THE STATE OF LAKE HURON IN 2018

SPECIAL PUBLICATION 2020-01

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THE STATE OF LAKE HURON IN 2018

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Frontispiece. Map of Lake Huron showing major geographical features and statistical districts. The main basin of Lake Huron is waters outside of the North Channel and Georgian Bay.

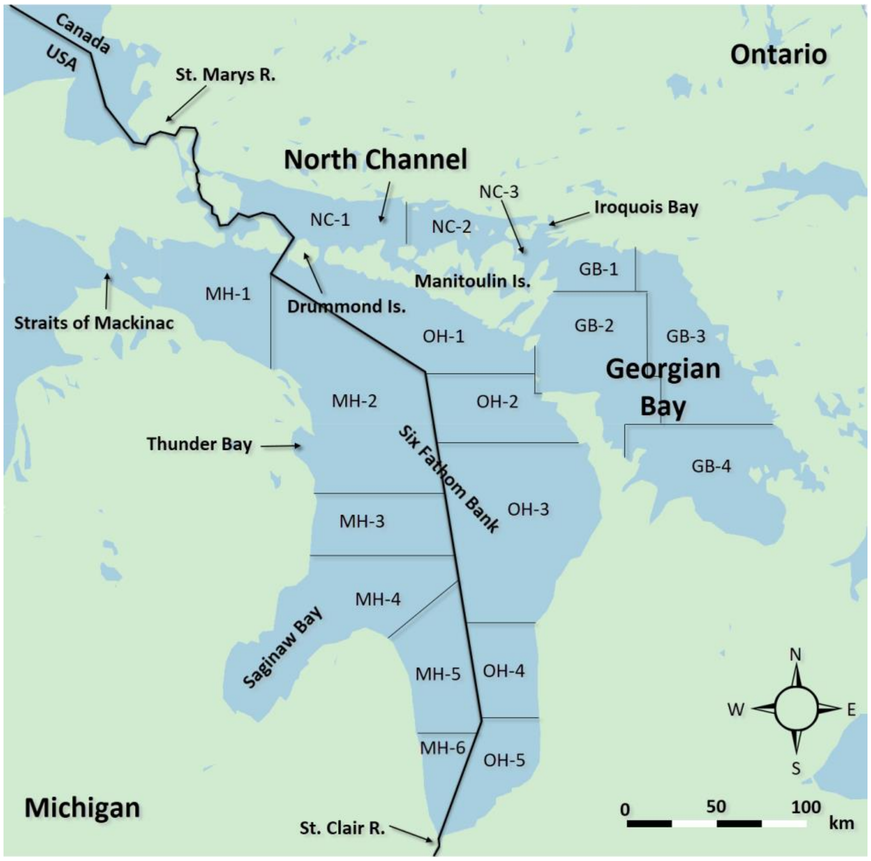

TABLE OF CONTENTS

ABSTRACT[3]

Fish community objectives (FCOs) that envisioned the future state of fish populations and aquatic habitats in Lake Huron were developed in the mid-1990s to promote ecosystem recovery from the profound ecological disturbances that occurred in the 19th and 20th centuries. More recently, new invasive species, including the spiny water flea (*Bythotrephes longimanus*), zebra and quagga mussels (*Dreissena* spp.), and Round Goby (*Neogobius melanostomus*), have had profound ecological effects on the fish community. This report summarizes recent changes in the ecology of Lake Huron during the most-recent reporting period (2011-2017) and describes the current state of the fish communities in relation to the FCOs. Offshore phosphorus levels increased during the current reporting period from the low levels observed in the previous period but may remain low enough to limit zooplankton production. Chlorophyll concentrations appear to have stabilized while Secchi depth and silica concentrations have continued to increase. The biovolume of spring phytoplankton has remained low but stable over the past two reporting periods from 2005 to 2017. The biomass of crustacean zooplankton has remained low since a major decline in the early 2000s but was elevated somewhat near the end of the last reporting period (2010) and early in the current period (2012). Changes in the community structure of zooplankton first observed in 2004 have persisted. The density of the native amphipod *Diporeia* spp. has remained very low, particularly at sites less than 90 m. Quagga mussel density in offshore waters

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[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/Sp20_01.pdf.

has continued to increase during the reporting period. The biomass of offshore prey fish has remained relatively low in this reporting period, with Alewife (*Alosa pseudoharengus*) biomass at very low levels and Rainbow Smelt (*Osmerus mordax*) biomass continuing to decline beyond the already relatively low levels observed in 2010. The biomass of Bloater (*Coregonus hoyi*), however, was higher in this reporting period than in the previous period. The mean total lakewide biomass of offshore prey fish in Lake Huron was 35% higher in the current reporting period (14.1 kg•ha^{-1}) than in the previous period (10.5 kg•ha^{-1}) but remains low compared to historical data. The index of total prey-fish biomass in 2017 was the second-lowest observed in the time series. The mean total commercial harvest of all fish species for the current reporting period was 3.5 million kg, 28.3% less than in the previous reporting period (4.9 million kg) and 60.5% below the overarching FCO. Yields of Lake Whitefish (*C. clupeaformis*) and other coregonines continued to decline during the current reporting period and remain below the productive potential envisioned in the FCOs. Declines in Lake Whitefish yield were most evident in the northern and central main basin and were due to large reductions in reproduction, recruitment, and fishing effort. Cisco (*C. artedi*) remains relatively abundant in northern areas of the lake, and a multi-agency program to rehabilitate its population is scheduled to begin in 2018. Natural reproduction and recruitment of wild Lake Trout (*Salvelinus namaycush*) have been observed since 2004 and were sustained throughout the current reporting period. Wild adult Lake Trout continues to make up large proportions of fishery and survey catches in the northern main basin and North Channel but are less prevalent in the southern main basin and Georgian Bay. Wild recruits of the Seneca strain dominated the assessment catch, suggesting this strain may be particularly suited to current conditions in the lake. Estimated survival of stocked Lake Trout declined just before the previous reporting period, and low survival has continued throughout the current period. While there are positive signs of Lake Trout rehabilitation, yield levels remain below the FCOs. Adult Sea Lamprey (*Petromyzon marinus*) abundance in 2015 was the lowest in the time series and was below the management target maximum for the first time in over 30 years. The index of adult abundance during the current reporting period was 16% lower than in the previous period but has increased in this reporting period and remains near the target. The Sea Lamprey marking rate on adult Lake Trout also declined to below the target maximum during the reporting period, and the marking rate in 2017 was the lowest observed in the time series. Reduced Sea Lamprey abundance is likely due to increased control effort in large tributaries, particularly those associated with the St. Marys River and North Channel. Chinook Salmon (*Oncorhynchus tshawytscha*) abundance has been in decline since the 1980s, but growth and condition have increased since the last reporting period, and harvest remains low compared to earlier time periods. Most Chinook Salmon are now naturally produced, as the early survival of stocked fish has decreased substantially. Steelhead (*O. mykiss*), Brown Trout (*Salmo trutta*), Coho Salmon (*O. kisutch*), Pink Salmon (*O. gorbuscha*), and Atlantic Salmon (*S. salar*) continue to support recreational fisheries throughout the lake, although angling effort has declined since the early 2000s. Walleye (*Sander vitreus*) yield was reduced compared to the previous reporting period and is less than the productive potential envisioned in the FCO. Yield of Yellow Perch (*Perca flavescens*) was similar in this and previous reporting periods, remains below the FCO, and recruitment may be limited by predation from Walleye and Double-crested Cormorants (*Phalacrocorax auritus*). Populations of Lake Sturgeon (*Acipenser fulvescens*), Northern Pike (*Esox lucius*), and Muskellunge (*E. masquinongy*) appear to be stable in most parts of the lake, and natural reproduction of Northern Pike and Muskellunge may have improved due to higher water levels observed during the current reporting period. Smallmouth Bass (*Micropterus dolomieu*) populations appear to be increasing in several areas of the lake while Channel Catfish (*Ictalurus punctatus*) populations appear to be stable. Although some encouraging signs of progress in the Lake Huron ecosystem are evident, most FCOs remained unmet as of 2017. Many large-scale changes in the ecology of the lake indicate that an ecosystem regime shift has occurred. Whether the lake has achieved a new stable state or remains in a state of flux remains uncertain. In recognition of this shift, the Lake Huron Technical Committee recommended that the FCOs be revisited to ensure that they remain relevant to an altered ecosystem.

INTRODUCTION TO THE STATE OF LAKE HURON IN 2018[4]

Mark P. Ebener[5] and Stephen C. Riley

The 1998 revision to *A Joint Strategic Plan for the Management of Great Lakes Fisheries* (Joint Plan) (GLFC 2007) provides for cooperative management of fisheries among state, provincial, and tribal agencies through information sharing, consensus building, strategic planning, and commitments to ecosystem-based management. The lake committees are the action arm of the Joint Plan, and they coordinate management, set fish-stocking rates, establish harvest limits, coordinate law enforcement, and, most importantly for this report, set objectives that envision the future state of the fish community and habitat.

The Lake Huron Committee (LHC), composed of fishery managers from the Michigan Department of Natural Resources, the Ontario Ministry of Natural Resources and Forestry, and the Chippewa Ottawa Resource Authority, established fish community objectives (FCOs) for Lake Huron (DesJardine et al. 1995). These FCOs are intended to define desirable structures for fish communities and to provide a means for measuring progress toward their achievement. The LHC has charged the Lake Huron Technical Committee with producing state of the lake reports that document progress, typically every five years. This state of the lake report describes the status of Lake Huron's fish communities during the current reporting period of 2011 to

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[4] Complete publication including maps of place names, abstract, other chapters, scientific fish names and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp20_01.pdf.

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2017, evaluates progress toward achieving the FCOs, and identifies impediments to achievement of the FCOs as well as new and emerging issues affecting management. This fifth state of the lake report builds upon descriptions of the lake and its history presented in previous reports (Ebener 1995; Ebener 2005; Bence and Mohr 2008; Riley 2013).

Lake Huron and Its Fisheries

Lake Huron is the second largest of the Laurentian Great Lakes and is mostly oligotrophic, except for Saginaw Bay and some nearshore areas. The lake has a deep main basin that includes the much-shallower Saginaw Bay and two semi-isolated basins, Georgian Bay and the North Channel. Georgian Bay is also largely oligotrophic, except in southeast waters while the North Channel is more mesotrophic. Each basin is subdivided into statistical districts for reporting and management. Basin morphometry, hydrology, geology, and limnology were summarized in DesJardine et al. (1995) and Ebener (1995). The St. Marys River is a connecting channel from Lake Superior to the North Channel and the main basin while water from Lake Michigan enters Lake Huron through the Straits of Mackinac. The St. Clair and Detroit Rivers connect Lake Huron with Lakes Erie and Ontario. Although the human population of the basin is low compared to three of the other four Great Lakes, it is a prime destination for fishing, boating, and other recreational activities.

Prior to the 1950s, the Lake Trout (see Table 1 for an alphabetical list of common fish names and their corresponding scientific names) was the dominant predator in the lake, and Walleye and Burbot were subdominant. The prey community was dominated by Cisco, sculpins, and deepwater ciscoes. Round Whitefish, Lake Whitefish, and Ninespine Stickleback were also abundant. The structure and function of fish communities began to change in the late 1800s and became radically altered by 1960 through invasions of Sea Lamprey, Alewife, and Rainbow Smelt, overexploitation of important species, and habitat degradation in nearshore areas and tributaries (Berst and Spangler 1973). A new wave of invasive species, including the spiny water flea (*Bythotrephes longimanus*), dreissenids, and Round Goby, have further affected fish communities since approximately the mid-1980s.

Table 1. Common and scientific names of fish species (updated from Nelson et al. 2004) referenced in this report. A single asterisk (*) indicates the species is imperiled or endangered, and double asterisks (**) indicate the species is considered extirpated from Lake Huron.

Common Name	Scientific Name
Native species (cold water):	
Blackfin Cisco**	*Coregonus nigripinnis*
Bloater	*C. hoyi*
Burbot	*Lota lota*
Cisco (formerly Lake Herring)	*C. artedi*
Deepwater Cisco**	*C. johannae*
Deepwater Sculpin	*Myoxocephalus thompsonii*
Kiyi**	*C. kiyi*
Lake Trout	*Salvelinus namaycush*
Lake Whitefish	*C. clupeaformis*
Longjaw Cisco**	*C. alpenae*
Round Whitefish	*Prosopium cylindraceum*
Shortjaw Cisco*	*C. zenithicus*
Shortnose Cisco**	*C. reighardi*
Native species (cool water):	
Emerald Shiner	*Notropis atherinoides*
Lake Sturgeon	*Acipenser fulvescens*
Muskellunge	*Esox masquinongy*
Northern Pike	*E. lucius*
Ninespine Stickleback	*Pungitius pungitius*
Slimy Sculpin	*Cottus cognatus*

Common Name	***Scientific Name***
Smallmouth Bass	*Micropterus dolomieu*
Trout-Perch	*Percopis omiscomaycus*
Walleye	*Sander vitreus*
Yellow Perch	*Perca flavescens*
Native species (warm water):	
Black Crappie	*Pomoxis nigromaculatus*
Bluegill	*Lepomis macrochirus*
Channel Catfish	*Ictalurus punctatus*
Largemouth Bass	*Micropterus salmoides*
Pumpkinseed	*Lepomis gibbosus*
Rock Bass	*Ambloplites rupestri*
White Sucker	*Catostomus commersoni*
Non-native species (cold water):	
Atlantic Salmon	*Salmo salar*
Brown Trout	*Salmo trutta*
Chinook Salmon	*Oncorhynchus tshawytscha*
Coho Salmon	*O. kisutch*
Pink Salmon	*O. gorbuscha*
Rainbow Smelt	*Osmerus mordax*
Rainbow Trout (steelhead)	*Oncorhynchus mykiss*
Round Goby	*Neogobius melanostomus*
Sea Lamprey	*Petromyzon marinus*
Steelhead (Rainbow Trout)	*Oncorhynchus mykiss*

Common Name	Scientific Name
Non-native species (cool water):	
Alewife	*Alosa pseudoharengus*
Chain Pickerel	*Esox niger*
Ruffe	*Gymnocephalus cernuus*
Threespine Stickleback	*Gasterosteus aculeatus*
Tubenose Goby	*Proterorhinus marmoratus*
Non-native species (warm water):	
Bighead Carp	*Hypophthalmichthys nobilis*
Grass Carp	*Ctenopharyngodon idella*
Rudd	*Scardinius erythropthalmus*
Silver Carp	*H. molitrix*

The commercial fishery operates in all three basins and is composed of state, provincial and indigenous fisheries. The main basin produces approximately 84% of the total commercial yield followed by Georgian Bay (10%) and the North Channel (6%). Ontario commercial fisheries account for approximately 60% of the total lakewide commercial yield. In response to a negotiated settlement between Chippewa and Ottawa tribes, the state of Michigan, and the U.S. federal government, gillnet effort in Michigan waters of the northern main basin was reduced by 3.4 million m (11 million ft) beginning in 1999, and a number of gillnet operations converted to trapnets. Furthermore, the settlement led to annual limits or yield guidelines established for Lake Trout and Lake Whitefish in U.S. waters (Lenart and Caroffino 2018); yield limits already existed in Canadian waters. The commercial fishery uses primarily large- and small-mesh gillnets and trapnets to harvest fish (see Ebener et al. 2008a, b). Coregonines, especially Lake Whitefish, continue to dominate commercial yield followed in importance by Lake Trout, with much-smaller yields of Yellow Perch, Walleye, Round Whitefish, and Cisco.

Although most recreational fisheries remain concentrated within 10-15 km of ports, bigger and safer boats have made the whole basin and shoreline accessible to recreational fishing. Recreational fisheries operate in offshore and nearshore areas, tributaries, and off piers throughout Lake Huron. Chinook Salmon, Lake Trout, Yellow Perch, and Walleye make up most of the recreational yield. A popular offshore fishery developed in the 1960s following the introduction of Coho and Chinook Salmon by the state of Michigan, and this fishery now also targets Lake Trout and Rainbow Trout (steelhead). Nearshore recreational fisheries have traditionally accounted for more than half of the recreational-fishing effort in Michigan waters (Fielder et al. 2002). Eastern and southern Georgian Bay, Saginaw Bay, the St. Marys River, the North Channel, and waters adjacent to river mouths are important nearshore fishing areas for prominent species, including Yellow Perch, Walleye, Smallmouth Bass, Cisco, Lake Whitefish, and steelhead. Major recreational fisheries for Walleye redeveloped in Saginaw Bay following initiation of a stocking program in 1972.

Fish Community Objectives

The overarching management objective for Lake Huron was to restore over the next two decades an ecologically balanced and self-sustaining fish community dominated by top predators and capable of sustaining combined commercial and sport yields of 8.9 million kg annually (DesJardine et al. 1995). During 1912-1940, the average commercial yield was 8.9 million kg, appeared stable, and was assumed to be the best measure of the lake's long-term potential yield (DesJardine et al. 1995). Yields included only commercial catches until 1986 when Michigan began to report recreational yield. From 1972 to 1999, total reported fishery yields increased substantially from a low of 2.0 million kg to more than 6.3 million kg. During the current reporting period (2011-2017), the commercial harvest of all species averaged 3.5 million kg. If recreational yield is assumed to comprise 25% of the total yield (Bence et al. 2008), then total yield in this reporting period roughly approximated 4.9 million kg, which is 11% lower than in the previous (2005-2010) reporting period and 45% below the FCO. This estimate of total yield is likely biased high because the recreational salmonine fishery was much reduced in the current reporting period (see Borgeson et al., this volume).

Besides the overarching FCO, there are 12 specific FCOs that address individual species, aggregations of species, species diversity, and habitat (DesJardine et al. 1995). Yield-based FCOs were established for salmonine predators, percids, coregonines, esocids, and Channel Catfish, and, like the overall objective, they are based partially or wholly on historical commercial yields, which were viewed as the best measure of Lake Huron's productivity. The yield levels for these FCOs are

- Coregonines: 3.8 million kg Lake Whitefish and Cisco
- Salmonine predators: 2.4 million kg all species, Lake Trout dominant
- Percids: 1.2 million kg (0.7 Walleye and 0.5 Yellow Perch)
- Channel Catfish: 0.2 million kg
- Esocids: 0.1 million kg (Northern Pike and Muskellunge)

The yield-based objectives for salmonine predators, esocids, Channel Catfish, and Yellow Perch are defined as sustainable levels while the objectives for Walleye and for Lake Whitefish and Cisco are defined in terms of having population biomass levels capable of supporting the yield objective. These are important distinctions when evaluating if the FCO has been achieved. Sustainable implies that the observed level of yield can occur each year without affecting abundance or biomass and that the habitat remains suitable to meet the objective. Alternatively, "capable of achieving a given level of yield" implies that, even if the yield objective is not attained, the FCO could be achieved based on the total biomass of the fishable population. The salmonine yield objective is assumed to occur after Lake Trout populations are deemed rehabilitated because, during the rehabilitation, management actions will restrict fishery yields (DesJardine et al. 1995).

Species diversity is a basic premise for many of the FCOs. The species diversity objective seeks to recognize and protect the array of indigenous species in Lake Huron. The genetic diversity objective calls for promoting and protecting locally adapted strains and stocking strains that are matched to the environment they are to inhabit (DesJardine et al. 1995). The salmonine predator, coregonine, and prey-fish objectives all seek to maintain a diversity of species.

Protection of endangered or rare species is also a key component of the FCOs. The coregonine objective calls for restoring historically abundant populations of Cisco and for protecting rare deepwater ciscoes (*C. reighardi*). The Lake Sturgeon objective aims at restoring its abundance to levels allowing for removal from threatened-species status in Michigan waters and for rehabilitated populations in Canadian waters (DesJardine et al. 1995).

Suppression of Sea Lamprey populations is integral to achievement of many FCOs (DesJardine et al. 1995). The related FCO is to suppress abundance by 75% by 2000 and 90% by 2010 from the peak levels observed in the 1980s and early 1990s because, for many years, there was more Sea Lamprey in Lake Huron than in all the other Great Lakes combined (see Mullet et al. 2003). Further, its predation truncated the age structure and reduced the abundance of Lake Trout, Lake Whitefish, Burbot, and probably other species (Morse et al. 2003; Dobiesz et al. 2005; Stapanian et al. 2008; Ebener et al. 2010b). Chemical control of larval Sea Lamprey populations in the St. Marys River and other large tributaries to the North Channel has been successful in reducing abundance lakewide (Nowicki and Sullivan, this volume), but continued suppression of populations will be required for the foreseeable future.

Lastly, FCOs recognize that fish and their habitats are interconnected, and thus ecosystem-level management will be required to achieve FCOs (DesJardine et al. 1995). The habitat FCO seeks to

- Protect and enhance existing habitat
- Rehabilitate degraded habitats
- Achieve no net loss of the productivity of habitats
- Restore damaged habitat
- Reduce or eliminate contaminants

Most of the in-lake habitat is intact while the most-severe habitat loss and degradation occurred in tributaries, Saginaw Bay, and protected embayments, where issues include excessive nutrients, contaminated sediments, aquatic invasive species, and dams, which block spawning migrations and result in overly warm waters (ECCC and USEPA 2017). While chemical-contaminant levels have declined in fish, they are still high enough to warrant fish-consumption advisories. Overall, habitat was rated "fair" in the most-recent Lakewide Action and Management Plan (ECCC and USEPA 2018).

We have taken a bottom-up approach in this state of the lake report, which describes the status of the fish community and habitat during the current reporting period (2011-2017) and compares it to that of the previous reporting period (2005-2010). We begin with the status of lower trophic levels then proceed to the offshore demersal fish community, whitefishes and ciscoes, Lake Trout, Sea Lamprey, introduced salmonines, nearshore fish communities, species and genetic diversity, and habitat. This report ends with emerging management issues that may prevent achievement of the FCOs.

STATUS OF LOWER TROPHIC LEVELS IN LAKE HURON IN 2018[6]

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Introduction

There is no specific fish community objective for lower trophic levels in Lake Huron, but DesJardine et al. (1995) called for the prey-fish community objective to be matched to primary production at lower trophic levels. Thus there is considerable interest in the status of lower trophic-level production and how dynamics of the lower food web affect fish production in Lake Huron, particularly because of the collapse of Alewife populations and the subsequent decline in Chinook Salmon in the lake (Riley et al. 2008). The degree to which declines in lower trophic-level production were important in

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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/Sp20_01.pdf.

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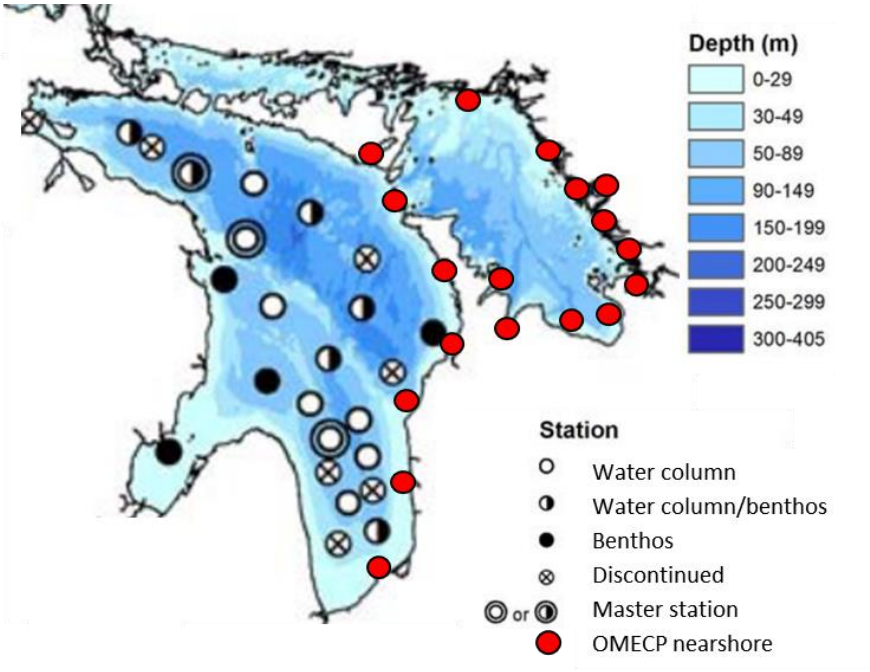
the Alewife collapse (suggested by Barbiero et al. 2011; Bunnell et al. 2014) is an open question. Other researchers believe it was caused by increased predation by Pacific Salmon (He et al. 2015; Bence et al. 2016), high overwinter mortality during 2003-2004 (Dunlop and Riley 2013; Riley and Dunlop 2016), and combinations of these mechanisms (Riley et al. 2008; Kao et al. 2016). Here we provide a compilation of the information on lower trophic levels with a focus on offshore data for the two most-recent reporting periods (2005-2010 and 2011-2017). This information is essential for evaluating the likelihood of the various proposed mechanisms. We also review the changes that have occurred in the lake since 1983, 1997, or 2001 depending on the variable, and speculate on the changes that have occurred over the past several decades. Much of this information has been presented in recent publications (Barbiero et al. 2018b; Burlakova et al. 2018a, b, c; Kovalenko et al. 2018; Jude et al. 2018; Reavie et al. 2014; Sgro and Reavie 2018), and we refer the reader to those sources for a more-detailed account of methods and analyses.

Lake Huron is the second largest of the Great Lakes by area, the third largest by volume, and perhaps the most complex of the Laurentian Great Lakes. It has three distinct basins: the main basin (which includes Saginaw Bay), the North Channel, and Georgian Bay (see Frontispiece). Lake Huron has been part of several Canadian and U.S. sampling efforts since the mid-1900s. The Great Lakes National Program Office (GLNPO) of the U.S. Environmental Protection Agency (EPA) has measured nutrients, zooplankton, phytoplankton, benthos, and *Mysis diluviana* (hereafter, *Mysis*) in the offshore waters of the main basin since 1983 (Barbiero et al. 2018a). For this chapter, we combined the north and south part of the main basin for most of the variables. Lake Huron was also sampled in 2007, 2012, and 2017 as part of the Cooperative Science and Monitoring Initiative. Additional comparisons of the years 2009 and 2015 were made through Ontario Ministry of Environment, Conservation and Parks, which performed sampling at 18 standard sites along the Canadian shoreline of the main basin and Georgian Bay (Fig. 1).

Fig. 1. Map of Lake Huron showing the Great Lakes National Program Office sampling sites in 2007, 2011, and 2017 (all dots not red) and Ontario Ministry of Environment, Conservation and Parks (OMECP) sampling sites in 2009 and 2015 (red dots). Symbols indicate type of sampling at each site. Revised from Barbiero et al. (2018a).



Nutrients and Water Clarity

Nutrients, in particular phosphorus (P), limit primary production in most freshwater lakes (Guildford and Hecky 2000). Although nitrogen (N) and silica (Si) can also limit primary production, these nutrients are less limiting in the Laurentian Great Lakes (Chapra and Dolan 2012); consequently, nutrient-loading goals outlined in the Great Lakes Water Quality Agreement (GLWQA) (https://binational.net/2012/09/05/2012-glwqa-aqegl/) are primarily related to P (ECCC and USEPA 2018). In Lake Huron, N has remained relatively stable, Si has increased, and P has declined in the last 20 years (Barbiero et al. 2018b), making the offshore waters increasingly P limited (Dove and Chapra 2015). Therefore, total phosphorus (TP), and in particular spring TP, are likely good indicators of productivity and have been widely used as an index of lake trophic level (Carlson 1977).

Spring TP increased from 2.0 µg•L^{-1} during the previous reporting period to 2.7 µg•L^{-1} during the present reporting period, although there was an overall decline from 1983 through 2017 (Table 2; Fig. 2). There was no increase in spring TP from 2009 to 2015 at the nearshore Canadian stations (Fig. 1) where the average concentration was about 4.0 µg•L^{-1} (Table 2). The long-term decline in spring TP is expected based on declines in P loading following the implementation of the GLWQA (ECCC and USEPA 2018). However, the decline was faster than expected from declining P loading alone through 2010, and Barbiero et al. (2018b) suggested that this faster decline was associated with an increase in nearshore dreissenid biomass, with P either being intercepted by nearshore mussels (Hecky et al. 2004; Cha et al. 2011) or incorporated into the increasing mussel biomass and removed from the water column. If intercepted by nearshore mussels, TP should increase if nearshore mussel biomass declines, as observed for mussels in water less than 50 m (see below). The small increase in TP in Lake Huron in recent years in the GLNPO data may support this mechanism, but there was no increase in the Canadian nearshore data. In any case, TP in Lake Huron is the same as or lower than levels in Lakes Superior and Michigan and is indicative of ultra-oligotrophic conditions.

Table 2. Least square means for various lower trophic-level measures for the previous (2005-2010) and present (2011-2017) reporting periods. Significant differences (see *P* value) between the two reporting periods are based on a mixed-model analysis of variance, with station as the random effect and time period as the fixed effect. If a change-point year is given, it was detected in the data series with 95% confidence. Years in parenthesis indicate the 95% confidence interval for that change-point year. Change-point analysis is based on the whole data set from 1983 for total phosphorus (TP), total dissolved phosphorus (TDP), dissolved reactive silica (Si), and Secchi depth; from 1998

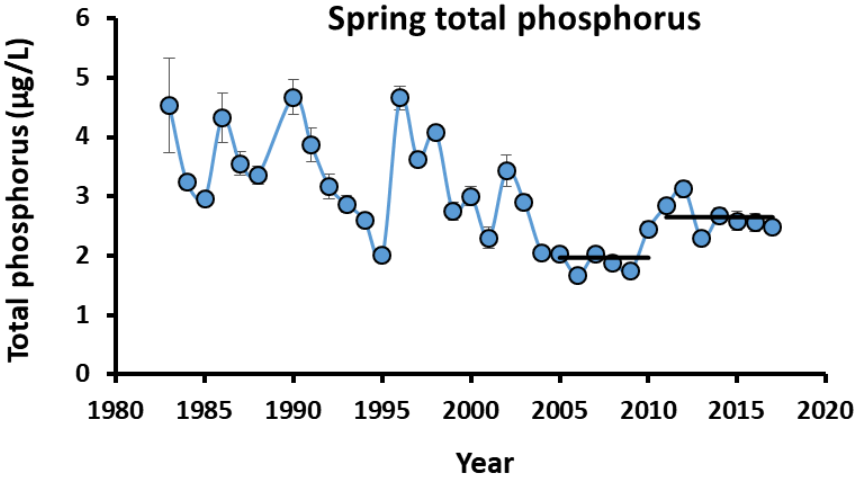
for satellite-derived chlorophyll (SatChl); from 2001 for phytoplankton; from 1997 for zooplankton; from 1998 for *Diporeia* spp. (*Diporeia*); and from 2006 for *Mysis diluviana* (*Mysis*). Significantly higher values are in bold, NS is not significant, GB is Georgian Bay, MB is main basin, GLNPO refers to the EPA offshore monitoring program, and None indicates that no change point was detected. Canada refers to the Canadian nearshore stations, and the analyses for those data compare 2009 with 2015. No change-point analysis was possible on the Canadian data. The Canadian chlorophyll data is from surface-water samples (Chl). Comparisons for *Diporeia* spp. are based on 4th root transformed values.

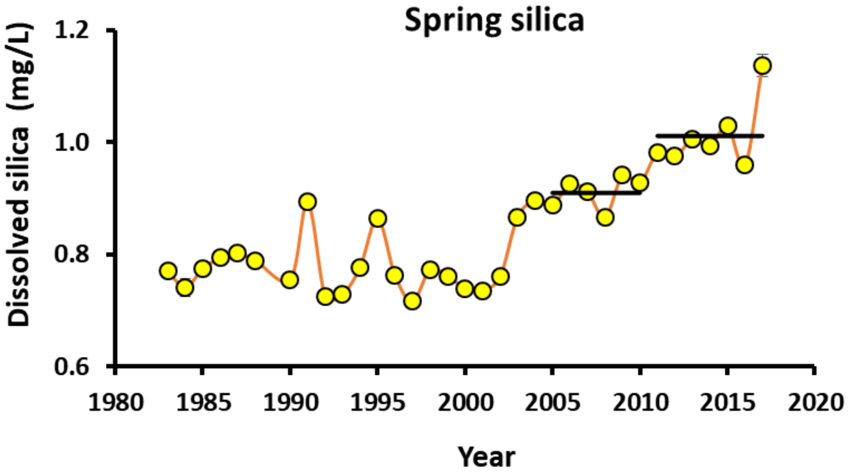
Attribute	2005 to 2010	2011 to 2017	*P*	Change-Point Year
Spring TP GLNPO (μg•L^{-1})	2.0	**2.7**	<0.000	2004 (2000-2004) 2010 (2010-2010)
Spring TP Canada (μg•L^{-1})	4.4	4.1	NS	
Spring TDP GLNPO (μg•L^{-1})	1.2	**1.6**	<0.000	None
Spring Si GLNPO (μg•L^{-1})	0.91	**1.01**	<0.000	2003 (2001-2003) 2011 (2011-2012)
Spring Si Canada (μg•L^{-1})	0.96	**1.04**	0.0343	
Spring Secchi GLNPO (m)	14.6	**18.3**	<0.000	1987 (1985-2004) 2005 (2005-2005)
Spring Secchi Canada (m)	7.7	**11.2**	0.009	
Summer Secchi GLNPO (m)	14.6	15.7	NS	1998 (1996-2000)
Summer Secchi Canada (m)	8.3	7.1	0.003	
Annual SatChl GB (μg•L^{-1})	1.25	1.66	NS	None
Annual SatChl MB (μg•L^{-1})	0.61	0.62	NS	2005 (2005-2005)
Spring SatChl GB (μg•L^{-1})	1.12	1.39	NS	2015 (2014-2017)
Spring SatChl MB (μg•L^{-1})	**0.67**	0.58	0.011	2003 (2003-2003) 2007 (2007-2007)
Summer SatChl GB (μg•L^{-1})	1.28	1.4	NS	None
Summer SatChl MB (μg•L^{-1})	0.47	0.51	NS	2005 (2004-2006)
Summer Chl Canada (μg•L^{-1})	**1.9**	1.6	0.009	
Fall SatChl GB (μg•L^{-1})	1.41	**2.27**	0.048	2013 (2012-2013)
Fall SatChl MB (μg•L^{-1})	0.76	0.82	NS	2005 (2001-2007)

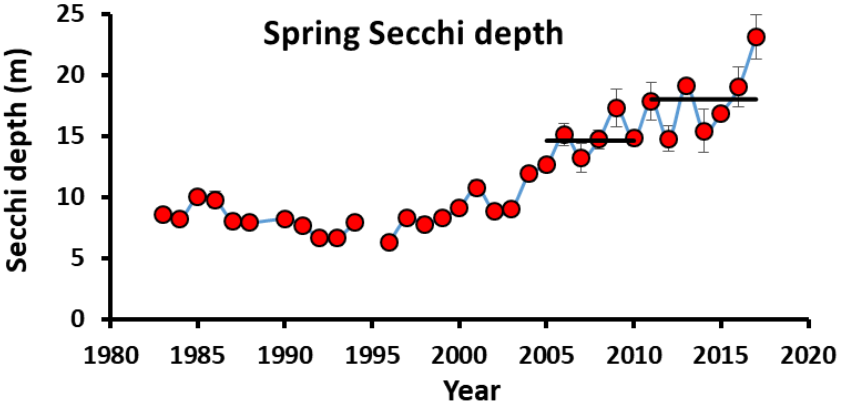
Attribute	2005 to 2010	2011 to 2017	*P*	Change-Point Year
Spring phytoplankton (mm^3•L^{-1})	**0.073**	0.048	0.011	None
Spring diatoms (mm^3•L^{-1})	**0.035**	0.023	0.002	None
Spring cyanophytes (mm^3•L^{-1})	0.013	0.002	NS	None
Spring dinoflagellates (mm^3•L^{-1})	0.003	0.004	NS	2002 (2002-2005)
Spring cryptophytes (mm^3•L^{-1})	0.009	0.010	NS	None
Spring chrysophytes (mm^3•L^{-1})	**0.011**	0.006	0.007	2008 (2008-2016)
Summer phytoplankton (mm^3•L^{-1})	0.140	0.131	NS	None
Summer diatoms (mm^3•L^{-1})	0.054	0.043	NS	None
Summer cyanophytes (mm^3•L^{-1})	0.017	0.015	NS	None
Summer dinoflagellates (mm^3•L^{1})	0.029	0.035	NS	None
Summer cryptophytes (mm^3•L^{-1})	0.005	0.007	NS	None
Summer chrysophytes (mm^3•L^{-1})	0.029	0.030	NS	2007 (2007-2011)
Spring zooplankton (mg•m^2)	814	**962**	0.002	2004 (2004-2004)
Spring calanoid (mg•m^2)	617	**767**	<0.000	2004 (2004-2005)
Spring *Limnocalanus* (mg•m^2)	109	88	0.053	None
Spring cyclopoid (mg•·m^2)	71	103	0.002	2005 (2003-2009) 2014 (2008-2014)
Summer zooplankton (mg•m^2)	1,740	1,782	NS	2003 (2001-2003)
Summer calanoid (mg•m^2)	913	**1085**	0.004	2003 (1998-2003)
Summer *Limnocalanus* (mg•m^2)	**547**	403	0.002	None
Summer cyclopoid (mg•m^2)	53	**74**	0.008	2004 (2002-2004)
Summer bosminid (mg•m^2)	18	26	NS	2003 (1999-2003)
Summer daphniid (mg•m^2)	118	135	NS	2003 (2001-2003)
Summer *Bythotrephes* (mg•m^2)	25	**34**	0.026	2003 (2001-2003)

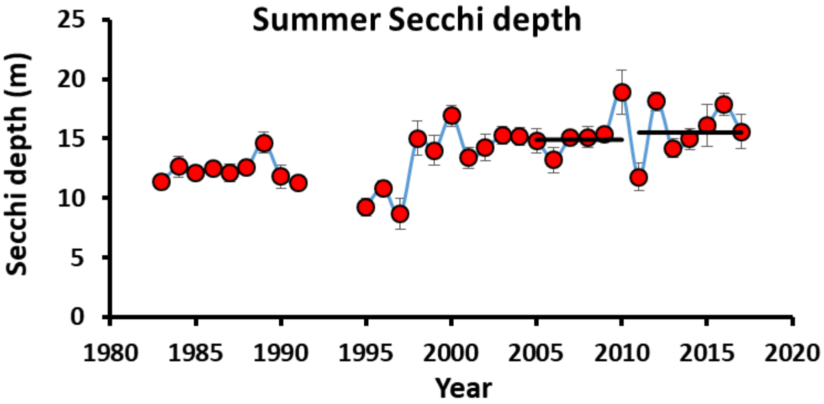
Attribute	2005 to 2010	2011 to 2017	*P*	Change-Point Year
Spring *Mysis* (number•m^2)	**17**	10	0.050	None
Summer *Mysis* (number•m^2)	40	38	NS	None
Diporeia <90 m (number•m^2)	**38**	2	0.031	Violates assumptions
Diporeia >90 m (number•m^2)	399	338	NS	2004 (2002-2004)

Fig. 2. Changes in total phosphorus, dissolved silica, and Secchi depth in Lake Huron from 1983 to 2017. Data from the main basin obtained from Great Lakes National Program Office surveys. Horizontal lines indicate average for the period 2005-2010 and 2011-2017. Error bars represent +/- 1 standard error but some are too small to be visible in all years.




Spring silica
Dissolved silica (mg/L)
1.2
1.0
0.8
0.6
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year


Spring Secchi depth
Secchi depth (m)
25
20
15
10
5
0
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year



Silica concentrations have increased since the early 2000s, and there was a further significant increase from 0.9 mg•L^{-1} in the previous reporting period to 1.0 mg•L^{-1} in the present reporting period in both the GLNPO and Canadian data (Table 2; Fig. 2). Such an increase in Si is expected when diatoms become less abundant because they use Si to make their frustules (Mida et al. 2010; Evans et al. 2011). Increased Si is also to be expected if diatom concentrations in the deep chlorophyll layer (DCL) have declined, which has been observed (see below).

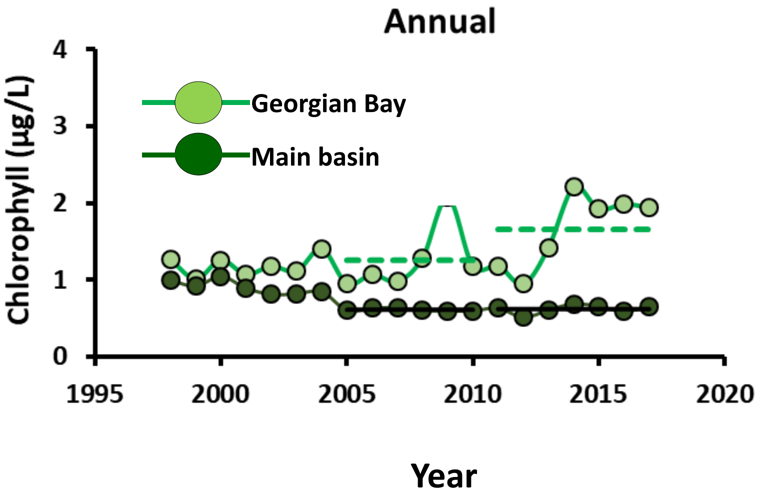
Spring Secchi depths have increased in Lake Huron since the mid-1990s, and water clarity was higher in the present reporting period than in any previous period on record (Table 2; Fig. 2). Spring values averaged 23 m in the main basin in 2017, reflecting highly oligotrophic conditions. In the Canadian nearshore sites, spring Secchi depths increased from 7.7 m in 2009 to 11.2 m in 2015. However, the increase in water clarity is higher because the 2015 value is biased low as the Secchi depth was on the bottom at several stations in 2015, and the bottom depth was assigned. High spring water clarity is also consistent with the decline in spring diatoms. Summer

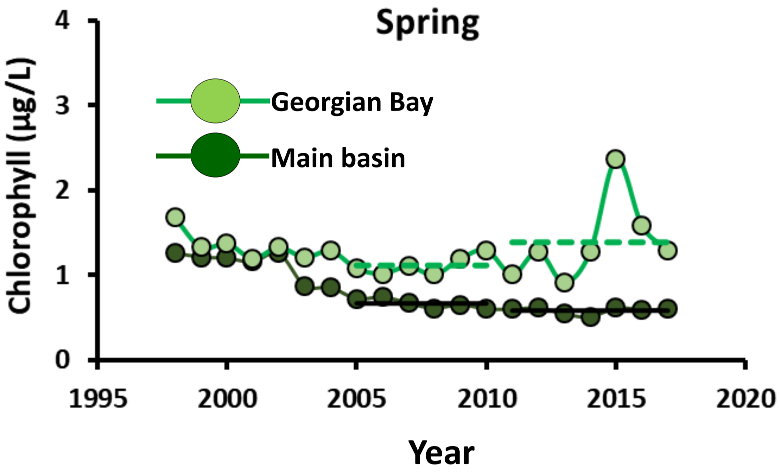
Secchi depth in the main basin increased around 1996 and has remained at about 15 m since then (Table 2; Fig. 2). At the Canadian nearshore sites, summer Secchi depth averaged 8 m in 2009 and 7 m in 2015 (Table 2).

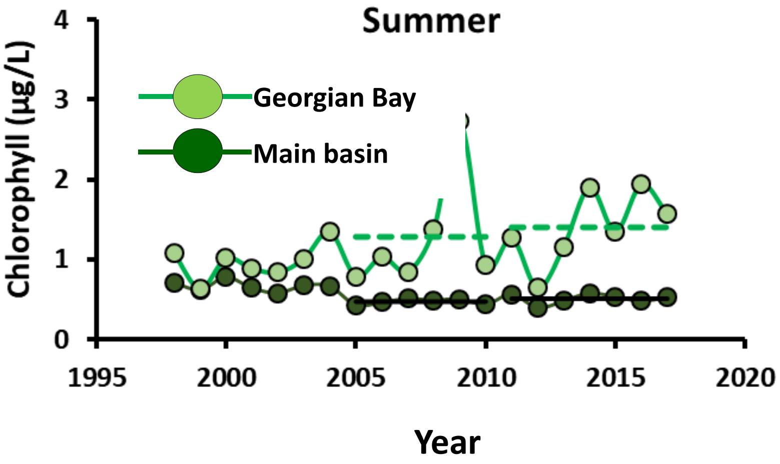
Phytoplankton

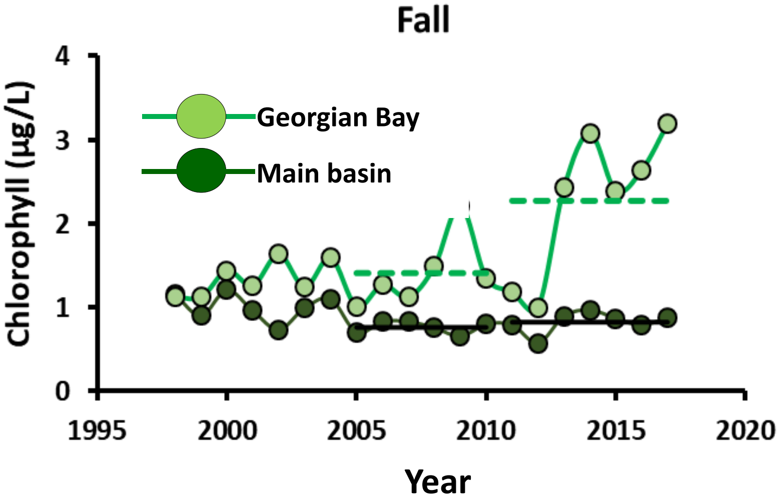
Chlorophyll concentrations at the lake surface, either measured during GLNPO cruises or estimated from satellite-derived imagery (SatChl), have remained stable during the reporting period. SatChl data are integrated over larger areas and longer periods than are data collected from research vessels. They are also available for areas like Georgian Bay, which are not consistently sampled with ships. Although SatChl levels are highly correlated with *in situ* chlorophyll measurements (Lesht et al. 2018), satellites only can estimate surface chlorophyll concentrations and exclude the DCL. SatChl data show decreasing concentrations in the main basin from 1998 to 2005; thereafter, concentrations remained steady through 2017, with summer values of about 0.5 µg•L^{-1} in the main basin and 1.4 µg•L^{-1} in Georgian Bay, (Fig. 3; Table 2; Barbiero et al. 2018b). This early decline is consistent with the observed changes in TP, water clarity, and Si. SatChl levels in Georgian Bay are more variable with periods of higher concentrations in 2009 and 2013. Average summer surface chlorophyll at Canadian nearshore sites declined significantly from 1.9 µg•L^{-1} in 2009 to 1.6 µg•L^{-1} in 2015 (Table 2) but was only sampled those two specific years.

Fig. 3. Changes in chlorophyll concentrations calculated from satellite imagery in the main basin and Georgian Bay for areas with bottom depths >30 m. Horizontal lines indicate averages for the reporting periods 2005-2010 and 2011-2017. Annual is the average for March-November, Spring is March-May, Summer is June-August, and Fall is September-November. Values are calculated from two different satellites, SeaWiFS (1998-2007) and MODIS (2008-2017).


Annual
Chlorophyll (µg/L)
4
3
2
1
0
Georgian Bay
Main basin
1995
2000
2005
2010
2015
2020
Year

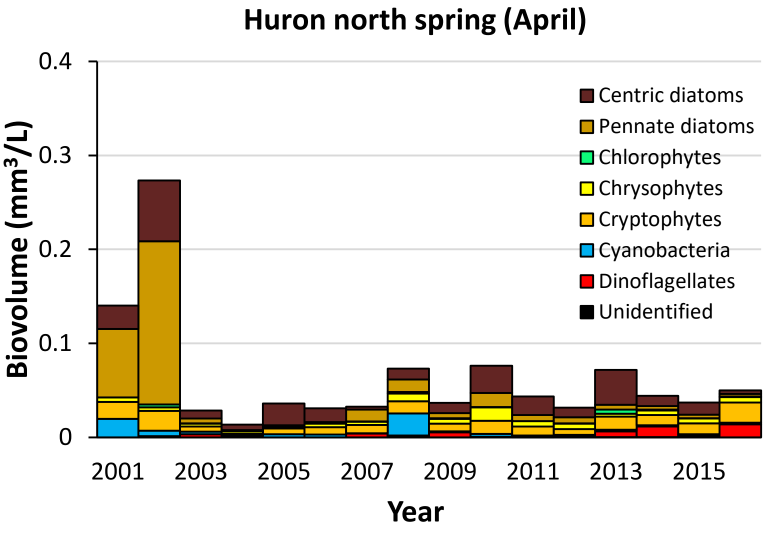

Spring
Chlorophyll (µg/L)
4
3
2
1
0
Georgian Bay
Main basin
1995
2000
2005
2010
2015
2020
Year

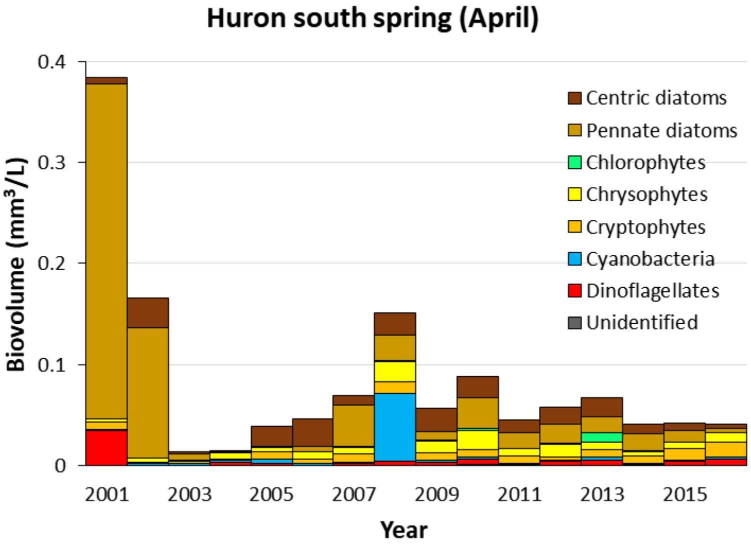

Summer
Chlorophyll (µg/L)
Georgian Bay
Main basin
0
1
2
3
4
1995
2000
2005
2010
2015
2020
Year

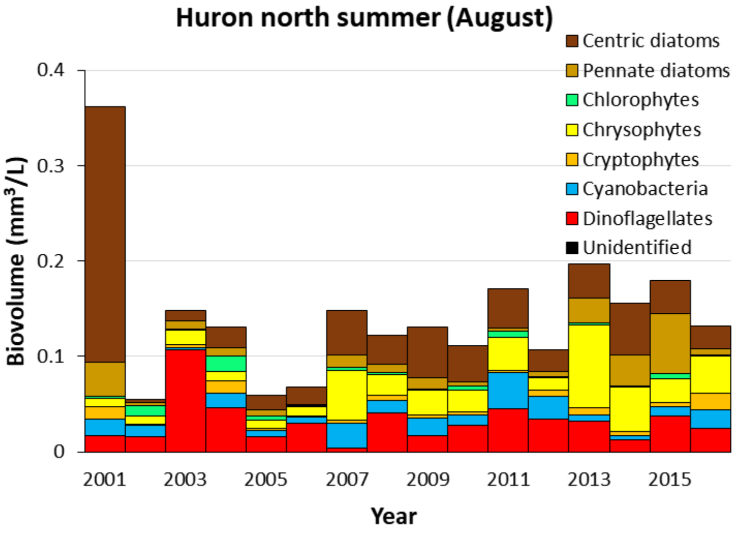

Fall
Chlorophyll (µg/L)
Georgian Bay
Main basin
0
1
2
3
4
1995
2000
2005
2010
2015
2020
Year

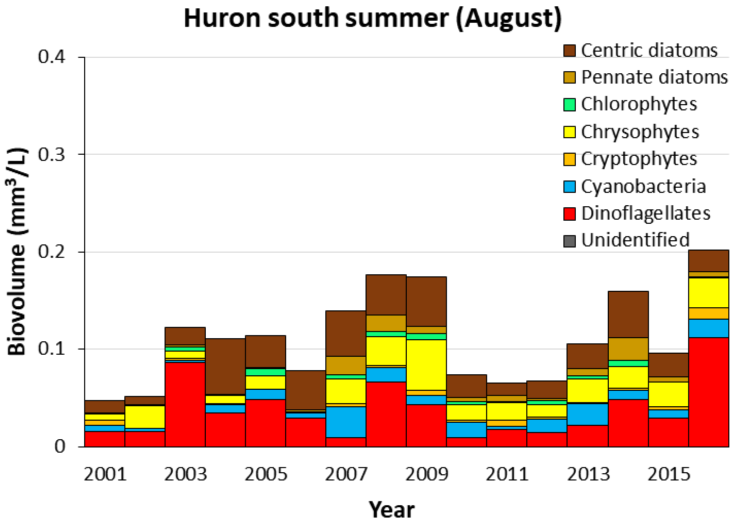
Phytoplankton biovolume during the spring of 2003-2016 was less than half of that observed during 2001-2002, and most of that decline was due to lower diatom abundance (Fig. 4; Reavie et al. 2014; Barbiero et al. 2018b). Since 2003, only 20-60% of the spring phytoplankton biovolume in Lake Huron consisted of diatoms compared to 80-90% in 2001-2002. Total spring phytoplankton biovolume increased from 2003 to 2008 and then declined somewhat; total biomass was significantly lower during the reporting period (0.048 $mm^3 \cdot L^{-1}$) than during the previous reporting period (0.073 $mm^3 \cdot L^{-1}$), primarily due to declines in diatoms and chrysophytes (Table 2). The proportions of different spring phytoplankton groups for 2007-2016 were 49% diatoms, 17% cryptophytes, 15% chrysophytes, 11% cyanophytes, 7% dinoflagellates, and 2% chlorophytes. The long-term decline in spring biovolume is consistent with the observed decline in SatChl and increase in Si. Summer biovolumes showed no significant changes in any phytoplankton groups or in total biovolume between reporting periods (Table 2). The average proportions of phytoplankton biovolume during the summer 2007-2016 samples were 35% diatoms, 24% dinoflagellates, 23% chrysophytes, 12% cyanophytes, 4% cryptophytes and 3% chlorophytes (Bramburger and Reavie 2016).

Fig. 4. Phytoplankton biovolume by major groups during April and August surveys by the Great Lakes National Program Office. Presentation is separated by northern and southern stations, which tend to have unique physical, chemical, and biological properties (Cai and Reavie 2018).


Huron north spring (April)
Biovolume (mm³/L)
0.4
0.3
0.2
0.1
0
2001
2003
2005
2007
2009
2011
2013
2015
Year
Centric diatoms
Pennate diatoms
Chlorophytes
Chrysophytes
Cryptophytes
Cyanobacteria
Dinoflagellates
Unidentified


Huron south spring (April)
Biovolume (mm³/L)
0.4
0.3
0.2
0.1
0
2001
2003
2005
2007
2009
2011
2013
2015
Year
Centric diatoms
Pennate diatoms
Chlorophytes
Chrysophytes
Cryptophytes
Cyanobacteria
Dinoflagellates
Unidentified


Huron north summer (August)
Centric diatoms
Pennate diatoms
Chlorophytes
Chrysophytes
Cryptophytes
Cyanobacteria
Dinoflagellates
Unidentified
Biovolume (mm³/L)
0.4
0.3
0.2
0.1
0
2001
2003
2005
2007
2009
2011
2013
2015
Year


Huron south summer (August)
Centric diatoms
Pennate diatoms
Chlorophytes
Chrysophytes
Cryptophytes
Cyanobacteria
Dinoflagellates
Unidentified
Biovolume (mm³/L)
0.4
0.3
0.2
0.1
0
2001
2003
2005
2007
2009
2011
2013
2015
Year

In mesotrophic to oligotrophic systems, an increase in phytoplankton often occurs below the thermocline and is termed the DCL (Fahnenstiel and Scavia 1987). The DCL can include a large portion of the chlorophyll present in the water column and can contribute significantly to total lake production during the stratified season. For example, the DCL was estimated to contribute 30-60% of total primary production in Lake Michigan during the 1980s (Fahnenstiel and Scavia 1987). Chlorophyll concentrations within Lake Huron's DCL are often 2-3 times greater (1.57 ± 0.12 µg•L^{-1}, mean ± 2 SE) than those in the epilimnion (0.59 ± 0.04 µg•L^{-1}, mean ± 2 SE) based on sampling during 2002-2017 (Scofield 2018). However, phytoplankton biovolume was not higher in the Lake Huron DCL, likely because phytoplankton can compensate for the lower light levels by producing more chlorophyll per unit biomass. Scofield (2018) showed that the chlorophyll:carbon ratio is up to two times higher in the DCL than in the epilimnion in Lake Huron, indicating that using chlorophyll as a proxy would overestimate the contribution of DCL phytoplankton to total phytoplankton biovolume. Scofield (2018) also found that the DCL in Lake Huron forms deeper than in the other Laurentian Great Lakes and has less chlorophyll than in all other lakes, except Lake Superior. Furthermore, the chlorophyll concentrations in the DCL have decreased through the 2000s in Lake Huron (Scofield 2018) as has phytoplankton biovolume in the DCL from 2007 to 2016 (Bramburger and Reavie 2016). The DCL contained 40% diatoms, 28% chrysophytes, 18% dinoflagellates, 6% cryptophytes, 6% cyanophytes, and 2% chlorophytes during 2007-2016 and was more similar to the spring than to the summer epilimnetic assemblage. This finding indicates that the DCL is a productive and distinct layer of phytoplankton (Bramburger and Reavie 2016). Although the DCL in Lake Huron was contributing to total primary production, this contribution was probably relatively lower in Lake Huron than in Lake Ontario, which is more mesotrophic (Scofield et al. 2017; Scofield 2018).

Recent paleolimnological investigations in Lake Huron revealed several shifts in primary producers over the last 200 years, with the most-recent shift in the 1990s associated with increased temperature, decreased P loading, and the proliferation of dreissenids (Reavie et al. 2017; Sgro and Reavie 2018). The composition of phytoplankton assemblages shifted notably to dominance by smaller centric diatoms in the genus *Cyclotella sensu lato* across the Great Lakes basin, which appears to be explained best by stratification and mixing changes associated with a warming atmosphere and/or decreased nutrient inputs over the last few decades (Reavie et al. 2017).

Zooplankton and *Mysis*

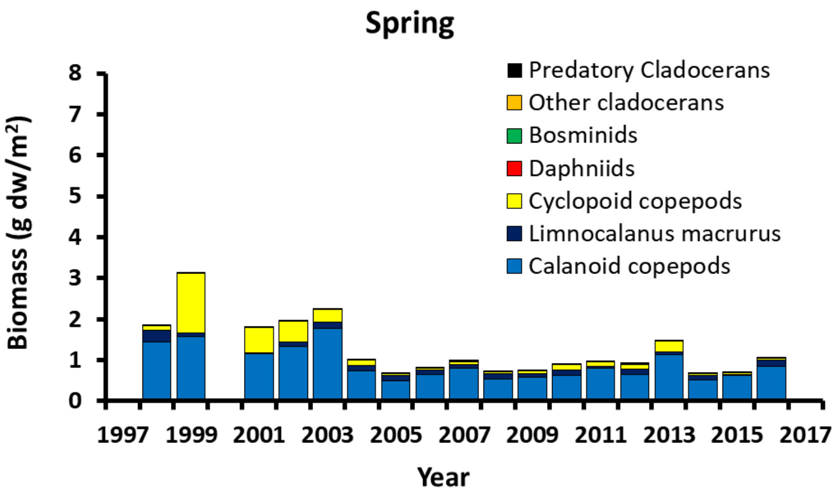
Lake Huron's current zooplankton community structure is similar to that of Lake Michigan (Barbiero et al. 2012, 2018b). Spring zooplankton biomass is dominated by calanoid copepods while summer biomass includes cladocerans like *Daphnia mendotae* and *Bosmina longispina*. The predatory cladoceran *Bythotrephes longimanus* is present from summer (Fig. 5) into fall (Nowicki et al. 2017). *Limnocalanus macrurus* and the other dominant calanoid copepod, *Leptodiaptomus sicilis*, occur primarily below the thermocline.

Spring and summer calanoid and cyclopoid biomass increased significantly from the previous reporting period (2005-2010) to the current reporting period (2011-2017) while summer *Limnocalanus macrurus* biomass decreased significantly (Table 2). Total summer zooplankton biomass did not change while spring zooplankton biomass increased slightly over the same reporting periods, but these changes are minor compared to the dramatic decline in zooplankton biomass that occurred from 2002-2004 owing to the large decline of daphniids (Fig. 5). We detected change points in the summer time series in 2003 and in the spring time series in 2004 for most groups, except for *L. macrurus* (Table 2). Similar declines since 1997 have also occurred in Lake Michigan but not in Lakes Ontario or Superior (Barbiero et al. 2019).

Mysis has been sampled in Lake Huron with specialized larger nets in spring and summer since 2006 (Jude et al. 2018). Biomass of *Mysis* has remained relatively stable since 2006, although it declined in spring but not in summer from 2005-2010 to 2011-2017 (Table 2). *Mysis* density is low compared to Lakes Michigan, Superior, and Ontario (Fig. 6; Jude et al. 2018).

Mysid density, based on tows made for zooplankton when sampled at night, declined in 2005, one year later than other zooplankton groups, perhaps as a result of the two-year life cycle of mysids in Lake Huron (Jude et al. 2018). Lake Huron had the largest relative decline in mysids from pre-2005 to post-2005 of any of the Great Lakes, although their density in Lake Huron was already lower than in the other lakes before 2005. We suggest that the larger post-2005 relative decline in mysid abundance in Lake Huron was the result of increasing water clarity in a relatively shallow Great Lake, as compared to Lakes Superior, Michigan, and Ontario. Mysids are more vulnerable to predation at higher light levels (Boscarino et al. 2010) and, therefore, migrate to the bottom of the lake during the day. With the same high water clarity, mysids have to reside in a higher-light environment in a shallow rather than in a deep lake and, therefore, experience higher predation risk. Low food resources have also been implicated (Mida Hinderer et al. 2012), and both mechanisms likely contribute to the low biomass of mysids. Lower density is also reflected in a lower proportion of pelagic crustacean biomass consisting of mysids, which represents 10-20% of the zooplankton biomass in the other deep Great Lakes but only 3% in Lake Huron (Jude et al. 2018).

Fig. 5. Whole water-column zooplankton dry biomass in grams per square meter from the spring (April) and summer (August) Great Lakes National Program Office surveys in Lake Huron from 1997 to 2017. Spring samples were not collected in 1997 and 2000.


Spring
Predatory Cladocerans
Other cladocerans
Bosminids
Daphniids
Cyclopoid copepods
Limnocalanus macrurus
Calanoid copepods
Biomass (g dw/m²)
0
1
2
3
4
5
6
7
8
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
Year

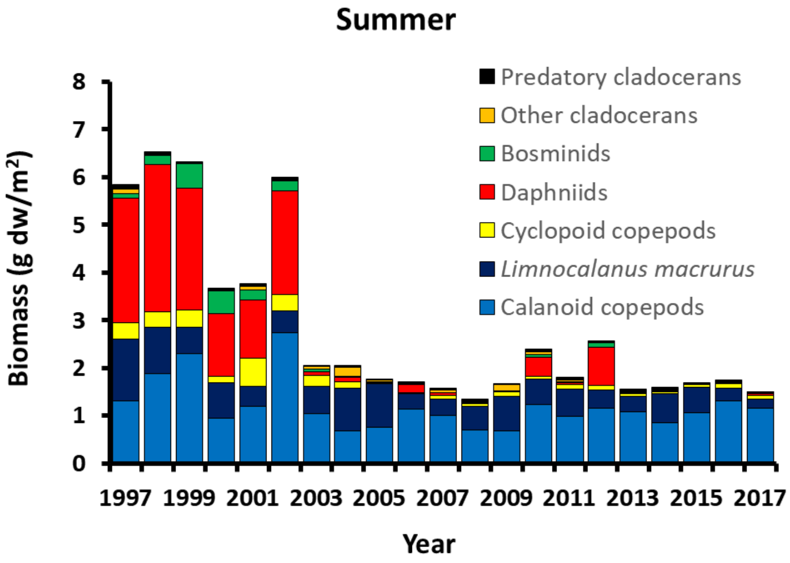
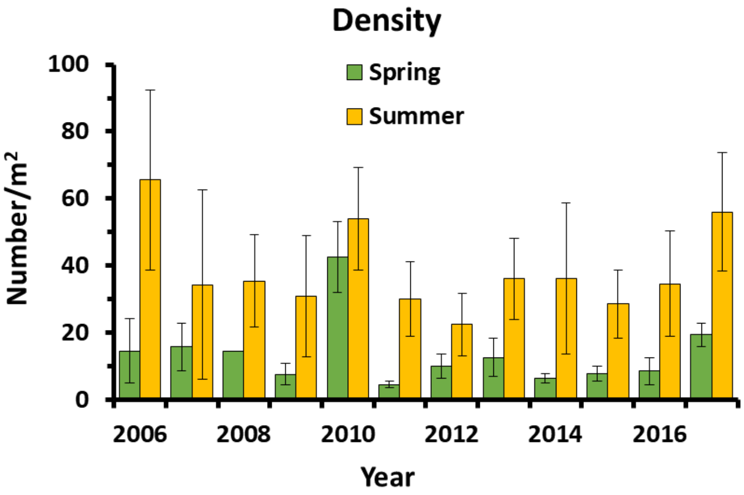
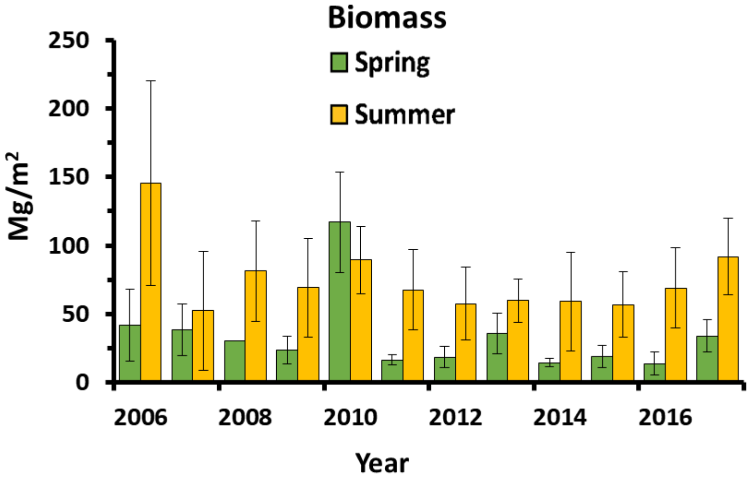

Summer
Predatory cladocerans
Other cladocerans
Bosminids
Daphniids
Cyclopoid copepods
Limnocalanus macrurus
Calanoid copepods
Biomass (g dw/m²)
0
1
2
3
4
5
6
7
8
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
Year

Fig. 6. Mysid density in number per square meter and biomass in milligrams dry weight per square meter, 2006 to 2017 (Jude et al. 2018; Great Lakes National Program Office, unpublished data). Error bars represent ± 1 standard error.





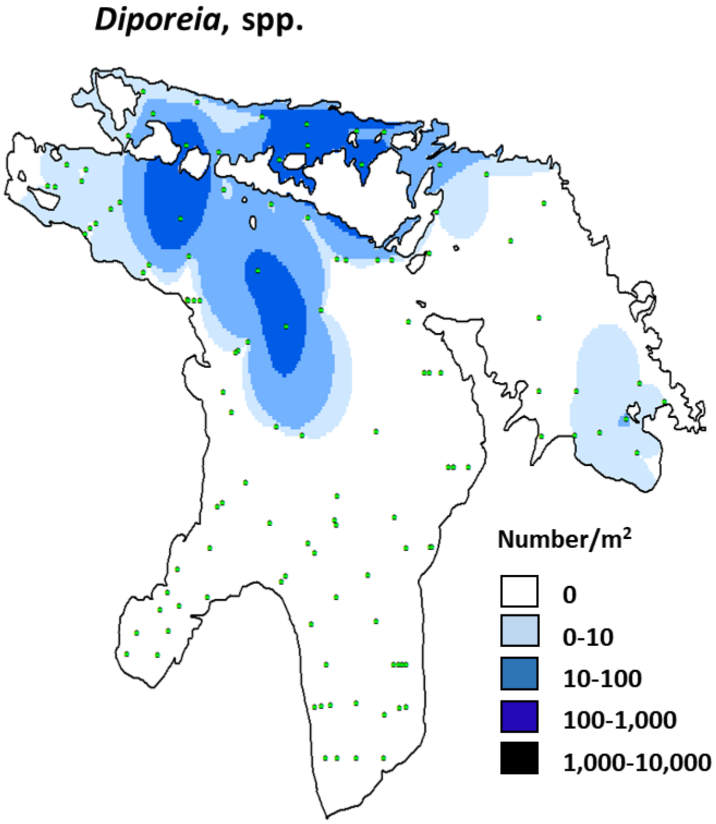
Benthos

The quagga mussel (*Dreissena bugensis*) has continued to increase in abundance lakewide through 2017 and is now found everywhere in the lake, including the deepest areas (Figs. 7, 8). The increase has not continued at all depths, however, as quagga mussel abundance in both the 0-30-m-depth and the 31-50-m-depth zones declined after about 2009 (Fig. 8). Similarly, quagga mussel densities at nearshore stations along the Canadian shore of the main basin, Georgian Bay, and North Channel were low after 2009. Mussels in deeper water are in cold temperatures year-round, grow slowly, filter at lower rates, and have less access to phytoplankton. These deeper-water mussels, therefore, have less effect on the rest of the ecosystem than mussels in shallower waters (Karatayev et al. 2018). Thus the effect of an increase in quagga mussels in deep water is less than an increase in shallower water. Barbiero et al. (2018b) suggested that nearshore mussels are more important than overall mussel abundance in affecting the lower trophic-level changes that occurred over the last two decades in Lakes Huron and Michigan. Zebra mussels (*D. polymorpha*) had large initial ecosystem effects in shallow water like Saginaw Bay (Nalepa and Fahnenstiel 1995) but have declined in abundance and are no longer a major component of the benthic fauna of Lake Huron.

The steep decline of burrowing amphipods, *Diporeia* spp. (hereafter, diporeia), was a major change in the benthos in Lake Huron (Burlakova et al. 2018b; Kovalenko et al. 2018). Diporeia had been the most-abundant benthic species by biomass in the 1990s. Declines have been dramatic at all depths and have continued through the present reporting period. Fish that fed extensively on diporeia, such as Lake Whitefish, have been negatively affected (Pothoven and Nalepa 2006; Gobin et al. 2015). We compared whole-lake surveys in 2007, 2012, and 2017 and found significant declines in diporeia density from 367 to 67 m^{-2} in 90 m and deeper and from 167 to 22 m^{-2} in 0-90 m from 2007 to 2017 (significant year effect, $P = 0.0001$ for both depths). We also analyzed data from the spatially more-limited annual surveys (Fig. 9) and found a significant decline from the previous (2010-2015) to the present reporting period (2011-2017) for sites shallower than 90 m, but not for sites deeper than 90 m (Table 2); a significant negative change point occurred in 2004 at the deep sites. The shallow sites show a continuous decline since 1998, which violated assumptions of the analysis to detect change points. However, the decline from 1998 to 2016 is highly significant (significant year effect, mixed model ANOVA, $P < 0.0001$). Declines in diporeia also have occurred in Lakes Michigan and Ontario but not in Lake Superior where quagga mussels are rare.

Although the correlation of the diporeia decline with the increase in quagga mussels is striking across both time and space (Fig. 8), the mechanism linking the increase in quagga mussels with the decline in diporeia has so far been elusive (Nalepa et al. 2018). When abundant, quagga mussels likely intercept food resources used by diporeia, especially diatoms. But the diporeia decline started before the large increase of quagga mussels in Lake Huron (Figs. 8, 9), a pattern also seen in Lake Ontario (Watkins et al. 2007, 2013) and Lake Michigan (Nalepa et al. 2009). Perhaps material transport to deeper bottoms were limited by nearshore-dwelling zebra mussels before quagga mussels became abundant, as zebra mussels had large effects on the Saginaw Bay system in the early 1990s (Nalepa and Fahnenstiel 1995). Pathogens have also been proposed as a cause for the diporeia decline, perhaps associated with mussels, but the search for such pathogens has not yielded definitive results (Faisal and Winters 2011; Bistolas et al. 2017).

Fig. 7. Distribution (number/m^2) of *Diporeia* spp. and quagga mussels in Lake Huron in 2017. Sampling sites indicated by green dots.



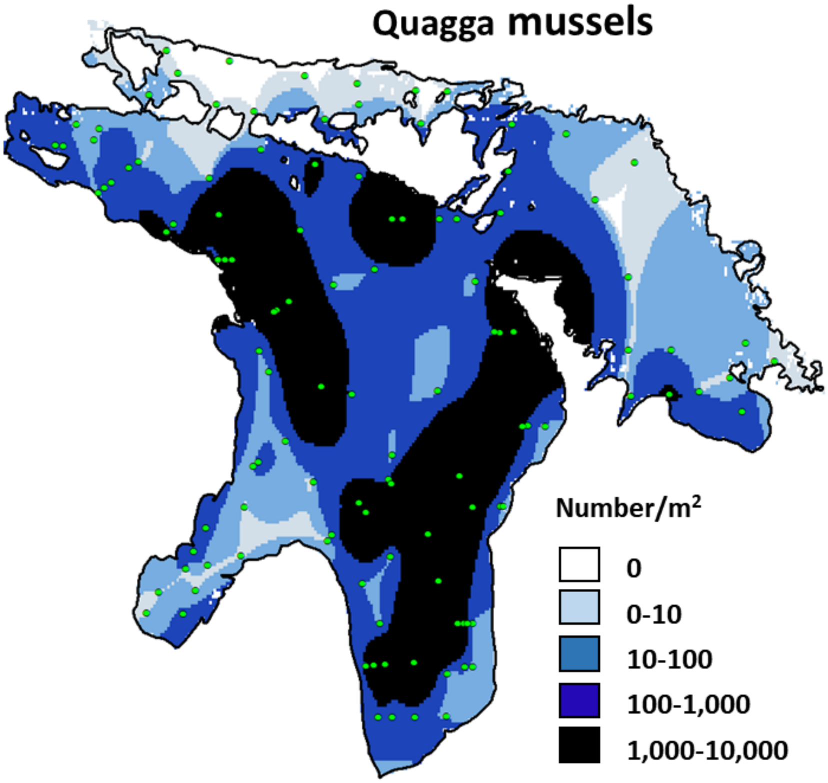
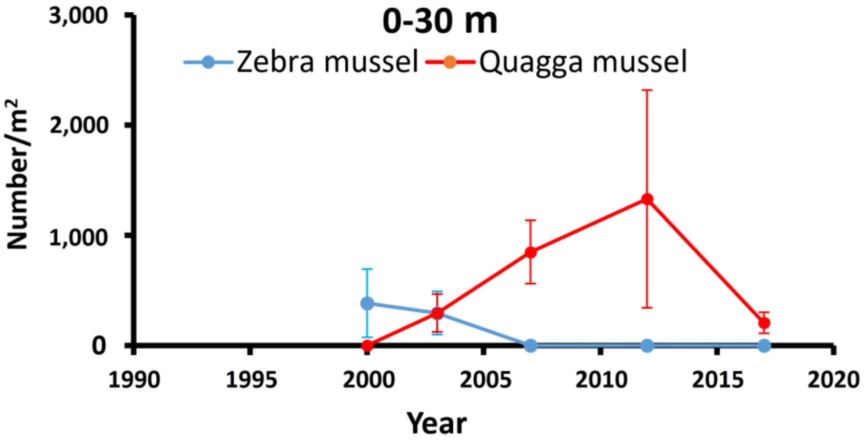
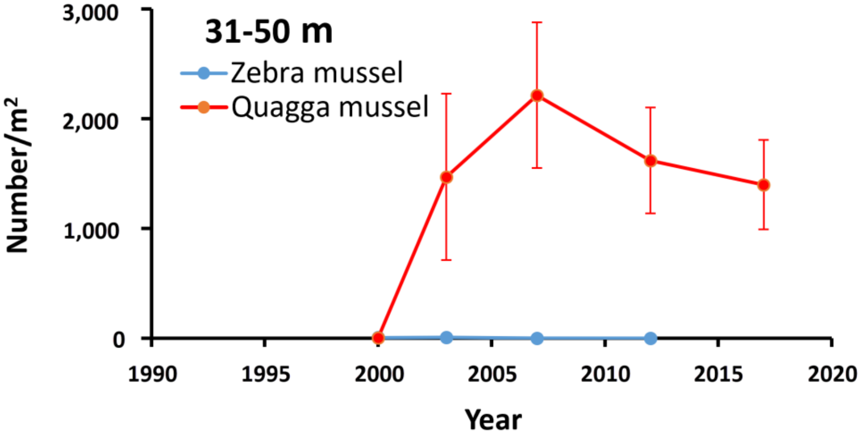
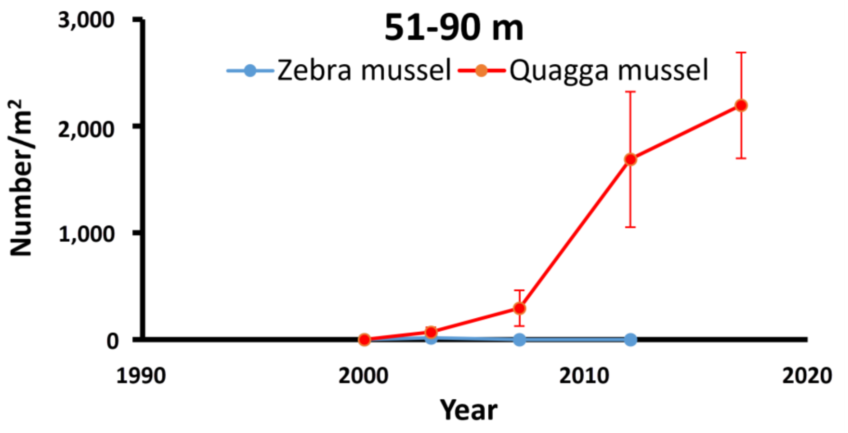
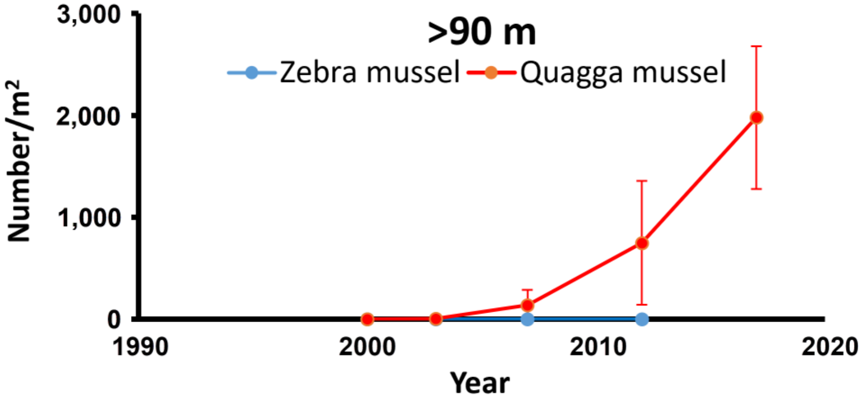

Quagga mussels
Number/m²
0
0-10
10-100
100-1,000
1,000-10,000

Fig. 8. Densities of quagga mussels (mean ± 1 SE) in different depth strata of Lake Huron from 2000 to 2017 (Nalepa et al. 2018). Whole-lake density is weighted by the area of the lake in each of nine depth zones.






51-90 m
Zebra mussel
Quagga mussel
Number/m^2
3,000
2,000
1,000
0
1990
2000
2010
2020
Year


>90 m
Zebra mussel
Quagga mussel
Number/m^2
3,000
2,000
1,000
0
1990
2000
2010
2020
Year

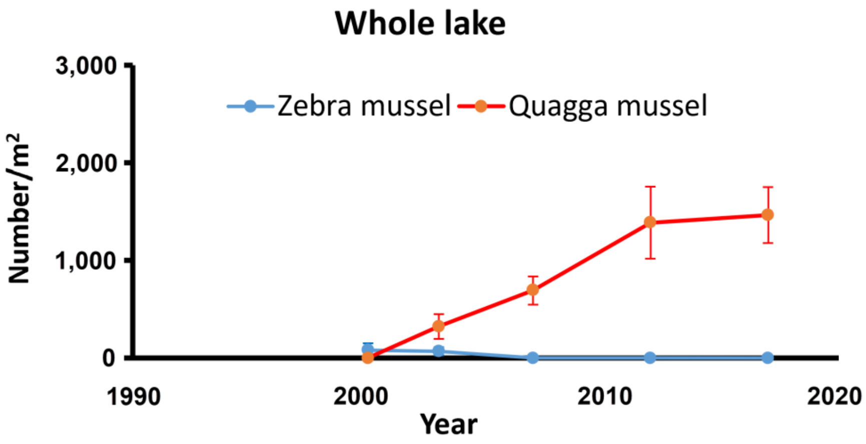
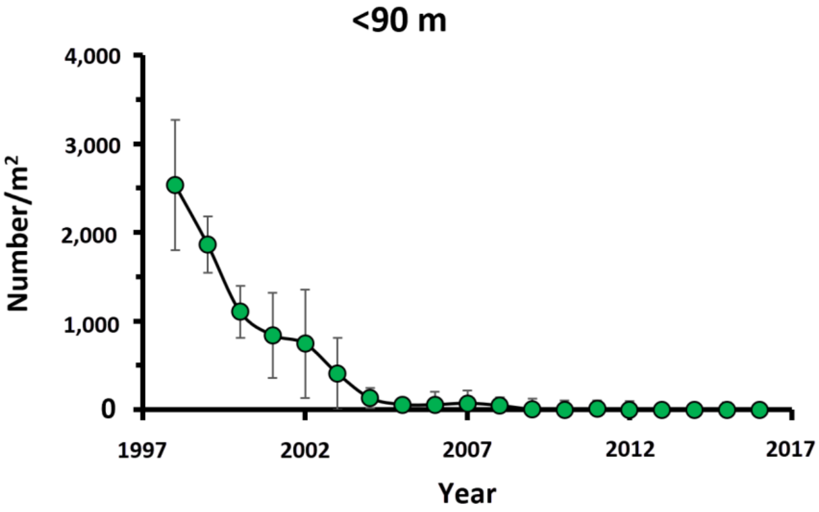
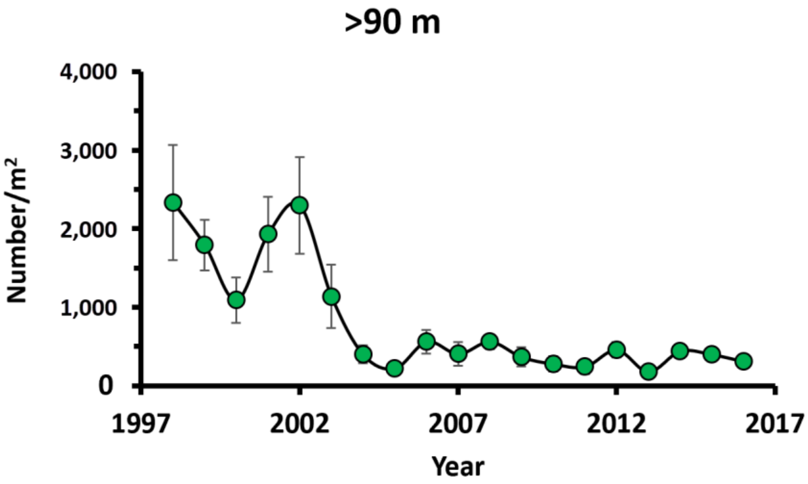


Fig. 9. Average density of *Diporeia* spp. from 1998 to 2016 in Lake Huron at depths less than and greater than 90 m. Error bars are ± 1 SE. Based on Great Lakes National Program Office surveys (Burlakova et al. 2018b).





Summary and Discussion

We compared the most-recent reporting periods 2005-2010 and 2011-2017 whenever possible (Table 2) to assess indicators of lower trophic-level production. We found that spring TP levels in the main basin had increased since the previous reporting period, which should lead to increased productivity, but we also observed increases in silica and spring water clarity and declines in spring chlorophyll and spring diatom biovolumes. Changes in silica, water clarity, and chlorophyll were comparable at the Canadian nearshore stations sampled in 2009 and in 2015, but those surveys show no significant change in spring TP when analyzed together or when analyzed separately for Georgian Bay and the main basin (*P* = 0.27 for Georgian Bay sites and *P* = 0.75 for main-basin sites). At the same time, there was an increase in spring calanoid and cyclopoid copepods, which is consistent with higher spring TP but not consistent with declines in spring diatoms. In summer, there were no changes in mixed-layer chlorophyll and phytoplankton biovolume, but there were declines in chlorophyll and phytoplankton biovolume in the DCL. Signals from summer zooplankton were mixed with a decrease in *L. macrurus* and an increase in other calanoids and in cyclopoids, which resulted in no change in total summer zooplankton biomass between the two reporting periods. With the exception of the increase in spring zooplankton, these observations can be reconciled with an effect of an increasing population of quagga mussels, which likely has more impact in spring than in summer (Fahnenstiel et al. 2010). In summer, mussels below the thermocline do not have access to epilimnetic production, indicating that quagga mussels cannot have large direct effects on summer phytoplankton and zooplankton. We note that both variable nutrient loading and climate effects interact with mussel effects (Warner and Lesht 2015) and that detecting long-term changes given inter-annual variability is difficult over the relatively short 13-year window (2005-2017), which is the focus of this chapter.

The largest recent changes in lower trophic levels occurred between 2002 and 2005 prior to the most-recent reporting periods (Table 2). These changes include declines in most of the lower trophic-level indicators in the main basin, including TP, chlorophyll, phytoplankton (in particular, spring diatoms), most zooplankton, *Mysis*, and diporeia at >90 m. The smaller spring diatom bloom in 2003 was followed by low biomass of daphniids and some of the other zooplankton in the August sampling of 2003. This trend of low spring zooplankton biomass started in 2004 and continued through 2017. The decline in diporeia at <90 m started earlier than the zooplankton decline, with a continuous decline evident since 1998. At the same time, the benthic community continued to change toward dominance of quagga mussels across all depths as zebra mussel populations declined. The timing of these changes in Lake Huron is very similar to observations in Lake Michigan, although the changes were more abrupt, and quagga mussels were less abundant in Lake Huron (Barbiero et al. 2018b).

The open water of Lake Huron's main basin is now highly oligotrophic and similar to Lake Superior in nutrient levels and in the composition and abundance of phytoplankton and zooplankton. However, Lake Superior still has diporeia in abundance, a higher biomass of *Mysis*, and very low abundance of quagga mussels, making the benthic ecosystem of these two lakes quite different. Because Lake Superior still has a spring diatom bloom, it seems likely that the presence of quagga mussels was an important factor in the observed changes in Lakes Huron and Michigan (Vanderploeg et al. 2010; Warner and Lesht 2015; Barbiero et al. 2018b). Quagga mussels may directly decrease the spring diatom bloom through grazing or perhaps by affecting nutrient supplies with implications for diporeia and long-lived copepods that depend on diatoms. However, the strong temporal correlations between lower trophic levels in Lakes Michigan and Huron suggest additional effects of weather events, perhaps through the timing and extent of ice cover and onset of stratification (Barbiero et al. 2018b). Warner and Lesht (2015), using data from 1998 to 2008, found spring TP to have larger effects on chlorophyll *a* than did quagga mussels in Lakes Huron and Michigan, and TP was affected by climate-related events, such as ice cover.

One of the most-dramatic changes in Lake Huron was the disappearance of summer daphniids in 2003. We speculate that this decline is an effect of algal concentrations being below a threshold where daphniids can survive, which has been suggested to be between 0.5 to 1 $\mu g \bullet L^{-1}$ chlorophyll (Semenchenko et al. 2006). Chlorophyll levels in Lake Huron have been below 0.5 $\mu g \bullet L^{-1}$ in the summer from 2005 onwards and below 1 $\mu g \bullet L^{-1}$ in the spring since 2003. Chlorophyll levels in Lake Huron's DCL are also low, and the DCL forms in the hypolimnion, deeper, for example, than in Lake Ontario (Scofield 2018). In addition, daphniids are more affected by low food quality than are copepods, and high carbon-to-phosphorus (C:P) ratios (equals low food quality) are expected when water clarity is high and P levels are low (Sterner et al. 1997). A molar C:P ratio of around 300 is limiting for daphniids, and ratios over 250 can decrease daphniid growth rates (Urabe and Watanabe 1992; Sterner 1993). The summer particulate C:P ratio in the mixed layer has increased significantly in Lake Huron from a median of 222 during 1998-2004 to a median of 264 during 2005-2015 (mixed-model ANOVA year effect, $P = 0.011$). Interestingly, this increase also was observed in Lake Michigan (from 188 to 254, $P < 0.0001$), another lake with declines in daphniids. In contrast, the median ratio declined from 253 to 223 in Lake Superior (but not significantly), and the ratio remained below 170 in Lakes Ontario and Erie. Therefore, we believe that declines in both food quantity and quality are contributing to the decline of daphniids in Lake Huron resulting in a zooplankton community similar to that in Lake Superior.

The large decline in adult Alewife biomass in 2003 coincided with major changes in Lake Huron's zooplankton community. Is it possible that direct or indirect effects of the Alewife decline contributed to the changes in the zooplankton community? Declines in cyclopoid copepods and bosminids are often associated with declines in Alewife abundance, as decreased fish predation is associated with higher abundances of larger calanoids and daphniids (Brooks and Dodson 1965; Wang et al. 2010). Thus the decline in cyclopoids and bosminids and an increase in larger calanoid copepods like *L. macrurus* are consistent with a decline in Alewife predation. However, the decline in daphniids in Lake Huron is not consistent with a decline in Alewife. Invertebrate predators (*B. longimanus* or *Mysis*) could have increased when Alewife declined, and both species are known to negatively affect cladocerans either directly through predation (Lehman and Cáceres 1993; Bunnell et al. 2012; Pothoven and Höök 2014) or indirectly through increased vertical migrations of daphniids resulting in slower development (Pangle et al. 2007). However, both species decreased with the Alewife population decline. Eshenroder and Lantry (2012) also discuss daphniid declines and added the possibility that predation on resting eggs by quagga mussels may have been a contributing factor. We believe this is less likely as daphniid resting eggs are relatively large and may be egested unharmed with pseudofeces. Also, sufficient resting eggs were present 7-10 years after the daphniid decline to initiate small daphniid populations (2010 and 2012). Therefore, daphniids appear to have declined because of low food quality and quantity both in the epilimnion and the DCL. Consequently, without an increase in phytoplankton, we should not expect a return to the zooplankton communities or biomass present in the late 1990s.

Lastly, it is important to note that Lake Huron also consists of Saginaw Bay, Georgian Bay, and the North Channel. Georgian Bay has higher chlorophyll levels than the main basin, and, although variable, chlorophyll may have increased in Georgian Bay from 2005-2010 to 2011-2017 (Fig. 3). There were fewer mussels and *Cladophora* in the nearshore of Georgian Bay (<20 m) than in the nearshore of the lower lakes, perhaps indicating less effect of mussels. Saginaw Bay continues to be productive and may contribute 30% of the nutrients to the southern main basin (Stow et al. 2014) even though nutrient exports from Saginaw Bay have decreased following the dreissenid invasion (Cha et al. 2011). The zooplankton community in Saginaw Bay changed between 1991-1996 and 2009-2010 in ways that are typical of decreased Alewife predation in smaller lakes (Wang et al. 2010), with declines in bosminids and cyclopoids and increases in daphniids and calanoids (Pothoven et al. 2013). Zebra mussels had large effects on the Saginaw Bay ecosystem in the early 1990s (Nalepa and Fahnenstiel 1995) and mussel abundance continues to be high in Saginaw Bay (Foley et al. 2017a), with an increasing mayfly population (*Hexagenia* spp.; Siersma et al. 2014). Thus Saginaw Bay continues to be a productive area of the lake (see Stow 2014).

Acknowledgments

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STATUS OF OFFSHORE PREY FISH IN LAKE HURON IN 2018[8]

Stephen C. Riley[9], Edward F. Roseman, Darryl W. Hondorp, Timothy P. O'Brien, and Steven A. Farha

The fish community objective (FCO) for prey fish (DesJardine et al. 1995) in Lake Huron is

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

The historical offshore prey-fish community in Lake Huron included shallow-water and deepwater ciscoes, sculpins, Ninespine Stickleback, and Trout-Perch but, by the 1960s, was dominated by invasive Alewife and Rainbow Smelt (Berst and Spangler 1973; Riley et al. 2008). Invasions of dreissenids, the predatory zooplankters *Bythotrephes longimanus* and *Cercopagis pengoi*, and the Round Goby have caused disruptive changes to food webs since the 1980s-1990s (Barbiero et al. 2018b). Six species (forms) of native deepwater ciscoes have been extirpated from the lake, yet one species (Bloater) remains common, although this species may represent a hybrid swarm (i.e., *hybrida*; Eshenroder et al. 2016). One shallow-water cisco remains abundant locally but the formerly widespread typical *artedi* form is likely extirpated. The estimated biomass of the remaining native

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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/Sp20_01.pdf.

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prey-fish species has been reduced since the mid-2000s relative to historical levels (Riley et al. 2008, 2018).

Alewife, Rainbow Smelt, and Bloater

Alewife, Rainbow Smelt, and Bloater were the most-abundant offshore prey fish in the early years of the U.S. Geological Survey (USGS) bottom-trawl survey, and the most-striking change in recent years was the collapse of Alewife populations in 2004 (Riley et al. 2008). Bottom-trawl and acoustic estimates of young-of-the-year (YOY) Alewife biomass were lower during this reporting period (2011-2017) than during the previous reporting period (2005-2010) in all basins, and bottom-trawl estimates were higher than acoustic estimates (Table 3). In 2013 and 2016 of this reporting period and in 2005 and 2006 of the previous reporting period, the bottom-trawl survey produced relatively high YOY biomass estimates that were not reflected in the acoustic results.

Bottom-trawl-based biomass estimates for yearling-and-older (YAO) Alewife in this reporting period were approximately double those of the previous period but remained low, and again bottom-trawl estimates were higher than acoustic estimates (Table 3). Acoustic estimates of YAO Alewife biomass were zero in all basins during the previous reporting period, which precludes estimation of the percent change between the current and previous reporting periods (Table 3). Alewife biomass estimates from acoustics were variable among lake basins, but no clear pattern among basins was evident over the past two reporting periods for YOY or YAO fish. Alewife is the primary prey of salmonine piscivores in Lake Huron, and its continuing near absence from the lake may have affected food-web dynamics (e.g., Bunnell et al. 2011). Our data indicate that Alewife has shown no sign of recovery since its collapse in 2004.

Table 3. Mean biomass in kilograms per hectare for young-of-the-year (YOY) and yearling-and-older (YAO) Alewife, Rainbow Smelt, and Bloater in the three basins of Lake Huron during the previous (2005-2010) and present (2011-2017) reporting periods. Bottom-trawl biomass estimates were made only for the main basin whereas acoustic estimates were made for all three basins.

		Main Basin				Georgian Bay		North Channel	
Species	**Reporting period**	**YOY Trawl**	**YOY Acoustic**	**YAO Trawl**	**YAO Acoustic**	**YOY Acoustic**	**YAO Acoustic**	**YOY Acoustic**	**YAO Acoustic**
Alewife	2005-2010	0.92	0.04	0.20	0.00	0.05	0.00	0.13	0.00
	2011-2017	0.75	0.02	0.61	<0.00	<0.00	<0.00	0.02	<0.00
	Proportional change	-0.18	-0.44	2.06	-	-0.94	-	-0.87	-
Smelt	2005-2010	2.60	0.73	1.94	3.26	0.63	4.05	1.60	13.42
	2011-2017	1.14	0.47	1.13	2.70	0.27	2.86	1.28	12.90
	Proportional change	-0.56	-0.35	-0.42	-0.17	-0.58	-0.29	-0.20	-0.04
Bloater	2005-2010	0.96	0.54	3.56	5.26	0.47	3.90	1.13	3.68
	2011-2017	1.32	0.57	9.12	7.01	0.28	1.64	0.73	3.93
	Proportional change	0.38	0.05	1.56	0.33	-0.40	-0.58	-0.36	0.07

The biomass of YAO Rainbow Smelt has remained low during the last two reporting periods and continued to exhibit a steady decline in the main basin since the early 1990s. The mean bottom-trawl-based biomass for YAO Rainbow Smelt in the main basin for the reporting period was 42% less than during the previous reporting period while the acoustic estimate was 17% less (Table 3). Biomass estimates for YAO Rainbow Smelt from the acoustic survey in the main basin were generally higher than bottom-trawl-based estimates in most years, and acoustic estimates were consistently higher in all years in the North Channel than in the main basin or Georgian Bay.

Anomalously high bottom-trawl-based biomass estimates for YOY Bloater have been observed in the main basin in some years during the last two reporting periods but were not observed in the acoustic data. Bottom-trawl surveys indicate that the mean biomass of YOY Bloater in the main basin was 38% higher in the current reporting period than in the previous reporting period while the acoustic time series shows an increase of only 5% and indicates a decrease in biomass in the North Channel and Georgian Bay (Table 3). Acoustic data indicate that YOY Bloater biomass tended to be higher in the main basin and North Channel than in Georgian Bay, but differences among basins were variable among years.

The biomass of YAO Bloater showed a dramatic increase from the previous reporting period in bottom-trawl surveys until 2012; thereafter, biomass declined to levels near the lowest observed in the survey. The 2012 biomass for YAO Bloater was among the highest ever observed in the bottom-trawl survey and was similar to levels observed at its peak abundance during 1985-1995. These high YAO Bloater biomass estimates in 2011 and 2012 were not observed in the acoustic survey. Bottom-trawl surveys indicate that YAO Bloater biomass in the main basin increased by 156% over the previous reporting period while acoustic data indicate an increase of only about 33% (Table 3). Bottom-trawl data suggest that YAO Bloater biomass in the main basin was trending downward during the current reporting period while acoustic data suggest it is level or trending upward. There is no clear pattern in the relative biomass estimates from acoustic and bottom-trawl surveys for YAO Bloater in the main basin; acoustic estimates were higher in some years and the opposite was true in others. Differences in acoustic-based YAO Bloater biomass among the three basins were also highly variable among years, although biomass appeared to be greater in the main basin in the last four years of the current reporting period.

Ninespine Stickleback, Sculpins, and Trout-Perch

Ninespine Stickleback, Deepwater Sculpin, Slimy Sculpin, and Trout-Perch are currently minor components of salmonine diets in Lake Huron (Roseman et al. 2014) but were more important in the diet of Lake Trout before the establishment of Alewife and Rainbow Smelt (e.g., Van Oosten and Deason 1938). Sticklebacks are sampled by both bottom-trawl and acoustic surveys, although the acoustic-survey samples include Threespine Stickleback, which is rarely encountered in the trawl survey. Both surveys indicated that stickleback biomass in the main basin declined 43% in the bottom-trawl survey and 67% in the acoustic survey from the previous reporting period to the current reporting period (Table 4). Main-basin biomass estimates from the bottom-trawl survey were higher than those from the acoustic survey during 2011-2013 of the current reporting period, after which the two surveys produced virtually identical estimates. Acoustic estimates indicated that stickleback biomass was generally greater in the North Channel than in the other two basins but was variable among years.

Deepwater Sculpin, Slimy Sculpin, and Trout-Perch are sampled only by the bottom-trawl survey. The estimated mean biomass of all three species was higher during the current reporting period than during the previous reporting period (Table 4), although most estimates remained near the lowest observed in the time series. These species, along with Ninespine Stickleback, showed similar increases in biomass through the 1990s, all peaked in abundance during 1989-1997, and all showed nearly simultaneous declines in abundance through the early 2000s.

Table 4. Mean biomass in kilograms per hectare of sticklebacks, sculpins, Trout-Perch, Emerald Shiner, and Round Goby in the three basins of Lake Huron during the previous (2005-2010) and current (2011-2017) reporting periods. Bottom-trawl biomass estimates were made only for the main basin whereas acoustic estimates were made for all three basins.

		Main Basin		**Georgian Bay**	**North Channel**
Species	**Reporting Period**	**Trawl**	**Acoustic**	**Acoustic**	**Acoustic**
Sticklebacks	2005-2010	0.07	0.06	0.08	0.14
	2011-2017	0.04	0.02	0.02	0.07
	Proportional change	-0.43	-0.67	-0.79	-0.50
Slimy Sculpin	2005-2010	<0.00	-	-	-
	2011-2017	<0.00	-	-	-
	Proportional change	18.14	-	-	-
Deepwater Sculpin	2005-2010	0.14	-	-	-
	2011-2017	0.22	-	-	-
	Proportional change	0.55	-	-	-
Trout-Perch	2005-2010	0.03	-	-	-
	2011-2017	0.03	-	-	-
	Proportional change	0.10	-	-	-
Emerald Shiner	2005-2010	-	0.13	0.07	0.04
	2011-2017	-	0.10	0.01	0.07
	Proportional change	-	-0.26	-0.79	0.53
Round Goby	2005-2010	0.09	-	-	-
	2011-2017	0.22	-	-	-
	Proportional change	1.40	-	-	-

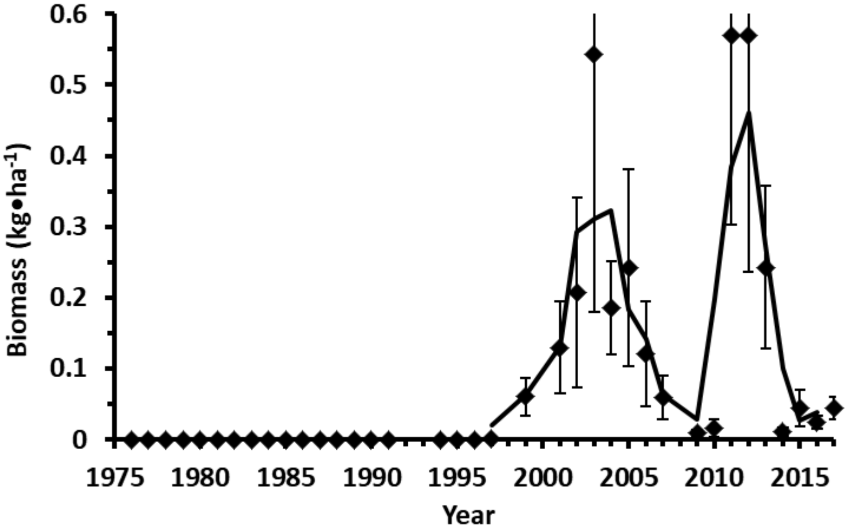
Emerald Shiner

Emerald Shiners are important in some predator diets in Lake Huron (Roseman et al. 2014) but are sampled only by the acoustic survey, and no comparable biomass estimates are available for Lake Huron before the current and previous reporting periods. Acoustic estimates indicate that the biomass of Emerald Shiner in the current reporting period has decreased from the previous period by 26% in the main basin and 79% in Georgian Bay but has increased by 53% in the North Channel (Table 4). Emerald Shiner biomass was highly variable among years and sub-basins, and substantial spikes in its biomass were observed in the main basin in 2006, 2011, and 2013. Although little data exist, Emerald Shiner abundance is thought to be reduced in recent decades in Lake Huron, and recent increases in its biomass may be related to the absence of Alewife (Schaeffer et al. 2008).

Round Goby

The Round Goby was first captured in the Lake Huron bottom-trawl survey in 1997, and since then it has become a critical component of food webs throughout the Great Lakes (e.g., Foley et al. 2017b). Round Goby abundance is difficult to estimate as it is cryptic and may migrate between nearshore and offshore environments (Kornis et al. 2012). Peaks in the estimated biomass of Round Goby in Lake Huron were observed in 2003, 2011, and 2012, and biomass has varied substantially since this species invaded the lake (Fig. 10). The estimated mean biomass of Round Goby in the main basin during the current reporting period was more than double that of the previous reporting period (Table 4). Because many Round Goby live near shore and are not well sampled by bottom trawls (e.g., Taraborelli et al. 2009), our estimates of their biomass may not reflect actual lakewide status.

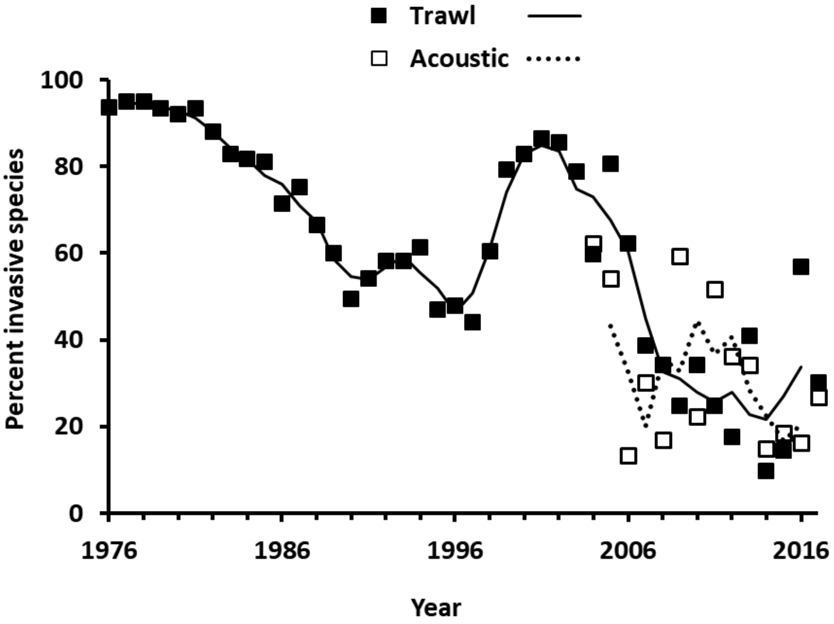
Fig. 10. Estimated biomass in kilograms per hectare of Round Goby in the main basin of Lake Huron based on bottom-trawl surveys, 1976-2017. The solid diamonds are annual mean estimates of biomass, the solid line is the three-year moving average of estimated biomass, and the error bars are 95% confidence limits for mean biomass.



Invasive Species

The mean proportion of the offshore prey-fish community biomass made up of invasive species was lower during the current reporting period than during the previous reporting period. Invasive species made up 28% of the biomass of the offshore prey-fish community in the current reporting period in both the bottom-trawl and acoustic surveys. In the previous reporting period, invasive species made up 44% of the biomass in bottom-trawl surveys and 35% in acoustic surveys (Fig. 11). All estimates of the proportion of invasive species in prey-fish biomass for the current and previous reporting periods are lower than the long-term average for the bottom-trawl survey prior to 2005 when they made up 73%, on average, of the biomass. The decline in biomass of invasive species in the offshore prey-fish community of the main basin during the last two reporting periods is consistent with the species diversity FCO (DesJardine et al. 1995), although biomass variability has been high during the two most-recent reporting periods (Fig. 11).

Fig. 11. The proportion of the total biomass of offshore prey fish in the main basin of Lake Huron that is made up of invasive species based on bottom-trawl surveys (solid squares and solid line) during 1976-2017 and on acoustic surveys (open squares and dashed line) during 2004-2017. Symbols are annual biomass estimates and lines are three-year moving averages of percent invasive species biomass.



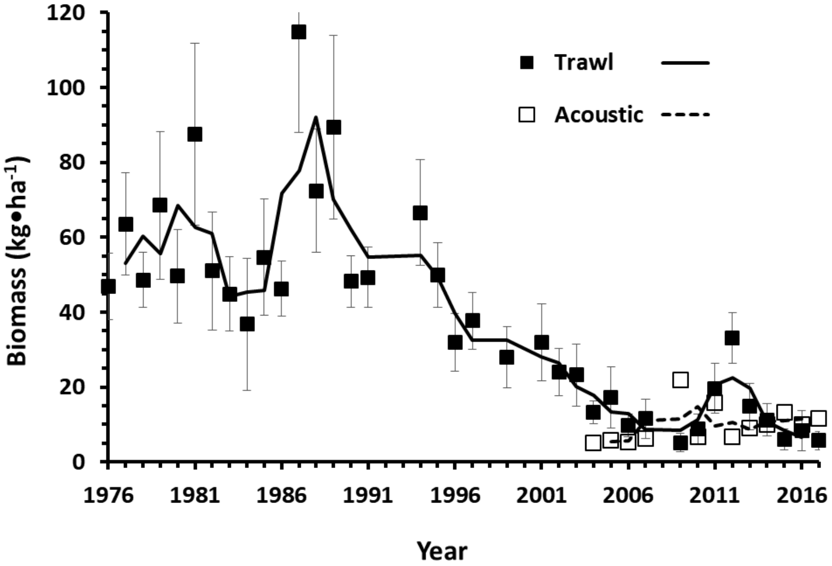
Total Biomass Index

Estimates of total offshore prey-fish biomass in the main basin have remained relatively low during the current reporting period (Fig. 12). Bottom-trawl surveys indicate that mean total prey-fish biomass increased 34% from 10.5 kg•ha^{-1} during the previous reporting period to 14.1 kg•ha^{-1} during the current reporting period. Acoustic surveys indicate total prey-fish biomass increased 19.4% from 9.1 kg•ha^{-1} during the previous reporting period to 10.9 kg•ha^{-1} during the present reporting period. Differences between the surveys may reflect primarily the high biomass estimates for Bloater in bottom-trawl surveys in the current reporting period, which were not observed in the acoustic survey.

Progress and Outlook

The estimated biomass of offshore prey fish in Lake Huron has remained at low levels through the last two reporting periods; the mean total prey-fish biomass during the last two reporting periods was about 20% of the mean during 1976-1996. Because the abundance of fish predators has remained stable or increased in parts of the lake, the FCO (DesJardine et al. 1995) is implied to have remained unmet, although current prey-fish biomass levels may be matched to the reduced primary production and biomass of zooplankton (Rudstam et al., this volume). Both the bottom-trawl and acoustic surveys indicate that total offshore prey-fish biomass was higher during the current reporting period than during the previous reporting period, but, still, bottom-trawl-based biomass estimates remain low compared to those observed prior to 2005. The bottom-trawl-based estimate of total main-basin prey-fish biomass in 2017 was the second lowest observed in the time series (Fig. 12). The status of most prey species has changed little since the previous state of the lake report (Riley 2013), and most prey species remain at low abundance relative to historical data.

Fig. 12. Estimated total offshore prey-fish biomass in the main basin of Lake Huron based on bottom-trawl (1976-2017) and acoustic (2004-2017) surveys. The squares are annual estimates of mean biomass, the line is the three-year moving average biomass, and the error bars are the 95% confidence limits for mean biomass.



The peak estimated biomass of offshore prey fish in Lake Huron occurred in the late 1980s and has declined since then, and a similar decline has occurred in Lake Michigan (Bunnell et al. 2014). These declines may be associated with reduced nutrient inputs (Dove and Chapra 2015; Barbiero et al. 2018b; Rudstam et al., this volume) and with invasive species, including dreissenids, and Round Goby, but similar declines in some species have occurred in Lake Superior (Gorman et al. 2010) where these invasive species are not abundant. Low biomass of offshore prey fish in Lake Huron also may be due to high predation levels by fish predators or Double-crested Cormorants. The abundance of Walleye (Fielder et al., this volume) and Lake Trout (He et al. 2012; Lenart et al., this volume) has increased in Lake

Huron while other predators, such as Chinook Salmon (Gonder et al., this volume) and Burbot (USGS, unpublished data), appear to be at low abundance in recent times. The relative importance of “bottom-up” (food web) or “top-down” (predation) factors in regulating prey-fish biomass in the Great Lakes is a subject of widespread debate (e.g., Bunnell et al. 2014), and further investigation is required to understand the factors responsible for continued low offshore prey-fish biomass in Lake Huron.

Continuing low levels of prey-fish biomass may have serious implications for the growth, condition, and survival of predatory fish in Lake Huron (Roseman and Riley 2009). Low biomass of Rainbow Smelt and Alewife is consistent with the species diversity FCO for Lake Huron (DesJardine et al. 1995) but may be responsible for decreased abundance and condition of Chinook Salmon (e.g., Dettmers et al. 2012; Borgeson et al., this volume), which previously relied on these species as primary prey (Diana 1990; Roseman et al. 2014). Ongoing ecosystem changes linked to invasive species may have caused a shift in Lake Huron toward a benthic- and/or nearshore-dominated food web (e.g., Hecky et al. 2004; Burlakova et al. 2018c) that is not conducive to Alewife survival or recruitment.

Differences between the bottom-trawl and acoustic surveys in the estimation of total prey-fish biomass are to be expected, as the surveys target different components of the fish community (pelagic for the acoustic survey, benthic/benthopelagic for the bottom-trawl survey). Differences in biomass estimates for individual species between the surveys on Lake Huron were often large, and may be due to differences in survey timing, spatial coverage, catchability, or methods of biomass estimation or data interpretation. Differences between bottom-trawl and acoustic-survey abundance or biomass estimates of individual species are commonly observed (e.g., Godø and Wespestad 1993; Connerton et al. 2017), and scientists working on Lake Huron are currently developing methods to integrate data from the two surveys. Because the catchability of a particular fish species is usually unknown, biomass estimates from both surveys are indices, not estimates of absolute biomass (Riley and Dunlop 2016).

The abundance of Round Goby is difficult to assess accurately in bottom-trawl surveys, which also affects the total prey-fish biomass estimate. The density of Round Goby is very high in some areas of the Great Lakes (e.g., Chotkowski and Marsden 1999; Steinhart et al. 2004), much higher than estimated here, and this species now makes up a substantial portion of the diets of multiple fish predators in Lake Huron (Roseman et al. 2014). Round Goby is cryptic and tends to occupy more-complex habitats than are sampled by bottom trawls, and many individuals are resident in nearshore environments where bottom-trawl surveys are not conducted. The estimates of total prey-fish biomass produced by the USGS may not reflect the actual biomass of all prey fish currently extant in the lake, now that Round Goby has become an important component of food webs.

In summary, total offshore prey-fish biomass in Lake Huron has remained at low levels since 2010, and there is no evidence of a recent sustained increase in biomass indices for any species. The estimated biomass of Alewife has remained extremely low. Biomass of YAO Bloater was among the highest ever observed early in the current reporting period based on bottom-trawl data, but this peak was not observed in the acoustic data, and the bottom-trawl-based biomass estimate has since declined to less than 10% of the maximum biomass observed in the time series. Emerald Shiner biomass was elevated in the main basin in three years during the past two reporting periods, but the most-recent estimates were relatively low. Several species showed increased biomass since the last reporting period, but estimated biomass for all species during the current reporting period remains low compared to historical data. It is difficult to place our estimates of prey-fish biomass in the context of primary production and predator demand, as required by the FCO (DesJardine et al. 1995), because these estimates are temporally and spatially variable, poorly quantified, and are likely to be dependent on ongoing food-web changes. Nonetheless, the low offshore prey-fish biomass observed since 2010 in both the bottom-trawl and acoustic surveys indicate little progress toward meeting the FCO.

Acknowledgments

We thank the captains and crews of the USGS R/V *Grayling*, *Sturgeon*, and *Arcticus* and the many technicians that provided field support. We also thank the vessel crews and technical staff of the U.S. Fish and Wildlife Service and the Ontario Ministry of Natural Resources and Forestry. S. Nelson, L. Zhang, and D. Benes provided database and computer support. All sampling and handling of fish were carried out in accordance with guidelines for the care and use of fish by the American Fisheries Society. Data used to generate this report are at the U.S. Geological Survey, Great Lakes Science Center, Great Lakes Research Vessel Operations 1958-2018 (ver. 3.0, April 2019): U.S. Geological Survey Data Release, https://doi.org/10.5066/F75M63X0.

STATUS OF WHITEFISHES AND CISCOES IN LAKE HURON IN 2018[10]

Adam Cottrill[11], Erin Dunlop, Steve Lenart, and Ji He

The fish community objectives (FCOs) for Lake Huron (DesJardine et al. 1995) group together Lake Whitefishes and Ciscoes in the objective for coregonines (subfamily containing all Whitefishes and Ciscoes) as follows

> *Maintain the present diversity of coregonines.*
>
> *Manage lake whitefish and ciscoes at levels capable of sustaining annual harvests of 3.8 million kg.*
>
> *Restore lake herring to a significant level and protect, where possible, rare deepwater ciscoes.*

The coregonines of Lake Huron were comprised historically of Lake Whitefish, Round Whitefish (genus *Prosopium*), two species of shallow-water ciscoes, and seven deepwater ciscoes. The deepwater ciscoes comprised *Coregonus alpenae*, *C. hoyi*, *C. zenithicus*, *C. kiyi*, *C. johannae*,

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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/Sp20_01.pdf.

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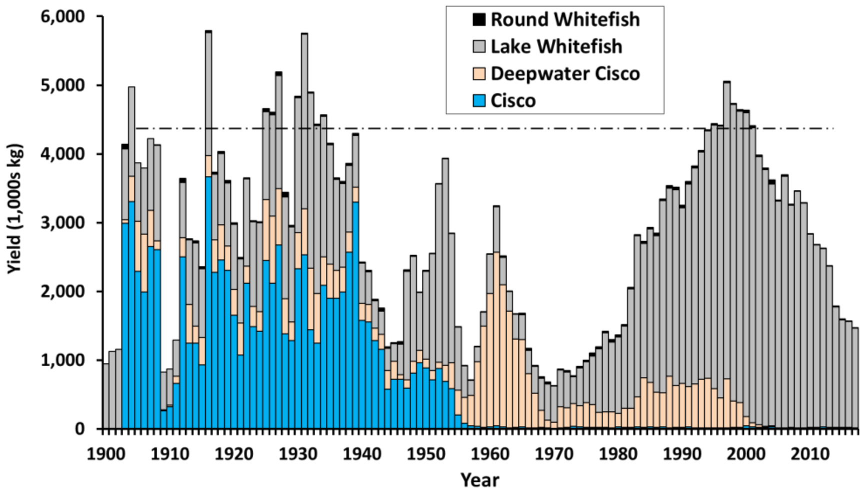
C. nigripinnis, and *C. reighardi* (see Eshenroder et al. 2016). The deepwater cisco subcomplex was altered dramatically throughout the 19th and 20th centuries causing five deepwater ciscoes to introgress into a hybrid swarm across all three basins (Eshenroder et al. 2016).

Average annual yield of all coregonines in Lake Huron was 2.12 million kg during the current reporting period of 2011-2017, 1.68 million kg below the productive capacity of 3.8 million kg envisioned in the FCOs. The total coregonine yield has been declining steadily since it peaked in 1997 at 5.05 million kg and has been below the FCO target since 2003. Coregonine yield continued to be dominated by Lake Whitefish, with other coregonines harvested only sporadically in commercial, recreational, and subsistence fisheries. For example, there was no reported harvest of deepwater ciscoes from the commercial fishery in several years during this reporting period, which represents the first time since yield statistics were collected and reported that deepwater ciscoes were not harvested from Lake Huron (Fig. 13).

Lake Whitefish

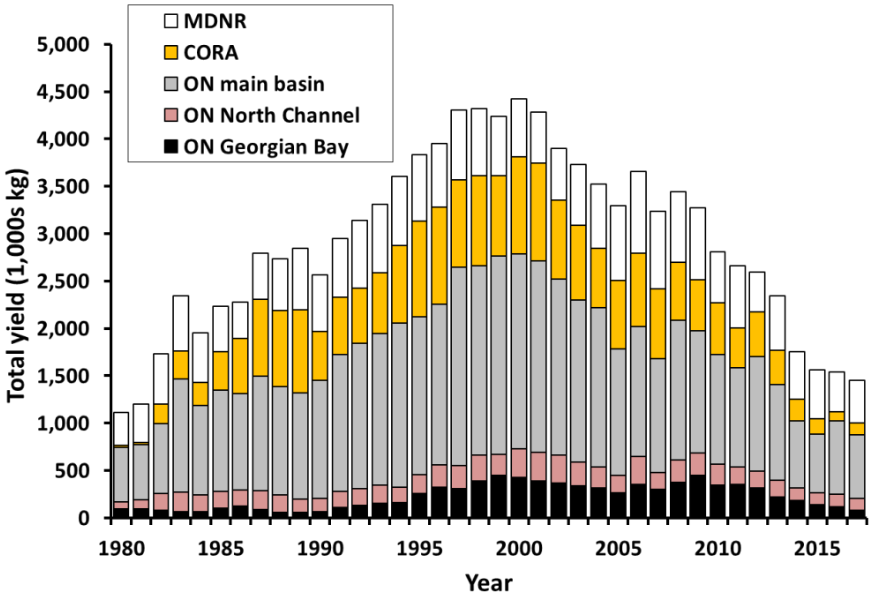
Lake Whitefish continued to be the dominant species harvested by the commercial fishery during the current reporting period of 2011-2017, with annual harvest averaging 2.09 million kg and representing 65-77% of total commercial yield. The proportion of the lakewide harvest composed of Lake Whitefish declined during the current reporting period and has declined almost continuously since peaking at 4.43 million kg in 2000 (Fig. 13). The lakewide yield declined from 2.8 million kg in 2010 to 1.4 million kg in 2017.

Fig. 13. Total annual commercial yield of coregonines from Lake Huron, 1900-2017. The dashed horizontal line indicates the fish community objective of 3.8 million kg.



The decline in yield was most pronounced in the northern and central portions of the main basin and in southern Georgian Bay, although the harvest has declined throughout Lake Huron from the peaks observed in the late 1990s and early 2000s (Fig. 14). During this reporting period, yield from the Ontario waters of the northern and central main basin averaged 16% and 36% from their peak values in 2000 while the yield in southern Georgian Bay averaged 43% of its 2000 peak.

Fig. 14. Total annual commercial yield of Lake Whitefish reported by each management agency in the three basins of Lake Huron during 1980-2017. MDNR is the Michigan DNR, CORA is the Chippewa Ottawa Resource Authority, and ON is the Ontario Ministry of Natural Resources and Forestry.



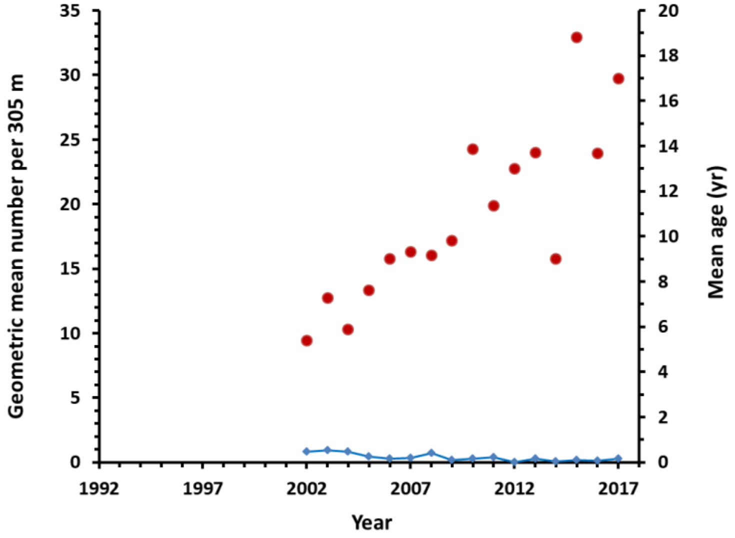
Part of the decline in lakewide yield was associated with a reduction in commercial fishing effort during the current reporting period. Between 1980 and 2010, total large-mesh-gillnet effort fluctuated without trend at 14,000 km•y^{-1} and peaked in 2002 at 17,700 km. Total gillnet effort declined steadily after 2002, and the effort in the current reporting period was among the lowest in the last 40 years. Total lakewide gillnet effort in 2017 was 11,900 km, a 33% decline from its peak in 2002. Lakewide trapnet effort, like gillnet effort, has declined steadily since 1999 after being relatively stable at approximately 10,000 lifts•y^{-1} through most of the 1980s and 1990s. The number of trapnet lifts declined during the current reporting period from 6,350 in 2010 to 3,340 in 2017.

Notwithstanding reductions in fishing effort, the decline in commercial yield of Lake Whitefish is largely attributable to substantial reductions in recruitment, which appears to be most pronounced in the northern half of the main basin and in southern Georgian Bay. Pre-recruit indices of individual year-classes at ages 1-3 in graded-mesh-gillnet surveys in those locations declined quickly (Fig. 15). All pre-recruit indices for year-classes following 2001 in Georgian Bay and 2003 in the central main basin were well below the long-term average, and several year-classes were not observed at all. In southern Georgian Bay and the central main basin, a declining trend in catch-per-unit effort (CPUE) and a concomitant increase in mean age of Lake Whitefish were evident. In the southern main basin, CPUE has declined to a lesser degree, but mean age has remained essentially unchanged.

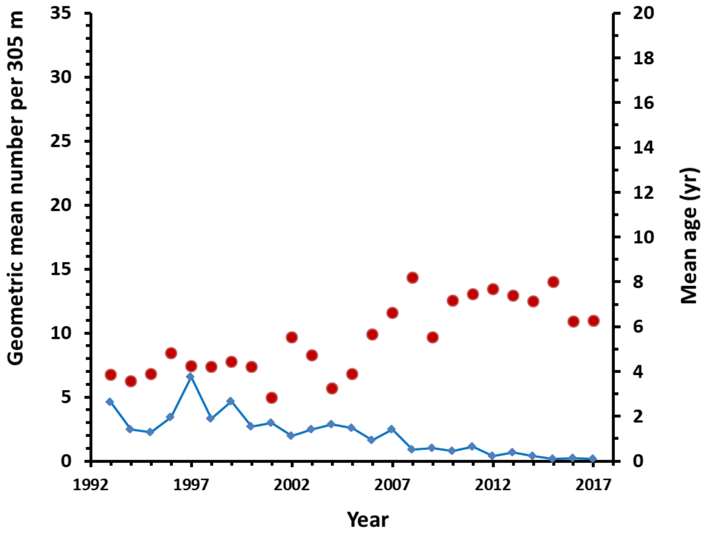
Gillnet surveys in northern U.S. waters show similar patterns indicating a dramatic decline in recruitment beginning with the 2003 year-class and no evidence that recruitment of subsequent year-classes improved. Mean CPUE and mean age observed in gillnet surveys in the northwestern part of the main basin near Thunder Bay also show a declining trend in CPUE and a concomitant increase in mean age from 7 to 17 years (Fig. 15).

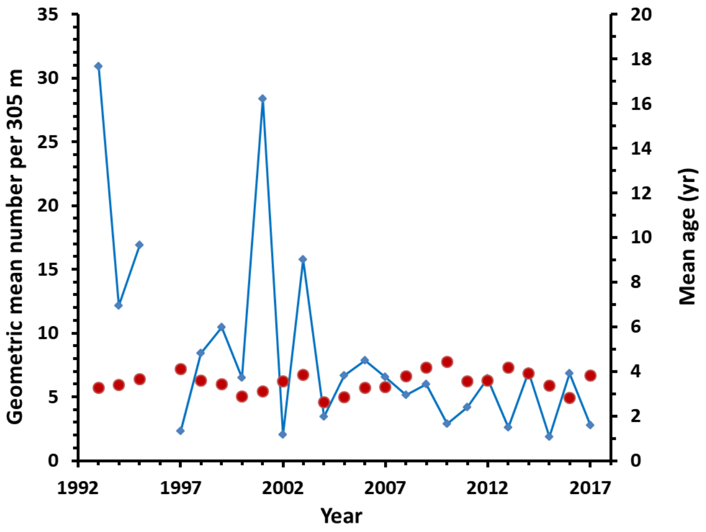
Fig. 15. Geometric mean catch-per-unit effort (blue line) and mean age (red circles) of Lake Whitefish caught in graded-mesh-gillnet surveys in four regions of Lake Huron, 1993-2017.

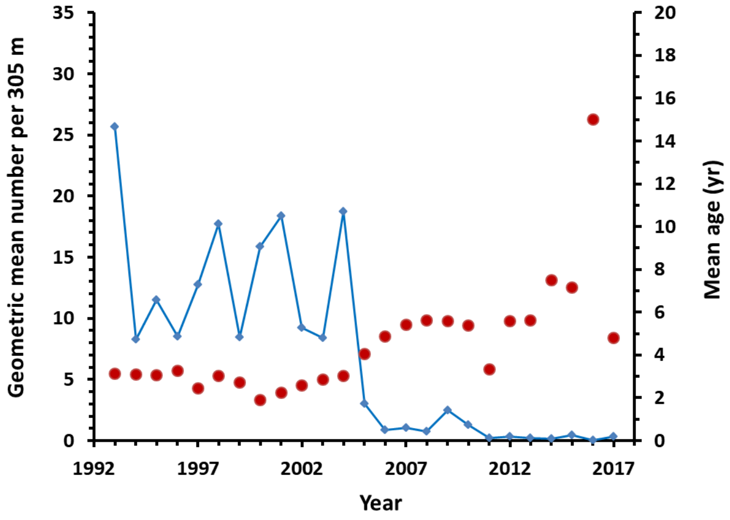
Northern-central Michigan main basin



Central Ontario main basin




Southern Ontario main basin

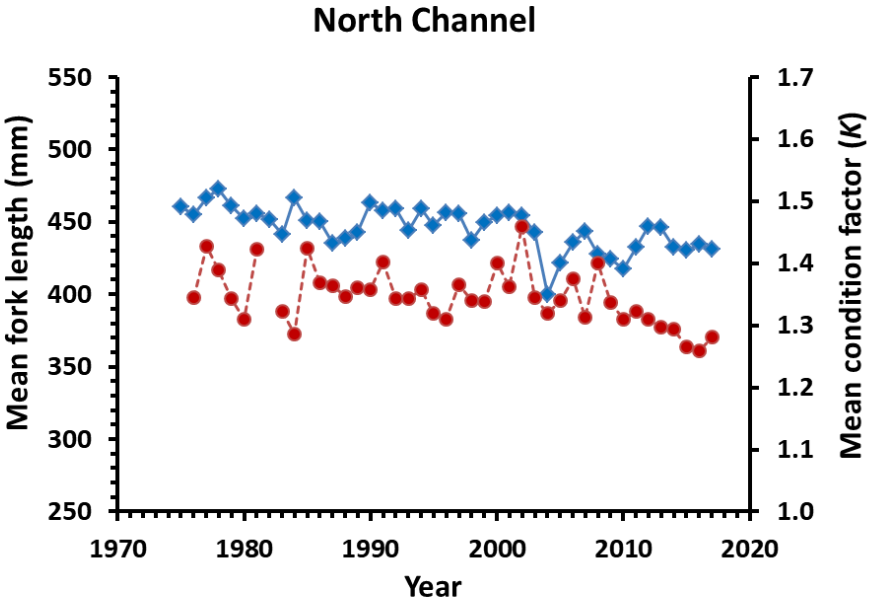

Southern Georgian Bay

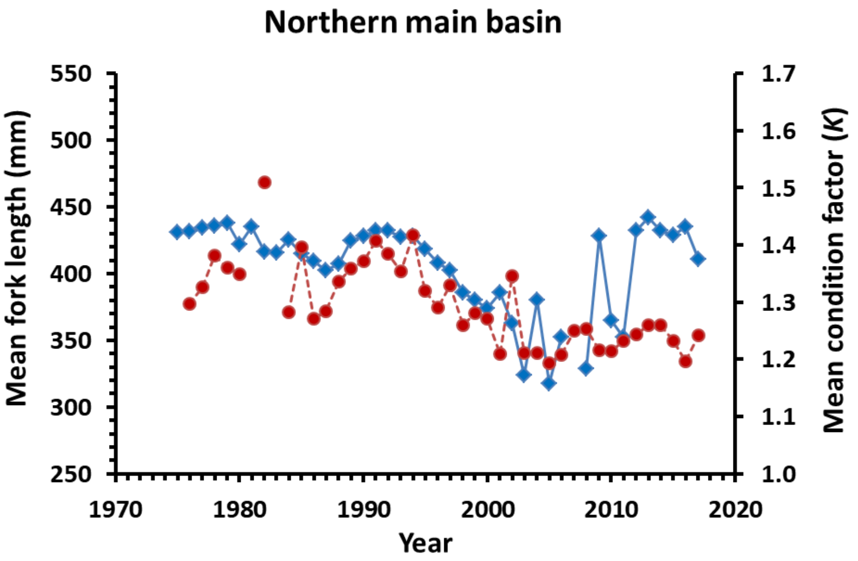
The recruitment decline was seen also in the age-composition of the commercial harvest, with the mean age now approaching or exceeding 10 years or more in many parts of the lake. This change is evident also in the number of young fish estimated in statistical catch-at-age (SCAA) assessments, which are used to estimate the abundance, biomass, and population dynamics of Lake Whitefish populations over most of Lake Huron. Dramatic declines in the SCAA-predicted number of age-4 fish recruiting to the population were widely evident. After successive, strong year-classes through most of the 1990s and early 2000s, the number of age-4 fish entering the population has declined, typically to levels comparable to the earliest and lowest parts of the modeled time series (Lenart and Caroffino 2018). While SCAA models indicate nominal recruitment for U.S. waters, recruitment continues to be suppressed in Ontario waters, particularly in the central and northern main basin and in southern Georgian Bay.

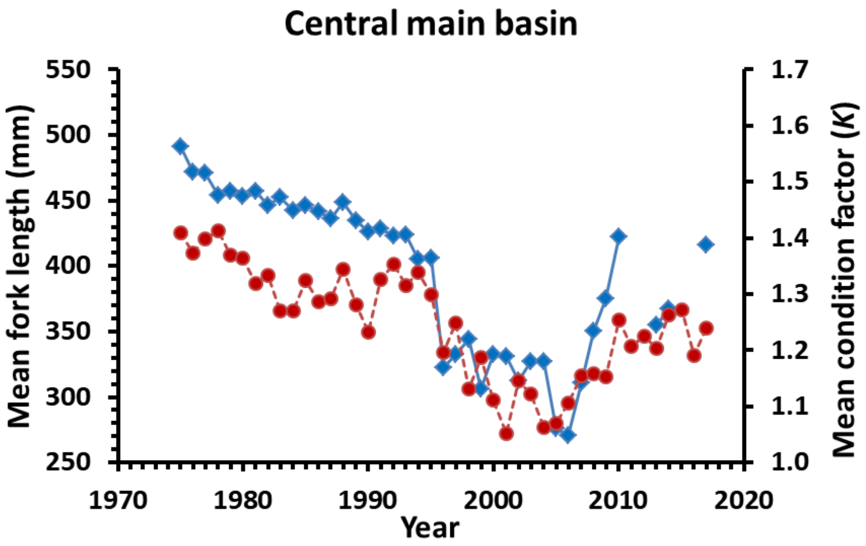
Similar patterns in SCAA estimates of total- and spawning-stock biomass were evident. While close synchrony in temporal patterns of biomass is lacking, enough similarities exist to suggest that broad-scale ecological phenomena have been influencing population dynamics. In most parts of the lake, current levels of biomass are considerably lower than they were in the mid-1990s and early 2000s. The magnitude of the decline and exact timing varied by region. The SCAA models for U.S. waters of the main basin indicate that the decline has leveled off (biomass has increased slightly in recent years) whereas models in many Ontario management areas suggest that the decline is continuing and that current biomass is lower than at any time since the late 1970s or early 1980s.

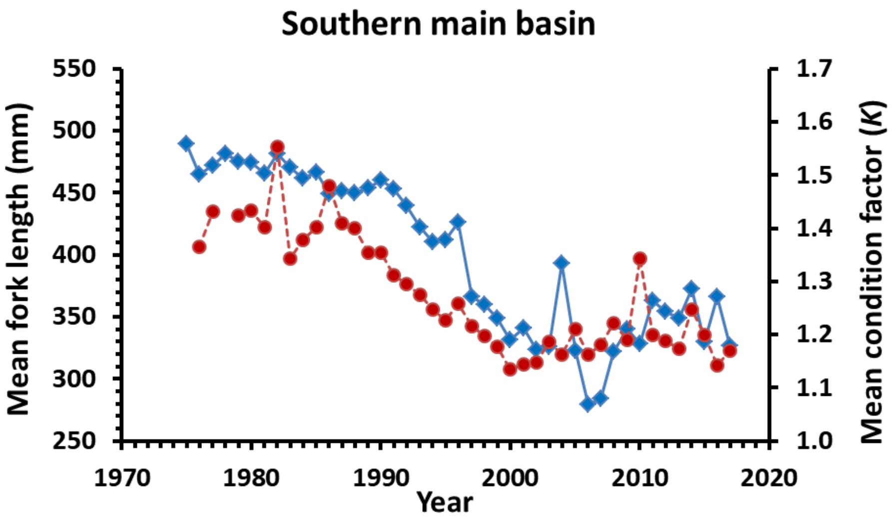
As recruitment and population abundance declined in Lake Huron, growth (as represented by mean fork length at age 4) and condition of Lake Whitefish changed, but the timing and magnitude of the changes and any associated recovery differed by lake region (Fig. 16). Substantial changes in both condition and length at age 4 were evident in all three regions of the main basin; however, only the mean length of age-4 fish changed notably in southern Georgian Bay. In contrast, both mean length of age 4 fish and condition consistently declined in the North Channel through the current reporting period. The rapid and substantial changes that occurred in growth and condition prior to this reporting period were associated with a lakewide regime shift, although a lesser amount of the variation was attributed to other factors, such as density dependence and increases in growing degree days (Riley and Adams 2010; Fera et al. 2015; Gobin et al. 2015).

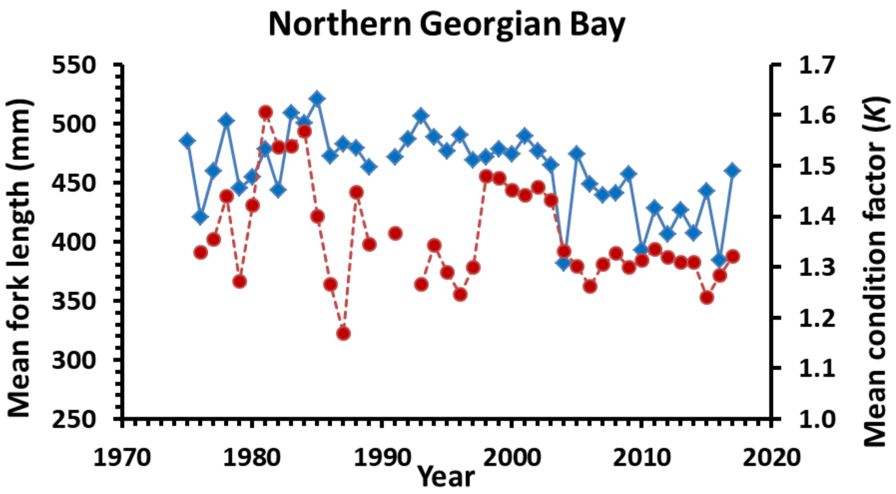
Fig. 16. Mean fork length (blue diamonds and line) and mean condition factor (red circles and line) of age-4 Lake Whitefish caught in six regions of Ontario waters of Lake Huron, 1975-2017.

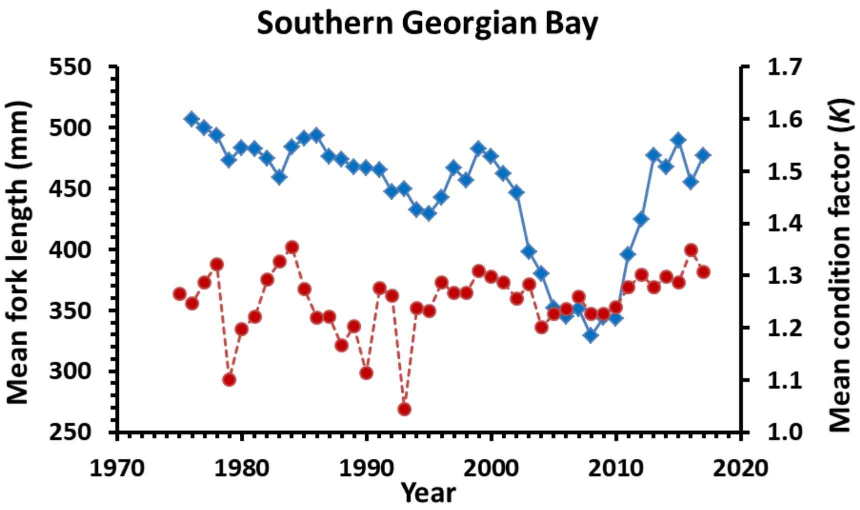



Northern main basin
Mean fork length (mm)
550
500
450
400
350
300
250
Mean condition factor (K)
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
1970
1980
1990
2000
2010
2020
Year


Central main basin
Mean fork length (mm)
550
500
450
400
350
300
250
Mean condition factor (K)
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
1970
1980
1990
2000
2010
2020
Year


Southern main basin


Northern Georgian Bay



Length at age and condition of Lake Whitefish have recovered in some but not all areas during 2011-2017. Length at age in both the northern main basin and southern Georgian Bay returned to levels observed in the 1980s and early 1990s, and both indices for the central main basin have recovered partially. Condition has stabilized in the northern main basin but continues to be below the long-term average. In the southern main basin, there is little evidence of recovery in either condition or length at age, with values during the current reporting period similar to the low values observed between 2000 and 2010. The increased prevalence of Round Goby in the diet of Lake Whitefish may account for the recent growth spurt in some locations (Pothoven and Madenjian 2013).

The ecosystem changes resulting from the invasion and proliferation of dreissenids are the most likely cause of the changes in growth and condition and in the low recruitment of Lake Whitefish that continued into the current reporting period (Pothoven and Madenjian 2008; Rennie et al. 2009; Fera et al. 2015; Gobin et al. 2015). In addition to those changes, Lake Whitefish has undergone shifts in distribution, diet, and density dependence (Pothoven and Madenjian 2008; Riley and Adams 2010; Pothoven and Madenjian 2013; Rennie et al. 2015; Gobin et al. 2016; Fera et al. 2017). These changes occurred not only in Lake Huron but broadly across the Great Lakes (except in Lake Superior) and in inland lakes that contain dreissenids (Pothoven et al. 2001; Lumb and Johnson 2008; Rennie et al. 2012; Herbst et al. 2013; Rennie et al. 2013; Rennie et al. 2015; Fera et al. 2017). Multi-agency research and monitoring programs are underway to investigate the role of zooplankton density and loss of the spring plankton bloom on larval growth and survival. Current conditions in Lake Huron do not appear capable of supporting the same levels of spawning biomass and recruitment as in the 1990s and early 2000s resulting potentially in lower yields for the foreseeable future (Gobin et al. 2016).

Cisco

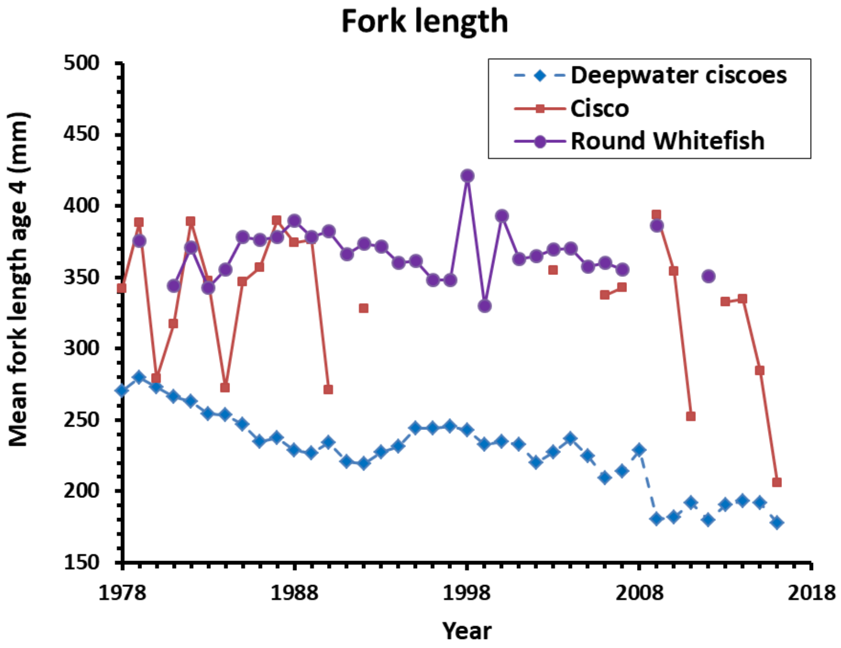
Cisco continues to be common in Georgian Bay, the North Channel, St. Marys River, and the very northern Michigan waters of Lake Huron’s main basin. Sporadic catches of juveniles in central and southern main-basin index netting indicate that Cisco is widely spread in Ontario waters but less so in Michigan waters.

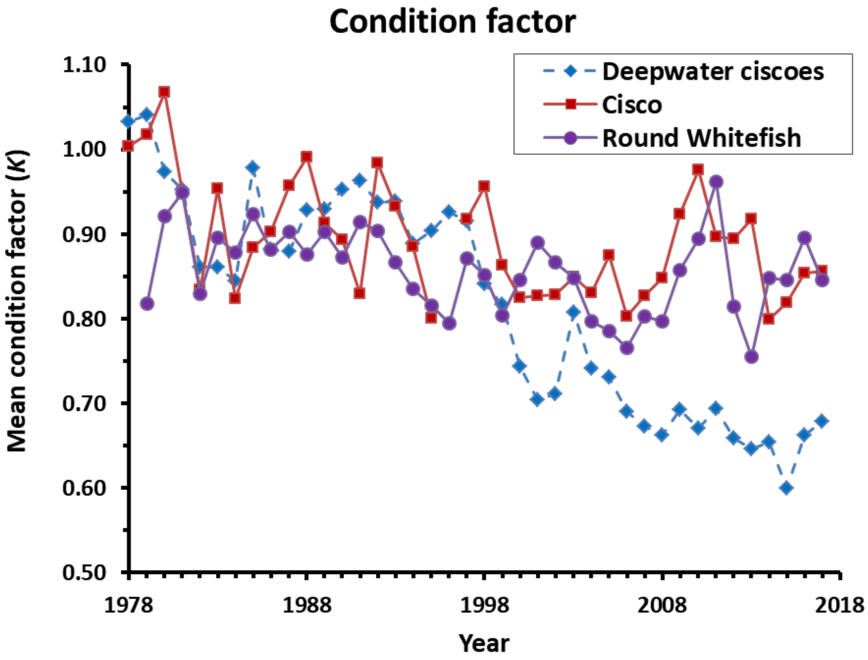
The lakewide commercial yield of Cisco averaged 18,400 kg•y^{-1} during the reporting period. Virtually all of it was taken from the North Channel and northern U.S. waters. Total yield has remained essentially unchanged over the past 40 years, averaging 19,300 kg•y^{-1} since 1980. However, over that time, yield shifted away from Georgian Bay and Ontario waters of the main basin to the North Channel and U.S. waters of the northern main basin.

In Ontario waters, mean fork length, mean length at age 4, and condition factor of Cisco have been much more variable than the same metrics for other coregonines, but trends are not evident over the last 40 years (Fig. 17). In U.S. waters of the main basin, Cisco is largely restricted to areas from the Straits of Mackinac to Drummond Island. More importantly, the species remains absent from Saginaw Bay where it once supported the largest Cisco fishery and spawning stock in Lake Huron (Koelz 1929). The lack of recovery in Saginaw Bay diminishes the possibility of achieving the coregonine FCO.

Rehabilitation strategies for the western main basin have received increased focus in recent years because fishery agencies are recognizing the important ecological role that Cisco historically played in the pelagic fish community. Recovery efforts are expected to commence in 2018, with implementation of a 10-year stocking study set to begin in Saginaw Bay.

Fig. 17. Mean fork length at age 4 (mm) and mean condition factor (*K*) for deepwater ciscoes, Cisco, and Round Whitefish caught in Ontario waters of the main basin during 1978-2017. Condition factor was estimated as weight/length^3 x 10,000 (see Anderson and Newman 1996; Blackwell et al. 2000).





Deepwater Ciscoes

Deepwater ciscoes were once a substantial component of the total coregonine yield from Lake Huron (Fig. 13). Lakewide commercial harvest averaged only 170 kg•y^{-1} during the reporting period, and in several years there was no harvest. In comparison, 717,000 kg were reported in 1997, which represented 12% of the total commercial yield in that year.

Despite the extremely low commercial harvest during the current reporting period, deepwater ciscoes continue to be common in the prey-fish community in offshore waters of Lake Huron and represented more than half of pelagic biomass in 2017 (O’Brien et al. 2018). While deepwater ciscoes are captured consistently in graded-mesh-gillnet surveys of southern

Georgian Bay and central and southern waters of the main basin, catches were much lower during the reporting period than prior to 2000, even in the smallest of survey mesh sizes, suggesting changes in selectivity are not affecting survey catches. Moreover, condition and mean length of age-4 fish continued to be much smaller than observed in the 1980s and 1990s (Fig. 17). Mean length at age 4 and mean condition factor appear to have stabilized during the current reporting period in most areas after declining for close to two decades, but both statistics continue to be among the lowest values observed in the time series. Individuals large enough to be vulnerable to commercial fishing were rare as fish larger than 200 mm constituted only 5% of survey catches compared to almost 80% of the fish sampled between 1990 and 2000.

Round Whitefish

Total yield of Round Whitefish during the reporting period ranged from 4,100 to 18,000 kg•y^{-1}, which was lower than reported between 1980 and 2005 when yields regularly exceeded 25,000 kg•y^{-1}. Most of the commercial harvest during the reporting period occurred in northern Georgian Bay, North Channel, and U.S. waters of the northern main basin. Round Whitefish are rarely observed in the commercial fishery in other parts of the lake owing possibly to low market demand, although they were historically abundant and large-sized in central U.S. waters (R. Eshenroder, Great Lakes Fishery Commission, personal communication, 2019). Unlike Cisco, the total number of Round Whitefish observed has declined over the reporting period in many locations, particularly in the North Channel and the northern main basin, although these declines could reflect changing fisheries or sampling programs rather than a change in abundance.

The time series for mean length at age 4 and condition factor of Round Whitefish has been extremely variable because of small sample sizes or inconsistent sampling in many locations, making it difficult to discern trends. The Ontario Ministry of Natural Resources and Forestry central-main-basin survey was a notable exception; here, Round Whitefish condition factor increased steadily since its low point in 2006. Condition factor during the current reporting period was comparable to that observed during the 1990s, although it was still lower than the highest values reported in the

1980s. Index catches of Round Whitefish from the central main basin have been slowly declining since the mid-1990s resulting in the current reporting period having the lowest catches in the time series.

Conclusion

Owing to widespread changes documented in the lower food web (Rudstram, et al., this volume), the yield objective for coregonines is unlikely to be met in the foreseeable future. Declines and very low levels of recruitment, relative abundance, and reduced yield of Lake Whitefish cannot be rectified by management, notwithstanding the importance of the species to the lake's ecology and fisheries. While deepwater ciscoes continue to be a major component of the offshore pelagic fish community, their total biomass and the growth of individual fish limit their potential yield. Round Whitefish continues to be widespread in the nearshore waters of the basin but is rarely harvested in the commercial fishery. Similarly, Cisco is largely absent from the southern half of the main basin. Rehabilitation of Cisco in Saginaw Bay will continue to be an important objective if the potential coregonine yield envisioned in the FCOs for Lake Huron is to be met.

STATUS OF LAKE TROUT IN LAKE HURON IN 2018[12]

Stephen J. Lenart[13], Chris Davis, Ji X. He, Adam Cottrill, Stephen C. Riley, Scott R. Koproski, and Paul Ripple

The collapse of Lake Trout populations in Lake Huron during the 1940s and subsequent efforts that began during the 1970s to re-establish self-sustaining populations through planting of hatchery-reared fish and control of Sea Lamprey have been well documented (Eshenroder et al. 1995; Johnson et al. 2004). Despite minimal progress toward rehabilitation being realized over the ensuing decades, fishery managers, nonetheless, anticipated a dominant role for Lake Trout in the salmonine community (DesJardine et al. 1995). Lake Huron fish community objectives (FCOs) state that management agencies should

> *Establish a diverse salmonine community that can sustain an annual harvest of 2.4 million kg with lake trout the dominant*

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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/Sp20_01.pdf.

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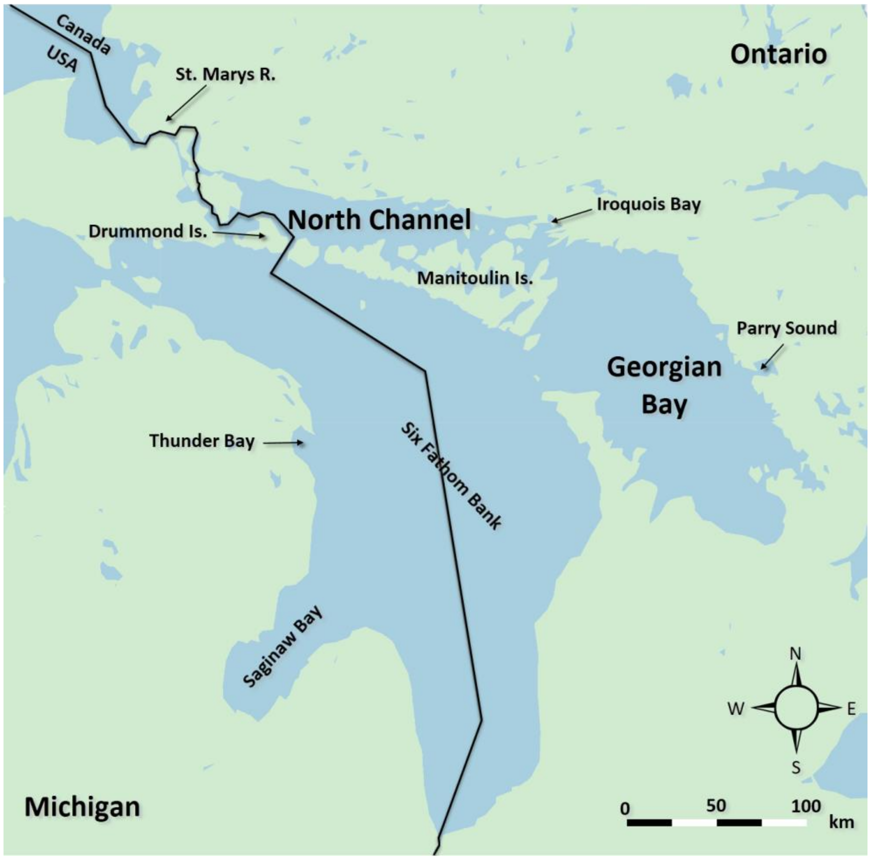
species and anadromous (stream-spawning) species also having a prominent place.

Lakewide yields of 1.4 to 1.8 million kg of Lake Trout were considered plausible by DesJardine et al. (1995) once self-sustaining populations were achieved. Managers also acknowledged the need to control harvests of Lake Trout and further reduce Sea Lamprey predation if restoration and the yield objective were to be realized. Lakewide and agency-specific management strategies (Ebener 1998; OMNRF 2012), coupled with formal management agreements such as the 2000 Consent Decree (https://www.michigan.gov/dnr/0,4570,7-350-79136_79236_80538_80541-424734--,00.html), provided an essential framework for attaining rehabilitation goals, yet impediments remained through the early 2000s. Nonetheless, this framework, along with dynamic changes in the lake's ecology (Riley et al. 2008; Riley and Adams 2010), proved critical to the continued progress toward rehabilitation, which has been realized across broad areas of the lake since the previous state of the lake report (Riley 2013).

Lakewide yields of Lake Trout were stable during the current reporting period (2011-2017), ranging between 0.35 and 0.42 million kg•yr^{-1}, and the average yield was down only slightly from that observed during the previous reporting period (2005-2010). No major patterns in yields were obvious, except perhaps a slight increase in recreational-fishery yields in U.S. waters during 2016 and 2017. Commercial fisheries remain the dominant source of exploitation of Lake Trout, accounting for roughly 70% of the lakewide yield in the main basin. It is worth noting, however, that commercial fishing effort has generally declined during the current reporting period concurrent with declines in Lake Whitefish abundance because the two species co-occur and effort for Lake Whitefish has decreased. Consequently, the stable yields can be attributed to increased catch rates, although regional differences are evident. Comparing current yields to the FCO benchmark has limited value given that Lake Trout stocks are still in an early phase of rehabilitation. Should ecosystem productivity prove insufficient to support higher levels of reproduction and recruitment than currently observed in the southern main basin and Georgian Bay (Fig. 18), achieving the sustained yields identified in the salmonine FCO (1.4 to 1.8 million kg) appear unlikely.

Fig. 18. Map of Lake Huron.



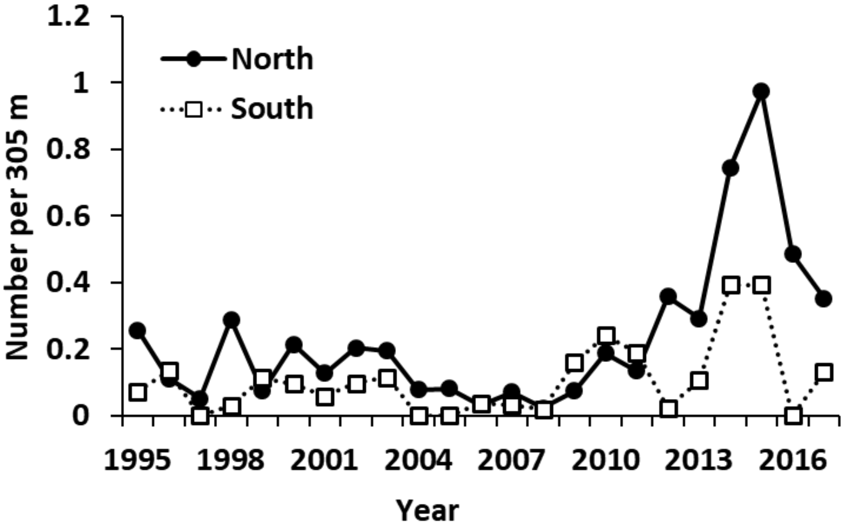
Natural Reproduction

Prior to 2004, evidence of reproduction by Lake Trout in Lake Huron was limited to a few discrete areas (Anderson and Collins 1995; Johnson and VanAmberg 1995; Reid et al. 2001). Enhanced Sea Lamprey control on the St. Marys River (Morse et al. 2003) substantially reduced Sea Lamprey-induced Lake Trout mortality (Madenjian et al. 2008; He et al. 2012) and enabled improved survival of Lake Trout stocked in the main basin after 1996, triggering a build-up of adult stocks throughout the main basin. Following substantial ecological changes that occurred during the early 2000s (Riley et al. 2008), including the collapse of Alewife populations, widespread natural reproduction of Lake Trout was observed in the main basin (Riley et al. 2007). By 2010, wild Lake Trout was recruiting to the adult stock throughout the main basin (He et al. 2012) as well as in the western end of the North Channel. The Ontario Ministry of Natural Resources and Forestry (OMNRF) had focused most of its rehabilitation effort in Georgian Bay, but survival of fish stocked after 2001 was poor, wild fish were rare, and, during the 2000s, progress toward rehabilitation objectives lagged relative to the progress in the main basin.

Genetic strain selection has played an important role in the reproductive success of Lake Trout. Stocking of yearlings has been the primary management tool used to bolster populations. During 1995-2010, annual basinwide stocking averaged 3.1 million fish. Georgian Bay and U.S. waters of the main basin received the most yearlings, but, more importantly, Seneca-strain Lake Trout became the dominant strain stocked in the main basin beginning in the mid-1990s while stocking in Georgian Bay relied principally on Great Lakes strains, although 5% were of Seneca-strain origin. Based on collections of unclipped Lake Trout during 2009-2012, 52-94% of 1,100 fish that were genotyped from the main basin and North Channel were estimated to be of Seneca-strain origin. While Seneca-strain Lake Trout was also represented in samples of unclipped Lake Trout from Georgian Bay, Manitou-strain fish represented the largest proportion (roughly 37%) of wild recruits (Scribner et al. 2018). Manitou-strain Lake Trout originated from an inland lake on Manitoulin Island. Given the apparent importance of strain to the rehabilitation process, the use of Great Lakes strains for stocking in Georgian Bay may partly, and paradoxically, explain the contrast in rehabilitation success relative to the main basin. During the current reporting period, an average of 3.3 million yearling Lake Trout were stocked annually into Lake Huron’s three basins; 10% in the North Channel, 41% in Georgian Bay, and 49% in the main basin. Beginning in 2013, a native Parry Sound, Ontario, strain (see Reid et al. 2001) replaced the Lewis Lake strain in the mix of fish stocked into U.S. waters of the main basin. The number of Parry Sound-strain fish stocked into U.S. waters of the main basin is now nearly equal to the number of Seneca-strain fish.

Wild Lake Trout continued to recruit to survey and fishery catches throughout much of Lake Huron during the reporting period, indicating that many areas continue to be favorable for natural reproduction. The consistent natural reproduction may partially be due to the lack of Alewife in the lake and the increase in thiamine levels in Lake Trout eggs (Riley et al. 2011). Wild Lake Trout made up 40-70% on an annual basis of the fishery and survey catches in the north-central main basin and western end of the North Channel in 2017, compared to 12-52% during the previous reporting period (2005-2010). The contribution of wild Lake Trout to fisheries and surveys is lower in the southern main basin, the eastern end of the North Channel, and much of Georgian Bay, indicating that most of the reproduction occurs in the northern part of the main basin where there is a large concentration of favorable spawning habitat (Riley et al. 2014). The southern shore of Drummond Island was set aside as a Lake Trout refuge in 1985 and likely enhances reproduction overall. Surveys conducted in U.S. waters indicate a substantial increase in relative abundance of wild juvenile Lake Trout during 2011-2015 (Fig. 19), with abundant 2010 and 2011 year-classes. Relative abundance of wild juveniles in U.S. waters during the reporting period remains higher than most years in the time series, and production of wild year-classes continues to be documented, although abundance of wild juveniles declined somewhat after 2014.

Fig. 19. Geometric mean number of wild Lake Trout <533-mm total length caught per 305 m of graded-mesh net in U.S. waters of the main basin of Lake Huron during the spring of 1995-2017. The north area includes all Michigan waters from Thunder Bay north, while the south area is all Michigan waters south of Thunder Bay.



Although no comparable index of wild-fish abundance exists for Ontario waters, substantial numbers of unclipped Lake Trout started to appear in OMNRF monitoring programs during the previous reporting period (2005-2010), and that trend continued during the current reporting period. Unclipped Lake Trout made up more than 25% of commercial catches in all three basins during the previous reporting period whereas unclipped fish made up more than 75% of commercial catches in the North Channel and Ontario's main basin during the current reporting period. In contrast, the proportion of wild fish in commercial catches in Georgian Bay remained unchanged between reporting periods, fluctuating at around 25%.

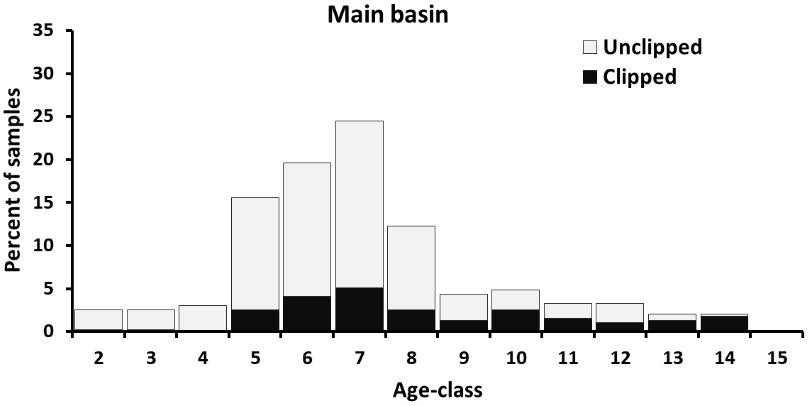
The status of localized remnant populations in Parry Sound and Iroquois Bay has been of special interest for assessing population recovery and its sustainability. Surveys conducted by the OMNRF during the current reporting period indicate that the population in Parry Sound meets the recovery target for adult abundance (OMNRF 2012). The population is composed almost exclusively of wild fish, and recruitment remains strong. One concern noted during these surveys, however, was a relatively high incidence of Sea Lamprey marks on Lake Trout. In contrast to Parry Sound, surveys in Iroquois Bay indicate a population with few adult Lake Trout, low levels of natural reproduction, and few signs of progress toward rehabilitation objectives (OMNRF 2012). Such disparate patterns highlight the important influence of local dynamics on these smaller, isolated populations.

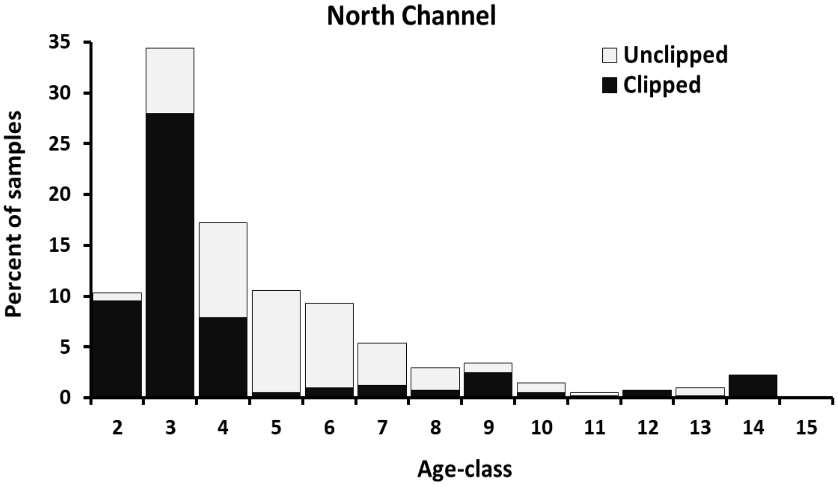
Age Structure and Survival

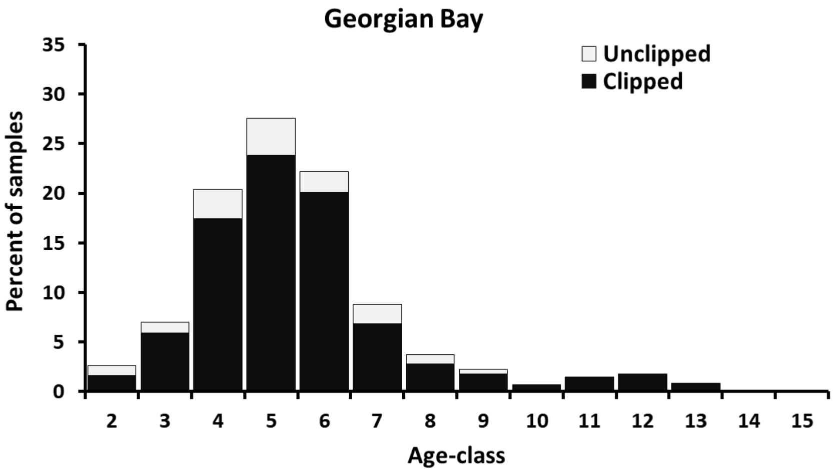
Age composition of wild Lake Trout has broadened substantially in some parts of Lake Huron during the current reporting period. In the main basin, wild fish were numerically the dominant form for most year-classes younger than age 10, and they made up a large proportion of year-classes up to age 13. This trend is evident in the western part of the North Channel as well, where wild fish dominated year-classes from age 5 through age 10 and were represented in year-classes through age 13 (Fig. 20). Wild Lake Trout were also present in Georgian Bay, but they were much less abundant than stocked (clipped) fish at all ages.

High initial survival of stocked Lake Trout, coupled with low mortality on adult fish, has allowed hatchery fish stocked after 1996 to persist in the population insomuch as age-20 and older fish were relatively common in northern Lake Huron. In contrast to the main basin and parts of the North Channel, the age distribution of Lake Trout in Georgian Bay, excluding Parry Sound, continues to be made up of young fish, a result of poor post-stocking survival. While fish older than 12 years are occasionally observed in Georgian Bay, most are between 4 and 8 years of age, and the mean age continues to be below the age of maturity.

Fig. 20. The proportion of fin-clipped and unclipped Lake Trout in commercial-fishery catches observed by the Ontario Ministry of Natural Resources and Forestry in Ontario's three basins of Lake Huron during 2017.







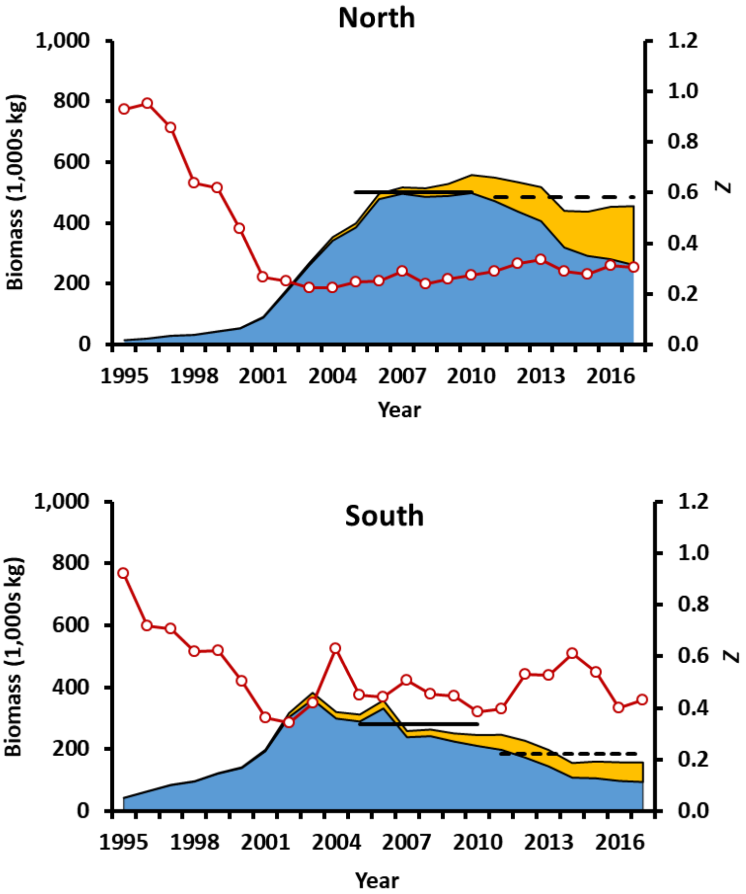
Survival of stocked Lake Trout has shown a marked decline after 2000 (He at al. 2012). That decline has continued during the current reporting period (2011-2017) and is consistent with observations from Lake Superior after wild fish resurged there (Hansen et al. 1994). During 2002-2009, as adult abundance increased in the main basin and after Alewife populations collapsed, catch rates of age-7 Lake Trout per million stocked catch-per-unit-effort (CPUE/age-7 recruit) in U.S. waters averaged 1.8 in northerly waters and 3.1 in southerly waters. During the present reporting period, the average CPUE/age-7 recruit declined to 0.3 in both the northern and southern main basin. Thus, in U.S. waters, survival of stocked Lake Trout declined 83-90% from the previous reporting period to the present reporting period. A decline in the survival of fish stocked in Georgian Bay was also evident, as CPUE/age-5 recruit declined from approximately 1.0 for year-classes stocked in the 1990s to nearly nothing for year-classes after 2000. Unlike in the main basin where the presence of an increasing adult stock was evident, adult biomass in Georgian Bay during the current reporting period was lower than in the previous decade, suggesting an alternative, unexplained mechanism behind the poor survival of stocked fish. There is no comparable metric of stocked-fish survival for the North Channel.

Research into Lake Trout movements coupled with genetic information on the contributions of Lake Trout strains to natural reproduction (Scribner et al. 2018) provide an improved understanding of stock structure and movement dynamics in Lake Huron. Binder et al. (2015, 2017), using acoustic telemetry, demonstrated strong spawning-site fidelity, with little evidence of mixing among spawning populations from Thunder Bay and Drummond Island within U.S. waters of the main basin. Fish from these spawning populations moved across adjacent jurisdictional- and management-unit boundaries during the non-spawning season with a small proportion exhibiting long-range movement. These observations suggest the need to re-evaluate the spatial delineation of management-unit boundaries for Lake Trout in Lake Huron (He 2019).

Abundance and Survival

In the main basin, statistical catch-at-age stock assessments are now structured to provide estimates of abundance, biomass, and mortality across broad spatial scales (i.e., northern and southern waters). Total spawning biomass in the northern main basin increased during the reporting period over that during the previous reporting period due to the increase in abundance of wild fish (Fig. 21). Mortality rates in the northern main basin are much lower than the 40% rehabilitation target (Ebener 1998), and Sea Lamprey-induced mortality has remained well below the high levels observed during the mid-1990s. Mortality on adult fish in the southern main basin is higher than in the north yet still near the mortality target. The decline in survival of stocked fish has resulted in a lower spawning biomass during this reporting period as compared to the previous reporting period. Natural reproduction in the south has been insufficient to offset continued declines in the survival of stocked fish, and current mortality rates may be unsustainable under these conditions, suggesting a need to re-evaluate the use of a total mortality target as a stand-alone management tool in the south. Nonetheless, spawning biomass of wild fish has increased in the southern main basin since the last reporting period, although the source(s) of recruitment there need further exploration, particularly recruitment from the Six Fathom Bank refuge.

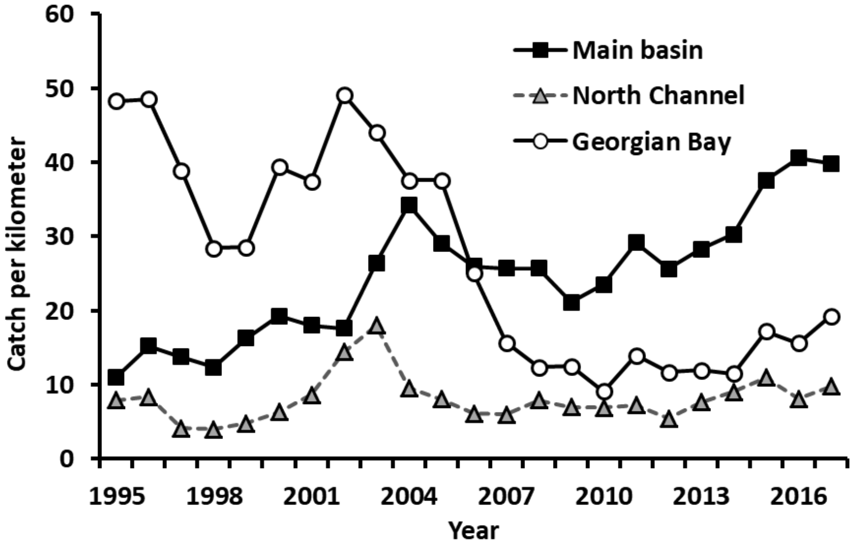
Fig. 21. Statistical catch-at-age estimates of wild (orange) and hatchery (blue) female Lake Trout-spawning biomass and instantaneous total mortality rate (*Z*, red line/white circles) in the northern and southern main basins of Lake Huron during 1995-2017. The northern area includes statistical districts MH-1, MH-2 and OH-1, and the southern area includes districts MH-3, 4, 5, and 6 and OH-3, 4, and 5. Black horizontal lines represent average spawning biomass for the previous (solid) and current (dashed) reporting periods. Instantaneous mortality (*Z*) is the average for ages 6-11 fish of both sexes.



Stock assessment models do not exist for Georgian Bay or the North Channel; consequently, inferences on trends in abundance and mortality are drawn from commercial fishery statistics. The commercial catch rate of Lake Trout in Georgian Bay shows that abundance was highest between 1995 and 2002 and declined precipitously from 50 kg•km^{-1} in 2002 to less than 10 kg•km^{-1} in 2010. The commercial catch rate in Georgian Bay during the current reporting period has increased over the previous reporting period, although catch rates remained below 20 kg•km^{-1}. Commercial catch rate in the North Channel remains lower than in other parts of Ontario waters, but trends have been slightly positive since 2005 (Fig. 22).

Sea Lamprey marking of Lake Trout was substantially lower during this reporting period than during previous reporting periods. Although Sea Lamprey marking of Lake Trout has generally remained above the target rate of five A1-A3 marks per 100 fish in all basins since 2010, Sea Lamprey-induced mortality has remained near 0.1 yr^{-1} for more than a decade and has contributed to the population expansion and the natural reproduction observed in northern Lake Huron. Sea Lamprey marking rates have declined substantially since 2014 in the North Channel and Georgian Bay.

Fig. 22. The number of Lake Trout caught per kilometer of gillnet in Ontario commercial fisheries of the main basin, North Channel, and Georgian Bay during 1979-2017.



Achievement of Rehabilitation Milestones

The Lake Huron Lake Trout Rehabilitation Guide (Guide) (Ebener 1998) identified three milestones by which progress toward rehabilitation should be measured

Milestone 1	Achieve a reproductive potential of hatchery Lake Trout sufficient to produce measurable wild recruitment.
Milestone 2	Achieve sustainable levels of spawning biomass of wild Lake Trout.
Milestone 3	Ensure the fish community associated with Lake Trout does not inhibit its survival or reproduction.

Milestones 1 and (thus far) Milestone 3 have been achieved in the main basin and the western end of the North Channel, and progress continues toward achievement of Milestone 2. In Georgian Bay, Milestone 1 has not yet been achieved with signs of natural recruitment remaining low. Recruitment may be increasing in some areas as recent surveys in southern Georgian Bay showed higher abundance of spawning Lake Trout during the current reporting period than previously observed, and the number of wild fish has been slowly increasing.

The Guide also identified criteria whereby stocking should be reduced

- *Survival of hatchery-reared lake trout declines*
- *Wild lake trout make up 25% of the mature portion of the population*
- *Abundance of wild fish is stable or increasing over the most recent three- to five-year time period*

In 2016, the Lake Huron Committee (LHC) approved a more-detailed protocol developed by the Lake Huron Technical Committee by which these criteria should be measured (http://www.glfc.org/pubs/lake_committees/huron/LHC%20-%20lake%20trout%20stocking%20reduction%20protocol%20FINAL.pdf). The LHC decided in 2016 to implement stocking reductions in the main basin of Lake Huron in response to the sustained rehabilitation progress observed since the last reporting period. Beginning in 2018, stocking of Lake Trout was to be reduced 50% in statistical districts MH-1 and MH-2 and eliminated in statistical districts MH-3, 4, 5, and 6 for a total reduction of approximately 65% in Michigan's waters of Lake Huron. Similarly, the OMNRF reallocated stocking to priority rehabilitation zones in Georgian Bay and the North Channel and increased stocking density to 4.5 yearlings per hectare as recommended in the revised draft rehabilitation plan for Ontario waters (OMNRF 2012). Additionally, stocking by the OMNRF has been adjusted to emphasize the native Parry Sound and Iroquois Bay strains or those strains that have already contributed to natural reproduction, i.e., Seneca and Manitou.

Summary

In summary, Lake Trout populations in the north-central main basin and western North Channel continue to demonstrate progress toward rehabilitation. We have presented evidence that these populations share common dynamics suggesting population boundaries exist at a broader spatial scale than do current management boundaries. Wild recruitment continues to be evident in these areas demonstrating the effectiveness of focusing rehabilitation efforts in priority areas that have suitable spawning habitat and where exploitation is controlled to acceptable levels. In the southern main basin, progress is also evident yet, given the lower amount of wild recruitment, fishery expectations may need to be tempered if long-term sustainability is to be achieved. Indeed, as stocks shift from being regulated by stocking to being regulated by natural recruitment, management strategies may need to be re-evaluated. Research that focuses on obtaining a better understanding of the spatial scale and source(s) of recruitment, as well as the degree of stock intermixing, would prove valuable in this regard. In Georgian Bay, progress has been slower yet recent indicators are more positive than previously, and expectations are that the revised restoration strategy will result in further advancement toward rehabilitation objectives. The control of Sea Lamprey remains an obvious priority and any long-term interruption in treatment of large Sea Lamprey-producing tributaries would hamper or degrade progress. Fish community dynamics do not appear to be inhibiting Lake Trout natural reproduction in the main basin, but the abundance and composition of its prey will influence Lake Trout growth and recruitment so continued monitoring of predator-prey dynamics should remain a priority.

This latest chapter in the long story of Lake Trout rehabilitation in Lake Huron is encouraging. Over the past two reporting periods, Lake Trout stocks in Lake Huron have provided the only example of sustained natural reproduction and recruitment observed in the Great Lakes, outside of Lake Superior, in over fifty years.

STATUS OF SEA LAMPREY IN LAKE HURON IN 2018[14]

Shawn M. Nowicki[15] and W. Paul Sullivan

Controlling the abundance of Sea Lamprey in Lake Huron began in 1960 in response to the collapse of Lake Trout populations and high Sea Lamprey-induced mortality on Lake Whitefish (Morse and Young 2005; Smith and Tibbles 1980). Reducing Sea Lamprey abundance is critical to the recovery and maintenance of the Lake Huron fish community and essential for achieving the fish community objective (FCO) (DesJardine et al. 1995) to

> *Reduce sea lamprey abundance to allow the achievement of other fish-community objectives.*
>
> *Obtain a 75% reduction in parasitic sea lampreys by the year 2000 and a 90% reduction by the year 2010.*

Abundance of juvenile (parasitic life stage) Sea Lamprey has not been estimated consistently, therefore, estimates of adult (reproductive life stage) abundance serve as a surrogate for juvenile abundance (Steeves et al. 2012). A 75% reduction in abundance from levels observed during 1989-1993 was achieved in 2015 and nearly again in 2016, but the 90% reduction in abundance by 2010 is unachieved. The index of adult abundance in 2015 was 24,000 ± 1,800 and was less than the management goal of abundance of

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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/Sp20_01.pdf.

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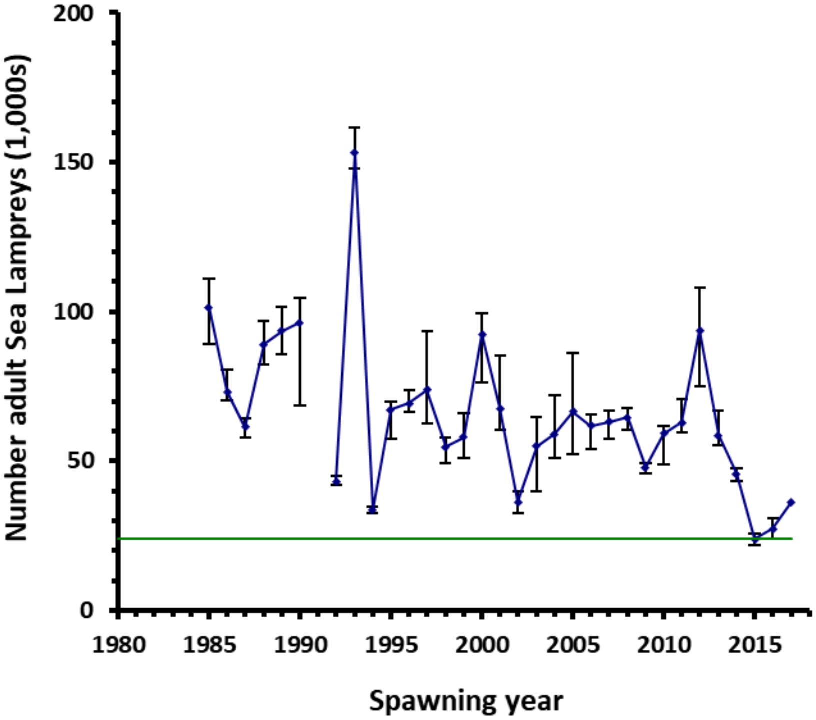
24,000 ± 11,000 (Fig. 23; Sullivan et al. 2016; J. Barber, USFWS, personal communication, 2018).

Fig. 23. Index of mean adult Sea Lamprey abundance in Lake Huron and 95% CI (vertical bars) about the mean, 1985-2017. The target level of abundance is shown by the green horizontal line.

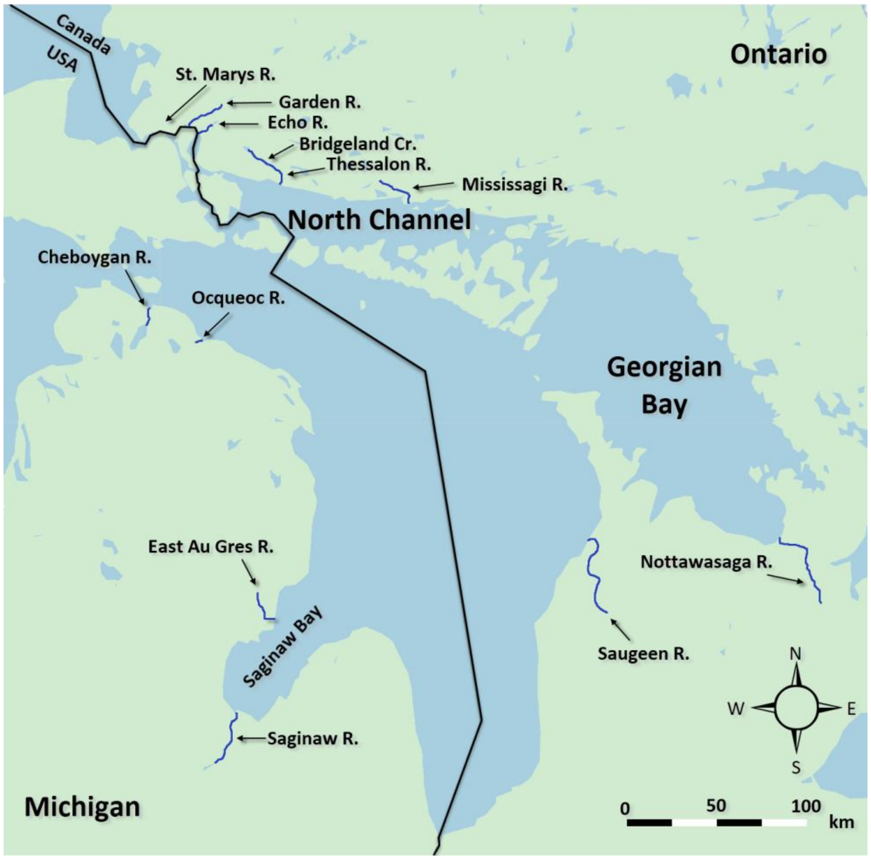


During the current reporting period (2011-2017) the Great Lakes Fishery Commission (GLFC) decided not to focus on single-year estimate of abundance when evaluating achievement of target levels of adult Sea Lamprey. Instead, the GLFC now uses a three-year average to determine if targets are met and a five-year average to determine if the metrics are increasing, decreasing, or stable (Marsden and Siefkes 2019). The Lake Huron Committee (LHC) has not adopted this policy for evaluating achievement of the FCO.

Adult Abundance

Methods for estimating Sea Lamprey abundance in Lake Huron changed during the reporting period from a lakewide absolute number to an index based on selected tributaries (J. Barber, USFWS, personal communication, 2018). Prior to 2015, trapping of adults in selected tributaries was combined with mark-recapture studies and information on stream flow to extrapolate to tributaries without traps, so as to produce a lakewide abundance comprising all producing tributaries (Mullett et al. 2003; Steeves et al. 2012). The target level of abundance necessary to achieve the FCO then was 73,000 Sea Lampreys (Steeves et al. 2012; Walter and Treble 2012). The extrapolation approach was eliminated in 2015 in favor of an index of abundance based on the sum of the mark-recapture estimates for a suite of tributaries that had a history of large spawning runs and consistent population estimates based on trapping. These tributaries include the St. Marys, Cheboygan, Echo, Ocqueoc, and East Au Gres Rivers and Bridgeland Creek, a tributary to the Thessalon River (Fig. 24). The new target level of adult Sea Lamprey abundance is 24,000, which represents 25% of the average adult abundance found in index tributaries during 1989-1993, making it consistent with the target based on extrapolation. The index of abundance during the current reporting period was 16% lower than during the previous, 2005-2010, reporting period (Fig. 23; Sullivan et al. 2016).

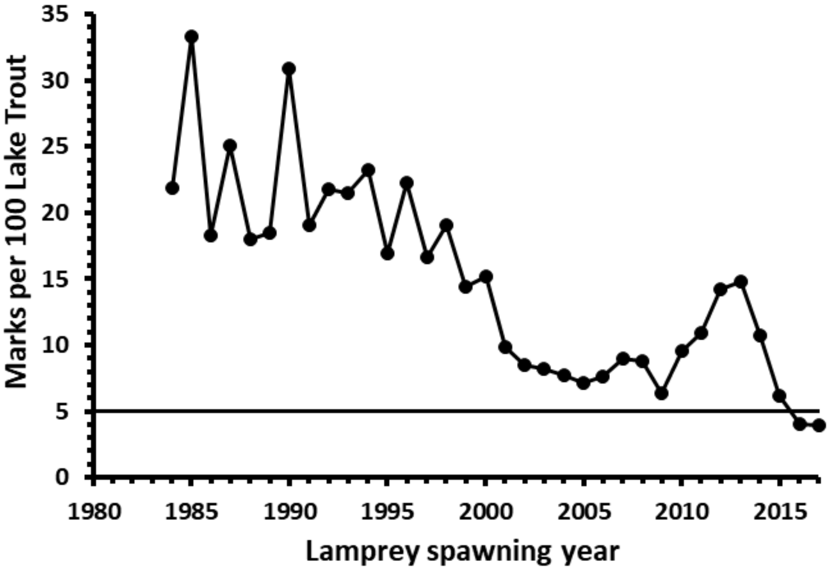
Fig. 24. Map of Lake Huron.



Marking Rates on Lake Trout

The LHC adopted a Sea Lamprey-marking-rate target on Lake Trout (Bence et al. 2008) as a second metric for evaluating success of the control program. King (1980) developed the classification protocol that is used throughout the Great Lakes for reporting Sea Lamprey-marking statistics, and the LHC chose a maximum of 5 marks per 100 Lake Trout as their target. Marking rates were above the target during the previous reporting period averaging 6 marks per 100 fish (Sullivan et al. 2016) and increased steadily through 2013 before declining to below the target in 2016 and 2017. The 2017 rate was 3.9 marks per 100 Lake Trout, which is the lowest marking rate in the time series (Fig. 25). Lake Trout-marking data for Lake Huron are provided by the Michigan DNR, Chippewa Ottawa Resource Authority, the U.S. Geological Survey, and the Ontario Ministry of Natural Resources and Forestry.

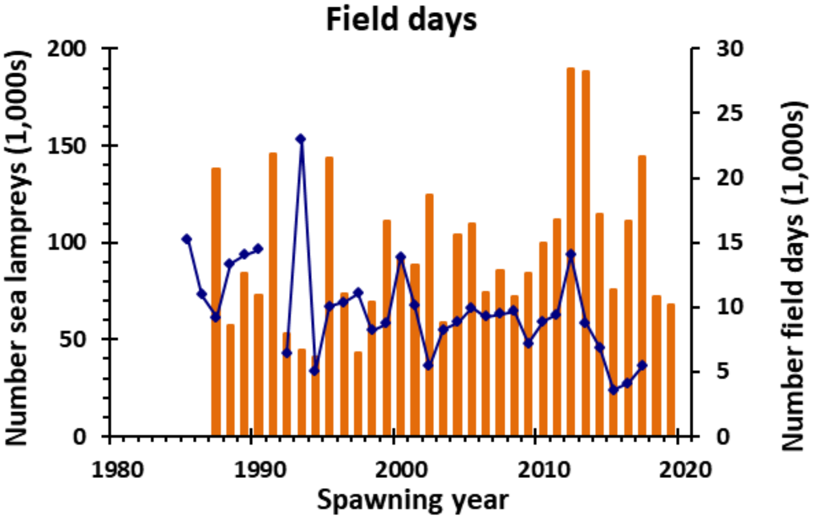
Fig. 25. The number of A1-A3 Sea Lamprey marks per 100 Lake Trout >532 mm total length observed in standardized spring surveys throughout Lake Huron during 1978-2017. The black horizontal line represents the target marking rate of 5 A1-A3 marks per 100 Lake Trout.

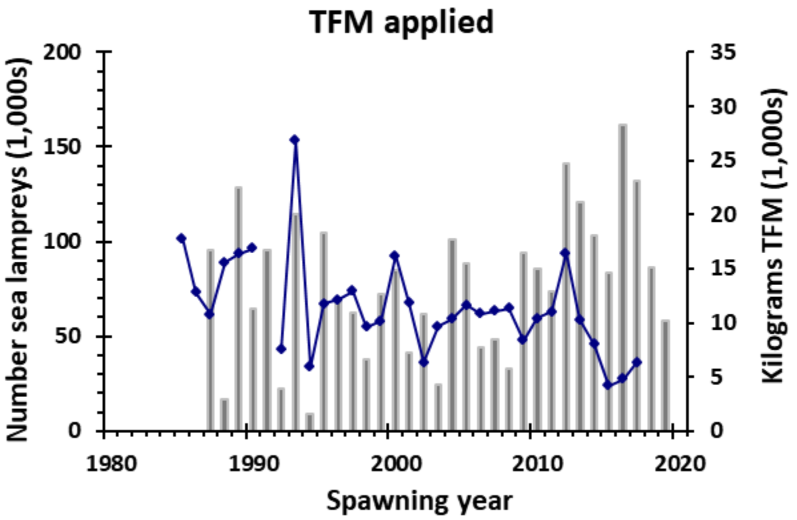


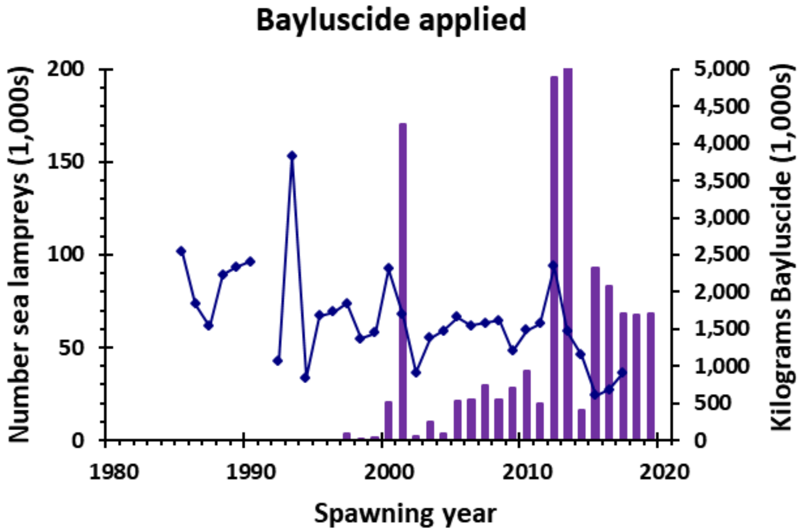
Lampricide Control

The use of lampricides to kill larval Sea Lamprey in tributaries has been the primary method of control on Lake Huron (Morse and Young 2005; Smith and Tibbles 1980). The number of tributaries treated annually increased during the previous reporting period when funding for larval assessment was de-emphasized in favor of lampricide control. Treatment of backwaters, seeps, rivulets, and lentic areas also increased during the previous reporting period due to the de-emphasis of larval assessment (Sullivan et al. 2016; Adair and Young 2009). These increases in treatment were maintained through the beginning of the current reporting period (Fig. 26). The application of Bayluscide to treat larval populations in lentic areas and in the St. Marys River increased from an average of roughly 500 kg during the previous reporting period to an average of 1,500 kg during the current reporting period, with 92% being applied to the St. Marys River. We infer that these additional lampricide treatments contributed to the declines in Sea Lamprey abundance and marking of Lake Trout observed during the present reporting period (Figs. 23, 25).

Fig. 26. Index of adult Sea Lamprey abundance (points), number of staff field days (bars), and the kilograms of TFM and Bayluscide active ingredient (bars) applied to tributaries of Lake Huron during 1985-2017. The index of abundance and control actions are offset by two years on the x-axis to illustrate when the treatment effect would first be observed on adult abundance.



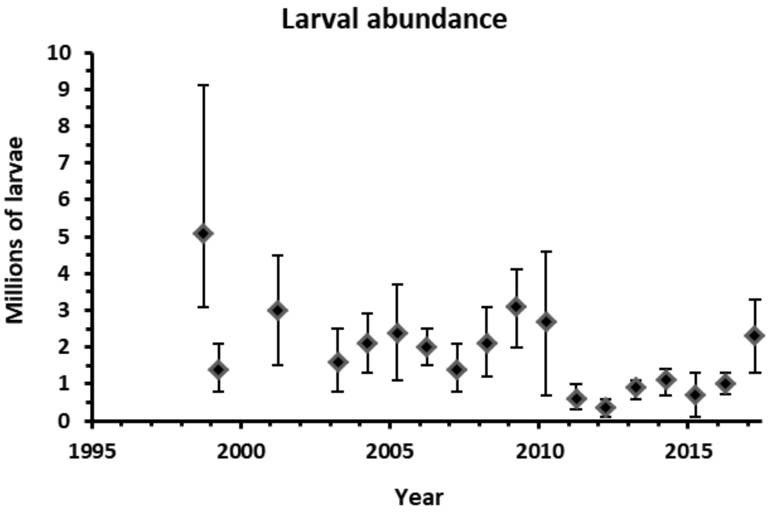

TFM applied

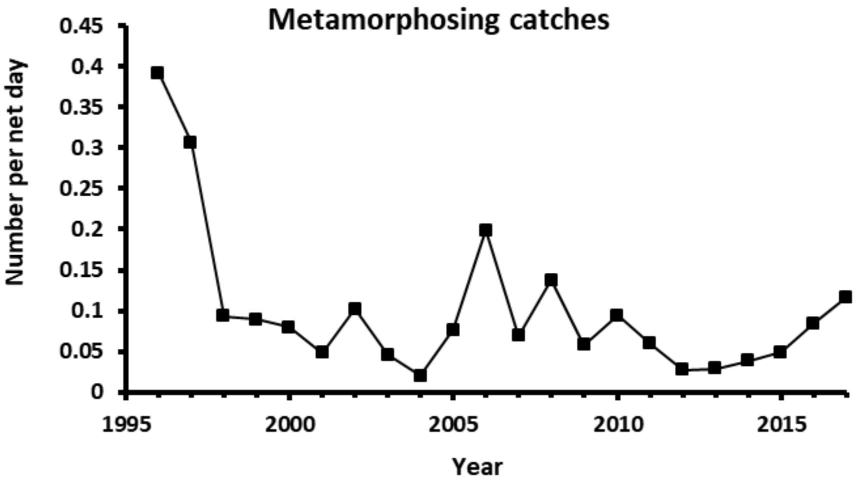

Bayluscide applied

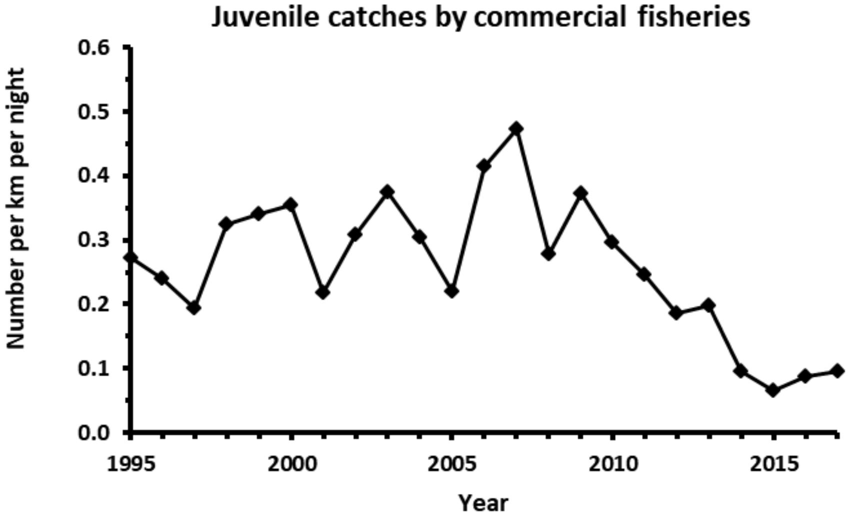
St. Marys River

Sea Lamprey marking and the mortality associated with marking (see Bence et al. 2003) were so high during the early 1990s that Lake Trout restoration efforts were suspended until a control strategy could be developed for the St. Marys River (Morse and Young 2005). In 1998 and 1999, large-scale treatments of the St. Marys River with Bayluscide were initiated to suppress an abundant larval population (Morse and Young 2005). An average of 132 ha (95-143 ha) of the St. Marys River were treated annually with Bayluscide during 2005-2009. In 2010 and 2011, Bayluscide treatments were expanded to 875 ha and 873 ha, respectively, as part of a strategy focusing even more on the St. Marys River and on the nearby large Sea Lamprey-producing tributaries to the North Channel (Sullivan et al. 2016). During 2012 to 2017, an average of 328 ha (268-383 ha) were treated annually in the St. Marys River. The increase in treatments after 2004, including treatment of the St. Marys River and expanded treatments of North Channel tributaries, reduced numbers of larvae and metamorphosing larvae in the river and in northern Lake Huron (Fig. 27, top panel). The larval population estimate in the St. Marys River during 2017 was 2.3 million (95% CI 1.3-3.3 million) (Fig. 27) and has remained at a mostly suppressed level. Catches of metamorphosing Sea Lamprey migrating out of the river showed a similar declining pattern (Fig. 27, middle panel) as did the catch-per-unit effort of juveniles in commercial fisheries in northern Lake Huron (Fig. 27, bottom panel).

Fig. 27. Annual measures of larval, metamorphosing, and juvenile Sea Lamprey abundance in the St. Marys River and northern Lake Huron, 1995-2017. Mean annual larval abundance (diamonds) and 95% CI about the mean (vertical lines) were estimated based on deep-water electrofishing. In the middle panel, metamorphosing Sea Lamprey migrating out of the St. Marys River was captured in fyke nets suspended from navigation buoys. In the bottom panel, juvenile Sea Lamprey were captured by commercial fisheries targeting Lake Whitefish, Lake Trout, and other species in Ontario waters of northern Lake Huron.


Larval abundance
Millions of larvae
10
9
8
7
6
5
4
3
2
1
0
1995
2000
2005
2010
2015
Year


Metamorphosing catches
Number per net day
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1995
2000
2005
2010
2015
Year



Regional Treatment Strategies

In 2009, the GLFC began emphasizing treatments in regions of northern Lakes Huron and Michigan—hence a regional treatment strategy. Tributaries selected as part of this regional strategy were added to a list of tributaries already ranked for treatment based on estimates of larval abundance or treatment history. Most of these regional treatments began during the previous reporting period but continued into the present reporting period. The 2010 and 2011 regional treatments focused on all Sea Lamprey-producing streams in the North Channel area. During 2012 and 2013, streams geographically proximate to those selected in the previous year were treated. Success of the 2010-2013 treatments was to be measured by an unspecified reduction in adult abundance and marking rates in northern Lake Huron.

The regional objective in 2014-2015 was to determine the reduction in adults achieved by treating in consecutive years those tributaries in Lakes Michigan and Huron that had a history of producing large numbers of larvae. The rationale was based on the hypothesis that most of the adults at any one time are survivors of the previous treatment, which are typically conducted on a four-year rotation (Morse et al. 2003). Adult abundance fell below the target level for the first time in 2015, although the effect of the 2014 treatment would not manifest until 2016 (Fig. 23). Adult abundance during 2016 was reduced by 41% from the 2014 estimate.

The regional strategy for 2016-2017 was to chemically treat the largest Sea Lamprey-producing tributaries in the upper Great Lakes on a rotational basis beginning with Lake Superior in 2016. Eighteen of the largest Lake Huron Sea Lamprey-producing tributaries were to be treated under this strategy in 2018. In addition to the selected regional-strategy treatments, an additional 18 streams, 6 lentic areas, and 295 ha of the St. Marys River were scheduled for treatment in 2018.

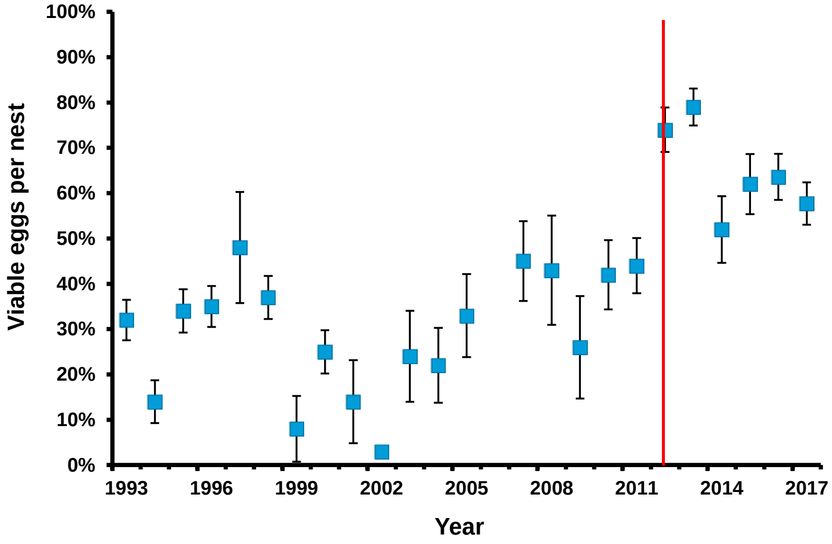
Barriers

All 17 barriers designed or modified to block adult Sea Lamprey from reaching spawning habitats continued to be operated and maintained during the current reporting period. Barriers on the Nottawasaga and Saugeen Rivers, both highly productive Sea Lamprey tributaries, are currently being rehabilitated. Proposals to remove dams and culverts to increase tributary connectivity and passage of migratory fish or to address safety and fiscal liabilities related to deteriorating structures portend a future where Sea Lamprey populations reach unacceptable levels.

Sterile-Male Release Technique

The Sterile Male Release Technique (SMRT) has been employed as an alternative control method on Lake Huron (Bergstedt et al. 2003; Bergstedt and Twohey 2007) that continued into the current reporting period. The release of sterilized males began on the St. Marys River in 1991 but was discontinued in 2012 of the current reporting period. Egg viability in Sea Lamprey nests in the river was studied to evaluate the SMRT beginning in 1993 (Bergstedt et al. 2003), and viability averaged 29% through 2011. After the SMRT was discontinued, egg viability increased to an average of 64% (Fig. 28). The SMRT was discontinued due to concerns about the lack of male Sea Lamprey available for sterilization once populations begin to decline, the uncertainty in the stock-recruitment relationship in the river, and the difficulty in evaluating its effectiveness when there were concurrent lampricide applications. A related research project began in the upper Cheboygan River during 2017 to investigate the probability of eradication in a semi-closed system with a presumably low number of adults. Outcomes of the Cheboygan River project are expected during the next reporting period.

Fig. 28. Mean percentage of viable Sea Lamprey eggs (blue squares) and 95% CI (vertical lines) about the mean observed in nests on the St. Marys River during 1993-2017. Red vertical line represents the cessation of the sterile-male release technique in the river in 2012.



Potential Threats to Control

The Mississagi and Garden River First Nations have expressed concerns with the ongoing use of lampricides in the Mississagi and Garden Rivers, and both First Nations do not support treatments. The Mississagi and Garden Rivers are estimated to have the greatest potential for Sea Lamprey production in Lake Huron, and lack of lampricide control on them is expected to have detrimental effects on fish communities (Dobiesz and Bence 2018). Both tributaries were last treated in 2013 and 2014 and were scheduled for treatment again in 2016 and 2017, but both treatments were postponed because of First Nation concerns. The GLFC and its partners continue to engage both First Nations to discuss the threat that uncontrolled larval populations in these rivers pose to fish populations that support commercial, recreational, and indigenous people’s fisheries.

Consultations with other resource-management agencies to remove barriers to Sea Lamprey spawning migrations have increased over the reporting period. If an important Sea Lamprey-blocking structure is removed or allowed to deteriorate, the subsequent increase in larval and juvenile production will lead to increases in adult abundance and marking rates in Lake Huron, as was observed when a barrier on the Manistique River, a tributary to northern Lake Michigan, deteriorated to the point where it no longer blocked Sea Lamprey. The deteriorated barrier opened over 490 km of the Manistique River to adult Sea Lamprey for spawning and resulted in chemical treatment of the river every three years since 2003 at a cost of over $800,000 US per treatment. Larval Sea Lamprey abundance continues to increase in the upper reaches of the Manistique River even after the treatments.

Conclusions and Recommendations

Adult Sea Lamprey abundance in 2015 was below the management target of 24,000 for the first time in over 30 years (Fig. 23). In addition, marking rates on Lake Trout were below target levels in the following two years, 2016 and 2017 (Fig. 25). Increased lampricide treatments since 2010 coupled with enhanced controls, such as treating isolated backwater areas, placing TFM bars in rivers, and treating during the most-appropriate month, likely were responsible for the reductions in abundance and marking. Refining estimates of abundance and using "fish community" marking statistics are being evaluated to better understand interactions between Sea Lamprey and fish other than Lake Trout and to more accurately describe spatial variation in marking as it relates to abundance of both Sea Lamprey and its prey (Sullivan et al. 2012; Walter and Treble 2012). We recommend that the GLFC and its partners

- Continue regional treatment strategies on the largest tributaries, e.g., Mississagi, Garden, St. Marys, and Saginaw Rivers, to suppress abundance
- Improve the accuracy of Sea Lamprey abundance and marking of fish to better measure efficacy of the control program on the fish community (Walter and Treble 2012)
- Maintain the effectiveness of barriers and improve fish passage on large Sea Lamprey-producing tributaries (Walter and Treble 2012)

STATUS OF INTRODUCED SALMONINES IN LAKE HURON IN 2018[16]

David J. Borgeson[17], David Gonder, Ronald G. Green

The salmonine fish community objective (FCO) for Lake Huron (DesJardine et al. 1995) is to

> *Establish a diverse salmonine community that can sustain an annual harvest of 2.4 million kg with lake trout the dominant species and anadromous (stream-spawning) species also having a prominent place.*

The FCO anticipates that rehabilitated Lake Trout populations could sustain 1.4-1.8 million kg of yield, and the remainder of salmonine productivity will come from introduced Chinook and Coho Salmon, Rainbow Trout (steelhead), Brown Trout, and Pink and Atlantic Salmon. These anadromous species help diversify the salmonine community and provide additional harvest opportunities and value to the fisheries.

The number of introduced salmonines stocked annually was reduced during the current reporting period in response to changes in the Lake Huron ecosystem (Rudstam et al., this volume). An average of 701,000 salmonines were stocked during the previous reporting period (2005-2010) compared to

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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/Sp20_01.pdf.

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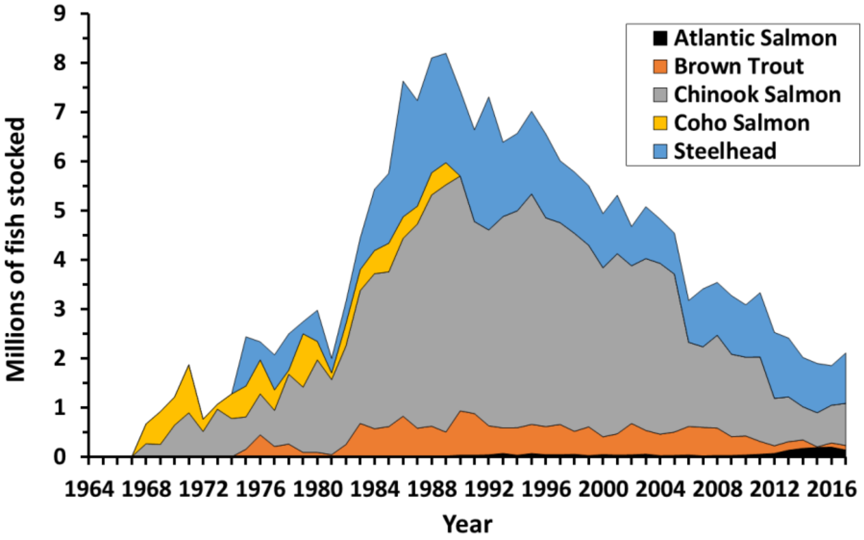
432,000 during the current reporting period (2011-2017), with the largest declines being for Chinook Salmon and Brown Trout (Fig. 29). Stocking of introduced salmonines continues to be a concern to Lake Huron managers given the magnitude of change in the ecosystem, the sustained levels of natural reproduction by Chinook Salmon and steelhead, and the uncertainty this lends to the success of or need for predator stocking (He et al. 2015, 2016).

Fig. 29. Number of introduced salmonines stocked in Lake Huron, 1968-2017.



The harvest of introduced salmonines declined during the current reporting period, likely in response to reduced stocking levels and likely declines in survival of these fish. The harvest of introduced salmonines from Michigan waters averaged 15,000 fish annually during the reporting period compared with an average of 17,000 fish during the previous reporting period (Michigan DNR, unpublished data). There is no annual creel survey conducted in Ontario waters. Consequently, no accurate estimate of the total yield of introduced salmonines is available for Lake Huron. Yet the available harvest data illustrate that yield is far below what would be expected with a rehabilitated population of Lake Trout.

Chinook Salmon

The state of Michigan began stocking Chinook Salmon into Lake Huron in 1968 (Johnson et al. 1995; Whelan and Johnson 2004), and, in Ontario, community hatchery program (CHP) facilities began stocking them in 1985. Chinook Salmon was chosen for introduction because it was relatively inexpensive to raise and was potentially of great recreational value (Whelan and Johnson 2004). Stocking increased from 250,000 fish in 1968 to 5 million fish in 1989 (Ebener 1995, Appendix), at which time management concerns were raised about the sustainability of these stocking levels. Subsequently, stocking was capped at 1990-1991 levels (Johnson et al. 1995). Stocking was further reduced during the current reporting period (Fig. 29) because of continued management concerns about the sustainability of both prey fish and Chinook Salmon populations (Johnson et al. 2010; He et al. 2016). An average of 939,160 Chinook Salmon were stocked per year in Lake Huron during the reporting period and 854,039 were stocked in 2017.

Chinook Salmon biomass increased slightly during the current reporting period. Biomass in the main basin declined by more than 90% between the 1980s and the previous reporting period (2005-2010), subsequently, biomass increased during the current reporting period to about 20% of peak levels (He et al. 2015). Increased natural mortality of age-0 fish is thought to have been responsible for the decline in biomass through 2010 (Brenden et al. 2012; Bence and He 2015). Information from recreational-fishery harvests in Owen Sound (Fig. 30) show that returns to the fishery, i.e., surrogates for abundance and biomass, in Georgian Bay have changed in a similar fashion to those in the main basin (Fig. 31).

Predation on age-0 Chinook Salmon, particularly in years of low Alewife abundance, is likely a large contributing factor to age-0 natural mortality (Johnson et al. 2007). Chinook Salmon growth and condition declined abruptly in Lake Huron after the collapse of Alewife populations in 2004 (Bence et al. 2008), but both growth and condition recovered to pre-Alewife collapse levels from the previous reporting period to the current reporting period in the main basin (Fig. 32) (He et al. 2016). Measures of condition (Fulton's *K*) indicate a similar recovery in condition and growth based on sampling of recreationally caught fish at derbies in Ontario (Fig. 33). The recovery of growth and condition suggests that a lower abundance of Chinook Salmon is more in balance with the current reduced pelagic prey-fish biomass than when its abundance was much higher (see Riley et al., this volume). However, Chinook Salmon has demonstrated a continued reliance on Alewife and Rainbow Smelt as its primary prey (Roseman et al. 2014), which limits its ability to respond to changes in the prey-fish community.

Fig. 30. Map of Lake Huron.

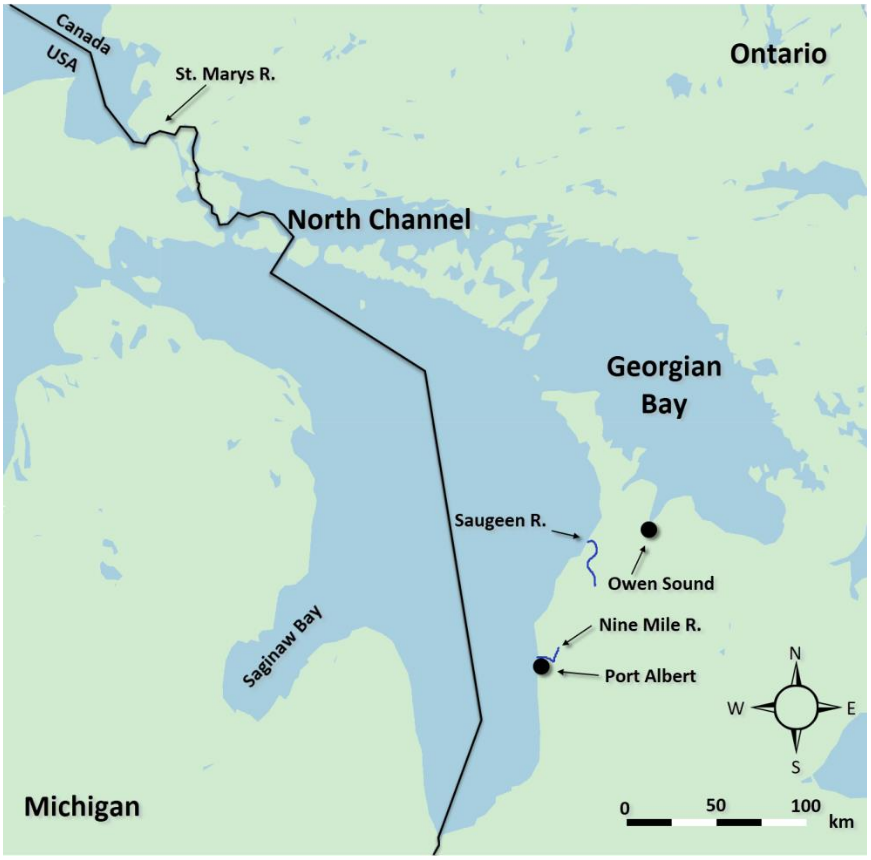
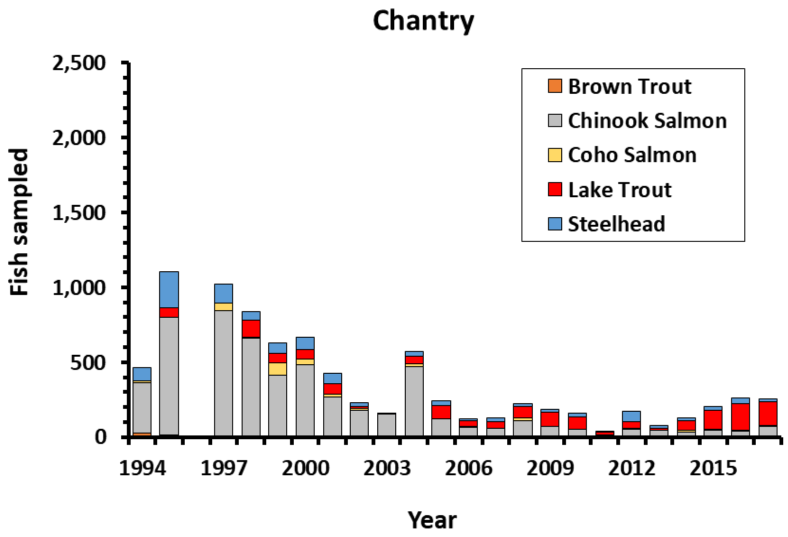
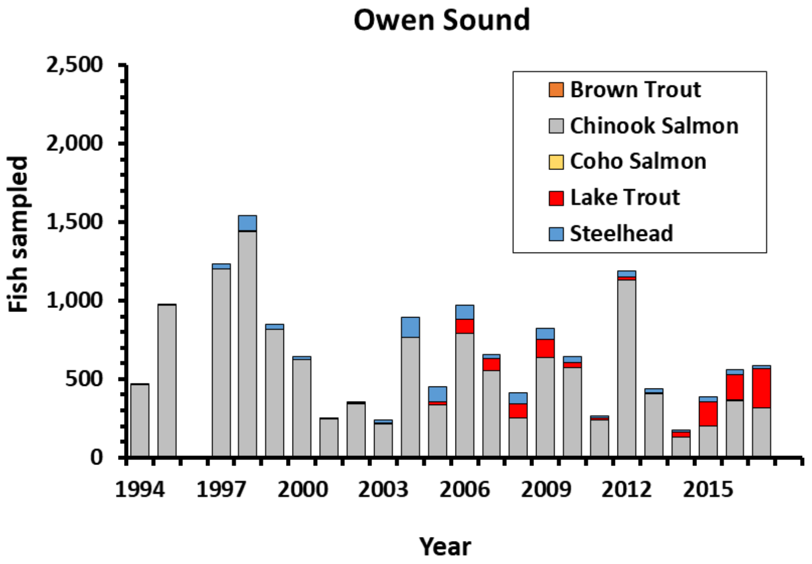


Fig. 31. Number of salmonines sampled annually from the recreational-fishery harvest in the Chantry Chinook Classic and Owen Sound Salmon Spectacular fishing events in Georgian Bay, Lake Huron, during 1994-2017.


Chantry
2,500
2,000
1,500
1,000
500
0
Fish sampled
Brown Trout
Chinook Salmon
Coho Salmon
Lake Trout
Steelhead
1994
1997
2000
2003
2006
2009
2012
2015
Year


Owen Sound
2,500
2,000
1,500
1,000
500
0
Fish sampled
Brown Trout
Chinook Salmon
Coho Salmon
Lake Trout
Steelhead
1994
1997
2000
2003
2006
2009
2012
2015
Year

Recreational-fishery harvest and effort during the reporting period continued to be low because of the decline in abundance and biomass of Chinook Salmon (Fig. 34). The recreational-fishing effort targeted at salmonines and the associated harvest of Chinook Salmon remained low during the current reporting period (Fig. 34), averaging 166,776 angler hours per year, representing a 21% decline from the average of 211,819 angler hours in the previous reporting period. During the 2000-2004 reporting period, the salmonine recreational effort averaged 897,159 angler hours per year, more than five times the average in this reporting period. Return to the creel of hatchery-origin Chinook Salmon in Michigan waters has also remained low because of the continued low abundance of Alewife. Over 82% of Chinook Salmon in the Michigan creel harvest prior to August 1 of 2013-2017 were classified as unclipped and further illustrates the poor survival and lowered abundance of stocked fish (Michigan DNR, unpublished data).

Fig. 32. Estimated asymptotic total length (mm) of Chinook Salmon in the main basin of Lake Huron, 1983-2017 (He et al. 2016).

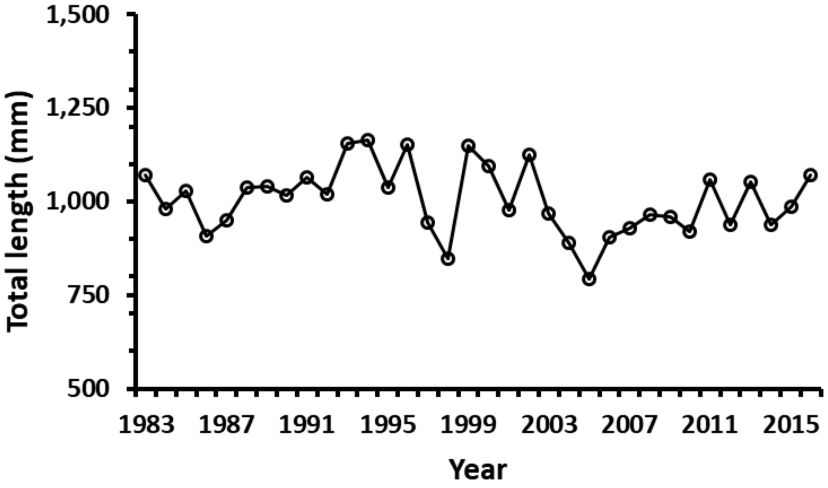
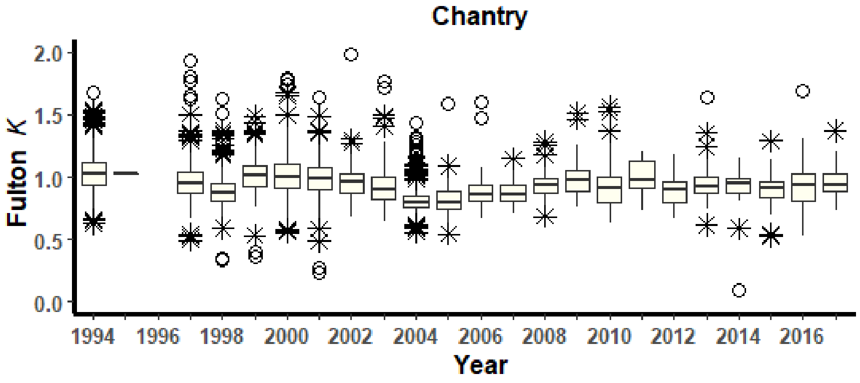


Fig. 33. Box and whisker plots of Fulton's condition factor *K* as calculated from total length (mm) and round weight (g) of Chinook Salmon sampled from recreational-fishery harvests at the Chantry Chinook Classic and Owen Sound Salmon Spectacular fishing events in Georgian Bay, 1994-2017. Boxes show the median as a solid line, the boundaries of the box are the 1st and 3rd quartile range, stars are outliers 1.5 times the size of the quartile range, and open circles are outliers 3.0 times quartile range. There was no data for 1995 and 1996 at both locations and no data for 2013 in Owen Sound.



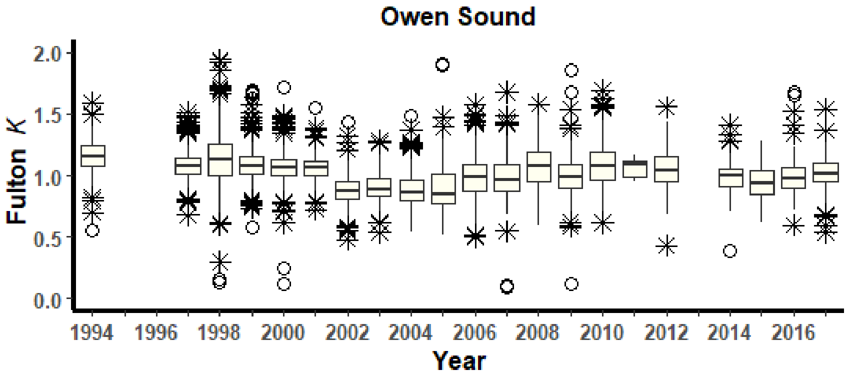
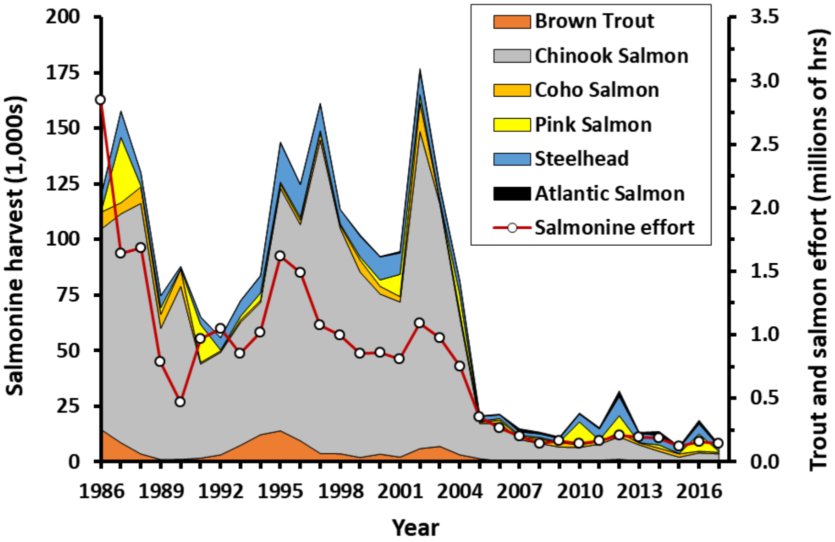


Fig. 34. Recreational-fishery harvest of salmonines (area colors) other than Lake Trout and the number of angler hours (red line and white circles) targeted at trout and salmon in the Michigan waters of Lake Huron during 1987-2017.

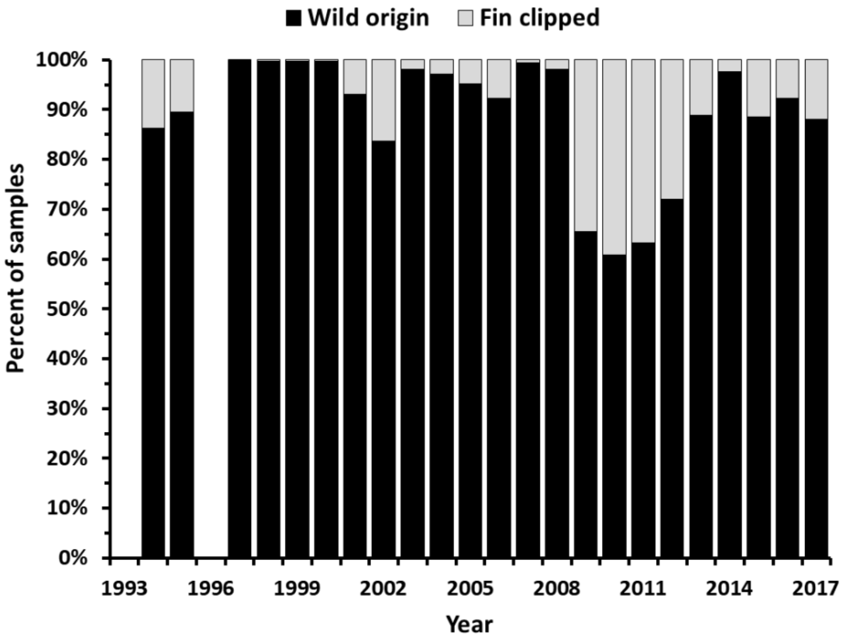


Additionally, the proportion of Chinook Salmon stocked in Lake Huron that moves to Lake Michigan to feed has increased when compared to the period before Alewife populations collapsed (Clark et al. 2017). It is likely that a proportion of the wild Chinook Salmon produced in the Lake Huron basin also moves to Lake Michigan to feed. This differential interlake movement complicates management decisions about the appropriate stocking rate for Chinook Salmon (Maguffee et al. 2017). Research to quantify the interlake movement of wild Chinook Salmon using otolith microchemistry are ongoing and preliminary analyses show that up to 4% of wild angler-caught Chinook Salmon in Lake Michigan were produced in Lake Huron (Maguffee et al. 2017).

Returns of Chinook Salmon stocked in Ontario waters are assessed through biological sampling at recreational-fishing events, such as the Owen Sound Salmon Spectacular (OSSS) (Fig. 35). The OSSS derby occurs as Chinook Salmon returns to the Sydenham River in Owen Sound where all fish are fin clipped before being stocked. The terminal nature of this fishery allows for a complete assessment of the percentage of stocked Chinook Salmon in the catch that is not possible during the mixed-stock fishery earlier in the year, as other CHP organizations do not fin clip their fish. Stocked Chinook Salmon accounted for an average of 16% of the catch annually at the OSSS during 2011-2017, and similarly, low contributions of hatchery fish were seen in earlier years (Fig. 35). Thus, wild Chinook Salmon has largely dominated the catch in Owen Sound because there is so much high-quality spawning habitat in nearby Georgian Bay tributaries (Johnson et al. 2010).

The contribution of stocked Chinook Salmon to the recreational-fishery harvest has declined to such low levels that the state of Michigan reduced stocking levels by 50% in both 2006 and 2012 (Fig. 29). However, it is likely Chinook Salmon will persist in Lake Huron because wild fish now account for over 80% of the harvest in the offshore fishery, with most of them likely being produced in Ontario tributaries (Johnson et al. 2010; Marklevitz et al. 2016).

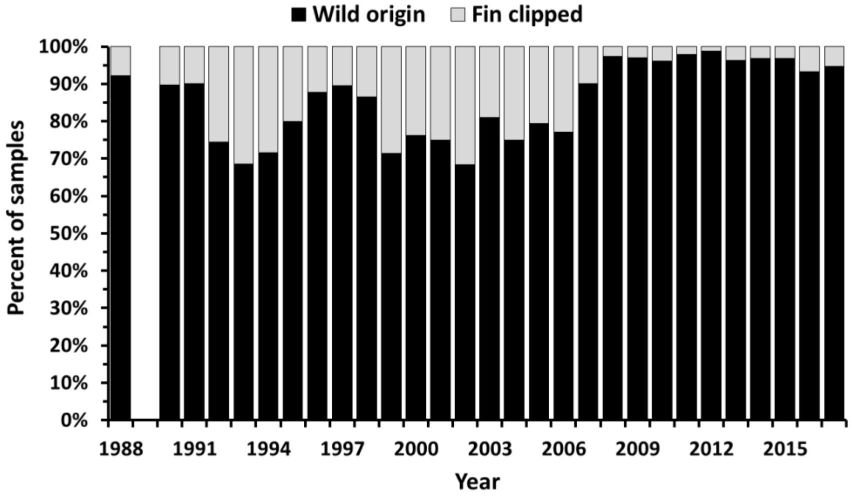
Fig. 35. Percent of fin-clipped and wild-origin Chinook Salmon caught by recreational anglers at the Owen Sound Salmon Spectacular in Owen Sound Bay during 1994-2017.



Steelhead

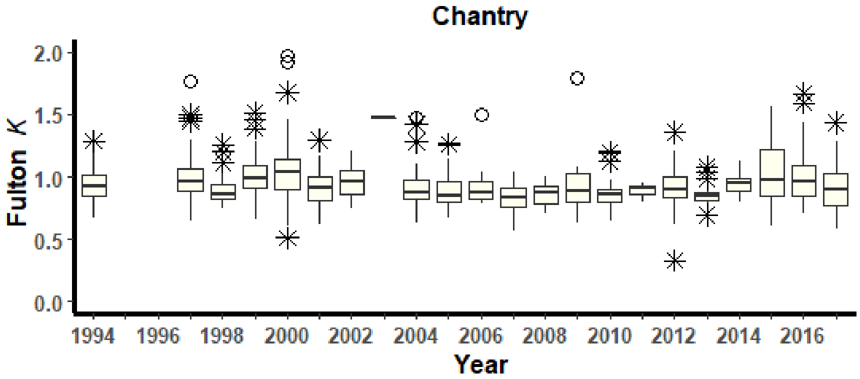
Steelhead was introduced in Ontario waters in 1883 (Kerr 2010) and Michigan waters in the late 1800s. Despite this long history of stocking, natural reproduction has sustained the bulk of steelhead production and harvest in Ontario (Gonder 2005) while most recruitment in Michigan waters is believed to come from stocked fish. As with Chinook Salmon, the greater production of wild steelhead in Ontario is because there is more tributary habitat for reproduction than in Michigan. Biological sampling of steelhead caught at the fishway on the Nine Mile River, Ontario, occurs annually and provides an opportunity to evaluate the contribution of stocked fish to a naturalized, self-sustaining population that does not receive direct supplemental stocking. Over 90% of the steelhead captured at the fishway was of wild origin during the reporting period (Fig. 36). It is unclear why the rates of clipped steelhead declined in 2007 and have stayed low through this reporting period at this fishway. Declines in the proportion of stocked steelhead marked with either a fin clip or coded wire tag in Michigan waters that may stray into Ontario tributaries is a potential explanation.

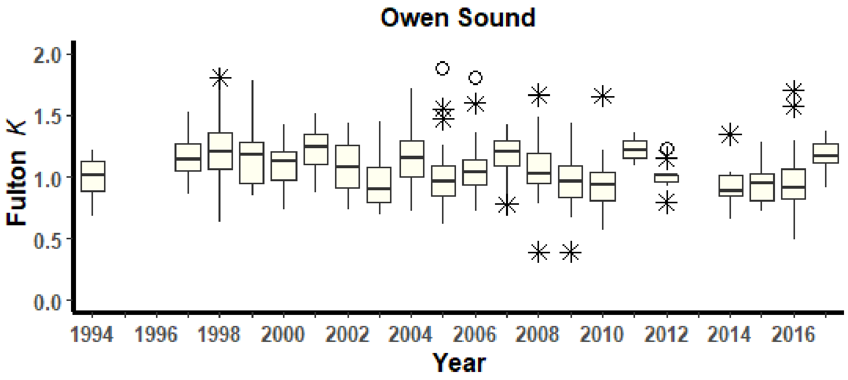
Fig. 36. Percent of fin-clipped and wild-origin steelhead caught at the fishway on Nine Mile River during 1989-2017.



Steelhead appears to have been less impacted by changes in the fish community than Chinook Salmon. Terrestrial invertebrates are a staple for steelhead, but Rainbow Smelt was also an important prey of recreationally caught fish during 2009-2011 (Roseman et al. 2014). In addition, condition factor of steelhead sampled at recreational-fishing events in Ontario does not show the declines exhibited by Chinook Salmon after the collapse of Alewife populations (Fig. 37).

Fig. 37. Box and whisker plots of Fulton's condition factor *K* as calculated from total length (mm) and round weight (g) of steelhead sampled from recreational-fishery harvests at Chantry Chinook Classic and Owen Sound Salmon Spectacular fishing events in Georgian Bay, 1994-2017. Boxes show the median as a solid line, the boundaries of the box are the 1st and 3rd quartile range, stars are outliers 1.5 times the size of the quartile range, and open circles are outliers 3.0 times the quartile range. There was no data for 1995 and 1996 at both locations and no data for 2013 in Owen Sound.





The recreational harvest of steelhead declined in relation to angling effort targeted at salmonines as Chinook Salmon populations declined in Michigan waters (Fig. 34). Michigan found that holding steelhead in acclimation pens in tributaries prior to stocking did not improve the recreational harvest over directly stocking steelhead in tributaries during 2011-2013.

Recreational-fishing effort for steelhead in tributaries is an important component of the salmonine fishery in Ontario and may now rival the effort directed at Chinook Salmon in open-water fisheries. Approximately 80,000 rod hours were directed at steelhead and produced a harvest of over 7,000 fish on a 6 km section of the Saugeen River from the fall of 2015 through the spring of 2016, which is directly comparable to estimates of Chinook Salmon targeted effort and harvest generated from a 2015 creel in Owen Sound Bay of Georgian Bay. Owen Sound is one of the most-active, if not the most-active, ports in the Chinook Salmon fishery in Ontario waters of the lake.

In summary, the continued dominance of wild fish in Ontario tributaries, their importance to the current recreational fishery in tributaries, and no clear signs of reductions in their abundance, condition, or growth, indicate that steelhead continues to be less impacted by the Alewife collapse than Chinook Salmon.

Brown Trout

Brown Trout was introduced in Ontario waters in 1913 (Kerr 2010) and Michigan in the late 1800s. The annual number of Brown Trout stocked in Lake Huron by Michigan averaged nearly 350,000 in the 1990s and, combined with Ontario, approached 600,000 during 1990-2000. Brown Trout stocked into Michigan waters was mainly spring yearlings whereas all life stages were stocked into Ontario by CHP facilities.

Michigan suspended all Brown Trout stocking in Lake Huron in 2012 of the current reporting period (Fig. 29) because of poor survival and low returns to the recreational fishery. In the early 1970s, recreational anglers caught about 10% of the Brown Trout that was stocked into Michigan waters. After 1995, post-stocking survival of spring yearlings declined abruptly because of predation by primarily Walleye (Johnson and Rakoczy 2004). Michigan tried to coordinate Brown Trout stocking with the arrival of large aggregations of Alewife to nearshore areas in the spring to buffer the walleye predation on the newly planted fish, but survival remained low (Johnson and Rakoczy 2004). Consequently, the harvest of Brown Trout declined throughout the late 1990s (Fig. 34), and return to the recreational fishery in Michigan waters declined to 0.23% in 2005 and 2006 (Johnson et al. 2009). Michigan tried stocking larger fall yearlings during 2001-2003 and 2009-2011 to increase post-stocking survival, but less than 2% of these fish were caught by the recreational fishery (Johnson et al. 2009).

Survival of stocked Brown Trout is also poor in Ontario waters. An average of 88,000 fish of all life stages were stocked annually by Ontario CHP facilities during the reporting period (2011-2017). Despite these efforts, few fish were observed in the recreational-fishery harvest. There is little evidence of significant natural reproduction of Brown Trout in Lake Huron (Johnson and Rakoczy 2004; Michigan DNR and OMNRF, unpublished data), so it is unlikely that significant populations will persist without stocking.

Atlantic Salmon

Atlantic Salmon has been stocked in Lake Huron since 1987 and it appears to be better suited to the current Lake Huron ecosystem than Chinook Salmon or Brown Trout. Atlantic Salmon tend to have a more-diverse diet than other salmonines, and this diet may help explain why it is less impacted by the declines in Alewife abundance (Roseman et al. 2014). An average of 32,000 Atlantic Salmon were reared and stocked annually in the St. Marys River during 2005-2011, and returns to the recreational fishery appeared to be high relative to other species during the reporting period based on anecdotal information.

Michigan initiated an Atlantic Salmon rearing program in state hatcheries and increased the number stocked beginning in 2013 of the current reporting period because of the apparent success of the St. Marys River fish. Michigan stocked an average of 137,000 spring yearlings annually during the reporting period. Natural reproduction of Atlantic Salmon was recently documented in the St. Marys River (Tucker et al. 2014). However, contribution of these fish to the spawning population and recreational fishery has been negligible (Lake Superior State University, Michigan DNR and OMNRF, unpublished data), thus stocking will be required to maintain a viable population in Lake Huron.

Coho and Pink Salmon

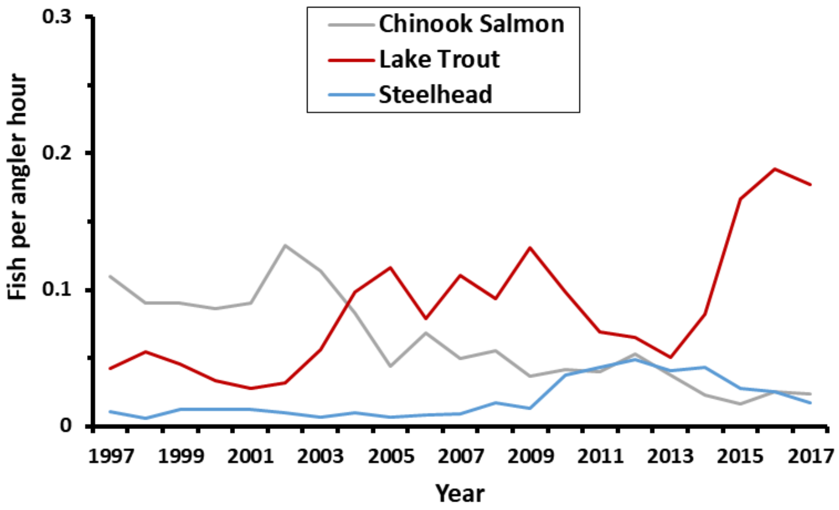
Coho Salmon was first stocked into Lake Huron by Michigan in the early 1960s while Pink Salmon was accidentally introduced into Lake Superior in the 1950s (Nunan 1967) and subsequently found its way into Lake Huron. Coho Salmon was last stocked in Lake Huron in 1989, and Pink Salmon have never been stocked, but both species continue to be harvested by the offshore recreational fishery. The recreational harvest of Pink Salmon exhibits noticeable annual variability related to alternately weak and strong year-classes (Fig. 34). Coho and Pink Salmon have been documented spawning in several Lake Huron tributaries, including the St. Marys River (Michigan DNR and OMNRF, unpublished data), and it is likely that these populations are well established and will continue to persist. Both species appear to have adapted to the changes in the prey-fish community of Lake

Huron. Diets of both species are much more varied than Chinook Salmon. Pink Salmon diet was dominated by Rainbow Smelt and invertebrates during 2009-2011 (Roseman et al. 2014).

The Recreational Fishery

The collapse of Alewife populations in Lake Huron in 2004 had a dramatic effect on the trout and salmon fishery. Chinook Salmon had been the primary focus of the Michigan fishery, and, when its abundance and harvest declined, angling effort targeting trout and salmon declined quickly and has remained low through 2017 (Fig. 34). The reduction in angling effort contributed to a decline in harvest of all salmonines in Michigan waters. Much of the angler effort in Michigan was redirected to Lake Trout after the decline in Chinook Salmon abundance, and, consequently, the Lake Trout catch rate increased (Fig. 38). Additionally, the catch rate of steelhead increased gradually after 2004 in Michigan waters and then declines modestly (Fig. 38).

Fig. 38. The number of Chinook Salmon, Lake Trout, and steelhead caught per angler hour in recreational fisheries targeting salmonines in Michigan waters of Lake Huron during 1997-2017.



The decline in recreational-fishery effort in Ontario directed at introduced salmonines after the Alewife collapse was similar, although not of the same magnitude, as the decline in Michigan. As in the last reporting period, fisheries directed at Chinook Salmon continue to exist, although fish appear to be less abundant (Fig. 31). The continued presence of fisheries directed at Chinook Salmon is thought to be the result of persistent natural reproduction in Ontario tributaries. During the current reporting period, as in Michigan waters, Lake Trout has become a more-prominent species in the open-lake recreational fishery (Fig. 31). Additionally, tributary fisheries for steelhead appear to be comparable to, or larger than, open-lake fisheries at Ontario ports. Thus the recreational fishery in Ontario continues to evolve in response to changes in the fish community, and species other than Chinook Salmon are gaining more prominence.

The introduced salmonid component of the Lake Huron fish community fell short of providing the complementary yield to Lake Trout necessary to achieve the yield objective during the reporting period. The collapse of Alewife populations in 2004 and the subsequent reduction in Chinook Salmon abundance, and to a lesser extent Brown Trout, is preventing achievement of the yield objective.

Introduced salmonine populations and the fisheries they support appear to be stable for the foreseeable future. Chinook Salmon abundance has stabilized at a lower level during the current reporting period and is providing recreational fisheries, particularly in Ontario. Steelhead and Atlantic Salmon seem less affected by changes in the prey-fish community than other salmonines, and, in Ontario, tributary fisheries for steelhead are of similar magnitude to open-lake fisheries. Pink and Coho Salmon continued to persist during the current reporting period although at lower level of abundance than other salmonids. Natural reproduction provided the bulk of recruitment for introduced salmonids in Lake Huron during the current reporting period.

STATUS OF NEARSHORE FISH COMMUNITIES IN LAKE HURON IN 2018[18]

David G. Fielder[19], Arunas P. Liskauskas, James C. Boase, and Justin A. Chiotti

The nearshore region of Lake Huron spans the coastal areas of the lake, shallow areas around islands, drowned river mouths, and the St. Marys River, all in waters less than 30 m deep (Edsall and Charlton 1997). The nearshore-zone surface is roughly 18,000 km^2 and represents 31% of the total lake surface area (Fig. 39). In 2017, the last year of this 2011-2017 reporting period, nearshore ports accounted for 57% of the recreational-fishing effort in Michigan waters, and much of the open-water fishing probably occurred in the nearshore area as well (Michigan DNR, unpublished data). Nearshore substrates include bedrock, coarse beach, sandy beach, silt, clay wetlands, and drowned-river-mouth sediments (Fetzer et al. 2017; Wei et al. 2004; Larson et al. 2013). Fish communities reflect these diverse habitat types. Habitat diversity, in combination with elevated nutrients and warmer temperatures, results in greater species richness relative to more-open waters (Fetzer et al. 2017). Coastal wetlands provide important spawning and nursery habitat for many fish species (Liskauskas et al. 2007); they support a high level of fish-species diversity (Cooper et al.

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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/Sp20_01.pdf.

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2018), and they support a relatively high level of fish production (Sierszen et al. 2012; Trebitz and Hoffman 2015; Sierszen et al. 2019).

Fig. 39. Lake Huron and its nearshore area (shaded) less than 30 m deep based on NOAA's Great Lakes Environmental Research Laboratory bathymetry dataset.

Nearshore fish communities continue to reflect the profound food-web changes in Lake Huron of the early 2000s. The ongoing paucity of Alewife and Rainbow Smelt has contributed to improved percid reproductive success, especially in Saginaw Bay (Riley et al., this volume; Fielder et al. 2007). The nearshore zone has become of greater importance in sustaining fisheries because open-water pelagic niches remain reduced or restructured (Rudstam et al., this volume; Riley et al., this volume) while many nearshore areas remain productive and serve as nursery grounds for important open-water fish, such as coregonines (Ebener et al. 2010a; Fetzer et al. 2017). Shoreline regions of the main basin and embayments, however, may not be exhibiting productivity gains theorized by a nearshore-shunt mechanism (Hecky et al. 2004). A study in 2012 found a loss of reproductive success of fish, including Lake Whitefish, stemming likely from declines or shifts in zooplankton production from spring to fall in the nearshore zone (Michigan DNR, unpublished data).

Saginaw Bay, portions of Georgian Bay, and the North Channel are more productive than other nearshore areas and likely help sustain key offshore fish (Fig. 40). For example, Saginaw Bay was historically the single largest site of Cisco commercial harvest (Baldwin et al. 2009) on Lake Huron, and the bay is now the target of Cisco reintroduction. There is also a growing awareness that Lake Whitefish in Lake Huron depends on nursery habitat and sufficient first foods from more-productive regions of the nearshore environment (Cottrill et al., this volume).

While nearshore processes are not fully understood, fish community-level responses are generally well documented. State, federal, provincial, and tribal agencies maintain a series of nearshore assessments for analyses of the status and trends of important species. Percids largely dominate the cool-water habitat of the nearshore zone of Lake Huron while esocids and centrarchids provide diverse fishing opportunities. Many of these species are also exploited commercially, especially in Ontario and in 1836 treaty-ceded waters. In the following, we report on progress during 2011-2017 in achieving the fish community objectives (FCOs) established for Lake Huron by DesJardine et al. (1995).

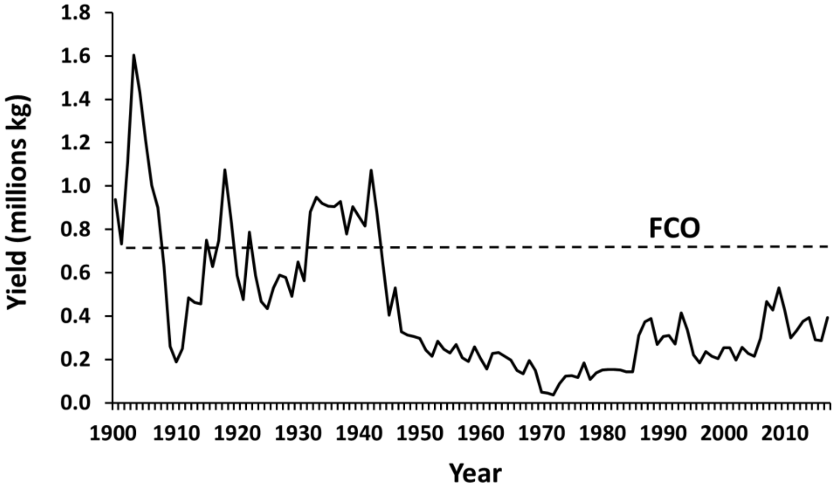
Fig. 40. Map of Lake Huron.

Walleye

> *Reestablish and/or maintain walleye as the dominant cool-water predator over its traditional range with populations capable of sustaining a harvest of 0.7 million kg.*

The mean yield of Walleye from Lake Huron declined slightly from 394,000 kg in the previous reporting period (2005-2010) to 339,000 kg during the current reporting period (2011-2017) (Fig. 41; Fielder et al. 2013). The recovery target for the Saginaw Bay stock of Walleye was attained in 2009 during the previous reporting period (Fielder and Baker 2004; Fielder and Thomas 2014) whereas abundance of the population stabilized or declined slightly during the current reporting period. The population appears to have reached carrying capacity; growth rate of Walleye declined to the Michigan statewide average during the reporting period (Fielder and Thomas 2014). Despite the attainment of recovery targets for Lake Huron’s largest Walleye population, lakewide yield was still only about half that specified by the FCO. The recreational harvest of Walleye in Ontario waters is not included in Fig. 41, so the true yield is greater than depicted but likely still well below the FCO.

Fig. 41. Yield of Walleye from Lake Huron during 1885-2017. Horizontal line indicates the fish community objective (FCO) of 0.7 million kg. The yield by recreational and indigenous fisheries in Ontario is not included in the figure. Data through 2009 are from Baldwin et al. (2009); more-recent data are unpublished from various agencies.

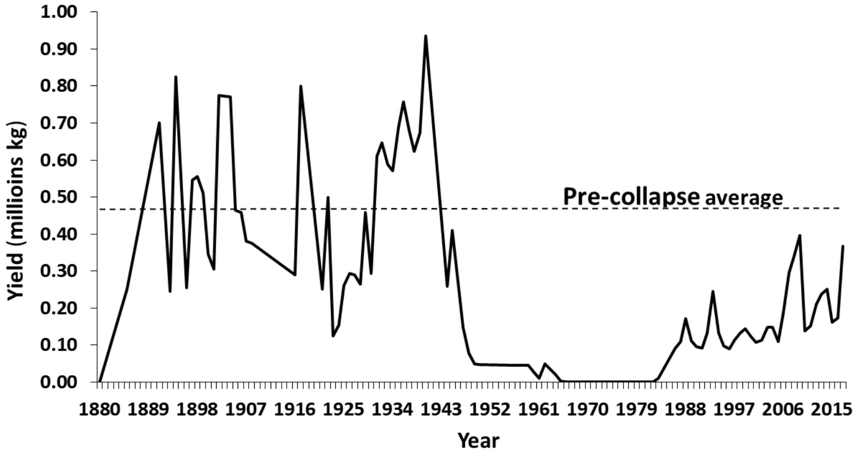


DesJardine et al. (1995) recognized that the recovery of the Saginaw Bay stock of Walleye was integral to the attainment of the lakewide FCO. Recreational-fishery yields have not replicated values sustained by the commercial fishery prior to the stock collapse in the mid-twentieth century (Fig. 42). The average recreational yield in Saginaw Bay has been 0.23 million kg since achieving Michigan DNR recovery targets in 2009, which is still 0.24 million kg less than the historical yield. The rate of exploitation on the Saginaw Bay Walleye population by the historical commercial fishery likely was greater than that achieved by the recreational fishery following its recovery in 2009. The recreational exploitation rate ranged from 9% to 22% during the reporting period. If the 0.24 million-kg yield was achieved, the lakewide yield would amount to 0.64 million kg and be within 90% of the FCO.

The Michigan DNR allowed for increased exploitation by the recreational fishery in Saginaw Bay during the current reporting period to reduce predation by Walleye on suppressed Yellow Perch stocks. The minimum total-length limit was reduced from 381 mm (15 in) to 330 mm (13 in), and the daily possession limit was increased from five to eight per angler beginning in the fall of 2015. While harvest increased, substantial gains in yield were not realized by the regulation changes. The limited effect on harvest is attributed to declining recreational-fishing effort since the late 1980s, which continued during the current reporting period. Analysis of creel data indicates that at least half the variability in recreational-fishing effort in Saginaw Bay is explained by the quality of Yellow Perch fishing (Fielder et al. 2014), which was poor during the reporting period.

A performance-based customized management strategy modeled after that of Lake Erie was implemented during the current reporting period to better manage the Saginaw Bay Walleye population and fishery. The new strategy departs from using default statewide harvest regulations to using regulations tailored to trends in the population and fishery. Intensive creel and fishery-independent surveys and model-based inferences based on statistical catch-at-age and stochastic simulation, along with tagging studies, form the basis for this new approach (Fielder 2014; Fielder and Bence 2014; Fielder and Thomas 2014; Fielder et al. 2014; Fielder et al. 2016). Supplemental to these efforts, telemetry studies confirmed the outmigration of about 37% of the Walleye that spawned in Saginaw Bay into the main basin during May-October (Hayden et al. 2014). Apparently, Walleye originating in Saginaw Bay is shared widely among fisheries elsewhere. The new models were adapted to this discovery by treating Saginaw Bay and main-basin Walleye as one population for analytical purposes (Fielder and Bence 2014; Fielder et al. 2016). The sizable St. Marys River population was not included in this single-population approach. It sustained 267,000 angler hours of effort in 2017, or 36% as much as Michigan's waters of the main basin; the harvest was nearly 14,000 fish during the open-water months of 2017 (Michigan DNR, unpublished data).

Fig. 42. Yield of Walleye from Saginaw Bay during 1880-2017. Yield since 1973 is exclusively by the recreational fishery whereas prior to 1973 the yield was taken principally by the commercial fishery. The horizontal line indicates the average yield prior to the collapse of the population in the mid twentieth century. Data through 2006 are from Baldwin et al. (2009); more-recent data is Michigan DNR, unpublished.



The average commercial harvest of Walleye from Ontario waters during the current reporting period was 92,000 kg (UGLMU 2017a) and was similar to that of the previous reporting period. The southern main-basin fishery accounts for close to 90% of the commercial harvest of Walleye from Ontario waters, and, although harvest declined slightly to 80,000 kg during the current reporting period from 86,000 kg in the previous reporting period, it has been increasing recently because of strong recruitment from the 2014 and 2015 year-classes. Independent fisheries assessments corroborated the strength of these two year-classes, which resulted in record catch-per-unit effort in 2017 (UGLMU 2017b). The average commercial harvest of Walleye from the North Channel and Georgian Bay increased modestly, 8% and 10%, respectively, from the previous reporting period; no trends within the reporting period were discernable. Targeted commercial gillnet effort was the lowest on record in 2017, which is reflective of a declining trend.

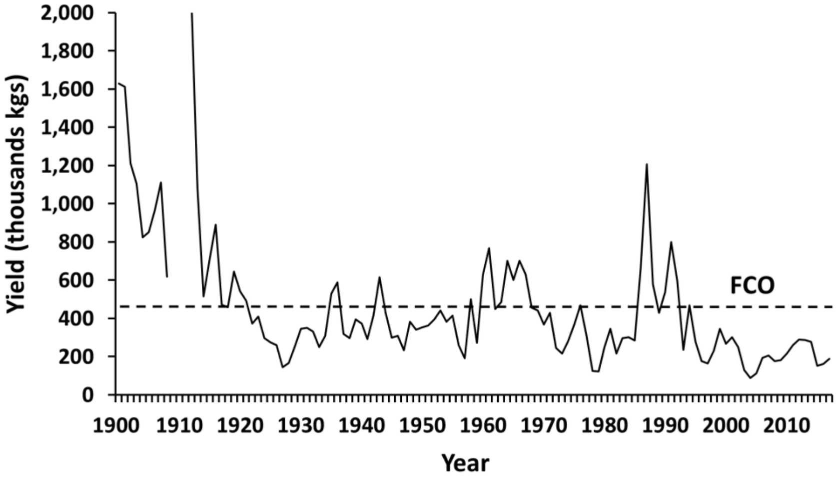
The most-consistent monitoring of Walleye in Ontario waters occurred in Severn Sound where both spawner abundance and relative catch rate declined from the previous reporting period (UGLMU, unpublished data). Similarly, spawner abundance and catch rate declined or remained at low levels in the Moon River, McGregor Bay, and the French River areas. In contrast, the Shawanaga River in eastern Georgian Bay and the Spanish River in the North Channel support larger spawning aggregations of 20,000-30,000 adults; relative abundance was the highest observed in Ontario waters. The annual recreational harvest of Walleye ranged from 300 fish in Severn Sound (suppressed population) to 2,000 in the Shawanaga River area and 5,000 during the open-water season in the Spanish River area (Upper Great Lakes Management Unit, unpublished data). An expanded Walleye and nearshore fish community monitoring and assessment program was initiated in 2015 to develop stock-specific benchmarks to support the development of a Walleye management plan for Ontario waters.

Yellow Perch

> *Maintain yellow perch as the dominant nearshore omnivore while sustaining a harvestable annual surplus of 0.5 million kg.*

Yield of Yellow Perch from all sources averaged 231,000 kg during the reporting period (2011-2017) and was greater than the 181,000 kg harvested during the previous reporting period (2005-2010) but still well below the FCO (Fig. 43). Historically, the Saginaw Bay Yellow Perch population was the single largest population in the lake (Baldwin et al. 2009). Yellow Perch has benefited from the collapse of Alewife populations (as did Walleye) and enjoys good reproductive success, but recruitment is poor (Fielder and Thomas 2014). Natural mortality routinely exceeds 90% between age 0 and age 1 due to predation by many species (Fielder and Thomas 2014) but primarily by Walleye and Double-crested Cormorant (hereafter, cormorant) (DeBruyne et al. 2017). Yellow Perch grows fast in Saginaw Bay, a reflection of its low adult abundance (Fielder and Thomas 2014).

Fig. 43. Yellow Perch yield from Lake Huron, 1900-2017. Horizontal line represents the fish community objective (FCO) of 0.5 million kg. Data through 2006 is from Baldwin et al. (2009); more-recent data are unpublished from various agencies.



Historically, Walleye predation on Yellow Perch in Saginaw Bay was buffered by abundant pelagic prey, such as Cisco and shiner species, in particular young Cisco that used the bay as nursery grounds prior to invasion of Lake Huron by Alewife (Fielder and Thomas 2014). The collapse of Alewife populations and the failure of Cisco to recover may constitute a broken predator-prey linkage between the offshore and the nearshore of the main basin that fishery management is attempting to repair by introducing Cisco to Saginaw Bay (Cottrill et al., this volume).

Both recreational and commercial fisheries for Yellow Perch in Saginaw Bay are greatly reduced compared to historical fisheries and, for all practical purposes, are collapsed. The average harvest of Yellow Perch from Saginaw Bay was 220,000 fish during the current reporting period compared to 1.7 million fish during 1986-2000. Similarly, commercial yield from Saginaw Bay averaged just 18,000 kg during the current reporting period compared to an average yield of 42,000 kg during 1985-2000. Along with liberalizing the recreational-fishery creel limit and minimum-length limit for Walleye, the recreational daily possession limit of Yellow Perch was reduced from 50 to 25 fish per day. In addition, one inner Saginaw Bay commercial license was temporarily relocated to the southern main basin partly to reduce exploitation on Yellow Perch. These management efforts were implemented in late 2015, and it is currently unclear if they are having the desired effects. Attainment of the FCO will not be possible until the Saginaw Bay Yellow Perch population and fisheries are restored.

The recreational fishery for Yellow Perch in the Les Cheneaux Islands area of the northern main basin was historically robust, producing annual recreational harvests as high as 439,000 fish (Lucchesi 1988), but, by 2000, less than 1,000 Yellow Perch were being harvested (Fielder 2008). Cormorant predation was implicated as a likely cause of the decline in harvest (Fielder 2008), and management actions to reduce the size of the local cormorant colony resulted in an increase in the population and fishery (Fielder 2010). Cormorant-management authority by the state of Michigan was revoked by court order in 2015, and, by 2017, the number of nesting adults had increased by 85% (U.S. Department of Agriculture APHIS, unpublished data). Declines in the recreational fishery are anticipated as cormorant consumption of Yellow Perch increases.

The commercial yield of Yellow Perch from Ontario waters of Lake Huron averaged 175,000 kg during the current reporting period (UGLMU 2017a), an increase of 65% over the previous reporting period. The southern main-basin fishery accounted for 99% of the commercial harvest in Ontario waters. This population experiences a high mortality rate and has been influenced by periodic strong year-classes, which result in wide swings in catch rates. In the North Channel, commercial harvest and catch rates declined during the reporting period, continuing a trend that began in the early 1990s. In Georgian Bay, commercial harvest and catch rates varied without trend. The absence of larger, older individuals that would be attractive to recreational and commercial fishers in both systems may be a result of predation by fish and cormorants.

Current recreational fisheries for Yellow Perch in Ontario waters are much reduced from historical fisheries and are not closely monitored (OMNRF 2015). Localized winter fisheries exist in Severn Sound where harvests approached 5,000 fish in 2013. Other fisheries at main-basin ports and locations around Manitoulin Island were not monitored during the current reporting period. Small-fish surveys and Walleye index netting encounter

Yellow Perch at most locations in Ontario. Relative abundance in small-fish surveys declined in the main basin and Georgian Bay but was relatively stable in the North Channel (J. Speers, OMNRF, personal communication, 2017). The Walleye surveys are not conducted regularly, but, in this survey, Yellow Perch is the most frequently caught species in the North Channel and Georgian Bay with catches consisting primarily of juveniles and young adults (J. Speers, OMNRF, personal communication, 2017).

Lake Sturgeon

> *Increase the abundance of lake sturgeon to the extent that the species is removed from its threatened status in United States waters.*
>
> *Maintain or rehabilitate populations in Canadian waters.*

The abundance of adult Lake Sturgeon in Lake Huron during the current reporting period was a fraction of that in the early 1900s (Haxton et al. 2014). The Province of Ontario in September 2009 listed Lake Sturgeon as a threatened species in the Great Lakes. Consequently, no commercial or recreational harvest of Lake Sturgeon has been allowed since January 1, 2010, although indigenous subsistence fisheries for Lake Sturgeon continue to be permitted throughout the province. Lake Sturgeon remains listed as a threatened species in the state of Michigan but is not listed by the U.S. government. The only Lake Sturgeon harvest now allowed in the Lake Huron basin is in Michigan waters of the St. Clair River and Lake St. Clair where the recreational creel limit is one fish per year and requires a special license.

Spawning aggregations of Lake Sturgeon have been documented in the Garden, Mississagi, Spanish, Moon, Musquash, Nottawasaga, and St. Clair Rivers, but, historically, spawning occurred in 33 tributaries to Lake Huron. While spawning has been documented in the Cheboygan River, it takes place above barriers to migration from Lake Huron. These fish are believed to originate from the upper river, not from Lake Huron.

Both the Ontario Ministry of Natural Resources and Forestry (OMNRF) and the Michigan DNR published Lake Sturgeon rehabilitation strategies during this reporting period. The OMNRF recovery plan was established in 2011 (Golder Associates Ltd. 2011), with the goal to maintain existing populations throughout their current range and, where feasible, to restore, rehabilitate, or re-establish populations within their current or historical habitats. In 2012, the Michigan DNR published a rehabilitation strategy (Hayes and Caroffino 2012) having goals to develop self-sustaining populations that would allow removal of Lake Sturgeon from the state list of threatened species and to maintain populations of sufficient size to support state and tribal fisheries. More recently, tributaries within Michigan waters, previously deferred for rehabilitation because they did not meet minimum viable population criteria for investment, are getting a second evaluation (D. Borgeson, Michigan DNR, personal communication, 2017).

Based on OMNRF and Michigan DNR assessments, the St. Marys, Mississagi, Spanish, Nottawasaga, and St. Clair River populations are viewed as stable (Pratt 2008; Hayes and Caroffino 2012). Spawning surveys in the Mississagi and Nottawasaga Rivers consistently have captured hundreds of Lake Sturgeon while over 50 fish commonly were captured during surveys in the Spanish River. Since the last reporting period (2005-2010), spawning activity has been observed in five new locations, including the Garden River, a tributary to the St. Marys River; the Moon and Musquash Rivers in eastern Georgian Bay; and the Manitou River on Manitoulin Island (L. Mohr, OMNRF, retired, personal communication, 2017). Larval Lake Sturgeon has been collected at multiple locations in the Garden River since 2014, and an acoustic telemetry study is currently underway to describe movement of adult fish in this river and in the St. Marys River system (Boase et al. 2015; Chiotti et al. 2018). Bauman et al. (2011) estimated population size in the St. Marys River at 505 individuals

(95% CI = 388-692). However, research since 2007 on the St. Marys River has yet to confirm spawning, even though anecdotal evidence of spawning behavior exists, including 26 juvenile Lake Sturgeon (<1,000 mm total length) collected in 2017. The Anishinabek/Ontario Fisheries Resource Center (A/OFRC) and Magnetawan First Nation captured no Lake Sturgeon in the Magnetawan River in 2014; the only confirmed capture occurred in 2009 (Boase et al. 2015). Roughly 15,000 (95% CI 8,146-26,856) Lake Sturgeon are present in the upper St. Clair River (USFWS, unpublished data). Of 11 tributaries assessed for the presence of juvenile Lake Sturgeon during this reporting period, juveniles (<1,000 mm total length) were captured at four tributaries, including the Blind, Echo, Serpent, and Spanish Rivers, all located in the North Channel.

Fishery agencies implanted 284 adult Lake Sturgeon with acoustic transmitters to study migration patterns in the St. Clair-Detroit River system and in southern Lake Huron during 2012-2015 (Kessel et al. 2018). Using the Great Lakes Acoustic Telemetry Observation System, millions of detections have been documented since 2012, providing valuable information regarding the movements of these fish. As of 2017, 74 Lake Sturgeon were detected acoustically in Lake Huron. Movements have been concentrated in the southern basin with limited use of large embayments (three fish entering Saginaw Bay and one entering Georgian Bay (D. Hondorp, USGS, personal communication, 2017). Stationary receivers at the mouth of the Saginaw River did not detect any Lake Sturgeon entering this system, suggesting recolonization of historical tributaries in Lake Huron from the St. Clair-Detroit River population would be slow; therefore, supplemental stocking in tributaries that can support a reintroduction may be necessary to achieve restoration targets over shorter time scales. Mean residence time and movement patterns obtained as a result of the telemetry study have contributed to population modeling efforts in southern Lake Huron.

Northern Pike and Muskellunge

> *Maintain northern pike as a prominent predator throughout its natural range.*
>
> *Maintain muskellunge (*Esox masquinongy*) in numbers and at sizes that will safeguard and enhance its species status and appeal.*
>
> *Sustain a harvestable annual surplus of 0.1 million kg of these esocids.*

In Georgian Bay and the North Channel, Northern Pike relative abundance remained low during the current reporting period (OMNRF, Upper Great Lakes Management Unit, unpublished data) and was similar to levels observed during the previous reporting period of 2005-2010 (Fielder et al. 2013), which is a likely response to low lake levels that persisted until 2013. Evidence of increased recruitment in the form of higher catch rates of younger year-classes (ages 1-3 years) within the current reporting period was apparent around Severn Sound, Moon River, Shawanaga River, and French River of Georgian Bay and the Spanish River of the North Channel. In some locations, such as Severn Sound and the Spanish River, Northern Pike size and age structure are dominated by younger year-classes with few large adults whereas the Moon, Shawanaga, and the French Rivers contained a broad size structure that included older and larger adults (OMNRF, Upper Great Lakes Management Unit, unpublished data).

Harvest of Northern Pike ranged from 300 in the Spanish River, to 500 in the Shawanaga River, and to 1,200 from Severn Sound (OMNRF, Upper Great Lakes Management Unit, unpublished data). Greater than 75% of the catch was released, which may account, in part, for the low harvests. Historically, harvest rates were much higher, averaging 5,000 fish in Severn Sound through the 1980s and 1990s (SSRAP 2002), reflecting a downward trend in recreational-fishing effort, more-restrictive harvest regulations imposed in 2003, and more catch and release (OMNRF, Upper Great Lakes Management Unit, unpublished data). The commercial yield of Northern Pike from all three basins in Ontario waters has remained low throughout the reporting period, averaging less than 1,000 kg (UGLMU 2017a) and continuing the downward trend from the previous reporting period. An unknown amount of harvest occurs in indigenous fisheries situated throughout Georgian Bay and the North Channel.

Northern Pike was at record levels of abundance in the Les Cheneaux Islands area during the current reporting period, increasing steadily since the implementation of management to reduce cormorant predation (implemented in 2004). Recent gains also may owe to improved reproductive success stemming from high water levels. Recreational harvest peaked at 3,800 in 2011 and was 3,000 in 2017. Northern Pike is also an important component of the recreational fishery in the St. Marys River, with 4,000 harvested in Michigan and Ontario combined in 2017.

Relative abundance of Muskellunge populations during the reporting period in Ontario waters was variable (Liskauskas 2017) and similar to values observed during the previous reporting period (Fielder et al. 2013). There has been evidence of increased abundance of adult Muskellunge in the Spanish River in 2016, a positive sign of population recovery after 30 years of near extirpation. The size structure of spawning adults is very similar across a large geographical area of the North Channel and southern Georgian Bay (Liskauskas 2017).

Radio-telemetry studies in Lake Huron indicate that Muskellunge homes to the spawning areas where it originated and that its nursery habitats are nearby (LeBlanc et al. 2014; Weller et al. 2016). Genetic studies support the telemetry findings in that the Lake Huron populations were genetically structured and diverse (Wilson et al. 2016). Muskellunge continues to be avidly sought by anglers for its trophy qualities, more so in Ontario waters than in Michigan waters where it is less abundant. Based on volunteer angler logs provided by members of Muskies Canada, both catch rate and average size have increased during the current reporting period (Taillon and Heinbuck 2017).

Centrarchids

> *Sustain smallmouth and largemouth bass and the remaining assemblage of sunfishes (*Centrarchidae *spp.) at recreationally attractive levels over their natural range.*

In Severn Sound, the only location in Ontario waters where long-term nearshore surveys have been conducted, relative abundance of Smallmouth Bass declined during the current reporting period, but all nearshore species declined at this location. Populations in eastern Georgian Bay and the North Channel comprised broad size ranges, multiple year-classes, and abundant juveniles, indicating strong recruitment. In the St. Marys River in 2017, over 3,000 Smallmouth Bass were harvested in Michigan and Ontario waters combined. The proliferation and consumption of Round Goby appears to have benefitted growth and survival of Smallmouth Bass. Similar responses of Smallmouth Bass to proliferation of Round Goby have been noted in Lake Erie (Steinhart et al. 2004) and in northern Lake Michigan (Kaemingk et al. 2012).

The distribution of Largemouth Bass is more restricted than that of Smallmouth Bass, but it is prominent in warmer nearshore waters in areas like Severn Sound. Due to restrictive harvest regulations instituted in 2003 and catch and release rates approaching 90%, annual harvests of Largemouth and Smallmouth Bass combined are modest in Ontario waters, ranging from 1,000 fish in the Shawanaga River area to 2,000 fish in Severn Sound (OMNRF, Upper Great Lakes Management Unit, unpublished data).

Other centrarchids, such as Rock Bass, Black Crappie, Pumpkinseed, and Bluegill, occur in most nearshore surveys. Their relative abundance, especially that of Black Crappie, has declined in Severn Sound from peak levels observed in the 1980s (SSRAP 2002) and has remained low during the current reporting period (UGLMU, unpublished data). The status of these centrarchids is not well documented in Michigan waters.

Channel Catfish

> *Maintain channel catfish as a prominent predator throughout its natural range while sustaining a harvestable annual surplus of 0.2 million kg.*

Channel Catfish remains widely distributed in all three of Lake Huron's basins. The combined commercial and recreational yield of Channel Catfish from Ontario waters is unknown. It supported commercial yields >34,000 kg in 1989 (OMNRF, unpublished data) in the southern main basin primarily for live export, but restrictions on exports were imposed due to viral hemorrhagic septicemia, which caused Ontario yields to decline to <200 kg during the current reporting period (UGLMU 2017a). Channel Catfish is seasonally abundant in the French and Moon Rivers of Georgian Bay, especially in spring where it can be the most frequently encountered species and comprise the largest component of fish biomass in surveys. At these two locations, populations are characterized by broad size ranges, including juveniles and adults, with some individuals exceeding 10 kg in weight. Channel Catfish was identified as a species of concern in the Spanish River Area of Concern as a result of its absence since 1980 in fish community surveys. Nearshore surveys conducted in the Spanish River delta during the current reporting period captured consistent numbers of juveniles and adults (UGLMU, unpublished data), indicating the species had likely recovered or had been missed in previous surveys.

Recreational harvest of Channel Catfish is a minor component of the Saginaw Bay fishery. Commercial yields averaged 42,000 kg during the current reporting period, down from 64,000 kg during the previous period (Michigan DNR, unpublished data). Some of the decline is due to declining small-mesh trapnet effort, but the catch rate in 2017 was the lowest observed since 1972. Why abundance of Channel Catfish appears to be declining in Saginaw Bay is unclear. Interest in the species is declining due possibly to fish-consumption advisories.

Threats to the Nearshore Fish Community

Round Goby has expanded its distribution to nearly all nearshore areas since its arrival in Lake Huron. Its distribution, however, is disproportionately focused on rocky substrates and on aggregations of dreissenids (Coulter et al. 2015). Round Goby was captured at most locations during small-fish surveys in Ontario during this reporting period, although its relative abundance has generally remained low (J. Speers, OMNFR, personal communication, 2017). Round Goby serves as prey for many predators and constitutes an energy pathway from dreissenids to nearshore piscivores (Johnson et al. 2005; Pothoven et al. 2017).

The nearshore areas of Lake Huron are most susceptible to impacts from a potential invasion of Asian carps. Productive environments like Saginaw Bay, the St. Marys River, and Severn Sound may experience the greatest impacts (Lohmeyer and Garvey 2009). Asian carps were not detected in any of the basins of Lake Huron during the current reporting period. The Ruffe, an introduced species, has not been collected in Lake Huron since 2012 and is not considered established, even though it was collected earlier from Thunder Bay and the Cheboygan and Trout Rivers (Bowen and Keppner 2017).

Climate warming remains a threat to the nearshore environment of Lake Huron. If unabated, the climate of lower Michigan and southern Ontario is estimated to become more like that of Indiana by 2030 and more like that of Missouri by 2095 (Kling et al. 2003). Predicted effects from climate warming for Lake Huron include declines of 1.2-7.9 m in lake levels, lack of winter ice cover, longer stratification in nearshore areas, more algal blooms, and large areas of anoxia (Hayhoe et al. 2010). Although impacts may be most severe for cold-water species, the nearshore area will likely see shifts in abundance with centrarchids and ictalurids favored (Casselman 2002; Collingsworth et al. 2017). Warming may also promote the resurgence of invasive species, such as Alewife. Coastal wetlands are particularly susceptible to fluctuating water levels. If prospects are for sustained lower lake levels, changes to fish community composition in the form of lower diversity and altered composition, as was experienced during a recent low-water cycle, may become the norm (Midwood and Chow-Fraser 2012).

Recommendations

In a comprehensive review and analysis of nearshore fish communities in Lake Huron, Fetzer et al. (2017) found the nearshore region to be heterogeneous in habitat types and species assemblages but more homogenous than previously suspected when examined from the same shoreline types. Main-basin nearshore zones were still largely dominated by cold-water species for much of the year; species richness in embayments and archipelagos was generally increasing but still dominated by a few common species, such as Walleye and Yellow Perch; and species richness was really an artifact of numerous but much-less-abundant species that make up the overall community. In other words, the distribution and abundance of species was lopsided. Fetzer et al. (2017) also agreed that warming is already one of the dominant factors driving changes in species richness in the nearshore area of Lake Huron.

Here we reiterate the management implications and recommendations of Fetzer et al. (2017)

- The open nearshore areas of the main basin, being characteristic of the lake's cold-water community, are not a high priority for research.
- Existing nearshore data should be better integrated with environmental data using a spatial framework.

In addition to the above recommendations from Fetzer et al. (2017), we offer these recommendations

- Barrier removal and meaningful fish passage at first-order barriers should remain a high priority for managers. Health and resiliency of Lake Huron's nearshore fish communities depend on connectivity and the degree to which habitat types are intact. Restoration of access to tributary spawning habitat remains an important need for many nearshore species, including Lake Sturgeon and Walleye.
- New efforts for Cisco rehabilitation in Lake Huron should continue for the benefit of both nearshore and offshore fish communities. The current lack of abundant pelagic planktivores has consequences for predator-prey dynamics in places like Saginaw Bay.

- Decision making for the management of the pelagic prey base in Lake Huron should take into account that continued success of some nearshore species is dependent on the scarcity of certain non-native prey fish. Management over Lake Huron’s fish community should be holistic, with careful consideration of interdependence between offshore and nearshore components.
- Every effort should be made to guard against future invasions of non-native species. New invasions and climate change appear to constitute the two largest threats to the nearshore areas of Lake Huron.
- Managers should work with Federal agencies to restore the ability to manage cormorants to levels that do not suppress or cause depensatory mortality of nearshore fish.
- Coordinated efforts to develop and implement a juvenile index of Lake Sturgeon abundance should continue. Restoration stocking in Michigan waters that was previously deferred should be restarted.
- Habitat-suitability models of Lake Sturgeon and identification of specific tributaries suitable for its reintroduction should be high priorities for research.

SPECIES AND GENETIC DIVERSITY IN LAKE HURON IN 2018[20]

Wendylee Stott[21], Edward F. Roseman, and Chris Wilson

Fish community objectives (FCOs) for species and genetic diversity (DesJardine et al. 1995) complement the species- or genera-specific objectives by recognizing that diversity within and among species can improve ecosystem resiliency through portfolio effects (DuFour et al. 2015). In Lake Huron, native species (such as Lake Trout and Lake Whitefish), and non-native species (such as Alewife and Pacific salmon) play important roles in the ecosystem. The FCOs recognize the importance of genetic diversity within all fish populations to ensure their long-term sustainability. This section summarizes the current state of species diversity and recent genetic analyses of important biota in the fish community.

Species Diversity

The species diversity FCO (DesJardine et al. 1995) is to

> *Recognize and protect the array of other indigenous fish species because they contribute to the richness of the fish community. These fish–cyprinids, rare ciscoes, suckers, burbot, gar (*Lepisosteidae *spp.), and sculpins–are important because of their*

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[20] Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp20_01.pdf.

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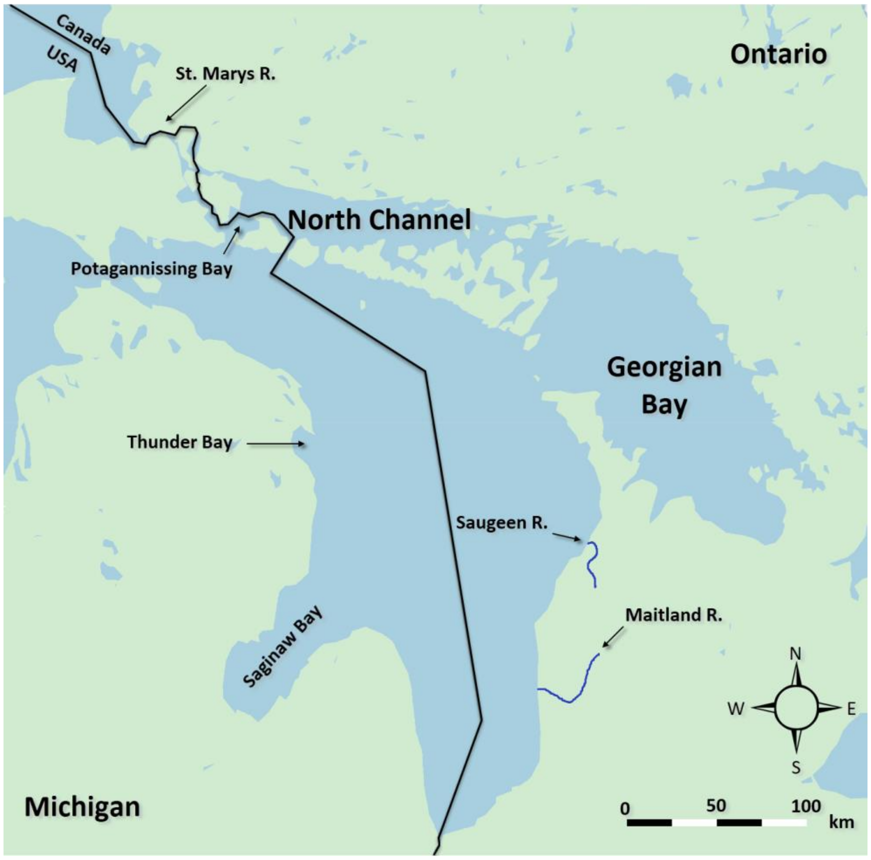
> *ecological significance; intrinsic value; and social, cultural, and economic benefits.*

No additional extirpations of the remaining 96 native fish species of Lake Huron (Roseman et al. 2009; Roth et al. 2013) have been reported since the last state of the lake report (Riley 2013), but new invasive fish species were captured during the current reporting period (2011-2017). Tubenose Goby was captured in the St. Marys River during invasive-species surveys (USFWS 2018) and in Georgian Bay during the Great Lakes Coastal Monitoring Project (Brady 2015). In addition, two Chain Pickerel were caught in the lower St. Marys River https://nas.er.usgs.gov/queries/SpecimenViewer.aspx?SpecimenID=775483) in January 2015 (Fig. 43). A possible invasion pathway for Tubenose Goby and Chain Pickerel into Lake Huron is secondary spread after introductions. The Tubenose Goby originated in Eastern Europe and was originally introduced to the Great Lakes basin via ballast water (Stepien and Tumeo 2006) whereas Chain Pickerel was stocked into Lake Erie (Emery 1985). Other potential invasive species like Bighead Carp, Silver Carp, Rudd, and Fourspine Stickleback have not yet been reported in Lake Huron, although they all have the potential to do so. Cudmore et al. (2017) concluded there is a high risk that diploid Grass Carp will spread to Lake Huron from Lakes Erie and Michigan by 2024. The capture of juvenile and adult diploid Grass Carp in Ohio waters of western Lake Erie (Chapman et al. 2013; Embke et al. 2016; Wieringa et al. 2017) suggests it may spread to Lake Huron sooner than expected.

The Smallfish Community Assessment Program conducted by the Ontario Ministry of Natural Resources and Forestry (OMNRF) has gathered abundance and species composition data about the nearshore fish community in Ontario waters since 2003 and tracks the distribution of invasive and non-native species (J. Speers, OMNRF, personal communication, 2017). Round Goby accounted for around 50% of catches in the survey between 2014 and 2016, but, in 2017, its contribution declined to 15% and cyprinids became the most frequently caught group. Overall abundance of Round Goby in this reporting period doubled from that reported in the previous period, but abundance fluctuates greatly year to year, and the last peak was in 2012 (Nevers et al. 2018; USGS 2018; Riley et al., this volume). An analysis of

Round Goby invasion fronts in the Maitland and Saugeen Rivers in Ontario using genetic markers (Bronnenhuber et al. 2011) indicated that both rivers were colonized recently from the lake and Round Goby is moving upstream via contiguous spread. Bronnenhuber et al. (2011) suggested that the spread of Round Goby into rivers could be slowed by creating barriers to upstream movement.

Fig. 44. Map of Lake Huron.



Abundance of Alewife and Rainbow Smelt, invasive species, remained low during the current reporting period (e.g., USGS 2018; Riley et al., this volume), although both were abundant in the recent past. Acoustic surveys conducted by the U.S. Geological Survey, Great Lakes Science Center have reported zero or near-zero catches of Alewife since 2004 (USGS 2018), and its abundance remains low in bottom-trawl surveys (USGS 2018). However, Alewife reappeared in the Smallfish Community Assessment in southern Ontario waters of the main basin in 2017 (J. Speers, OMNRF, personal communication, 2017). Rainbow Smelt was most abundant in the North Channel and Georgian Bay during the reporting period (USGS 2018).

Aquatic invertebrate species introductions and extirpations can have an impact on native and non-native species diversity. Native mussel species, such as the Hickorynut (*Obovaria olivarian*), remain listed as threatened or endangered in Ontario (http://www.dfo-mpo.gc.ca/species-especes/sara-lep/identify-eng.html?province=Ontario); in Michigan waters, the Clubshell Mussel (*Pleurobema clava*), Northern Riffleshell Mussel (*Epioblasma torulosa rangiana*), Rayed Bean Mussel (*Villosa fabalis*), and Snuffbox Mussel (*E. triquetra*) are listed as endangered (https://www.fws.gov/midwest/Endangered/clams/snuffbox/pdf/SnuffboxFactSheetFeb2012.pdf). The Smallfish Community Assessment Program captured no invasive Bloody Red Shrimp (*Hemimysis anomala*) in 2017 of the current reporting period (J. Speers, OMNRF, personal communication, 2017). The last time Bloody Red Shrimp was reported in the survey was 2011, when it was captured in Ontario's southern main basin (J. Speers, OMNRF, personal communication, 2017). No new invasive invertebrate species have been reported in Lake Huron since 2011, but a rotifer (*Brachionus leydigii)* and zooplanktor (*Thermocyclops crassus)* were found in Lake Erie and could invade Lake Huron. Their potential impacts on the Lake Huron ecosystem are currently undetermined.

Some native species continue to increase in abundance, possibly in response to declines in Alewife and Rainbow Smelt. Trout-Perch, Ninespine Stickleback, Slimy Sculpin, and Deepwater Sculpin biomasses are increasing, although they are still low compared to historical levels (USGS 2018). Estimates of diversity for species caught in the Smallfish Community Assessment remain high and stable at most locations (J. Speers, OMNRF, personal communication, 2017). Lakewide, age-0 Bloater density from acoustic and mid-water trawl surveys increased from <50 fish•ha^{-1} in 2011 to around 300 fish•ha^{-1} in 2017 (USGS 2014; USGS 2018). In contrast, biomass of age-1+ Bloater has remained relatively stable between 4 and 5 kg•ha^{-1} since 2011 (USGS 2018). However, Bloater biomass is not distributed evenly across Lake Huron; the highest catches are reported in the main basin as compared to the North Channel and Georgian Bay. Bloater continues to account for most of the biomass of pelagic fish species in the main basin, amounting to roughly 50% in 2011 and 60% in 2017 (USGS 2018).

Walleye and Lake Trout populations continue to respond to ecosystem changes. Reduced predation on Walleye fry by Alewife has fostered recovery of Walleye in western Lake Huron (Johnson et al. 2015). In 2013, naturally produced Lake Trout accounted for almost half of all individuals less than eight years old captured in the main basin (Johnson et al. 2015), and wild-origin fish were reported throughout the lake. The Seneca strain of Lake Trout continues to support most of the natural reproduction by Lake Trout in the lake (Scribner et al. 2018), but other strains, such as the Manitou strain stocked by the OMNRF, have been successful in specific locations (Scribner et al. 2018).

The continued reduction of the Alewife population has encouraged research and progress toward Cisco rehabilitation in Lake Huron. Since 2015, the U.S. Fish and Wildlife Service has collected gametes from Cisco in the northern main basin. Two year-classes of captive broodstock are in development, and, in October 2018, the first production lot was scheduled to be stocked into outer Saginaw Bay (USFWS 2017).

Trends identified by Barbiero et al. (2012) for native crustacean zooplankton and rotifers continued during the current reporting period. For example, *Limnocalonus macrurus* abundance remains highest in the hypolimnion while calanoid copepodites are more abundant in the epilimnion and metalimnion (Nowicki et al. 2017). *Conochilas* spp. remain the most-abundant rotifer since declines in *Keratella* spp. associated with the *Bythotrephes longimanus* invasion (Barbiero and Warren 2011).

Species invasions are still a significant threat to native species diversity in Lake Huron, especially as climate change, new pollutants, and habitat alterations continue to impact the Great Lakes (Mandrak and Cudmore 2010; DuFour et al. 2015). Therefore, existing monitoring programs should continue, and new methods (e.g., eDNA, metagenomics) are needed to improve capabilities for finding rare and invasive species that occur in small numbers or that are localized in areas difficult to sample with traditional gears (Lacoursière-Roussel et al. 2016; Balasingham et al. 2018; Currier et al. 2018) before they become abundant.

Genetic Diversity

The genetic diversity FCOs (DesJardine et al. 1995) are to

> *Maintain and promote genetic diversity by conserving locally adapted strains.*
>
> *Ensure that strains of fish being stocked are matched to the environments they are to inhabit.*

Advances in genetic methods provide new approaches to monitoring species diversity, population structure, and success of stocking programs. Genetic analyses can be used to monitor migration patterns and identify larval fish caught in assessment surveys. Brenden et al. (2015) found that contributions of Walleye from Lakes St. Clair and Erie to the recreational fishery in Saginaw Bay varied by season and age-class. Using microsatellite DNA variation, they distinguished among Walleye from Lakes St. Clair, Erie, and Huron and determined that almost 25% of the recreational harvest from Saginaw Bay is produced elsewhere. Seneca-strain Lake Trout contributed the most to natural reproduction around the lake, except for in the North Channel (Scribner et al. 2018). The appearance of Seneca-strain hatchery fish in Canadian waters of Lake Huron (where they were not stocked until recently) suggests that stocked Lake Trout are straying from stocking sites in Michigan waters into the North Channel and Georgian Bay (Binder et al. 2017; Scribner et al. 2018).

The number of studies of within-species genetic structure has increased during the current reporting period (2011-2017). Genetic structure of Yellow Perch in Lakes Erie, Huron, and St. Clair and in the Detroit and St. Clair Rivers was analyzed using 15 microsatellite DNA loci (Sullivan and Stepien 2014). Significant genetic differences were found among all bodies of water. Yellow Perch from Saginaw Bay and Thunder Bay were genetically distinct from those in the St. Clair River, in the Detroit River, and in Lake St. Clair (Sepulveda-Villet and Stepien 2012; Sullivan and Stepien 2014). A range-wide study of Round Whitefish (Morgan et al. 2018) found significant differences among the upper Great Lakes and suggested that Round Whitefish in Georgian Bay may be (or were in the past) an important source population for Lakes Superior, Michigan, and possibly Nipigon.

Genetic structure of Muskellunge from across the Great Lakes was analyzed using microsatellite DNA variation (Kapuscinski et al. 2013; Turnquist et al. 2017), including sites in Lake Huron and Georgian Bay. Significant genetic structuring (based on microsatellites) of Muskellunge across small spatial scales was observed in Lake Huron and Georgian Bay (Scribner et al. 2015; Wilson et al. 2016), with some evidence of introgression from supplemental stocking in Michigan waters (Scribner et al. 2015). Scribner et al. and Wilson et al. highlighted the importance of local habitat patches for supporting discrete, localized populations. Kapuscinski et al. (2013) and Turnquist et al. (2017) suggested that management plans for Muskellunge should focus on preserving spawning and nursery habitat associated with individual populations.

STATUS OF HABITAT IN LAKE HURON IN 2018[22]

Arunas P. Liskauskas[23], Bretton Joldersma, David G. Fielder, Greg Mayne, and Rob Hyde

DesJardine et al. (1995) defined fish community objectives (FCO) for Lake Huron's habitat as

> *Protect and enhance fish habitat and rehabilitate degraded fish habitats.*
>
> *Achieve no net loss of the productive capacity of habitat supporting Lake Huron fish communities and restore damaged habitats.*
>
> *Support the reduction or elimination of contaminants.*

The inventory and characterization of aquatic habitats in Lake Huron continued throughout the current reporting period (2011-2017). Both the Lake Huron Environmental Objectives (EOs) (Liskauskas et al. 2007) and

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[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/Sp20_01.pdf.

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the Lake Huron Biodiversity Conservation Strategy (Franks Taylor et al. 2010) have been helpful in providing a habitat framework, strategy, and actions that are still relevant. More recently, the Lake Huron Lakewide Action and Management Plan (LAMP) updated the status of terrestrial and aquatic habitat and actions necessary to address key environmental threats (ECCC and USEPA 2018). The LAMP should be viewed as the principle mechanism for coordinating the implementation strategies to restore habitat in Lake Huron that are being developed by the EO and the Biodiversity Conservation Strategy.

In 2016, the Council of Lake Committees developed environmental principles for sustainable fisheries in the Great Lakes basin to stimulate progress in addressing EOs and FCOs (GLFC 2016). The environmental principles prioritize impediments at appropriate scales so that governmental and nongovernmental entities can begin to reduce them. They focus on the identification of functional habitats ("dynamic systems of hydraulically-connected areas that support requirements of desired fish species for sustained production"), where the prospects for environmental improvement can be enhanced. This approach began in Lake Huron at the end of the current reporting period (2011-2017) and will be the basis for gauging progress on aquatic-habitat improvements.

As formalized through the LAMP, governmental and nongovernmental agencies have continued to invest in aquatic-habitat-related activities during this reporting period. In this chapter, we will describe these numerous projects and their actions to restore and protect habitat in the Lake Huron basin.

Spawning and Nursery Habitats–Wetlands Environmental Objective

The spawning and nursery habitats objective (Liskauskas et al. 2007) is

> *Maintain, protect and restore the integrity and connectivity of wetland spawning, nursery and feeding areas throughout the Lake Huron basin.*

The Nature Conservancy has helped protect Lake Huron shorelines and the associated spawning and nursery habitats during the reporting period. In the Thunder Bay area, 567 ha were acquired. This purchase included 2.4 ha of coastal wetland that serve as spawning and nursery habitat for Yellow Perch and Smallmouth Bass, 81 ha of coastal fen, and 283 ha of inland wetlands that help to maintain the health of the adjacent coastal wetland, shoal, and reef habitats. Since 2012, the Nature Conservancy of Canada has been leading an international effort to conserve habitat on Cockburn Island in northern Lake Huron. Through 2017, 10,730 ha (over 60% of the island) and 48 km of undeveloped shoreline has been protected in an effort to protect one of the largest Great Lakes islands and coastal ecosystems (http://www.natureconservancy.ca/en/where-we-work/ontario/featured-projects/cockburn-island.html).

Ducks Unlimited (https://www.ducks.org) and the U.S. Fish and Wildlife Service restored riverine-wetland-habitat quality and aquatic connectivity of former emergent wetlands adjacent to the Shiawassee River near Saginaw Bay (Fig. 45). These activities will help fish and other aquatic organisms regain access to a large wetland complex, thus improving the prospects for fish production in the Saginaw River watershed.

In Ontario, Parks Canada reached an agreement to acquire a privately owned 1,324 ha parcel of land that allowed for the expansion of the national park located on the Bruce Peninsula. The property includes 6.5 km of uninterrupted shoreline and associated coastal wetland areas and is home to at least 10 federally listed species at risk and dozens of ecologically, geologically, and culturally significant areas (https://www.canada.ca/en/parks-canada/news/2018/12/government-of-canada-finalizes-purchase-of-driftwood-cove-property-grows-bruce-peninsula-national-park.html).

Fig. 45. Map of Lake Huron showing important riverine habitats.

Coastal wetlands in the Lake Huron basin have been characterized as some of the most abundant and highest quality in all the Great Lakes, but gauging the health of these wetlands is challenging, especially during substantial changes in lake levels observed during the current reporting period. Starting in 2014, lake levels have been on the rise in Lake Huron, with annual means well above chart datum throughout the end of the reporting period (Canadian

Hydrographic Service http://www.waterlevels.gc.ca/C&A/pdf/NetworkMeans2018.pdf; U.S. Army Corp of Engineers https://www.lre.usace.army.mil/Portals/69/docs/GreatLakesInfo/docs/WaterLevels/LTA-GLWL-Graph_2016.pdf The state of wetlands in the Georgian Bay Biosphere Reserve (https://www.gbbr.ca/) was identified as undetermined because some fish species were found to benefit from low water while other species benefit from high water (Chow-Fraser 2006; Seilheimer and Chow-Fraser 2007; Chow-Fraser and Croft 2015). A decline in the recruitment of young-of-the-year Muskellunge, a species particularly vulnerable to degraded wetlands, was evident in parts of eastern Georgian Bay (LeBlanc et al. 2014) and was due to a combination of sustained low lake levels and increased shoreline modifications that affected macrophyte composition and fish community structure. Ecosystem health report cards on the coastal wetlands in Georgian Bay were developed during the reporting period (GBBR 2013, 2018).

A further evaluation of the change in spatial distribution of coastal wetlands in Georgian Bay was funded by Georgian Bay Forever (https://georgianbayforever.org/), a nonprofit group dedicated to scientific research and public-education initiatives. Using automated remote sensing, the foundation estimated that, in southern Georgian Bay, there was a 10.8% net loss of coastal wetlands between the high-water year of 1987 and the low-water year of 2013 whereas, in northern Georgian Bay, there was a 7.3% net gain during the same time (Adams et al. 2015). These north and south differences in wetland changes were due to basin morphology, with steeper sloping shorelines in the north facilitating the migration of wetlands into deeper water. Similar loss of wetlands in Georgian Bay was also predicted by Fracz and Chow Fraser (2013) using global circulation models; they found that hydrological disconnection of existing coastal wetlands (13% by number and 6% by area) would occur in addition to losses resulting from the sustained decreases in Lake Huron lake levels experienced from 2000 through 2013.

Additional multi-agency efforts to characterize the status of coastal wetlands in Lake Huron were completed during the current reporting period. Coastal wetland sub-indicators identified in the 2017 state of the Great Lakes technical report (ECCC and USEPA 2017) and the 2018 Lake Huron LAMP (ECCC and USEPA 2018) were rated fair and deteriorating for plant communities but were rated fair and improving for fish. Additionally, a synthesis of the state of 157 wetlands sampled in 30 quaternary watersheds using several U.S. and Canadian datasets provided a comprehensive analysis of wetland condition. Index scores for water quality and the presence of wetland vegetation and fish indicated a very good to excellent condition for most coastal wetlands along the Canadian shoreline, especially those in eastern and northern Georgian Bay. Some coastal wetlands of the Bruce Peninsula were rated in fair or poor condition. In Michigan, results were more variable, with most wetlands being rated poor or fair, especially in Saginaw Bay where high turbidity and dense stands of the invasive reed *Phragmites australis* have impacted wetland health by outcompeting native species and reducing plant diversity (Minchinton et al. 2006).

The extent and composition of Lake Huron coastal wetlands were not available for the current reporting period. The last aerial mapping of wetland coverage occurred in 2004 when Lake Huron had the highest extent of coastal wetlands (61,461 ha) of all the Great Lakes (Chow-Fraser 2008). In areas of eastern and northern Georgian Bay, more-recent wetland inventories using satellite imagery from 2002-2008 (Midwood et al. 2012) identified a much-greater total wetland area of 17,350 ha versus 3,659 ha from a previous inventory conducted through the Great Lakes Coastal Wetland Consortium (Ingram et al. 2004). Because a basinwide inventory was not currently available, the status and trend for wetland extent were undetermined (ECCC and USEPA 2017). Prospects for prioritizing coastal wetland protection and enhancement in the basin continue to improve through the Great Lakes Coastal Wetland Monitoring Program, which has been instrumental in providing insights into wetland condition (Uzarski et al. 2017).

Spawning and Nursery Habitats–Tributaries Environmental Objective

The spawning and nursery habitats objective (Liskauskas et al. 2007) is

> *Protect and restore connectivity and functionality of tributary spawning and nursery areas throughout the Lake Huron Basin.*

Tributaries are an essential habitat because they provide spawning and nursery habitat to one-third of Lake Huron's fish species, including Walleye and Lake Sturgeon (Lane et al. 1996). However, tributaries are among the most-altered habitats in Lake Huron as a result of dams, spillways, locks, water-level-control structures, and other destructive actions. These man-made structures deny fish access to critical spawning habitat, alter flow and temperature regimes, and sequester nutrients (Edsall and Charlton 1997). Liskauskas et al. (2007) reported that over 800 barriers occur throughout the Lake Huron watershed in the state of Michigan, with 86% of that habitat no longer accessible to migrating fish. Although the loss of hydrological connectivity due to dams and barriers is recognized as a critical threat to biodiversity (ECCC and USEPA 2017; Franks Taylor et al. 2010), no progress was made during the reporting period at removal of first-order barriers that impede migratory fish.

Notwithstanding the lack of progress in barrier removal, actions addressing this EO were undertaken in U.S. waters, the largest of which were projects associated with the St. Marys River. Historically, the St. Marys River rapids provided an expansive area of reproductive habitat for species, such as Lake Whitefish, Lake Sturgeon, Lake Trout, Walleye, and others (Duffy et al. 1987), but, due to the development of hydroelectric facilities, locks for shipping navigation, and the construction of compensating gates, most of the rapids were destroyed (OMOE and Michigan DNR 1992). The remaining rapids have been subject to abrupt fluctuations in flow rates and water levels that have degraded habitat conditions for fish. Despite these alterations, Koshinsky and Edwards (1983) listed 38 species of fish collected from the rapids. Under the supervision of the International Lake Superior Board of Control, the U.S. Army Corps of Engineers has been automating the Compensating Works gates to reduce fluctuations in flow rates and water level, thus preventing fish from being stranded when gates are lowered and protecting eggs and fry from being flushed out when gates are raised. This automation is expected to improve spawning habitat for Lake Sturgeon, Walleye, steelhead, Atlantic Salmon, Coho Salmon, and Chinook Salmon (https://ijc.org/en/helping-fish-st-marys-rapids-push-button).

A portion of the historic St. Marys River rapids was restored during the reporting period. Little Rapids is a small subset of the larger St. Marys River rapids that was located near Sault Ste. Marie, MI. The Little Rapids suffered a similar fate to the larger rapids, with much of their flow reduced. Based on recommendations following a feasibility study funded by the National Oceanic and Atmospheric Administration's Great Lakes Restoration Initiative Program, outdated culverts were replaced with a 183-m-long bridge, which increased current velocities above minimum critical levels (0.24 $m \cdot s^{-1}$) to 70% of the fish-spawning habitat in the Little Rapids study site (http://www.glc.org/wp-content/uploads/Little-Rapids-Fact-Sheet.pdf). Current velocities at transects in the Little Rapids ranged from 0.34 to 0.97 $m \cdot s^{-1}$ after completion of the bridge (A. Moerke, Lake Superior State University, personal communication, 2017).

Two fish-passage projects were implemented in the Saginaw Bay watershed during the reporting period. A rock-ramp fish-passage structure on a tributary to the Saginaw River was modified in 2011 at a cost of $1.3 million, while a new rock-ramp structure was created on another Saginaw River tributary in 2015 at a cost of $3.5 million. Rock ramps help migrating fish traverse low-head dams or spillways and help preserve dams and impoundments that are important to local municipalities. To date, evaluation of rock ramps suggests that in spring White Sucker and Redhorse Sucker successfully migrate through the structures but Lake Sturgeon do not (Wigren et al. 2019; Stoller 2013). To maintain effectiveness, rock ramps require ongoing maintenance, but responsibility for those costs has not been resolved fully.

Rehabilitation of numerous tributaries occurred on Manitoulin Island and areas of eastern Georgian Bay during the reporting period. The Manitoulin Streams Improvement Association (http://www.manitoulinstreams.com/) assisted local communities with the rehabilitation of aquatic ecosystems on the island. Their work has restored fish habitat in tributaries that had been altered by logging and improper land use, such as Blue Jay Creek, and the Manitou, Mindemoya, and Kagawong Rivers. To date, 34 habitat-rehabilitation projects have been completed on seven tributaries, and environmental assessments have been completed on 184 waterways. In 2014, a five-year review by the Manitoulin Streams Improvement Association resulted in identification of 10 tributaries for restoration with the goal to enhance access for fish and to improve spawning habitat, primarily for anadromous salmonids.

The Eastern Georgian Bay Stewardship Council (http://georgianbaystewardship.ca/), a nonprofit volunteer organization, was involved in several projects to improve spawning habitat for Walleye, Lake Sturgeon, and other fish species. Spawning-habitat-restoration projects involved installing appropriately sized rock substrates and enhancing access to traditional spawning areas in six tributaries, including the Moon, Musquash, Shebeshekong and Key Rivers, during the reporting period.

The Lake Huron LAMP includes restoration of stream connectivity and function through dam removal and the construction of fish-passage alternatives as a management need (ECCC and USEPA 2018). A broader perspective on tributary health in the Lake Huron basin was provided in the 2017 state of the Great Lakes technical report (ECCC and USEPA 2017). Aquatic-habitat connectivity for Lake Huron was determined to be poor due to the loss of tributary connectivity, with over 86% of major tributaries no longer connected to the Lake Huron basin and to dams impeding migratory fish (Franks Taylor et al. 2010). Connectivity to the lake did vary across the basin with more access to spawning habitats in Ontario waters, particularly eastern Georgian Bay and the North Channel, and much less in areas like Saginaw Bay (Franks Taylor et al. 2010).

Spawning and Nursery Habitats–Reefs Environmental Objective

The spawning and nursery habitats objective (Liskauskas et al. 2007) is

> *Protect and restore reef spawning areas throughout the Lake Huron Basin.*

The EO for offshore and nearshore reef habitats highlights the importance of these features in providing spawning and nursery areas to fish (Eshenroder et al. 1995). The colonization by invasive zebra and quagga mussels (*Dreissena polymorpha* and *D. bugensis*) (Nalepa et al. 2007) and, in some cases, the resulting proliferation of attached *Cladophora* (Depew et al. 2011), has compromised reef areas for spawning.

Several studies were initiated in U.S. waters during the reporting period to address reef destruction or alteration. In the Thunder Bay area, the Michigan Department of Environmental Quality (http://www.uvm.edu/rsenr/thunderbay/DLZ_Thunder%20Bay%20Flier.pdf) led an improvement project that resulted in the construction of eight small reefs in 2010 and 25 larger reefs in 2011. These reefs were constructed to compensate for the loss of natural reefs that had been degraded by over 50 years of kiln-dust deposition. Egg deposition and fry production by spawning Lake Trout were higher on the larger reefs than on the smaller reefs (Marsden et al. 2016).

In Saginaw Bay in 2016, a restoration project that assessed potential reef restoration sites was completed. The project targeted historical spawning reefs in Saginaw Bay itself and reefs near the mouth of the Saginaw River (Kalejs 2017). The project is intended to create important spawning and juvenile habitat for Walleye, Smallmouth Bass, suckers, Lake Whitefish, Cisco, Lake Trout, and Burbot.

Lake Trout spawning reefs in the Drummond Island area of northern Lake Huron were studied using fine-scale acoustic telemetry during the reporting period (Binder et al. 2018). Tracking of adult Lake Trout implanted with acoustic transmitters revealed areas of aggregation on five reefs and egg depositions in atypical areas. This fine-scale approach expanded the conceptual models of critical spawning habitat for Lake Trout. Building upon these observations, Riley et al. (2014) found that Lake Trout was using drumlins (landforms created in subglacial environments by the action of ice sheets) as primary spawning habitat. Identifying the locations of these glacially derived bedforms will be crucial in quantifying the extent of spawning locations for Lake Trout and other reef-spawning species in Lake Huron.

Shoreline Processes—Environmental Objective

The shoreline processes objective (Liskauskas et al. 2007) is

> *Protect and rehabilitate nearshore habitats and reestablish the beneficial structuring forces of natural water exchanges, circulation, and flow that they provide.*

During the current reporting period, the Great Lakes Nearshore Framework (ECCC and USEPA 2016) and the Great Lakes Aquatic Habitat Framework (Wang et al. 2015) were developed to advance protection of nearshore areas in the Great Lakes, including in Lake Huron. The Great Lakes Nearshore Framework was developed pursuant to the updated 2012 Great Lakes Water Quality Agreement (https://www.ijc.org/en/what/glwqa-ijc) and is meant to be a systematic, integrated, and collective approach for assessing the health of nearshore areas and identifying and communicating cumulative impacts and stresses. The Great Lakes Nearshore Framework is aimed at reducing the impact of nonpoint-source runoff, shoreline hardening, climate change, habitat loss, invasive species, dredging and contaminated sediments, bacterial contamination, contaminated groundwater, and other threats that directly or indirectly affect fish production in the nearshore area. During 2017, updated nearshore bathymetry and substrate information was collected for the main basin of Lake Huron. Delineation and classification of regional units along the lake’s coast will begin in early 2019. The long-term goal of the framework is to develop a coordinated geospatial data framework with ongoing contributions from partner agencies, organizations, and communities.

Shoreline stewardship guides, which encourage and inform landowners to conduct environmental assessments of their properties and maintain them in ways that support healthy ecosystems, were created during the reporting period because development of the shoreline continues in many localized areas. These guides were developed for southern (https://www.lakehuron.ca/stewardship-plans-and-guides) and eastern Georgian Bay (https://www.gbbr.ca/our-environment/life-on-the-bay-guide/) and for a large portion of the eastern main basin (https://www.lakehuron.ca/stewardship-plans-and-guides). The Southern Georgian Bay Shoreline Initiative from Tobermory to Port Severn has helped coordinate efforts to assess and monitor shoreline alterations, water quality, and promote community-based stewardship and information sharing (ECCC and USEPA 2018). Aerial imagery acquired in 2014 indicated that this 696 km area of shoreline had experienced increased development and road densities since 2011 (Lunney 2017). Unfortunately, this initiative ended in 2017.

Cladophora has been used as an indicator of nuisance algae. Its recent status in Lake Huron was considered fair, with an undetermined overall trend in abundance (ECCC and USEPA 2017). Approximately 15% of the Lake Huron shoreline was impacted by submerged macro-algae, predominately *Cladophora*, *Chara* and periphyton, which was found mostly near the mouths of drains and streams (Barton et al. 2013; Grimm et al. 2013), with portions of Saginaw Bay and the southeast shore of the main basin being the most affected (ECCC and USEPA 2017). The impact to fish habitat due to increased filamentous algae colonization is not well understood at this time.

Contaminants

The FCOs call for "reduction or elimination of contaminants" that bioaccumulate in the environment and cause "physical deformities, reproductive failures, tumors, and physiological effects among exposed invertebrates and fish", and they encourage management agencies "to undertake policy and legal action" necessary to achieve the goal (DesJardine et al. 1995).

The latest Lake Huron LAMP (ECCC and USEPA 2018) reported the status of chemical concentrations in the air, water, sediment, fish, and wildlife to range from “fair” to “excellent”, with chemical contaminant concentrations generally decreasing since the 1970s (ECCC and USEPA 2017) but with some legacy contaminants in sediments still representing potential future risks (ECCC and USEPA 2017). Organic contaminants from agriculture, industry, and houses continue to exceed water-quality benchmarks in areas near Saginaw Bay during the reporting period (Baldwin et al. 2016).

During the reporting period per- and polyfluoroalkyl substances (PHAS) have emerged as new chemicals of concern to human health and contamination of fish in the state of Michigan. Areas of the lower Au Sable River downstream of a military base were found to contain high enough concentrations of PHAS in groundwater to prompt the state of Michigan in 2012 to issue fish-consumption advisories (https://www.mlive.com/news/grand-rapids/2018/03/new_fish_advisories_issued_for.html). Since 2012, monitoring the extent of PHAS contamination of groundwater and fish and wildlife has been a high priority in Michigan, and many water bodies now have fish-consumption advisories due to PHAS. In the Saginaw River, there are advisories that restrict consumption of Bluegill, Sunfish, Smallmouth Bass, and Largemouth Bass (https://www.michigan.gov/som/0,4669,7-192-45414_45929_83470_83473-463860--,00.html).

Recommendations

Climate change will continue to modify the terrestrial and aquatic habitat of Lake Huron to the detriment of some fish species but to the advantage of others. We observed wide oscillations in water levels, precipitation, and temperatures during the reporting period (http://glisa.umich.edu/media/files/2017-Climate-trends-and-impacts-summary.pdf) that may potentially affect egg incubation and hatching, coastal wetlands, nutrient cycling, and ultimately, fish production (Collingsworth et al. 2017; Wang et al. 2018).

We recommend that the Lake Huron Committee consider the following actions

- Continue to work toward integration of the Lake Huron EOs and the Biodiversity Conservation Strategy into the LAMP process
- Work to improve wetland mapping and evaluation; support efforts that assess wetland health, function, and vulnerability to climate change; and protect and strengthen existing wetland conservation laws, especially those of coastal wetlands
- Support ongoing efforts to restore historic rock-reef habitats and to evaluate progress
- Elevate the need for and investment in restoration of the connectivity of tributary habitat with emphasis on removal of barriers to fish passage that do not reduce the efficacy of Sea Lamprey control

LAKE HURON IN 2018: AN OVERVIEW[24]

Stephen C. Riley[25], Erin S. Dunlop, David G. Fielder, and Arunas P. Liskauskas

By the time modern assessment programs began in the 1960s-1970s, the fish community of Lake Huron was dominated by invasive species, including Sea Lamprey, Alewife, and Rainbow Smelt. Lake Trout had been extirpated from all but two remote bays while two forms of deepwater ciscoes were extirpated and five others were reduced to a hybrid swarm resulting in a much-reduced commercial and recreational yield (Berst and Spangler 1973; Eshenroder et al. 2016). In fact, when the first Lake Huron state of the lake report was published in 1995, the fish community of the lake was described as “a distant image of what once existed” (Ebener 1995).

Today, Lake Huron and the other Great Lakes continue to be impacted by several more-recent invasive species that have altered food webs in profound ways. Dreissenids appear to have shifted energy pathways to favor benthic production (Burlakova et al. 2018c), and phytoplankton and zooplankton abundance have decreased (Barbiero et al. 2018b; Rudstam et al., this volume). These changes are commonly observed after dreissenids invade (Higgins and Vander Zanden 2010) and may be responsible for the reduction

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[24] Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp20_01.pdf.

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in abundance of Alewife and other fish species that rely on zooplankton as prey. The invasion of Round Goby has further altered food webs, and gobies have become common in the diets of fish predators (Roseman et al. 2014).

For reasons that are not entirely clear, the trophic shifts in Lake Huron have affected the fish community in ways that have not been observed elsewhere. The most-dramatic example is the near-total collapse of Alewife populations, which crashed to near zero in 2003-2004 and have shown no sign of recovery (Riley et al., this volume). The collapse of Alewife populations may have been responsible for widespread reductions in the abundance and harvest of Chinook Salmon (e.g., Borgeson et al., this volume) and for increasing abundance of native species, such as Walleye (Fielder et al. 2007) and Lake Trout (Riley et al. 2007, 2011; He et al. 2012). These changes have led to potential management conflicts between maintenance of popular recreational fisheries for Chinook Salmon and restoration of Lake Trout (Dettmers et al. 2012), which is a longstanding management goal (Eshenroder et al. 1999; Krueger and Ebener 2004). Defining the status of different system components on a lakewide scale is challenging because trends in nutrients or species abundance vary spatially across regions of the lake. Here we summarize the most-recent changes in the ecology of Lake Huron and impacts on fisheries.

Nutrient levels and lower trophic communities in Lake Huron have shown substantial changes since the early 2000s, and some changes have continued into the present reporting period (Barbiero et al. 2018b; Rudstam et al., this volume). Although offshore phosphorus levels had declined through the end of the previous reporting period, they have increased during the current reporting period but may remain low enough to limit zooplankton production (Rudstam et al., this volume). Chlorophyll concentrations appear to have stabilized while Secchi depth and silica concentrations have continued to increase. After declining drastically in 2003, the biovolume of spring phytoplankton has remained low but stable over the past two reporting periods. The biomass of crustacean zooplankton has remained low since a major decline in the early 2000s but was elevated somewhat in 2010 (the end of the last reporting period) and again in 2012 (early in the current period, 2011-2017). *Diporeia* spp. density in Lake Huron had declined by 2005 (the beginning of the previous reporting period) and has remained very low since, particularly at shallower sites. Quagga mussel density in offshore waters was increasing during the previous reporting period (Nalepa et al. 2007) and since then has continued to increase (Rudstam et al., this volume).

The biomass of offshore prey fish has remained relatively low in this reporting period. Alewife biomass remains at very low levels, and there is no evidence of Alewife recovery since the collapse of 2004. Rainbow Smelt biomass in this reporting period continued to decline beyond the already relatively low levels observed in 2010. The abundance of Bloater, a native species, increased early in this reporting period but has since declined. The mean estimated total lakewide biomass of offshore prey fish in Lake Huron was higher in the current reporting period than in the previous period but remains low compared to historical data, and the index of total biomass in 2017 was the second-lowest observed (Riley et al., this volume).

Recent yields of Lake Whitefish and other coregonines in Lake Huron continued to decline throughout the current reporting period and remain well below the fish community objectives (FCOs) (Cottrill et al., this volume). Declines in Lake Whitefish yield are most evident in the northern and central main basin and are attributed to serious declines in recruitment and reductions in fishing effort. Monitoring programs show a drastic decline in relative abundance of Lake Whitefish, reaching near-zero catches at some locations. Condition and spawning-stock biomass of Lake Whitefish in Lake Huron were also very low during the current reporting period compared to previous periods. The diet, growth, habitat, and population regulation of Lake Whitefish have changed in recent years and are related to ecosystem changes in the lake (Riley and Adams 2010; Gobin et al. 2015; Rennie et al. 2015; Fera et al. 2015, 2017). Similar changes in growth, recruitment, and yield have been observed in Lake Whitefish stocks in Lake Michigan, suggesting common drivers in these systems. Harvest and yield of deepwater ciscoes were relatively low during this reporting period compared to historic estimates (Cottrill et al., this volume), and biomass was reduced after showing high biomass early in the current reporting period (Riley et al., this volume). Cisco remains relatively abundant in northern areas of the lake, and a multi-agency program to rehabilitate Cisco in Lake Huron began in 2018. The recent changes to food webs and coregonine ecology in Lake Huron suggest that current conditions in the lake are less suitable for sustained high production of Lake Whitefish observed in the past.

Natural reproduction and recruitment of wild Lake Trout have been observed in Lake Huron since 2004 (Riley et al. 2007) and have been sustained through the current reporting period (Lenart et al., this volume). Wild adult Lake Trout continues to make up large proportions of fishery and survey catches in the northern main basin and the North Channel but is less prevalent in the southern main basin and Georgian Bay. Many of the wild recruits, particularly in the northern main basin, were of Seneca-strain origin, suggesting this strain may be particularly suited to current conditions (Scribner et al. 2018). Estimated survival of stocked Lake Trout showed a marked decline in Georgian Bay and the main basin just before the previous reporting period, and this low survival has continued throughout the current period (Lenart et al., this volume). Although the widespread appearance of wild fish in fishery and survey catches is unprecedented in the Great Lakes outside of Lake Superior and is a positive sign of Lake Trout rehabilitation, yield remains well below levels specified in the FCOs.

Non-native salmonines have been stocked in Lake Huron for decades to provide a variety of angling opportunities (Borgeson et al., this volume). Chinook Salmon, in particular, is the mainstay of a popular and economically important sport fishery. **Most Chinook Salmon in the main basin of Lake Huron are now naturally produced**, and the early survival of stocked fish has decreased substantially (Borgeson et al., this volume). Chinook Salmon abundance in the lake has been in decline since about the 1980s (Brenden et al. 2012), but harvest declined abruptly after the collapse of Alewife populations in 2004 (Borgeson et al., this volume). The growth and condition of Chinook Salmon in Lake Huron have increased significantly since the last reporting period, but harvest remains low compared to earlier time periods. **Other salmonines, including steelhead, Brown Trout, Coho Salmon, Pink Salmon, and Atlantic Salmon, continue to support recreational fisheries** throughout the lake, although angling effort has declined since the early 2000s.

A milestone in Sea Lamprey control in Lake Huron was achieved during the current reporting period: the index of adult abundance in 2015 was the lowest in the time series and was below the target maximum for the first time in over 30 years (Nowicki and Sullivan, this volume). The index of adult abundance during the current reporting period was 16% lower than in the previous period but has increased in this reporting period and remains near the target maximum. The Sea Lamprey marking rate on adult Lake Trout was above target during the previous reporting period and has since declined to below target level in 2016; **the marking rate in 2017 was the lowest observed in the time series**. Reduced Sea Lamprey abundance is likely due to increased control effort in tributaries, particularly the St. Marys River (Nowicki and Sullivan, this volume).

The relative abundance of economically and culturally important **species that make up nearshore fish communities has been stable** in recent years in Michigan waters of the main basin, but it varies among sites (Fetzer et al. 2017). **Species richness in recent years increased** at two embayment sites and appeared to have decreased or remained stable at five exposed coastal sites. Catch-per-unit effort (CPUE) of Yellow Perch, Alewife, Lake Whitefish, and Rainbow Smelt declined significantly at most sites during this reporting period, but Walleye CPUE increased (Fetzer et al. 2017). Walleye yield was reduced compared to the previous reporting period and remains below the FCO (Fielder et al., this volume). Yield of Yellow Perch in Lake Huron was similar for this and previous reporting periods and remains below the FCO; recruitment may be limited by intense predation by Walleye and cormorants (Fielder et al., this volume). Populations of Lake Sturgeon, Northern Pike, and Muskellunge appear to be stable in most parts of the lake (Fielder et al., this volume), and natural reproduction of Northern Pike and Muskellunge may have improved due to higher water levels observed during the current reporting period. Smallmouth Bass populations appear to be increasing in several areas of the lake while Channel Catfish populations appear to be stable (Fielder et al., this volume). We suggest that expanded monitoring of the very nearshore fish community in embayments and near tributaries might be useful, as recently recommended for Lake Michigan (Bunnell et al. 2018).

CONCLUSIONS AND EMERGING MANAGEMENT ISSUES FOR THE LAKE HURON FISH COMMUNITY IN 2018 AND MANAGEMENT DIRECTIVES[26]

Randall M. Claramunt[27], Thomas K. Gorenflo, and Ken Lacroix

In this chapter, the Lake Huron Committee (LHC) highlights and evaluates what has transpired in Lake Huron during the reporting period of 2011-2017, discusses key emerging issues, and identifies actions to be implemented during the next five-year reporting period. The preceding chapters in this state of the lake report provide a synthesis of ecological and fishery data intended to support the LHC as it pursues attainment of the fish community objectives for Lake Huron (FCOs) identified in Desjardine et al. (1995). However, the major challenges or impediments that could prevent achievement of these FCOs have not changed in the interim (e.g., habitat degradation, Sea Lamprey control, and invasive species) and are still impeding progress toward meeting some FCOs. Those stressors are now exacerbated by substantial environmental disturbances (e.g., lower trophic-level upheavals, water-level fluctuations, and declining trends in number of ice-cover days). Providing effective fishery management in a lake

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[26] Complete publication including maps of place names, abstract, other chapters, scientific fish names, and references is available at http://www.glfc.org/pubs/SpecialPubs/Sp20_01.pdf.

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undergoing such ecological disturbances is challenging and requires that stakeholders be well informed, which this report can foster.

From a management perspective, progress toward achievement and/or maintenance of our FCOs for Lake Huron during this 2011-2017 reporting period can be characterized as mostly disappointing with a few exceptions. The overall FCO objective that represented the vision of the LHC in the early 1990s, the goal of an "...ecologically balanced fish community…capable of sustaining annual harvests of 8.9 million kg", is far from being realized. As described in the complete report, the continuing colonization by non-native aquatic species disrupted energy flows and ecosystem functions. As a result, Lake Huron's fish community remains in a state of flux resulting in uncertainty that exacerbates the many challenges facing the Lake Huron management agencies. Simply put, the state of Lake Huron is in continual change and far from being balanced, and the disruption of the energy flow in the system brings into question the basic concept of having a sustainable fishery.

Lake Whitefish had been the mainstay of commercial fisheries in Lake Huron since fishing began such that its dramatic decline has greatly impacted generational operations across the lake. The coregonine FCOs envisioned a diverse coregonine community at levels of abundance that could support annual harvests of 3.8 million kg. Based on trends in the commercial fisheries and population indicators and trends described in Cottrill et al. (this volume), the LHC believes current coregonine populations are not at levels capable of sustaining the envisioned harvest expressed. Barring a favorable change in the ecosystem, the prognosis of achieving the coregonine FCOs during the next reporting period is doubtful. Most fishery managers and researchers agree that the magnitude of the decline in Lake Whitefish is a result of ecosystem disruption initiated by dreissenids for which there is no foreseeable remedy or simple return to the previous state of the ecosystem. In some areas of Lake Huron, population indicators suggest the decline has at least leveled out, and the LHC is hopeful that some stability might be restored albeit at much reduced levels of abundance relative to those of the mid-1990s. The LHC recommends a focus on the remaining productive areas to provide a contrast with areas that continue to show declines in Lake Whitefish abundance to better determine causative factors and to identify potential management actions during the next reporting period. In the near term, however, fisheries that depended on Lake Whitefish for decades will likely continue to suffer the consequences of an unstable and disrupted ecosystem.

A second component of the coregonine objective speaks to the restoration of "…lake herring [now Cisco] to a significant level and protect, where possible, rare deepwater ciscoes". Cisco remains largely confined to protected embayments of the northern main basin and North Channel (Eshenroder et al. 2016) but are mostly absent from the southern two-thirds of the main basin, including Saginaw Bay, which was the most-important spawning grounds (Van Oosten 1929). Recovery is viewed as essential for stabilizing and increasing the abundance of severely reduced prey fish (Riley et al. 2008). As noted in Cottrill et al. (this volume), Cisco has not expanded its range or abundance as anticipated in the objective. However, the LHC has recently agreed to implement a stocking program in outer Saginaw Bay in the hope of re-establishing Cisco in a portion of Lake Huron that historically supported a vast Cisco population. Similarly, deepwater ciscoes have not achieved expectations; instead, their populations have declined compared to the mid-1990s (Cottrill et al., this volume). Recovery of Cisco would likely improve the stability, balance, and sustainability of the fish community, making it more like that envisioned in DesJardine et al. (1995). Notably, achieving lakewide rehabilitation of Lake Trout, as called for in Desjardine et al. (1995), may not be possible without an abundant Cisco population as part of a diverse pelagic prey base.

The marked declines of both coregonine and introduced salmonine populations, which began more than a decade ago, continued during this reporting period and were the primary drivers for the failure to achieve the overall FCO. Collapse of the Alewife population, coupled with sequestration and redirection of energy and nutrients away from important fish species by dreissenids, prevented the achievement of the overall FCO and the individual objective for introduced salmonines. Fishery management actions to rebuild and diversify the prey base have the best potential to bring about a better balance in the salmonine community—an effort that would be enhanced by the development of a predator-prey framework to better inform management actions. Without the recovery of Cisco and a diverse prey-fish community in Lake Huron, reduced Alewife populations will continue to limit the contribution of anadromous salmonines to the overall salmonine objective.

During the early 1990s when the Lake Huron FCOs were drafted, natural reproduction of Lake Trout in Lake Huron was rare (Lenart et al., this volume). Now, after nearly 50 years of extensive efforts to rehabilitate Lake Trout, natural reproduction has expanded greatly and occurs lakewide. This highly encouraging development is further evidenced by plans to reduce or even discontinue stocking in U.S. waters for the first time since stocking was initiated in the early 1970s. Accordingly, Lake Huron management agencies are now transitioning from a rehabilitation regimen based on hatchery-reared fish to a management regimen increasingly based on wild fish. If rehabilitation continues to expand as expected, the Lake Trout FCO, defined as having populations capable of supporting a harvest of 1.4-1.8 million kg, becomes obtainable.

Two objectives may be directly at odds and pose a quandary for Lake Trout rehabilitation—minimizing Sea Lamprey impacts versus restoring connectivity between tributary habitat and the lakes proper. Restoring connectivity was recommended in Fielder et al. (this volume) and Liskauskas et al. (this volume) because they believed it was necessary for achieving the FCOs for Walleye and Lake Sturgeon and to ensure genetic and species diversity. Restoring connectivity will require removal of the first downstream barrier on important tributaries and other barriers further upstream to allow passage of certain lake-dwelling adult fish to their spawning and nursery habitats. Unfortunately, these recommendations are at odds with those made for Sea Lamprey and Lake Trout. Nowicki and Sullivan (this volume) recommended maintaining barriers to fish migration to suppress Sea Lamprey abundance to levels low enough to permit achievement of other FCOs (Nowicki and Sullivan, this volume). Further, Lenart et al. (this volume) recommended focusing control on large Sea Lamprey-producing tributaries, the same tributaries that are the focus of Walleye and Lake Sturgeon rehabilitation efforts (Fielder et al., this volume; Lenart et al., this volume).

Failure to treat tributaries, if tributary connectivity is restored, may lead to substantially increased Sea Lamprey abundance (Dobiesz and Bence 2018). Efforts to reduce the amount of chemicals used in the Sea Lamprey control program in the late 1990s resulted in major increases in their abundance throughout the Great Lakes that took the better part of two decades to reverse (e.g., Grunder and Barber 2019; Nowicki and Sullivan, this volume). Meeting demands to increase fish passage while controlling Sea Lamprey abundance is an extremely challenging task that is being researched by the Great Lakes Fishery Commission and its partner agencies through development of new fish-passage techniques, such as those being employed on the Boardman River of Lake Michigan (www.glfc.org/fishpass.php). New fish-passage techniques will be required on Lake Huron tributaries to keep disparate management actions from derailing progress toward achieving the FCOs. Sea Lamprey is likely to persist as a major impediment to achievement and/or maintenance of FCOs for several reasons (1) the usual operational challenges associated with controlling this invader, (2) the increasingly complex and often contentious concerns related to fish-passage/barrier removal issues, and 3) the growing cultural adversity to the use of chemicals in the environment.

The backdrop of the aforementioned management challenges is a continued state of low or declining productivity of fish populations in Lake Huron. Declines in nutrients (e.g., phosphorus) and cascading effects of lower plankton biomass and/or total loss of spring diatoms blooms will likely be of concern to fishery managers through the next reporting period. Because lower-trophic-level productivity forms the foundation for fish community structure and abundance, which in turn supports fisheries, managers will need to work with stakeholders to set reasonable expectations for the fishery. In addition to continued threats from food-web disruption, the LHC is very concerned about other potential threats, including establishment of new invasive species (e.g., Asian carps), contaminants (e.g., PFAS, PFOA), and outbreaks of pathogens and the resulting fish diseases (e.g., VHS). Lake Michigan is experiencing similar management challenges. The Lake Michigan Committee (LMC) recently identified three action items to help promote progress toward meeting their FCOs during this challenging management paradigm shift, and the LHC believes that these items are directly applicable to Lake Huron (Wesley et al. 2019). The LHC also supports better coordination between the LHC and the LMC to promote achievement of FCOs for both lakes given that similar environmental and biological stressors are at play in both lakes (Madenjian 2019). Accordingly, the LHC has identified several priorities for Lake Huron, including

- Evaluate the existing FCOs. Invasive species have fundamentally changed energy flows in Lake Huron, thereby affecting all trophic levels and reducing the prospect of achieving some of the existing FCOs. Given these changes, the LHC plans to reaffirm, redefine, and modify some or all the FCOs or produce a completely new document. However, the LHC also recognizes that the complexity of revising FCOs will be exacerbated by a Lake Huron ecosystem that remains in flux, making for extraordinary uncertainty. Establishing new or revised objectives will, therefore, be a daunting task.
- Encourage prioritization of assessment and research needs, foster expanded data collection/analysis processes, and assist, where possible, to alleviate potential shortfalls in information and outreach. Examples include building predator-prey models to help inform future management actions, strengthening the prevention and early detection and control of invasive species, and continuing support for routine monitoring of food webs.
- Increase coordination with other environmental organizations to promote and expand ecosystem management through a multidisciplinary approach. Examples include better linkages between the FCOs and the lakewide management plans, coordination of non-fisheries-focused stakeholders or industries that are linked to fisheries outcomes (e.g., habitat-focused stakeholders), and prioritization of highly important projects and endeavors that can improve funding.
- Increase communication and coordination between the LHC and the Lake Huron Technical Committee to identify critical information needs that can better support management by addressing new and continued threats to the fishery. As highlighted in this volume, expanding research and monitoring programs is critical to both measuring progress and taking actions that promote achievement of our FCOs. In addition to expanding existing monitoring programs, new initiatives will also be required to produce consistent estimates of prey-fish biomass from acoustic and bottom-trawl surveys (Riley et al., this volume) and to

monitor the abundance of invasive and rare species (Stott et al., this volume), recruitment of Lake Sturgeon (Fielder et al., this volume), and gains and losses in wetland habitat (Liskauskas et al., this volume). Although not specifically stated, development of sampling programs to monitor and better understand recruitment patterns of important species, such as Lake Whitefish, Cisco, Lake Trout, Walleye, and Round Goby, would be valuable to management agencies. New research and monitoring initiatives will be necessary to determine cause/effect relationships between invasive species and the ecosystem changes observed in Lake Huron and to forecast potential future alternative states. Expanding monitoring and research efforts will likely require modifications to existing sampling programs, discontinuation of other programs, and embarking on new and creative initiatives. The LHC will need to decide if more-intensive ecosystem research and management strategies should be championed to improve the prospects of meeting the existing FCOs or if the combined effects of invasive species and food-web disruption indicate that a more-modest effort built around revised FCOs, which reduces fishery expectations, is more appropriate.

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