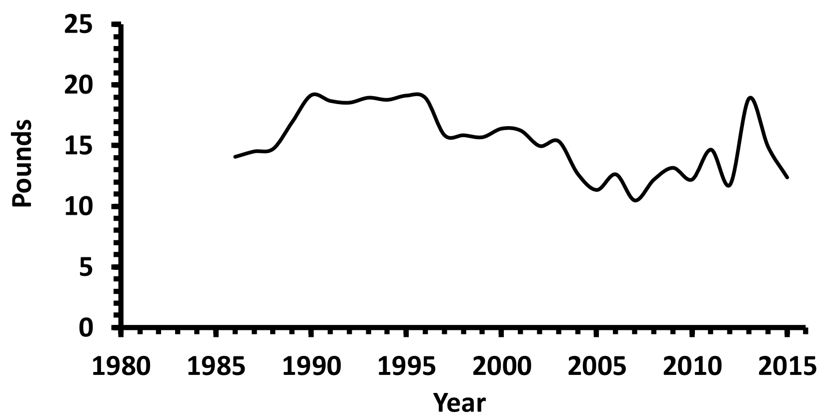
The use of the PPR improved the synthesis of biological data and is now the primary tool used to inform fishery managers of the status of predator-prey dynamics in Lake Michigan. The PPR was, however, based on previous food-web dynamics where Chinook Salmon biomass dominated the predator community and Alewife biomass exceeded Round Goby biomass; neither of these situations occurred during this reporting period. Thus, the auxiliary indicators become essential for interpreting the PPR.

Fig. 7. Five auxiliary indicators used to evaluate the predator-prey ratio in Lake Michigan: (a) standard weight of a 35-inch Chinook Salmon, (b) average weight of age-3 female Chinook Salmon, (c) catch-per-angler hour of Chinook Salmon in the charter fishery, (d) percent composition of trout and salmon in the recreational fishery, and (e) age structure of the Alewife population.

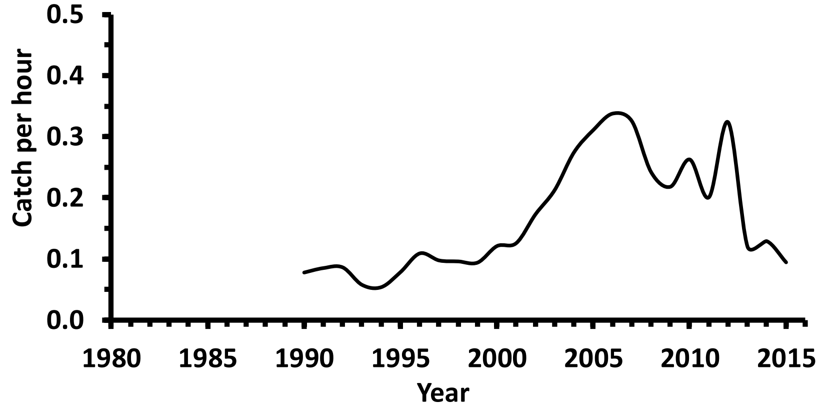
a.




b.

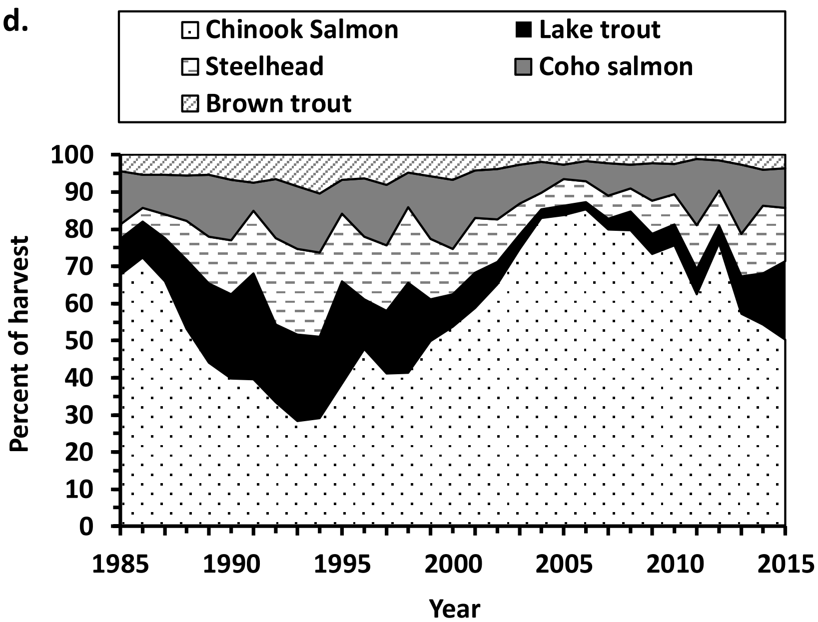


c.

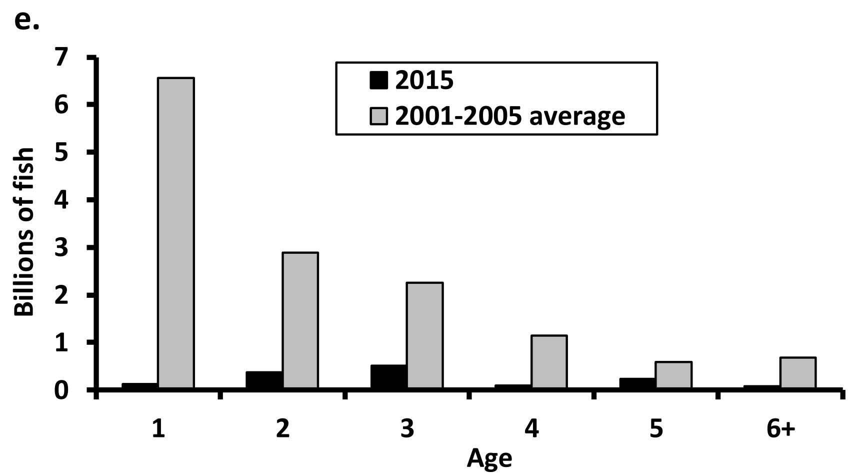


0.5
0.4
0.3
0.2
0.1
0.0
Catch per hour
1980
1985
1990
1995
2000
2005
2010
2015
Year


d.



Chinook Salmon
Lake trout
Steelhead
Coho salmon
Brown trout
100
90
80
70
60
50
40
30
20
10
0
Percent of harvest
1985
1990
1995
2000
2005
2010
2015
Year




# Trophic Overlap

Stable isotope ratios were measured in five salmonine predators from Lake Michigan during this reporting period to understand better how predators are adjusting to a changing prey base. Muscle tissues were collected from angler-caught fish throughout Lake Michigan during April through September 2014, and accepted analytical methods were used (Turschak et al. 2014) to determine stable isotope ratios of carbon ($\delta^{13C}$) and nitrogen ($\delta^{15N}$) relative to reference standards. The $\delta^{13C}$ values were adjusted for lipid content. Trophic niche space and niche overlap among species were determined using a probabilistic method described by Swanson et al. (2015).

Niche overlap was highly variable among salmonine predators during this reporting period. It was low between Lake Trout and Chinook Salmon, Coho Salmon, and Rainbow Trout (Steelhead); moderate between Lake Trout and Brown Trout; and high to very high among Chinook Salmon, Coho Salmon, and Steelhead. The high niche overlap among Chinook Salmon, Coho Salmon, and Steelhead indicate they probably use similar feeding locations and have similar diets.

Lake Trout isotopic signatures were unique when compared to the other salmonine predators due to elevated levels of $\delta^{15N}$. In Lake Michigan, offshore profundal species like *Mysis diluviana*, Deepwater and Slimy Sculpin, and Round Goby are enriched in $\delta^{15N}$ when compared with Alewife. Also, larger alewives are more enriched in $\delta^{15N}$ than smaller alewives (Turschak and Bootsma 2015). Thus, Lake Trout diets likely include more deep-water prey fish like Bloater, Slimy and Deepwater Sculpin, and Round Goby, as well as more large Alewife, than do Pacific salmonines. High variability in stable isotope ratios for Lake Trout and Brown Trout are consistent with a diverse diet. Competition for declining offshore prey fish will likely be highest among Chinook Salmon, Coho Salmon, and Steelhead than for Lake Trout, which appears to have more flexibility.

## Recommendations

The PPR is now the primary tool used to inform managers on the status of predator-prey dynamics in Lake Michigan, and it is expected to improve synthesis of data. Accordingly, we recommend the following priority research actions intended to increase the usefulness of the PPR and the likelihood of achieving the FCOs in the coming years

- Broaden the PPR to include biomass ratios for all predators and their prey
- Develop associated management actions based on those biomass ratios that allow for adjustments in all predators to bring a comprehensive balance between predator populations and prey production
- Promote rehabilitation of native prey fish to achieve a mixture of native and non-native prey fish capable of supporting the overall harvest of salmonines envisioned in the FCOs

# STATUS OF INSHORE AND BENTHIVORE FISH COMMUNITIES IN 2016[7]

**Kyle Broadway[8], David Caroffino, David Clapp, Randall Claramunt, Kevin Donner, Robert Elliott, Scott Hansen, Steve Lenart, and Jason Smith**

The fish community objectives (FCOs) for inshore and benthivore fish (Eshenroder et al. 1995) are to

> *Maintain self-sustaining stocks of yellow perch, walleye, smallmouth bass, pike, catfish, and panfish. Expected annual yields should be 0.9 to 1.8 million kg (2 to 4 million lb) for Yellow Perch and 0.1-0.2 million kg (0.2 to 0.4 million lb) for walleye.*

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[7]Complete publication including map of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp19_01.pdf.

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**R. Elliott**. U.S. Fish and Wildlife Service, Green Bay Fish and Wildlife Conservation Office, 2661 Scott Tower Drive, Green Bay, WI 54229.

**S. Hansen**. Wisconsin Department of Natural Resources, 110 S. Neenah Ave., Sturgeon Bay, WI 54235

**S. Lenart**. U.S. Fish Wildlife Service, Alpena Fish and Wildlife Conservation Office, 480 W. Fletcher St, Alpena, MI 49707

[8]Corresponding author (e-mail: broadway@illinois.edu).

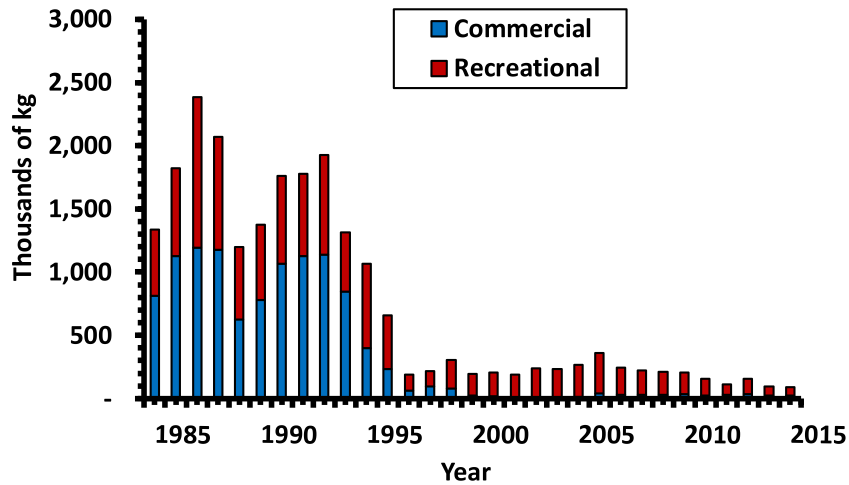
*Maintain self-sustaining stocks of lake whitefish, round whitefish, sturgeon, suckers, and burbot. The expected annual yield of lake whitefish should be 1.8-2.7 million kg (4 to 6 million lb).*

This chapter addresses the inshore and benthivore FCOs with specific focus on the current status of Yellow Perch, Lake Sturgeon, Lake Whitefish, and Cisco populations. Inshore and benthivore fish populations were addressed separately in the 2000 state of Lake Michigan report (Holey and Trudeau 2005) but were included in a common section in the 2005 (Clapp and Horns 2008) and 2011 (Bunnell 2012) reports, reflecting a shift from a species-focused to an ecosystem- and habitat-focused analysis (see Fetzer et al. 2016). This chapter reflects the same ecosystem approach as the two previous reports. Cisco were originally addressed within the planktivore objective (Eshenroder et al. 1995) but are now included within the inshore and benthivore section, as their recent expansion in Lake Michigan has thus far occurred only inshore.

## Yellow Perch

The annual total harvest of Yellow Perch averaged 122,000 kg (268,000 lb) during the reporting period (2011-2015) and was approximately one-half the average harvest of 253,000 kg reported for the previous reporting period (2005-2010) (Clapp et al. 2012). Most of the Yellow Perch harvest during the current reporting period was taken by the recreational fishery, as the annual commercial harvest only ranged between 21,000 to 35,000 kg (47,000 to 77,000 lb) (Fig. 8). Thus, most of the decline in harvest from the previous to the current reporting period occurred in the recreational fishery, and, while that harvest remained relatively stable in the current reporting period (Fig.1), graded-mesh gillnet surveys conducted during the reporting period show that adult abundance remains well below the peak levels observed in the late 1980s and early 1990s.

Fig. 8. Commercial and recreational fishery harvests of Yellow Perch in 1,000s of kilograms from Lake Michigan during 1985-2015. The harvest data were taken from the Lake Michigan Committee (LMC) lakewide extractions database.

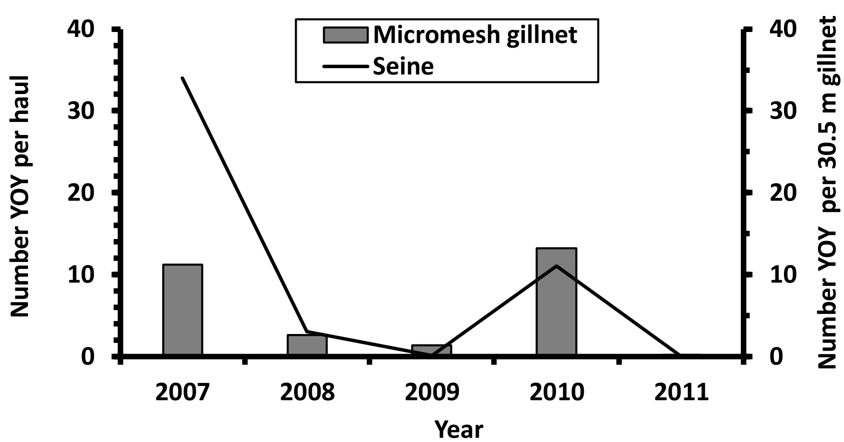



Survey catch rates of age-0 Yellow Perch during the reporting period were low in most jurisdictions and years, except in 2015 when trawl and seine surveys conducted in Indiana and Illinois waters indicated production of a moderately strong year-class. The 2005 and 2010 year-classes made up most of the adult population during the reporting period. In 2014, for example, the 2010 year-class made up greater than 35% of the adult population in Illinois waters and greater than 70% of the adult population in Michigan waters. The 2005 year-class made up a substantial portion of the adult population in Wisconsin waters in 2015.

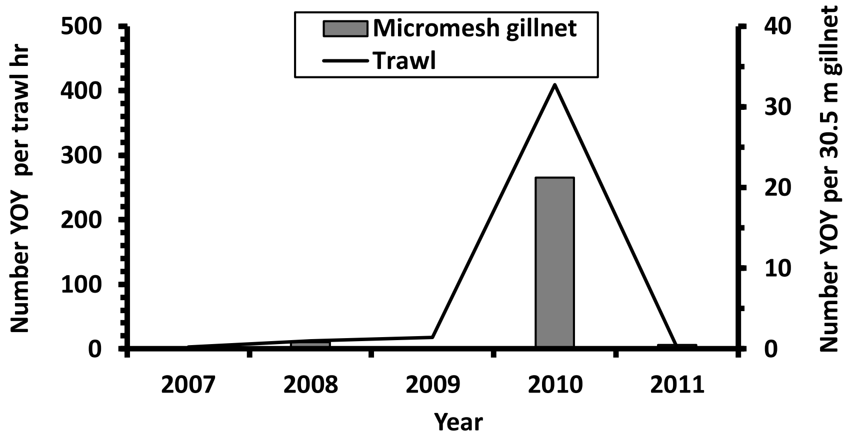
During the reporting period the Yellow Perch Task Group conducted an evaluation of the lakewide summer "micromesh" gillnet assessment, which was implemented by all agencies in 2007. The micromesh survey was developed to standardize assessment of young-of-the-year abundance in areas where standard trawl and seine surveys could not be conducted due to rough bottoms. The evaluation indicated excellent correspondence between micromesh gillnet catches and indices of abundance in the traditional trawl and seine surveys in both Wisconsin and Michigan waters (Fig. 9). The micromesh gillnets also caught good numbers of yearling Yellow Perch, indicating possibilities for assessment of yearling fish that are not yet susceptible to adult survey gears.

Fig. 9. Comparison of catch-per-unit effort (number per 305 m of gillnet) for young-of-the year (YOY) Yellow Perch between the newly developed standard micromesh gillnet survey and (a) the traditional seine survey in Wisconsin waters and (b) the bottom-trawl survey in Michigan waters, both in Lake Michigan during 2007-2011.

a.



b.




The LMC convened a multi-jurisdictional Yellow Perch Summit at the University of Illinois Chicago on March 22, 2014. The purpose of the meeting was to update anglers and stakeholders about the changing ecology of Lake Michigan and the current status of Yellow Perch populations, fisheries, and management. The summit included nine presentations by invited experts and a breakout session where smaller groups of constituents could comment and provide input to fishery managers (Lake_Michigan_Yellow_Perch_Summit_Report_2014.pdf). The summit continued a long history of communication among fishery managers, researchers, and anglers regarding Yellow Perch management.

# Lake Sturgeon

The abundance of adult wild Lake Sturgeon in Lake Michigan, as described by Clapp et al. (2012), remained relatively unchanged through 2015. The Menominee and Peshtigo Rivers continue to support the largest populations in the lake with annual spawning migrations of several hundred adults (Elliott and Gunderman 2008; M. Donofrio, Wisconsin DNR, 2015 and E. Baker, Michigan DNR, 2015, personal communications). The Lower Fox, Oconto, Manistee, Muskegon, Grand, and Kalamazoo Rivers continue to support smaller populations of at most slightly more than 75 adults (Hayes and Caroffino 2012; Elliott and Gunderman 2008). Adult Lake Sturgeon have been observed occasionally in the lower Manistique, Cedar, Milwaukee, Boardman, and St. Joseph Rivers during spawning time, but sustainable spawning populations are not known to exist in these rivers. Abundance in these rivers is considered very low, less than 25 adults per river (Hayes and Caroffino 2012; B. Eggold, Wisconsin DNR, 2015, personal communication).

Agency monitoring and assessment surveys conducted during the current reporting period have provided additional data on abundance and levels of reproduction for some populations. In 2012, the Michigan DNR updated their statewide rehabilitation strategy for Lake Sturgeon, and, as part of the strategy, they estimated adult abundance for all extant populations in Michigan waters (Hayes and Caroffino 2012). Population surveys conducted on the Muskegon River (Harris et al. 2017) captured 8-55 adult Lake Sturgeon per year during the 2008-2013 spawning seasons and documented 110 individual fish: 8 females, 42 males, and 60 fish of unknown sex. The Michigan DNR also captured 11-19 adult Lake Sturgeon per year during the 2011-2015 spawning migrations on the Kalamazoo River, which included 67 different adults: 11 females and 56 males (E. Baker, Michigan DNR, unpublished data). Coordinated surveys conducted by the states of Wisconsin and Michigan on the Peshtigo River captured 16-64 adult Lake Sturgeon in 1-2 days of effort each year during the 2009-2015 spawning runs, and their catches included 224 different adults over the 6-year period (M. Donofrio, Wisconsin DNR, unpublished data). Genetic analysis of age-0 Lake Sturgeon catches on the Manistee River revealed that the effective population size (accounts for inbreeding) of reproductive adults varied without trend, ranging between 21 and 66 adults per year during 2005-2014 (C. Jerome and K. Scribner, Michigan State University, unpublished data).

Assessments of natural reproduction and recruitment continued in several rivers during the reporting period and included standardized larval surveys conducted throughout the spring drift period. Larval surveys on the Manistee River captured 70-726 larvae$\cdot$y$^{-1}$ during the reporting period (LRBOI 2016). Surveys in the Menominee River caught 374, 1,222, and 1,289 larvae in 2012, 2013, and 2014, respectively, and surveys in the Oconto River caught 135, 1,125, and 297 larvae in 2013, 2014, and 2015, respectively. Total production was estimated to be 35,696 larvae in 2012, 104,944 larvae in 2013, and 149,790 larvae in 2014 in the Menominee River, as compared to 2,663 larvae in 2013, 24,348 larvae in 2014, and 4,503 larvae in 2015 in the Oconto River (Lawrence 2015). Surveys on the Kalamazoo River captured very few larvae despite known egg deposition below the Allegan Dam during 2011-2015 (E. Baker, Michigan DNR, 2015, unpublished data). High-flow releases from the Allegan Dam appear to be displacing eggs and limiting egg and larval survival in the Kalamazoo River. Late-summer nighttime spotlight surveys of age-0 fish captured and marked as many as 58 in the Peshtigo River, 21 in the Oconto River, 36 in the Manistee River, and 77 in the Muskegon River during 2011-2015 (LRBOI 2013, 2014; Smith 2014; Mann and Elliott 2016), but no age-0 sturgeon were observed during these surveys in the Grand River in 2015 and 2016.

Mortality of age-0 Lake Sturgeon associated with 3-trifluoromethyl-4-nitrophenol (TFM) treatments aimed to kill larval Sea Lamprey has been documented on some Lake Michigan tributaries. A kill of age-0 Lake Sturgeon was documented in the Manistee River in 2013 and in the Muskegon River in 2014, both of which were high-alkalinity streams (Seelye et al. 1988; LRBOI 2013, 2014; Smith 2014). No mortality of age-0 Lake Sturgeon was observed during the 2011 TFM treatment on the Peshtigo River (Mann and Elliott 2016). Meetings between the U.S. Fish and Wildlife Service, Michigan DNR, and Little River Band of Ottawa Indians during the reporting period concluded that concentrations of TFM needed to kill larval lamprey in the Manistee and Muskegon Rivers would likely continue to kill age-0 Lake Sturgeon. Consequently, these agencies planned to collect age-0 Lake Sturgeon from these rivers just prior to future TFM treatments, hold them in a streamside rearing facility where they would not be exposed to TFM during treatment, and return them to the river after the treatment.

The coordinated use of streamside facilities to culture Lake Sturgeon for reintroduction and rehabilitation stocking continues to be an important component of Lake Sturgeon restoration. Since 2006, Lake Michigan fishery agencies along with other volunteer groups have used rearing facilities located on the Milwaukee, Kewaunee, Cedar, Whitefish, Manistee, and Kalamazoo Rivers to rear and stock into these rivers 4-6-month-old fingerlings (Table 2). Appropriate donor sources were used as parents, progeny were reared in river water to facilitate imprinting, and genetic diversity was maximized by equalizing family contribution and meeting effective population size targets (see Welsh et al. 2010). Beginning in 2011, facilities were upgraded to increase capacity for separating families and to improving feeding and filtration procedures to increase survival, production, and genetic diversity (Table 2). Over 31,000 Passive Integrated Transponder (PIT) tagged or ventral fin-clipped fall fingerlings were stocked from streamside rearing facilities during 2005-2015. Agencies intend to use these facilities and protocols for at least 20 years to establish sustainable founding populations of at least 750 adults in each river.

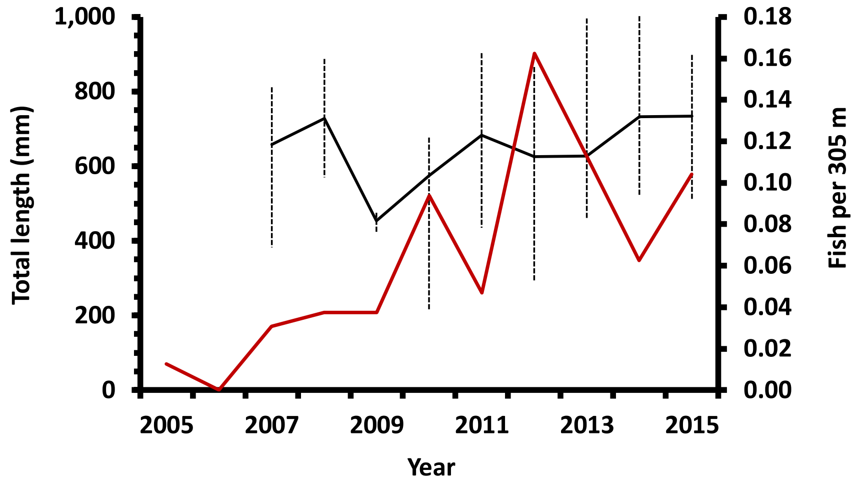
Table 2. The number (N) and effective population size (Ne; Welsh et al. 2010) of fingerling Lake Sturgeon stocked into Lake Michigan tributaries from streamside rearing facilities during 2005-2015. For the Manistee River, the number of male and female donors was inferred from a genetic parentage analysis of progeny; otherwise the number of donors of each sex was as observed.

| | Tributary | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Milwaukee | | Kewaunee[1] | | Cedar | | Whitefish | | Manistee | | Kalamazoo | |
| Year | N | $N_e$ | N | $N_e$ | N | $N_e$ | N | $N_e$ | N | $N_e$ | N | $N_e$ |
| 2005 | | | | | | | | | 51 | 37.0 | | |
| 2006 | 27 | <8 | | | | | 25 | NA | 89 | 58.6 | | |
| 2007 | 158 | <8 | 67 | 13.3 | 189 | 3.2 | 722 | 3.2 | 29 | 27.4 | | |
| 2008 | 767 | 13.3 | 0 | 0 | 0 | 0 | 0 | 0 | 47 | 31.9 | | |
| 2009 | 2,038 | 13.3 | 2,388 | 13.3 | 75 | 13.1 | 198 | 9.5 | 34 | 27.9 | | |
| 2010 | 1,192 | 13.3 | 17 | 12.4 | 951 | 6.4 | 1,420 | 9.5 | 74 | 56.7 | | |
| 2011 | 1,616 | 13.3 | 260 | 20 | 292 | 9.5 | 456 | 12.8 | 4 | 4.8 | 106 | 9 |
| 2012 | 1,609 | 23.3 | 1,446 | 23.3 | 345 | 8.7 | 516 | 8.7 | 28 | NA | 0 | 0 |
| 2013 | 1,679 | 23.9 | 1,607 | 23.9 | 160 | NA | 148 | NA | 376 | 74.4 | 2 | NA |
| 2014 | 1,648 | 26.7 | 1,466 | 26.7 | 345 | >4.8 | 606 | >4.8 | 91 | 52.5 | 35 | NA |
| 2015 | 1,432 | 26.7 | 1,407 | 26.7 | 1,067 | 10.7 | 1,180 | 10.7 | 242 | NA | 12 | NA |

[1]In 2007, fish were stocked into the Manitowoc River, Wisconsin.

The catch-per-unit effort (CPUE) (number of fish per 305 m of gillnet) of juvenile Lake Sturgeon in lakewide assessment plan (LWAP) surveys along the eastern shore of Lake Michigan from Leland to New Buffalo increased 10-fold from 2005-2006 to 2015 (Fig. 10). Nearly all of these juveniles lacked a PIT tag or a fin clip, suggesting they were of wild origin. Wild juveniles originating from each year-class since 1991 were found in Muskegon Lake from 2009-2013 (Harris et al. 2017). The average annual CPUE of stocked juveniles in standardized gillnet assessments conducted near tributaries where stocking occurred during 2013-2015 was higher than the CPUE in similar LWAP survey nets fished near tributaries where stocking did not occur. Also, through 2015, 21 marked fish released from streamside rearing facilities were recaptured in Lake Michigan 40 to 320 km from their river of origin (Eggold et al. 2012; E. Baker, Michigan DNR, 2015, personal communication), suggesting that, while density of stocked fish may remain highest near their river of origin, stocked fish also disburse widely. The length at age of stocked and wild juveniles was similar across all locations, suggesting that growth is similar throughout the lake (Fig. 10).

Fig. 10. Annual average total length (solid black line), range in length (vertical dashed lines) and average annual catch-per-unit-effort (red line) of 70 juvenile Lake Sturgeon less than 1,000 mm total length captured in annual lakewide surveys in Michigan waters of Lake Michigan from Leland south to New Buffalo during 2005-2015.




Management actions were implemented during the reporting period to allow Lake Sturgeon greater access to numerous tributaries to Lake Michigan. Federal, state, local, and private funds were used to remove, modify, or construct fish-passage structures at the lower five dams on the Milwaukee River during 2011-2015 and should now allow unimpeded movement of adult Lake Sturgeon within the lower 50 km of the river. On the Menominee River, a tributary to Green Bay, grant funding obtained during the reporting period aided the construction of upstream and downstream fish-passage facilities at the lower two hydroelectric dams. These structures include a fish lift, sorting, and transport facility and downstream guidance and exclusion racks and passage flumes, which now provide access to an additional 37 km of high-quality spawning and juvenile rearing habitat. During each year beginning in the fall of 2014, up to 30 female and 60 male adult Lake Sturgeon were moved upstream through the new passage facilities on the Menominee River as part of a multi-year project to optimize passage effectiveness and to promote long-term population expansion. Preliminary results indicate that most fish passed through these two dams continued their migrations to upstream spawning grounds, and then returned downstream to Green Bay within a year.

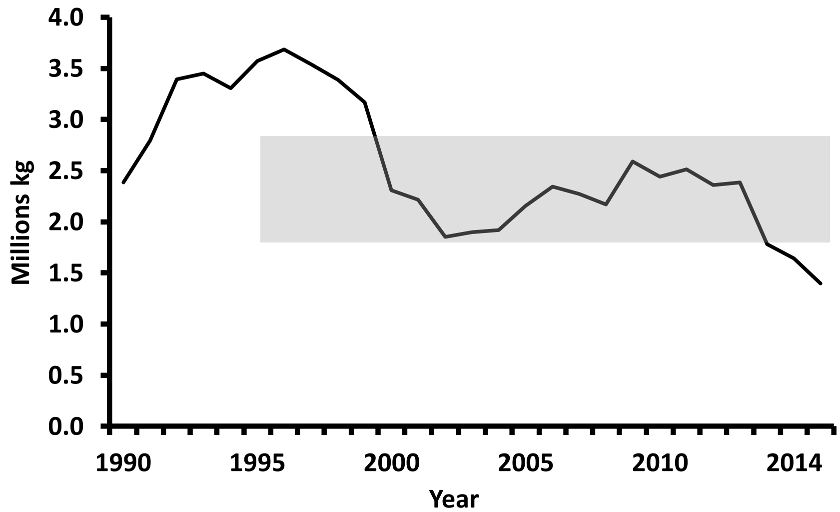
# Lake Whitefish

The average annual commercial yield of Lake Whitefish during the reporting period (2011-2015) was 1.91 million kg, representing a 12% decline from the mean annual yield of 2.34 million kg during the previous reporting period (2005-2010) (Fig. 11). The lakewide annual harvest in 2014 and 2015 was below the yield objective established by the LMC of 1.8 to 2.7 million kg.

Commercial trap- and gill-net fishing effort declined moderately during the reporting period after steadily increasing through the previous reporting period. Commercial trapnet effort, which accounts for the majority of the yield, declined from over 11,000 lifts in 2011 to only 7,800 in 2015. By way of comparison, when yields were peaking in the mid-1990s, trapnet effort was as high as 13,442 lifts, but it subsequently declined to 6,300 lifts in 2005 before increasing to levels observed in 2011. These changes in trapnet effort both before and during the reporting period were the result of changes in the tribal fishery in 1836 ceded waters. Nonetheless, the average annual number of trapnet lifts of 9,400 during the present reporting period is still greater than the average annual 7,756 lifts made during the previous reporting period. Commercial fishers continued to struggle with both filamentous algae and dreissenids fouling their nets.

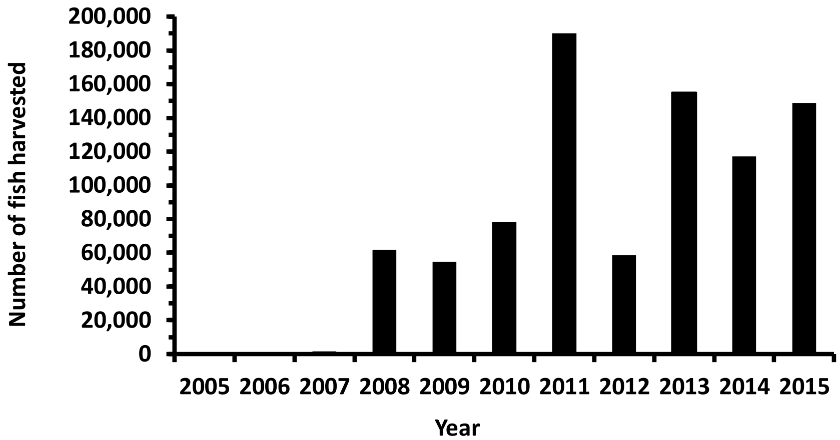
Although some populations have shown a modest improvement in growth recently, Lake Whitefish growth generally continues to be negatively affected by the invasion of dreissenids and their impact on *Diporeia* spp. abundance (Pothoven et al. 2001; Rennie et al. 2009). Mean total length of an age-7 Lake Whitefish in northern units fell from 536 mm during 1990-1994 to 478 mm during 2000-2004 to 468 mm during 2010-2014. This decline in growth has been implicated in changes in overall Lake Whitefish production (Kratzer et al. 2007; Gobin et al. 2016).

Fig. 11. Annual commercial yield (round weight) of Lake Whitefish from Lake Michigan during 1990-2015 (solid line) in comparison to the fish community yield objective (shaded area) established in 1995.




Despite the declining lakewide trends in Lake Whitefish abundance, growth, and recruitment, abundance and recruitment of the lower Green Bay populations have shown a contrarian increase during the previous and present reporting periods. The reemergence of river-running populations in tributaries to Green Bay beginning around the mid-1990s is thought to be responsible for increased abundance and recruitment. Lake Whitefish have been documented spawning in the Menominee, Peshtigo, Oconto, and Fox Rivers. Not only has the Green Bay commercial-fishery catch rate increased dramatically during this period, but an ice sport fishery began around 2007 in lower Green Bay and harvested as many as 190,000 fish in some years (Fig. 12). Commercial-fishery catch rates in lower Green Bay increased substantially over the same time period from an average of 52 kg dressed weight per trapnet lift during 1990-1994 to an average of nearly 200 kg per trapnet lift during this reporting period.

Fig. 12. The estimated number of Lake Whitefish harvested by the recreational ice fishery in Wisconsin waters of Green Bay during 2007-2015.




To achieve the objective, fishery agencies should focus on stock-specific management to protect each spawning population that contributes to the lakewide yield. Genetic and biological characteristics, along with reproductive potential, vary considerably among spawning populations and these demographics provide for long-term stability (Ebener and Copes 1985; Ebener et al. 2010; Belnap 2014; Modeling Subcommittee, Technical Fisheries Committee 2016; Andvik et al. 2016; Nathan et al. 2016). The lake comprises 15 Lake Whitefish management units, each with a total allowable catch limit (Ebener et al. 2008; Modeling Subcommittee, Technical Fisheries Committee 2016), but fish move freely between them, confounding interpretation of population status and yields (Molton et al. 2012; Li et al. 2015). Agencies should identify and protect from overharvest the less-productive populations in those management units where they mix with more-productive populations.

Consideration should be given to re-evaluating the FCO for Lake Whitefish, which was established when Lake Whitefish recruitment was stronger and primary production in the lake was unaltered by dreissenids. In Lake Huron, dreissenid invasions are not only linked to reduced Lake Whitefish growth, but dreissenids are also suspected of causing a reduction in Lake Whitefish recruitment, resulting in 50-90% declines in adult biomass (Gobin et al. 2015; Modeling Subcommittee of the Technical Fisheries Committee 2016). Lake Michigan may no longer be capable of supporting the large biomass levels observed during the 1980s and 1990s.

## Ciscoes

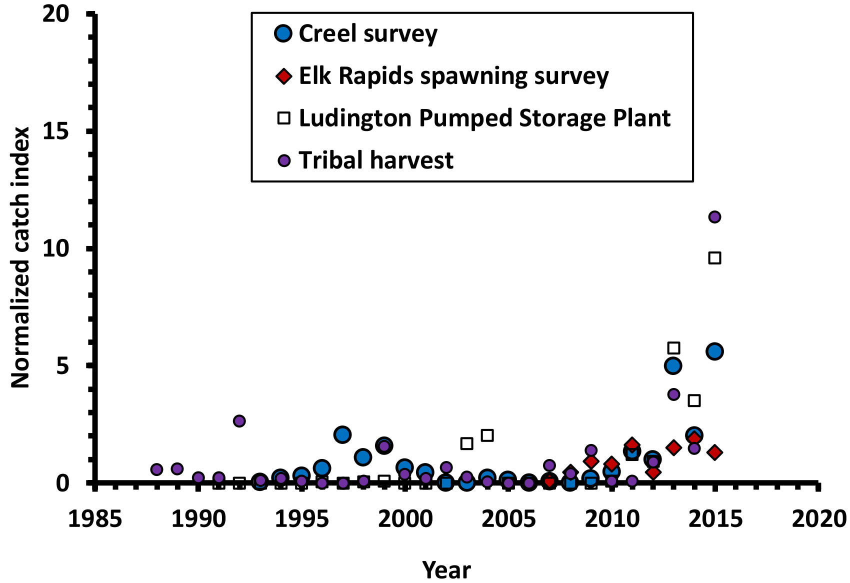
Ciscoes were historically the most-abundant forage species in Lake Michigan (Madenjian et al. 2011) and served as vital components to the ecological structure and function of the fish community (Fitzsimons and O'Gorman 2006). Ciscoes supported large commercial fisheries until the 1960s when populations were nearly extirpated due to a combination of commercial overharvest and habitat degradation and possibly the introduction of non-native species (Wells and McLain 1973; Baldwin et al. 2009; Madenjian et al. 2011). The historical assemblage of ciscoes, as described in Koelz (1929), comprised eight species: *Coregonus alpenae*, *C. artedi*, *C. hoyi*, *C. johannae*, *C. kiyi*, *C. nigripinnis*, *C. reighardi*, and *C. zenithicus* (Smith 1964; Bailey and Smith 1981; Todd and Smith 1992; Eshenroder et al. 2016). Although all eight species were historically abundant and widespread, only two species, *C. artedi* and *C. hoyi*, persist today.

Restoration of the *C. artedi* (common name Cisco) populations is currently of great interest among fisheries management agencies. The abundance and spatial distribution of Cisco appear to be expanding in northern Lake Michigan, notably in Little Traverse Bay, Grand Traverse Bay, and near Ludington, and evidence of increased recruitment suggests that population impediments and recruitment bottlenecks may have recently subsided (Eshenroder et al. 2016). In 2015, adult and juvenile Cisco were captured at 28 locations from Naubinway and Sturgeon Bay in the north to Green Bay and western Lake Michigan and south to White Lake and Grand Haven. Total annual harvest of Cisco in tribal commercial fisheries increased from

100 to 3,000 kg during 2009-2015 while, during the same period, total annual recreational harvest in Michigan waters increased from 130 to over 6,000 fish; catch rates in gillnet fishery-independent surveys at Elk Rapids and the Ludington Pumped Storage Plant increased 3- to 10-fold (Fig. 13). Additionally, evidence of sustained recruitment comes from spring neuston netting in Grand Traverse Bay where catches of larvae increased from 0 in 2004 to 10.1 ± 4.5 per 1,000 $m^3$ in 2011. Current evidence of Cisco recovery is encouraging, although factors limiting further expansion remain unidentified, and historical abundance in areas, such as Green Bay, is far from being achieved.

Cisco is arguably the most complex and diverse of the cisco species, being highly variable in morphology, habitat use, and behavior (Koelz 1929; Hubbs and Lagler 1958; Scott and Crossman 1973). The morphological diversity associated with *C. artedi* has led to descriptions of three forms: a “slim terete” form *C. artedi artedi*, a “deep compressed” form *C. artedi albus*, and a deep-bodied form *C. artedi manitoulinus* resembling western Canadian tullibee. The form(s) of Cisco that remain in Lake Michigan is unclear and subject to ongoing study. Koelz (1929) described only the slim-terete form based on his early 1900s collections. Yule et al. (2013) collected 108 ciscoes from Grand Traverse Bay between 2007 and 2011 and concluded that the *C. artedi artedi* form was most representative. Eshenroder et al. (2016) collected 25 fish from Grand Traverse Bay in 2015 and designated them as an albus-like form.

Fig. 13. Normalized catch of Cisco in four different fisheries in Michigan waters of Lake Michigan from 1988 to 2015. Catch rate in fishery-independent gillnet surveys at Elk Rapids and the Ludington Pumped Storage Plant are shown as the average number of fish per 305 m of gillnet per night. Indices were standardized by estimating the mean and then dividing each data point by the respective series mean.




Few spawning locations for Cisco have been identified in Lake Michigan, which prevents a meaningful genetic description of population structure. However, preliminary analysis of neutral genetic markers from four Lake Michigan locations (not all spawning locations) provide evidence of stock structure (W. Stott, U.S. Geological Survey, 2015, personal communication). Cisco collected while spawning in Grand Traverse Bay represented a distinct population whereas fish collected from Little Traverse Bay, Leland, and Ludington in eastern and northeastern areas during the summer and early fall represented a mix of genetic signatures. Efforts to describe better the genetic diversity and stock structure of Cisco are ongoing.

Cisco historically has been considered a mainly offshore planktivore that primarily forages on native invertebrates as follows (in order): copepods, cladocerans, midge larvae, *Mysis diluviana*, and fish (Anderson and Smith 1971; Eshenroder et al. 2016). Currently, a limited amount of information exists on diets and foraging strategies of Cisco in Lake Michigan. In Grand

Traverse Bay during 2014, Cisco consumed benthic prey during the spring, including Round Goby and chironomid pupae, and shifted to pelagic resources, including Alewife and spiny water flea (*Bythotrephes longimanus*) during the fall. The abundance of exotic prey items in diets suggests that Cisco has adapted to major changes in the food web. However, it is uncertain if the current ecosystem can support Cisco at their historical levels of abundance. A more temporal and spatial examination of diets, including juvenile diets, is needed.

In 2013, the Little Traverse Bay Bands of Odawa Indians initiated an experimental program to evaluate the efficacy of stocking as a tool for Cisco restoration. Gametes for this investigation were collected annually in late fall from a spawning population near Elk Rapids. Larvae were reared in round tanks following the guidance of other pilot Cisco rearing programs (Fischer et al. 2016; Johnson et al. 2017). Approximately 140,000 Cisco were stocked in Little Traverse Bay as spring fingerlings, fall fingerlings, and spring yearlings in 2014 and 2015.

The LMC in 2013 formed a Native Planktivore Task Group to, among other charges, evaluate the potential for Cisco restoration. The charge to the task group was to evaluate critically the feasibility of coregonine restoration in Lake Michigan and to specifically develop options for stocking *C. artedi* as a restoration tool. Despite the recent proliferation of research devoted to Cisco in Lake Michigan, there remains an insufficient understanding of extant populations. Further evaluations are needed to guide future rehabilitation efforts.

## Progress in Meeting Fish Community Objectives

Most recreationally and commercially important inshore fish species continue to be self-sustaining and a few such species are expanding in number. Walleye yield averaged 0.14 million kg (0.32 million lb) during this reporting period (2011-2015) and has been well within the target range of 0.1 to 0.2 million kg (0.2 to 0.4 million lb) in eight of the past 10 years. As many as 50,000 Smallmouth Bass are caught and released annually in Michigan’s Grand Traverse Bay, and condition of Smallmouth Bass in northern Lake Michigan is at an all-time high (Kaemingk et al. 2012). Cisco populations are expanding for the first time in more than fifty years, resulting in new fisheries.

In contrast to these improvements, the yield of Yellow Perch during the reporting period was well below the target range of 0.9 to 1.8 million kg (2 to 4 million lb). The average annual commercial yield for Lake Whitefish during the reporting period was 1.9 million kg, which is within the target range of 1.8 to 2.7 million kg (4 to 6 million lb). However, in both 2014 and 2015 total annual harvest was below the yield objective for the first time since 2000. As indicated in previous reports, the ability of managers to meet Lake Whitefish harvest objectives in the future may be compromised if growth and recruitment continue to decline and if diseases are not abated.

Although most Lake Sturgeon populations are below target abundances (Hay-Chmielewski and Whelan 1997; Wisconsin DNR 2000; LRBOI 2008; Welsh et al. 2010; Hayes and Caroffino 2012), lakewide rehabilitation efforts are designed to achieve abundance targets that better ensure sustainability within the next 20-25 years. Habitat improvement, fish passage, and protective regulations for Lake Sturgeon are being addressed.

# Recommendations

Recommendations relating to attainment of inshore and benthivore FCOs center around improving habitat, expanding surveys, addressing threats, and improving management. Some recommendations are more related directly to specific species whereas others are broad and address issues for multiple species. We recommend that the LMC

- Improve habitat where degradation has depressed recruitment of inshore and benthivore fish
- Improve fish passage for Lake Sturgeon as well as Lake Whitefish, Burbot, and suckers
- Restore wetlands and tributary habitat to benefit Northern Pike, Muskellunge, Walleye, and Yellow Perch
- Improve in-lake reef habitat for Cisco
- Expand the LWAP to include evaluation of Lake Sturgeon populations
- Adopt lakewide fish health monitoring

Almost 20 years after its initial implementation, the LWAP survey (Schneeberger et al. 1998) has proven to be a valuable tool. Originally, the survey was not designed to include Lake Sturgeon, but, as populations expanded, it is proving to be useful in assessing survival and distribution. The design should be modified to better measure the impacts of restoration efforts. River-spawning Lake Whitefish populations are re-establishing in Green Bay, and additional tributary sampling would better document how widespread re-establishment is around the lake. The current LWAP design is generally ineffective at capturing Cisco and should be modified if improved metrics regarding abundance, spawning locations, stock structure, and diet are desired. Lakewide fish health monitoring should be adopted into LWAP surveys for important inshore and benthivore fish captured during LWAP surveys to provide for an improved understanding of the effects of diseases and pathogens on fish populations.

# STATUS OF SEA LAMPREY IN LAKE MICHIGAN IN 2016[9]

**Scott A. Grunder[10] and Jessica Barber**

The Lake Michigan Committee's (LMC) fish community objective (FCO) for Sea Lamprey is "suppress the Sea Lamprey to allow the achievement of other fish-community objectives." Sea Lamprey control was critical to the biological and socioeconomic recovery of the Lake Michigan fishery (Fetterolf 1980), and it remains instrumental in maintaining fish community structure (Eshenroder 1987; Eshenroder et al. 1995; Holey et al. 1995; Lavis et al. 2003). Implementation of integrated pest-management techniques resulted in substantial reductions in Sea Lamprey abundance by the mid-1960s (Smith and Tibbles 1980; Lavis et al. 2003), but Sea Lamprey continue to inflict unacceptable levels of mortality on Lake Trout, and, thus, Sea Lamprey remain a major impediment to Lake Trout rehabilitation in Lake Michigan (Bronte et al. 2008). In addition, major gaps exist in the understanding of Sea Lamprey-host interactions, which ultimately influence estimates of host mortality (Bence et al. 2003). In this chapter, we report on progress made during this reporting period (2011-2015) to suppress Sea Lamprey abundance and achieve the FCO.

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[9]Complete publication including map of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp19_01.pdf.

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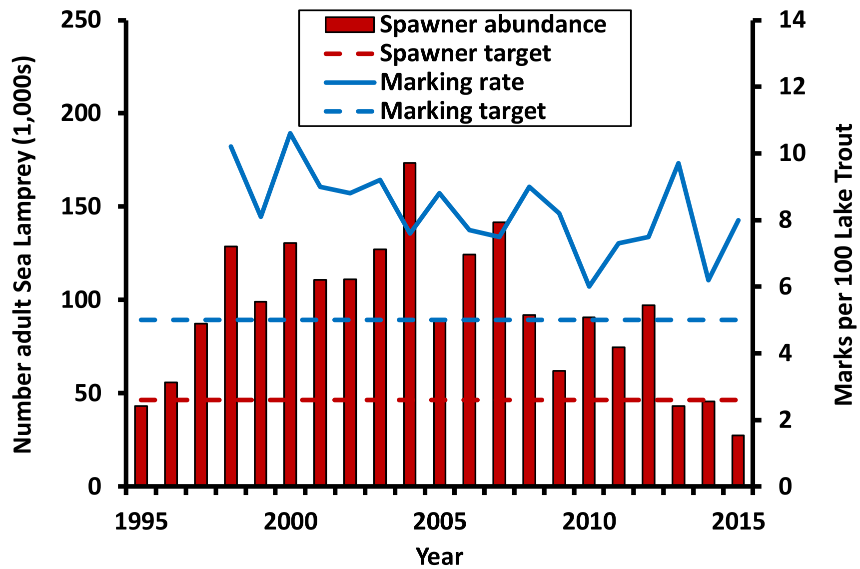
In 2004, the LMC set target levels for abundance of adult Sea Lamprey and marking rates on Lake Trout (Bronte et al. 2008). These criteria call for marking rates of 5 marks per 100 Lake Trout or less that result in an annual Sea Lamprey-induced mortality rate of 0.05 $year^{-1}$ or less. The adult Sea Lamprey-abundance target in Lake Michigan was set at approximately half the abundance corresponding to marking rates during 1995-1999, the five-year period with the lowest marking rate in the series (Fig. 14).

## Current Status

Adult Sea Lamprey abundance declined during the reporting period and was below the LMC target during 2013-2015 for the first time since 1995. Abundance during the reporting period was about 35,000 lampreys and declined by roughly 50% from the previous reporting period (2005-2010) (Fig. 14). Lampricide control effort was increased in 2001 and again in 2006 with expanded treatment schedules (Siefkes et al. 2013). Then, beginning in 2012, targeted treatment strategies that focused on regularly treating some of the largest larvae-producing tributaries were implemented. In addition, the Manistique River has been treated biennially since 2003. The reductions in Sea Lamprey abundance are likely a result of the repeated treatments of the Manistique River and targeted control efforts in northern Lakes Michigan and Huron that began during this reporting period.

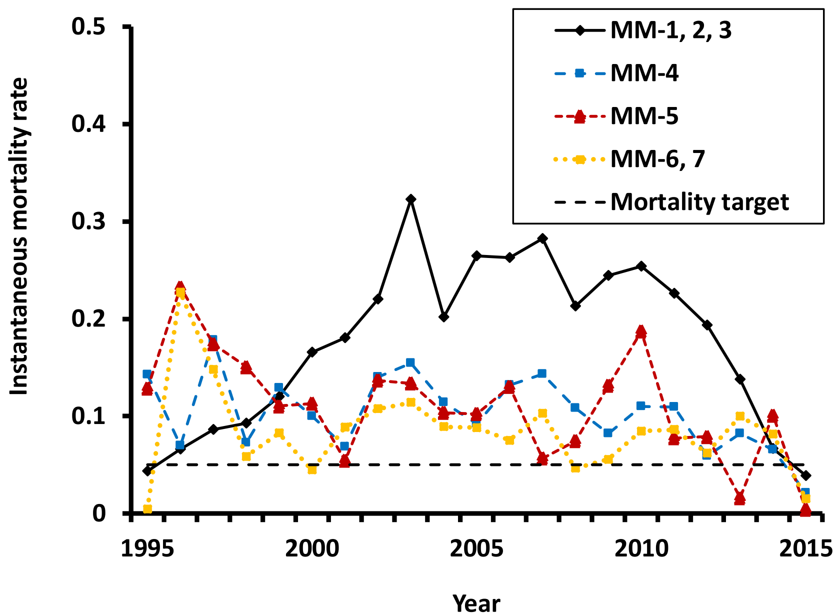
During 2015, an index of Sea Lamprey abundance was created to replace the regression-model estimates derived from multiple variables (see Mullett et al. 2003). The current index is the summation of mark-recapture estimates from a subset of streams characterized by a consistent trapping history and large spawning runs. Correction factors were developed for each lake to scale index estimates to lakewide estimates (http://www.glfc.org/status.php).

Fig. 14. Estimated abundance of spawning adult Sea Lamprey (1,000s) and marking rates on Lake Trout >532 mm total length during 1995-2015 (GLFC 2012) in comparison to Lake Michigan Committee targets for abundance and marking rate. Sea Lamprey abundance and the target were estimated with a conversion factor developed from an index of adult Sea Lamprey. Marking-rate data were for the August-November period. Thus, marking rates in year *t* corresponded with spawner abundance in year *t* + 1.




Estimates of Sea Lamprey-induced mortality rates on Lake Trout during the reporting period fell below levels observed during the previous reporting period. In all four management units within the 1836 ceded waters of the state of Michigan, marking rates during the reporting period were above but approaching the 5% target, particularly in northern waters (MM-1, 2, 3) where marking rates have been greater than in other units (Fig. 15). Thus, although lakewide marking remained above the target rate during the reporting period, Sea Lamprey induced mortality of Lake Trout is declining in large areas of the lake, and, in 2015, mortality was below the target.

Fig. 15. Average instantaneous Sea Lamprey-induced mortality rate on age 6-11 Lake Trout in four management units (comprising Statistical Districts MM-1-3, MM-4, MM-5, and MM-6-7) of 1836 treaty waters in Michigan waters of Lake Michigan during 1995-2015 (Modeling Subcommittee, Technical Fisheries Committee 2016). See Frontispiece for locations of statistical districts.




## Summary and Recommendations

Management targets for Sea Lamprey abundance were achieved during the reporting period, but the lakewide marking-rate target on Lake Trout was not achieved. However, in large areas of Lake Michigan, Sea Lamprey marking rates on Lake Trout declined during the reporting period to below levels observed during the previous reporting period, and, in many areas, Sea Lamprey-induced mortality in 2015 was the lowest observed in two decades.

Increased lampricide applications and enhanced applications on large tributaries to Lake Michigan since 2005 appear to have been successful at achieving reductions in Sea Lamprey abundance and marking rate on Lake Trout. Fishery and Sea Lamprey managers are developing revised control strategies to meet and maintain the FCOs for the lake. Recommendations to foster achievement of the objectives include

- Continue the large-scale treatment strategy on those tributaries with the highest larval production, such as the Muskegon, Ford, Manistique, Manistee, Pere Marquette, and Grand Rivers
- Construct a barrier on the Manistique River in the immediate future
- Improve the metrics used to measure efficacy of control actions on the Lake Michigan fish community
- Involve staff from the U.S. Fish and Wildlife Service and the Great Lakes Fishery Commission in plans to remove the 6th Street Dam on the Grand River in downtown Grand Rapids to ensure continued blockage of migrating Sea Lamprey in a river that has the highest larval production potential in the Lake Michigan basin.

# HABITAT CONDITIONS IN THE LAKE MICHIGAN WATERSHED IN 2016[11]

**Steven R. Robillard[12], Robert F. Elliott, Matthew E. Herbert, Candy S. Schrank, Joseph Sheahan, Darin Simpkins, and Lisa Walter**

The physical/chemical habitat fish community objectives for Lake Michigan (Eshenroder et al. 1995) are to

> *Protect and enhance fish habitat and rehabilitate degraded habitats.*
>
> *Achieve no net loss of the productive capacity of habitat supporting Lake Michigan's fish communities. High priority should be given to the restoration and enhancement of historic riverine spawning and nursery areas for anadromous species.*

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[11]Complete publication including map of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp19_01.pdf.

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*Pursue the reduction and elimination of toxic chemicals, where possible, to enhance fish survival rates and allow for the promotion of human consumption of safe fish.*

The health and integrity of physical and chemical habitats are critical for protecting or restoring healthy fish populations and sustainable fisheries and for maintaining the biological integrity of the fish community. Here we document changes in Lake Michigan's fish habitat during 2011-2015.

## Current Status

Progress has been made during 2011-2015 to restore the connectivity of tributaries and enhance historical spawning and nursery habitat. A recent assessment of tributaries indicates that only 17% have biologically meaningful connectivity with the lake proper (Januchowski-Hartley et al. 2014). Thus, since 2011, 590 km of streams were reconnected on 25 tributaries through either dam removal, culvert-passage enhancement, or other fish-passage mechanisms (J. Sheahan, U.S. Fish and Wildlife Service, Green Bay Ecological Services Field Office, 2015, personal communication). We note, however, an inconsistency in how stream lengths are reported so the preceding estimate should be considered a minimum for the aggregate length of tributaries that have been reconnected since the previous state of the lake report (Cogswell et al. 2012).

Three tools were recently developed to assess connectivity and the potential for increased connectivity to benefit fish populations. First, The Nature Conservancy is developing models to prioritize habitat for 42 fish species using 39 data sources of fish occurrence. Second, a decision support tool (Fishwerks) for prioritizing Great Lakes barrier removal has been developed (https://greatlakesconnectivity.org/; Moody et al. 2017). Third, the advocacy group Downstream Strategies in conjunction with the Great Lakes Basin Fish Habitat Partnership is developing a tool that will document for the basin the likelihood of occurrence for Brook Trout, Walleye, other cold-water and large river species, and lithophilic species.

Two notable habitat restoration projects were begun or were underway during the reporting period. First, construction of a Lake Sturgeon passage facility was begun in 2014 on the Menominee River, a tributary of Green Bay (Clapp et al., this volume), and the upstream-movement portion of the structure was completed in 2015. In 2016, the downstream-movement portion of the structure was completed. In Grand Traverse Bay, a spawning-habitat enhancement project was undertaken in August 2015 when 450 tons of rock were added to an existing structure to improve spawning habitat for Cisco, Lake Trout, and Lake Whitefish (Calabro 2016). Ongoing monitoring will be used to track habitat usage and evaluate effectiveness of the reef enhancement.

Several habitat mapping projects to quantify and delineate fish spawning grounds have taken place during the reporting period. First, nearshore spawning reefs along the coastline were mapped (https://coast.noaa.gov/llv/#/lake/michigan). Second, maps were created of substrates at two offshore reefs in Illinois (Redman et al. 2017). Third, bathymetric and substrate maps of Yellow Perch spawning areas were made for nearshore Illinois waters (Dub and Czesny 2016).

While concentrations of some pollutants like banned pesticides have greatly decreased, other chemicals have emerged as concerns regarding the quality of chemical habitat due to increasing use and discharge during the reporting period. These include ingredients of pharmaceutical and personal care products, and perfluorinated and polybrominated compounds, which are less bioaccumulative (Crimmins et al. 2012; EC 2015; EPA 2013a, 2013b, 2013c; Gewurtz et al. 2013; Howard and Muir 2013; Williams and Schrank 2015, 2016; Xia et al. 2011a, 2011b). The two main toxins that elicit consumption advisories across all four Lake Michigan states are the highly bioaccumulating and lipophilic polychlorinated biphenyls (PCBs) and mercury (via methylation and biomagnification). McGoldrick and Murphy (2015) examined chemical contaminants in Lake Trout from all Great Lakes and reported on the 2008-2012 average burdens in Lake Michigan. The greatest whole-body contaminant burdens in order of ranking were: total PCBs, organochlorine pesticides, mercury, polybrominated diphenyl ethers, and perfluorinated chemicals.

Environmental dredging to remove PCBs from the north harbor at Waukegan, Illinois, was completed in 2013 with funding through the Environmental Protection Agency Superfund. Dredging was conducted in all areas of the harbor where sediments exceeded 1 ppm, and dredging activities resulted in meeting the goal of a surface-weighted average concentration of 0.20-0.25 ppm in sediments (http://www.waukeganharborcag.com/wp-content/uploads/2017/11/WHAOC-dredging-BUI-recommendation-33114.pdf). Post-dredging fish-tissue sampling is ongoing to evaluate if the fish-consumption beneficial-use impairment can be removed.

Chemical contaminants in Lake Michigan fish were declining through the previous reporting period, and those declines were expected to continue into the present reporting period. PCB concentrations in Lake Michigan Chinook and Coho Salmon declined 4.0 and 2.6% per year, respectively, between the mid-1980s and 2010 (Rasmussen et al. 2014). Chang et al. (2012) found consistent temporal declines in many persistent bioaccumulating compounds in Lake Michigan air, sediment, water, gulls, and Lake Trout during 1999-2010, and these declines were greater than the declines that occurred during 1980-2003. Although these time periods partially overlap, somewhat obscuring the trends, they do suggest that declines before 1999 were larger than those after 1999. Unfortunately, concentrations of PCBs, DDTs, dieldrin, and other organochlorine pesticides did not decline as fast as other contaminants (Chang et al. 2012). Chang et al. (2012) did not consider how variables, such as fish age or sex, influenced their understanding of the declines in PCB concentrations. Declines in growth rate and changes in sex ratio have confounding effects on contaminant concentrations in Great Lakes fish (Madenjian et al. 2015b; Madenjian et al. 2016). Further, Zananski et al. (2011) found decreasing concentrations of mercury in whole Lake Trout during 2001-2010. Dellinger et al. (2014), however, found no significant change in mercury concentration for Lake Michigan Lake Trout and Lake Whitefish during 1994-2009 but did note declines in total PCBs, DDE, DDT, and toxaphene. Kreis et al. (2009) predicted that 5- to 6-year-old Lake Trout may approach 0.05 ppm total PCBs and fall into the unlimited consumption concentration range by 2033, but progress toward this prediction has not been evaluated recently. Analyses, such as those conducted by Kreis et al. (2009), should be a priority for evaluating progress toward the habitat objectives and for developing fish-consumption advisories.

## Summary

Funding from the Great Lakes Restoration Initiative has been instrumental in re-establishing fish passage and restoration of habitats vital to spawning fish. A Lake Sturgeon passage facility was completed on the Menominee River and in-lake spawning habitat was expanded at a site in Grand Traverse Bay during the reporting period. Species-mapping and decision support tools for prioritizing habitat remediation proposals and a comprehensive basinwide surveillance program for early detection of non-native species were also developed during the reporting period and were based on recommendations from the previous state of the lake report (Bunnell 2012). We recommend that these new tools for the prioritization of habitat enhancements should be utilized and vetted by fishery managers. Emerging contaminants, such as per- and polyfluoroalkyl substances, polybrominated diphenyl ethers, pharmaceuticals, and personal care products, may pose new threats to fish health and safe fish consumption; thus, additional monitoring and research are needed to determine the risks that these and other non-bioaccumulating chemicals pose to the health of Lake Michigan fish and the people that consume them.

# CONCLUSIONS FOR THE STATE OF LAKE MICHIGAN IN 2016[13]

**Jay K. Wesley[14], Bradley T. Eggold, Thomas K. Gorenflo, Jeremy Price, and Victor J. Santucci, Jr.**

The entirety of the fish community objectives (FCOs) should be considered when assessing progress at achieving them. Eshenroder et al. (1995) provided an overarching goal of maintaining the biological integrity of the aquatic system before describing objectives for specific fish. The 10 guiding principles that together defined a multi-jurisdictional management philosophy for Lake Michigan's fish community and fisheries were identified. Arguably, the most relevant of these 10 principles to this report focus on: (1) recognition of lake productivity limits, (2) preservation and restoration of fish habitat, (3) prioritization of native species restoration, (4) naturalization of non-indigenous salmonines, and (5) prevention of the introduction of non-indigenous species.

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[13]Complete publication including map of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp19_01.pdf.

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In this state of the lake report, the agency representatives on the Lake Michigan Committee (LMC) evaluate what has transpired during the reporting period (2011-2015). We also review progress on recommendations made in the concluding chapter of the previous state of the lake report (Robillard et al. 2012). Lastly, we offer recommendations to be implemented during the next reporting period.

## Progress toward Specific Fish Community Objectives

Harvest of all salmonines from Lake Michigan in 2015 at the end of this five-year reporting period was about 2 million kg, which was below the target range of 2.7 to 6.8 million kg established by Eshenroder et al. (1995). In addition, the percentage of the lakewide harvest that was Lake Trout was 29% and above the target range of 20-25%. Considerable progress toward rehabilitation of Lake Trout in Lake Michigan was made during this reporting period as population biomass, spawner abundance, and natural reproduction increased substantially, with most of the natural reproduction occurring in southern waters. Abundance of invasive Round Goby, an important prey of juvenile and adult Lake Trout, appears to favor rehabilitation by providing a diet item that is not high in thiaminase, which interferes with reproduction (Tillitt et al. 2005). Lake Trout biomass continues to increase due to increased stocking rates and increased natural reproduction even though mortality is higher in northern waters than in southern areas due to relatively high Sea Lamprey predation and commercial harvests. Natural reproduction accounts for 50-75% of Chinook Salmon population abundance, and this natural reproduction aligns with the fourth guiding principle that seeks to achieve self-sustainability of native and non-indigenous salmonines. Natural reproduction enables natural feedback mechanisms between predators and prey and likely confers greater biological integrity compared with hatchery-dependent populations.

The lakewide level of planktivore biomass in Lake Michigan in 2015 was only 6-9% of that called for in the planktivore objective, which also aims for a diversity of prey fish to meet predator demand. Total prey-fish diversity during the reporting period remained the same as in the previous reporting period with Round Goby representing a greater proportion of total prey-fish biomass as Alewife and Rainbow Smelt biomass continued to decline.

Accurate estimation of Round Goby population biomass has been a challenge, and we are quite certain that both Round Goby and total prey-fish biomass is being underestimated by current agency surveys. The prey-fish biomass values specified in the planktivore objective were intended to provide harvest opportunities and to satisfy predator demand for successful achievement of the salmonine objectives, but they did not anticipate the arrival of Round Goby. Planktivore levels in 2015, however, suggest an imbalance between predators and prey fish that could lead to further instability in the fish community.

Success at achieving the objective for inshore fish was mixed during the reporting period. The abundance of Walleye was enough in most years to allow harvest levels to be within the range established in the FCOs. Unfortunately, Yellow Perch abundance was relatively low as harvest was less than 15% of the minimum yield expectation of 0.9 million kg. Numerous factors can affect harvest, including regulations and weather, but ongoing population assessments indicate that Yellow Perch abundance is well below that necessary to allow sustainable harvests at the level specified in the objective for inshore fish. Smallmouth Bass abundance and growth continue to increase in Green Bay, Grand Traverse Bay, and major harbors, providing excellent angling opportunities. Smallmouth Bass and other nearshore fish have benefited from Round Goby in their diets. Other species mentioned in this objective appeared to be maintaining healthy, self-sustaining populations as envisioned in the FCOs.

The goal of self-sustaining stocks in the benthivore objective was met for all species except Lake Sturgeon, which continues to require stocking and in-stream habitat improvements to sustain its populations. Remnant populations of Lake Sturgeon persist and spawn each year in the lowermost sections of at least eight Lake Michigan tributaries. Use of streamside rearing facilities to boost larval Lake Sturgeon survival and subsequent population increases and connectivity projects on the Milwaukee and Menominee Rivers are consistent with the guiding principles of preserving native species, protection and enhancement of threatened and endangered species, and the genetic stock concept (Eshenroder et al. 1995).

The Lake Whitefish component of the benthivore objective was not met during the reporting period. The benthivore objective calls for achieving Lake Whitefish biomass levels capable of sustaining annual yields of 1.8 to 2.7 million kg (4 to 6 million lb), but annual harvests were below the objective in the final three years of the reporting period. Suppressed Lake Whitefish growth (Pothoven et al. 2001; Pothoven and Madenjian 2008, 2013) and reproduction have reduced recruitment to the fishable population and to harvest potential. Research that links large-scale environmental drivers of Lake Whitefish reproduction (e.g., water clarity, water currents, ice cover, and climate change) with more localized habitat conditions and productivity near spawning and nursery grounds is needed to determine the causative factors of the reduced recruitment (aside from reduced growth), as well as to determine a prognosis for the future.

Research is needed to determine the causative factors of the reduced reproduction, as well as to determine a prognosis for the future of Lake Whitefish populations and fisheries. The declining Lake Whitefish abundance may be related to the ecosystem disruption caused by dreissenids. Unless there is a change in the Lake Michigan ecosystem, we expect that Lake Whitefish will remain at the lower end or below the abundance range stated in the objective.

The aim of the Sea Lamprey objective is to suppress its abundance such that other FCOs can be achieved. The salmonine and benthivore objectives are the most impacted by an excessive abundance of Sea Lamprey, but Sea Lamprey does affect other species and has indirect impacts on multiple trophic levels. Relatively high Sea Lamprey abundance in northern Lake Michigan contributed to the modestly high mortality experienced by adult Lake Trout during the first three years of the reporting period. On a positive note, Sea Lamprey abundance in northern Lake Michigan declined substantially toward the end of the reporting period, and, if this level of suppression continues, the Sea Lamprey objective is within reach.

Progress toward the physical/chemical habitat objective continues in support of a lakewide priority to protect and restore fish habitat. Increasing connectivity between Lake Michigan and its tributaries is a major focus of the habitat objective because only 17% of Lake Michigan’s tributaries have a biologically meaningful connection to the lake. Improvements were made in 25 rivers through dam removal, culvert enhancements, and other fish-passage efforts. Decision support tools have been developed and have prioritized the removal of barriers to fish passage. Mapping tools are also being developed to further assess and prioritize other Lake Michigan habitats for protection and enhancement. Legacy contaminants, such as PCBs and mercury, continue to accumulate in fish warranting consumption advisories, but contaminant levels in fish continue to decline slowly due to cleanup of contaminated sites and other pollution-abatement activities. Emerging concerns with pharmaceutical and personal care products, as well as with PFAS, are being evaluated for their potential impacts on fish and human health. No new introductions of non-indigenous aquatic species were detected in Lake Michigan during the reporting period, even with increased surveillance efforts. Invasive non-indigenous species continue to be the primary impediment to achievement of most of Lake Michigan's FCOs.

## Lake Michigan Committee Action-Items Progress, 2011-2015

The LMC proposed three actions in 2011 to address important topics that would assist in achieving FCOs. The three action items and updates on each are provided below.

1. **Action Item:** Examine FCOs with respect to changing conditions in Lake Michigan. We will reaffirm, redefine, or modify some or all the FCOs or embark on the production of a completely new document. We recognize that updating or modifying FCOs is hampered by a dramatically changing Lake Michigan ecosystem that will make identifying new objectives and benchmarks a daunting task filled with a high degree of uncertainty, especially since existing FCOs seem unattainable.

**Update:** We met to discuss modifications to our FCOs. Discussions included abundance targets along with harvest targets for salmonines and Lake Whitefish, given concerns that other variables, such as fishing effort, may also affect harvest. There was some support for modification of the specified targets for these objectives; however, the general principles of the objectives were affirmed (e.g., establishing a diverse salmonine community and self-sustaining Lake Trout populations). Changes in the food web and a decrease in lakewide productivity were also a concern relative to attainability of current objectives and expectations for pelagic prey fish, salmonines, and Yellow Perch. We established a Lower Trophic Food Web Task Group to address some of these issues. A paper titled "Are Changes in Lower Trophic Levels Limiting Prey-Fish Biomass and Production in Lake Michigan?" was published as a product of that task group (Bunnell et al. 2018). Discussions on updating FCOs will continue to be a priority.

2. **Action Item:** Encourage the development and prioritization of research needs, foster other data collection/analysis processes, and assist, where possible, in alleviating potential shortfalls in information.

**Update:** The Lake Michigan Technical Committee (LMTC) discussed research priorities at their 2012 winter meeting and posted an updated list on the Great Lakes Fishery Commission website. Standardized sampling and data collection/analysis were major topics at winter and summer LMTC meetings. We adopted a predator-prey ratio analysis to assess the ecological balance between salmonine predators and prey fish (Claramunt et al., this volume) and to inform salmon and trout stocking decisions. Members of the LMC and LMTC also participated in development of sampling objectives and priorities for the Lake Michigan Cooperative Science Monitoring Initiative, a once-every-5-

year lakewide effort conducted by federal and state agencies.

3. **Action Item:** Increase coordination with other environmental organizations to promote further ecosystem management through a multi-disciplinary approach.

**Update:** We have become more involved with development of the Lake Michigan Lakewide Action and Management Plan (LAMP) (https://binational.net//wp-content/uploads/2014/10/lake-michigan-lamp-2013-eng.pdf) by having a representative on the LAMP Working Group. Conversely, during the reporting period, LAMP Working Group members consistently attended and participated in LMTC meetings and in annual LMC meetings. We are also more involved with identifying Great Lakes Restoration Initiative-funded habitat projects and delisting of Areas of Concern (see https://www.epa.gov/great-lakes-aocs/list-great-lakes-aocs). Collaborative efforts continue to grow with the EPA, NOAA, U.S. Geological Survey, and state and tribal partners to collect and analyze physical, chemical, and biological data to better understand lake productivity and lower trophic-level dynamics.

# Lake Michigan Committee Action Items, 2016-2020

We propose the following actions for the next (now current) five-year reporting period to better focus our actions on FCOs

1. Research and evaluate bottlenecks that may be affecting Lake Whitefish growth and recruitment
2. In collaboration with the LMTC, examine existing FCOs with respect to the changing food web in Lake Michigan; where appropriate, we will evaluate modification to some or all of the objectives or consider producing a completely new document
3. Develop a native planktivore management strategy for Lake Michigan using information provided by the Native Planktivore Task Group report and other sources
4. Balance predator and prey-fish populations through stocking and harvest management strategies
5. Support research to better estimate Round Goby population biomass in the Great Lakes.

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# LITERATURE CITED

Anderson, E.D., and Smith, Jr., A.L. 1971. Synoptic study of food habits of 30 fish species from western Lake Superior. Minn. Agri. Experi. Station, Tech. Bull. 279. 199 pp.

Andvik, R., Sloss, B.L., VanDeHey, J.A., Claramunt, R.M., Hansen, S.P., and Isermann, D.A. 2016. Mixed stock analysis of Lake Michigan's lake whitefish *Coregonus clupeaformis* commercial fishery. J. Great Lakes Res. **42**: 660-667.

Bailey, R.M., and Smith, G.R. 1981. Origin and geography of the fish fauna of the Laurentian Great Lakes basin. Can. J. Aquat. Sci. **38**: 1539-1561.

Baldwin, N.A., Saalfeld, R.W., Dochoda, M.R., Buettner, H.J., and Eshenroder, R.L. 2009. Commercial Fish Production in the Great Lakes 1867-2015 [online]. Available from http://www.glfc.org/databases/commercial/commerc.php [accessed 08 June 2019].

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. J. Great Lakes Res. **38**: 368-380.

Belnap, M.J. 2014. Stock characteristics of lake whitefish in Lake Michigan. MS Thesis. Univ. Wis. Stevens Point, Stevens Point, WI.

Bence, J.R., Bergstedt, R.A., Christie, G.C., Cochran, P.A., Ebener, M.P., Koonce, J.R., Rutter, M.A., and Swink, W.D. 2003. Sea lamprey (*Petromyzon marinus*) parasite-host interactions in the Great Lakes. J. Great Lakes Res. **29**(Suppl. 1): 253-282.

Bence, J.R., Johnson, J.E., He, J.X., Schaeffer, J.S., Riley, S., Young, R.J., Ebener, M., Reid, D., Mohr, L.C., Gonder, D., Cottrill, A., Woldt, A., Morse, T.J., Christie, G.C., and Ridgeway, M. 2008. Offshore predators and their fish community. *In* The state of Lake Huron in 2004. *Edited by* J.R. Bence and L.C. Mohr [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp08_1.pdf [accessed 14 April 2019].

Bronte, C.R., Krueger, C.C., Holey, M.E., Toneys, M.L., Eshenroder, R.L., and Jonas, J.L. 2008. A guide for the rehabilitation of lake trout in Lake Michigan [online]. Available from http://www.glfc.org/pubs/misc/2008-01.pdf [accessed 14 April 2019].

Bunnell, D.B. [ED.]. 2012. The state of Lake Michigan in 2011 [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp12_1.pdf [accessed 14 April 2019].

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 11 others. 2014. Changing ecosystem dynamics in the Laurentian Great Lakes: bottom-up and top-down regulation. Bioscience **64**: 26-39.

Bunnell, D.B., Madenjian, C.P., Desorcie, T.J., Kostich, M.J., Woelmer, W., Adams J.V. 2015. Status and trends of prey fish populations in Lake Michigan, 2014 [online]. Available from http://www.glfc.org/pubs/lake_committees/common_docs/CompiledReportsfromUSGS2015.pdf [accessed 14 April 2019].

Bunnell, D.B., Carrick, H.J., Madenjian, C.P., Rutherford, E.S., Vanderploeg, H.A., Barbiero, R.P., Hinchey-Malloy, E., Pothoven, S.A., Riseng, C.M., Claramunt, R.M., and eight others. 2018. Are changes in lower trophic levels limiting prey-fish biomass and production in Lake Michigan? [online]. Available from www.glfc.org/pubs/misc/2018-01.pdf [accessed 14 April 2019].

Calabro, E.J. 2016. Effectiveness of critical Lake Trout *Salvelinus namaycush* and coregonid reef spawning habitat restoration in northern Lake Michigan: mitigating from environmental and invasive egg predator impacts. M.Sc. thesis, Biol. Dept., Central Mich. Univ., Mt. Pleasant, MI.

Chang, F., Pagano, J.J., Crimmins, B.S., Hopke, P.K., Milligan, M.S., and Holsen, T.M. 2012. Temporal trends of polychlorinated biphenyls and organochlorine pesticides in Great Lakes fish, 1999-2009. Sci. Total Environ. **439**: 284-290. doi:10.1016/j.scitotenv.2012.09.019.

Clapp, D.F., and Horns, W. [EDS.]. 2008. The state of Lake Michigan in 2005 [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp08_2.pdf [accessed 14 April 2019].

Clapp, D.F., Elliott, R.F., Lenart, S.J., and Claramunt, R.M. 2012. Inshore and benthivore fish communities. *In* The State of Lake Michigan in 2011. *Edited by* D.B. Bunnell [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp12_1.pdf [accessed 14 April 2019].

Claramunt, R.M., Clapp, D.F., Breidert, B., Elliott, R.F., Madenjian, C.P., Warner, D.M., Peeters, P.J., Robillard, S.R., and Wright, G.M. 2008. Status of Chinook salmon. *In* The state of Lake Michigan in 2005. *Edited by* D.F. Clapp and W. Horns [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp08_2.pdf [accessed 14 April 2019].

Claramunt, R.M., Warner, D.M., Madenjian, C.P., Treska, T.J., and Hanson, D. 2012. Offshore salmonine food web. *In* The State of Lake Michigan in 2011. *Edited by* D.B. Bunnell [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp12_1.pdf [accessed 14 April 2019].

Clark, R.D. 2012. Review of Lake Michigan red flags analysis. Mich. State Univ., Quant. Fish. Center Tech. Rep. T2012-01.

Clark, R., Jones, M., and Tsehaye, I. 2014. Instruction manual for the Lake Michigan Chinook salmon-alewife predator-prey ratio analysis. Mich. State Univ., Quant. Fish. Center Rep. T2014-02.

Cogswell, S.F., Whelan, G.E., and Sturtevant, R. 2012. Habitat conditions in the Lake Michigan watershed. *In* The state of Lake Michigan in 2011. *Edited by* D.B. Bunnell [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp12_1.pdf [accessed 14 April 2019].

Crimmins, B.S., Pagano, J.J, Xia, X., Hopke, P.K., Milligan, M.S., and Holsen, T.M. 2012. Polybrominated diphenyl ethers (PBDEs) in Great Lakes lake trout: Turning the corner on PBDEs in the Great Lakes 1982-2008. Environ. Sci. Technol. **46**: 9890-9897. doi:10.1021/es302415z.

Dellinger, J.A., Moth, M.D., Dellinger, M.J., and Ripley, M.P. 2014. Contaminant trends in freshwater fish from the Laurentian Great Lakes: a 20-year analysis. Human and Ecological Risk Assessment: An International Journal **20**: 461-478.

Dexter, Jr., J.L., Eggold, B.T., Gorenflo, T.K., Horns, W.W., Robillard, S.R., and Shipman, S.T. 2011. A fisheries management implementation strategy for the rehabilitation of lake trout in Lake Michigan [online]. Available from http://www.glfc.org/pubs/lake_committees/michigan/impstr_rehablktrout.pdf [accessed 014 April 2019].

Dub, J.D., and Czesny, S.J. 2016. Yellow perch population assessment in southwestern Lake Michigan July 1, 2014-June 30, 2015 [online]. Available from https://www.ideals.illinois.edu/bitstream/handle/2142/91669/INHS2016_43.pdf?sequence=2&isAllowed=y [accessed 08 June 2019].

Ebener, M.P., and Copes, F.A. 1985. Population statistics, yield estimates, and management considerations for two lake whitefish stocks in Lake Michigan. N. Am. J. Fish. Manage. **5**: 435-438.

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 [online]. Available from http://www.miseagrant.umich.edu/downloads/research/journals/08-310.pdf [accessed 14 April 2019].

Ebener, M.P., Brenden, T.O., Wright, G.M., Jones, M.L., and Faisal, M. 2010. Spatial and temporal distributions of lake whitefish spawning stocks in northern Lakes Michigan and Huron. J. Great Lakes Res. 36(Suppl. 1): 38-51.

EC (Environment Canada). 2015. Polybrominated diphenyl ethers (PBDEs) in fish and sediment [online]. Available from https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/polybrominated-diphenyl-ethers-fish-sediment.html [accessed 08 June 2019].

Eggold, B., Baumgartner, M., Fajfer, S., Holtgren, M., Baker, E., Elliott, R., and Holleback, M. 2012. Lake sturgeon rehabilitation using streamside rearing facilities [online]. Available from https://www.glft.org/documents/671-glft_final_-_proj_2005-671-pdf [accessed 14 April 2019].

Elliott, R.F. 2008. Status and trends of lake sturgeon. *In* The state of Lake Michigan in 2005. *Edited by* D.F. Clapp and W. Horns [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp08_2.pdf [accessed 14 April 2019].

Elliott, R.F., and Gunderman, B.J. 2008. Assessment of remnant lake sturgeon populations in the Green Bay basin, 2002-2006 [online]. Available from https://www.fws.gov/midwest/sturgeon/documents/Final%20Report%20Project%20113-610_Elliott%20and%20Gunderman_2008.pdf [accessed 14 April 2019].

EPA (Environmental Protection Agency). 2013a. Contaminants of emerging concern (CECs) in fish: polybrominated diphenyl ethers (PBDEs) [online]. Available from https://www.epa.gov/sites/production/files/2018-11/documents/cecs-pbdes-factsheet.pdf [accessed 14 April 2019].

EPA (Environmental Protection Agency). 2013b. Contaminants of emerging concern (CECs) in fish: perfluorinated compounds (PFCs) [online]. Available from https://www.epa.gov/sites/production/files/2018-11/documents/cecs-pfcs-factsheet.pdf [accessed 14 April 2019].

EPA (Environmental Protection Agency). 2013c. Contaminants of emerging concern (CECs) in fish: pharmaceuticals and personal care products (PPCPs) [online]. Available from https://www.epa.gov/sites/production/files/2018-11/documents/cecs-ppcps-factsheet.pdf [accessed 14 April 2019].

Eshenroder, R.L. 1987. Socioeconomic aspects of lake trout rehabilitation in the Great Lakes. Trans. Am. Fish. Soc. **116**: 309-313.

Eshenroder, R.L., and Amatangelo, K.L. 2002. Reassessment of the lake trout population collapse in Lake Michigan during the 1940s [online]. Available from http://www.glfc.org/pubs/TechReports/Tr65.pdf [accessed 14 April 2019].

Eshenroder, R.L., Holey, M.E., Gorenflo, T.K., and Clark, Jr., R.D. 1995. Fish-community objectives for Lake Michigan [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp95_3.pdf [accessed 14 April 2019].

Eshenroder, R.L., Vecsei, P., Gorman, O.T., Yule, D.L., Pratt, T.C., Mandrak, N.E., Bunnell, D.B., and Muir, A.M. 2016. Ciscoes (*Coregonus, subgenus Leucichthys*) of the Laurentian Great Lakes and Lake Nipigon [online]. Available from www.glfc.org/pubs/misc/Ciscoes_of_the_Laurentian_Great_Lakes_and_Lake_Nipigon.pdf [accessed 14 April 2019].

Fetterolf, Jr., C.M. 1980. Why a Great Lakes Fishery Commission and why a sea lamprey international symposium? Can. J. Fish. Aquat. Sci. **37**: 1588-1593.

Fetzer, W.W., Roth, B.M., Infante, D.M., Clapp, D.F., Claramunt, R.M., Fielder, D.G., Forsyth, D.K., He, J.X., Newcomb, T.J., Riseng, C.M., and 2 others. 2016. Spatial and temporal dynamics of nearshore fish communities in Lake Michigan and Lake Huron. J. Great Lakes Res. **43**: 319-343.

Fischer, G.J, Holmes, K.L., and Wiermaa, E.M. 2016. Lake Herring (*Coregonus artedi*) intensive culture manual [online]. Available from https://www.uwsp.edu/cols-ap/nadf/Project%20Results/Project%20Reports/Lake%20Herring/UWSP%20NADF%20Lake%20Herring%20Manual.pdf [accessed 14 April 2019].

Fitzsimons, J.D., and O'Gorman, R. 2006. Status and assessment, research, and restoration needs for Lake Herring in the Great Lakes. Can. Tech. Rep. Fish. Aquat. Sci. 2638.

Gewurtz, S.B., Backus, A.M., and De Silva, A.O. 2013. Perfluoroalkyl acids in the Canadian environment: multi-media assessment of current status and trends. Environ. Int. **59**: 183-200. doi:10.1016/j.envint.2013.05.008.

GLFC (Great Lakes Fishery Commission). 1981. A joint strategic plan for management of Great Lakes fisheries [online]. Available from http://www.glfc.org/pubs/misc/jsp81.pdf [accessed 02 April 2019].

GLFC (Great Lakes Fishery Commission). 2007. A joint strategic plan for management of Great Lakes fisheries (as revised, 10 June 1997) [online]. Available from http://www.glfc.org/fishmgmt/jsp97.pdf [accessed 14 April 2019].

GLFC (Great Lakes Fishery Commission). 2012. Lake-level, five-year plans for achieving sea lamprey control targets in each great lake [online]. Available from http://www.glfc.org/pubs/slcp/LL_5YearPlan.pdf [accessed 14 April 2019].

Gobin, J., Lester, N.P., Cottrill, A., Fox, M.G., and Dunlop, E.S. 2015. Trends in growth and recruitment of Lake Huron lake whitefish during a period of ecosystem change, 1985 to 2012. J. Great Lakes Res. **41**: 405-414.

Gobin, J., Lester, N.P., Fox, M.G., and Dunlop, E.S. 2016. Effects of changes in density-dependent growth and recruitment on sustainable harvest of lake whitefish. J. Great Lakes Res. **42**: 871-882.

Hanson, S.D., Holey, M.E., Treska, T.J., Bronte, C.R., and Eggebraaten, T.H. 2013. Evidence of wild juvenile lake trout recruitment in western Lake Michigan. N. Am. J. Fish. Manage. **33**: 186-191.

Happel, A., Jonas, J.L., McKenna, P.R., Rinchard, J., He, J.X., and Czesny, S.J. 2017. Spatial variability of lake trout diets in Lakes Huron and Michigan revealed by stomach content and fatty acid profiles. Can. J. Fish. Aquat. Sci. **75**: 95-105.

Harris, B.S., Ruetz, III, C.R., Wieten, A.C., Altenritter, M.E., and Smith, K.M. 2017. Characteristics of lake sturgeon *Acipenser fulvescens* Rafinesque, 1817 in a tributary of Lake Michigan, USA: status of the Muskegon River population. J. Appl. Ichthyology. **33**: 338-346.

Hay-Chmielewski, E.M., and Whelan, G. [EDS.]. 1997. Lake sturgeon rehabilitation strategy. Mich. Dept. Nat. Resour., Fish. Div., Spec. Rep. No. 18.

Hayes, D.B., and Caroffino, D.C. [EDS]. 2012. Michigan's lake sturgeon rehabilitation strategy. Mich. Dept. Nat. Res., Fish. Spec. Rep. 62.

He, J.X., Bence, J.R., Johnson, J.E., Clapp, D.F., and Ebener, M.P. 2008. Modeling variation in mass-length relations and condition indices of lake trout and Chinook salmon in Lake Huron: a hierarchical bayesian approach. N. Am. J. Fish. Manage. **137**: 801-817.

Hensler, S.R., Jude, D.J., and He, J. 2008. Burbot growth and diets in Lakes Michigan and Huron: an ongoing shift from native species to round gobies. Am. Fish. Soc. Symp. **59**: 91-107.

Holey, M.E., and Trudeau, T.N. [EDS.]. 2005. The state of Lake Michigan in 2000. *Edited by* M.E. Holey and T.N. Trudeau [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf [accessed 14 April 2019].

Holey, M.E., Rybicki, R.W., Eck, G.W., Brown, Jr., E.H., Marsden, J.E., Lavis, D.S., Toneys, M.L., Trudeau, T.N., and Horrall, R.M. 1995. Progress toward lake trout restoration in Lake Michigan. J. Great Lakes Res. **21**: 128-151.

Howard, P.H., and Muir, D.C.G. 2013. Identifying new persistent and bioaccumulative organics among chemicals in commerce. III: byproducts, impurities, and transformation products. Environ. Sci. Technol. **47**: 5259–5266. doi:10.1021/es4004075.

Hubbs, C.L., and Lagler, K.F. 1958. Fishes of the Great Lakes region. Univ. Mich. Press, Ann Arbor, MI.

Huo, B., Madenjian, C.P., Xie, C.X., Zhao, Y., O'Brien, T.P., and Czesny, S.J. 2014. Age and growth of round gobies in Lake Michigan, with preliminary mortality estimation. J. Great. Lakes Res. **40**: 712-720.

Januchowski-Hartley, S.R., McIntyre, P.B., Deibel, M., Doran, P.J., Infante, D.M., Joseph, C., and Allan, J.D. 2013. Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. Front. Ecol. Environ. **11**: 211-217.

Johnson, J.E., Fielder, D.G., Hughes, M., and Espinoza, R. 2017. Pilot cisco egg take and culture study. Mich. Dept. Nat. Resour., Fish. Rep. 18.

Jonas, J.L., Clapp, D.F., Bence, J.R., and Holey, M.E. 2005. Salmonine community. *In* The state of Lake Michigan in 2000. *Edited by* M.E. Holey and T.N. Trudeau [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/Sp05_1.pdf [accessed 14 April 2019].

Jones, M., Clark, R., and Tsehaye, I. 2014. Workshops to revise and improve the Lake Michigan red flags analysis [online]. Available from https://www.canr.msu.edu/qfc/publications/pdf-publications/2014-publications/Jones%20-%20Workshops%20to%20revise%20and%20improve%20-%20with%20addendum.pdf [accessed 14 April 2019].

Kaemingk, M.A., Galarowicz, T.L., Clevenger, J.A., Clapp, D.F., and Lenon, H.L. 2012. Fish assemblage shifts and population dynamics of smallmouth bass in the Beaver Archipelago, northern Lake Michigan: a comparison between historical and recent time periods amidst ecosystem changes. Trans. Am. Fish. Soc. **141**: 550-559.

Kay, J.J. 1990. A non-equilibrium thermodynamic framework for discussing ecosystem integrity. *In* An ecosystem approach to the integrity of the great lakes in turbulent times. *Edited by* C.J. Edwards and H.A. Regier [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp90_4.pdf [accessed 14 April 2019].

Koelz, W. 1929. Coregonid fishes of the Great Lakes. Bull. U.S. Bureau Fish. **1048**: 297-643.

Kornis, M.S., Mercado-Silva, N., and Vander Zanden, M.J. 2012. Twenty years of invasion: a review of round goby *Neogobius melanostomus* biology, spread and ecological implications. J. Fish Biol. **80**: 235-285.

Kratzer, J.F., Taylor, W.W., Turner, M. 2007. Factors affecting growth of lake whitefish in the upper Laurentian Great Lakes. Adv. Limnol. **60**: 459-470.

Kreis, R.G., Zhang, X., Zhang, X., Murphy, E., Rygwelski, K.R., Rossmann, R., Warren, G., Horvatin, P., and Hinchey, E.K. 2009. Lake Michigan mass balance study post audit: integrated, multi-media PCB modeling and forecasting for lake trout. Presented at 6th Biennial Lake Michigan State of the Lake Conference, Milwaukee, WI, September 29-October 01, 2009.

Lavis, D.S., Henson, M.P., Johnson, D.A., Koon, E.M., and Ollila, D.J. 2003. A case history of sea lamprey control in Lake Michigan: 1979-1999. J. Great Lakes Res. **29**(Suppl. 1): 584-598.

Lawrence, D.A. 2015. Production, drift behavior and morphological analysis of outmigrating larval lake sturgeon in the Menominee and Oconto Rivers, Wisconsin. M.S. Thesis. Univ. Wis. Green Bay.

Li, Y., Bence, J.R., and Brenden, T.O. 2015. An evaluation of alternative assessment approaches for intermixing fish populations: a case study with Great Lakes lake whitefish. ICES J. Marine Sci. **72**: 70-81.

Li, Y., Bence, J.R., Zhang, Z., and Ebener, M.P. 2017. Why do lake whitefish move long distances in Lake Huron? Bayesian variable selection of factors explaining fish movement distance. Fish. Res. **195**: 169-179.

LRBOI (Little River Band of Ottawa Indians). 2008. Nmé (lake sturgeon) stewardship plan for the Big Manistee River and 1836 reservation. Nat. Resour. Dept., Spec. Rep. 1, Manistee, MI.

LRBOI (Little River Band of Ottawa Indians). 2013. Mortality of age-0 lake sturgeon post-sea lamprey treatment in the Big Manistee River, Michigan. Spec. Tech. Rep. Aug. 2013, Manistee, MI.

LRBOI (Little River Band of Ottawa Indians). 2014. Assessment of age-0 lake sturgeon pre and post sea lamprey treatment in the Muskegon River, Michigan. Spec. Tech. Rep. October 2014, Manistee, MI.

LRBOI (Little River Band of Ottawa Indians). 2016. Final report of lake sturgeon research and reclamation activities: 215. Little River Band Ottawa Indians Rep. 2015-1, Manistee, MI.

Madenjian, C.P., O'Gorman, R., Bunnell, D.B., Argyle, R.L., Roseman, E.F., Warner, D.M., Stockwell, J.D., and Stapanian, M.A. 2008. Adverse effects of alewives on Laurentian Great Lakes fish communities. N. Am. J. Fish. Manage. **28**: 263-282.

Madenjian, C.P., Rutherford, E.S., Blouin, M.A., Sederberg, B.J., and Elliott, J.R. 2011. Spawning habitat unsuitability: an impediment to cisco rehabilitation in Lake Michigan. N. Am. J. Fish. Manage. **31**: 905-913.

Madenjian, C.P., Bunnell, D.B., Warner, D.M., Pothoven, S.A., Fahnenstiel, G.L. Nalepa, T.F. Vanderploeg, H.A., Tsehaye, I., Claramunt, R.M., and Clark, Jr., R.D. 2015a. Changes in the Lake Michigan food web following dreissenid mussel invasions: a synthesis. J. Great Lakes Res. **41**(Suppl. 3): 217-231.

Madenjian, C.P., Ebener, M.P., and Sepulveda, M. 2015b. PCB concentrations of lake whitefish (*Coregonus clupeaformis*) vary by sex. J. Great Lakes Res. **41**: 1185-1190. doi:10.1016/j.jglr.2015.09.010.

Madenjian, C.P., Ebener, M.P., and Krabbenhoft, D.P. 2016. Mercury accumulation, and the mercury-PCB-sex interaction, in lake whitefish (*Coregonus clupeaformis*). Environments **3**(1): doi:10.3390/ environments3010007.

Mann, K. and Elliott, R. 2016. Draft report, age 0 lake sturgeon abundance and distribution in the Peshtigo River, Wisc. Green Bay Fish Wildl. Conserv. Office, New Franken, WI.

McGoldrick, D.J., and Murphy, E.W. 2015. Concentration and distribution of contaminants in lake trout and walleye from the Laurentian Great Lakes (2008-2012). Environ. Pollut. **217**: 85-96. doi:10.1016/j.envpol.2015.12.019.

Modeling Subcommittee, Technical Fisheries Committee. 2016. Technical fisheries committee administrative report 2016: status of lake trout and lake whitefish populations in the 1836 treaty-ceded waters of Lakes Superior, Huron and Michigan, with recommended yield and effort levels for 2016 [online]. Available from https://www.michigan.gov/documents/dnr/2016StatusStocksReport_533811_7.pdf [accessed 14 April 2019].

Molton, K.J., Brenden, T.O., and Bence, J.R. 2012. Control rule performance for intermixing lake whitefish populations in the 1836 treaty waters of the Great Lakes: a simulation-based evaluation. J. Great Lakes Res. **38**: 686-698.

Moody, A.T., Neeson, T.M., Wangen, S., Dischler, J., Diebel, M.W., Herbert, M., Khoury, M., Yacobson, E., Doran, P.J., Ferris, M.C., and 2 others. 2017. Pet project or best project? online decision support tools for prioritizing barrier removals in the Great Lakes and beyond. Fisheries **42**(1):57-65.

Mullett, K.A., Heinrich, J.W., Adams, J.V., Young, R.J., Henson, M.P., McDonald, R.B., and Fodale, M.F. 2003. Estimating lake-wide abundance of spawning-phase sea lampreys (*Petromyzon marinus*) in the Great Lakes: extrapolating from sampled streams using regression models. J. Great Lakes Res. **29**(Supple. 1): 240-252.

Nalepa, T.F., Fanslow, D.L., and Lang, G.A. 2009. Transformation of the offshore benthic community in Lake Michigan: a recent shift from the native amphipod *Diporeia* spp. to the invasive mussel *Dreissena rostriformis bugensis*. Fresh. Biol. **54**: 466-479.

Nathan, L.R., Sloss, B.L., VanDeHey, J.A., Andvik, R.T., Claramunt, R.M., Hansen, S., and Sutton, T.M. 2016. Temporal stability of lake whitefish genetic stocks in Lake Michigan. J. Great Lakes Res. **42**: 433-439.

Patterson, K.A., Stein, J.A., and Robillard, S.R. 2016. Progress toward lake trout rehabilitation at a stocked and unstocked reef in southern Lake Michigan. N. Am. J. Fish. Manage. **36**: 1405-1415.

Pothoven, S.A., Nalepa, T.F., Schneeberger, P.J., and Brandt, S.B. 2001. Changes in diet and body condition of lake whitefish in southern Lake Michigan associated with changes in benthos. N. Am. J. Fish. Manage. **21**: 876-883.

Rasmussen, P.W., Schrank, C., and Williams, M.C.W. 2014. Trends of PCB concentrations in Lake Michigan coho and Chinook salmon, 1975-2015. J. Great Lakes Res. **40**: 748-754. doi:10.1016/j.jglr.2014.05.011.

Redman, R., Mackey, S., Dub, J., and Czesny, S. 2017. Lake trout spawning habitat suitability at two offshore reefs in Illinois waters of Lake Michigan. J. Great Lakes Res. **43**: 335-344. doi:10.1016/j.jglr.2017.01.003.

Rennie, M.D., Sprules, W.G., and Johnson, T.B. 2009. Factors affecting the growth and condition of lake whitefish (*Coregonus clupeaformis*). Can. J. Fish. Aquat. Sci. **66**: 2096-2108.

Riley, S.C., Roseman, E.F., Nichols, S.J., and O'Brien, T.P. 2008. Deepwater demersal fish community collapse in Lake Huron. Trans. Am. Fish. Soc. **137**: 1879-1890.

Riley, S.C., Rinchard, J., Honeyfield, D.C., Evans, A.N., and Begnoche, L. 2011. Increasing thiamine concentrations in lake trout eggs from Lakes Huron and Michigan coincide with low alewife abundance. N. Am. J. Fish. Manage. **31**: 1052-1064.

Robillard, S.R., Breidert, B., Eggold, B.T., Gorenflo, T.K., and Wesley, J. 2012. Conclusions. *In* The state of Lake Michigan in 2011. *Edited by* D.B. Bunnell [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp12_1.pdf [accessed 14 April 2019].

Rutherford, E., Marshall, E., Clapp, D., Horns, W., Gorenflo, T., and Trudeau, T. 2005. Lake Michigan environmental objectives [online]. Available from http://www.glfc.org/pubs/lake_committees/michigan/lmenvironobj.pdf [accessed 14 April 2019].

Schneeberger, P., Toneys, M., Elliott, R., Jonas, J., Clapp, D., Hess, R., and Passino-Reader, D. 1998. Lakewide assessment plan for Lake Michigan fish communities [online]. Available from http://www.glfc.org/pubs/lake_committees/michigan/lwasses01.pdf [accessed 14 April 2019].

Scott, W.B., and Crossman, E.J. 1973. Freshwater fishes of Canada. Vol. 184. Ottawa, Ontario. Fish. Res. Board Can. Bull. 960 pp.

Seelye, J.G., Johnson, D.A., Weise, J.G., and King, Jr., E.L. 1988. Guide for determining application rates of lampricides for control of sea lamprey ammocoetes [online]. Available from http://www.glfc.org/pubs/TechReports/Tr52.pdf [accessed 14 April 2019].

Siefkes, M.J., Steeves, T.B., Sullivan, W.P., Twohey, M.B., and Li, W. 2013. Sea lamprey control: past, present, and future [online]. Available from http://www.uvm.edu/rsenr/wfb117/Siefkes%20et%20al.%202014%20lamprey%20chapter%20proofs.pdf [accessed 14 April 2019].

Smith, K. 2014. 2014 Assessment of age-0 lake sturgeon in the Muskegon River, Michigan. Mich. Dept. Nat. Res.

Smith, S.H. 1964. Status of the deepwater cisco populations of Lake Michigan. Trans. Am. Fish. Soc. **93**:155-163.

Smith, B.R., and Tibbles, J.J. 1980. Sea lamprey (*Petromyzon marinus*) in Lakes Huron, Michigan, and Superior: history of invasion and control, 1936-78. Can. J. Fish. Aquat. Sci. **37**: 1780-1801.

Swanson, H.K., Lysy, M., Power, M., Stasko, A.D., Johnson, J.D., and Reist, J.D. 2015. A new probabilistic method for quantifying *n*-dimensional ecological niches and niche overlap. Ecology **96**: 318-324.

Tillitt, D.E., Zajicek, J.L., Brown, S.B., Brown, L.R., Fitzsimons, J.D., and Honeyfield, D.C. 2005. Thiamine and thiaminase status in forage fish of salmonines from Lake Michigan. J. Aquat. Anim. Health **17**: 13-25.

Todd, T.N., and Smith, G.R. 1992. A review of differentiation in Great Lakes ciscoes. Polish Arch. Hydrobio. **39**: 261-267.

Tsehaye, I., Jones, M.L., Bence, J.R., Brenden, T.O., Madenjian, C.P., and Warner, D.M. 2014a. A multispecies statistical age-structured model to assess predator-prey balance: application to an intensively managed Lake Michigan pelagic fish community. Can. J. Fish. Aquat. Sci. **71**: 627-644.

Tsehaye, I., Jones, M.L., Brenden, T.O., Bence, J.R., and Claramunt, R.M. 2014b. Changes in the salmonine community of Lake Michigan and their implications for predator-prey balance. Trans. Am. Fish. Soc. **143**: 420-437.

Turschak, B.A., and Bootsma, H.A. 2015. Lake Michigan trophic structure as revealed by stable C and N isotopes. J. Great Lakes Res. **41**: 185-196.

Turschak, B.A., Bunnell, D., Czesny, S., Hook, T.O., Janssen, J., Warner, D., and Bootsma, H.A. 2014. Nearshore energy subsidies support Lake Michigan fishes and invertebrates following major changes in food web structure. Ecology **95**: 1243-1252.

Wells, L., and McLain, A.L. 1973. Lake Michigan: man's effects on native fish stocks and other biota [online]. Available from http://www.glfc.org/pubs/TechReports/Tr20.pdf [accessed 14 April 2019].

Welsh, A., Elliott, R., Scribner, K., Quinlan, H., Baker, E., Eggold, B., Holtgren, M., Krueger, C., and May, B. 2010. Genetic guidelines for the stocking of lake sturgeon (*Acipenser fulvescens*) in the Great Lakes basin [online]. Available from http://www.glfc.org/pubs/misc/2010-01.pdf [accessed 14 April 2019].

Williams, M.C.W., and Schrank, C. 2015. Polybrominated diphenyl ethers (PBDEs) in Wisconsin fish: 2002-2012 [online]. Available from http://dnr.wi.gov/files/PDF/pubs/fh/AdminReports/FH077.pdf [accessed 14 April 2019].

Williams, M.C.W., and Schrank, C. 2016. Perfluorinated compounds (PFCs) in fish from Wisconsin's major rivers and Great Lakes [online]. Available from http://dnr.wi.gov/files/PDF/pubs/fh/AdminReports/FH083.pdf [accessed 14 April 2019].

Xia, X., Hopke, P.K., Holsen, T.M., and Crimmins, B.S. 2011a. Modeling toxaphene behavior in the Great Lakes. Sci. Total Environ. **409**: 92-799. doi:10.1016/j.scitotenv.2010.10.051.

Xia, X., Hopke, P.K., Crimmins, B.S., Pagano, J.J., Milligan, M.S., and Holsen, T.M. 2011b. Toxaphene trends in the Great Lakes fish. J. Great Lakes Res. **38**: 31-38. doi:10.1016/j.jglr.2011.11.001.

Yule, D.L., Moore, S.A., Ebener, M.P., Claramunt, R.M., Pratt, T.C., and Salawater, L.L. 2013. Morphometric variation among spawning cisco aggregations in the upper Great Lakes: are historic forms still present? Adv. Limn. **64**: 119-132.

Zananski, T.J., Holsen, T.M., Hopke, P.K., and Crimmins, B.S. 2011. Mercury temporal trends in top predator fish of the Laurentian Great Lakes. Ecotoxicology **20**: 1568-1576. doi:10.1007/s10646-011-0751-9.

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