THE STATE OF LAKE ERIE IN 2015

Great Lakes Fishery Commission

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THE STATE OF LAKE ERIE IN 2015

Special Editors

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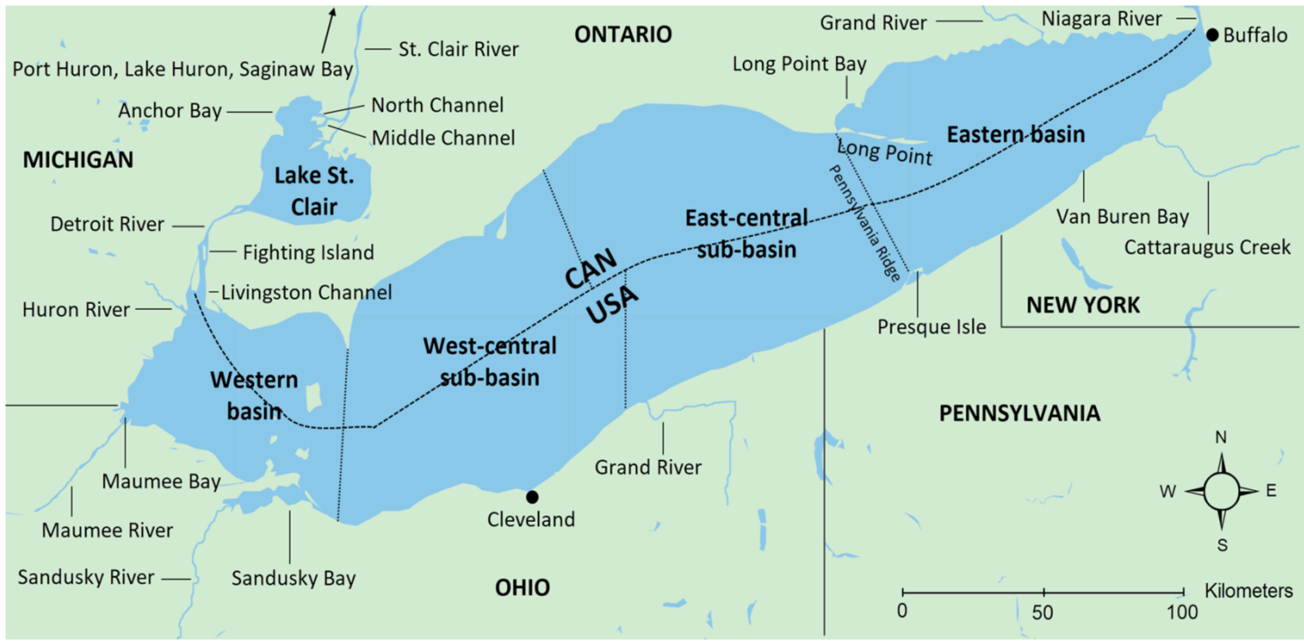
Frontispiece. Map of Lake Erie showing the eastern and western basins, two sub-basins of the central basin, international boundary line, and major geographical features.



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ABSTRACT[3]

The inaugural state of the lake report for Lake Erie covered information collected largely through 2003, and the second report covered information collected in 2004-2008. This third state of the lake report uses information collected in 2009-2015 to assess progress toward meeting fish community objectives (FCOs) established by the Lake Erie Committee (LEC) of the Great Lakes Fishery Commission. The LEC, comprised of representatives of fisheries management agencies from the five jurisdictions bordering the lake—Michigan, New York, Ohio, Ontario, and Pennsylvania—established fish community goals and objectives in 2003 to help coordinate and guide agency efforts for collective fishery benefits. The goals call for having mesotrophic and oligotrophic conditions in Lake Erie with habitats that support balanced, well-functioning fish communities for the benefit of associated fisheries. The first goal is that mesotrophic waters in the western basin, central basin, and nearshore eastern basin should have a cool-water fish community with Walleye (*Sander vitreus*) as a key predator. A second goal is that oligotrophic waters offshore in the eastern basin should have a cold-water fish community with Lake Trout (*Salvelinus namaycush*) and Burbot (*Lota lota*) as key predators. Achievement of these goals is predicated on making progress toward 13 objectives aimed at sustaining valuable fisheries in all five

[3]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

jurisdictions. These objectives are intended to ensure suitable environmental conditions and habitats that can support key predators and their prey, interacting through a well-functioning food web. As of 2015, none of the 13 FCOs were deemed fully attained. Seven FCOs that addressed ecosystem conditions, various habitats, contaminants, and genetic diversity of fish stocks were considered partially achieved. Six FCOs that addressed basin-specific sustainable harvests of fish stocks, food-web structure, productivity and fishery yield, and protection of rare fish species were mostly achieved. One rare fish species, Lake Sturgeon (*Acipenser fulvescens*), continued to show signs of improvement during 2009-2015 with successful spawning documented on constructed reefs in the St. Clair-Detroit River System (SCDRS). However, another rare fish species, Cisco (*Coregonus artedi*), showed no sign of improvement as the few individuals captured appear to be migrants from Lake Huron and not from a remnant Lake Erie stock. Compared to 2004-2008, in 2009-2015, the average annual fishery yield of Lake Whitefish (*C. clupeaformis*) and Walleye declined, yield of Rainbow Smelt (*Osmerus mordax*) and White Bass (*Morone chrysops*) rose, and yield of Yellow Perch (*Perca flavescens*) changed little. The cool-water fish community persisted with Walleye as the top predator lakewide. A new lakewide habitat suitability map was produced for juvenile and adult Walleye. Total phosphorus (TP) and water transparency failed to meet the LEC's FCOs in the western basin whereas they mostly met or were close to the FCOs in the central and eastern basins. High loadings of dissolved reactive phosphorus (DRP) to the western basin, especially in years when TP was also high, were the likely cause of four of the largest harmful algal blooms (HABs) ever recorded, each of which occurred during 2011-2015. The large HABs were linked to increasing incidents of hypoxia in the central basin. Improvements in environmental conditions through management of phosphorus loads into the western basin are needed to fulfill the fish community goal. In the eastern basin, the cold-water fish community experienced generally suitable oligotrophic conditions. Abundance of adult (≥age 5) Lake Trout peaked in 2015 and was above the rehabilitation goal for the second consecutive year due to successful stockings of Lake Champlain-strain fish in earlier years. However, no natural recruitment was detected. Burbot abundance was substantially lower in 2009-2015 than in 2004-2008. Lake Trout and Burbot suffer high mortality from Sea Lamprey (*Petromyzon marinus*), and lamprey numbers, despite an increasingly aggressive control regime, were well above target as were lamprey marks on Lake Trout. Cold-water predators eat mainly exotic Rainbow Smelt and Round Goby (*Neogobius melanostomus*) in the absence of native *Diporeia* spp. and Cisco. Restoration of a naturally reproducing and abundant Lake Trout population and improved recruitment of Burbot are needed to fulfill the cold-water fish community goal.

Management efforts to address recommendations from this second state of the lake report include several key accomplishments during 2009-2015. Interagency monitoring programs that assess multiple trophic levels were continued in all three of Lake Erie's basins. Modeling efforts to improve percid stock assessments were continued with the Quantitative Fisheries Center at Michigan State University. Research was initiated at several universities on genetic and microchemistry techniques to identify discrete percid stocks, and research was supported that leveraged the strengths of the Great Lakes Acoustic Telemetry Observation System to better understand percid spatial ecology in relation to environmental stressors. Environmental objectives were developed in support of the LEC's FCOs. A Cisco rehabilitation plan was developed that outlines a framework for restoration. An LEC position statement was completed on offshore wind-power development. Projects were initiated in the SCDRS to improve fish habitats of potential use by Lake Erie fish. Strategies were implemented to promote assessment of data-poor fisheries, such as those for Lake Whitefish and White Bass. A new fishery management plan was developed for Yellow Perch, and lastly, a new fishery management plan was implemented for Walleye. The LEC remains committed to achieving fish community stability through management—promoting healthy stocks of top predators, minimizing impacts from invasive species, and protecting and/or restoring important coastal nearshore and tributary habitats. Emerging issues of concern include HABs precipitated by increases in DRP, Grass Carp (*Ctenopharlyngodon idella*), climate change, and Sea Lamprey production in the SCDRS.

Priorities for the next five years are to (1) continue to work with relevant partners to reduce DRP loads to levels that prevent HABs and minimize hypoxia in the western and central basins; (2) continue efforts to attain the LEC environmental objectives and address habitat issues throughout the Lake Erie basin; (3) support research to inform Lake Erie fisheries management of the effects of climate change and invasive species; (4) support research that reduces knowledge gaps surrounding interactions between environmental variables and fish populations; (5) support research on percid stock discrimination and behavior (tagging), recruitment mechanisms, and mechanisms affecting food webs and fish community structure in each basin; (6) support Sea Lamprey control to attain the allowable maximum number of spawning-phase Sea Lamprey and of marking rate on Lake Trout; (7) continue efforts to better understand the role of the SCDRS as a source of Sea Lamprey to Lake Erie; and (8) continue to develop sustainable harvest policies for Walleye and Yellow Perch stocks that meet FCOs and stakeholders' needs while accounting for changing environmental conditions and highly variable recruitment.

INTRODUCTION TO THE STATE OF LAKE ERIE IN 2015[4]

Richard Drouin[5]

This state of Lake Erie (SOLE) report is the third in a sequence of state of the lake reports designed to evaluate progress toward achieving the fish community goals and objectives for Lake Erie (Ryan et al. 2003). The first SOLE report covered 1999-2003 and focused on the status of the forage base, key top-predator fish populations, Sea Lamprey control (see Table 1 for common and scientific names of fish and their role in the food web), habitat management, and emerging issues of the time (Tyson et al. 2009). The second SOLE report presented information collected during 2004-2008 and focused on status and trends in each of the lake's three basins, including changes in the ecosystem and habitat that influence structure of the lower food web, changes in the fish communities, and changes in associated fisheries (Markham and Knight 2017). This report focuses on information presented at the 2015 state of the lake conference and compares status and trends from 2009-2015 to those presented in the 2004-2008 report, summarizing the status in 2009-2015 of the ecosystem and associated cool- and cold-water fish. This report will also review the actions taken by the Lake Erie Committee (LEC) of the Great Lakes Fishery Commission and its

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[4]Complete publication including maps of place names, abstract, other chapters, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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partners to address recommendations and priorities identified in the second SOLE report (2009) (Markham and Knight 2017).

Description of Lake Erie and Its Fish Communities

Lake Erie is the shallowest and most southerly of all the Great Lakes. It has three distinct basins (western, central, and eastern) that differ in shape, depth, hydrology, and productivity. Nutrient inputs differ among basins influencing the range of trophic conditions and fish communities present across the lake. The western and central basins of Lake Erie are generally considered mesotrophic and are dominated by cool-water percid fisheries (Walleye and Yellow Perch) whereas the eastern basin of Lake Erie is less productive and is generally characterized as oligotrophic and more suitable for cold-water fish like Lake Trout, Lake Whitefish, and Burbot.

The LEC's fish community objectives (FCOs) recognize that the lake's trophic state varies along a continuum of productivity ranges, both from west to east and from nearshore to offshore. Under mesotrophic conditions, Lake Erie can support a cool-water fish community consisting of Walleye, Yellow Perch, Smallmouth Bass, Northern Pike, and Muskellunge with a forage base dominated by shiners, primarily Emerald Shiner. However, measures of three lower trophic indicators (total phosphorous, transparency, chlorophyll *a*) indicate that the western basin of Lake Erie has shifted to a eutrophic state (FTG 2015). Eutrophic conditions generally favor a centrarchid fish community dominated by black bass and sunfish but with numerous other fish, including White Bass, White Perch, Channel Catfish, and Freshwater Drum and a forage base dominated by Gizzard Shad. The offshore waters of the eastern basin remain within the oligotrophic range required to support a cold-water salmonid community consisting of Lake Trout, Lake Whitefish, Burbot, and Rainbow Trout. The eastern-basin forage community is dominated by Rainbow Smelt.

There are several ongoing stressors that continue to play an important role in shaping Lake Erie’s ecosystem and its ability to support desired fish communities. Nutrient enrichment and associated algae blooms are once again a priority focus for Lake Erie. Allan et al. (2015) identified seven categories of Great Lake stressors, including habitat modification, coastal development, climate change, and nonpoint-source and toxic-chemical pollution. Mapping these cumulative stressors indicates that nearshore coastal areas like river mouths, estuaries, and wetlands are still the area’s most vulnerable to anthropogenic stressors. As identified in the 2009 SOLE report (Markham and Knight 2017), continued modification and degradation of these areas may influence recruitment patterns and stock sizes, especially of those fish that depend on these habitats. Lastly, invasive species continue to threaten the integrity of Lake Erie’s fish communities. Sea Lamprey numbers remain above management targets and Asian carps—Bighead Carp, Black Carp, Silver Carp, and Grass Carp—threaten to colonize the lake. Suppressing Sea Lamprey and preventing establishment of Asian carps, along with efforts to detect their presence and to respond to reported captures, remain top priorities.

Table 1. Common and scientific names of Lake Erie fish (indigenous, introduced, invasive) referenced in this report, their role in the food web as adults, and their current fishery use (commercial, recreational, both = commercial and recreational; protected; none; N/A = not applicable).

Common Name	Scientific Name	Role in Food Web	Fishery Use
Indigenous fish:			
Black bass	*Micropterus* spp.	Omnivore	Recreational
Burbot	*Lota lota*	Benthic piscivore	Both
Channel Catfish	*Ictalurus punctatus*	Nearshore omnivore	Both
Cisco	*Coregonus artedi*	Pelagic planktivore	Protected
Emerald Shiner	*Notropis athernoides*	Pelagic planktivore	Commercial
Freshwater Drum	*Aplodinotus grunniens*	Benthic omnivore	Both
Gizzard Shad	*Dorosoma cepedianum*	Pelagic planktivore	Commercial
Lake Sturgeon	*Acipenser fulvescens*	Benthic omnivore	Protected
Lake Trout	*Salvelinus namaycush*	Offshore piscivore	Recreational
Lake Whitefish	*Coregonus clupeaformis*	Benthic omnivore	Commercial
Largemouth Bass	*Micropterus salmoides*	Omnivore	Recreational
Muskellunge	*Esox masquinongy*	Nearshore piscivore	Recreational
Northern Pike	*Esox lucius*	Nearshore piscivore	Recreational
Northern Madtom	*Noturus stigmosus*	Benthivore	None
Shiner	*Notropis* spp.	Planktivore	Commercial

Common Name	Scientific Name	Role in Food Web	Fishery Use
Indigenous fish:			
Smallmouth Bass	*Micropterus dolomieu*	Omnivore	Recreational
Sunfish	*Lepomis* spp.	Nearshore omnivore	Recreational
Trout-Perch	*Percopsis omiscomaycus*	Benthic planktivore	None
Walleye	*Sander vitreus*	Piscivore	Both
White Bass	*Morone chrysops*	Pelagic piscivore	Both
Yellow Perch	*Perca flavescens*	Benthic omnivore	Both
Introduced fish:			
Rainbow Smelt	*Osmerus mordax*	Benthic planktivore	Commercial
Rainbow Trout	*Oncorhynchus mykiss*	Pelagic omnivore	Recreational
Invasive species:			
Alewife	*Alosa pseudoharengus*	Pelagic planktivore	None
Bighead Carp[1]	*Hypophthalmichthys nobilis*	Planktivore	N/A
Black Carp[1]	*Mylopharyngodon piceus*	Molluscivore	N/A
Grass Carp[1]	*Ctenopharyngodon idella*	Herbivore	None
Round Goby	*Neogobius melanostomus*	Benthic omnivore	None

Common Name	Scientific Name	Role in Food Web	Fishery Use
Invasive species:			
Sea Lamprey	*Petromyzon marinus*	Ectoparasite of fish	None
Silver Carp[1]	*Hypophthalmichthys molitrix*	Planktivore	N/A
White Perch	*Morone americana*	Pelagic omnivore	Both

[1]Of the four invasive Asian carps (Bighead Carp, Black Carp, Grass Carp, Silver Carp), only the Grass Carp is currently found in Lake Erie, and it is too rare to be purposely exploited by the fisheries.

Goals and Fish Community Objectives of the Lake Erie Committee

The LEC comprises representatives from the five fisheries management agencies surrounding the Lake Erie basin—the Michigan DNR, the Ohio DNR, the Pennsylvania Fish and Boat Commission, the New York State Department of Environmental Conservation, and the Ontario Ministry of Natural Resources and Forestry. The LEC seeks to establish a balanced, stable, and predictable fish community in each of the lake's three basins most suited to that basin's trophic status. In 2003, the LEC established two broad fish community goals with the ultimate purpose of providing valuable long-term sustainable fisheries. Success at meeting these goals is based on progress toward meeting the 13 FCOs (Ryan et al. 2003) and ensuring suitable environmental conditions, which support the key predator and prey species required to sustain valuable fisheries in all jurisdictions on the lake.

The LEC's goals are

- To secure a balanced, predominantly cool-water fish community with Walleye as a key predator in the western basin, central basin, and the nearshore waters of the eastern basin, characterized by self-sustaining indigenous and naturalized species that occupy diverse habitats, provide valuable fisheries, and reflect a healthy ecosystem
- To secure a predominantly cold-water fish community in the deep offshore waters of the eastern basin with Lake Trout and Burbot as key predators

The FCOs of the LEC (Ryan et al. 2003) are

a. *Ecosystem conditions—maintain mesotrophic conditions (10-20 µg•L^{-1} phosphorus) that favor a dominance of cool-water organisms in the western, central, and nearshore waters of the eastern basin; summer water transparencies should range from 3-5 m (9.75-16.25 ft) in mesotrophic areas*

b. *Productivity and yield—secure a potential annual sustainable harvest of 13.6-27.3 million kg (30-60 million lbs) of highly valued fish*

c. *Nearshore habitat—maintain nearshore habitats that can support high quality fisheries for smallmouth bass, northern pike, muskellunge, yellow perch, and walleye*

d. *Riverine and estuarine habitat—protect and restore self-sustaining, stream-spawning stocks of walleye, white bass, lake sturgeon, and rainbow trout*

e. *Western basin—provide sustainable harvests of walleye, yellow perch, smallmouth bass, and other desired fish* *f.* *Central basin—provide sustainable harvests of walleye, yellow perch, smallmouth bass, rainbow smelt, rainbow trout, and other desired fish*

g. *Eastern basin—provide sustainable harvests of walleye, smallmouth bass, yellow perch, lake whitefish, rainbow smelt, lake trout, rainbow trout, and other salmonids; restore a self-sustaining population of lake trout to historical levels of abundance*

h. *Contaminants—reduce contaminants in all fish species to levels that require no advisory for human consumption and that cause no detrimental effects on fish-eating wildlife, fish behavior, fish productivity, and fish reproduction*

i. *Fish habitat—protect, enhance, and restore fish habitat throughout the watershed to prevent degradation and foster restoration of the fish community*

j. *Genetic diversity—maintain and promote genetic diversity by identifying, rehabilitating, conserving, and/or protecting locally adapted stocks*

k. *Rare, threatened, and endangered species—prevent extinction by protecting rare, threatened, and endangered fish species (for example, lake sturgeon and cisco) and their habitats*

l. *Forage fish—maintain a diversity of forage fish to support terminal predators and to sustain human use*

m. *Food web structure—manage the food web structure of Lake Erie to optimize production of highly valued fish species; recognize the importance of* Diporeia *and* Hexagenia *as key species in the food web and as important indicators of habitat suitability*

The LEC fish community goals and the underlying FCOs are intended to support a functioning ecosystem with balanced fish communities under the premise that a food web with interactions among co-evolved species will provide stable, resilient, predictable fish communities and the desired yields from associated fisheries. Therefore, an assessment of key habitat metrics and key organisms in the Lake Erie food web, particularly those that support top predators, provides insight into the stability and predictability of the fish community and related fisheries. This report provides such an assessment along with documenting progress toward meeting the FCOs since the last reporting period. The report also serves to focus attention on emerging issues critical to Lake Erie's fish communities.

ENVIRONMENTAL CONDITIONS IN LAKE ERIE IN 2015[6]

Geoffrey B. Steinhart, Zy Biesinger, and James L. Markham[7]

Lake Erie, the shallowest and most productive of the Great Lakes, has experienced substantial changes to its environment. The human population in the surrounding area has increased more than ten-fold from 1860 to today, resulting in widespread habitat changes and increased pollution. For example, approximately 90% of the wetlands around Lake Erie have been drained, diked, or destroyed by human activities (Herdendorf 1987). The loss of natural filtering of wetlands combined with increases in nutrient inputs from agriculture runoff and sewage caused large-scale shifts from oligotrophy and mesotrophy to eutrophy and hyper-eutrophy (Ryan et al. 2003). Algal blooms and hypoxia became common, and, ultimately, the lake was labeled as "dead" in the 1960s (Sweeny 1993; Scavia et al. 2014).

The United States and Canada signed the Great Lakes Water Quality Agreement (GLWQA) in 1972, which established phosphorus loading limits

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[6]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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in Lake Erie to control phytoplankton abundance and reduce hypoxia. Annual load targets for total phosphorus (TP) were set at 11,000 t•year^{-1} (Ryan et al. 2003), much lower than the annual loadings estimated for the early 1970s when they exceeded 20,000 t (Gopalan et al. 1998). Improved land use and wastewater practices reduced TP loadings 55% by the mid-1980s. The Lake Erie fish community, especially Walleye and Yellow Perch populations, responded positively to these changes beginning in the late 1970s and through the 1990s, although the mechanisms for the response were not clear (Knight 1997; Ludsin et al. 2001). The arrival of dreissenids (zebra mussel, *Dreissena polymorpha*, and quagga mussel, *D. bugensis*) in 1987 brought additional changes to Lake Erie. Phytoplankton biomass declined 68-86% (Makarewicz 1993), and primary production declined 22-55% (Millard et al. 1999). The combined effects of the GLWQA and dreissenid proliferation caused Lake Erie's western basin to return to a mesotrophic state. The central basin became oligotrophic (Bertram 1993), and the eastern basin periodically became ultra-oligotrophic. Both changes adversely affected Yellow Perch (Charlton 1994; MacDougall et al. 2001). In recent years, however, trophic conditions in Lake Erie changed once again. Cyanobacteria blooms (*Microcystis* spp.) returned to the western basin, possibly due to increased dissolved reactive phosphorus (DRP), despite TP loading remaining below targets (Scavia et al. 2014; Kane et al. 2014). In 1999, the Lake Erie Forage Task Group initiated annual assessments of lower trophic levels to aid scientists and managers by measuring conditions and documenting changes in the ecosystem. The assessment program comprises 18 stations lakewide where water-column profiles are made of temperature, dissolved oxygen (DO), light level, water transparency (Secchi depth), TP, chlorophyll *a*, phytoplankton, and zooplankton. Benthos are also sampled. Here we present data summaries for several of these lower-trophic parameters and relate them to the FCOs of the LEC (Ryan et al. 2003).

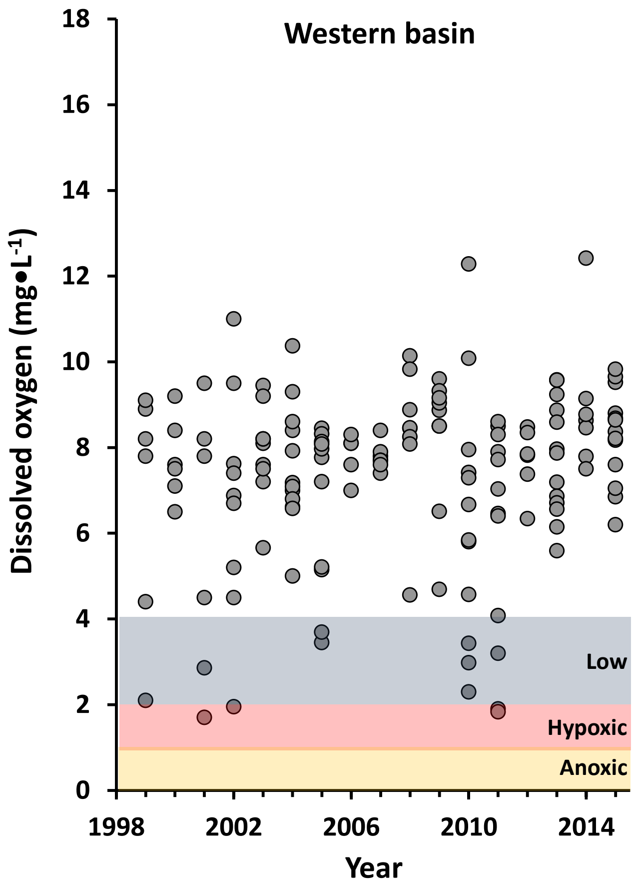
Hypolimnetic Dissolved Oxygen

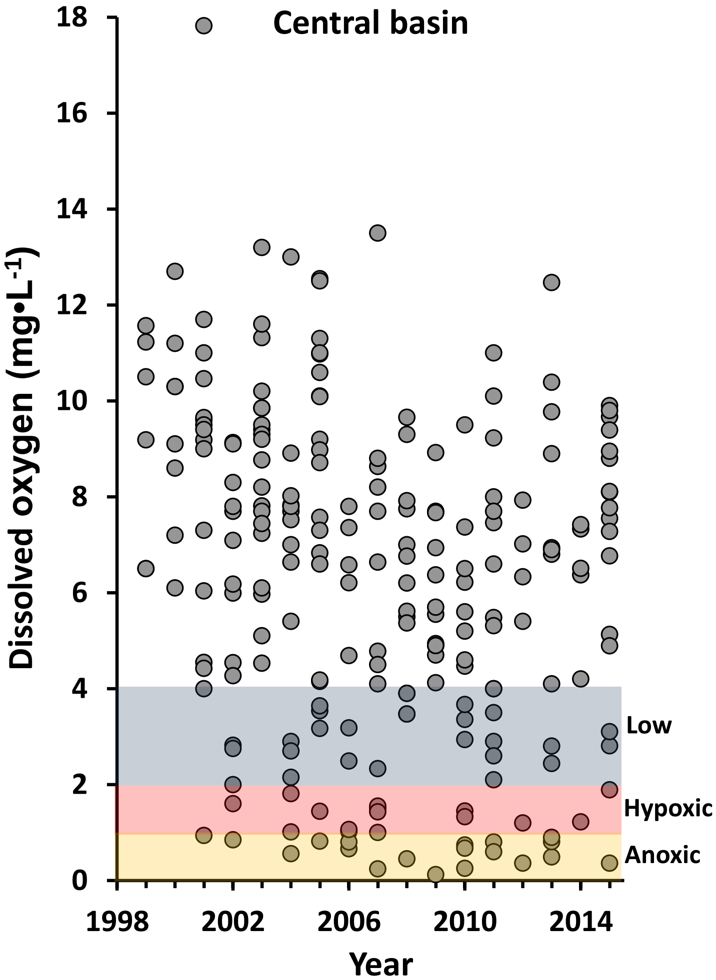
…protect, enhance, and restore fish habitat…

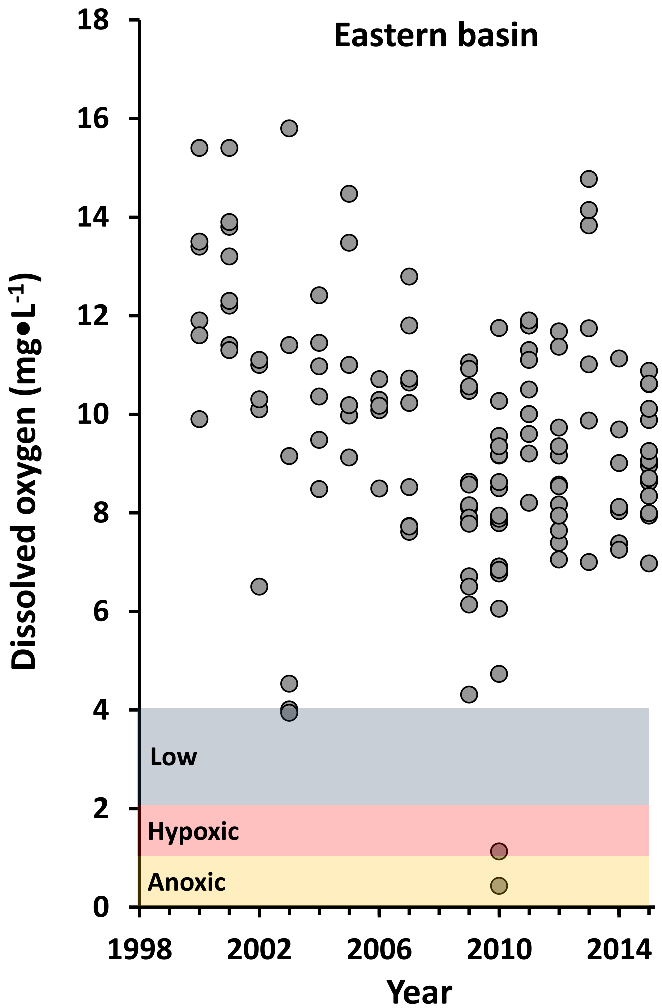
Concentration of DO in the hypolimnion is an important component of fish habitat and an indicator of ecosystem health. Low DO (2-4 mg•L^{-1}) is stressful to fish and other aquatic organisms and can cause a reduction in feeding or migration to areas of higher DO (Breitburg 2002; Roberts et al. 2009, 2011). Hypoxic (1-2 mg•L^{-1}) or anoxic (<1 mg•L^{-1}) conditions can be lethal if fish do not migrate. However, hypoxic and anoxic conditions can concentrate prey, which can actually increase fish growth in some instances (Brandt et al. 2011). Given the bathymetry of Lake Erie, low DO is common only in the central basin where thermal stratification occurs within a few meters of the bottom and the low volume of water in the hypolimnion limits oxygen storage capacity (Burns 1976). In the shallow western basin, mixing of the water column by winds generally prevents thermal stratification, and DO typically remains above 4 mg•L^{-1}. In the deep eastern basin, DO is rarely limiting owing to a thick (>20 m) hypolimnion with ample oxygen storage capacity.

Low levels of hypolimnetic DO were most common in the central basin of Lake Erie (Fig. 1). In the western basin, potentially harmful levels of DO were found in only 8% of all measurements and occurred in only 6 of 17 years. From 2004-2008, 23% of DO readings in the central basin were hypoxic or anoxic. From 2009-2015, 20% of all central-basin DO measurements were hypoxic or anoxic. Mean hypolimnetic DO in the central basin was 5.6 mg•L^{-1} during 2004-2008 and 5.4 mg•L^{-1} during 2009-2015. The eastern basin of Lake Erie rarely experienced low DO. However, there was a sharp decline in eastern-basin DO during 2004-2007 (mean 12.5 mg•L^{-1} in 2004-2005 and 9.8 mg•L^{-1} in 2006-2007) whereas, during 2009-2015, DO was relatively stable albeit at near the lower level (mean 9.2 mg•L^{-1}).

Fig. 1. Dissolved oxygen concentrations (mg•L^{-1}) near bottom at offshore sites in each of Lake Erie's three basins during June-August, 1999-2015. Shaded areas indicate low DO concentrations where fish may be affected (gray) and possibly die (hypoxic in pink and anoxic in yellow).




Central basin
Dissolved oxygen (mg•L-1)
18
16
14
12
10
8
6
4
2
0
Low
Hypoxic
Anoxic
1998
2002
2006
2010
2014
Year


Eastern basin
Dissolved oxygen (mg•L-1)
Year
Low
Hypoxic
Anoxic
18
16
14
12
10
8
6
4
2
0
1998
2002
2006
2010
2014

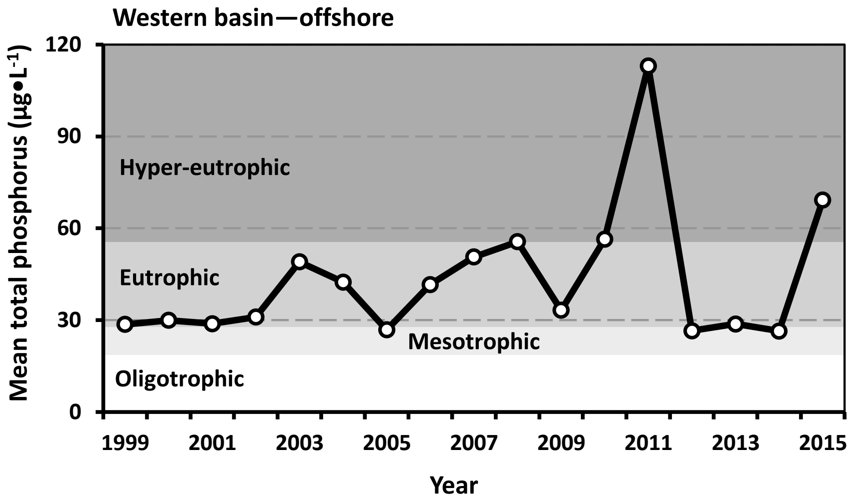
Phosphorus

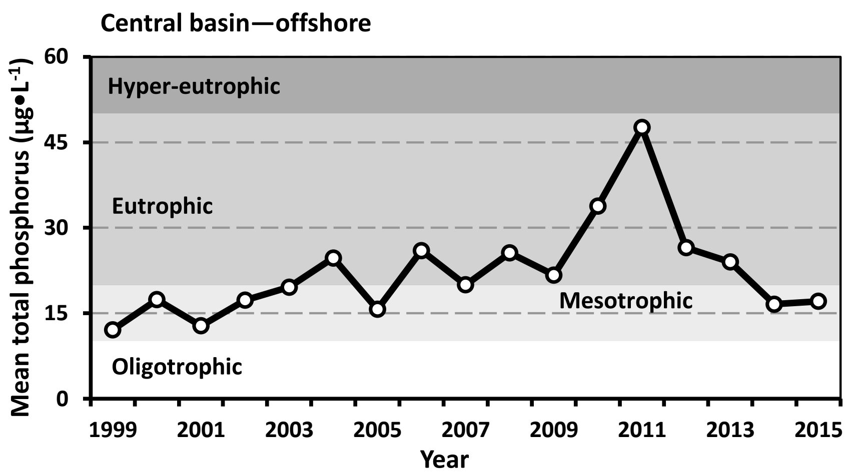
…maintain mesotrophic conditions (10-20 µg•L^{-1} phosphorus)… in the western, central, and nearshore waters of the eastern basin…

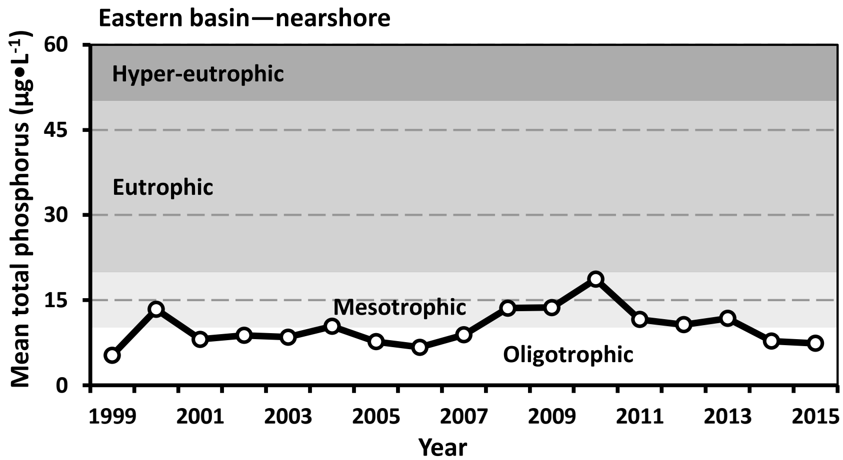
The average annual concentration of TP in the western basin exceeded the target range of 10-20 µg•L^{-1} from 1999 through 2015 (Fig. 2). During 2004-2008, mean TP in the western basin was 43.4 µg•L^{-1}, and it increased to 50.5 µg•L^{-1} during 2009-2015. Since 2009, concentrations have been in the hyper-eutrophic range in three years, including an extremely high peak of 113 µg•L^{-1} in 2011, a year with exceptionally large algal blooms.

Despite apparently stable loading of TP to the western basin during 2004-2008, a higher proportion was DRP, a form more readily available for algal uptake than particulate-bound forms (Scavia et al. 2014). High loadings of DRP to the western basin, especially in years when TP was also high, were the probable cause of four of the largest harmful algal blooms ever recorded, each of which occurred during 2011-2015 (Fig. 3). Reasons for the rise in DRP loads include changes in agricultural practices that increased runoff from farmland, increased number of storms and high wind events that re-suspend nutrients, and a flourishing population of dreissenids that recycle nutrients (Reutter et al. 2011).

Fig. 2. Mean total phosphorus (µg•L^{-1}) weighted by month at offshore sites in Lake Erie's three basins and at nearshore sites in the lake's eastern basin, May-September, 1999-2015. Shaded areas show the range of TP concentrations within each of four trophic classes. Note that the scale of the western-basin panel differs from that of the other panels.


Western basin—offshore
Mean total phosphorus (µg•L-1)
120
90
60
30
0
Hyper-eutrophic
Eutrophic
Mesotrophic
Oligotrophic
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year


Central basin—offshore
Mean total phosphorus (µg•L-1)
60
45
30
15
0
Hyper-eutrophic
Eutrophic
Mesotrophic
Oligotrophic
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year


Eastern basin—nearshore
Hyper-eutrophic
Eutrophic
Mesotrophic
Oligotrophic
Mean total phosphorus (µg•L-1)
60
45
30
15
0
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year

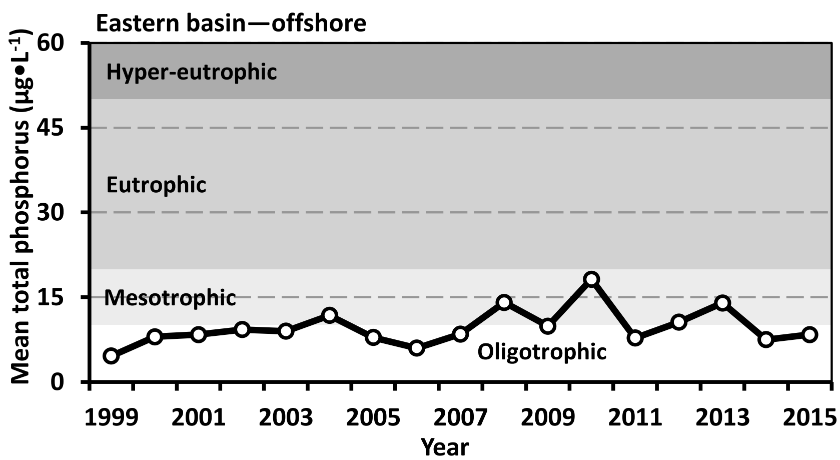
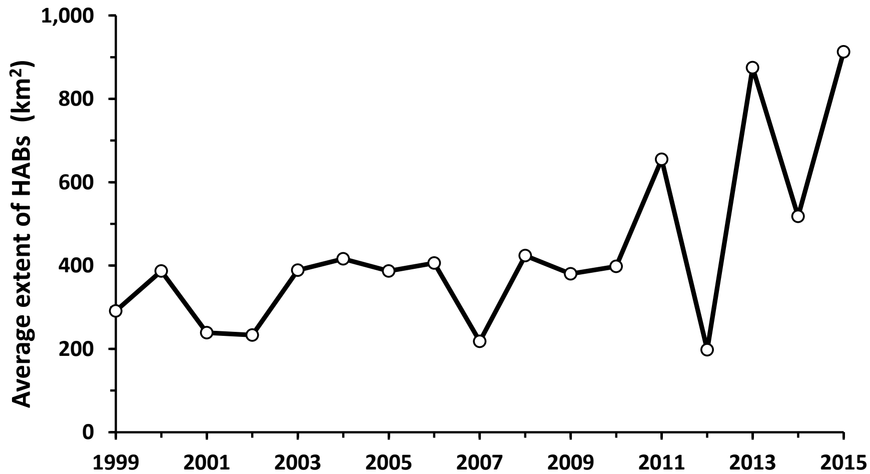

Eastern basin—offshore
Hyper-eutrophic
Eutrophic
Mesotrophic
Oligotrophic
Mean total phosphorus (µg•L-1)
60
45
30
15
0
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year

Fig 3. Average extent (km^2) of harmful algal blooms (HABs) in the western basin of Lake Erie, 1999-2015 (Michigan Tech Research Institute, unpublished data).



An increase in TP concentration was also evident in the central and eastern basins in 2009-2015, although concentrations in these basins met or were close to the LEC's FCOs. In the central basin, mean TP concentration rose from 22.4 $\mu g \cdot L^{-1}$ in 2004-2008 to 26.8 $\mu g \cdot L^{-1}$ in 2009-2015 (Fig. 2). Although central-basin TP was, on average, higher in 2009-2015 than in the previous reporting period, it was in the target mesotrophic range in two of seven years. In nearshore waters in the eastern basin, TP was generally below the desired mesotrophic value in 2004-2008 (mean 9.5 $\mu g \cdot L^{-1}$) but was more frequently classified as mesotrophic in 2009-2015 (mean 11.7

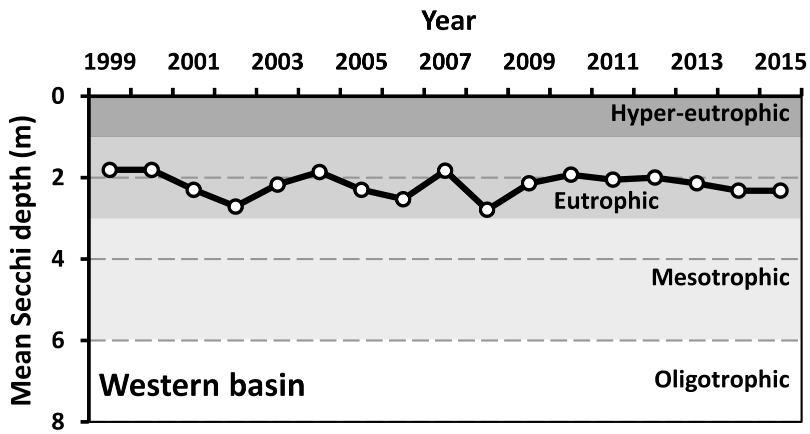
$\mu g \cdot L^{-1}$). In the eastern-basin's offshore waters, TP averaged 9.7 $\mu g \cdot L^{-1}$ during 2004-2008 and 10.9 $\mu g \cdot L^{-1}$ during 2009-2015. In general, eastern-basin waters showed little increase in TP through time and, compared to central-basin waters, they reached the LEC's target TP levels more frequently during 2009-2015. The timing of past changes in TP concentration among Lake Erie's three basins suggested a lag in response from the western basin to the eastern basin. For example, marked increases in TP from 2002-2003 in the western basin were followed a year later by TP increases in the central and eastern basins. However, in other years, when TP was high in the western basin (e.g., 2008, 2011), TP was also high in the central basin and only rose in the eastern basin after a two-year lag (Fig. 2). Clearly the patterns of how nutrients move through the system or are entrained within certain biota, habitat, or basins deserves additional study.

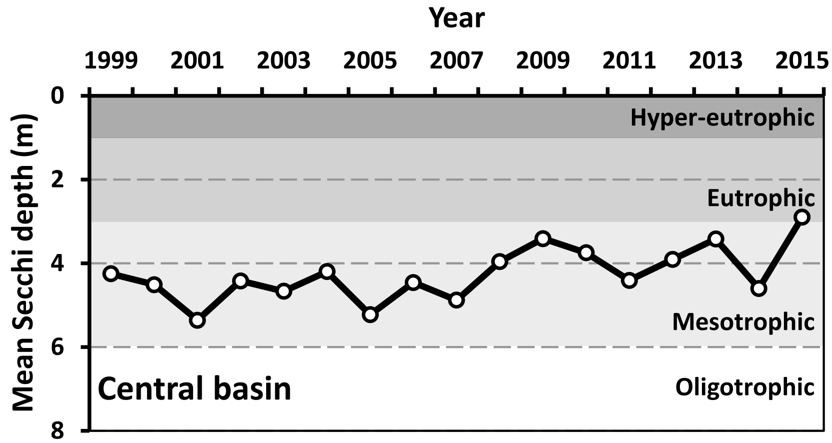
Transparency

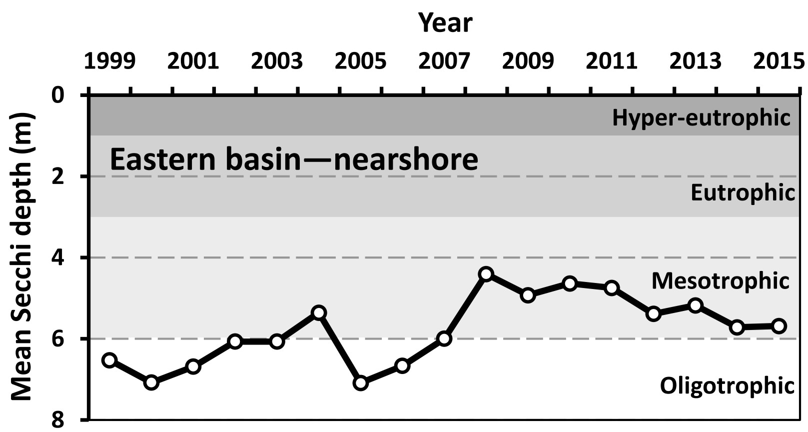
…summer water transparencies should range from 3-5 m (9.75-16.25 ft) in mesotrophic areas…

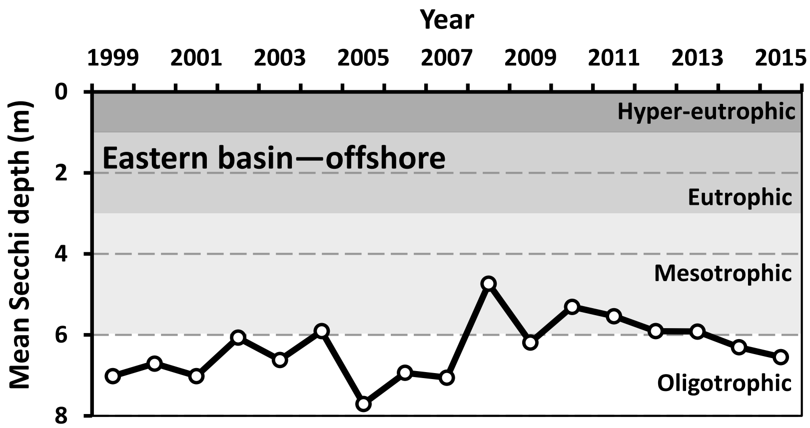
In the western basin, water transparencies were indicative of eutrophic conditions rather than the mesotrophic target range. During 2004-2008, mean Secchi depth was 2.3 m, and, during 2009-2015, it was 2.1 m (Fig. 4). Water transparency in the central basin was also lower in 2009-2015 than in 2004-2008, although it remained in the targeted mesotrophic range until 2015 when it declined to the eutrophic range. The nearshore waters of the eastern basin frequently had Secchi depths in the oligotrophic range (>6 m) in the early to mid-2000s. However, in 2009-2015, nearshore Secchi depths were in the targeted mesotrophic range (mean 5.2 m). In the eastern-basin's offshore waters, Secchi depths met oligotrophic status during 2004-2008 (6.5 m) and 2009-2015 (6.0 m). For fish production, the desired transparency in oligotrophic areas is generally >6 m (Leach et al. 1977).

Fig. 4. Mean Secchi depth (m) weighted by month in the western and central basins of Lake Erie and near shore and offshore in the lake's eastern basin during June-August, 1999-2015. Shaded areas show the range of Secchi depths within each of four trophic classes.




Year
1999
2001
2003
2005
2007
2009
2011
2013
2015
Mean Secchi depth (m)
0
2
4
6
8
Hyper-eutrophic
Eutrophic
Mesotrophic
Oligotrophic
Central basin


Year
1999
2001
2003
2005
2007
2009
2011
2013
2015
Mean Secchi depth (m)
0
2
4
6
8
Hyper-eutrophic
Eastern basin—nearshore
Eutrophic
Mesotrophic
Oligotrophic

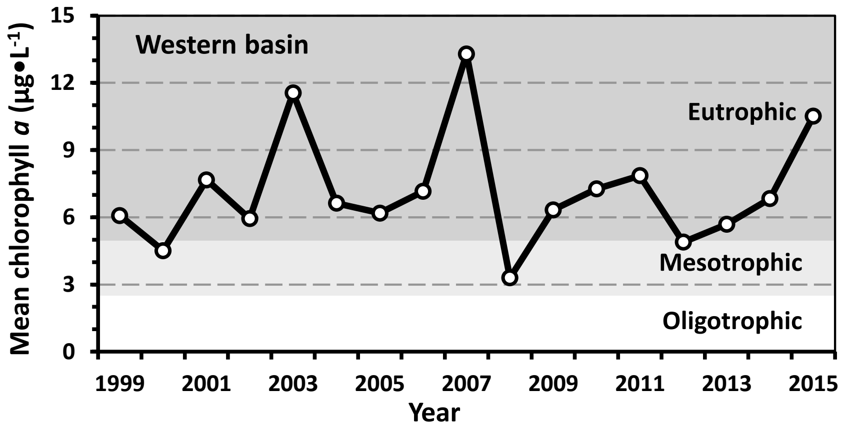


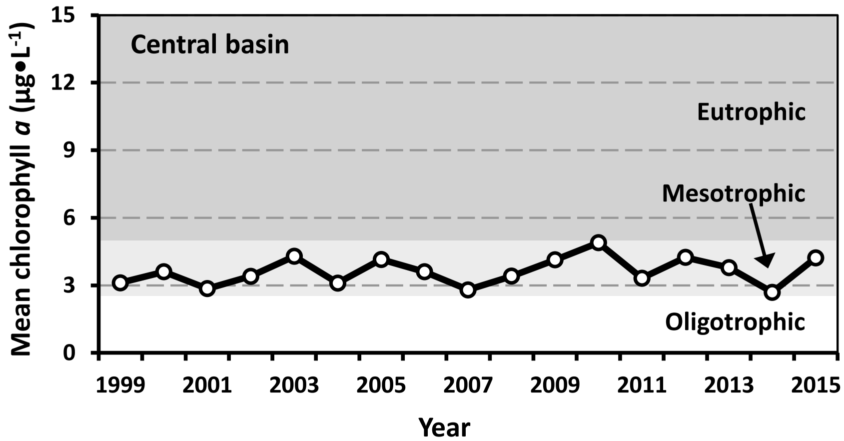
Chlorophyll *a*

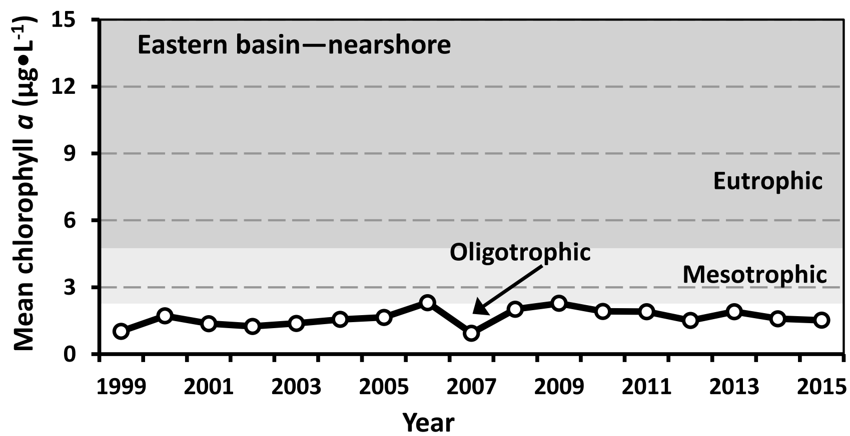
…maintain mesotrophic conditions…in the western, central, and nearshore waters of the eastern basin…

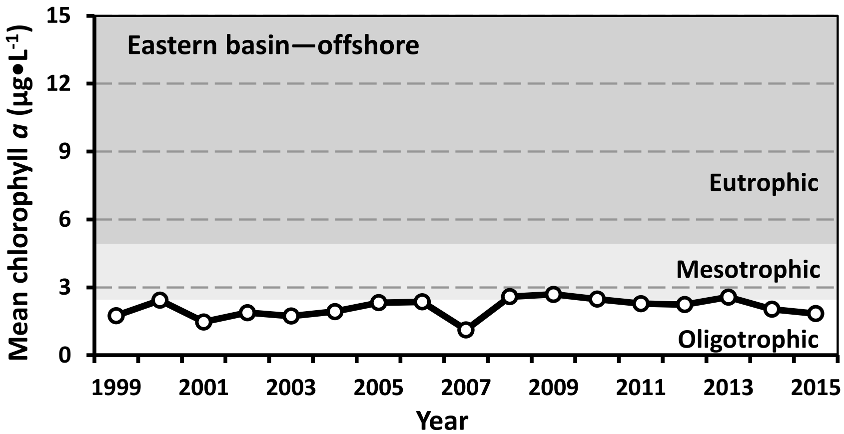
In Lake Erie, chlorophyll *a* concentration, a surrogate for algal biomass, is an additional metric used to determine if trophic status in the western, central, and eastern basins is meeting the LEC's FCOs. High chlorophyll *a* levels are indicative of both high algal productivity and biomass, which are related to trophic status. Across all basins there have been few trends in chlorophyll *a* concentration (Fig. 5). Although chlorophyll *a* levels in the western basin were more variable than in the other basins, they were almost exclusively in the eutrophic range (>5 $\mu g \cdot L^{-1}$) since 1999. The central basin has chlorophyll *a* levels indicative of the targeted mesotrophic condition. In both the nearshore and offshore eastern basin, chlorophyll *a* concentrations were typically oligotrophic.

Fig. 5. Mean chlorophyll *a* concentration (µg•L^{-1}) weighted by month in the western and central basins of Lake Erie and near shore and offshore in the lake's eastern basin during June-August, 1999-2015. Shaded areas show the range of chlorophyll *a* concentration within each of three trophic classes.




Central basin
Eutrophic
Mesotrophic
Oligotrophic
Mean chlorophyll a (μg•L-1)
15
12
9
6
3
0
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year


Eastern basin—nearshore
Eutrophic
Oligotrophic
Mesotrophic
Mean chlorophyll a (μg•L-1)
15
12
9
6
3
0
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year



Zooplankton

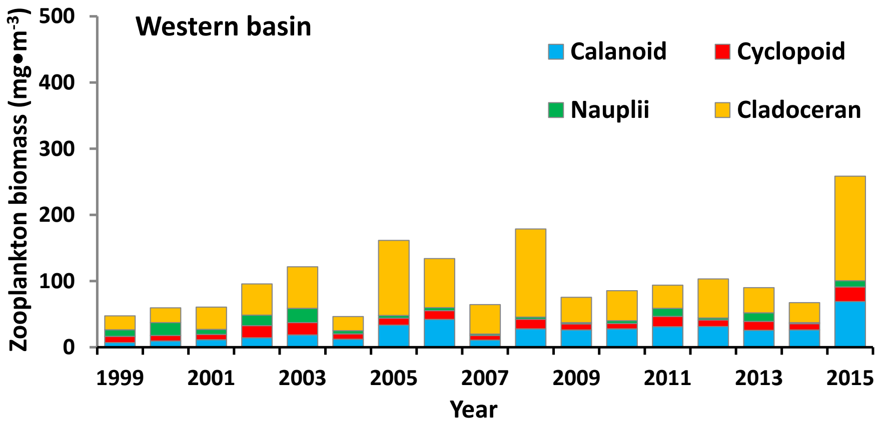
…manage the food web structure of Lake Erie to optimize production of highly valued fish species…

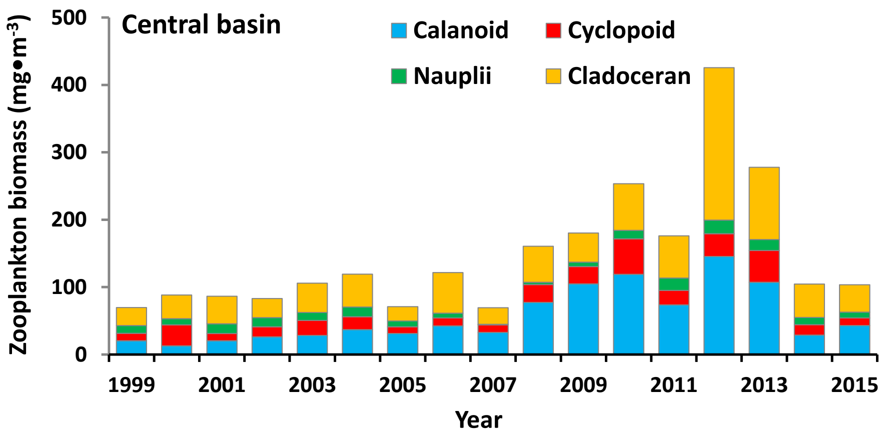
In Lake Erie, the dominant zooplankters by biomass are cladocerans and calanoid copepods, but, across basins, zooplankton biomass and species composition vary (Fig. 6). During 1999-2015, cladocerans were the most abundant zooplankter by biomass in all three basins, composing 66% of the total zooplankton biomass in the western basin, 49% in the central basin, and 43% in the eastern basin. In the western basin, the second most abundant zooplankton group was cyclopods (14% by biomass). In the central and eastern basins, calanoids were the second most abundant group (28% and 31% of total zooplankton biomass, respectively). Cladocerans are an important food source for larval and juvenile fish as well as for adults of planktivorous species like coregonines. Therefore, the composition of the zooplankton community appears favorable for feeding and growth of most fish.

In the western basin, mean zooplankton biomass was relatively unchanged (from 114 mg•m^{-3} in 2005-2009 to 104 mg•m^{-3} in 2009-2015) whereas, in the central basin, mean zooplankton biomass almost doubled (going from 99 mg•m^{-3} in 2004-2008 to 191 mg•m^{-3} in 2009-2015) (Fig. 6). In the eastern basin, zooplankton biomass was lower than in the other three basins but did increase sharply like in the central basin (a mean of 46 mg•m^{-3} during 2004-2008 doubled to 85 mg•m^{-3} during 2009-2014; data from 2015 were not available).

When predation pressure from fish is high, total zooplankton biomass can decline, and composition of the zooplankton community can shift toward smaller species and sizes (Brooks and Dodson 1965). These shifts do not appear to be occurring in any area of the lake—zooplankton biomass has not decreased in any basin (Fig. 6), biomass of cladocerans has remained relatively constant or increased in all basins (Fig. 7), and mean length of cladocerans has remained constant or increased since 1999 (Fig. 7). Thus, predation pressure on the zooplankton community from fish is not extremely high in Lake Erie.

Fig. 6. Crustacean zooplankton biomass (mg•m^{-3}) in the epilimnion of the western, central, and eastern basins of Lake Erie, 1999-2015. Samples were collected with a plankton net of 63-μm mesh towed vertically through the epilimnion.


Western basin
Calanoid
Cyclopoid
Nauplii
Cladoceran
Zooplankton biomass (mg•m-3)
500
400
300
200
100
0
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year


Central basin
Calanoid
Cyclopoid
Nauplii
Cladoceran
Zooplankton biomass (mg•m-3)
500
400
300
200
100
0
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year

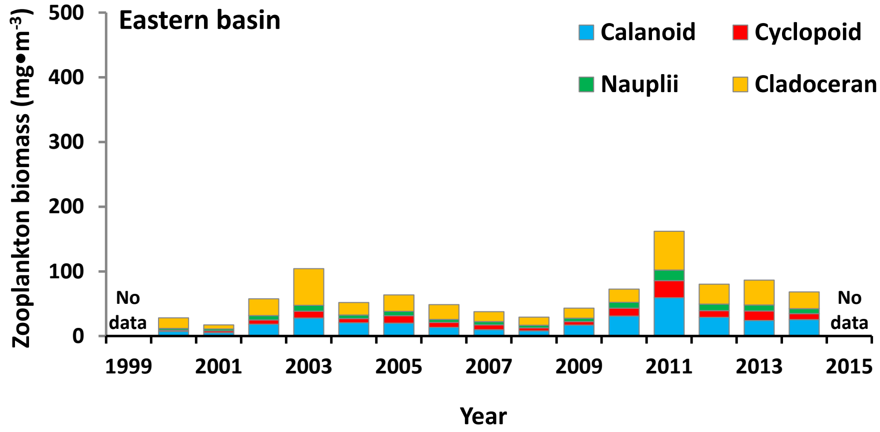
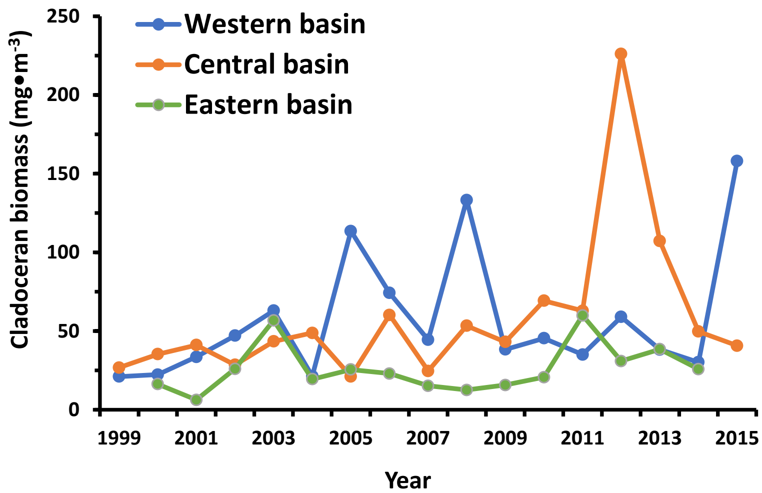
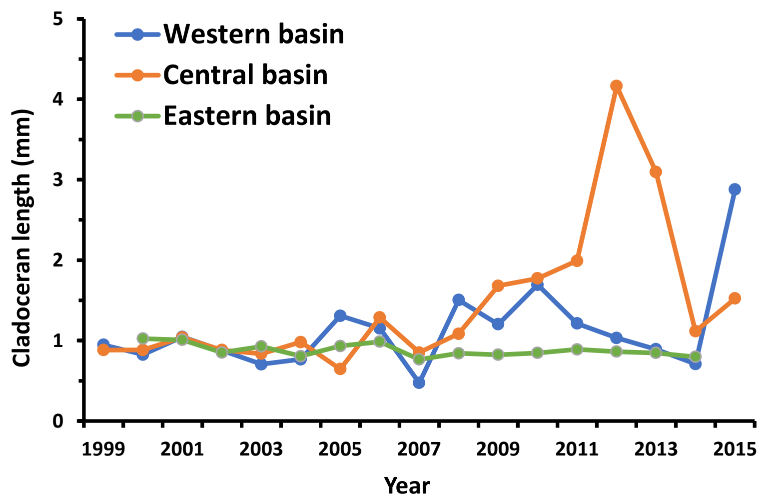


Fig. 7. Cladoceran biomass (mg•m^{-3}, top panel) and mean length (mm, bottom panel) in the epilimnion of the western, central, and eastern basins of Lake Erie, 1999-2015. Samples were collected with a plankton net of 63-µm mesh towed vertically through the epilimnion.


Western basin
Central basin
Eastern basin
Cladoceran biomass (mg•m-3)
250
200
150
100
50
0
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year


Western basin
Central basin
Eastern basin
Cladoceran length (mm)
5
4
3
2
1
0
1999
2001
2003
2005
2007
2009
2011
2013
2015
Year

Dreissenids

…manage the food web structure of Lake Erie…

Dreissenids colonized Lake Erie in the 1980s (Mills et al. 1993). Zebra mussels colonized first followed by quagga mussels. Both species caused substantial ecological and economic effects (Hecky et al. 2004; Nakano and Strayer 2014). Although zebra mussels were the more abundant species soon after colonization, quagga mussel numbers and biomass increased in the early 1990s such that it became the dominant form in the central and eastern basins by 1998. In 2009-2012, quagga mussels made up 87% of dreissenids by number and 98% by biomass (Karatayev et al. 2014). Zebra mussels were only common in the shallow, rocky western basin. Lakewide, dreissenid density in 2009-2012 was less than 20% of that in 2004 (Karatayev et al. 2014). The lakewide drop was driven mainly by declines in the central and eastern basins where dreissenid densities decreased by more than 75% and 90%, respectively, from 2002 to 2009-2012. Dreissenid populations were undoubtedly affected by hypoxia events, especially in the central basin (L. Burlakova, SUNY Buffalo State, personal communication, 2016). In the western basin, however, dreissenid density increased three-fold from 2002 to 2009-2012 (Karatayev et al. 2014).

PROGRESS TOWARD ACHIEVING LAKE ERIE ENVIRONMENTAL OBJECTIVES IN 2009-2015: HABITAT-RELATED PROJECTS[8]

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[8]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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In accordance with A Joint Strategic Plan for Management of Great Lakes Fisheries (GLFC 2007), natural-resource managers from the five jurisdictions around Lake Erie identified environmental conditions that are required to support the achievement of the fish community objectives (FCOs) of the Lake Erie Committee (LEC) (Ryan et al. 2003). Of the 13 FCOs, three focus on habitat—nearshore habitat, riverine-estuarine habitat, and fish habitat in general. Achievement of two FCOs (contaminants and threatened and endangered species) is heavily dependent on habitat. Environmental conditions that support the FCOs occur over various spatial scales and require coordinated and collaborative efforts across jurisdictions to address objectives and implement management actions. Until 2004, habitat and contaminant objectives were addressed through position statements and supported through individual and multi-agency initiatives, such as the Lake Erie Lakewide Management Plan (Tyson 2009). In 2005, 10 Lake Erie Environmental Objectives (LEEOs) were adopted by the LEC to form a systematic framework for addressing environmental and habitat issues (Table 2; LEC 2005). Achievement of and progress toward environmental objectives directly affect progress toward the related FCOs.

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Table 2. Environmental themes and objectives for Lake Erie and the fish community objectives (FCOs) to which they are linked (Ryan et al. 2003; LEC 2005).

Theme	Objective	Linked FCOs
Water levels and climate change	Recognize and anticipate natural water-level changes and long-term effects of global climate change and incorporate them into management decisions	Fish habitat, nearshore habitat
Coastal and shoreline processes	Restore natural coastal systems and nearshore hydrological processes	Fish habitat, nearshore habitat
Rivers and estuaries	Restore natural hydrological functions in Lake Erie rivers and estuaries	Riverine and estuarine habitat
Open-water transparency	Re-establish open-water transparency consistent with mesotrophic conditions favorable to Walleye in the central basin and areas of the eastern basin	Ecosystem conditions
Dissolved oxygen	Maintain dissolved oxygen conditions necessary to complete all life-history stages of fish and aquatic invertebrates	Ecosystem conditions
Wetlands and submerged macrophytes	Restore submerged aquatic macrophyte communities in estuaries, embayments, and protected nearshore areas	Fish habitat, nearshore habitat

Theme	Objective	Linked FCOs
Contaminants	Minimize the presence of contaminants in the aquatic environment such that the uptake of contaminants by fish is significantly reduced	Contaminants
Fish habitat protection	Halt cumulative incremental loss and degradation of fish habitat and reverse, where possible, loss and degradation of fish habitat	Fish habitat
Fish access	Improve access to spawning and nursery habitat in rivers and coastal wetlands for native and naturalized fish species	Fish habitat
Habitat impacts of invasive species	Prevent the unauthorized introduction and establishment of additional non-native biota into the Lake Erie basin that have the capability to modify habitats in Lake Erie	Food web structure, forage fish

Three LEEOs specifically recognize the importance of supporting restoration of coastal hydrological functions that can enable the fish community to adapt to forecasted declines in water levels (LEC 2005). Four LEEOs deal with current conditions, including contaminants, in Lake Erie as a whole or in priority management areas (PMAs). PMAs are specific locations where remediation of degraded environmental conditions contribute to the FCOs. At the time this report was written, the geographical locations of PMAs were being identified based on their potential to support rehabilitation of fish stocks with depressed reproductive potential or to enable restoration of extirpated stocks. Three LEEOs recognize the negative effect on Lake Erie and its fish community from direct anthropogenic effects and biota-mediated habitat degradation (Table 2).

Efforts toward achieving the LEEOs occurred over a variety of habitats, including open-water areas, tributaries, and coastal wetlands. Some efforts targeted habitats of focal species, such as Walleye and Lake Trout, whereas other efforts were more holistic in terms of habitats and focal species. The following sections describe the key habitat-related projects that occurred during 2009-2015 and show the LEEO themes they address.

Actions and Progress in Support of Lake Erie Environmental Objectives

Lake Erie Geographic Information System

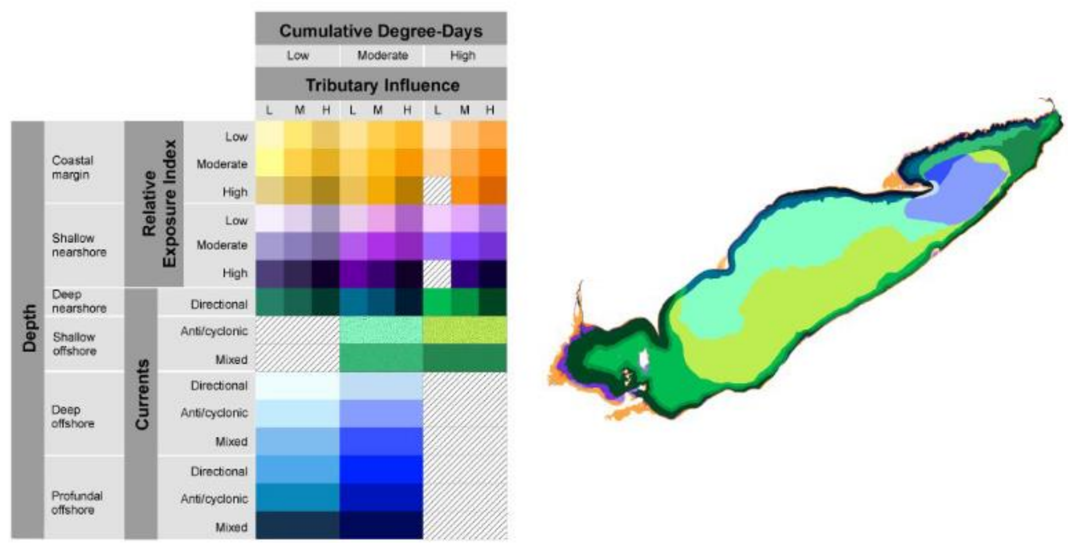
LEEO themes:

- *Water levels and climate change*
- *Coastal and shoreline processes*
- *Rivers and estuaries*
- *Open-water transparency*
- *Dissolved oxygen*
- *Wetlands and submerged macrophytes*
- *Fish habitat protection*
- *Fish access*

Accessibility of geo-spatial databases, maps, and decision support tools are improving our understanding of interactions among fish populations and environmental variables. The Great Lakes Aquatic Habitat Framework (GLAHF) is an online database of geo-referenced data for coastal, large river-mouth, and open-water habitats across the Great Lakes (www.glahf.org). The GLAHF provides a Geographic Information System (GIS) framework for consistent geographic classification and integration of habitat monitoring, fisheries assessment, and other environmental data that can be used to develop assessment programs, track restoration efforts, forecast ecological change, and develop environmental indicators.

GLAHF scientists supported the Lake Erie Habitat Task Group (HTG) on several projects. For example, the Lake Erie GIS project (a database of open-water habitats and fisheries data) has now been incorporated into the GLAHF along with other Lake Erie datasets, including total phosphorus and chlorophyll *a* concentrations (2001-2011), an updated substrate layer, and benthic invertebrate densities (1999-2011). The incorporation of these and other datasets has allowed for classification of ecological units across Lake Erie (Fig. 8). This classification allowed Pandit et al. (2013) to develop and visualize a Walleye habitat suitability model (see Walleye Habitat below). The integration of these datasets in the GLAHF also allows for the interpretation and visualization of Great Lakes habitat data with user-defined criteria, enabling the mapping and assessment of species-specific habitat and providing a decision support tool for fisheries assessment and management. For example, the GLAHF has been used to select representative sites along a gradient of geomorphologic and anthropogenic influences for a nearshore habitat assessment (see Nearshore Habitat below). Beyond the direct use by LEC member agencies, the GLAHF has been used to guide strategic initiatives and to develop lake-based environmental indicators of the state of the ecosystem. For example, in 2012, the GLAHF team facilitated data sharing and evaluation of different pilot assessment approaches for the Great Lakes Water Quality Agreement (GLWQA). Although the GLAHF does not directly contribute to the LEEOs, it provides biologists and managers with the ability to display and interpret geo-spatial data in support of assessment and management decisions and provides a critical supporting role in the progress toward eight of the 10 LEEOs.

Fig. 8. Map of Lake Erie showing the various ecological units (by color) as determined by use of the Great Lakes Aquatic Habitat Framework (GLAHF). Classification of aquatic ecological units is based on similarities in depth and thermal regime as well as similarities in currents for habitats in the open lake and in the amount of exposure and tributary influence for habitats around the periphery of the lake. Full resolution and descriptions of the classifications of aquatic ecological units can be found using the GLAHF explorer at ArcGIS Web Application ([ArcGIS Web Application (glahf.org)]()).



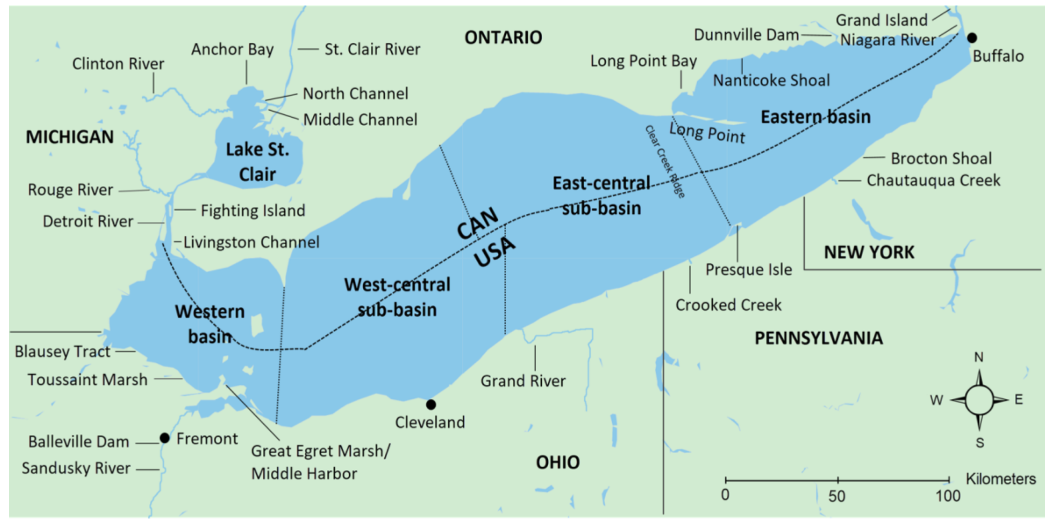
Fish Habitat

Lake Trout Habitat

LEEO themes:
- *Fish habitat protection*
- *Habitat impacts of invasive species*

The Lake Erie Lake Trout Management Plan identified two key impediments for Lake Trout rehabilitation: insufficient biomass of spawning fish and insufficient spatial coverage of current stocking (Markham et al. 2008). To begin addressing these impediments, potential spawning locations needed to be identified so that young Lake Trout could be released on them, increasing spatial coverage of stocking and, hopefully, in subsequent years, concentrating the biomass of spawners on the most likely areas for successful reproduction. In 2006, a GIS model was produced by the Lake Erie HTG that predicted the locations of potential Lake Trout spawning habitat based on a combination of steep slopes (>5%) and hard substrate (bedrock and glacial till) using the National Oceanic and Atmospheric Administration's existing bathymetric and substrate data layers (Haltuch et al. 2000). Efforts in subsequent years focused on if the location and characteristics of potential Lake Trout spawning habitat could be verified. Newly developed field equipment and GIS tools were used to identify suitable habitat and structure based on comparisons with environmental characteristics from historical Lake Trout spawning sites. Analysis of data from one historical spawning site (Brocton Shoal) showed that bathymetric heterogeneity may also be indicative of spawning substrates (Biberhofer et al. 2010). Therefore, bathymetric heterogeneity was incorporated into the GIS model to identify and prioritize which sites to survey in Lake Erie's eastern basin (Fig. 9).

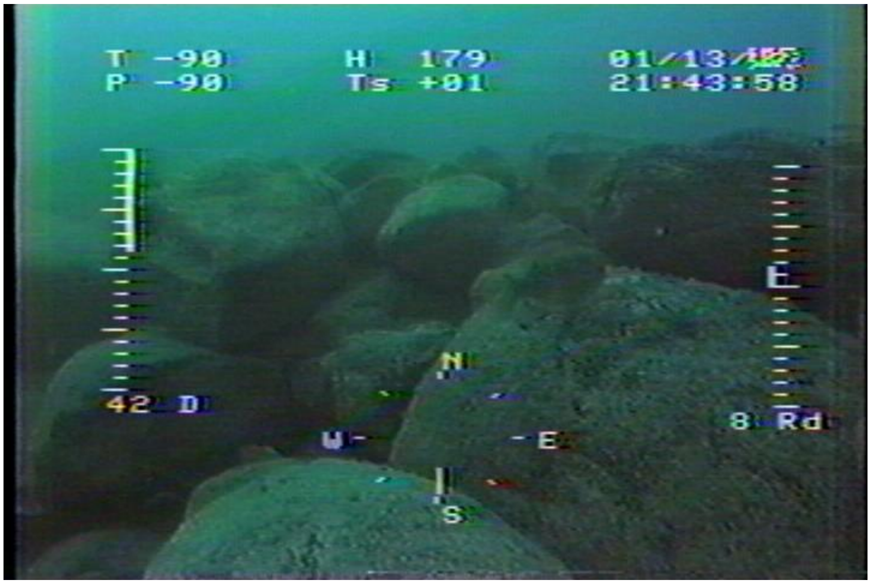
Fig. 9. Map of Lake Erie showing the eastern and western basins, two sub-basins of the central basin, international boundary line, and locations of habitat-related projects in 2009-2015.

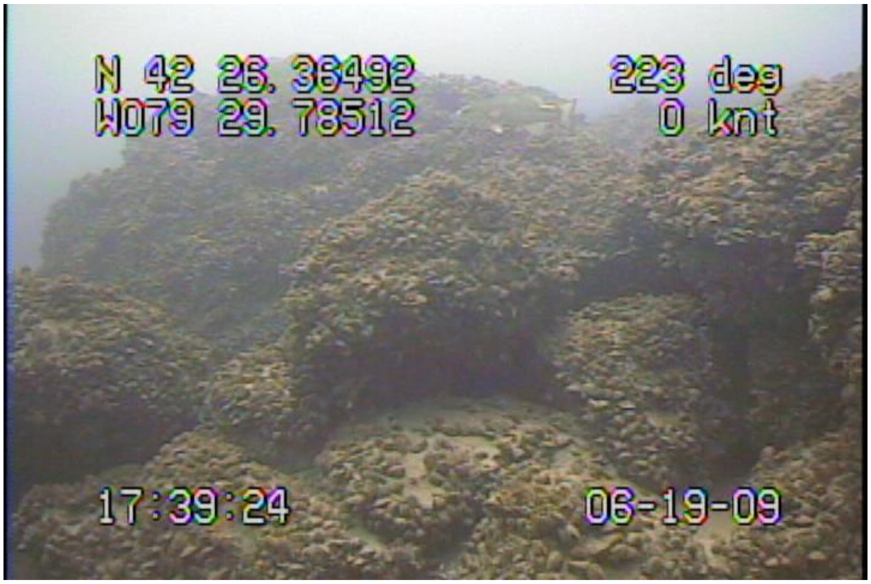


In 2007-2009, numerous surveys were conducted in Lake Erie's eastern basin with sidescan sonar (covering 128 km^2) and with RoxAnn™ acoustic seabed classification (covering 121 km^2). The surveys identified several areas that had physical habitat characteristics deemed suitable for Lake Trout spawning (Biberhofer et al. 2010). These areas include sites within the Brocton Shoal complex (a shallow-water nearshore site east of Presque Isle, Pennsylvania) and multiple sites in Ontario. All of these potential spawning sites are located adjacent to deeper waters that are assumed to serve as nursery habitat for Lake Trout. Little suitable spawning substrate for Lake Trout was found at Long Point Ridge, Pennsylvania Ridge, Presque Isle Knob, and Clear Creek Ridge (see Holcombe et al. 2005 for locations of lake-floor geomorphology features of Lake Erie). The surveys make progress toward the LEEO theme of fish habitat protection by identifying locations suitable for Lake Trout spawning that may need protection or possible rehabilitation (Table 2).

Detailed follow-up surveys with sidescan sonar and underwater cameras indicated that some areas with the desired physical habitat characteristics for spawning by Lake Trout, such as cobble substrates, were covered by *Cladophora* spp. and dreissenids. These organisms can clog interstitial spaces necessary for egg protection and reduce energy from waves and currents over coarse substrates that, combined with dreissenid pseudofeces, likely increases siltation (Fig. 10). Clogging reduces the volume of interstitial spaces and siltation can smother fish eggs deposited onto otherwise suitable habitat. Due to this alteration of typical offshore spawning sites, nearshore areas that historically may not have been prime spawning locations may now be the best sites remaining for Lake Trout reproduction.

Fig. 10. Images from Brocton Shoal in the late 1980s (top photo, Edsall et al. 1992) and in 2009 (bottom photo, Biberhofer et al. 2010) showing that, in the intervening years, increased siltation and the presence of dreissenids have degraded Lake Trout spawning habitat.





Higher wave and current energy associated with environments in nearshore areas may reduce the density of *Cladophora* spp. and minimize siltation within interstitial spaces. A survey east of Presque Isle, Pennsylvania, indicated that Lake Trout may be spawning in shallow water (~5-10-m depths) near shore (J. Grazio, Pennsylvania Department of Conservation and Natural Resources, personal communication, 2015). Shallow-water spawning has been corroborated by a New York State Department of Environmental Conservation (NYSDEC) survey that found Lake Trout in spawning condition at depths <2 m. Potential reproductive success in nearshore habitats still needs to be assessed as it is possible that the high energy in these areas may be detrimental to egg development and larval success. At offshore sites, the effects of altered habitat on Lake Trout spawning success should be investigated to understand better the likelihood of reproduction at historical spawning locations.

Analysis of underwater video and substrate and habitat classification maps were used to identify the locations of highly suitable Lake Trout spawning habitat, which were considered for stocking Lake Trout. In 2009, this detailed information was used to select locations on Nanticoke Shoal and near Brocton Shoal for stocking. The high-resolution substrate data were also used to select areas for placement of egg-trap buckets, deployed to determine if Lake Trout was spawning over suitable substrates.

Walleye Habitat

LEEO themes:

- *Water levels and climate change*
- *Open-water transparency*
- *Dissolved oxygen*

The assumption that Walleye habitat is limited to areas ≤13 m deep was evaluated during 2009-2011 using the latest scientific literature, geo-spatial analyses, and historical data sets. Historically, the total allowable catch (TAC) for the Walleye fishery has been allocated among management jurisdictions based proportionally on the surface area of the lake with ≤13-m depths (STC 2007). Pandit et al. (2013) used data from fishery-independent index gillnetting conducted in Ontario waters during 1989-2008 (Ontario Ministry of Natural Resources and Forestry (OMNRF) and Ontario Commercial Fisheries' Association Partnership Index Program) and in Ohio waters during 1990-2009 (Ohio DNR) to describe habitats suitable for Walleye based on its presence or absence. Walleye was caught in waters ranging from 2.7-25.0 °C with 0.2-15.0 mg•L^{-1} of dissolved oxygen (DO) and turbidity ranging from 0.25-11.0 m Secchi depth. Using stepwise logistic regression, a species habitat model was developed with these abiotic parameters (Christie and Regier 1988; Lester et al. 2004). The results demonstrated that sites with Walleye were warmer, shallower, and more turbid than sites without Walleye. Juvenile Walleye tended to be caught at sites that were warmer and more turbid and had higher DO concentrations than at sites where adult Walleye was caught. Significant interactions among the water temperature, turbidity, and DO indicated the importance of multiple environmental variables in defining habitat suitability. For example, Walleye habitat increased with increasing water temperatures but only if the water was turbid. The species habitat model was used to determine the amount of suitable Walleye habitat in the western and eastern basins and then these amounts were compared to those determined from the ≤13-m-depth model. For the western basin, which is within the TAC area of Lake Erie (Kayle et al. 2015), both the ≤13-m model and the species habitat model produced similar estimates of the amount of suitable Walleye habitat. 100% of the surface area was deemed suitable by the ≤13-m model, and 95% of the surface area was deemed suitable by the species habitat model. For the eastern basin, which is outside the TAC area of Lake Erie (Kayle et al. 2015), the species habitat model indicated that 63% of the surface area was suitable Walleye habitat whereas the ≤13-m model showed that only 20% of the surface area was suitable. The resultant habitat suitability models for Walleye were incorporated into the GLAHF to map the total suitable area by life stage. These projects advance three LEEOs (Table 2) by establishing suitable ranges of water clarity, DO, and temperature for juvenile and adult Walleye and by producing lakewide habitat suitability maps based on water temperature, turbidity, and DO.

Since 2011, the use of acoustic telemetry to track the movement of fish has expanded across Lake Erie. Supported by the Great Lakes Acoustic Telemetry Observatory System, acoustic telemetry studies provide insight into habitat-related behaviors (such as lakewide movement, spawning, and thermal and vertical preferences) in addition to providing information relevant to bioenergetics, mortality estimates, and spatial exploitation patterns. Preliminary results from telemetry of Walleye demonstrate a greater use of deep offshore habitats (i.e., >13 m) than previously assumed and as suggested by Pandit et al. (2013). This finding highlights the importance of considering the inclusion of offshore waters in the Lake Erie FCO for east-basin Walleye habitat.

Central-Basin Habitat—Hypoxia

Lake Erie's central basin undergoes extensive seasonal hypoxia (DO <2.0 $mg \cdot L^{-1}$) linked to intense algal blooms resulting from excessive nutrient loadings. Nutrient abatement in the early 1970s reduced point-source inputs of phosphorus (Richards et al. 2009) and resulted in a gradual change in trophic status from eutrophic to oligotrophic through the mid-1990s (Conroy et al. 2005). Hypoxia also declined through this period. However, during the past two decades, the dissolved reactive phosphorus component of the total nutrient loadings has increased, driving more frequent and intense algal blooms with attendant increases in hypoxia (Zhou et al. 2013). This situation led water resource managers to establish a goal for reducing hypoxia in the GLWQA protocol of 2012 (IJC 2012).

In 2008, there was increasing concern about the influence of hypoxic conditions on assessment of age-0 Yellow Perch. High survey catches of age-0 fish in or near hypoxic areas produced high variance in the recruitment prediction for age-2 Yellow Perch. For example, one Ohio DNR bottom trawl collected 10,700 age-0 Yellow Perch, a value twice as high as the next largest catch in the 22-year survey and 255 times as high as the average catch that year. In response to this anomaly and similar results elsewhere in Lake Erie's Ohio and Ontario waters, trawl samples in which hypoxic conditions were observed were excluded from stock assessments. Field study of the phenomenon from 2011-2013 provided evidence of changes in catchability of demersal fish species linked to the aggregative effects of hypoxia (Kraus et al. 2015). The effect of spatially varying catchability on stock assessment has not been evaluated. Although this work directly addresses the LEEO for DO, future investigations are needed to understand (1) how to make progress toward achieving GLWQA goals of reducing the severity and extent of hypoxia, (2) spatial variability in catchability of fish due to varying concentrations of DO, and (3) the effects of the interim decision rule to exclude hypoxic trawls from Yellow Perch stock assessments.

Nearshore Habitat

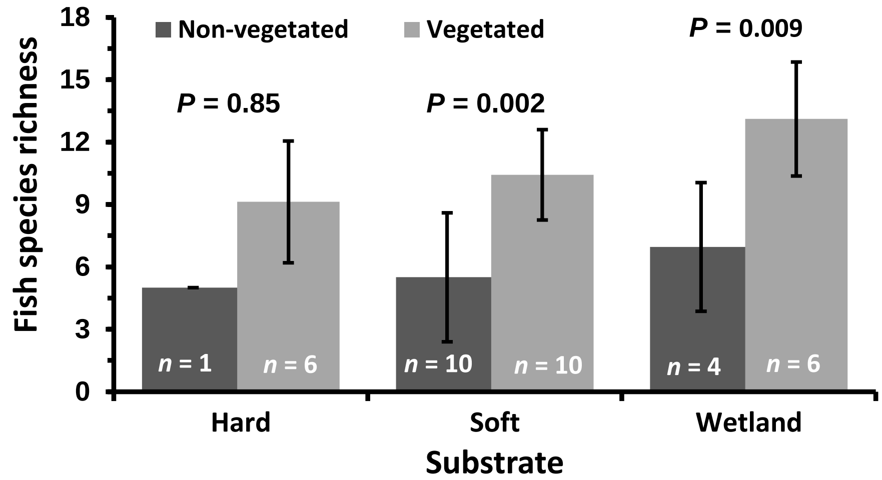
LEEO themes:

- *Water levels and climate change*
- *Coastal and shoreline processes*
- *Rivers and estuaries*
- *Wetlands and submerged macrophytes*
- *Fish habitat protection*
- *Fish access*

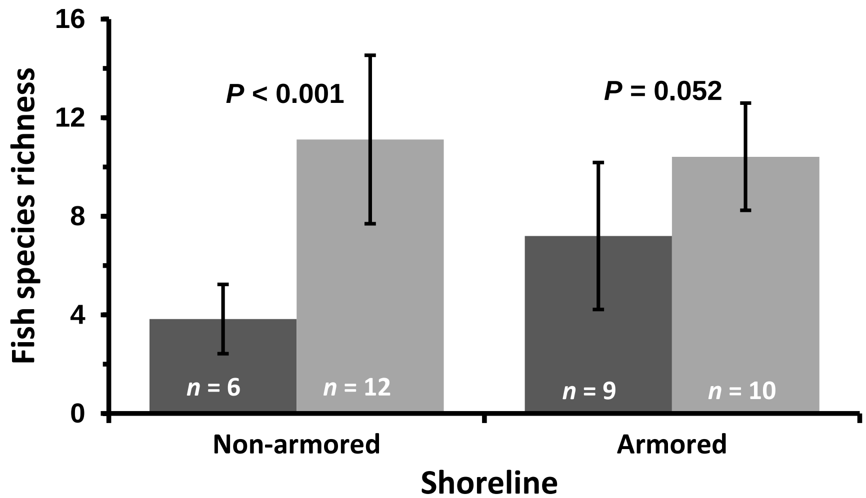
Habitat degradation in Lake Erie is responsible, in part, for changes in the lake's fish community structure (Koonce et al. 1996). Extensive alteration of spawning and nursery habitats near shore has potentially impeded achievement of management goals for fish identified in the FCOs. For example, extensive shoreline armoring has eliminated access of Northern Pike to spawning areas in many coastal wetlands. The LEEOs have set out specific conditions needed in the nearshore to aid in achieving the FCOs, particularly relating to water level and climate, natural coastal systems and hydrological processes, and submerged macrophyte communities (Davies et al. 2005). However, state, provincial, and federal fisheries agencies do not typically have any regulatory authority over shoreline construction projects. Thus, if the LEEOs and FCOs are to be achieved, nearshore processes and fish habitats should be considered in local, state, and provincial permitting of shoreline construction.

To address information needs for nearshore areas, research and assessment programs have been quantifying composition of the fish community that is associated with various habitat types. In 2009, the Ohio DNR began an annual electrofishing survey in the western basin to assess the composition and abundance of the nearshore fish community by habitat. Sites were selected using the Lake Erie GIS (now the GLAHF) to represent a gradient of geomorphologic and anthropogenic influences. Working with the University of Toledo (UT) Lake Erie Center in 2011, an optimal survey design was developed for assessing the nearshore fish community (Ross et al. 2016). During this project, relationships between shoreline habitat and the associated fish community were explored preliminarily. Findings included greater fish species diversity at sites with shoreline vegetation than at sites without (Fig. 11; Ross 2013). Building on these preliminary findings, researchers at UT and Bowling Green State University have begun examining the influence of physical shoreline characteristics on Lake Erie fish communities. This research links fish community data with aquatic and terrestrial (shoreline) habitat data from digital sources and with aquatic vegetation and substrate surveys. The aim is to better understand the effects of shoreline development on productive capacity of nearshore environments and to identify specific characteristics of Lake Erie nearshore habitat associated with FCO-identified species. This information is necessary to inform regulators and engineers who can then incorporate biological criteria into the permitting process for shoreline modifications. This research directly addresses LEEOs and FCOs by fostering the creation and maintainence of valuable nearshore habitats for FCO-identified fish species and the resiliency of the Lake Erie’s coast.

Fig. 11. Fish species richness in Lake Erie (±1 SD) along vegetated and non-vegetated shorelines (top panel) by substrate type (hard, soft, wetland) and (bottom panel) by shoreline type (with and without armoring). *N* = number of shorelines sampled. Note that the scales of the two panels differ.



Non-vegetated
Vegetated
P = 0.85
P = 0.002
P = 0.009
Fish species richness
18
15
12
9
6
3
0
n = 1
n = 6
n = 10
n = 10
n = 4
n = 6
Hard
Soft
Wetland
Substrate



P < 0.001
P = 0.052
Fish species richness
16
12
8
4
0
n = 6
n = 12
n = 9
n = 10
Non-armored
Armored
Shoreline

Riverine and Estuarine Habitat

St. Clair-Detroit River System

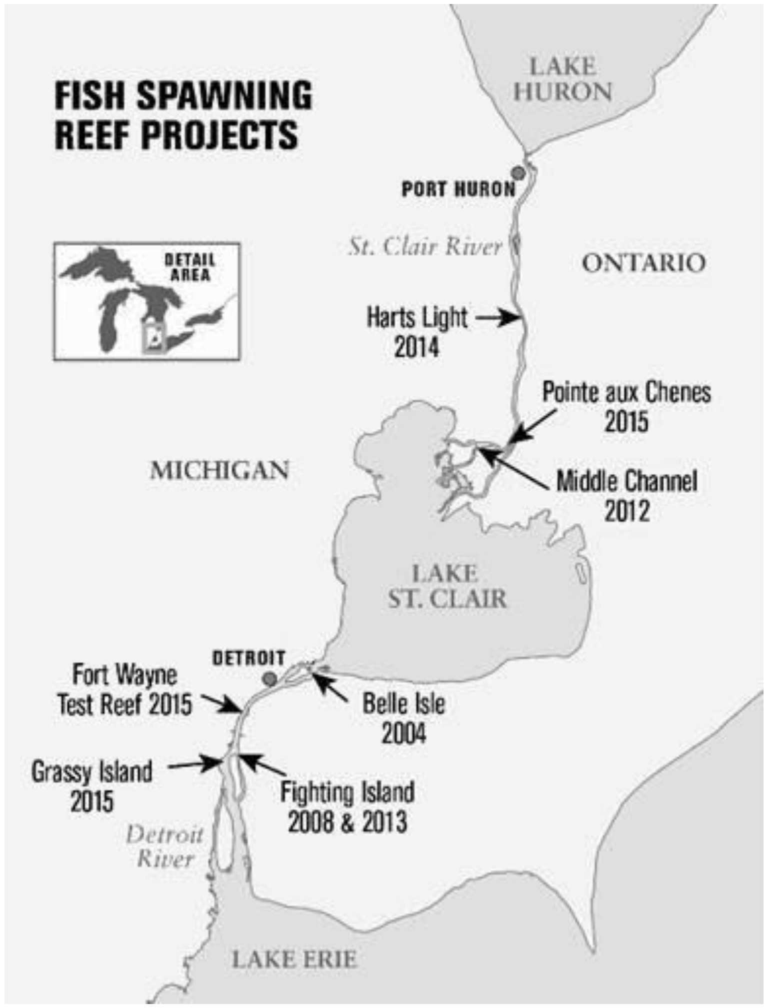
LEEO themes:

- *Coastal and shoreline processes*
- *Rivers and estuaries*
- *Wetlands and submerged macrophytes*
- *Fish habitat protection*
- *Fish access*

Historically, Lake Sturgeon, Walleye, and Lake Whitefish migrated from Lake Erie to the Detroit River to spawn, depositing and fertilizing eggs in rocky areas with fast-flowing currents. Beginning in 1874, the St. Clair-Detroit River System (SCDRS) was extensively modified by dredging for ship channels and by disposal of dredged materials, which damaged spawning reefs made of natural limestone and changed river flows. Dredging in combination with shoreline development and overfishing reduced native fish populations in the St. Clair and Detroit Rivers. In 1987, both rivers and two direct tributaries to the SCDRS (Clinton River, Rouge River) were classified as Great Lakes Areas of Concern (AOCs). After the AOC designations, plans were made to remove the Beneficial Use Impairments (BUIs) in the SCDRS. A BUI is a change in the chemical, physical, or biological integrity of a Great Lakes system sufficient to cause significant environmental degradation (https://www.epa.gov/great-lakes-aocs). A major component of habitat restoration in the SCDRS is reef construction. Locations of constructed reefs were selected based on a bio-physical model that identified the best potential locations for Lake Sturgeon spawning (Bennion and Manny 2014). The goals of reef construction were to (1) construct fish spawning reefs to enhance the productivity of native fish species with special emphasis on Lake Sturgeon, (2) remove the Detroit River and St. Clair River BUIs resulting from the loss of fish and wildlife habitat and populations, and (3) improve understanding of fish communities and fish habitat restoration. The process for reef site placement and evaluation has evolved; lessons learned from each reef built will be applied to potential future reefs (Manny et al. 2015; Vaccaro et al. 2016).

Since 2004, seven spawning reefs totaling 5.1 ha and one test reef have been constructed in the St. Clair and Detroit Rivers to restore habitat lost during channelization. In the Detroit River, the reefs and years of construction are Belle Isle (2004), Fighting Island (2008, expanded in 2013), and Grassy Island (2015), and Fort Wayne (test reef, 2015). In the St. Clair River, the reefs and years of construction are Middle Channel Reef (2012), a reef near Port Huron (2012), Pointe aux Chenes Reef (2014), and Harts Light Reef (2014) (Fig. 12). The construction of reef complexes contributed to the advancement of two LEEOs (restore natural hydrological functions in rivers; reverse, where possible, loss and degradation of fish habitat).

Fig. 12. Map of the St. Clair-Detroit River System showing locations where spawning reefs were constructed and years of construction.



Map courtesy of Michigan Sea Grant.

Monitoring the constructed reefs was accomplished through collaborations among the OMNRF, the U.S. Geological Survey, the U.S. Fish and Wildlife Service (FWS), and the Michigan DNR. The reefs were used for spawning by Lake Sturgeon (Roseman et al. 2011; Bouckaert et al. 2014), Walleye (Manny et al. 2010), catostomids (Manny et al. 2010), and Lake Whitefish (Roseman et al. 2012). Use was confirmed by the collection of ripe adults and eggs on and around the reefs. Larval fish monitoring, which began in 2006, documented successful reproduction of key species for Lake Erie originating within the SCDRS (McDonald et al. 2014; Pritt et al. 2014, 2015). Juvenile fish were sampled, relationships among species and habitats were explored, and work was initiated to determine the most efficient sampling strategy for long-term monitoring of juveniles (Francis et al. 2014). Analysis of the effects of reef habitat construction on genetic diversity revealed that these habitat projects are likely maintaining the genetic diversity of the SCDRS Lake Sturgeon population (Marranca et al. 2015). The implementation of this multi-agency monitoring program and the data it has provided follow two recommendations put forward in the previous state of Lake Erie report (Markham and Knight 2017). The recommendations are to (1) continue and expand successful collaborative monitoring, assessment, planning, and research efforts in support of management activities (Drouin and Soper 2017); and (2) achieve a better understanding of the relationship between suitable habitat and improved fish populations (Markham et al. 2017).

Since 2010, shoreline habitat projects have been completed throughout the SCDRS with the goal of removing BUIs by improving habitat and habitat complexity and by providing nursery and refuge areas for aquatic organisms. Along the St. Clair River, multiple projects to enhance shoreline habitat were completed in 2011-2015. The projects improved habitat condition and connectivity between the shoreline and main channel along >1,900 m of shoreline. Post-construction assessments indicate that all life stages of fish are using these newly remediated areas (Fischer et al. 2018). Additionally, habitat projects that began in 2010 within the Blue Heron Lagoon and Lake

Okonoka on Belle Isle in the Detroit River (Fig. 12) improved connectivity between the main channel and this wetland nursery area. Completion of these shoreline habitat projects has made progress toward two LEEOs, which are to improve coastal shoreline to promote naturally occurring vegetation and to provide linkages to terrestrial ecosystems.

Upper Niagara River

LEEO themes:

- *Coastal and shoreline processes*
- *Rivers and estuaries*
- *Wetlands and submerged macrophytes*
- *Fish habitat protection*
- *Fish access*

During the past century, the upper Niagara River ecosystem has been heavily altered by human disturbance with detrimental effects to fish habitat quality and quantity (NYSDEC 1994). Municipal and industrial pollution were direct causes of water-quality degradation and sediment contamination, leading to an overall reduction in the quality of the physical, chemical, and biological habitat in the river. The designation of the Niagara River as an AOC by the International Joint Commission in 1987 and the implementation of the 1994 Niagara River Remedial Action Plan resulted in a major reduction of contamination in the river (NYSDEC 1994; USEPA 2007). The physical loss and degradation of aquatic habitat due to past and current practices related to mining, commercial shipping, and recreational boating currently remains the critical limiting factor to the persistence and expansion of fish populations in the Niagara River (NYSDEC 1994; Wooster and Matthies 2008).

The overwhelming cause of habitat loss in the upper Niagara River is associated with development of the shoreline and nearshore areas that are critically important for the reproduction and recruitment of native fish.

Under natural conditions, the shallow nearshore zone supported submerged and emergent aquatic vegetation that provided a sheltered nursery area for early life stages of the fish. With the exception of the mid-river shoal areas around Strawberry Island and Grand Island (Fig. 13), most of the shallow-water habitat in the upper river is found close to the mainland where commercial, industrial, and residential land uses are concentrated. Much of the littoral and shoreline area was either excavated to create deep water for navigation or filled in to create developable land and to provide for waste disposal. As a result, the natural gradual transition from open water to upland was replaced with a steep gradient that no longer supports native plant communities and productive fish habitats. The most sizeable areas of degradation are on the east shore of the Tonawanda Channel where the cities of Buffalo, New York, and North Tonawanda, New York, are located and downstream of the Tonawanda Channel where the cities of Niagara Falls in New York and Ontario are located (Fig. 13).

Fig. 13. Map of the Upper Niagara River showing the location of various habitat improvement projects (HIP) and photograph of the mid-river habitat improvement project at Strawberry Island.


Niagara Falls, NY
Gill Creek
Cayuga Creek
Cayuga Island
Sandy Beach Shore Restoration
Niagara Falls, Ont.
United States
Canada
Tonawanda Channel
Navy Island
Welland River
Woods Creek
Gunn Creek
Tonowanda Creek / NYS Barge Canal
Tonawanda Island
Grand Island
Spicer Creek
Big Six Mile Creek
Chippawa Channel
Tonawanda
New York State
ERIE COUNTY
Motor Island
Strawberry Island HIP
Beaver Island
Strawberry Island
Black Creek
Scajaquada Creek
Fish Attraction Structure
Frenchman's Creek

Photo: P. Leuchner, Niagara Greenway Commission

Since 2010, several large-scale projects to improve habitat in the upper Niagara River have been implemented by the New York Power Authority (NYPA) in collaboration with the NYSDEC, FWS, tribal nations, and local organizations in partial fulfillment of the relicensing agreement for the Niagara Power Project (NYPA 2005). The common goal of these projects is to restore submerged and emergent wetland habitat in shallow-water areas in proximity to mid-river shoals and islands (i.e., between Strawberry and Motor Islands; Fig. 13). Wave and ice scour in this high-energy environment were mitigated during 2011-2015 by modifying substrates with coarse sediment, constructing rock berms, and anchoring large wood. These modifications will promote conditions in which emergent wetland vegetation can establish and create complexity and diversity in the plant community by varying water depth and structure. In addition to the mid-river habitat improvements, 3.2 ha of coastal marsh was restored at Beaver Island in 2010-2011 by removal of fill that was placed there in the 1960s (Fig. 13). The newly established wetlands and mid-river habitat will benefit the native fish community by providing foraging, spawning, and nursery habitat. In total, these projects restored about 7.3 ha of mid-river and coastal habitat and made progress toward the achievement of four LEEOs by modifying shoreline processes to promote recovery of vegetation, by halting and reversing habitat loss, and by providing access to spawning and nursery habitat for fish.

In 2015, the Niagara Riverkeeper Riparian Restoration Program collaborated with the Sandy Beach Club in Grand Island, New York, to remove 61 m of large concrete bulkhead in the upper river to restore the natural gradient of the shoreline and improve habitat (Sandy Beach Shore Restoration, Fig. 13). Shallow-water areas were enhanced and protected from ice and waves with the construction of protective rock berms and anchoring of large logs. The newly protected shallow-water areas were planted with emergent and submerged vegetation to enhance fish foraging and spawning habitat. This project, along with other riparian restoration projects in the Niagara River watershed, have made direct progress toward four LEEOs by altering coastal shoreline processes to promote reestablishment of vegetation, by halting and reversing habitat loss, and by providing access to spawning and nursery habitat for native fish.

In cooperation with the NYSDEC, The Niagara Musky Association received financial support in 2013 from the Niagara Relicensing Habitat Enhancement and Restoration Fund to construct fish attraction structures in the river. The attractors were designed to provide and enhance habitat for juvenile and adult recreational fish and to increase angling success. The attractors were modeled after the successful design of rock structures implemented by the NYPA in 2008 (NYPA 2010). Planning and permitting for this project were completed in 2014. A total of nine structures will be built with rock at four high-velocity locations in the Tonawanda Channel of the upper Niagara River to create hydraulic cover (Fig. 13). The fish attraction structures will range from a simple boulder field to rock piles and ridges near public fishing areas. Collectively, these projects will make progress toward achieving one LEEO by providing and enhancing fish habitat.

Restoration of Fish Access

Lake Erie tributaries and coastal wetlands historically provided important seasonal habitat to Walleye, White Bass, Northern Pike, and other species. However, these habitats are currently among the most impaired in the watershed. Dam construction, shoreline armoring, and coastal diking have reduced connectivity with the lake proper and reduced fish access to spawning and nursery habitats. Improving connectivity is a key component of achieving several of the conditions described in the FCOs and LEEOs (Ryan et al. 2003; LEC 2005).

From 2009-2015, LEC member agencies have been actively restoring connectivity between riverine, coastal, and lake ecosystems. In the eastern basin, the OMNRF has been involved with the restoration of connections between coastal wetlands and Long Point Bay at three locations, has contributed to watershed-level projects to improve water quality and fish passage in the Grand River, and has continued to pursue fish passage at the Dunnville Dam to benefit the Grand River stock of Walleye. Fish-passage projects were completed in the eastern basin by the NYSDEC on Chautauqua Creek and by the Pennsylvania Fish and Boat Commission (PFBC) on Fourmile Creek. In the central basin, the PFBC completed a fish-passage project on Crooked Creek. In aggregate, the three projects in New York and Pennsylvania restored access to more than 25 km of tributary habitat for native fish, such as Smallmouth Bass and catostomids and stocked non-native fish, such as Rainbow Trout.

The Ohio DNR has been involved with fish-passage projects in the coastal wetlands of the western basin at Middle Harbor, the Blausey Tract, Toussaint Marsh, and Great Egret Marsh and is evaluating fish use of these newly constructed passages. The Ohio DNR has also continued to work with local, state, and federal agencies (including the city of Fremont, the Ohio Environmental Protection Agency (EPA), the FWS, and the U.S. Army Corps of Engineers) to facilitate removal of the Ballville Dam on the Sandusky River. This dam impedes fish access to 35 km of quality habitat for resident and migratory species, including the Sandusky River stock of Walleye. The removal of the Ballville Dam is scheduled to begin in 2017 and to be completed in 2018. These projects have all restored directly or improved fish access to riverine and estuarine habitats in the Lake Erie basin—an LEEO aimed at fostering self-sustaining populations of fish included in the FCOs, such as Walleye, White Bass, and Northern Pike.

Contaminants

Contaminant concentrations in fish are a broad-scale ecosystem-level indicator of contaminant levels in the Great Lakes and provide information on the safe consumption of fish. Member agencies of the LEC annually collect fish for contaminant analysis and monitoring programs administered by state environmental protection agencies, the Ontario Ministry of the Environment and Climate Change, and Environment Canada. Each jurisdiction publishes annual consumption advisories for fish based on persistent bio-accumulative and toxic compounds, including PCBs, polybrominated diphenyl ethers (PBDEs), DDT, mirex, dioxins, and mercury (Table 3). In accordance with GLWQA Annex 10, an evaluation of the status and trends of these contaminants in Lake Erie and the other Great Lakes will be included in the 2017 state of the Great Lakes report (ECCC-USEPA 2017). In Lake Erie, mercury levels in Walleye fillets increased during the early 2000s. Since 2009, however, mercury and PCB levels remain below consumption advisory thresholds with relatively stable or slightly increasing trends.

Table 3. Jurisdictional agencies responsible for fish-consumption advisories and website addresses for related documents.

Agency	Advisory
Michigan Department of Health and Human Services	https://www.michigan.gov/mdhhs/0,5885,7-339----,00.html
Ontario Ministry of the Environment, Conservation and Parks	https://www.ontario.ca/page/eating-ontario-fish-2017-18
Ohio Department of Health	https://odh.ohio.gov/wps/portal/gov/odh/know-our-programs/Ohio-Sport-Fish-Consumption-Advisory
Pennsylvania Department of Environmental Protection	https://www.dep.pa.gov/Business/Water/CleanWater/WaterQuality/FishConsumptionAdvisory/Pages/default.aspx
New York State Department of Health	https://www.health.ny.gov/environmental/outdoors/fish/health_advisories/regional/western.htm

Contaminant trends and guidelines differ among jurisdictions. For Ontario waters, consumption advisories primarily involve PCB concentrations, and changes during 2009-2015 were mixed (MOECC 2009, 2015). For example, consumption limits increased for Yellow Perch and Walleye <400 mm, but consumption limits remained the same or declined for Walleye >550 mm

(MOECC 2009, 2015). Consumption limits declined for eastern-basin Rainbow Smelt and Rainbow Trout (MOECC 2009, 2015). As of 2015, Pennsylvania Department of Environmental Protection guidelines recommend very limited consumption of Walleye and Rainbow Trout and no consumption of Lake Trout >762 mm. New York State Department of Health guidelines recommend only modest consumption of most species, including Walleye and Yellow Perch, but more severe restrictions apply depending on age and gender. Michigan Department of Health and Human Services guidelines recommend restrictive consumption of Yellow Perch, Walleye, and Rainbow Trout. Since 2004, the Ohio EPA has relaxed advisories for Walleye, Yellow Perch, and Channel Catfish, and recommendations remain unchanged during 2009-2015 (Gorman and MacDougall 2016).

As of 2015, two emerging contaminant issues are of particular concern for Lake Erie: microcystin toxin in fish flesh from harmful algal blooms (HABs) and microplastics. A HAB of cyanobacteria (blue-green algae; e.g., *Microcystis aeruginosa*) can produce neurotoxins (e.g., anatoxin-a), hepatotoxins (e.g., microcystins,) and dermatoxins (e.g., lyngbyatoxins). Poste et al. (2011) found microcystin toxin can accumulate in Lake Erie Walleye in concentrations that may pose a concern for safe consumption. However, other studies suggest the accumulation and retention of toxins may be species dependent and of minimal concern (e.g., Dyble et al. 2011). Currently, our understanding of the dynamics among HABs, cyanobacteria toxins, the fish community, and safe consumption of fish caught during a bloom is incomplete. Consumption advisories have warnings about consuming fish caught during a HAB, and they may include adequately rinsing fillets and avoiding consumption of organs. Microplastics (≤5-mm diameter) are derived from pellets used for transport, microbeads in personal care products, and abrasive scrubbers; microfibers from synthetic fabrics; and the breakdown of larger plastic products. In Lake Erie, microplastics are found at concentrations like those in marine gyres (Driedger et al. 2015). Preliminary studies have found that persistent organic pollutants, such as polycyclic aromatic hydrocarbons and PCBs, can adhere to microplastics (L. Rios Mendoza, University of Wisconsin-Superior, personal communication, 2013). Microplastics can enter the food web and potentially threaten the growth, behavior, and survival of fish. Despite legislation on microbeads manufactured for personal products by the U.S. and Canadian governments (H.R.1321-U.S. Microbead-Free Waters Act of 2015 and Canadian Environmental Protection Act, 1999 (S.C. 1999, c. 33, subsection 90(1)), the long lifespan of these materials and the numerous sources of microplastics may result in continued increases in concentrations in Lake Erie.

Conflicting findings in the trends of contaminants complicate evaluation of progress toward the LEEO, which is minimizing the presence of contaminants in the lake. Some evidence suggests improvements whereas others point to either stable or deteriorating conditions. Differences in long-running monitoring programs limit interjurisdictional comparisons of consumption advisories and may result in conflicting trends. However, alterations to existing programs could compromise U.S. and Canadian agencies' long-term monitoring programs and their ability to analyze trends. Gorman and MacDougall (2016) recommended standardizing methods used to quantify fish-tissue contaminants across the Great Lakes to facilitate within and across lakes comparisons and trend-through-time analyses. The LEC's involvement in contaminant monitoring is limited to sample collection, and it has not taken a position on standardization. Microcystin toxin in fish flesh and microplastics represent emerging impediments to the LEEO of minimizing contaminants.

Acknowledgements

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STATUS OF FORAGE FISH IN LAKE ERIE IN 2015[10]

Richard Drouin[11], Eric Weimer, John Deller, Chelsea May, and Tom MacDougal

Qualitative objectives for forage fish were not specified in Ryan et al. (2003) but are implied in their overall yield objective of 13.6-27.3 million kg (30-60 million lb) of highly valued fish. Therefore, this report about progress during 2009-2015 provides a perspective on whether or not the status of forage fish is trending in a direction consistent with supporting the production of highly valued fish. The comparison of forage-fish abundance in this reporting period with that in the previous reporting period, 2004-2008 (Markham and Knight 2017), provides an assessment of whether or not the status of forage fish is consistent with the overall yield objective.

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[10]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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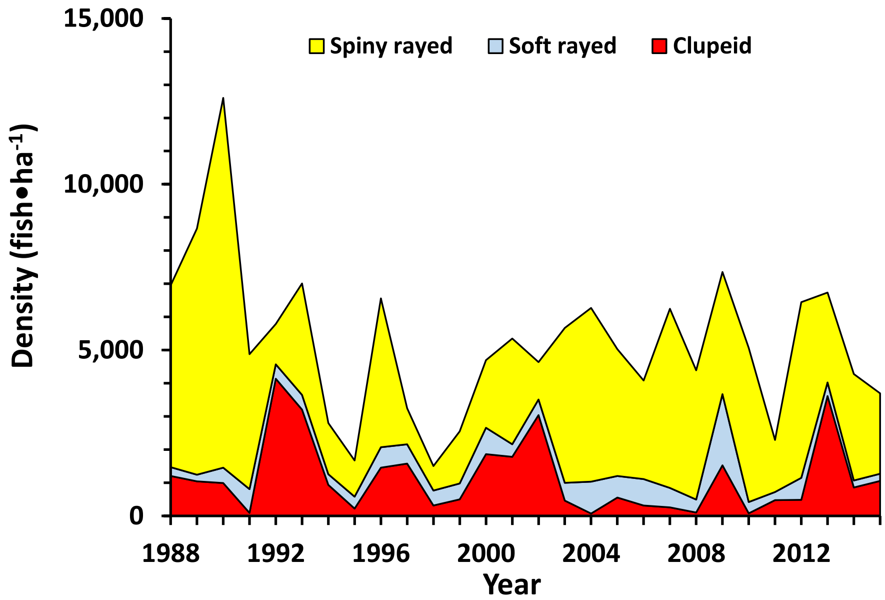
Western Basin

The mean density of forage fish in Lake Erie's western basin during 2009-2015 was 5,100 fish•ha^{-1}, virtually the same as that in the 2004-2008 reporting period. Interannual variation, however, was greater in 2009-2015 than in 2004-2008 as interagency surveys with bottom trawls produced annual estimates ranging from 2,200-7,300 fish•ha^{-1} in the previous period and 4,000-6,000 fish•ha^{-1} in this period (Fig. 14). During 2009-2015, forage-fish composition was again dominated by spiny-rayed species (mostly age-0 White Perch), although mean density for the period (3,400 fish•ha^{-1}) was down 20% from mean density for 2004-2008 (4,300 fish•ha^{-1}). In contrast, the mean density of clupeids (mainly age-0 Gizzard Shad) was considerably higher (1,150 fish•ha^{-1}) than in the previous period (260 fish•ha^{-1}), spiking in 2013 to 54% of the total forage estimate. Alewife has been absent or rare in the western basin since 2002 (O'Gorman et al. 2012). Soft-rayed forage fish (mainly Rainbow Smelt and shiners) once again contributed the smallest proportion of available forage in the western basin, and their mean density in 2009-2015 (605 fish•ha^{-1}) was similar to that in 2004-2008 (680 fish•ha^{-1}). Soft-rayed fish density rose to a time-series peak of 2,150 fish•ha^{-1} in 2009 and resulted in 30% of available forage in that year.

Fig. 14. Mean density (fish•ha^{-1}) of three categories of forage fish in Lake Erie's western basin, 1988-2015 (FTG 2016). Densities were estimated from August surveys with bottom trawls in Michigan, Ohio, and Ontario waters. The clupeid and spiny-rayed categories include only age-0 fish whereas the soft-rayed category includes fish of all ages.



Central Basin

Forage fish in the central basin of Lake Erie are estimated from surveys with bottom trawls, except in Ontario waters. The mean density of forage fish in Ohio waters of the central basin was slightly lower in 2009-2015 than in 2004-2008, the previous reporting period (2,270 vs. 2,390 fish•ha^{-1}; Fig. 15). In Ohio waters of the west-central sub-basin, mean density increased from 1,870 to 2,490 fish•ha^{-1} between the two time periods whereas, in Ohio waters of the east-central sub-basin, mean density decreased from 3,290 to 1,850 fish•ha^{-1} between the two periods (Fig. 16). In Pennsylvania waters of the east-central sub-basin, forage-fish density decreased 57% between the two reporting periods, although trawling was not conducted in 2010, 2011, and 2014.

Fig. 15. Mean density of four categories of forage fish (fish•ha^{-1}) in Ohio waters of Lake Erie's central basin, 1990-2015. The clupeid and spiny-rayed categories include only age-0 fish whereas the other soft-rayed and Rainbow Smelt categories include fish of all ages.

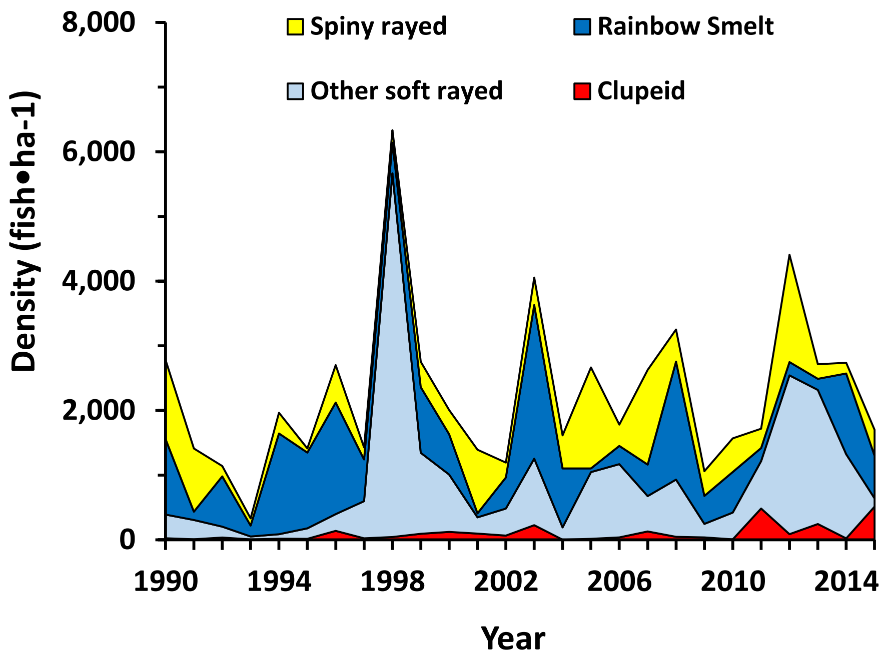
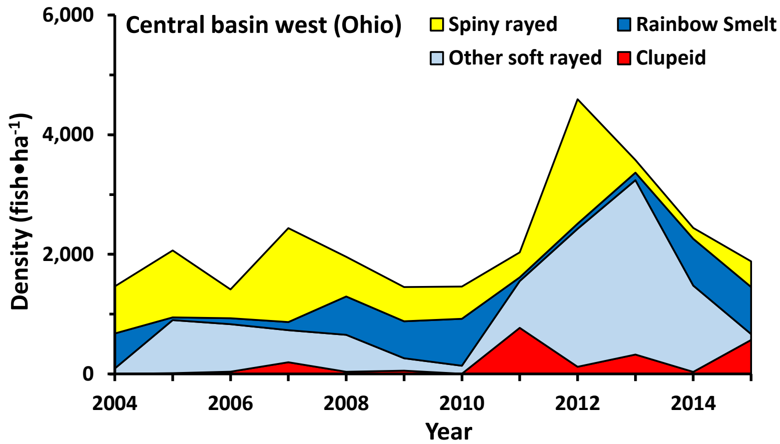
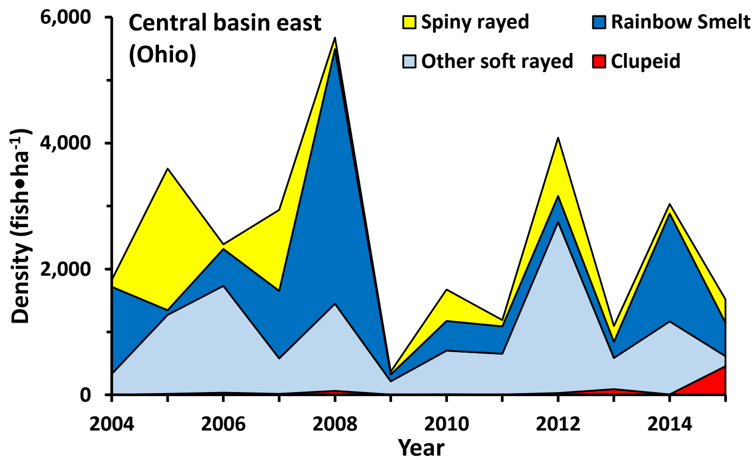
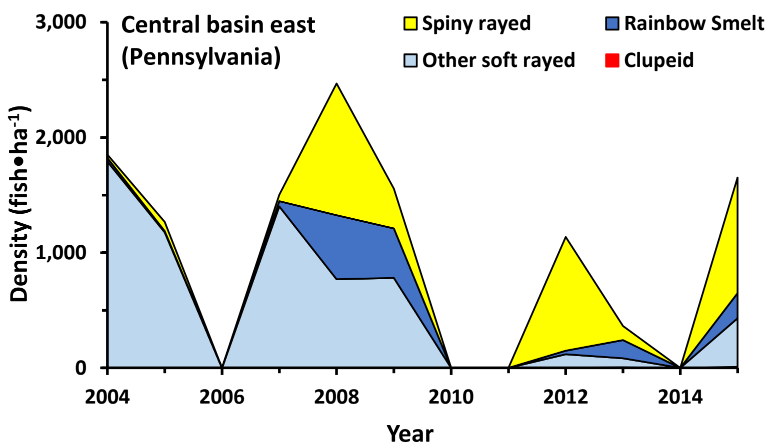


Fig. 16. Mean density (fish•ha^{-1}) of four categories of forage fish in three areas of Lake Erie's central basin (Ohio waters of the western sub-basin and Ohio and Pennsylvania waters of the eastern sub-basin) as determined by area swept with bottom trawls during October 2004-2015 (FTG 2016). The clupeid- and spiny-rayed categories include only age-0 fish whereas the other soft-rayed and Rainbow Smelt categories include fish of all ages. No trawling was done by Pennsylvania in 2006, 2010-11, or 2014. Note that the scale of the lower panel differs from that of the upper two panels.




Central basin east
(Ohio)
Spiny rayed
Rainbow Smelt
Other soft rayed
Clupeid
Density (fish•ha-1)
6,000
4,000
2,000
0
2004
2006
2008
2010
2012
2014
Year


Central basin east
(Pennsylvania)
Spiny rayed
Rainbow Smelt
Other soft rayed
Clupeid
Density (fish•ha-1)
3,000
2,000
1,000
0
2004
2006
2008
2010
2012
2014
Year

Rainbow Smelt and other soft-rayed fish continued to dominate the overall composition of the central-basin's forage fish in 2009-2015. Within these two categories, however, there was a shift in dominance between reporting periods such that Rainbow Smelt declined to 22% of the forage in 2009-2015 while other soft-rayed fish, such as shiners, increased to 46% of forage. The contribution of spiny-rayed fish declined from 36% to 23% of total forage from the 2004-2008 reporting period to the 2009-2015 period while clupeids increased from a barely detectable proportion of total forage in 2004-2008 to 11% of total forage in 2009-2015.

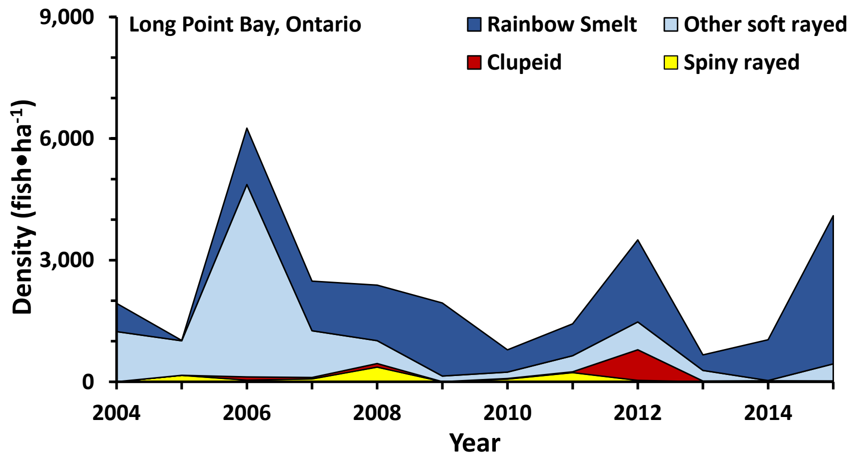
In the west-central sub-basin, mean density of clupeids (age-0 Gizzard Shad and Alewife) was >300% higher in 2009-2015 than in 2004-2008 and clupeid contribution to total forage-fish density averaged 12% in 2009-2015 as compared to 3% in 2004-2008 (Fig. 16). The density of other soft-rayed fish (shiners, Trout-Perch, Round Goby) nearly doubled from the 2004-2008 time period, with 37% of the 2009-2015 forage base in the west-central basin consisting of other soft-rayed fish. However, the contribution and density of spiny-rayed species (age-0 Yellow Perch and White Perch) decreased from 49% and 925 fish•ha^{-1} to 25% and 633 fish•ha^{-1} between 2004-2008 and 2009-2015.

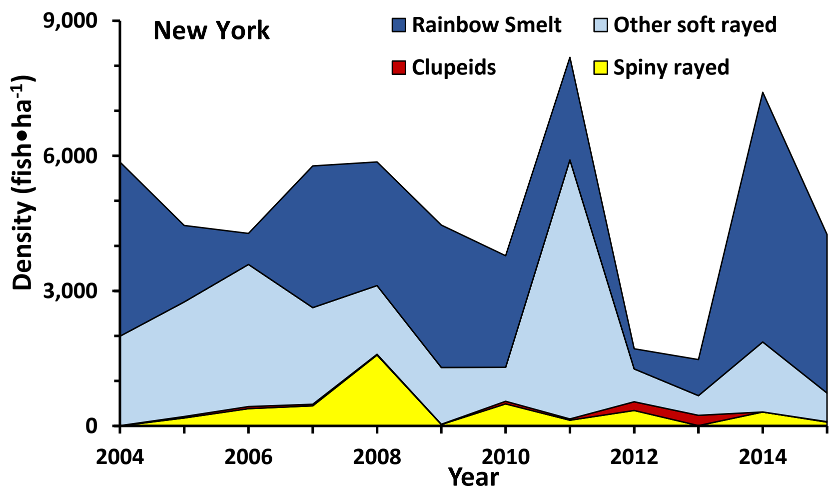
The decrease in spiny-rayed forage fish also occurred in the east-central sub-basin, with spiny-rayed forage fish in Ohio waters decreasing from 780 fish•ha^{-1} in 2004-2008 to 330 fish•ha^{-1} in 2009-2015 (Fig. 16). A different pattern was evident in the abbreviated data from Pennsylvania waters where the mean density of spiny-rayed fish increased from 330 fish•ha^{-1} in 2004-2008 to 610 fish•ha^{-1} in 2009-2015. Rainbow Smelt and other soft-rayed fish were again the dominant forage fish in the east-central sub-basin during 2009-2015. Historically, clupeids were never abundant in Ohio or Pennsylvania waters of the central basin. However, in 2009-2015, there was a four-fold increase in clupeids, especially age-0 Gizzard Shad in Ohio waters.

Eastern Basin

Assessments of forage fish in Lake Erie's eastern basin are accomplished through two separate bottom-trawl surveys, one conducted by the Ontario Ministry of Natural Resources and Forestry and the other by the New York State DEC. Density in 2004-2008 ranged from 4,170-5,700 fish•ha^{-1} and 1,020-6,260 fish•ha^{-1} in Ontario and New York waters, respectively, as compared with 1,490-8,260 fish•ha^{-1} and 840-5,040 fish•ha^{-1} during 2009-2015 (Fig. 17). Overall, the density of forage fish was higher in New York than in Ontario, except for clupeids—Gizzard Shad and Alewife. This was mostly due to a large number of Alewife in 2012. Rainbow Smelt was the dominant forage fish in the eastern basin, making up 64% and 55% of catches in Ontario and New York waters, respectively. Soft-rayed forage fish were dominated by Emerald Shiner, especially in New York. There was a decrease in the density of spiny-rayed fish due to lower recruitment of Yellow Perch. Clupeids remained a minor component of the forage-fish community (<5%) other than the aforementioned peak in Alewife density in 2012. Observations suggest that forage abundance has been sufficient to support both cool and cold-water piscivores. For example, Lake Trout in the eastern basin grow fast and are in good condition (see Markham et al., this volume).

Fig. 17. Mean density (fish•ha^{-1}) of four categories of forage fish in Ontario and New York waters of Lake Erie's eastern basin, 2004-2015 (FTG 2016). The clupeid and spiny-rayed categories include only age-0 fish whereas the other soft-rayed and Rainbow Smelt categories include fish of all ages.


Long Point Bay, Ontario
Rainbow Smelt
Other soft rayed
Clupeid
Spiny rayed
9,000
6,000
3,000
0
Density (fish•ha-1)
2004
2006
2008
2010
2012
2014
Year


New York
Rainbow Smelt
Other soft rayed
Clupeids
Spiny rayed
9,000
6,000
3,000
0
Density (fish•ha-1)
2004
2006
2008
2010
2012
2014
Year

STATUS OF WALLEYE AND YELLOW PERCH IN LAKE ERIE IN 2015[12]

Stephen A.C. Marklevitz[13], Megan Belore, Matthew D. Faust, and Todd C. Wills

This report responds to a commitment by fishery agencies on the Great Lakes to report progress on meeting fish community objectives (FCOs) established for each Great Lake (GLFC 2007). These objectives for Lake Erie do not specify targets for individual species, although they do specify broad ecological principles for achieving sustainability. Instead, an objective for highly valued species was adopted, and it seeks to maintain their yield in the aggregate at 13.6-27.3 million kg (Ryan et al. 2003). The issue addressed here is if populations of highly valued fish like Walleye and Yellow Perch are trending in a direction consistent with the overall objective. This question is answered through comparisons of the status of species during this

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[12]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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reporting period (2009-2015) with their status reported by Markham and Knight (2017) for the previous reporting period (2004-2008).

Walleye

Western- and Central-Basin Walleye

The western basin and its tributaries are the major spawning and nursery areas for Walleye in Lake Erie. Discrete spawning stocks exist in the Detroit, Maumee, and Sandusky Rivers and on reef complexes in Ohio and Ontario (Goodyear et al. 1982; DuFour et al. 2015). Spawning-site fidelity (natal homing) appears relatively high (Chen et al. 2017 but see Hayden et al. 2018). After spawning, stocks likely intermix as they move throughout Lake Erie (Zhao et al. 2011; Matley et al. 2020). Wang et al. (2007) and Raby et al. (2018) suggested that larger, older females were more likely to move further east. Walleye also moves north through the St. Clair-Detroit River System to as far away as northern Lake Huron (Vandergoot and Brenden 2014; Brenden et al. 2015; Hayden et al. 2019). Based on the information available to date, fisheries in the central basin are assumed to be dependent mostly on production and migration from western-basin tributaries and reefs. Spawning is known to occur within the central basin on nearshore reefs and in the Grand River, Ohio (Stepien et al. 2018). Although the contribution of the resulting offspring to the lakewide fishery remains unknown, it is suspected to be much less than that from stocks spawning in the western basin.

The Lake Erie Walleye Task Group (WTG) uses a statistical catch-at-age model developed with the Lake Erie Percid Management Advisory Group (LEPMAG) to estimate abundance and predict recruitment of Walleye in the western and central basins of Lake Erie (WTG 2016). This stock assessment model estimates the number of age-2 and older fish using data from fishery-dependent and fishery-independent sources. The 2016 model runs indicated that the number of Walleye in the western and central basins has declined since 2009, thus continuing a decade-long trend (Fig. 18). Walleye abundance decreased from a peak of 136 million fish in 2005 to 26 million fish in 2015. This abundance is the lowest since 1982 and far below the average of 80 million fish for the 2004-2008 reporting period but also below the average of 52 million fish for the 1980-2015 time series (Drouin and Soper 2017; Kayle and Murray 2017). Like other Walleye populations across North America, recruitment in the western basin of Lake Erie displays large inter-annual fluctuations with strong to moderate year-classes often followed by weak year-classes (Fig. 19; Vandergoot et al. 2010). Moderately strong 2007 and 2010 year-classes recruited to the fisheries in 2009 and 2012, respectively, and provided brief respites from declining numbers (Fig. 18). Except for the 2010 year-class, production of young-of-the-year Walleye was relatively weak from 2009-2013 (Fig. 19). Bottom trawling in the western basin during 2009-2013 caught an average of 11 age-0 Walleye•ha^{-1}, equal to the 2004-2008 average catch rate but well below the 1998-2015 average of 30 age-0 Walleye•ha^{-1}. However, much stronger year-classes were produced in 2014 and 2015 (age-0 Walleye catch rates of 29 and 84 fish•ha^{-1}, respectively), and, when Walleye from those two year-classes recruit to the fishery as age-2 fish in 2016 and 2017, Walleye abundance was expected to increase lakewide.

Fig. 18. Abundance and harvest (millions of fish) of age-2 and older Walleye in the western and central basins of Lake Erie, 1980-2015. Abundance estimates were based on results from the 2016 integrated statistical catch-at-age model (WTG 2016). Note that abundance and harvest are shown on different scales.

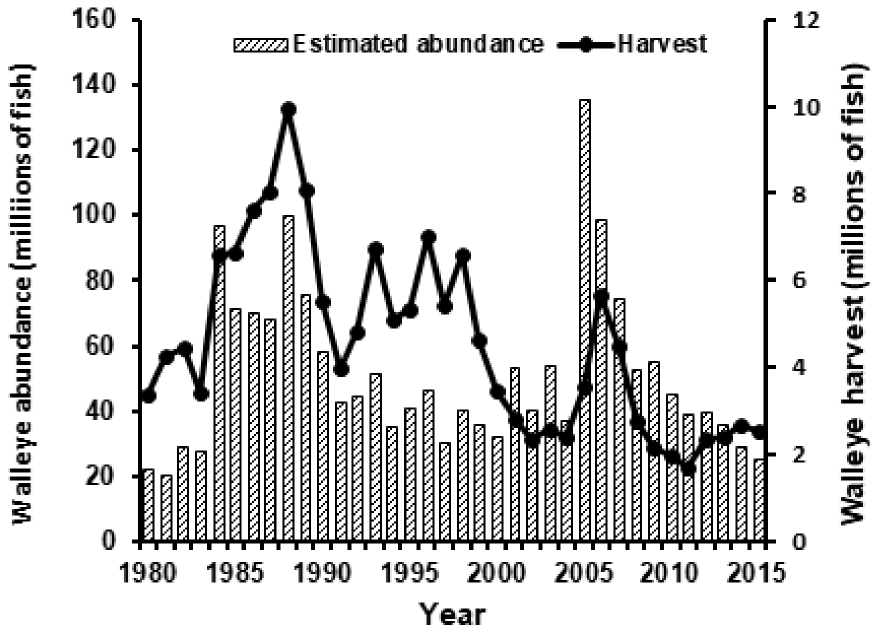
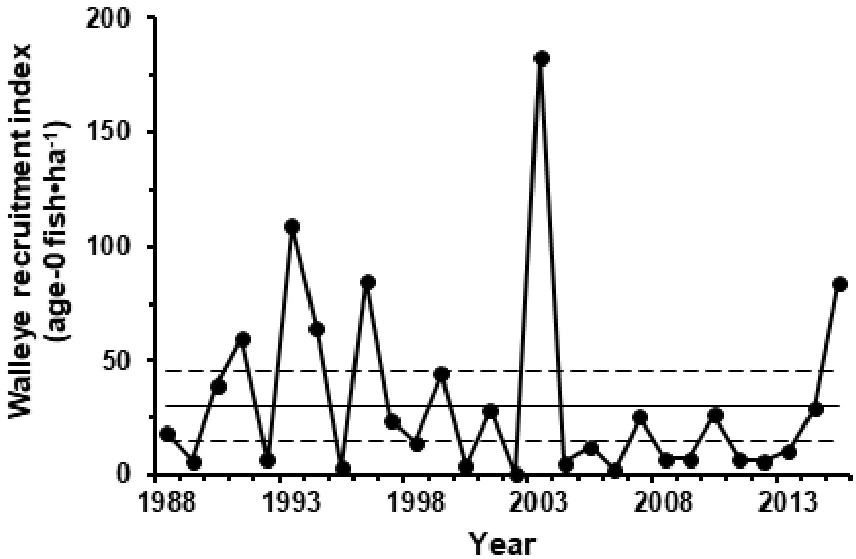


Fig. 19. Recruitment index (fish•ha^{-1}) of age-0 Walleye calculated from the catches in and area swept by bottom trawls in the western basin of Lake Erie, 1988-2015. Nets were towed by the Ohio Department of Natural Resources and the Ontario Ministry of Natural Resources and Forestry as part of the Interagency Trawling Program. Also shown is the 1988-2015 index average of 30 age-0 Walleye•ha^{-1} (solid line) with the 95% CI (dashed lines).



During 2009-2015, the annual harvest of age-2 and older Walleye from the western and central basins by the commercial and recreational fisheries ranged from 1.7 to 2.7 million fish and averaged 2.3 million fish (Fig. 18). The average harvest was below that in 2004-2008 (3.8 million fish) as well as below the 1980-2015 average of 4.5 million fish. The exploitation rate of the combined commercial and recreational fisheries was 6% during 2009-2015, which was near the 5% exploitation rate during 2004-2008 but below the long-term exploitation rate of 9%. The annual survival rate of age-2 and older Walleye in 2009-2015 averaged 68%, which was similar to the 69% annual survival rate during 2004-2008 and slightly higher than the 1980-2015 average of 65%.

Eastern-Basin Walleye

Walleye is an abundant top predator in the mesotrophic areas of Lake Erie's eastern basin (Kayle et al. 2015). Discrete stocks of Walleye spawn in tributaries to and nearshore areas of Ontario and New York waters, including the Grand River in Ontario and Cattaraugus Creek and Van Buren Bay in New York. An estimated 65% of the eastern-basin's resident stock of Walleye originates from Van Buren Bay (Zhao et al. 2011). Historically, stocks resident in the eastern basin were considered spatially and genetically distinct from stocks in the western and central basin (Wolfert and Van Meter 1978; Nepszy et al. 1991). However, more recent genetic analysis and tagging studies show that eastern-basin Walleye fisheries harvest resident stocks and seasonal migrants from western-basin stocks (Stepien and Faber 1998; McParland et al. 1999; Gatt et al. 2003; Wang et al. 2007; Vandergoot and Brenden 2014). Zhao et al. (2011) estimated that, on average, 90% of Walleye harvested in the eastern basin are seasonal migrants from the western basin.

The assessment of abundance, recruitment, and survival of eastern-basin Walleye is hindered by uncertainty of annual variation in the age and size structure of migrants from the western basin, resulting in the lack of a broadly accepted statistical catch-at-age model. Walleye abundance in the eastern basin peaked from 2005-2007 in association with recruitment of fish from the strong 2003 year-class in the western and central basin (Fig. 20; Zhao et al 2011). However, when the fish recruited from the moderate year-classes produced in the western and central basin in 2007 and 2010, they were not seen in moderate numbers in the eastern basin and did little to bolster Walleye numbers there (WTG, unpublished data). Walleye abundance is greater in New York waters of the eastern basin than in the basin's Ontario waters (Fig. 20; Zhao et al. 2011). During 2009-2015, annual harvest of the combined commercial and recreational fisheries in the eastern basin ranged from 86,000 to 200,000 Walleyes with an average harvest of 134,000 fish, which is essentially the same as the annual average of 137,000 fish for the 2004-2008 reporting period and for the 1998-2015 time series (Fig. 21). Zhao et al. (2011) calculated an exploitation rate of 6% by the recreational fishery and a survival rate of 75% for Walleye resident in the eastern basin during 1993-2007. This survival rate was higher than that for western-basin fish (65%) during the same time period (Zhao et al 2011; WTG 2016).

Fig. 20. Mean catch rates (fish•net lift^{-1}) of age-2 and older Walleye in gillnets fished during index surveys in Ontario and New York waters of Lake Erie's eastern basin, 1988-2015. Note that catch rates in Ontario and New York are plotted on different scales and that gillnets were not fished in Ontario in 1988, 1996, and 1997.

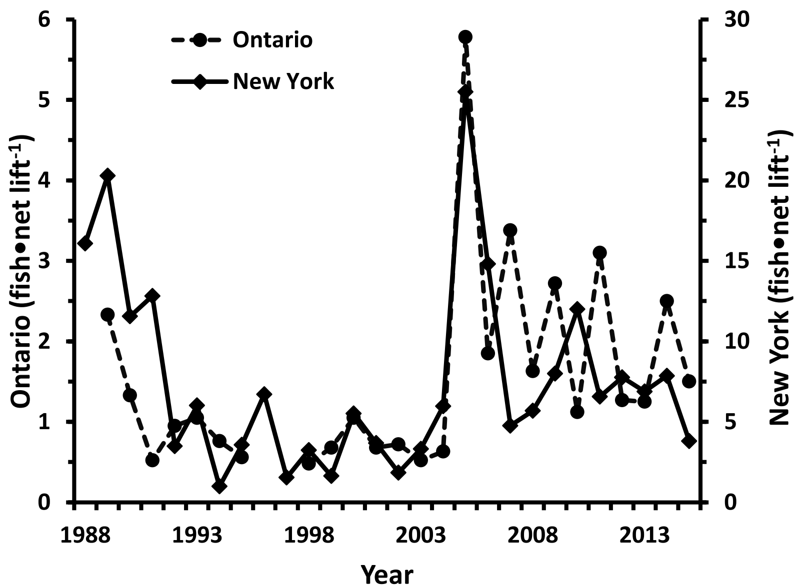
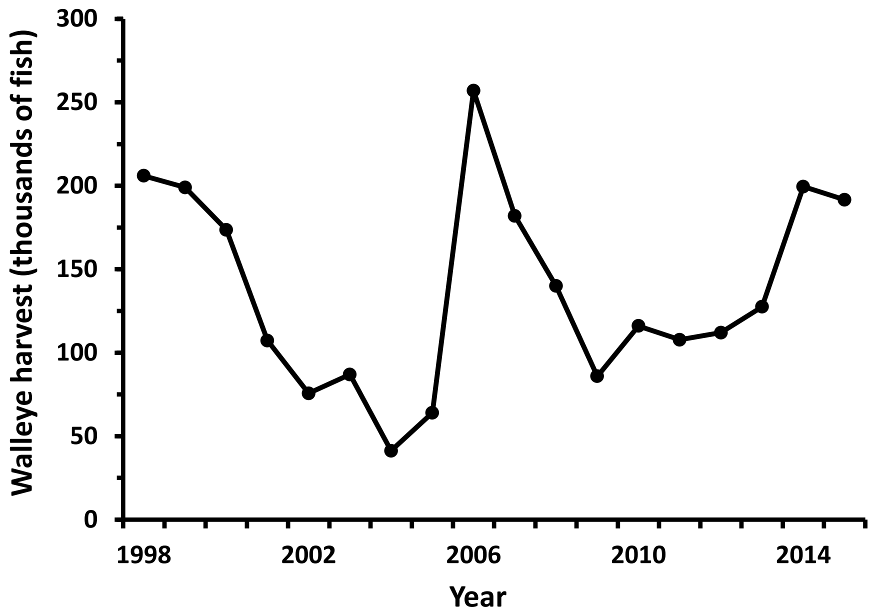


Fig. 21. Walleye harvest (thousands of fish) by commercial and recreational fisheries in the eastern basin of Lake Erie, 1998-2015 (Kayle et al. 2015; Walleye Technical Group, unpublished data).



Stock Structure

Delineation of stock structure is a knowledge gap facing Walleye management in Lake Erie (Kayle et al. 2015). The Lake Erie Walleye fishery comprises fish from discrete populations that spawn in tributaries, on open-water reef complexes, and in connecting waterways; because of this structure, populations are resilient due to "portfolio effects" (Strange and

Stepien 2007; Einhouse and MacDougall 2010; DuFour et al. 2015). Portfolio effects arise when stock-specific recruitment patterns are uncorrelated, likely due to differences in controlling mechanisms (DuFour et al. 2015). Fisheries receiving contributions from multiple populations or stocks exhibit more stable production and decreased risk of collapse from recruitment failure than fisheries focused on an individual population or stock (Hilborn et al. 2003; DuFour et al. 2015). However, the benefits of portfolio effects may be degraded by managing fisheries as an aggregate mixture of individual populations (DuFour et al. 2015).

In Lake Erie, stock discrimination of fish harvested by the Walleye fishery has been attempted during the past 20 years using a variety of genetic markers with mixed, and at times conflicting, results (e.g., Stepien and Faber 1998; McParland et al. 1999; Gatt et al. 2003; Strange and Stepien 2007; Stepien et al. 2010). For example, although significant differentiation has generally been shown between basins in Lake Erie (Strange and Stepien 2007) and among Great Lakes (Stepien et al. 2010), demonstrating within-basin differentiation has been more difficult (McParland et al. 1999; Gatt et al. 2003; Strange and Stepien 2007; Stepien et al. 2010). Analyses using microsatellite loci allowed some stocks from open-water reefs and the stock from the Huron River, Michigan, to be distinguished from all others, but many other important stocks like those spawning in the Maumee and Sandusky Rivers were indistinguishable (Strange and Stepien 2007; Stepien et al. 2010). Similarly, a mixed-stock analysis that used microsatellite loci to discriminate among Walleye stocks in the recreational harvest in Lake Huron's Saginaw Bay found it necessary to pool stocks from Lake Erie due to an inability to accurately classify fish to an individual stock level (Brenden et al. 2015). In addition, different genetic markers, such as allozymes and mitochondrial DNA, have led to different conclusions regarding stock structure (McParland et al. 1999). Conclusions are further confounded by the use of different stock definitions (e.g., stocks defined by basins, not sub-basins) owing to limitations imposed by the genetic markers used (Gatt et al. 2003). Even next-generation restriction site associated DNA sequencing, which arguably offers the most promise for stock discrimination (Cuéllar-Pinzón et al. 2016), has shown limited success for discriminating Walleye stocks in western Lake Erie despite employing >5,000 single nucleotide polymorphisms (loci) (A. Chen, S.A. Ludsin, and E.A. Marschall, The Ohio State University, unpublished data).

Otolith microchemistry (trace elements in the water that are incorporated into the calcium-carbonate matrix of otoliths) has shown promise for discriminating among western-basin Walleye stock (Hedges 2002; Bartnik 2005; Bigrigg 2008). Currently, however, only the Sandusky River stock can be discriminated from others in Lake Erie. Two of western Lake Erie's largest spawning stocks, the Ohio reef complex and Maumee River, cannot be differentiated (Chen et al. 2017). In addition, considerable effort is required to fully evaluate the efficacy of otolith microchemistry for stock discrimination before applying it to fishery-dependent and fishery-independent samples (Vandergoot et al. 2010). Pangle et al. (2010) recommended developing a multi-decadal library of otolith microchemical signatures at localized sites to better understand temporal variability in otolith microchemical signatures and to appropriately account for population structure when establishing status of the lakewide population. Limited ability to discriminate among stocks (regardless of methodology) make stock-specific Walleye management in Lake Erie, such as that advocated by DuFour et al. (2015), challenging to implement.

Yellow Perch

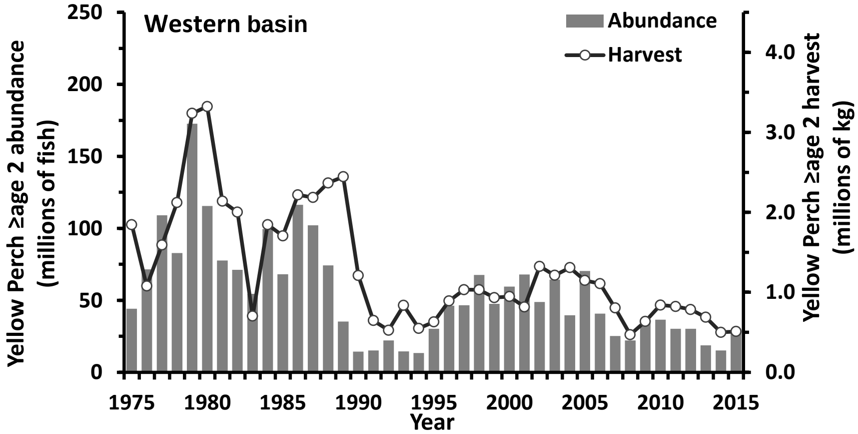
On average, Yellow Perch composed, by weight, 24% of the Ontario commercial harvest and 33% of the Ohio commercial harvest during 2009-2015. During this period, the average value of Yellow Perch landings in the commercial fisheries was CDN$12.9 million in Ontario and US$3.4 million in Ohio. Pennsylvania and New York have small-scale commercial fisheries for Yellow Perch, and Michigan does not allow commercial harvest of

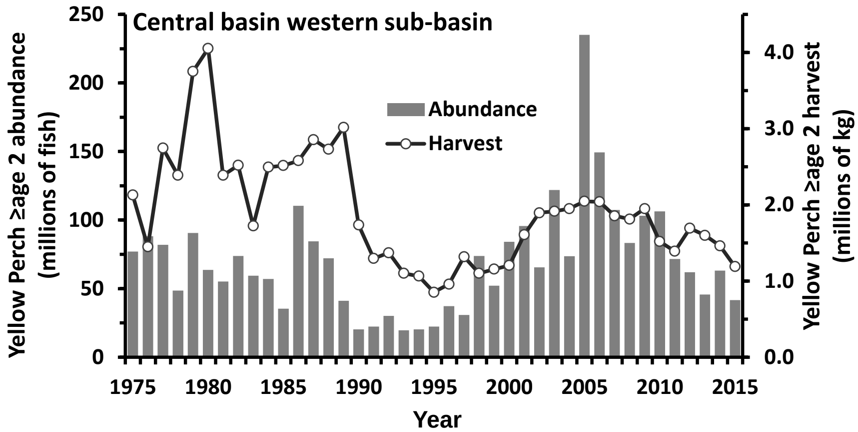
Yellow Perch from Lake Erie. During 2009-2015, anglers targeting Yellow Perch averaged 35%, 37%, and 17% of the total recreational fishing effort in Michigan, Ohio, and New York waters, respectively. In Ontario waters, Yellow Perch anglers accounted for about 34% of total recreational fishing effort and 58% of total recreational catch during a 2014 creel survey.

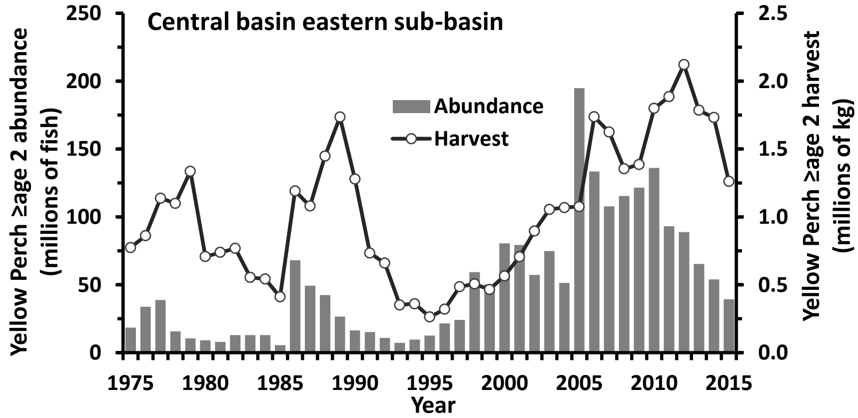
Abundance and Recruitment

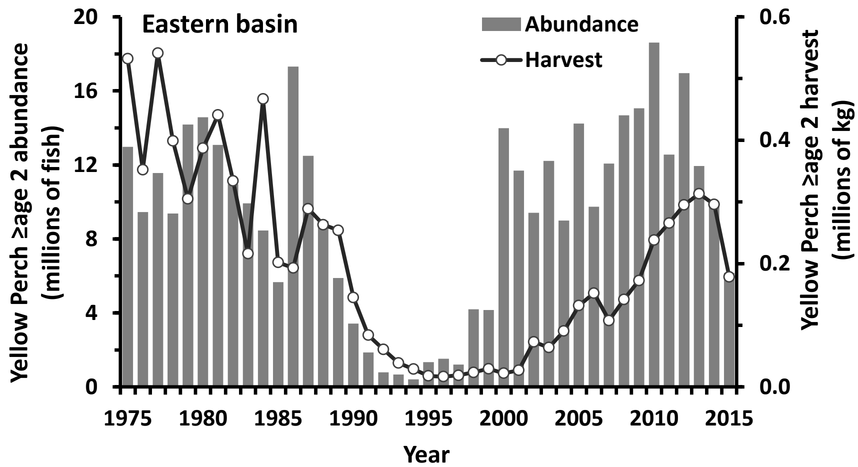
The Lake Erie Yellow Perch Task Group uses a statistical catch-at-age model to estimate abundance and predict recruitment of Yellow Perch in the four management units within Lake Erie, the western basin, the west-central sub-basin, the east-central sub-basin, and the eastern basin. In the western basin, average abundance of adult (≥age 2) Yellow Perch declined from 39.6 million fish in 2004-2008 to 28.0 million fish in 2009-2015 (Fig. 22). Higher abundance during 2004-2008 was due to the large 2003 year-class, which recruited to the adult population in 2005. From 2009-2015, abundance of adult Yellow Perch ranged from 15.2 to 36.5 million fish. Average number of age-2 Yellow Perch recruiting declined from 15.5 million fish in 2004-2008 to 13.3 million fish in 2009-2015. Moderate year-classes recruited to the adult population in 2009 (2007 year-class) and 2015 (2013 year-class). Moderate to strong year-classes were produced in 2014 and 2015, which will recruit to the fishery as age-2 fish in 2016 and 2017.

Fig. 22. Abundance (millions of fish) and harvest (millions of kg) of age-2 and older Yellow Perch in Lake Erie’s western basin, western and eastern sub-basins of the central basin, and eastern basin, 1975-2015 (YPTG 2016). Note that abundance in the eastern basin is shown on a different scale from that in the other three areas and that harvest is shown on different scales, except in the western basin and western sub-basin of the central basin.


Western basin
Abundance
Harvest
Yellow Perch ≥age 2 abundance (millions of fish)
Yellow Perch ≥age 2 harvest (millions of kg)
Year
250
200
150
100
50
0
4.0
3.0
2.0
1.0
0.0
1975
1980
1985
1990
1995
2000
2005
2010
2015


Central basin western sub-basin
Abundance
Harvest
Yellow Perch ≥age 2 abundance (millions of fish)
Yellow Perch ≥age 2 harvest (millions of kg)
Year
250
200
150
100
50
0
4.0
3.0
2.0
1.0
0.0
1975
1980
1985
1990
1995
2000
2005
2010
2015


Central basin eastern sub-basin
Abundance
Harvest
Yellow Perch ≥age 2 abundance (millions of fish)
Yellow Perch ≥age 2 harvest (millions of kg)
Year
0
50
100
150
200
250
0.0
0.5
1.0
1.5
2.0
2.5
1975
1980
1985
1990
1995
2000
2005
2010
2015


Eastern basin
Abundance
Harvest
Yellow Perch ≥age 2 abundance (millions of fish)
Yellow Perch ≥age 2 harvest (millions of kg)
Year
0
4
8
12
16
20
0.0
0.2
0.4
0.6
1975
1980
1985
1990
1995
2000
2005
2010
2015

In the west-central sub-basin, abundance of adult Yellow Perch declined from an average of 129.8 million fish during 2004-2008 to 70.5 million fish during 2009-2015. In general, total abundance in this area of Lake Erie has been declining since 2005 largely due to the waning numbers of fish in the large 2003 year-class (Fig. 22). Recruitment of age-2 Yellow Perch declined from 51.4 million fish during 2004-2008 to 26.6 million fish during 2009-2015. Recent moderately strong year-classes in the west-central sub-basin include those produced in 2007, 2008, and 2012 that recruited in 2009, 2010, and 2014.

In the east-central sub-basin, abundance of adult Yellow Perch declined from an average of 120.6 million fish during 2004-2008 to 85.5 million fish during 2009-2015 (Fig. 22). In addition, the average number of age-2 recruits declined from 51.9 million fish to 25.2 million fish between the two reporting periods. As in areas to the west, much of these declines can be attributed to the large 2003 year-class recruiting in 2005 and then moving through the population. Recent stronger year-classes include those produced in 2007 and 2008 that recruited in 2009 and 2010. Recruitment was poor in the east-central sub-basin from 2013-2015.

In the eastern basin, trends in abundance and recruitment of Yellow Perch differed from those in other areas of Lake Erie. Abundance of adults increased modestly from an average of 11.9 million fish during 2004-2008 to 13.0 million fish during 2009-2015. Recruitment remained essentially unchanged through the two time periods, with about 4.7 million age-2 fish recruiting annually during 2004-2008 and 4.4 million age-2 fish recruiting annually during 2009-2015. Strong Yellow Perch reproduction occurred in 2008 and 2010 in the eastern basin, and fish from those year-classes recruited in 2010 and 2012.

Harvest

Harvest of Yellow Perch in the western basin of Lake Erie during 2009-2015 was among the lowest in the 1975-2015 time series. On average, western-basin fisheries harvested 700 t of Yellow Perch annually during 2009-2015, which was lower than the average harvest of 1,000 t of Yellow Perch from 2004-2008 (Fig. 22; YPTG 2016). However, given that moderate to strong year-classes were produced during 2013-2015, harvest may increase as these fish recruit to the commercial and recreational fisheries in the western basin.

In the west-central sub-basin, fisheries harvested an average of 1,500 t of Yellow Perch annually during 2009-2015, which was lower than the average harvest of 1,900 t of Yellow Perch from 2004-2008 (Fig. 22; YPTG 2016). Harvest in the west-central sub-basin has been declining since 2012, and Yellow Perch harvest in 2015 was the lowest since 1999. Higher harvests of Yellow Perch during 2004-2008 largely comprised fish of the strong 2003 year-class, but harvest declined during 2009-2015 as the number of fish in this year-class was greatly reduced by 2009.

Fisheries in the east-central sub-basin harvested about 1,700 t of Yellow Perch annually during 2009-2015, a modest increase from the average harvest of 1,400 t of Yellow Perch annually during 2004-2008 (Fig. 22; YPTG 2016). Harvest during 2012 in the east-central sub-basin was the highest in the time series (1975-2015).

Eastern-basin fisheries harvested an average of about 251 t of Yellow Perch annually during 2009-2015, which was double the average harvest of 125 t of Yellow Perch annually during 2004-2008 (Fig. 22; YPTG 2016). In 2013, the Yellow Perch harvest in the eastern basin was the highest since 1984.

The current harvest policy of the Lake Erie Committee (LEC) for Yellow Perch uses a risk-based assessment of a constant fishing rate for stocks in the western and central basins. Development of a new Yellow Perch Management Plan by the LEPMAG will guide future interagency management of exploitation by the fisheries.

Stock Structure

The LEC's FCOs for Lake Erie explicitly recognize the importance of stock-based management along with the need to better understand and delineate stock structure for several exploited fish (Ryan et al. 2003). Various genetic markers have been used to provide insight into the structuring of Lake Erie's Yellow Perch population (Sepulveda-Villet et al. 2009; Sepulveda-Villet and Stepien 2011; Sullivan and Stepien 2014). Across the Yellow Perch's native range, mitochondrial DNA demonstrated broad-scale genetic structuring of populations, but these patterns broke down on Lake Erie, which indicated low genetic variability and little population structure (Sepulveda-Villet et al. 2009). In contrast, a subsequent analysis using microsatellite loci examined fine-scale genetic relationships among 13 spawning sites across Lake Erie (Sepulveda-Villet and Stepien 2011) and found greater population structuring than did previous studies (e.g., Strittholt et al. 1988; Sepulveda-Villet et al. 2009). However, genetic variation among spawning sites did not correspond to management units or physiographic basins so factors, such as ancestral lineages and environmental variation, were more likely responsible for the differences than isolation by distance (Sepulveda-Villet and Stepien 2011).

Otolith microchemistry (trace elements in water that are incorporated into the calcium-carbonate matrix of otoliths) has shown promise for discriminating some western-basin Yellow Perch stocks from others (Pangle et al. 2010). Larval Yellow Perch collected within Sandusky Bay could be accurately classified back to their collection site whereas the ability to do so for larvae collected at offshore sites (like western-basin reefs) was lower

(Pangle et al. 2010). The inability to accurately classify fish produced offshore is likely due to the homogeneous chemistry of water in the open lake and is further complicated by high interannual variation in otolith microchemistry signatures at most spawning sites. Therefore, Pangle et al. (2010) recommended development of a multi-decadal library of otolith microchemical signatures at localized spawning sites to allow better understanding of temporal variability in otolith microchemical signatures and to appropriately deal with the variation during stock discrimination.

Given the complexities associated with resolving the stock structure of Lake Erie's Yellow Perch population by a single method (e.g., Pangle et al. 2010), future studies may benefit from integrating information from multiple methods to increase the likelihood of correctly identifying stocks (Begg and Waldman 1999). For example, morphometric and genetic evidence indicated fine-scale differences among Yellow Perch within a given management unit for fish collected at various spawning sites across Lake Erie (Kocovsky and Knight 2012; Kocovsky et al. 2013). Similarly, combining natural tagging methods, such as genetic markers and otolith microchemistry, with information on pre-collection dispersal via particle backtracking models improved classification rates for larval and juvenile Yellow Perch in Lake Erie (Fraker et al. 2015).

Movement

In 2009, the Ontario Ministry of Natural Resources and Forestry and the Ontario Commercial Fisheries' Association launched a cooperative tagging study to describe the movement of Yellow Perch in the western and central basins. Tagging of Yellow Perch began in the western basin and was followed in subsequent years by tagging in the west-central sub-basin. In 2013, as a part of this study, the Ohio DNR began tagging Yellow Perch in the east-central sub-basin. Fish were tagged with Passive Integrated Transponder (PIT) tags, and Yellow Perch harvested by commercial and recreational fisheries was scanned to detect the tags (OMNRF 2016).

Results of the cooperative movement study showed that 75% of Yellow Perch PIT tagged in the western basin were recaptured in the western basin. The remaining 25% of recaptured fish came from the west-central sub-basin (21%) and the east-central sub-basin (4%). Yellow Perch that were PIT tagged in the west-central sub-basin and the east-central sub-basin were recaptured almost wholly within the central basin. For those PIT tagged in the west-central sub-basin, recaptures occurred in the east-central sub-basin (54%), the west-central sub-basin (40%), and the western basin (6%). For those PIT tagged in the east-central sub-basin, recaptures occurred in the east-central sub-basin (67%), the west-central sub-basin (33%), and the western basin (<1%). No recaptures were detected in the eastern basin (OMNRF 2016).

STATUS OF SMALLMOUTH BASS, LARGEMOUTH BASS, AND WHITE BASS IN LAKE ERIE IN 2015[14]

Michael Thorn[15], Richard Drouin, and Zak Slagle

This report responds to a commitment by fishery agencies on the Great Lakes to report progress on meeting fish community objectives established for each Great Lake (GLFC 2007). These objectives for Lake Erie do not specify targets for individual species, although they do specify broad ecological principles for achieving sustainability. Instead, an objective for highly valued species was adopted, and it seeks to maintain their yield in the aggregate at 13.6-27.3 million kg (Ryan et al. 2003). The issue addressed here is if populations of highly valued fish like Smallmouth Bass are trending in a direction consistent with the overall objective. This question is answered through comparisons of the status of species during this reporting period (2009-2015) with its status reported by Markham and Knight (2017) for the previous reporting period (2004-2008).

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[14]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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Smallmouth Bass

The success of Smallmouth Bass spawning nests in Lake Erie is negatively affected by angling (Steinhart et al. 2005), Round Goby predation (Steinhart et al. 2004a), and strong weather events (Goff 1985; Steinhart et al. 2005). Smallmouth Bass shows strong fidelity to spawning areas and will return to the same location to spawn year after year (Ridgway et al. 1991). Site fidelity is also apparent for summer home ranges (Ridgway and Shuter 1996; Hodgson et al. 1998). In general, tagging studies have found that Smallmouth Bass often remains within a relatively small geographical area throughout its life (Fraser 1955; Pflug and Pauley 1983; MDNR 2016). An Ohio DNR study conducted in the western basin of Lake Erie during 1998-2008 found strong site fidelity of jaw-tagged Smallmouth Bass, with most fish recaptured near release points.

Prior to the establishment of Round Goby, Smallmouth Bass diets in Lake Erie comprised crayfish, Yellow Perch, Gizzard Shad and, in the eastern basin, Rainbow Smelt (Cook 1995; Cook et al. 1997; Crane and Einhouse 2016). However, since the establishment of Round Goby in Lake Erie (1998-1999), Smallmouth Bass has shifted feeding away from traditional diet items and is now feeding heavily on Round Goby (Mullowney 2004; Steinhart et al. 2004b; Crane and Einhouse 2016). The diet shift to Round Goby increased growth rates of Smallmouth Bass (Steinhart et al. 2004b; Crane and Einhouse 2016).

In the western and eastern basins, there is a strong recreational fishery for Smallmouth Bass whereas, in the central basin, Smallmouth Bass is targeted in only a few localized areas. There is no commercial fishery for Smallmouth Bass in Lake Erie.

Recruitment and Relative Abundance

In the western basin of Lake Erie, there is no targeted sampling of young-of-the-year Smallmouth Bass. However, gillnetting surveys that assess Smallmouth Bass ≥age 1 are conducted in Ontario waters of the western basin and in Ohio waters of the western and central basins. In Ontario, the surveys are conducted cooperatively by the Ontario Ministry of Natural Resources and Forestry (OMNRF) and the Ontario Commercial Fisheries' Association as part of the Ontario Partnership Index Program. The cooperative survey showed that the relative abundance of Smallmouth Bass ≥age 1 was low and stable from 2000-2015 and that peak Smallmouth Bass abundance occurred during 1992-1998 (Fig. 23). In Ohio waters of the western and central basins, where the Ohio DNR has been conducting a gillnet survey targeting Smallmouth Bass since 2006, the trend in relative abundance of bass ≥age 1 agrees with that in Ontario waters of the western basin (i.e., no change between the 2006-2008 and 2009-2015 time periods; Fig. 24). In all years sampled by the Ontario Partnership Index Program, most of the Smallmouth Bass caught were ages 1, 2, or 3 with relatively few individuals ≥age 4 (Fig. 23). Alternatively, in most years, the Ohio DNR survey catch of fish ≥age 4 was equal to or greater than that of ages 1, 2, or 3 fish (Fig. 24; ODNR 2016). The Ohio DNR uses gillnets with mesh (stretch measure) up to 178 mm whereas the Ontario Partnership Index Program uses mesh up to 152 mm. Larger, older Smallmouth Bass are captured in larger mesh sizes (Belore and Cook 2012), so the Ohio DNR survey gear favors capturing more of them than does the Ontario survey gear. The oldest fish in the Ohio DNR gillnet survey was caught in 2015—it was 19 years old.

Fig. 23. Mean catch rates (fish•net lift^{-1}) of Smallmouth Bass in gillnets fished in Ontario waters of Lake Erie's western basin by the Ontario Ministry of Natural Resources and Forestry and the Ontario Commercial Fisheries' Association as part of the Ontario Partnership Index Program, 1990-2015. Mean catch rates are shown as the sum of the mean catch rates of two age groups of fish. Horizontal lines show the mean and 95% CI of the annual catch rates.

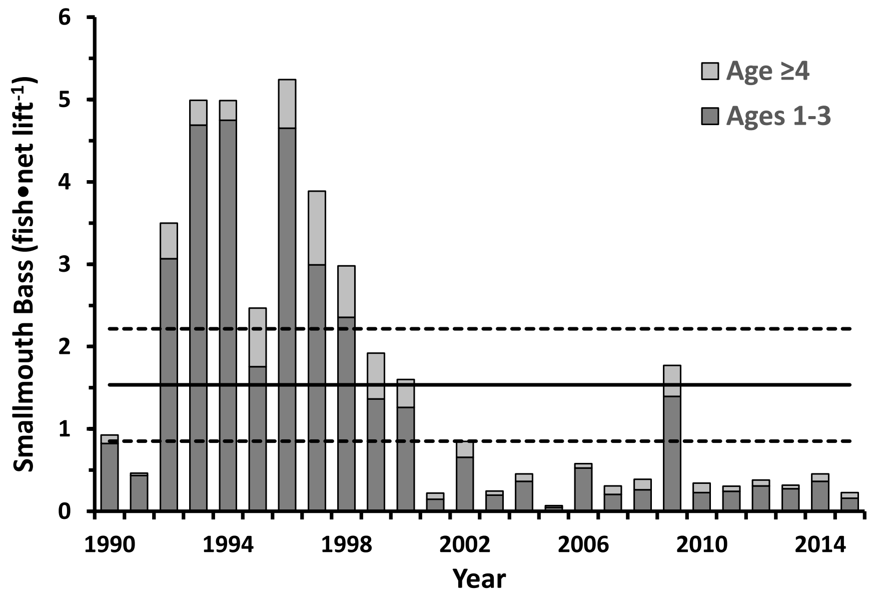
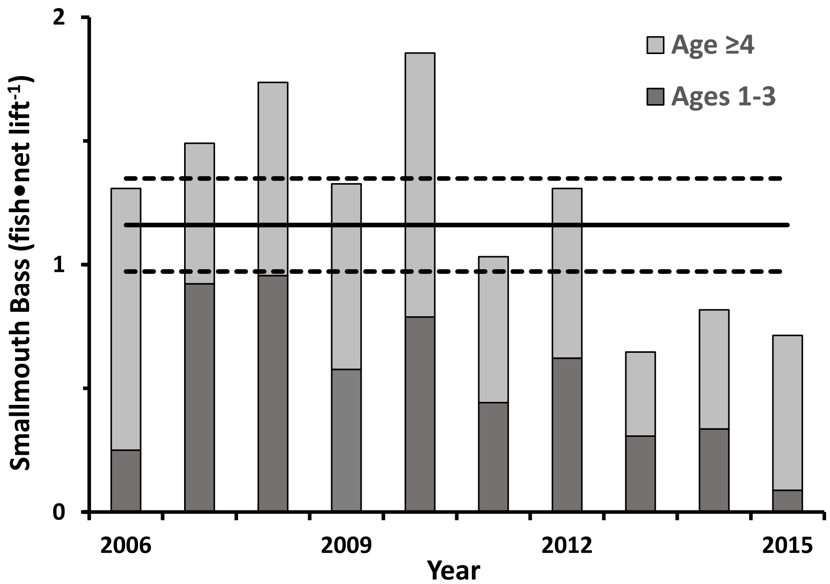


Fig. 24. Mean catch rates (fish•net lift^{-1}) of Smallmouth Bass in gillnets fished in Lake Erie's western and central basins by the Ohio DNR, 2006-2015. Mean catch rates are shown as the sum of the mean catch rates of two age groups of fish. Horizontal lines show the mean and 95% CI of the annual catch rates.



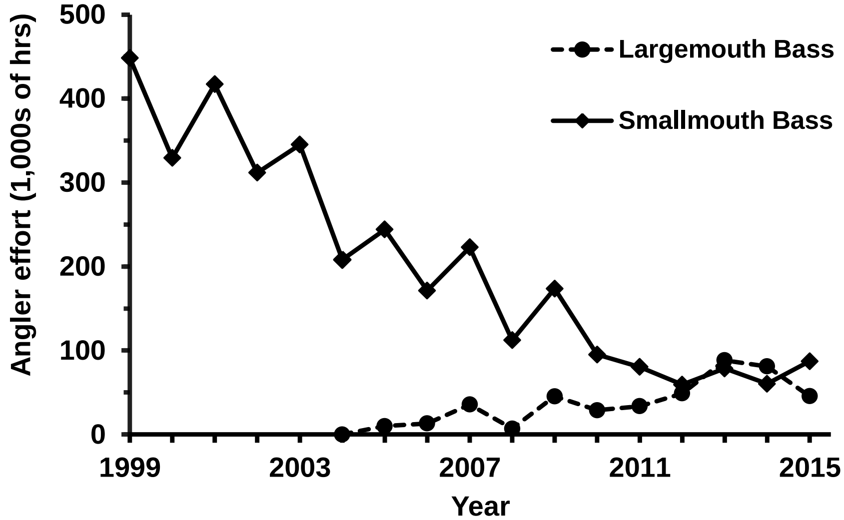
For Smallmouth Bass ≥age 1 in the central basin, the Ohio DNR gillnet survey provides a reliable index of abundance. The mean catch rate (fish•net lift^{-1} ± 1 SE) of Smallmouth Bass ≥age 1 in 2006-2008 was greater than that in 2009-2015 (west-central sub-basin: 9.3 ± 6.8 vs. 2.9 ± 1.0, east-central sub-basin: 12.3 ± 4.4 vs. 5.8 ± 1.5). In general, in the west-central sub-basin, there were more Smallmouth Bass ≥age 4 caught than age 1-3 bass whereas the opposite was true in the east-central sub-basin (ODNR 2016).

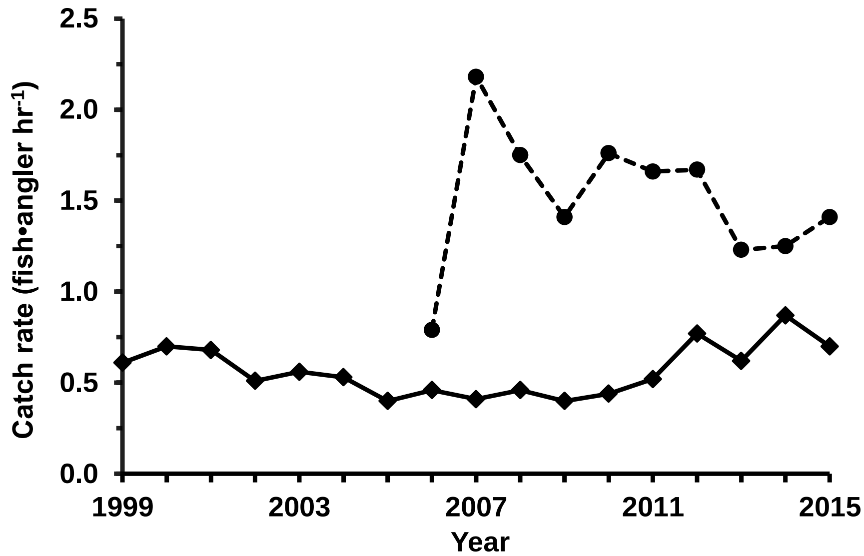
In Ontario's eastern-basin waters, abundance of Smallmouth Bass ≥age 1, as assessed by the Ontario Partnership Index Program, changed little between 1999-2003 and 2004-2008 (mean fish•net^{-1} ± 1 SE: 9.3 ± 4.2 vs. 10.3 ± 5.2), but it declined in 2009-2015 (2.6 ± 0.6). In New York waters of the eastern basin, nearshore gillnetting by the New York State Department of Environmental Conservation showed that the relative abundance of Smallmouth Bass ≥age 1 increased sharply in 1999-2003 and then decreased slowly in 2004-2015 (NYSDEC 2016).

Recreational Fishery and Harvest

In Lake Erie's western basin, the recreational fishery for Smallmouth Bass has declined since in the 1990s. The harvest of Smallmouth Bass in Ohio waters of the western basin was much smaller in 2004-2008 and 2009-2015 (mean fish•yr^{-1} ± 1 SE: 4,320 ± 1,297 and 3,786 ± 861, respectively) compared to that in 1999-2003 (35,660 ± 8,300) (ODNR 2016). Concurrent with the reduction in western-basin harvest was the reduction in overall angler effort in Ohio waters in 2004-2008 and 2009-2015 (mean hours•yr^{-1} ± 1 SE: 82,000 ± 12,236 and 52,600 ± 2,928, respectively) relative to that in 1999-2003 (226,960 ± 27,204) (Fig. 25; ODNR 2016). Some of the decline in harvest and effort after 2003 may have been due to the prohibition of the spring harvest of Smallmouth and Largemouth Bass in Ohio waters during 2004-2015. Although fishing effort and harvest decreased, the number of Smallmouth Bass caught per angler hour in 2009-2015 was equal to or greater than that in earlier time periods (Fig. 25; ODNR 2016). Although harvest has steadily decreased, the recreational catch has stabilized since 2004 owing to an increase in catch-and-release fishing following the general trend in black bass fisheries across North America (Allen et al. 2008). In Ontario waters, creel surveys have been conducted sporadically throughout the years. However, a comparison of data from a 2014 Ontario creel survey to that of earlier creel surveys (1985, 1990-1992, 1998, 2005, 2008) showed a pattern of harvest and effort similar to that in Ohio (Marklevitz et al. 2015).

Fig. 25. Angler effort (thousands of hours, top panel) and catch rates (fish•angler hr^{-1}, bottom panel) for Smallmouth Bass and Largemouth Bass in Ohio waters of Lake Erie's western and central basins as estimated from creel surveys conducted by the Ohio DNR, 1999-2015. For Largemouth Bass, effort was not recorded separately from other species prior to 2004, and catch rates were not recorded prior to 2006.





Angling effort for Smallmouth Bass in Ohio waters of the central basin was lower in 2009-2015 (mean hours•yr^{-1} ± 1 SE: 116,914 ± 23,376) than in 1999-2003 and 2004-2008 (481,160 ± 22,697 and 277,400 ± 34,190, respectively). The number of fish caught per hour was low in 2009-2015 and 2004-2008 (mean fish•hr^{-1} ± 1 SE: 0.03 ± 0.01 and 0.02 ± 0.01, respectively) relative to that in 1999-2003 (0.09 ± 0.01). Ohio anglers harvest few Smallmouth Bass (3,000-8,200 fish•yr^{-1}) mainly because the majority of them practice catch-and-release fishing. Creel surveys in the Ontario and Pennsylvania waters of the central basin indicate that little effort or harvest of Smallmouth Bass took place in these jurisdictions (Marklevitz et al. 2015; Pennsylvania Fish and Boat Commission, unpublished data).

In New York, the Smallmouth Bass fishery peaked in 1998 when angling effort was ~150,000 hours and harvest was ~39,000 fish (NYSDEC 2016). Since then the fishery in New York has declined, although it was relatively stable during 2004-2015, with angler effort averaging <50,000 hours•yr^{-1} and harvest averaging <25,000 fish•yr^{-1} (NYSDEC 2016). In Pennsylvania, the recreational fishery for Smallmouth Bass remained relatively stable between 2009-2015 and 2004-2008, with effort ranging from 20,485 to 47,863 hours•yr^{-1} and harvest ranging from 78 to 2,843 fish•yr^{-1} (includes some creel data from the central basin; Pennsylvania Fish and Boat Commission, unpublished data). However, this effort and harvest declined relative to 1999-2003 when angling effort was 32,089-120,512 hours•yr^{-1} and harvest was 2,524-15,540 fish•yr^{-1} (PFBC 2016). In the Ontario waters of the eastern basin, anglers expended a moderate amount of effort fishing for Smallmouth Bass in 2014 (69,282 hours), a decrease of 14% and 79% relative to creel surveys conducted in 2003 and 1998, respectively (Sztramko 2000; Arnold and Ryan 2004; Marklevitz et al. 2015). The number of Smallmouth Bass harvested follows a pattern similar to that of effort, with the lowest harvest of bass occurring in 2014 (17,223 fish; Marklevitz et al. 2015). Angler catch rates remained stable in Ontario and Pennsylvania (Marklevitz 2015; Pennsylvania Fish and Boat Commission, unpublished data) and steadily increased in New York during 2006-2013, remaining high in 2014-2015 (NYSDEC 2016). All Smallmouth Bass fisheries in the eastern basin are mainly catch-and-release fisheries, with >70% of fish released.

Stock Status

Distinct spawning aggregations of Smallmouth Bass are genetically divergent in Lake Erie (Stepien et al. 2007). Smallmouth Bass populations of the eastern basin are more genetically diverse than populations in the western and central basins (Borden and Stepien 2006; Stepien et al. 2007). There is also limited gene flow between lake and river spawning populations of Smallmouth Bass (Stepien et al. 2007; Borden 2008). The limited gene flow between populations of Smallmouth Bass in Lake Erie is consistent with their strong spawning-site fidelity and limited home range (Pflug and Pauley 1983; Ridgway et al. 1991).

Largemouth Bass

Largemouth Bass biology is similar to that of Smallmouth Bass, although Largemouth Bass prefers shallower, more heavily vegetated habitats close to shore or in wetlands adjacent to Lake Erie (Heidinger 1975). The most important Largemouth Bass fishery in Lake Erie is in the warmer, shallower western basin. The central and eastern basins (apart from Long Point Bay) lack much of the habitat preferred by Largemouth Bass.

Recruitment and Relative Abundance

Most agencies on Lake Erie do not survey Largemouth Bass because it inhabits areas that are outside of those sampled by traditional assessments and because exploitation of Largemouth Bass is low relative to other fish species that are recreationally important. However, beginning in 2013, the Ohio DNR began a yearly electrofishing survey of the shoreline that samples a variety of coastal and wetland habitats in the western basin. During 2013-2015, Largemouth Bass relative abundance was stable (mean fish•hr^{-1} ± 1 SE: 38.9 ± 5.9), and condition was high (mean relative weight ± 1 SE: 113.0 g ± 0.8).

Recreational Fishery and Harvest

The Largemouth Bass fishery in the western basin of Lake Erie has grown. Creel surveys conducted by the Ohio DNR began separating targeted fishing effort for Largemouth Bass from that for Smallmouth Bass in 2004. Since 2004, Largemouth Bass fishing effort has gradually increased such that, by 2013-2014, angler effort targeting Largemouth Bass surpassed that of effort targeting Smallmouth Bass for the first time in the Ohio waters of Lake Erie

(Fig. 25; ODNR 2016). Catch rates for Largemouth Bass were consistently high relative to catch rates for Smallmouth Bass, averaging ~1.5 fish•hr^{-1} since 2006.

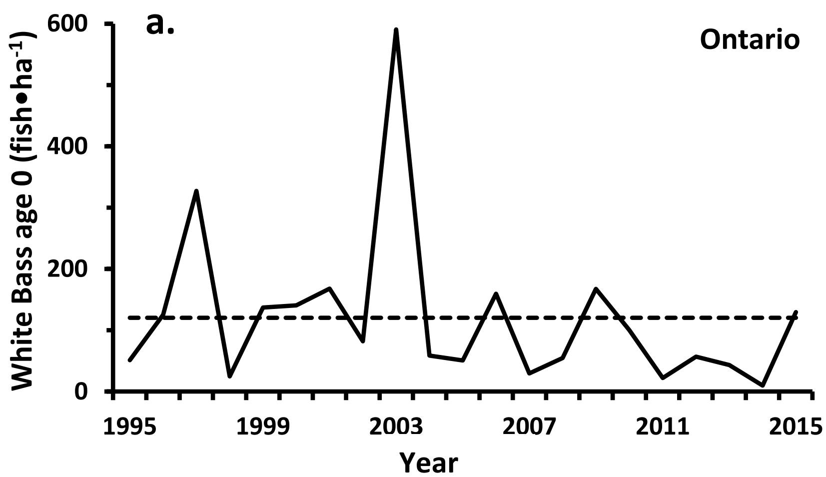
White Bass

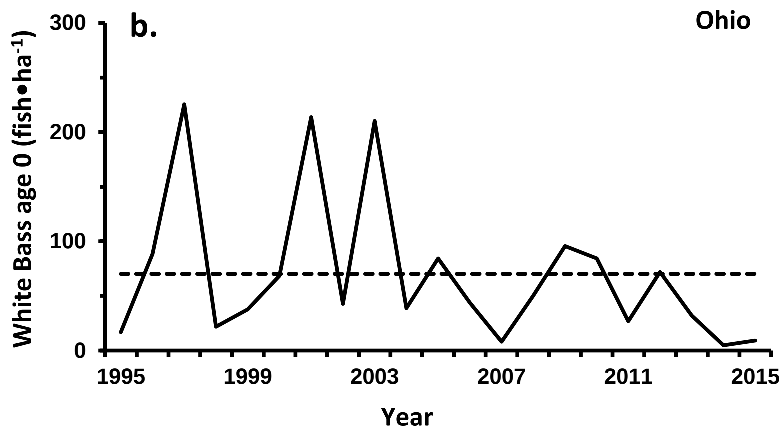
Although White Bass is commonly caught in commercial and recreational fisheries in Lake Erie, it is considered a bycatch in the commercial fishery and its harvest is not regulated. Growth rates of White Bass are high, and White Bass recruits to the commercial and recreational fisheries as early as age 2. However, the majority of fish caught and harvested are ≥age 3 (ODNR 2016; OMNRF 2016).

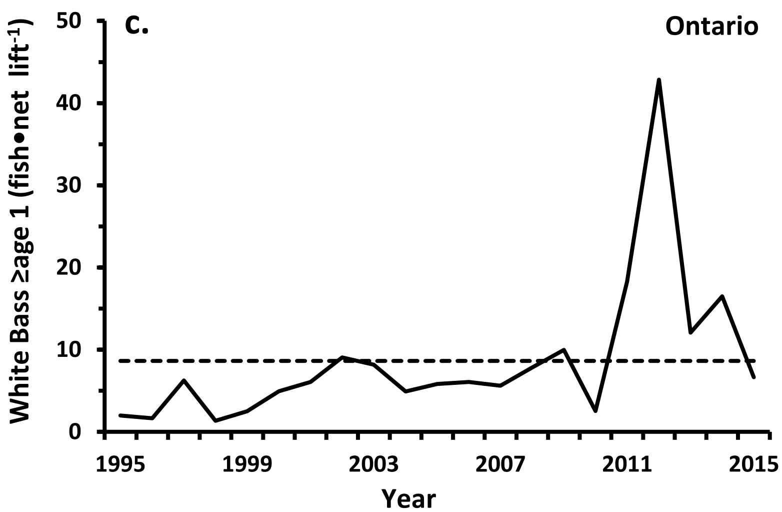
Recruitment and Relative Abundance

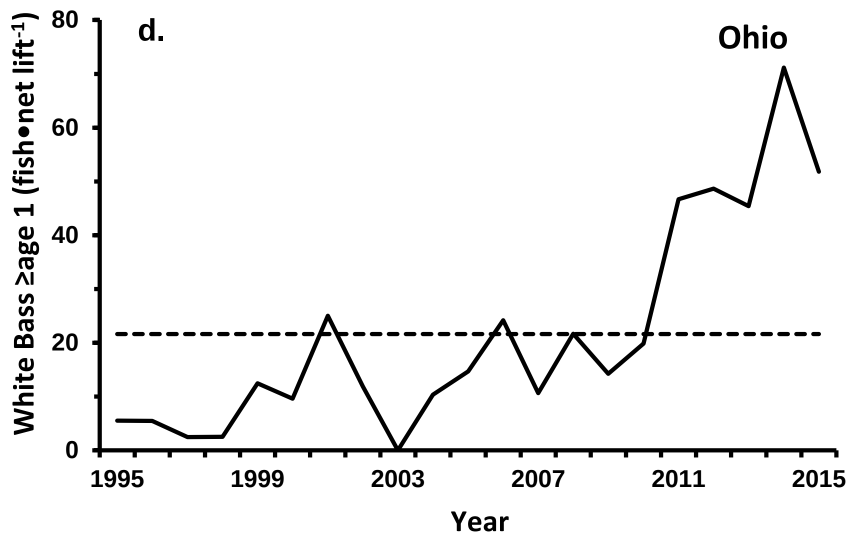
Catch rates of age-0 White Bass in trawling surveys conducted by the Ohio DNR and OMNRF indicated that relative abundance was high in 1999-2003 but declined thereafter and was low in 2004-2008 and 2009-2015 (Fig. 26, panels a, b). Although the number of age-0 fish has declined, the catch rate of White Bass ≥age 1 in Ohio DNR and OMNRF gillnet surveys increased during 2009-2015 relative to the catch rate in earlier time periods (Fig. 26, panels c, d). In 2012, the catch rate of White Bass ≥age 1 in Ontario waters peaked, mainly due to a glut of two-year-old fish. Age-0 fish were not particularly abundant in 2010, however, the large number of age-2 fish present in 2012 suggests that survival of the age 0-2 fish was much higher than that of age-0-2 fish from other year-classes. Relative abundance of White Bass ≥age 1 in Ohio waters of the western basin peaked in 2014, two years after relative abundance peaked in Ontario waters.

Fig. 26. Mean catch rates of age-0 (fish•ha^{-1}, panels a, b) and ≥age-1 (fish•net lift^{-1}, panels c and d) White Bass in assessment surveys conducted in Ontario (panels a, c) and Ohio (panels b and d) waters of Lake Erie's western basin, 1995-2015. For age-0 White Bass, catch rates are from the Interagency Trawling Program conducted by the Ohio DNR and the Ontario Ministry of Natural Resources and Forestry (OMNRF). For ≥age-1 White Bass, catch rates in Ontario waters are from the Partnership Index Program conducted by the OMNRF and the Ontario Commercial Fisheries' Association using suspended and bottom-set gillnets. Catch rates in Ohio waters are from the Western Basin Gillnet Survey conducted by the Ohio DNR using suspended gillnets. Dashed lines show the means of the annual catch rates. Note that the panel scales differ.



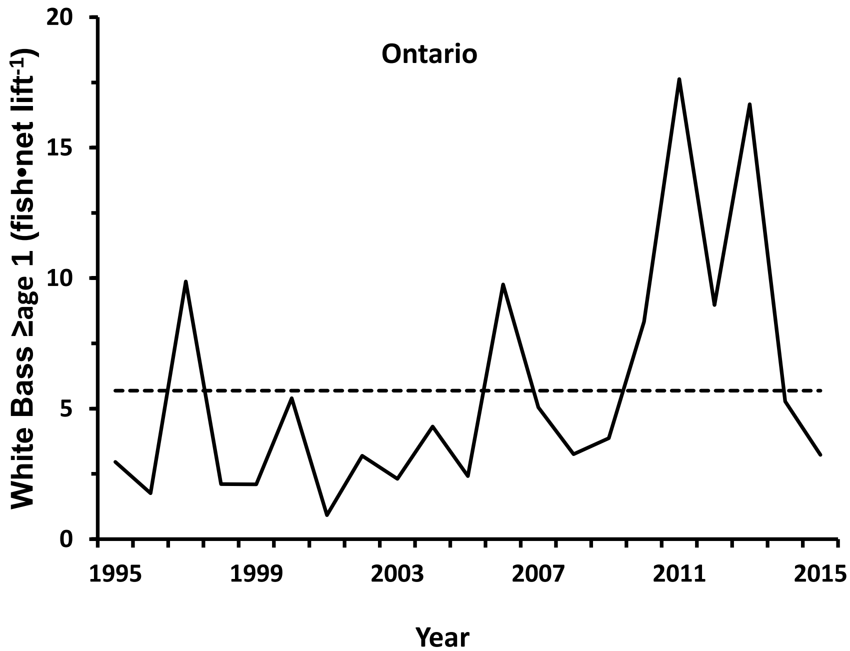

b.
Ohio
White Bass age 0 (fish•ha-1)
300
200
100
0
1995
1999
2003
2007
2011
2015
Year

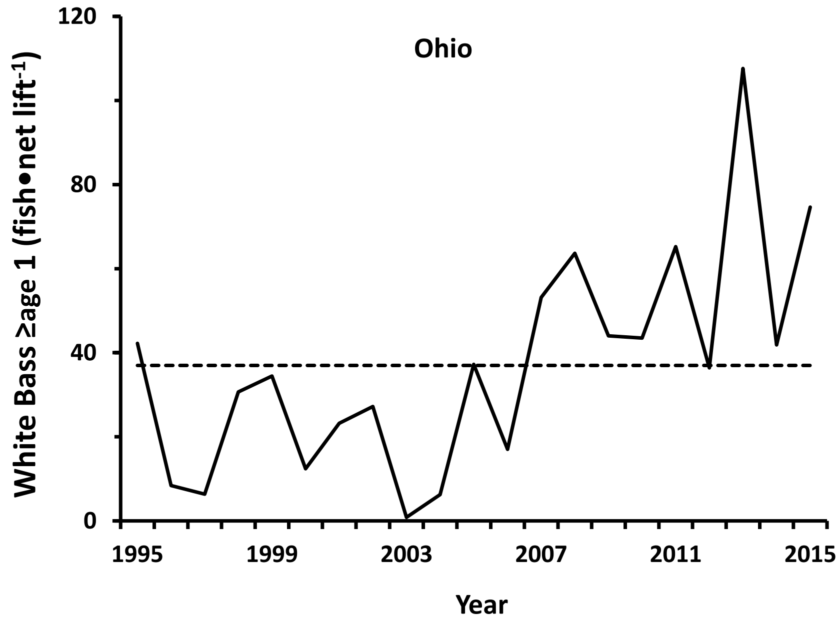

c.
Ontario
White Bass ≥age 1 (fish•net lift-1)
50
40
30
20
10
0
1995
1999
2003
2007
2011
2015
Year



In the west-central sub-basin, the catch rates of age-0 White Bass in Ohio DNR trawls were low in 2009-2015 and 2004-2008 (mean fish•ha^{-1} ± 1 SE: 14.8 ± 11.4 and 26.34 ± 13.3, respectively) relative to those in 1999-2003 (110.9 ± 69.6). However, the catch rates of White Bass ≥age 1 in Ohio DNR and OMNRF gillnet surveys increased in 2009-2015 relative to those in earlier time periods (Fig. 27). The highest catch rates of White Bass ≥age 1 in the 21-year time series occurred in 2011 and 2013 in Ontario waters and in 2011-2015 in Ohio waters.

Fig. 27. Mean catch rates (fish•net lift^{-1}) of White Bass ≥age 1 in assessment surveys conducted in Ontario waters of the central basin and Ohio waters of the west-central sub-basin, Lake Erie, 1995-2015. Catch rates in Ontario are from the Partnership Index Program conducted by the Ontario Ministry of Natural Resources and Forestry and the Ontario Commercial Fisheries' Association using suspended and bottom-set gillnets. Catch rates in Ohio are from the Western Basin Gillnet Survey conducted by the Ohio DNR using suspended gillnets. Dashed lines show the means of the yearly catch rates. Note that the panel scales differ.





In the eastern basin, catch rates of White Bass ≥age 1 in Ontario waters were higher in 2009-2015 (mean catch•net^{-1} ± 1 SE: 2.4 ± 1.0) than in 2004-2008 and 1999-2003 (0.9 ± 0.5 and 0.5 ± 0.1, respectively). Elevated catch rates of White Bass in 2009-2015 were driven by a strong 2012 year-class that provided a large number of age-1 and age-2 White Bass to the basin in 2013 and 2014, respectively. In New York waters, trends in White Bass abundance were similar to those in Ontario waters (NYSDEC 2016).

Commercial Harvest

White Bass harvested from Lake Erie by the commercial fishery contributes millions of dollars to local economies. The total value of White Bass harvested in 2015 by the commercial fishery in Michigan (seine and trapnet), Ohio (seine and trapnet), and Ontario (gillnet and trapnet) was US$2.9 million. The mean yearly harvest of White Bass from Lake Erie was 2,000 t from 2009-2015, which is higher than the mean yearly harvests of 1,700 and 1,600 t in 1999-2003 and 2004-2008, respectively. Much of the commercial harvest of White Bass is in the western basin and west-central sub-basin of Lake Erie. During 2009-2015, an average of 40% of White Bass landed in Ontario waters were caught in the western basin and 43% in the west-central sub-basin.

Stock Structure

The stock structure of White Bass in Lake Erie is not well understood. Large numbers of White Bass are known to spawn on western-basin reefs or shoals and in nearshore areas, as well as in the Sandusky and Maumee Rivers. Hayden et al. (2011) studied the degree of natal homing in Sandusky River White Bass using otolith microchemistry and found that White Bass showed fairly strong philopatry (73% of spawning individuals were natal to the Sandusky River). However, 27% of the fish found spawning in the river originated from other western-basin locations, which indicates that White Bass populations in the western basin of Lake Erie are likely not genetically distinct (Hayden et al. 2011).

STATUS OF LAKE STURGEON AND CISCO IN LAKE ERIE IN 2015[16]

Justin A. Chiotti[17], Tom MacDougall, James C. Boase, Zy Biesinger, Dimitry Gorsky, and Richard Drouin

This report responds to a commitment by fishery agencies on the Great Lakes to report progress on meeting fish community objectives established for each Great Lake (GLFC 2007). These objectives for Lake Erie do not specify targets for individual species, although they do specify broad ecological principles for achieving sustainability. Instead, an objective for highly valued species was adopted, and it seeks to maintain their yield in the aggregate at 13.6-27.3 million kg (Ryan et al. 2003). The issue addressed

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[16]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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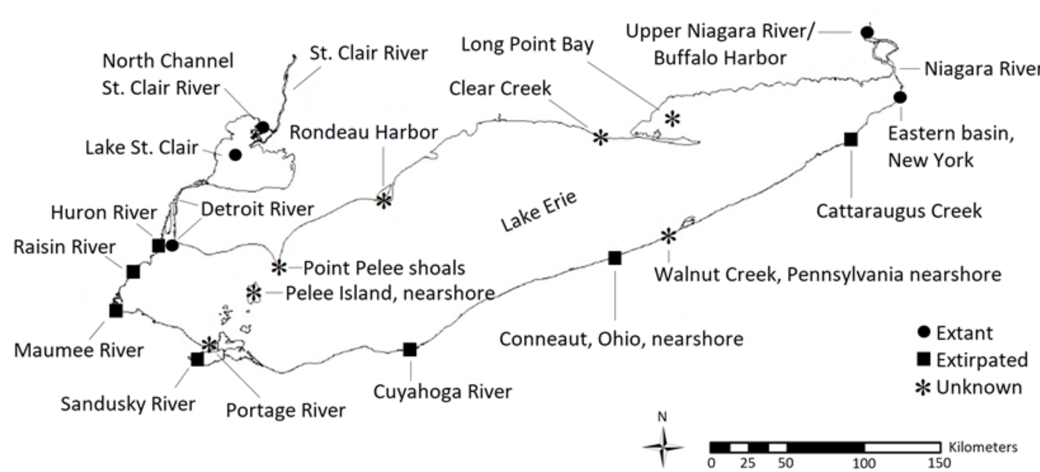
here is if populations of highly valued fish like Lake Sturgeon are trending in a direction consistent with the overall objective. This question is answered through comparisons of the status of species during this reporting period (2009-2015) with their status reported by Markham and Knight (2017) for the previous reporting period (2004-2008).

Lake Sturgeon

As a result of commercial fishing and habitat loss, Lake Sturgeon populations in Lake Erie declined such that in recent years, of the 19 historical populations, only 3 show evidence of recruitment—St. Clair River, Detroit River, and Upper Niagara River/Buffalo Harbor (Fig. 28). Currently, Lake Sturgeon is designated as threatened in Ontario, Michigan, and New York and endangered in Ohio and Pennsylvania. Commercial harvest of Lake Sturgeon has been prohibited from U.S. waters of the Great Lakes since 1977 and from Ontario waters since 2009 (OMNRF 2009). A recreational fishery exists in Lake St. Clair and the St. Clair River in Michigan but is prohibited in the Great Lakes waters of all other states and the Province of Ontario.

Fig. 28. Lake Erie, the St. Clair-Detroit River System, and the upper Niagara River showing the geographic location and status of 19 Lake Sturgeon populations.



Status of Populations

Lake Sturgeon populations are well below historical levels of abundance, except for those in the St. Clair-Detroit River System (SCDRS). Spawning has been verified at four locations in the SCDRS (Manny and Kennedy 2002; Caswell et al. 2004; Roseman et al. 2011), in Buffalo Harbor, and possibly the upper Niagara River (Legard 2015; Neuenhoff et al. 2018; DG, personal observation). The Ontario Ministry of Natural Resources and Forestry closely monitors Lake Sturgeon captured in Ontario waters by requiring commercial fisherman to submit daily catch reports of Lake Sturgeon captured as bycatch. Since 2011, when daily reporting of commercial catches began, 834 catch reports have included Lake Sturgeon. The Ohio DNR and the Fish and Wildlife Service are also working with commercial fishermen operating in the Ohio waters of Lake Erie to assess the presence of Lake Sturgeon captured as bycatch.

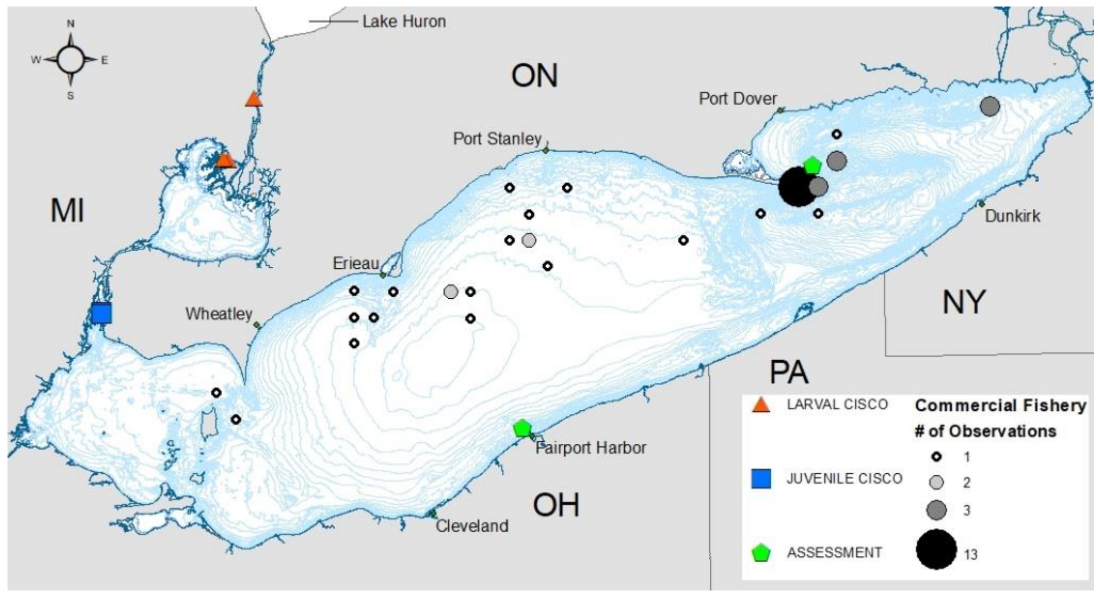
Since the 2004-2008 reporting period, two new spawning sites have been identified—both in the SCDRS. Lake Sturgeon spawning was documented through the collections of eggs and larvae on two constructed reefs, the Middle Channel Reef in the middle channel of the St. Clair River and the Fighting Island Reef in the lower Detroit River (Roseman et al. 2011; Bouckaert et al. 2014; see Marklevitz et al., Progress Toward Achieving Lake Erie Environmental Objectives in 2009-2015: Habitat-Related Projects, this volume for location of reefs). Tag-recovery and telemetry research indicate that robust Lake Sturgeon populations exist in the SCDRS comprising nearly 50,000 fish (95% CI = 34,164-68,381 fish) (Thomas and Haas 2002; Chiotti et al. 2013). Lake Sturgeon nursery areas (identified by consistent catches of juveniles in agency assessment surveys and commercial fishing gear) are in the North Channel of the St. Clair River, Anchor Bay in northeastern Lake St. Clair, the lower Detroit River east of Fighting Island, and the western basin of Lake Erie.

Lake Sturgeon was concentrated in the upper Niagara River's Buffalo Harbor in the spring of 2009. Subsequent sampling through 2015 found maturing sub-adult and sexually mature adult Lake Sturgeon. During 2012-2015, 131 Lake Sturgeon were captured during population assessments in Buffalo Harbor (C. Legard, New York State Department of Environmental Conservation, personal communication, 2016). An extensive acoustic array was placed in Buffalo Harbor during 2015 to monitor the movement of adult Lake Sturgeon. Sidescan sonar imagery for a roughly 18-km^2 section of Buffalo Harbor was collected in 2015 to identify potential Lake Sturgeon spawning habitat.

Cisco

The *albus* form of Cisco (upper case refers to the species and lower case refers to more than one species) once supported a thriving fishery in Lake Erie but is now considered extirpated from the lake. During 1995-2015, 45 unidentified ciscoes were collected, and 16 of these were taken during 2009-2015, mainly by the commercial fishery (Fig. 29). Assessment gillnets were set at historical Cisco spawning locations in the western basin in the fall of 2011, 2012, and 2014, but no Cisco was caught (CWTG 2016). Surveys conducted in the SCDRS collected larval cisco of unknown parentage in the St. Clair River in 2010, 2011, and 2013 and in the Detroit River in 2013 (CWTG 2016). Juvenile cisco (parentage unknown) was collected in floating fyke nets in the Livingston Channel of the Detroit River in 2011 and 2012.

Fig. 29. Bathymetric map of Lake Erie and the St. Clair-Detroit River System (SCDRS) showing locations where unidentified ciscoes were caught during 1995-2015. All cisco collected from Lake Erie were caught in the Ontario commercial gillnet and trawl fisheries (circles), except for two fish (green pentagons) caught in assessments. Locations where larval and juvenile ciscoes were caught in the SCDRS are indicated with red triangles and blue squares. The total number of cisco caught in Lake Erie during 1995-2015 is slightly higher than that shown because catches without location information have been excluded.



Genotypes of contemporary Lake Erie Cisco were compared to those of other Great Lake populations and to Lake Erie Cisco from the 1920s. Initial findings indicated that none of the contemporary samples could be assigned with confidence to any of the Cisco populations identified to date (CWTG 2016). However, results of a morphometrics analysis on 22 contemporary Lake Erie ciscoes indicated that one was a type of shallow-water Cisco not formerly abundant in Lake Erie, two were hybrids between Lake Whitefish and some unknown type of cisco, and 19 were similar to a type of hybrid deepwater cisco common in Lake Huron. None of the 22 were of the formerly dominat *albus* type of Cisco (Eshenroder et al. 2016). These results support the hypothesis that cisco captured currently in Lake Erie originated from Lake Huron and not from a remnant Lake Erie population.

STATUS OF LAKE WHITEFISH AND RAINBOW SMELT IN LAKE ERIE IN 2015[18]

Charles Murray[19] and James L. Markham

This report responds to a commitment by fishery agencies on the Great Lakes to report progress on meeting fish community objectives established for each Great Lake (GLFC 2007). These objectives for Lake Erie do not specify targets for individual species, although they do specify broad ecological principles for achieving sustainability. Instead, an objective for highly valued species was adopted, and it seeks to maintain their yield in the aggregrate at 13.6-27.3 million kg (Ryan et al. 2003). The issue addressed here is if populations of highly valued fish like Lake Whitefish are trending in a direction consistent with the overall objective. This question is answered through comparisons of the status of species during this reporting period (2009-2015) with their status reported by Markham and Knight (2017) for the previous reporting period (2004-2008).

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[18]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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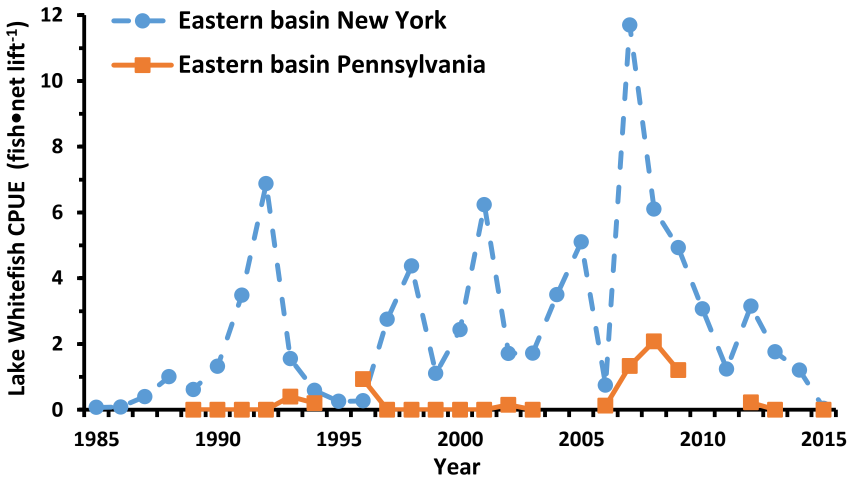
Lake Whitefish

Lake Whitefish once spawned throughout Lake Erie on shallow rocky substrates in late fall (Goodyear et al. 1982). However, by 1900, many spawning runs had deteriorated due to over-exploitation and environmental degradation (Trautman 1981), resulting in collapsed fisheries by 1960 (Regier and Hartman 1973). Major spawning aggregations and associated commercial fisheries persist in some of the historically used areas, such as around Maumee Bay, various reefs around western-basin islands, and near the mouth of the Detroit River.

Relative Abundance

In fall, Lake Whitefish migrates from the eastern basin to spawning grounds in the western basin and then returns to cold, hypolimnetic waters of the eastern basin by summer of the following year. Accordingly, fishery effort and harvest vary among seasons and basins owing to migrations. In Ontario waters, Lake Whitefish abundance was at record lows in four areas during 2009-2015 (Fig. 30). In New York waters, annual fish•net lift^{-1} averaged 2.2 during 2009-2015, down from 5.4 during 2004-2008. Assessment catch rates in Pennsylvania were also lower in 2009-2015 than in 2004-2008 (0.4 vs. 1.2), although assessments were not conducted in all years in each time period. Catch rates were highest in both states in 2009 but declined thereafter. In 2015, the Lake Whitefish catch rate in assessment gillnets set in New York waters was a record low. Collectively, gillnet assessments indicated that Lake Whitefish abundance during 2009-2015 was steadily declining after peaking in 2007 (Fig. 30). Recruitment was low during 2009-2015, although some age-0 Lake Whitefish were caught in 2015 during trawl assessments in Ohio, Pennsylvania, and New York waters (Fig. 31).

Fig. 30. Lake Whitefish catch-per-unit effort (CPUE; fish•net lift^{-1}) in assessment gillnets set in New York and Pennsylvania waters of the eastern basin (top panel) and in four areas of Ontario waters—the west-central and east-central sub-basins, the eastern basin, and along the Pennsylvania Ridge, a lakebed feature separating the central and eastern basins (bottom panel), Lake Erie, 1985-2008. Assessments in Ontario waters were conducted by the Ontario Ministry of Natural Resources and Forestry and the Ontario Commercial Fisheries' Association as part of the Partnership Index Program. Note that the scales of the two panels differ.



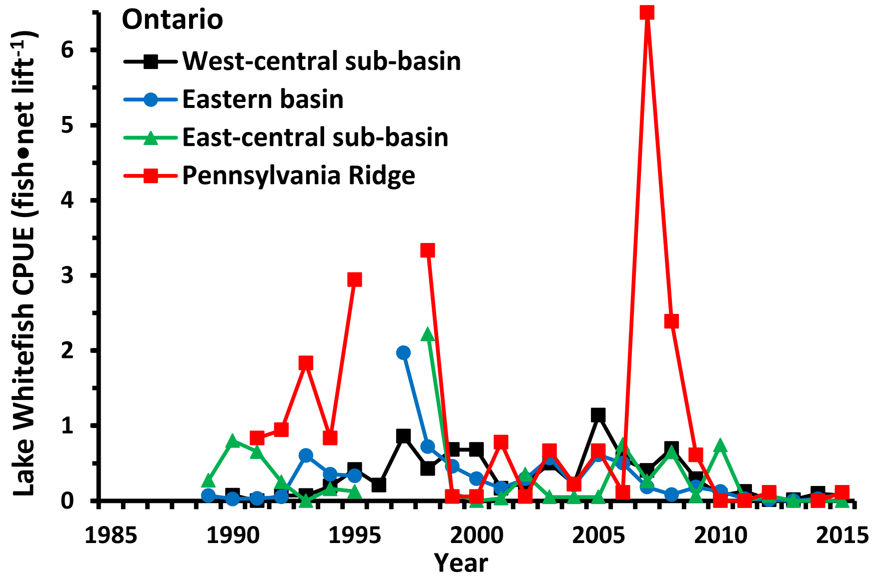
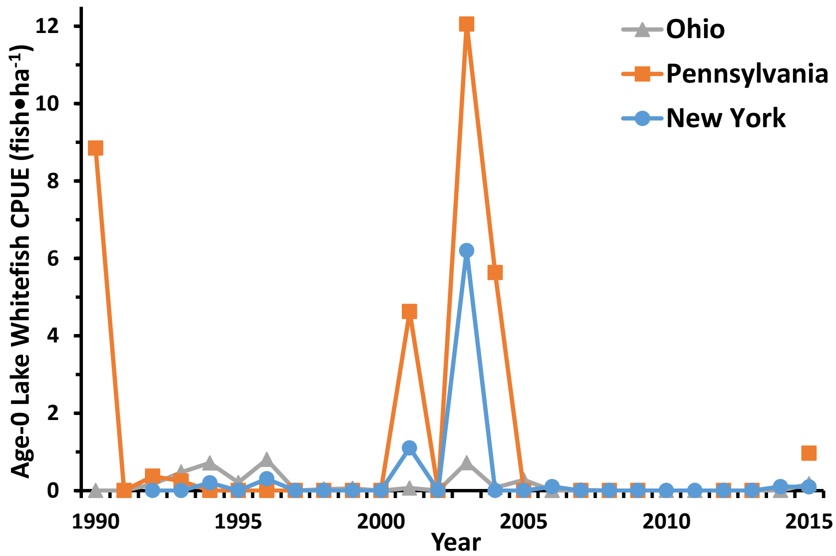


Fig. 31. Mean catch rates (CPUE; fish•ha^{-1}) of age-0 Lake Whitefish in Ohio, Pennsylvania, and New York waters of Lake Erie during fall assessments with bottom trawls, 1990-2015. Assessments were not conducted in New York waters in 1990-1991 or in Pennsylvania waters in 2006, 2010, 2011, and 2014.



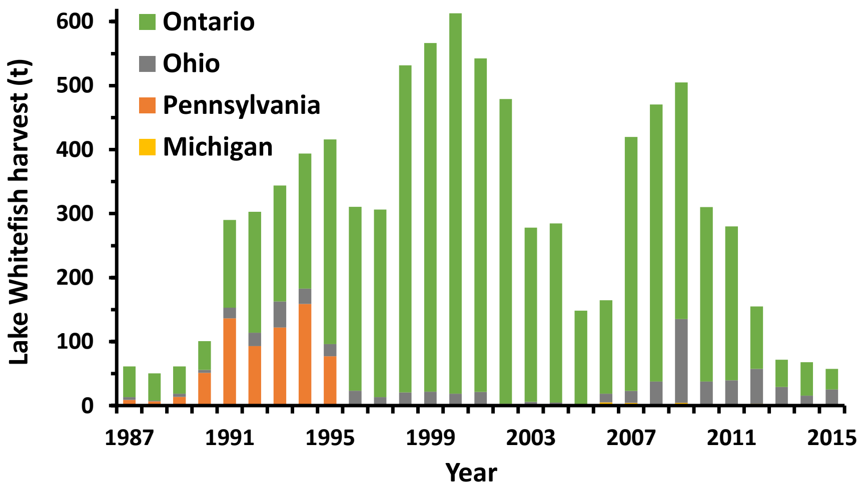
Diet and Condition

Lake Whitefish diets were sampled mainly in Ohio waters of Lake Erie's central basin during 2009-2015. Generally, Lake Whitefish is an opportunistic benthivore eating a variety of prey, including chironomids, cladoceran zooplankters, bivalves (sphaeriids and dreissenids), gastropods, isopods, segmented worms, and leeches (CWTG 2016). The relative importance of these prey in Lake Whitefish diet varied among years with no obvious pattern. Average condition (Fulton's K) for age-4 and older male and female Lake Whitefish during the 2009-2015 reporting period remained near the 1927-1929 values reported by Van Oosten and Hile (1947) (CWTG 2016). Although the condition factor declined for both sexes in 2013, it returned to historical means by 2015.

Harvest

Commercial harvest of Lake Whitefish from Lake Erie declined steadily within the 2009-2015 reporting period (Fig. 32). The annual lakewide harvest averaged 207 t during 2009-2015, a 31% decline from the 298-t annual harvest during 2004-2008 (Markham and Knight 2017) and a 58% decline from the annual harvest during 1987-2008 (496 t). A total of 505 t of Lake Whitefish was harvested in 2009, the second-highest harvest since 2000 when more than 610 t were harvested (CWTG 2016). In most years during 2009-2015, most (~75%) of the commercial harvest of Lake Whitefish was taken with gillnets in Ontario waters, although harvest by the Ohio trapnet fishery in 2013 and 2015 was substantial, accounting for about 40% of the harvest those years. During 2009-2015, the harvest of Lake Whitefish in Ohio averaged 47 t, a 200% increase over the 1987-2008 average from those waters whereas the 58-t average harvest in Ontario waters was a 43% decline from the 1987-2008 average. In Pennsylvania, the annual harvest of Lake Whitefish ranged from 7 to 159 t from 1987 to 1995, after which commercial gillnetting was banned. In Michigan, the fishery was closed during 1987-2005 and reopened in 2006. The annual harvest during 2009-2015 ranged from 0 to 4 t.

Fig. 32. Total commercial harvest (metric ton, t) of Lake Whitefish from Lake Erie by jurisdiction, 1987-2015. Pennsylvania ceased commercial harvest of Lake Whitefish with gillnets in 1996 and Michigan resumed the commercial harvest of Lake Whitefish in 2006. There was no commercial harvest of Lake Whitefish in New York.



Rainbow Smelt

Relative Abundance

Bottom-trawl surveys in Ohio waters of Lake Erie's central basin found that the average density of Rainbow Smelt in this reporting period (2009-2015) was 507 fish•ha^{-1}, a decrease of 29% from 2004-2008 and 44% from 1999-2003 (the two previous reporting periods). Acoustic surveys of the central basin found that the density of adult Rainbow Smelt ranged from 300 to 2,300 fish•ha^{-1} in 2010-2015 (FTG 2016). Rainbow Smelt composed 22% of the total forage fish in the central basin in 2009-2015.

In the lake's eastern basin, fall trawl surveys in New York and Ontario waters also found decreases in the average density of adult Rainbow Smelt during 2009-2015, as compared to the average density in 2004-2008 (FTG 2016). Average density (fish•ha^{-1}) of adults during 2009-2015 ranged from near zero to 1,654 in Ontario waters (average 443) and from 23 to 3,089 in New York waters (average 779). Acoustic assessments in the eastern basin during 2009-2015 estimated that the mean density of "Rainbow Smelt-sized" fish was 4,760 fish•ha^{-1} (FTG 2016). Despite its continued decline in abundance, Rainbow Smelt is still the dominant forage fish in the eastern basin.

Harvest

Rainbow Smelt made up 39-90% of the annual commercial harvest of fish from the eastern basin during 2009-2015. During 2009-2015, the annual commercial harvest of Rainbow Smelt in the eastern basin averaged 1,903 t, up from 1,362 t reported in 2004-2008 (Markham and Knight 2017) and the 1,680 t reported in 1999-2003 (Tyson et al. 2009).

STATUS OF LAKE TROUT, BURBOT, AND SEA LAMPREY IN LAKE ERIE IN 2015[20]

James L. Markham[21], Christopher Vandergoot, Tom MacDougall, Charles Murray, Chris Eilers, and Kevin Tallon

This report responds to a commitment by fishery agencies on the Great Lakes to report progress on meeting fish community objectives established for each Great Lake (GLFC 2007). These objectives for Lake Erie do not specify targets for individual species, although they do specify broad

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ecological principles for sustainability. Instead, an objective for highly valued species was adopted, and it seeks to maintain their yield in the aggregrate at 13.6-27.3 million kg (Ryan et al. 2003). The issue addressed here is if populations of highly valued fish like Lake Trout are trending in a direction consistent with the overall objective. This question is answered through comparisons of the status of species during this reporting period (2009-2015) with their status reported by Markham and Knight (2017) for the previous reporting period (2004-2008).

Lake Trout

No native stocks of Lake Trout exist in Lake Erie after decades of over-exploitation, pollution, loss of habitat, and invasive species caused its extirpation around 1965 (Hartman 1972; Christie 1974; Cornelius et al. 1995). Modern-day restoration efforts began in 1969 with the stocking of 17,000 yearlings by the Pennsylvania Fish and Boat Commission, but annual stockings and directed assessment programs did not begin until 1980 (Cornelius et al. 1995). Despite Lake Trout stocking in Lake Erie's eastern basin for more than 30 years, no naturally produced Lake Trout has been documented. Stocking sustains the population while Sea Lamprey control helps to minimize mortality of stocked fish. A revised Lake Erie Lake Trout Rehabilitation Plan, completed in 2008, provides targets for restoring a self-sustaining population of Lake Trout (Markham et al. 2008).

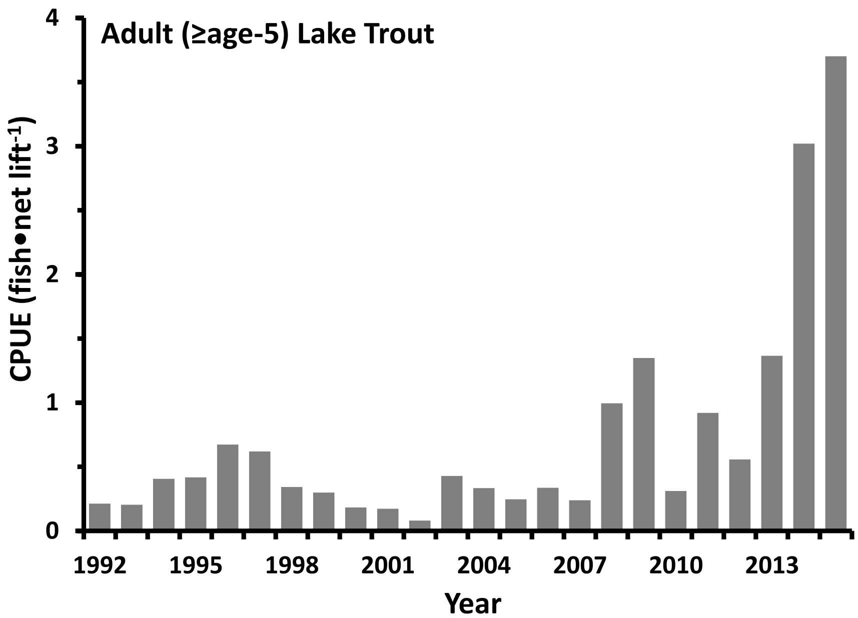
Stocking

Several changes in Lake Trout stocking occurred following the implementation of the revised rehabilitation plan in 2008. Stocking targets for Lake Erie increased from 120,000 to 200,000 yearlings annually. Stocking locations were expanded from Pennsylvania and New York waters of the eastern basin into Ohio waters of the central and western basins in 2012 to increase the likelihood of Lake Trout finding suitable spawning and rearing habitats in other regions of the Lake Erie. During 2009-2015, annual basinwide stocking ranged from 72,473 to 304,819 yearlings and averaged 222,566 yearlings, an increase of 85% over stocking in 2004-2008 (CWTG 2016). Lean strains of Lake Trout (specifically Finger Lakes (Seneca) and Lake Champlain strains) are the focus of the revamped stocking program due to their higher survival rates compared to other strains. Klondike Lake Trout, a non-lean, deepwater-spawning strain from Lake Superior was stocked into Lake Erie in 2004-2010. Stocking of the Klondike strain was discontinued after 2010 mainly due to low survival rates (50%) of adult fish (CWTG 2016).

Relative Abundance

The relative abundance of Lake Trout (all ages combined) has increased steadily in Lake Erie's eastern basin since 2001; nevertheless abundance was well below the rehabilitation plan's target of 8.0 fish•net lift^{-1} during 2009-2015. However, the abundance of adult (≥age-5) Lake Trout peaked in 2015 and was above the rehabilitation goal of 2.0 adult fish•net lift^{-1} for the second consecutive year (Fig. 33). Lake Trout ≤age 4, which had dominated assessment catches since 2001, was less abundant in 2014-2015 and Lake Trout >age 10 still composed a minor portion of the population. Lake Trout of all ages is more abundant in New York waters than in Pennsylvania and Ontario waters, coinciding with where most of the fish were stocked and demonstrating that the movement of stocked fish is not extensive (CWTG 2016).

Fig. 33. Relative abundance of adult (≥age-5) Lake Trout based on catch-per-unit-effort (CPUE; fish•net lift^{-1}) in standard assessment gillnets set in the eastern basin of Lake Erie, 1992-2015. Abundance is the sum of weighted Lake Trout CPUE from three jurisdictions. Weighting is by the proportion of the eastern basin >20 m deep within Pennsylvania (22%), Ontario (55%), and New York (23%) waters.



Much of the increase in Lake Trout relative abundance in the eastern basin during 2009-2015 was due to successful stockings of Lake Champlain-strain fish, which were first stocked into Lake Erie in 2009. The increase in adult abundance in 2014 and 2015 was mainly due to relatively high numbers of this strain at ages 5, 6, and 7 (CWTG 2016). Although the abundance of Klondike-strain Lake Trout declined during 2009-2015, Klondike-strain Lake Trout still contributed to the adult population.

Diet and Growth

Lake Trout diet in the eastern basin is almost exclusively comprised of fish. During 2009-2015, Rainbow Smelt remained the preferred prey for Lake Trout of the lean strains (61-98% frequency of occurrence) and the Klondike strain (50-92% frequency of occurrence). Round Goby was the second most common prey, with a frequency of occurrence of 7-41% for lean strains and 4-64% for the Klondike strain (CWTG 2016). In 2009-2015, the frequency of occurrence of Rainbow Smelt (83%) and Round Goby (20%) for lean-strain fish was similar to 2004-2008 (79% smelt and 26% goby). For the Klondike strain the frequency of occurrence of Rainbow Smelt in 2009-2015 and 2004-2008 was 74% and 52%, respectively, and frequency of occurrence of Round Goby was 31% and 43%, respectively. In general, Lake Trout, regardless of strain, eats mostly Rainbow Smelt when abundant. When Rainbow Smelt are not abundant, Lake Trout eats more Round Goby. Klondike-strain Lake Trout typically has a higher percentage of Round Goby in its diet than do lean-strain Lake Trout (CWTG 2011). Lake Trout growth rate and condition were high in eastern Lake Erie during 2009-2015, just as they have been since the early 1990s (CWTG 2016). Consistent with past results, mean length and weight of Klondike-strain Lake Trout were significantly lower than lean-strain Lake Trout at ages 5 and older (two sample t-test; $P < 0.01$) (CWTG 2015).

Harvest

Angler harvest of Lake Trout from Lake Erie remains low, although it has increased in recent years coincident with the increase in the population (CWTG 2016). Average annual harvest from New York and Pennsylvania waters during 2004-2008 was 297 fish, about half of the 2009-2015 harvest of 571 fish. During 2009-2015, much of the harvest occurred in 2013-2015 (853 to 1,000 fish annually). Harvests in 2009-2012 were much lower, ranging from 74 to 528 fish annually. In Ontario, Lake Trout remains a non-harvest species for the commercial fishery, and the recreational harvest is extremely low. For example, volunteer angler diarists during 2015 reported only one Lake Trout caught in Ontario waters of the eastern basin (OMNRF 2016).

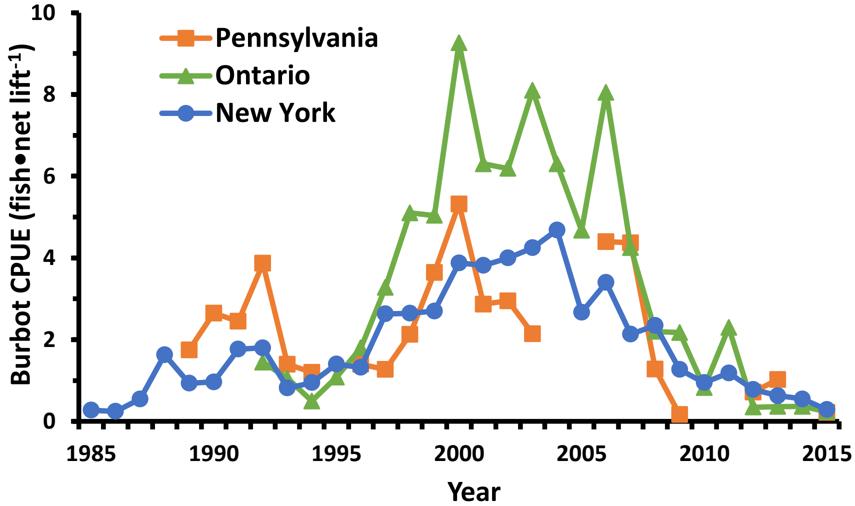
Burbot

Burbot made a substantial recovery in eastern Lake Erie during the mid- to late-1990s mainly due to improved water quality and control of the Sea Lamprey population (Stapanian et al. 2006). In addition, large numbers of adult Lake Trout during 1996-1997 buffered Burbot from Sea Lamprey predation, increasing survival of young adult Burbot to spawning age (Stapanian and Madenjian 2007). Annual surveys of the eastern basin with gillnets indicated that, after a period of high Burbot abundance and biomass during 1998-2008, there was a precipitous decline (CWTG 2016). Although specific mechanisms responsible for the decline were never explicitly identified, a senescing population due to a lack of recruitment and an increase in mortality associated with Sea Lamprey predation were thought to have contributed to the abrupt decline of the population (Stapanian et al. 2010a; CWTG 2016).

Relative Abundance

The relative abundance of Burbot in the eastern basin increased sharply after 1996, peaking in 2000 in Ontario and Pennsylvania and in 2004 in New York (Fig. 34). Burbot catch rates were highest in Ontario waters during most years from 1997-2008, the period when annual Burbot catch rates were nearly all ≥2 fish•net lift^{-1} across all three jurisdictions. Burbot abundance has continued to decrease throughout the eastern basin in recent years, and, during 2009-2015, it was substantially lower than during 2004-2008. Burbot catch rates were <0.3 fish•net lift^{-1} throughout the eastern basin in 2015 (Fig. 34).

Fig. 34. Relative abundance of Burbot based on gillnet catch-per-unit effort (CPUE; fish•net lift^{-1}) in Pennsylvania, Ontario, and New York waters of Lake Erie's eastern basin, 1985-2015 (CWTG 2016).



Recruitment

Little is known about Burbot reproduction in Lake Erie. Nearshore areas, such as Presque Isle and stream mouths in New York, appear to be important spawning habitats during late fall and winter. Stapanian et al. (2010a) speculated that recruitment declines from 2001 through 2008 were caused by lower survival of Burbot larvae and eggs from a combination of predation by an increasing Yellow Perch population and the deleterious effects of warm water temperatures in winter (i.e., reduced number of days for optimal spawning and egg development and increased destruction of eggs by turbulence associated with the reduced amount and duration of ice cover). Warm winters have been associated with lower reproductive success in Burbot populations worldwide, particularly near the southern extent of their range (Stapanian et al. 2010b). The specific mechanisms associated with lower recruitment and abundance have not been identified, and an overall understanding of Lake Erie Burbot ecology and biology would likely provide insight into these phenomena.

Diet

Burbot diets in the eastern basin during 2009-2015 were like those during 2004-2008, with Round Goby and Rainbow Smelt composing the bulk (>80%) of the diet. Prior to 2000, Rainbow Smelt dominated the diets of Burbot, with a frequency of occurrence as high as 90% in August (CWTG 2016). However, Round Goby was detected in Burbot stomachs in 2000, and, by 2003, it was the most frequent (>40%) food item. Just as in 2004-2008, Round Goby was found in 40-80% of Burbot stomachs during 2009-2015. Rainbow Smelt remained the second most common prey species with a 20-60% frequency of occurrence. Emerald Shiner, Gizzard Shad, Alewife, and Yellow Perch were occasionally eaten by Burbot. Growth and condition of adult Burbot in the eastern basin of Lake Erie remain stable.

Harvest

Burbot generally composes a minor portion of the commercial and recreational harvest in Lake Erie, with annual yields usually <3 t. The exception to this was in 1999 when a new commercial market drove harvest to >183 t. However, this market did not persist, and yield quickly fell. The average annual harvest in 2009-2015 was 1.2 t, a 61% decline from the 3.1-t average harvest in 2004-2008. Burbot composed <1% of the total commercial fisheries harvest in the eastern basin during 2009-2015.

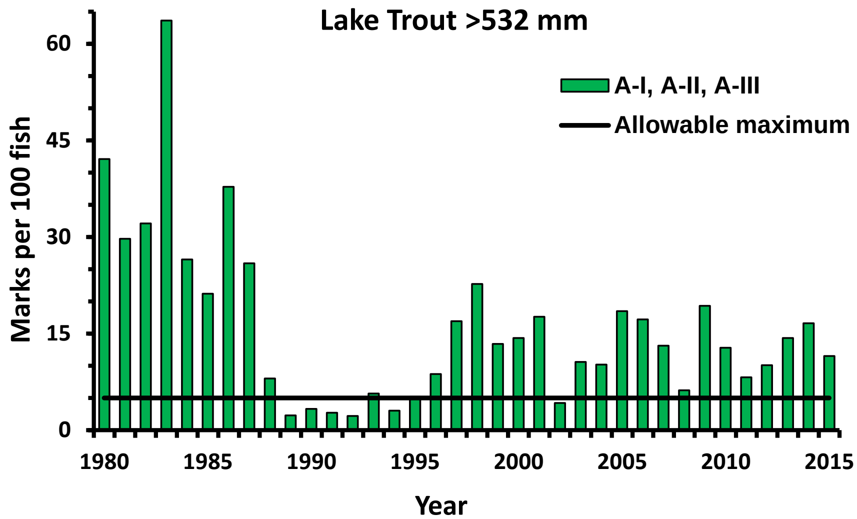
Sea Lamprey

Mortality from Sea Lamprey attacks hinders Lake Trout restoration and affects other species, such as Burbot and Lake Whitefish. A program to control Sea Lamprey by killing lamprey larvae in streams with a selective lampricide, 3-trifluoromethyl-4-nitrophenol (TFM), was implemented on Lake Erie in 1986. By the early 2000s, however, after more than 20 years of binational Sea Lamprey control, the program had produced mixed results. In 2008, a new back-to-back treatment strategy, similar to that used initially to successfully treat Lake Erie in 1986-1987, was implemented to reduce Sea Lamprey abundance. All nine Sea Lamprey-producing tributaries to the Lake Erie were treated with TFM in the spring of 2008 and again in the fall of 2009, except for one stream that was treated in 2009 and 2010. The back-to-back treatments, however, failed to suppress Sea Lamprey in Lake Erie, as evidenced by the large number of adult (spawning) Sea Lamprey in 2010-2011, the years when the treatments should have produced a sharp drop in the number of spawners (see Abundance section below). The multi-year delay in evaluating the efficacy of back-to-back treatments for reducing Sea Lamprey in Lake Erie was due to an inability to assess juvenile (feeding) Sea Lamprey in the lake.

Marking Rates

Sea Lamprey marking rates on Lake Trout have exceeded the target of 5 marks•100 fish^{-1} >532 mm in all but one year during 1995-2015 (Fig. 35; CWTG 2016). The average marking rate (Type A, Stages I, II, and III; Ebener et al. 2006) on Lake Trout >532 mm changed little between 2004-2008 and 2009-2015, marks•100 fish^{-1} were 13.0 and 13.3, respectively. However, the average frequency of Type A, Stage IV, marks on Lake Trout increased from 43.0 marks•100 fish^{-1} in 2004-2008 to 51.7 marks•100 fish^{-1} in 2009-2015. Marking rates (Type A, Stages I, II, and III) were more than two times higher on Klondike-strain Lake Trout compared to Seneca- and Lake Champlain-strain Lake Trout, and marking rates were nearly identical for the Seneca and Lake Champlain strains (CWTG 2016). Lake Trout >635 mm had the highest marking rates, most likely because Sea Lamprey prefer large (>609-mm) hosts when available (Swink 2003).

Fig. 35. Frequency of Type A, Stages I, II, and III marks (A-I, A-II, A-III; Ebener et al. 2006) on Lake Trout >532 mm (21 inches) in the eastern basin of Lake Erie during August-September 1980-2015. Horizontal line shows the allowable maxium of 5 marks per 100 Lake Trout >532 mm.

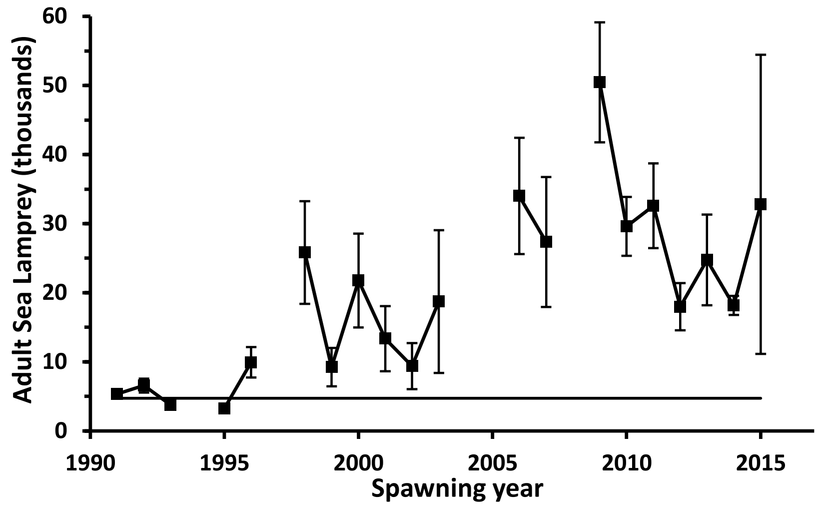


Marking rates for other cold-water fish increased during 2009-2015 relative to 2004-2008, with average marking rates on Burbot increasing from 8.8 to 14.5 marks•100 fish^{-1} (Type A, Stages I-IV) and on Lake Whitefish from 1.0 to 4.8 marks•100 fish^{-1} (CWTG 2016). Marking rates on Rainbow Trout were recorded during various surveys in New York, Pennsylvania, and Ohio in 2009-2015 ranging from 3.1 to 51.2 marks•100 fish^{-1} (Type A, Stages I-IV; CWTG 2016). Observations from various surveys conducted in New York waters found that Sea Lamprey does not exclusively attack cold-water fish. Sea Lamprey marks have been found on a variety of warm- and cool-water fish, including Smallmouth Bass, Yellow Perch, Walleye, Northern Pike, Lake Sturgeon, and Muskellunge, indicating that Sea Lamprey has the potential to affect mortality rates of fish other than Lake Trout and, thus, is a concern for Lake Erie's entire fish community (Markham 2016).

Abundance

Abundance of adult Sea Lamprey in Lake Erie peaked in 2009. Despite back-to-back treatments of the lake's Sea Lamprey-producing tributaries in 2008-2010, which were expected to result in fewer adults beginning in 2010, the numbers of adult Sea Lamprey in 2010-2015 remained above the allowable maximum of 4,730 animals (Fig. 36; Barber and Steeves 2019). Average abundance of adult Sea Lamprey in Lake Erie decreased from 37,300 in 2006-2009 to 26,000 in 2010-2015 (Barber and Steeves 2019).

Fig. 36. Number (±95% CI) of adult Sea Lamprey in Lake Erie, 1991-2015. The horizontal line shows the allowable maximum of 4,730. The allowable maximum is the mean number of spawning-phase animals during 1991-1995, a period when marking rates on Lake Trout were low and tolerable.



Treatment and Assessment

Sea Lamprey control in the Lake Erie basin during 2009-2015 included 33 treatments (19 U.S., 14 Canada) in 18 streams (10 U.S., 8 Canada). These treatments were an increase in effort from 2004-2008 when 20 treatments (12 U.S., 8 Canada) were conducted in 10 streams (6 U.S., 4 Canada). Nine streams (5 U.S., 4 Canada) are treated regularly every 3 to 5 years.

The back-to-back treatments in 2008-2010 were highly effective in reducing larval populations in treated streams—few residual Sea Lamprey larvae were found following the treatments. Rates of re-establishment of Sea Lamprey in previously infested streams were low following treatment, with only 5 of 11 streams containing Sea Lamprey larvae post-treatment. Although back-to-back treatments successfully reduced Sea Lamprey larvae in streams, they did not result in the hoped-for decline in adult Sea Lamprey in the lake, suggesting that Sea Lamprey is reproducing in untreated areas. Subsequently, efforts to find these areas were substantially increased, especially in the Saint Clair-Detroit River System (SCDRS).

During 2009-2015, a total of 39.2 ha in the SCDRS were surveyed to identify areas with a high density of Sea Lamprey larvae. Larvae were found to be widespread throughout the St. Clair River and its delta (typically in low densities) whereas none were found in the Detroit River.

In 2015, in cooperation with Walpole Island First Nation, the Great Lakes Fishery Commission’s Sea Lamprey control agents and partners completed the first year of an annual survey of downstream-migrating young juvenile Sea Lamprey in the St. Clair River. Nine floating fyke nets were deployed in December 2015 in the shipping channel of the St. Clair River. They captured 392 juvenile Sea Lampreys during a 33-day period.

EMERGING ISSUES, ACTIONS, AND PRIORITIES FOR LAKE ERIE FISHERIES MANAGEMENT POST-2015[22]

Todd C. Wills[23] and Cleyo Harris

Markham and Knight (2017) identified four major emerging issues from the 2009 State of Lake Erie Conference—increases in dissolved reactive phosphorus (DRP) that have precipitated harmful algal blooms, hypoxia, fish health (in particular viral hemorrhagic septicemia (VHSv)), and wind-power development. Clearly, ongoing increases in DRP and the resulting harmful algal blooms during 2009-2015 warrant further attention. The emergence of VHSv and other fish health concerns also warrant continued attention and are being addressed by individual jurisdictions through ongoing monitoring of fish health and research. The Lake Erie Committee (LEC) of the Great Lakes Fishery Commission has prepared and published a position statement on wind-power projects that recommends more emphasis and consideration be placed on the effects of such projects on the Lake Erie fish community and its associated habitat.

We discuss below a previously identified major issue, harmful algal blooms, along with three newly emerging issues—Grass Carp, climate change, and

[22]Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp21_01.pdf.

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Sea Lamprey production in the Saint Clair-Detroit River System (SCDRS). In addition, we detail actions taken during 2009-2015 on 2004-2008 priorities and identify priorities for 2016-2020.

Harmful Algal Blooms

In the decades prior to enactment of the Clean Water Act in 1972, Lake Erie experienced extensive blue-green algal blooms associated primarily with phosphorus loading from sewage treatment facilities and industrial sources. Phosphorus reduction brought about by the Great Lakes Water Quality Agreement caused algal blooms to largely disappear by the 1980s (IJC 1987). Since the late 1990s, however, algal blooms (in particular *Microcystis aeruginosa*) have reappeared in the western basin of Lake Erie due to excess DRP. Because these blooms can negatively affect human health and the Lake Erie's biota, they are considered harmful.

Total phosphorus loading to Lake Erie is not increasing, but there has been an increase in the dissolved reactive component since 1995, as measured in the Maumee River and other tributaries (Annex 4 2015). Increased DRP appears to be driving the increased incidence of harmful algal blooms in the western basin and is likely due to increasing precipitation on and river discharge from watersheds with extensive agriculture (Maccoux et al. 2016), as well as to nutrient recycling by dreissenids. In turn, the increased extent and severity of hypoxia in the central basin (see Steinhart et al., this volume) is directly attributable to increased harmful algal biomass in the western basin. The effects of increased harmful algal blooms on the Lake Erie fish community are unknown, but eutrophic conditions generally are sub-optimal for Walleye (Leach et al. 1977), and Walleye recruitment was relatively weak during 2009-2015. Similarly, hypoxic and anoxic conditions may affect fishery catch rates by altering the amount of available habitat and, therefore, the distribution or density of cool-water fish. Additional research is needed to determine the long-term effects of harmful algal blooms on fisheries, on fish behavior, and ultimately on production. Likewise, an important area for continued research is to determine if diminished percid recruitment is associated with changes in trophic status of the western basin, with direct effects from *Microcystis aeruginosa* or from other unrelated factors.

Grass Carp

Grass Carp, a large herbivorous cyprinid native to eastern Asia, was imported to the southern U.S. in the early 1960s where it was stocked for vegetation control. However, stocking for vegetation control in the northern U.S. did not occur until 1969, and it became prevalent through the 1970s. Concerns quickly arose regarding expansion and establishment of Grass Carp in other water bodies, and these concerns led to the development of methodologies for producing monosex Grass Carp and eventually to producing triploid (sterile) Grass Carp. Subsequently, many states required that all stocked Grass Carp must be triploid, although some states permitted the stocking of diploid Grass Carp (Mitchell and Kelly 2006).

Because of widespread stocking and escapement, Grass Carp is established throughout much of the Mississippi River basin and other U.S. areas. In some cases, ploidy evaluation of feral Grass Carp showed that the populations comprised triploid and diploid individuals (Schulz et al. 2001). Presently, Grass Carp has been collected from each of the Great Lakes, except for Lake Superior (Kocovsky et al. 2012). Grass Carp was first collected from the Lake Erie basin in the early 1980s, prior to the production of triploids (Mandrak 1989; Chapman et al. 2013). However, the establishment of wild naturally reproducing populations was unconfirmed. Chapman et al. (2013) assessed the ploidy of four Grass Carp collected from the Sandusky River close to its outlet to Lake Erie and found that two of the fish were diploid. The ploidy status of the other two fish could not be determined, although otolith microchemistry analysis indicated that they were likely of wild origin. In addition, Embke et al. (2016) found fertilized eggs in the Sandusky River, documenting that successful spawning had occurred. Grass Carp is occasionally captured by commercial fishing operations, and those captured are used in a variety of ongoing studies. Such research should continue given the ability of Grass Carp to negatively alter habitat and the fact that this species can serve as a potential surrogate for predicting the effects of invasive Asian carps.

Climate Change

Anthropogenic stressors (such as habitat degradation, over-exploitation, introduction of invasive species) shaped the fisheries of the Great Lakes during the past century. Only recently have scientists started to recognize climate change as an additional and emerging stressor, which has the ability to affect Lake Erie fish and fisheries through changes in habitat. Expected climate-induced changes include warmer temperatures throughout the water column, increased duration and intensity of precipitation, less winter ice cover, and longer periods of thermal stratification, with a resulting increase in the occurrence and duration of hypoxic and anoxic conditions. The potential effects of these changes range from simple thermal habitat changes (such as extended durations of temperatures that promote optimal growth) to complex interactive effects with other stressors that have the potential to increase the negative effects of eutrophication and invasive species (Collingsworth et al. 2017). The implications are relevant to all of Lake Erie, including the shallow western basin, which responds quickly to weather events and is struggling with increased DRP loads (see Harmful Algal Blooms above); the central basin where the water is deep enough to allow thermal stratification and hypoxia or anoxia during summer and early fall; and the eastern basin, which is home to the Lake Erie's weakly structured cold-water fish community. Expanded monitoring and continued research to develop an understanding of how climate variables like spring warming rate, precipitation, and wind speed affect Lake Erie fish communities remain important endeavors, as each of these variables are expected to change profoundly during this half-century.

Sea Lamprey

Mortality from Sea Lamprey attacks slows Lake Trout restoration and affects other cold-water fish, such as Burbot and Lake Whitefish. Sea Lamprey marks have been found on a variety of other warm- and cool-water fish whose susceptibility to Sea Lamprey mortality is less clear, including Smallmouth Bass, Yellow Perch, Walleye, Northern Pike, Lake Sturgeon, and Muskellunge. The number of adult Sea Lamprey in Lake Erie did not appear to be affected by the 2008-2010 back-to-back treatment of lamprey-producing streams, even though the treatments largely eliminated larvae from those streams. Additional research into other potential sources of Sea Lamprey, like the SCDRS, is warranted. Strategies for Sea Lamprey control in this large, lotic system should be considered even though control may be challenging, not only by the sheer size of the SCDRS but also by the presence of species of special concern like Lake Sturgeon and Northern Madtom.

Priorities

Actions on 2004-2008 Priorities in 2009-2015

During 2009-2015, in response to priority recommendations from Markham and Knight (2017), actions were taken to

1. Continue existing interagency monitoring programs that comprehensively assess multiple trophic levels in the food web of all three Lake Erie basins
2. Continue modeling efforts with the Quantitative Fisheries Center at Michigan State University to improve percid stock assessments

3. Initiate research at several universities on genetic and microchemistry techniques to identify discrete percid stocks
4. Support research that uses the Great Lakes Acoustic Telemetry Observation System to better understand percid spatial ecology in relation to environmental stressors
5. Develop environmental objectives in support of the LEC's fish community objectives (FCOs)
6. Develop a rehabilitation plan for Cisco that provides a framework for restoration
7. Complete an LEC position statement related to the effects of offshore wind-power development
8. Undertake projects in the SCDRS to improve fish habitats of potential use by migratory Lake Erie fish
9. Implement strategies that promote stock assessment of data-poor fisheries, such as Lake Whitefish and White Bass
10. Develop a new LEC fishery management plan for Yellow Perch
11. Implement a new LEC fishery management plan for Walleye

Priorities for 2016-2020

1. Continue to work with relevant partners to reduce DRP loads to levels that prevent harmful algal blooms and minimize hypoxia in the western and central basins
2. Continue efforts to attain the LEC environmental objectives and address habitat issues throughout the Lake Erie basin
3. Support research to inform Lake Erie fisheries management of the effects of climate change and invasive species
4. Support research that reduces knowledge gaps surrounding interactions between environmental variables and fish populations
5. Support research on percid stock discrimination and behavior (tagging), recruitment mechanisms, and mechanisms affecting food webs and fish community structure in each basin

6. Support Sea Lamprey control to attain the allowable maximum number of spawning-phase Sea Lamprey and of marking rate on Lake Trout
7. Continue efforts to better understand the role of the SCDRS as a source of Sea Lamprey to Lake Erie
8. Continue to develop sustainable harvest policies for Walleye and Yellow Perch stocks that meet FCOs and stakeholders' needs while accounting for changing environmental conditions and highly variable recruitment

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LITERATURE CITED

Allan, J.D., Smith, S.D.P., McIntyre, P.B., Joseph, C.A., Dickinson, C.E., Marino, A.L., Biel, R.G., Olson, J.C., Doran, P.J., and three others. 2015. Using cultural ecosystem services to inform restoration priorities in the Laurentian Great Lakes. Front. Ecol. Environ. **13**: 418-424.

Allen, M.S., Walters, C.J., and Myers, R. 2008. Temporal trends in largemouth bass mortality, with fishery implications. N. Am. J. Fish. Manage. **28**: 418-427.

Annex 4 (Annex 4 Objectives and Targets Task Team). 2015. Recommended phosphorus loading targets for Lake Erie [online]. Available from https://www.epa.gov/sites/production/files/2015-06/documents/report-recommended-phosphorus-loading-targets-lake-erie-201505.pdf [accessed 09 December 2020].

Arnold, E., and Ryan, P. 2004. Sport fisheries in eastern Lake Erie in 2003. Lake Erie fisheries assessment unit report 2004-1. Lake Erie Management Unit., Ont. Min. Nat. Resour. Forest., Port Dover, ON, Canada.

Barber, J., and Steeves, M. 2019. Sea Lamprey control in the Great Lakes 2018 [online]. Available from http://www.glfc.org/pubs/slcp/annual_reports/ANNUAL_REPORT_2018.pdf [accessed 09 December 2020].

Bartnik, S.E.H. 2005. Population dynamics of age-0 walleye in western Lake Erie. M.Sc. thesis. Univ. Windsor, Windsor, ON, Canada.

Begg, G.A., and Waldman, J.R. 1999. A holistic approach to fish stock identification. Fish. Res. **43**: 35-44.

Belore, M., and Cook, A. 2012. Lake Erie western basin smallmouth bass spawning survey 2012. Lake Erie Management Unit, Ont. Min. Nat. Resour. Forest., Wheatley, ON, Canada.

Bennion, D.H., and Manny, B.A. 2014. A model to locate potential areas for lake sturgeon spawning habitat construction in the St. Clair-Detroit River System. J. Great Lakes Res. **40**: 43-51.

Bertram, P.E. 1993. Total phosphorus and dissolved oxygen trends in the central basin of Lake Erie, 1970-91. J. Great Lakes Res. **19**: 224-236.

Biberhofer, H., Gorman, A.M., Kocovsky, P.M., MacDougall, T., Mackey, S.D., and Markham, J. 2010. Identifying potential lake trout spawning habitat in Lake Erie [online]. Available from https://www.fws.gov/midwest/fisheries/GLFWRA/30181-8-G021.pdf [accessed 09 December 2020].

Bigrigg, J.L. 2008. Determining stream origin for four purported walleye stocks in Lake Erie using otolith elemental analysis. M.Sc. thesis. The Ohio State Univ., Columbus, OH.

Borden, W.C. 2008. Assessment of genetic divergence between lacustrine and riverine smallmouth bass in Lake Erie and four tributaries. Northeast. Nat. **15**: 335-348.

Borden, W.C., and Stepien, C.A. 2006. Discordant population genetic structuring of smallmouth bass, *Micropterus dolomieu* Lacepede, in Lake Erie based on mitochondrial DNA sequences and nuclear DNA microsatellites. J. Great Lakes Res. **32**: 242-257.

Bouckaert, E.K., Auer, N.A., Roseman, E.F., and Boase, J.C. 2014. Verifying success of artificial spawning reefs in the St. Clair-Detroit River System for lake sturgeon (*Acipenser fulvescens* Rafinesque, 1817). J. of Appl. Ichthyol. **30**: 1393-1401.

Brandt, S.B., Costantini, M., Kolesar, S., Ludsin, S.A., Mason, D.M., Rae, C.M., and Zhang, H. 2011. Does hypoxia reduce habitat quality for Lake Erie walleye (*Sander vitreus*)? A bioenergetics perspective. Can. J. Fish. Aquat. Sci. **68**: 857-879.

Breitburg, D. 2002. Effects of hypoxia, and the balance between hypoxia and enrichment on coastal fish and fisheries. Estuaries **25**: 767-781.

Brenden, T.O., Scribner, K.T., Bence, J.R., Tsehaye, I., Kanefsky, J., Vandergoot, C.S., and Fielder, D.G. 2015. Contributions of Lake Erie and Lake St. Clair walleye populations to the Saginaw Bay, Lake Huron, recreational fishery: evidence from genetic stock identification. N. Am. J. Fish. Manage. **35**: 567-577.

Brooks, J.L., and Dodson, S.I. 1965. Predation, body size, and composition of plankton. Science **150**: 28-35.

Burns, N.M. 1976. Oxygen depletion in the central and eastern basins of Lake Erie, 1970. J. Fish. Res. Board Can. **33**: 512-519.

Caswell, N.M., Peterson, D.L., Manny, B.A., and Kennedy, G.W. 2004. Spawning by lake sturgeon (*Acipenser fulvescens*) in the Detroit River. J. Appl. Ichthyol. **20**: 1-6.

Chapman, D.C., Davis, J.J., Jenkins, J.A., Kocovsky, P.M., Miner, J.G., Farver, J., and Jackson, P.R. 2013. First evidence of grass carp recruitment in the Great Lakes basin. J. Great Lakes Res. **39**: 547-554.

Charlton, M.N. 1994. The case for research on the effects of zebra mussels in Lake Erie: visualization of information from August and September 1993. J. Biol. Syst. **2**: 467-480.

Chen, K.-Y., Ludsin, S.A., Corey, M.M., Collingsworth, P.D., Nims, M.K., Olesik, J.W., Dabrowski, K., van Tassell, J.J., and Marschall, E.A. 2017. Experimental and field evaluation of otolith strontium as a marker to discriminate between river-spawning populations of walleye in Lake Erie. Can. J. Fish. Aquat. Sci. **74**: 693-701.

Chiotti, J., Mohr, L., Thomas, M., Boase, J., and Manny, B. 2013. Lake sturgeon population demographics in the Huron Erie corridor, 1996-2012. Oral presentation at the 7th International Sturgeon Symposium, Vancouver Island Univ., Nanaimo, BC, Canada, July 21-25, 2013.

Christie, W.J. 1974. Changes in the fish species composition of the Great Lakes. J. Fish. Res. Board Can. **31**: 827-854.

Christie, G.C., and Regier, H.A. 1988. Measures of optimal thermal habitat and their relationship to yields for four commercial fish species. Can. J. Fish. Aquat. Sci. **45**: 301-314.

Collingsworth, P.D., Bunnell, D.B., Murray, M.W., Kao, Y., Feiner, Z.S., Claramunt, R.M., Lofgren, B.M., Hook, T.O., and Ludsin, S.A. 2017. Climate change as a long-term stressor for the fisheries of the Laurentian Great Lakes of North America. Rev. Fish Biol. Fisher. **27**: 363-391.

Conroy, J.D., Kane, D.D., Dolan, D.M., Edwards, W.J., Charlton, M.N., and Culver, D.A. 2005. Temporal trends in Lake Erie plankton biomass: roles of external phosphorus loading and dreissenid mussels. J. Great Lakes Res. **31**: 89-110.

Cook, A. 1995. Fish diet analysis program, Long Point Bay, Lake Erie 1985-1989. Lake Erie Management Unit, Ont. Min. Nat. Resour. Forest., Port Dover, ON, Canada.

Cook, A., McDonald, C., Tulen, L., and Wright, J. 1997. Lake Erie food web study 1995-1996: prey selection by Lake Erie fish species. File Report 1997-01, Lake Erie Management Unit, Ont. Min. Nat. Resour. Forest., Port Dover, ON, Canada.

Cornelius, F.C., Muth, K.M., and Kenyon, R. 1995. Lake trout rehabilitation in Lake Erie: a case history. J. Great Lakes Res. **21**(Suppl. 1): 65-82.

Crane, D.P., and Einhouse, D.W. 2016. Changes in growth and diet of smallmouth bass following invasion of Lake Erie by the round goby. J. Great Lakes Res. **42**: 405-412.

Cuéllar-Pinzón, J., Presa, P., Hawkins, S.J., and Pita, A. 2016. Genetic markers in marine fisheries: types, tasks, and trends. Fish. Res. **173**: 194-205.

CWTG (Coldwater Task Group). 2011. Report of the Lake Erie Coldwater Task Group, March 2011 [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/CWTG_docs/annual_reports/CWTG_report_2011.pdf [accessed 09 December 2020].

CWTG (Coldwater Task Group). 2015. Report of the Lake Erie Coldwater Task Group, March 2015 [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/CWTG_docs/annual_reports/CWTG_report_2015.pdf [accessed 09 December 2020].

CWTG (Coldwater Task Group). 2016. Report of the Lake Erie Coldwater Task Group, March 2016 [online]. Available from https://www.google.com/url?client=internal-element-cse&cx=000383001685146685654:hj1qvncd1be&q=http://www.glfc.org/pubs/lake_committees/erie/CWTG_docs/annual_reports/CWTGexesum2016.pdf&sa=U&ved=2ahUKEwiirumKqLfuAhVLZ80KHakvCAIQFjADegQICBAB&usg=AOvVaw2l_iVJh_4wHDVfm7zoEpHV [accessed 09 December 2020].

Davies, D.H., Haas, B., Halyk, L., Kenyon, R., Mackey, S., Markham, J., Roseman, E., Ryan, P., Tyson, J., and one other. 2005. Lake Erie environmental objectives. Report of the Environmental Objectives Sub-Committee of the Lake Erie Committee [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/EOs_July5.pdf [accessed 09 December 2020].

Driedger, A.G., Dürr, H.H., Mitchell, K., and Van Cappellen, P. 2015. Plastic debris in the Laurentian Great Lakes: a review. J. Great Lakes Res. **41**: 9-19.

Drouin R., and Soper. K. 2017. Lake Erie's western basin. *In* The state of Lake Erie in 2009, pp. 39-58. *Edited by* J.L. Markham and R.L. Knight [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp17_01.pdf [accessed 09 December 2020].

DuFour, M.R., May, C.J., Roseman, E.F., Ludsin, S.A., Vandergoot, C.S., Pritt, J.T., Fraker, M.E., Davis, J.J. Tyson, J.T., and three others. 2015. Portfolio theory as a management tool to guide conservation and restoration of multi-stock fish populations [online]. Available from http://dx.doi.org/10.1890/ES15-00237.1 [accessed 09 December 2020].

Dyble, J., Gossiauz, D., Lundrum, P., Kashian, D.R., and Pothoven, S. 2011. A kinetic study of accumulation and elimination of Microcystin-LR in yellow perch (*Perca flavescens*) tissue and implications for human fish consumption. Mar. Drugs. **9**: 2553-2571.

Ebener, M.P., King, Jr., E.L., and Edsall, T.A. 2006. Application of a dichotomous key to the classification of sea lamprey marks on Great Lakes fish [online]. Available from http://www.glfc.org/pubs/misc/2006-02.pdf [accessed 09 December 2020].

ECCC-USEPA (Environment and Climate Change Canada and the U.S. Environmental Protection Agency). 2017. State of the Great Lakes 2017 technical report [online]. Available from https://binational.net/wp-content/uploads/2017/09/SOGL_2017_Technical_Report-EN.pdf [accessed 09 December 2020].

Edsall, T.A., Brown, C.L., Kennedy, G.W., and French, III, J.R.P. 1992. Surficial substrates and bathymetry of five historical lake trout spawning reefs in near-shore waters of the Great Lakes [online]. Available from http://www.glfc.org/pubs/TechReports/Tr58.pdf [accessed 09 December 2020].

Einhouse, D.W., and MacDougall, T.M. 2010. An emerging view of the mixed-stock structure of Lake Erie's eastern-basin walleye population, pp. 151-164. *In* Status of walleye in the Great Lakes: proceedings of the 2006 symposium. *Edited by* E. Roseman, P. Kocovsky, and C. Vandergoot [online]. Available from http://www.glfc.org/pubs/TechReports/Tr69.pdf [accessed 09 December 2020].

Embke, H.S., Kocovsky, P.M., Richter, C.A., Pritt, J.J., Mayer, C.M., and Qian, S.S. 2016. First direct confirmation of grass carp spawning in a Great Lakes tributary. J. Great Lakes Res. **42**: 899-903.

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 09 December 2020].

Fischer, J.L., Roseman, E.F., Mayer, C.M., and Qian, S. 2018. Effectiveness of shallow water habitat remediation for improving fish habitat in a large temperate river. Ecol. Engin. **123**: 54-64.

Fraker, M.E., Anderson, E.J., Brodnik, R.M., Carreon-Martinez, L., DeVanna, K.M., Fryer, B.J., Heath, D.D., Reichert, J.M., and Ludsin, S.A. 2015. Particle backtracking improves breeding subpopulation discrimination and natal-source identification in mixed populations [online]. Available from https://doi.org/10.1371/journal.pone.0120752 [accessed 09 December 2020].

Francis, J., Chiotti, J.A., Boase, J., Thomas, M., Manny, B., and Roseman. E.F. 2014. An assessment of the nearshore fish communities in the St. Clair-Detroit River System. J. Great Lakes Res. **40**: 52-61.

Fraser, J.M. 1955. The smallmouth bass fishery of South Bay, Lake Huron. J. Fish. Res. Board Can. **12**: 147-177.

FTG (Forage Task Group). 2015. Report of the Lake Erie Forage Task Group, March 2015 [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/FTG_docs/annual_reports/FTG_report_2015.pdf [accessed 09 December 2020].

FTG (Forage Task Group). 2016. Report of the Lake Erie Forage Task Group, March 2016 [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/FTG_docs/annual_reports/FTG_report_2016.pdf [accessed 09 December 2020].

Gatt, M.H., McParland, T.L., Halyk, L.C., and Ferguson, M.M. 2003. Mitochondrial DNA variation and mixed-stock analysis of recreational and commercial fisheries in eastern Lake Erie. N. Am. J. Fish. Manage. **23**: 431-440.

GLFC (Great Lakes Fishery Commission). 2007. A joint strategic plan for management of Great Lakes fisheries (as revised, 10 June 1997) [online]. Available from www.glfc.org/pubs/misc/jsp97.pdf [accessed 09 December 2020].

Goff, G.P. 1985. Environmental influences on annual variation in nest success of smallmouth bass, *Micropterus dolomieu*, in Long Point Bay, Lake Erie. Environ. Biol. Fish **14**: 303-307.

Goodyear, C.S., Edsall, T.A., Ormsby Dempsey, D.M., Moss, G.D., and Polanski, P.E. 1982. Atlas of spawning and nursery areas of Great Lakes fishes, volume IX—Lake Erie. FWS/OBS-82/52. USFWS, Washington, DC. 211 pp.

Gopalan, G., Culver, D.A., Wu, L., and Trauben, B.K. 1998. Effects of recent ecosystem changes on the recruitment of young-of-the-year fish in western Lake Erie. Can. J. Fish. Aquat. Sci. **15**: 2572-2579.

Gorman, A., and MacDougall, T. 2017. Environmental objectives and habitat. *In* The state of Lake Erie in 2009, pp. 24-38. *Edited by* J.L. Markham and R.L. Knight [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp17_01.pdf [accessed 09 December 2020].

Haltuch, M.A., Berkman, P.A., and Garton, D.W. 2000. Geographic information system (GIS) analysis of ecosystem invasion: exotic mussels in Lake Erie. Limnol. Oceanogr. **45**: 1778-1787.

Hartman, W.L. 1972. Lake Erie: effects of exploitation, environmental changes and new species on the fishery resources. J. Fish. Res. Board Can **29**: 899-912.

Hayden, T.A., Miner, J.G., Farver, J.R., and Fryer, B.J. 2011. Philopatry and vagrancy of white bass (*Morone chrysops*) spawning in the Sandusky River: evidence of metapopulation structure in western Lake Erie using otolith chemistry. J. Great. Lakes Res. **37**: 691-697.

Hayden, T.A., Binder, T.R., Holbrook, C.M., Vandergoot, C.S., Fielder, D.G., Cooke, S.J., Dettmers, J.M., and Krueger, C.C. 2018. Spawning site fidelity and apparent annual survival of walleye (*Sander vitreus*) differ between a Lake Huron and Lake Erie tributary. Ecol. Freshw. Fish **27**: 339-349. https://doi.org/10.1111/eff.12350.

Hayden, T.A., Vandergoot, C.S., Fielder, D.G., Cooke, S.J., Dettmers, J.M., and Krueger, C.C. 2019. Telemetry reveals limited exchange of walleye between Lake Erie and Lake Huron: movement of two populations through the Huron-Erie corridor. J. Great Lakes Res. **45**: 1241-1250. https://doi.org/10.1016/j.jglr.2019.09.014.

Hecky, R.E., Smith, R.E.H., Barton, D.R., Guildford, S.J., Taylor, W.D., Charlton, M.N., and Howell, E.T. 2004. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. Can. J. Fish. Aquat. Sci. **61**: 1285-1293.

Hedges, K.J. 2002. Use of calcified structures for stock discrimination in Great Lakes walleye (*Stizostedion vitreum*). M.Sc. thesis. Univ. Windsor, Windsor, ON, Canada.

Heidinger, R.C., 1975. Life history and biology of the largemouth bass. *In* Black bass biology and management. *Edited by* R.H. Stroud and H.E. Clepper. Sport Fishing Inst., Washington, DC.

Herdendorf, C.E. 1987. The ecology of the coastal marshes of western Lake Erie: a community profile [online]. Available from https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.909.7619&rep=rep1&type=pdf [accessed 09 December 2020].

Hilborn, R., Quinn, T.P., Schindler, D.E., and Rogers, D.E. 2003. Biocomplexity and fisheries sustainability. Proc. Natl. Acad. Sci. **100**: 6564-6568.

Hodgson, J.R., Schindler, D.E., and He, X. 1998. Homing tendency of three piscivorous fish in a north temperate lake. Trans. Am. Fish. Soc. **127**: 1078-1081.

Holcombe, T.L., Taylor, L.A., Warren, J.S., Vincent, P.A., Reid, D.F., and Herdendorf, C.E. 2005. Lake-floor geomorphology of Lake Erie [online]. Available from https://www.ngdc.noaa.gov/mgg/greatlakes/erie/RP3/lakefloorgeomorphologyoflakeerie.pdf [accessed 09 December 2020].

IJC (International Joint Commission). 1987. Revised Great Lakes water quality agreement of 1978 as amended by protocol signed November 18, 1987 [online]. Available from https://www.ijc.org/sites/default/files/GLWQA_e.pdf [accessed 23 December 2020].

IJC (International Joint Commission). 2012. Great Lakes water quality agreement [online]. Available from https://www.ijc.org/sites/default/files/2018-07/GLWQA_2012.pdf [accessed 09 December 2020].

Kane, D.D., Conroy, J.D., Richards, R.P., Baker, D.B., and Culver, D.A. 2014. Re-eutrophication of Lake Erie: correlations between tributary nutrient loads and phytoplankton biomass. J. Great Lakes Res. **40**: 496-501.

Karatayev, A.Y., Burlakova, L.E., Pennuto, C., Ciborowski, J., Karatayev, V.A., Juette, P., and Clapsadl, M. 2014. Twenty-five years of changes in *Dreissena* spp. populations in Lake Erie. J. Great Lakes Res. **40**: 550-559.

Kayle, K.A., and Murray, C. 2017. Lake Erie's central basin, pp. 59-74. *In* The state of Lake Erie in 2009. *Edited by* J.L. Markham and R.L. Knight [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp17_01.pdf [accessed 09 December 2020].

Kayle, K., Oldenburg, K., Murray, C., Francis, J., and Markham, J. 2015. Lake Erie walleye management plan 2015-2019 [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/LEC_docs/position_statements/walleye_managment_plan.pdf [accessed 09 December 2020].

Knight, R.L. 1997. Successful interagency rehabilitation of Lake Erie walleye. Fisheries **22**: 16-17.

Kocovsky, P.M., and Knight, C.T. 2012. Morphological evidence of discrete stocks of yellow perch in Lake Erie. J. Great Lakes Res. **38**: 534-539.

Kocovsky, P.M., Chapman, D.C., and McKenna, J.E. 2012. Thermal and hydrologic suitability of Lake Erie and its major tributaries for spawning of Asian carps. J. Great Lakes Res. **38**: 159-166.

Kocovsky, P.M., Sullivan, T.J., Knight, C.T., and Stepien, C.A. 2013. Genetic and morphometric differences demonstrate fine-scale population substructure of the yellow perch *Perca flavescens*: need for redefined management units. J. Fish Biol. **82**: 2015-2030.

Koonce, J.F., Busch, W.D.N., and Czapla, R.F. 1996. Restoration of Lake Erie: contribution of water quality and natural resource management. Can. J. Fish. Aquat. Sci. **53**: 105-112.

Kraus, R.T., Knight, C.T., Farmer, T.M., Gorman, A.M., Collingsworth, P.D., Warren, G.J., Kocovsky, P.M., and Conroy, J.D. 2015. Dynamic hypoxic zones in Lake Erie compress fish habitat, altering vulnerability to fishing gears. Can. J. Fish. Aquat. Sci. **72**: 797-806.

Leach, J.H., Johnson, M.G., Kelso, J.R.M., Hartman, J., Numan, W., and Ents, B. 1977. Responses of percid fish and their habitats to eutrophication. J. Fish. Res. Board Can. **34**: 1964-1971.

LEC (Lake Erie Committee). 2005. Lake Erie environmental objectives [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/LEC_docs/other_docs/EOs_July5.pdf [accessed 09 December 2020].

Legard, C.D. 2015. Lake sturgeon monitoring in Buffalo Harbor. *In* NYS DEC Lake Erie 2014 annual report to the Great Lakes Fishery Commission [online]. Available from https://www.dec.ny.gov/docs/fish_marine_pdf/2014lerpt.pdf [accessed 09 December 2020].

Lester, N.P., Dextrase, A.J., Kushneriuk, R.S., Rawson, M.R., and Ryan, P.A. 2004. Light and temperature: key factors affecting walleye abundance and production. Trans. Am. Fish. Soc. **133**: 588-605.

Ludsin, S.A., Kershner, M.W., Blocksom, K.A., Knight, R.L., and Stein, R.A. 2001. Life after death in Lake Erie: nutrient controls drive fish species richness, rehabilitation. Ecol. Appl. **11**: 731-746.

Maccoux, M.J., Dove, A., Backus, S.M., and Dolan, D.M. 2016. Total and soluble reactive phosphorus loadings to Lake Erie: a detailed accounting by year, basin, country, and tributary. J. Great Lakes Res. **42**: 1151-1165.

MacDougall, T.M., Benoit, H.P., Dermott, R., Johannsson, O.E., Johnson, T.B., Millard, E.S., and Munawar, M. 2001. Lake Erie 1998: assessment of abundance, biomass and production of lower trophic levels, diets of juvenile yellow perch and trends in the fishery. Can. Tech. Rep. Fish. Aquat. Sci. No. 2376.

Makarewicz, J.C. 1993. Phytoplankton biomass and species composition in Lake Erie, 1970-1987. J. Great Lakes Res. **19**: 258-274.

Mandrak, N.E. 1989. Potential invasion of the Great Lakes by fish species associated with climatic warming. J. Great Lakes Res. **15**: 306-316.

Manny, B.A., and Kennedy, G.W. 2002. Known lake sturgeon (*Acipenser fulvescens*) spawning habitat in the channel between Lakes Huron and Erie in the Laurentian Great Lakes. J. Appl. Ichthyol. **18**: 486-490.

Manny, B.A., Kennedy, G.W., Boase, J.C., Allen, J.D., and Roseman, E.F. 2010. Spawning by walleye (*Sander vitreus*) and white sucker (*Catostomus commersoni*) in the Detroit River: implications for spawning habitat enhancement. J. Great Lakes Res. **36**: 490-496.

Manny, B.A., Roseman, E.F., Kennedy, G., Boase, J.C. Craig, J.M., Bennion, D.H., Read, J., Vacarro, L., Chiotti, J., and one other. 2015. A scientific basis for restoring fish spawning habitat in the St. Clair and Detroit Rivers of the Laurentian Great Lakes. Restor. Ecol. **23**: 149-156.

Markham, J.L. 2016. Coldwater gill net assessment. *In* NYS DEC Lake Erie 2015 annual report [online]. Available from https://www.dec.ny.gov/docs/fish_marine_pdf/2015lerpt.pdf [accessed 09 December 2020].

Markham, J.L., and Knight, R.L. [EDS.]. 2017. The state of Lake Erie in 2009 [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp17_01.pdf [accessed 09 December 2020].

Markham, J.L., Cook, A., MacDougall, T., Witzel, L., Kayle, K., Murray, M., Fodale, M., Trometer, E., Neave, F., and three others. 2008. A strategic plan for the rehabilitation of lake trout in Lake Erie, 2008-2020 [online]. Available from www.glfc.org/pubs/misc/2008-02.pdf [accessed 09 December 2020].

Markham, J.L., Gorman, A.M., Kayle, K.A., Ludsin, S.A., Tyson, J.T., and Knight, R.L. 2017. Progress, emerging issues, and priorities, pp. 110-121. *In* The state of Lake Erie in 2009. *Edited by* J.L. Markham and R.L. Knight [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp17_01.pdf [accessed 09 December 2020].

Marklevitz, S., Belore, M., Drouin, R., and Locke, B. 2015. Lake Erie aerial creel survey 2014. Lake Erie Management Unit. Ont. Min. Nat. Resour. Forest., Wheatley, ON, Canada. 74 pp.

Marranca, J.M., Welsh, A., and Roseman, E.F. 2015. Genetic effects of habitat restoration in the Laurentian Great Lakes: an assessment of lake sturgeon origin and genetic diversity. Restor. Ecol. **23**: 455-464.

Matley, J.K., Faust, M.D., Raby, G.D., Zhao, Y., Robinson, J., MacDougall, T., Hayden, T.A., Fisk, A.T., Vandergoot, C.S., and one other. 2020. Seasonal habitat-use differences among Lake Erie's walleye stocks. J. Great Lakes Res. **46**: 609-621.

McDonald, E., McNaught, S., and Roseman, E.F. 2014. Use of main channel and two wetland habitats by larval fish in the Detroit River. J. Great Lakes Res. **40**: 69-80.

McParland, T.L., Ferguson, M.M., and Liskauskas, A.P. 1999. Genetic population structure and mixed stock analysis of walleyes in the Lake Erie-Lake Huron Corridor using allozyme and mitochondrial DNA markers. Trans. Am. Fish. Soc. **128**: 1055-1067.

MDNR (Michigan Department of Natural Resources). 2016. Status of the fisheries in Michigan waters of Lake Erie and Lake St. Clair, 2015 [online]. Available from https://www.michigan.gov/documents/dnr/LSCFRS_2015AnnualReport_518039_7.pdf [accessed 09 December 2020].

Millard, E.S., Fee, E.J., Myles, D.D., and Dahl, J.A. 1999. Comparison of phytoplankton methodology in Lakes Erie, Ontario, the Bay of Quinte and the northwest Ontario lake size series, pp. 441-468. *In* State of Lake Erie (SOLE)—past, present, and future. *Edited by* M. Munawar, T. Edsall, and I.F. Munawar. Ecovision World Monograph Series. Aquat. Ecosyst. Health Manage. Soc., Backhuys Publishers, Leiden, The Netherlands.

Mills, E.L., Leach, J.H., Carlton, J.T., and Secor, C.L. 1993. Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. J. Great Lakes Res. **19**: 1-54.

Mitchell, A.J., and Kelly, A.M. 2006. The public sector role in the establishment of grass carp in the United States. Fisheries **31**: 113-121.

MOECC (Ministry of the Environment and Climate Change). 2009. Guide to eating Ontario sport fish 2009-2010, 25th edition [online]. Available from https://www.yumpu.com/en/document/read/32915779/guide-to-eating-ontario-sport-fish-2009-2010-foca [accessed 10 December 2020].

MOECC (Ministry of the Environment and Climate Change). 2015. Guide to eating Ontario fish 2015-2016, 28th edition [online]. Available from https://dr6j45jk9xcmk.cloudfront.net/documents/4460/fishguide2015-final-aoda-en-final.pdf [accessed 10 December 2020].

Mullowney, D.R.J. 2004. Food web study and diet trend of some Lake Erie predators: 1997-2001. File report 2004-01, Lake Erie Management Unit., Ont. Min. Nat. Resour. Forest., Wheatley, ON, Canada. 66 pp.

Nakano, D., and Strayer, D.L. 2014. Biofouling in fresh water: biology, impacts, and ecosystem engineering. Front. Ecol. Environ. **12**: 167-175.

Nepszy, S.J., Davies, D.H., Einhouse, D., Hatch, R.W., Isbell, G., MacLennan, D., and Muth, K.M. 1991. Walleye in Lake Erie and Lake St. Clair, pp. 145-168. *In* Status of walleye in the Great Lakes: case studies prepared for the 1989 workshop. *Edited by* P.J. Colby, C.A. Lewis, and R.L. Eshenroder [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp91_1.pdf [accessed 10 December 2020].

Neuenhoff, R.D., Withers, J.L., Davis, L.A., Markley, N.D., Dowell, S., Bartron, M.L., Gorsky, D., and Sweka, J.A. 2018. Discovery of an undocumented Lake Sturgeon spawning site in the headwaters of the Niagara River. J. Fish and Wild. Manage. **9**: 266-273.

NYPA (New York Power Authority). 2005. Investigation of habitat improvement projects for the Niagara Power Project. Niagara power project (FERC No. 2216). Prepared by Kleinschmidt Associates and Riveredge Associates. 310 pp.

NYPA (New York Power Authority). 2010. Fish attraction structure habitat improvement project: 2009 monitoring report. Niagara power project (FERC No. 2216). Prepared by Kleinschmidt Associates and Riveredge Associates. 16 pp.

NYSDEC (New York State Department of Environmental Conservation). 1994. Niagara River remedial action plan. Div. Water., Albany, NY. 415 pp.

NYSDEC (New York State Department of Environmental Conservation). 2016. NYS DEC Lake Erie 2015 annual report [online]. Available from https://www.dec.ny.gov/docs/fish_marine_pdf/2015lerpt.pdf [accessed 10 December 2020].

ODNR (Ohio Department of Natural Resources). 2016. Ohio's Lake Erie Fisheries, 2015. Annual status report. Federal Aid in Fish Restoration Project F-69-P. Ohio Dept. Nat. Resour., Division of Wildlife, Lake Erie Fisheries Units, Fairport and Sandusky, OH.

O'Gorman, R., Madenjian, C.P., Roseman, E.F., Cook, A., and Gorman, O.T. 2012. Alewife in the Great Lakes: Old invader—new millennium, pp. 705-732. *In* Great Lakes fisheries policy and management: a binational perspective (second edition). *Edited by* W.W. Taylor, A.J. Lynch, and N.J. Leonard. Mich. State Univ. Press, East Lansing, MI.

OMNRF (Ontario Ministry of Natural Resources and Forestry). 2009. The lake sturgeon in Ontario [online]. Available from https://www.fws.gov/midwest/sturgeon/documents/LakeSturgeon-Ont-2009.pdf [accessed 10 December 2020].

OMNRF (Ontario Ministry of Natural Resources and Forestry). 2016. 2015 status of major stocks [online]. Available from https://www.michigan.gov/documents/dnr/2015OMNRFLakeErieStatusMajorStocks_522339_7.pdf [accessed 10 December 2020].

Pandit, S.N., Zhao, Y., Ciborowski, J.J.H., Gorman, A.M., and Knight, C. 2013. Suitable habitat model for walleye (*Sander vitreus*): implications for inter-jurisdictional harvest quota allocations in Lake Erie. J. Great Lakes Res. **39**: 591-601.

Pangle, K.L., Ludsin, S.A., and Fryer, B.J. 2010. Otolith microchemistry as a stock identification tool for freshwater fish: testing its limits in Lake Erie. Can. J. Fish. Aquat. Sci. **67**: 1475-1489.

PFBC (Pennsylvania Fish and Boat Commission). 2016. Lake Erie fisheries status and trends report 2015. Report to the Lake Erie Committee, March 2016. Pennsylvania Fish and Boat Commission, Lake Erie Research Unit, Fairview, PA.

Pflug, D.E., and Pauley, G.B. 1983. The movement and homing of smallmouth bass, *Micropterus dolomieu*, in Lake Sammamish, Washington. Calif. Fish Game **69**: 207-216.

Poste, A.E., Hecky, R.E., and Guildford, S.J. 2011. Evaluating microcystin exposure risk through fish consumption. Environ. Sci. Tech. **45**: 5806-5811.

Pritt, J.J., DuFour, M.R., Mayer, C.M., Roseman, E.F., and DeBruyne, R.L. 2014. Sampling little fish in big rivers: larval fish detection probabilities in two Lake Erie tributaries. Trans. Am. Fish. Soc. **143**: 1011-1027.

Pritt, J., Roseman, E.F., Ross, J.E., and DeBruyne, R.L. 2015. Using larval fish community structure to guide long-term monitoring of fish spawning activity. N. Am. J. Fish. Manage. **35**: 241-252.

Raby, G.D., Vandergoot, C.S., Hayden, T.A., Faust, M.D., Kraus, R.T., Dettmers, J.M., Cooke, S.J., Zhao, Y., Fisk, A.T., and one other. 2018. Does behavioural thermoregulation underlie seasonal movements in Lake Erie walleye? Can. J. Fish. Aquat. Sci. **75**: 488-496. https://doi.org/10.1139/cjfas-2017-0145.

Regier, H.A., and Hartman, W.L. 1973. Lake Erie's fish community: 150 years of cultural stresses. Science **180**: 1248-1255.

Reutter, J.M., Ciborowski, J., DePinto, J., Bade, D., Baker, D., Bridgeman, T.B., Culver, D.A., Davis, S., Dayton, E., and three others. 2011. Lake Erie nutrient loading and harmful algal blooms: research findings and management implications [online]. Available from https://www.ijc.org/sites/default/files/2018-09/June2011LakeErieNutrientLoadingAndHABSfinal.pdf [accessed 10 December 2020].

Richards, R.P., Baker, D.B., and Crumrine, J.P. 2009. Improved water quality in Ohio tributaries to Lake Erie: a consequence of conservation practices. J. Soil Water Conserv. **64**: 200-211.

Ridgway, M.S., and Shuter, B.J. 1996. Effects of displacement on the seasonal movements and home range characteristics of smallmouth bass in Lake Opeongo. N. Am. J. Fish. Manage. **16**: 371-377.

Ridgway, M.S., MacLean, J.A., and MacLeod, J.C. 1991. Nest-site fidelity in a centrarchid fish, the smallmouth bass (*Micropterus dolomieu*). Can. J. Zool. **69**: 3103-3105.

Roberts, J.J., Höök, T.O., Ludsin, S.A., Pothoven, S.A., Vanderploeg, H.A., and Brandt, S.B. 2009. Effects of hypolimnetic hypoxia on foraging and distributions of Lake Erie yellow perch. J. Exp. Mar. Biol. and Ecol. **381**: 132-142.

Roberts, J.J., Brandt, S.B., Fanslow, D., Ludsin, S.A., Pothoven, S.A., Scavia, D., and Höök, T.O. 2011. Effects of hypoxia on consumption, growth, and RNA:DNA ratios of young yellow perch. Trans. Am. Fish. Soc. **140**: 1574-1586.

Roseman, E.F., Manny, B., Boase, J., Child, M., Kennedy, G., Craig, J., Soper, K., and Drouin, R. 2011. Lake sturgeon response to a spawning reef constructed in the Detroit River. J. Appl. Ichthyol. **27**(s2): 66-76.

Roseman, E.F., Kennedy, G., Manny, B.A., Boase, J., and McFee, J. 2012. Life history characteristics of a recovering lake whitefish *Coregonus clupeaformis* stock in the Detroit River, North America. Adv. Limnol. **63**: 477-501.

Ross, J.E. 2013. A coastal monitoring program for a large lake fish community: the first step in capturing long-term trends and addressing evolving questions. M.Sc. thesis. Univ. Toledo, Toledo, OH.

Ross, J.E., Mayer, C.M., Tyson, J.T., and Weimer, E.J. 2016. Comparison of electrofishing techniques and effort allocation across diel time periods, seasons, sites, and habitat in the Ohio coastal waters of western Lake Erie. N. Am. J. Fish. Manage. **36**: 85-95.

Ryan, P.A., Knight, R., MacGregor, R., Towns, G., Hoopes, R., and Culligan, W. 2003. Fish-community goals and objectives for Lake Erie [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp03_2.pdf [accessed 10 December 2020].

Scavia, D., Allan, J.D., Arend, K.K., Bartell, S., Beletsky, D., Bosch, N.S., Brandt, S.B., Briland, R.D., Daloğlu, I., and 19 others. 2014. Assessing and addressing the re-eutrophication of Lake Erie: central basin hypoxia. J. Great Lakes Res. **40**: 226-246.

Schulz, S.L.W., Steinkoenig, E.L., and Brown, B.L. 2001. Ploidy of feral grass carp in the Chesapeake Bay watershed. N. Am. J. Fish. Manage. **21**: 96-101.

Sepulveda-Villet, O.J., and Stepien, C.A. 2011. Fine-scale population genetic structure of the yellow perch *Perca flavescens* in Lake Erie. Can. J. Fish. Aquat. Sci. **68**: 1-19.

Sepulveda-Villet, O.J., Ford, A.M., Williams, J.D., and Stepien, C.A. 2009. Population genetic diversity and phylogeographic divergence patterns of the yellow perch (*Perca flavescens*). J. Great Lakes Res. **35**: 107-119.

Stapanian, M.A., and Madenjian, C.P. 2007. Evidence that lake trout served as a buffer against sea lamprey predation on burbot in Lake Erie. N. Am. J. Fish. Manage. **27**: 238-245.

Stapanian, M.A., Madenjian, C.P., and Witzel, L.D. 2006. Evidence that sea lamprey control led to recovery of the burbot population in Lake Erie. Trans. Am. Fish. Soc. **135**: 1033-1043.

Stapanian, M.A., Witzel, L.D., and Cook, A. 2010a. Recruitment of burbot *Lota lota* in Lake Erie: an empirical modeling approach. Ecol. Freshw. Fish **19**: 326-337.

Stapanian, M.A., Paragamian, V.L., Madenjian, C.P., Jackson, J.R., Lappalainen, L., Evenson, M.J., and Neufeld, M.D. 2010b. World-wide status of burbot and conservation measures. Fish and Fisheries **11**: 34-56.

STC (Standing Technical Committee). 2007. Quota allocation strategies [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/STC_docs/other_reports_and_docs/Quota%20allocation%20strategies%20-%20LEC.pdf [accessed 10 December 2020].

Steinhart, G.B., Marschall, E.A., and Stein, R.A. 2004a. Round goby predation on smallmouth bass offspring in nests during simulated catch-and-release angling. Trans. Am. Fish. Soc. **133**: 121-131.

Steinhart, G.B., Stein, R.A., and Marschall, E.A. 2004b. High growth rate of young-of-the-year smallmouth bass in Lake Erie: a result of the round goby invasion? J. Great Lakes Res. **30**: 381-389.

Steinhart, G.B., Leonard, N.J., Stein, R.A., and Marschall, E.A. 2005. Effects of storms, angling, and nest predation during angling on smallmouth bass (*Micropterus dolomieu*) nest success. Can. J. Fish. Aquat. Sci. **62**: 2649-2660.

Stepien, C.A., and Faber, J.E. 1998. Population genetic structure, phylogeography and spawning philopatry in walleye (*Stizostedion vitreum*) from mitochondrial DNA control region sequences. Mol. Ecol. **7**: 1757-1769.

Stepien, C.A., Murphy, D.J., and Strange, R.M. 2007. Broad- to fine-scale population genetic patterning in the smallmouth bass *Micropterus dolomieu* across the Laurentian Great Lakes and beyond: An interplay of behaviour and geography. Mol. Ecol. **16**: 1605-1624.

Stepien, C.A., Murphy, D.J., Lohner, R.N., Haponski, A.E., and Sepulveda-Villet, O.J. 2010. Status and delineation of walleye (*Sander vitreus*) genetic stock structure across the Great Lakes, pp. 189-216. *In* Status of walleye in the Great Lakes: proceedings of the 2006 symposium. *Edited by* E. Roseman, P. Kocovsky, and C. Vandergoot [online]. Available from http://www.glfc.org/pubs/TechReports/Tr69.pdf [accessed 10 December 2020].

Stepien, C.A., Snyder, M.R., and Knight, C.T. 2018. Genetic divergence of nearby walleye spawning groups in central Lake Erie: implications for management. N. Am. J. Fish. Manage. **38**: 783-793.

Strange, R.M., and Stepien, C.A. 2007. Genetic divergence and connectivity among river and reef spawning groups of walleye (*Sander vitreus vitreus*) in Lake Erie. Can. J. Fish. Aquat. Sci. **64**: 437-448.

Strittholt, J.R., Guttman, S.I., and Wissing, T.E. 1988. Low levels of genetic variability of yellow perch (*Perca flavescens*) in Lake Erie and selected impoundments, pp. 246-257. *In* The biogeography of the island region of western Lake Erie. *Edited by* J.F. Downhower [online]. Available from THE_BIOGEOGRAPHY_OF_THE_ISLAND_REGION_OF_WESTERN_LAKE_ERIE.pdf (37.58Mb) [accessed 10 December 2020].

Sullivan, T.J., and Stepien, C.A. 2014. Genetic diversity and divergence of yellow perch spawning populations across the Huron-Erie Corridor, from Lake Huron through western Lake Erie. J. Great Lakes Res. **40**: 101-109.

Sweeny, R.A. 1993. "Dead" Sea of North America?–Lake Erie in the 1960s and '70s. J. Great Lakes Res. **19**: 198-1999.

Swink, W.D. 2003. Host selection and lethality of attacks by sea lampreys (*Petromyzon marinus*) in laboratory studies. J. Great Lakes Res. **29**(Suppl. 1): 307-319.

Sztramko, L. 2000. Lake Erie aerial creel survey, 1998. Lake Erie Management Unit, Ont. Min. Nat. Resour. Forest., Port Dover, ON, Canada.

Thomas, M.V., and Haas, R.C. 2002. Abundance, age structure, and spatial distribution of lake sturgeon, *Acipenser fulvescens*, in the St. Clair system. J. Appl. Ichthyol. **18**: 495-501.

Trautman, M.B. 1981. The fish of Ohio. The Ohio State Univ. Press, Columbus, OH. 782 pp.

Tyson, J.T. 2009. Progress toward habitat-related fish community objectives. *In* The state of Lake Erie in 2004, pp. 91-105. *Edited by* J.T. Tyson, R.A. Stein, and J.M. Dettmers [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp09_2.pdf [accessed 10 December 2020].

Tyson, J.T., Stein, R.A., and Dettmers, J.M. [EDS.]. 2009. The state of Lake Erie in 2004 [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp09_2.pdf [accessed 10 December 2020].

USEPA (U.S. Environmental Protection Agency). 2007. Niagara River toxics management plan (NRTMP) progress report and work plan [online]. Available from https://www.epa.gov/sites/production/files/2015-09/documents/progressreport2007.pdf [accessed 10 December 2020].

Vaccaro, L., Bennion, D., Boase, J., Bohling, M., Chiotti, J., Craig, J., Drouin, R., Fischer, J., Kennedy, G., and four others. 2016. Science in action: lessons learned from fish spawning habitat restoration in the St. Clair and Detroit Rivers [online]. Available from https://www.michiganseagrant.org/wp-content/uploads/2018/11/16-501-Reef-Projects-Lessons-Learned.pdf [accessed 10 December 2020].

Vandergoot, C.S., and Brenden, T.O. 2014. Spatially varying population demographics and fishery characteristics of Lake Erie Walleyes inferred from a long-term tag recovery study. Trans. Am. Fish. Soc. **143**: 188-204.

Vandergoot, C.S., Cook, H.A., Thomas, M.V., Einhouse, D.W., and Murray, C. 2010. Status of walleye in western Lake Erie, 1985-2006, pp. 123-150. *In* Status of walleye in the Great Lakes: proceedings of the 2006 symposium. *Edited by* E. Roseman, P. Kocovsky, and C. Vandergoot [online]. Available from http://www.glfc.org/pubs/TechReports/Tr69.pdf [accessed 10 December 2020].

Van Oosten, J., and Hile, R. 1947. Age and growth of the lake whitefish, *Coregonus clupeaformis* (Mitchill), in Lake Erie. Trans. Am. Fish. Soc. **77**: 178-249.

Wang, H., Rutherford, E.S., Cook, H.A., Einhouse, D.W., Haas, R.C., Johnson, T.B., Kenyon, R., Locke, B., and Turner, M.W. 2007. Movement of walleyes in Lake Erie and Lake St. Clair inferred from tag return and fisheries data. Trans. Am. Fish. Soc. **136**: 539-551.

Wolfert D.R., and Van Meter, H.D. 1978. Movements of walleyes tagged in eastern Lake Erie. NY Fish Game J. **25**: 16-22.

Wooster, M., and Matthies, L. 2008. Buffalo and Niagara Rivers habitat assessment and conservation framework [online]. Available from https://www.dec.ny.gov/docs/regions_pdf/bnrhabreport.pdf [accessed 10 December 2020].

WTG (Walleye Task Group). 2016. Report for 2015 by the Lake Erie Walleye Task Group [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/WTG_docs/annual_reports/WTG_report_2016.pdf [accessed 10 December 2020].

YPTG (Yellow Perch Task Group). 2016. Report of the Yellow Perch Task Group [online]. Available from http://www.glfc.org/pubs/lake_committees/erie/YPTG_docs/annual_reports/YPTG_report_2016.pdf [accessed 10 December 2020].

Zhao, Y., Einhouse, D.W., and MacDougall, T.M. 2011. Resolving some of the complexity of a mixed origin Walleye population in the eastern basin of Lake Erie using a mark-recapture study. N. Am. J. Fish. Manage. **31**: 379-389.

Zhou, Y., Obenour, D.R., Scavia, D., Johengen, T.H., and Michalak, A.M. 2013. Spatial and temporal trends in Lake Erie hypoxia, 1987-2007. Environ. Sci. Tech. **47**: 899-905.

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