THE STATE OF LAKE SUPERIOR IN 2011

SPECIAL PUBLICATION 16-01

The Great Lakes Fishery Commission was established by the Convention on Great Lakes Fisheries between Canada and the United States, which was ratified on October 11, 1955. It was organized in April 1956 and assumed its duties as set forth in the Convention on July 1, 1956. The commission has two major responsibilities: first, develop coordinated programs of research in the Great Lakes, and, on the basis of the findings, recommend measures which will permit the maximum sustained productivity of stocks of fish of common concern; second, formulate and implement a program to eradicate or minimize sea lamprey populations in the Great Lakes.

The commission is also required to publish or authorize the publication of scientific or other information obtained in the performance of its duties. In fulfillment of this requirement the commission publishes two types of documents, those that are reviewed and edited for citation indexing and printing and those intended for hosting on the commission's website without indexing or printing. Those intended for citation indexing include three series: *Technical Reports*—suitable for either interdisciplinary review and synthesis papers of general interest to Great Lakes fisheries researchers, managers, and administrators, or more narrowly focused material with special relevance to a single but important aspect of the commission's program (requires outside peer review); *Special Publications*—suitable for reports produced by working committees of the commission; and *Miscellaneous Publications*—suitable for specialized topics or lengthy reports not necessarily endorsed by a working committee of the commission. One series, *Agency Reports*, is not suited for citation indexing and printing. It is intended to provide a Web-based outlet for fishery management agencies to document plans or reviews of plans while foregoing review and editing by commission staff. Those series intended for citation indexing follow the style of the *Canadian Journal of Fisheries and Aquatic Sciences*. The style for *Agency Reports* is at the discretion of the authors. Sponsorship of publications does not necessarily imply that the findings or conclusions contained therein are endorsed by the commission.

COMMISSIONERS

Canada	United States
Robert Hecky	Tom Melius
James McKane	Don Pereira
Tracey Mill	Doug Stang
Trevor Swerdfager	William Taylor
	David Ullrich

Great Lakes Fishery Commission
2100 Commonwealth Blvd., Suite 100
Ann Arbor, MI 48105-1563

THE STATE OF LAKE SUPERIOR IN 2011

Thomas C. Pratt[1], Owen T. Gorman[2], William P. Mattes[3], Jared T. Myers[4], Henry R. Quinlan[5], Donald R. Schreiner[6], Michael J. Seider[5], Shawn P. Sitar[7], Daniel L. Yule[2], and Peder M. Yurista[8]

Citation (online): Pratt, T.C., Gorman, O.T., Mattes, W.P., Myers, J.T., Quinlan, H.R., Schreiner, D.R., Seider, M.J., Sitar, S.P., Yule, D.L., and Yurista, P.M. 2016. The state of Lake Superior in 2011 [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/Sp16_01.pdf [accessed 21 April 2016].

April 2016

ISSN 1090-1051

---

[1]**T.C. Pratt**. Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Sciences, 1219 Queen Street East, Sault Ste Marie, ON P6A 2E5, Canada. (e-mail: thomas.pratt@dfo-mpo.qc.ca).

[2]**O.T. Gorman and D.L. Yule**. U.S. Geological Survey–Lake Superior Biological Station, 2800 Lakeshore Drive East, Ashland, WI, 54806, U.S.A.

[3]**W.P. Mattes**. Great Lakes Indian Fish and Wildlife Commission, 72682 Maple Street, P.O. Box 9, Odanah, WI, 54861, U.S.A.

[4]**J.T. Myers**. Wisconsin Department of Natural Resources, 141 South 3rd Street, Bayfield, WI, 54814, U.S.A.

[5]**H.R. Quinlan and M.J. Seider**. U.S. Fish and Wildlife Service, Ashland Fish and Wildlife Conservation Office, 2800 Lakeshore Drive East, Ashland, WI, 54806, U.S.A.

[6]**D.R. Schreiner**. Minnesota Department of Natural Resources, 5351 North Shore Drive, Duluth, MN, 55804, U.S.A.

[7]**S.P. Sitar**. Michigan Department of Natural Resources, 484 Cherry Creek Road, Marquette, MI, 49855, U.S.A.

[8]**P.M. Yurista.** U.S. Environmental Protection Agency, National Health and Ecological Effects Research Laboratory, Mid-Continent Ecology Division, Duluth, MN, 55804, U.S.A.

Printed on recycled paper.

TABLE OF CONTENTS

Abstract **1**
Introduction **2**
Habitat **9**
Physical Parameters 9
Contaminants 10
Primary Production, Zooplankton, and Macroinvertebrates 12
Survey Design and Methods 12
Primary Production 13
Zooplankton 15
Macroinvertebrates 25
Food-Web Dynamics 26
Conclusions and Recommendations 27
Inshore, Embayment and Tributary Fishes **28**
Pacific Salmon, Rainbow Trout, Brown Trout 28
Conclusions and Recommendations 30
Walleye 32
Conclusions and Recommendations 34
Lake Sturgeon 34
Conclusions and Recommendations 36
Brook Trout 38
Conclusions and Recommendations 39
Nearshore Fishes **40**
Lean Lake Trout 40
Abundance and Stocking 40
Harvest 42
Mortality and Growth 43
Conclusions and Recommendations 47
Lake Whitefish 48
Abundance 48
Management 54
Harvest and Effort 54
Conclusions and Recommendations 55
Rainbow Smelt 55
Cisco 56
Abundance 56
Management and Harvest 60
Food-Web Dynamics 63

Conclusions and Recommendations 63
Deepwater Ciscoes 64
Abundance 64
Harvest 69
Food-Web Dynamics 69
Other Prey Fishes 69
Nearshore Community Trends 70
Conclusions and Recommendations 73
Offshore Fishes 74
Siscowet Lake Trout 74
Abundance and Age Structure 74
Fishery Yield 77
Sea Lamprey Predation 77
Growth and Reproduction 79
Conclusions and Recommendations 79
Offshore Prey Fishes 80
Conclusions and Recommendations 83
Aquatic Nuisance Species 84
Conclusions and Recommendations 85
Sea Lamprey 86
Conclusions and Recommendations 88
Acknowledgments 89
References 90

ABSTRACT

This report describes for 2006-2011 the status of the Lake Superior ecosystem, especially of its fish communities and the progress made toward meeting Fish Community Objectives (FCOs) established by the Lake Superior Committee of the Great Lakes Fishery Commission. The FCOs associated with inshore, tributary, and embayment fish populations, those most disturbed by settlement, are not being met, although progress has been made. Nearshore and offshore fish populations remain healthy, and the FCOs associated with these species are generally being met, although poor recruitment of cisco (*Coregonus artedi*) is a concern. Declining prey-fish biomass and declines in lean lake trout (*Salvelinus namaycush*) abundance and growth are indicative of a lake trout-dominated ecosystem where even further reductions in prey fishes are possible if equilibrium has not yet established. Renewed interest in the development of a commercial siscowet (*S. n. siscowet*) lake trout fishery is putting more focus on the offshore community. The FCO for sea lamprey (*Petromyzon marinus)* will remain unachieved unless the population is reduced markedly. Nearshore and offshore habitats require continuing protection, and inshore, tributary, and embayment habitats require further restoration. Efforts to ensure that potentially invasive aquatic species are not introduced should continue. How Lake Superior will be affected by a changing climate remains uncertain. Changes in water temperature, ice cover, and wind speed are portenteous making further collaboration between fisheries and climate scientists necessary. Ultimately, agencies must continue to ensure that their surveys are effective and capable of addressing the requirements of today while being robust enough to anticipate future changes in the fisheries and the ecosystems on which they depend.

INTRODUCTION

Lake Superior is the largest and deepest of the Laurentian Great Lakes possessing many unique qualities. It contains ~10% of the world's fresh water, and, due to its size and hydrology, retains this water for a very long time (>170 years; review by Schertzer and Rao 2009). Anthropogenic impacts are modest. It is the most pristine of the Great Lakes with less than 2% of its watershed impacted by urbanization or agriculture and over 90% of the catchment covered by forests or waterways (Superior Work Group of the Lake Superior Lakewide Action and Management Plan 2015). Despite its size, Lake Superior has a relatively simple ecosystem dominated by native species and has long been held as an example of an ecosystem that is minimally disturbed and slow to change, particularly in the face of immense changes in the other Great Lakes (e.g., Bronte et al. 2003; Mills et al. 2003; Dobiesz et al. 2005). However, this view has recently been challenged as physical and ecosystem-level changes are beginning to be realized (Austin and Colman 2008; Kelly et al. 2011).

Fisheries data are collected and shared among management agencies under the umbrella of the Great Lakes Fishery Commission (GLFC). The GLFC was established by the Convention on Great Lakes Fisheries between Canada and the United States, ratified in 1955. One of the GLFC's major responsibilities is to develop coordinated programs of research in the Great Lakes, and, on the basis of the findings, recommend measures that will permit the maximum sustained productivity of stocks of fish of common concern. The GLFC, in cooperation with federal, state, provincial, and tribal natural-resource agencies, adopted *A Joint Strategic Plan for Management of Great Lakes Fisheries* (Joint Plan) in 1981 as an explicit statement for cooperative fishery management on the Great Lakes (GLFC 2007). Lake committees and attendant technical committees are the action arms for implementing the Joint Plan and for developing operational plans for managing the aquatic resources of each Great Lake. To meet this responsibility, Fish Community Objectives (FCOs) (Table 1) were developed and adopted by the Lake Superior Committee (LSC) to define objectives for the structure of the fish community and to develop means for measuring progress toward their achievement (Horns et al. 2003). Every five years, the Lake Superior Technical Committee is charged by the LSC to

produce a state-of-the-lake (SOL) report to assess how FCOs are being met and to identify new and emerging issues that will potentially affect fisheries management. This SOL report describes the status of the Lake Superior ecosystem, especially fish communities, and progress toward meeting FCOs from 2006 through 2011. The Lake Superior basin, including management units, major cities, and larger tributaries is shown in Fig. 1. The scientific names of fishes mentioned in this report are presented in Table 2, including whether the species is native or non-native to the watershed.

Table 1. The Lake Superior fish community goals and objectives (Horns et al. 2003) and an assessment of whether the goal and objectives were realized during the 2006-2011 reporting period.

Targeted Component	Fish Community Goals and Objectives	Achievement of Objective
Overall goal	To rehabilitate and maintain a diverse, healthy, and self-regulating fish community, dominated by indigenous species and supporting sustainable fisheries.	Mostly achieved
Habitat	Achieve no net loss of the productive capacity of habitat supporting Lake Superior fishes. Where feasible, restore habitats that have been degraded and have lost their capacity for fish production. Reduce contaminants so that fish are safe to eat. Develop comprehensive and detailed inventories of fish habitats.	Partially achieved
Prey species	A self-sustaining assemblage of prey dominated by indigenous species at population levels capable of supporting desired populations of predators and a managed commercial fishery.	Achieved

Table 1, continued

Targeted Component	Fish Community Goals and Objectives	Achievement of Objective
Lake trout	Achieve and maintain genetically diverse self-sustaining populations of lake trout that are similar to those found in the lake prior to 1940, with lean lake trout being the dominant form in nearshore waters, siscowet being the dominant form in offshore waters, and humper lake trout being a common form in eastern waters and around Isle Royale.	Achieved
Lake whitefish	Maintain self-sustaining populations within the range of abundance observed during 1990-99.	Achieved
Walleye	Maintain, enhance, and rehabilitate self-sustaining populations and their habitat over their historical range.	Partially achieved
Lake sturgeon	Rehabilitate and maintain spawning populations that are self-sustaining throughout their native range.	Partially achieved
Brook trout	Maintain widely distributed, self-sustaining populations in as many of the historical habitats as is practical.	Partially achieved
Pacific salmon, rainbow trout, brown trout	Manage populations that are predominantly self-sustaining but that may be supplemented by stocking that is compatible with restoration and management goals established for indigenous fish species.	Achieved
Sea lamprey	Suppress populations to levels that cause only insignificant mortality on adult lake trout.	Not achieved

Table 1, continued

Targeted Component	Fish Community Goals and Objectives	Achievement of Objective
Nuisance species	(1) Prevent the introduction of any non-indigenous aquatic species that is not currently established in Lake Superior; (2) prevent or delay the spread of non-indigenous nuisance species, where feasible; and (3) eliminate or reduce populations of non-indigenous nuisance species, where feasible.	Partially achieved
Species diversity	Protect and sustain the diverse community of indigenous fish species not specifically mentioned earlier (burbot, minnows [Cyprinidae], yellow perch, northern pike, and suckers [Catastomidae]). These species add to the richness of the fish community and should be recognized for their ecological importance and cultural, social, and economic value.	Achieved

Fig. 1. Map of Lake Superior showing jurisdictions, the 1836 and 1842 Treaty-ceded areas, major cities (filled squares), management units, and place names referenced in this report.

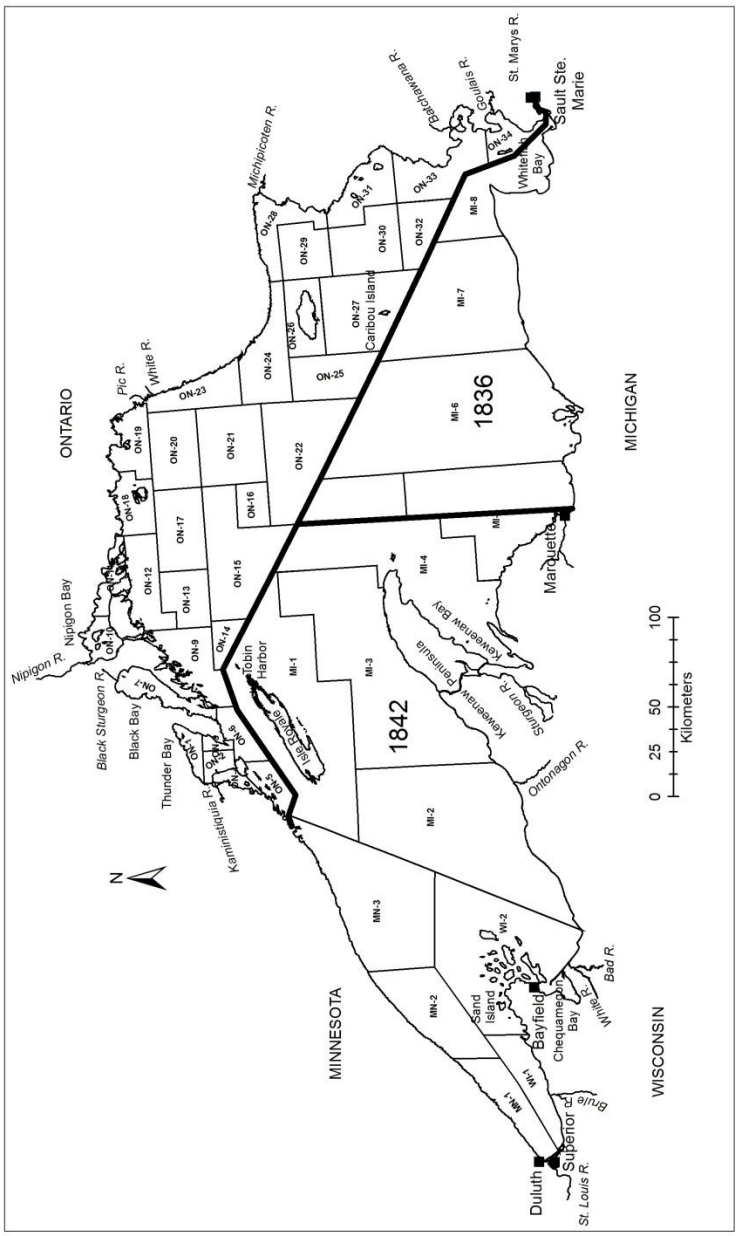

ONTARIO
MICHIGAN
MINNESOTA
WISCONSIN
1836
1842
Nipigon R.
Nipigon Bay
Black Sturgeon R.
Black Bay
Thunder Bay
Kaministiquia R.
Pic R.
White R.
Michipicoten R.
Batchawana R.
Goulais R.
St. Marys R.
Sault Ste. Marie
Whitefish Bay
Caribou Island
Tobin Harbor
Isle Royale
Marquette
Keweenaw Bay
Keweenaw Peninsula
Sturgeon R.
Ontonagon R.
Sand Island
Bayfield
Chequamegon Bay
White R.
Bad R.
Brule R.
Superior
Duluth
St. Louis R.
0 25 50 100
Kilometers
N

Table 2. Common names, scientific names, and origin (native or non-native) of Lake Superior fish species referenced in this report. Non-native fishes with asterisks introduced by management agencies.

Common Name	Scientific Name	Origin
northern brook lamprey	*Ichthyomyzon fossor*	Native
sea lamprey	*Petromyzon marinus*	Non-native
lake sturgeon	*Acipenser fulvescens*	Native
alewife	*Alosa pseudoharengus*	Non-native
longnose sucker	*Catostomus catostomus*	Native
rainbow smelt	*Osmerus mordax*	Non-native
northern pike	*Esox lucius*	Native
cisco	*Coregonus artedi*	Native
lake whitefish	*Coregonus clupeaformis*	Native
bloater	*Coregonus hoyi*	Native
kiyi	*Coregonus kiyi*	Native
shortjaw cisco	*Coregonus zenithicus*	Native
pink salmon	*Oncorhynchus gorbuscha*	Non-native*
coho salmon	*Oncorhynchus kisutch*	Non-native*
rainbow trout	*Oncorhynchus mykiss*	Non-native*
Chinook salmon	*Oncorhynchus tshawytscha*	Non-native*
pygmy whitefish	*Prosopium coulterii*	Native
round whitefish	*Prosopium cylindraceum*	Native
brown trout	*Salmo trutta*	Non-native*
brook trout	*Salvelinus fontinalis*	Native
splake	*Salvelinus fontinalis* x *S. namaycush*	Non-native*
lake trout	*Salvelinus namaycush*	Native
trout-perch	*Percopsis omiscomaycus*	Native

Table 2, continued

Common Name	Scientific Name	Origin
burbot	*Lota lota*	Native
ninespine stickleback	*Pungitius pungitius*	Native
slimy sculpin	*Cottus cognatus*	Native
spoonhead sculpin	*Cottus ricei*	Native
deepwater sculpin	*Myoxocephalus thompsonii*	Native
white perch	*Morone americana*	Non-native
ruffe	*Gymnocephalus cernua*	Non-native
walleye	*Sander vitreus*	Native
yellow perch	*Perca flavescens*	Non-native
round goby	*Neogobius melanostomus*	Non-native

HABITAT

Despite their implicit recognition under the Habitat Fish Community Objective (FCO) (Table 1), which seeks to maintain the productive capacity of the lake to support fishes, there are no specific physical, chemical, or lower trophic-level (below the level of fish) objectives in Lake Superior's FCOs. Nonetheless, these features of the ecosystem provide the basis for fish production and are routinely evaluated and assessed.

Physical Parameters

Summer (July-September) surface water temperatures have increased approximately 2.5°C during 1979-2006 (Austin and Colman 2007) and are increasing more rapidly than regional air temperatures due to a progressively earlier summer stratification that results from a decline in ice cover. Over the past century, the length of time Lake Superior is stratified during the summer has increased from 145 d to 170 d, while winter ice cover has decreased from an average of 23% to 12% (Austin and Colman 2008). Warmer temperatures and a longer ice-free season have contributed to declining water levels in all the Great Lakes (Gronewold et al. 2013). Lake Superior water levels were below the long-term average every year since 1998 and continue to decline slowly (Gronewold et al. 2013).

Increasing air and surface water temperatures and a reduction in the temperature gradient between air and water are destabilizing the atmospheric surface layer above Lake Superior. As a result, surface wind speeds above the lake increased by nearly 5% per decade since 1985, exceeding trends in wind speed over land (Desai et al. 2009). A numerical model of lake circulation suggests that the increasing wind speeds lead to increases in water-current speeds. Moreover, long-term warming reduces the depth of the surface mixed layer and lengthens the season of stratification (Desai et al. 2009). Desai et al. (2009) conclude that a warming climate will profoundly affect the biogeochemical cycles of Lake Superior and increase the transport of airborne pollutants into the basin, although the potential effects on fishes are not yet understood.

Contaminants

Keeping contaminant levels below levels of human concern is a key component of the Habitat FCO (Table 1). Lake Superior is subjected to long-term inputs of a broad array of contaminants, although the levels of many contaminants in Lake Superior fish are declining as a result of reduced emissions. Emissions of many major legacy contaminants (e.g., mercury, PCBs, dioxins, and pesticides) within the Lake Superior basin have declined significantly. By 2010, in-basin mercury and dioxin emissions had decreased 80% and 86%, respectively, relative to 1990 baseline levels (Lake Superior Binational Program 2012). These reductions are on target for achieving the goal of zero discharge by 2020 as set forth in the Zero Discharge Demonstration Program established in the Lake Superior Lakewide Management Plan (Lake Superior Binational Program 2012). However, only so much can be achieved by limiting in-basin emissions, as most of the remaining contaminant loadings are primarily atmospherically derived from outside the basin and cannot be locally controlled. Toxic chemicals with significant atmospheric input include PCBs, mercury, toxaphene, and polybrominated diphenyl ethers (PBDEs).

As a top-predator species, lake trout integrate contaminants from throughout the lower levels of the food web and are a useful indicator of the status of contaminant concentrations in fish. Lake trout from Lake Superior are typically less contaminated than those collected from the other Great Lakes (Carlson and Swackhamer 2006; Bhavsar et al. 2007, 2008; Carlson et al. 2010). Median total PCB concentrations in Lake Superior lake trout have continuously decreased an average of 7% annually since PCBs were phased out in the 1970s. Lake Superior supports an important cisco roe fishery with most of the harvest occurring near Sand Island, Wiconsin, and Thunder Bay, Ontario (Stockwell et al. 2009). Madenjian et al. (2014) collected cisco eggs from Thunder Bay during 2010, and reported PCB concentrations (mean = 130 $ng \cdot g^{-1}$) were below guidelines established by the U.S. Food and Drug Administration (2,000 $ng \cdot g^{-1}$) and by the Ontario Ministry of the Environment (844 $ng \cdot g^{-1}$). DDT and its metabolites have responded similarly, with concentrations in Lake Superior lake trout decreasing 6.8% (DDT) and 4.5% (DDT metabolites) annually since use of the chemical was banned in 1972 (McGoldrick et al. 2013). Given the substantial reduction in

PCB and DDT discharge and levels in fish, the rate of future reductions will likely slow as these chemicals reach equilibrium in Lake Superior and its biota.

Exceptions to the general trends described above exist. Two contaminants, toxaphene and mercury, are known to be higher in Lake Superior fish than in fish from the other Great Lakes. Toxaphene concentrations in Lake Superior lake trout have declined exponentially following the insecticide's ban in the mid-1980s (Xia et al. 2012), but mercury concentrations in Great Lakes fish have increased since about 1990 (Bhavsar et al. 2010; Zananski et al. 2011). In Lake Superior, mercury concentrations in lake trout are now approaching levels measured when the long-term monitoring programs were established in the 1970s. Similar temporal patterns have been observed for mercury concentrations in rainbow smelt in Lake Superior (McGoldrick et al. 2013). Increasing mercury concentrations may be due to Lake Superior having a large surface area available for atmospheric deposition and sedimentary rock substrates that provide a natural source of mercury (Zananski et al. 2011).

Recent discoveries of chemicals of emerging concern in the Lake Superior ecosystem have led to additional challenges. These emerging chemicals include personal care products, pharmaceuticals, flame retardants, synthetic musks, and surfactants. The potential toxicity and environmental fate and transport of these chemicals are largely unknown. Also, there are additional compounds in production with known persistent, bioaccumulative, and toxic characteristics, but the vast number of new chemicals makes comprehensive monitoring unfeasible. Available data show that concentrations of PBDEs, a class of flame retardants currently being phased out by industry in North America, have been declining since the early 2000s in lake trout (McGoldrick et al. 2013). Time trend data and even current concentrations in fish are largely unavailable for all of the other emerging chemicals, although these chemicals are gradually being integrated into existing monitoring programs.

Despite recent declines in the concentrations of many contaminants, the concentrations of mercury, dioxins/furans, PCBs, toxaphene, and chlordane in the flesh of certain Lake Superior fishes, particularly larger predatory fish, remain high enough to warrant consumption advisories for human health.

These advisories are issued by the states and province surrounding Lake Superior and are based on data from state and tribal programs that monitor contaminant concentrations in fish fillets, independently from federal monitoring programs. Since toxicity thresholds have not been established for the majority of chemicals of emerging concern, there is no way to determine whether these compounds are present in fish at levels unsafe for human consumption. Lake Superior's unique physical, thermal, and biological characteristics make it prone to retaining pollutants longer than the other Great Lakes. As a result, chemical contaminants continue to pose a risk to the ecological health of the lake and cause the states and province to issue fish-consumption advisories.

Primary Production, Zooplankton, and Macroinvertebrates

Survey Design and Methods

In 2011, a lakewide ecosystem survey, conducted as part of the Lake Superior Binational Program's Cooperative Science and Monitoring Initiative (CSMI) (Richardson et al. 2012), yielded statistically unbiased whole-lake estimates of biomass, carbon, and nitrogen for ecosystem components standardized to dry weight or carbon biomass. This survey was built on lakewide surveys conducted in 2005-2006 (Yurista et al. 2009; Kelly et al. 2011; Sierszen et al. 2011) and was the first to provide spatially coincident sampling of ecosystem components from water quality through the lower food web to fish. Sampling was based on a spatially balanced, random probability design (Stevens and Olsen 1999). Fifty-three sampling stations spanning nearly all 20-m depth bins were surveyed (Fig. 2). The design allowed for calculating lakewide- and depth-strata-specific estimates with statistical confidence bounds (Stevens and Olsen 2003). Ecosystem components sampled at each site included water chemistry, seston (comprising detritus, particulate-associated microbes, and phytoplankton), zooplankton, *Mysis diluviana*, benthic invertebrates (principally *Diporeia* spp.), and demersal and pelagic fish. Zooplankton populations were assessed at 12 transects (usually >10 km in length) using a Laser-Optical Plankton Counter (LOPC) (Herman et al. 2004).

Primary Production

Increasing water temperatures in spring in recent years have resulted in a rapid seasonal development of phytoplankton, and these increased temperatures have accelerated physiological processes, such as nutrient uptake, feeding, respiration, and growth (Goldman and Carpenter 1974). Increased spring temperatures have also accelerated thermal stratification of the water column, which influences the onset of the phytoplankton growing season (Austin and Colman 2008; Berger et al. 2010). Primary productivity has been relatively stable in Lake Superior over the past 40 years (Vollenweider et al. 1974; Urban et al. 2005), but Sterner (2010) determined that overall primary production, although stable, is at a higher level than previously believed, with mean water column production of ~300 mg $C \cdot m^{-2} \cdot d^{-1}$ as opposed to earlier estimates of <200 mg $C \cdot m^{-2} \cdot d^{-1}$.

The 2011 CSMI lakewide survey found that dry weight and carbon weight of organic matter decreased progressively from the base of the food web up to fish (Fig. 3). For seston, the weighted average concentration as particulate carbon in the photic zone (to 40 m) was 308 $\mu g \cdot L^{-1}$ (95% CI 302-314). This carbon was associated with an average concentration of ~0.8 $mg \cdot L^{-1}$ of suspended particulate matter. The average lakewide epilimnial concentrations of total phosphorus and chlorophyll *a* were 6 $\mu g \cdot L^{-1}$ and 0.8 $\mu g \cdot L^{-1}$, respectively. These concentrations are lower than recent estimates (Bunnell et al. 2014), which may explain some of the observed declines in zooplankton concentrations outlined below.

Fig. 2. Lake Superior stations (+) sampled for water quality, lower food web, pelagic (acoustic) fish, and benthic (trawl) fish parameters in 2011 as part of the Cooperative Science and Monitoring Initiative (CSMI). Also shown are 12 sampling transects (U.S. waters only, black lines) using *in situ* water-quality sensors and a Laser-Optical Plankton Counter (LOPC) to provide supplemental high-resolution data on spatial variability.

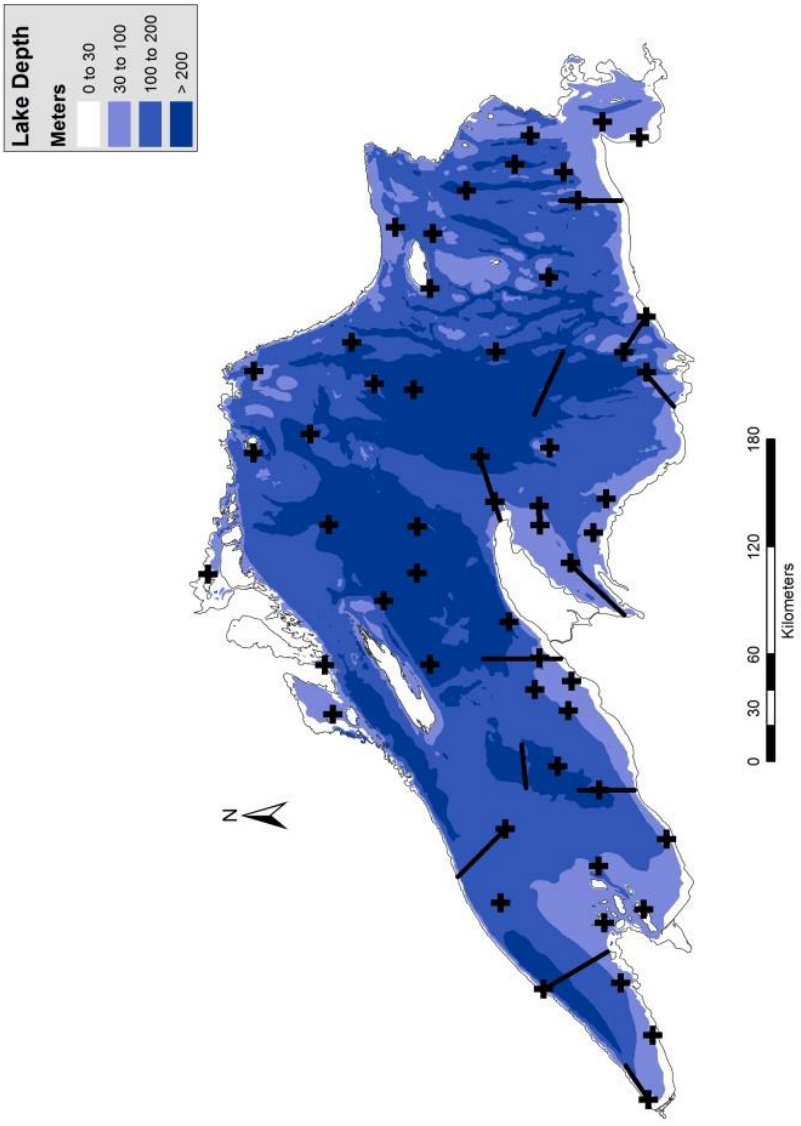
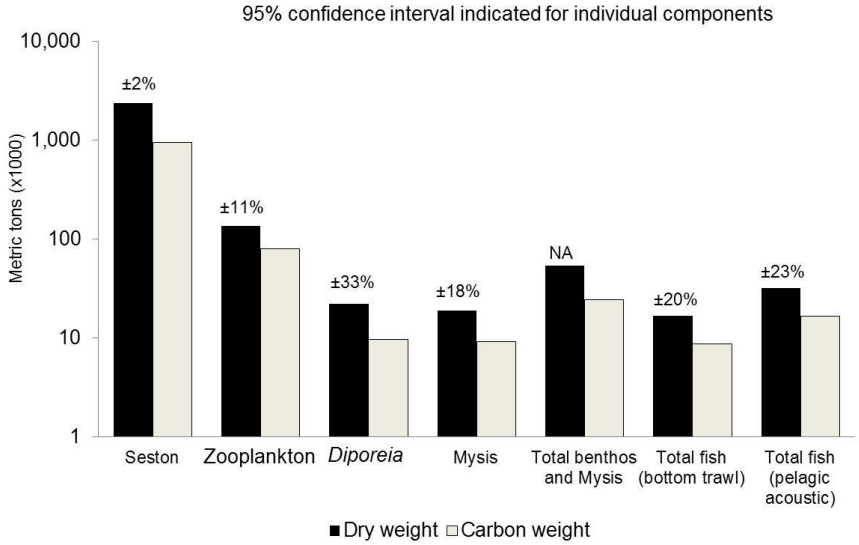

Lake Depth
Meters
0 to 30
30 to 100
100 to 200
> 200
N
0
30
60
120
180
Kilometers

Fig. 3. Whole-lake estimates of biomass (metric tons dry weight and carbon weight) for representative components of the Lake Superior food web in 2011. The estimates exclude the less than 5-m-depth shoreline zone, which was not sampled (2.3% of whole lake area). Estimates were standardized across components based on weight and tissue analyses conducted using 2005-2006 and 2011 samples.

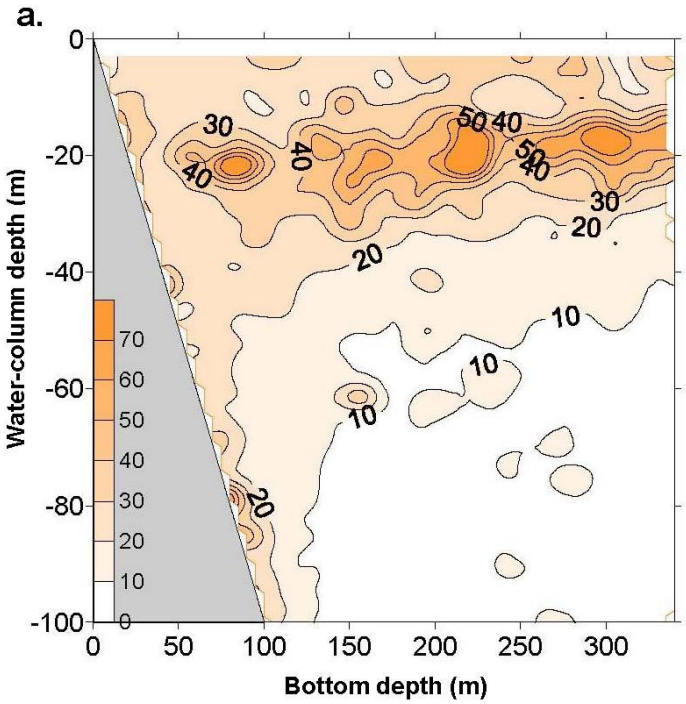


Zooplankton

Zooplankton biomass was primarily concentrated in the epilimnion with low biomass below about 50 m and high biomass in offshore (>80 m) waters in both 2006 and 2011 (Fig. 4). Volumetric-based zooplankton concentrations peaked at around the 50-m contour (Fig. 5a), whereas area-based concentrations peaked at contours greater than 200 m (Fig. 5b). Zooplankton concentrations were integrated lakewide by volume and depth strata to determine biomass available to prey fish (Fig. 5c). Biomass available to prey fish in 2011 was 126,000 metric tons (dry weight) compared to 141,000

metric tons in 2006, a decline of 11%. Differences in concentrations in the bottom strata with the greatest total volume (~150-200 m) were large enough that scaling/weighting by stratum and volume likely created much of the apparent decline. Scaling to whole-lake biomass will be particularly sensitive to differentially large weighting factors across the lake (Fig. 6a). Ultimately, the observed difference may be more apparent than real because sampling power is inadequate to detect small differences in a system so large.

Fig. 4. Zooplankton concentration isopleths ($mg \cdot m^{-3}$) based on Laser-Optical Plankton Counter (LOPC) tows plotted as a function of bottom depth and depth in the water column in U.S. waters of Lake Superior in 2006 (a) and 2011 (b).



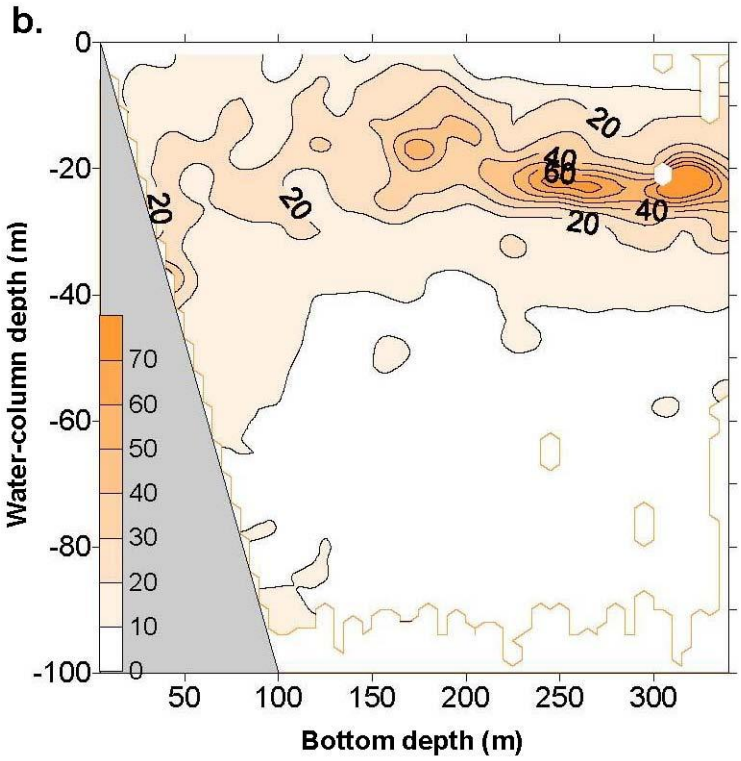
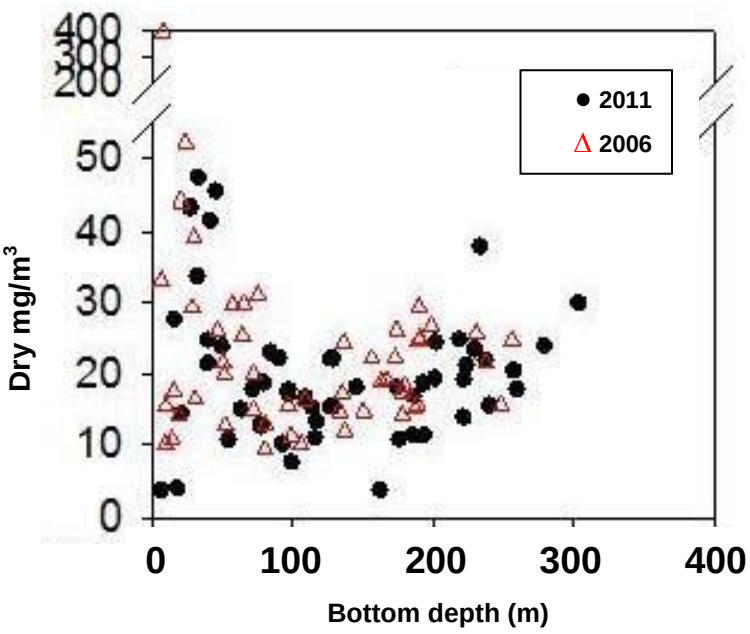
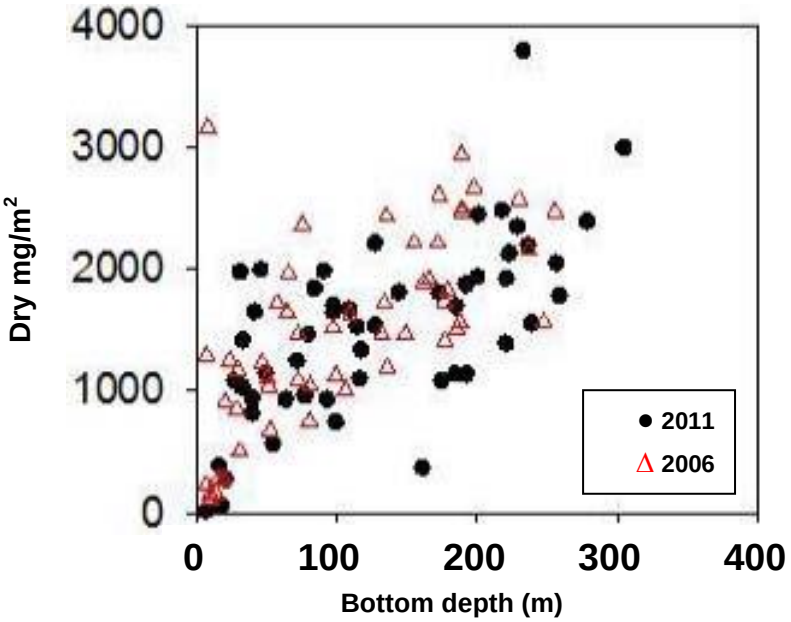


Fig. 5. Zooplankton concentrations in Lake Superior estimated by depth strata in 2006 (Δ) and 2011 (●): (a) volumetric concentrations ($mg \cdot m^{-3}$), (b) areal concentrations ($mg \cdot m^{-2}$), and (c) cumulative total biomass for top 140 m by depth strata weighted by hypsographic curve.

a.


400
300
200
50
40
30
20
10
0
0
100
200
300
400
Dry mg/m3
Bottom depth (m)
2011
2006

b.


4000
3000
2000
1000
0
Dry mg/m2
0
100
200
300
400
Bottom depth (m)
2011
2006

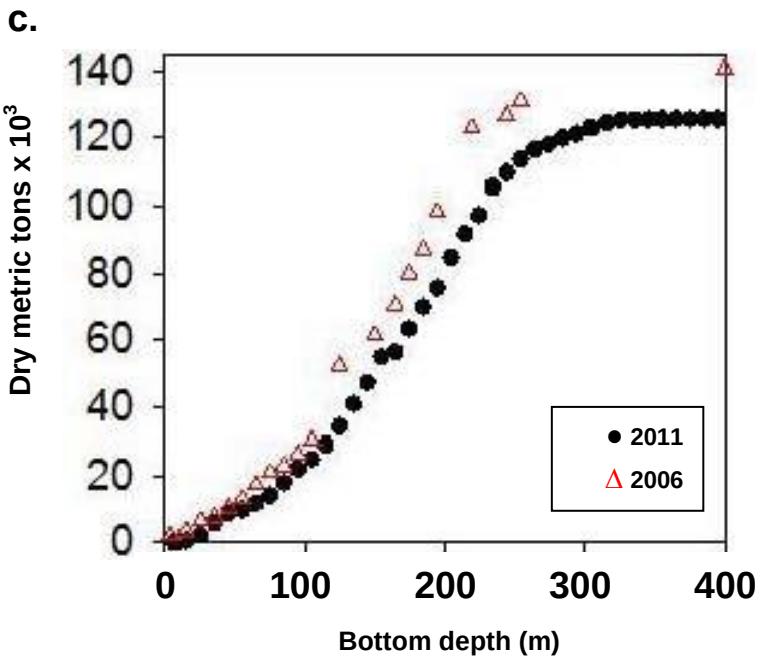
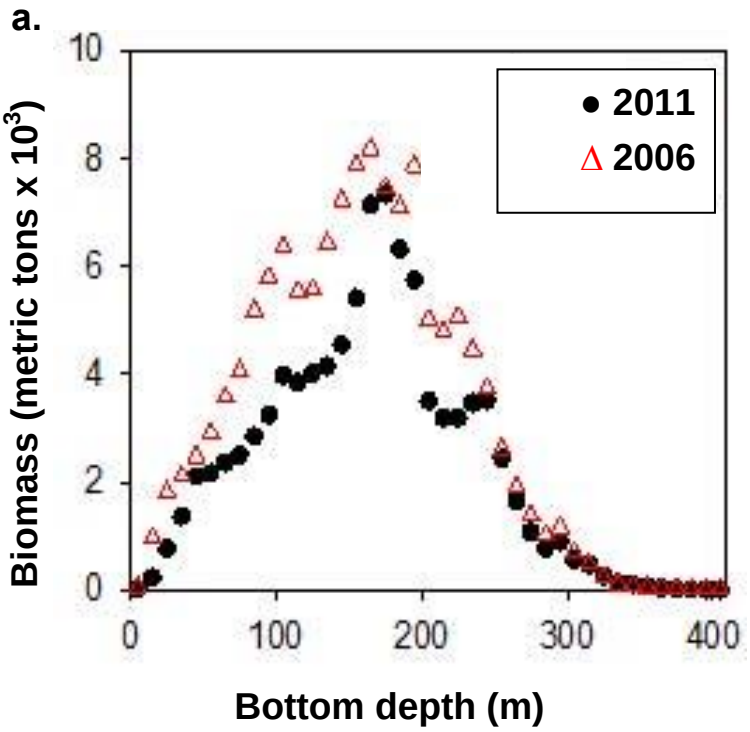
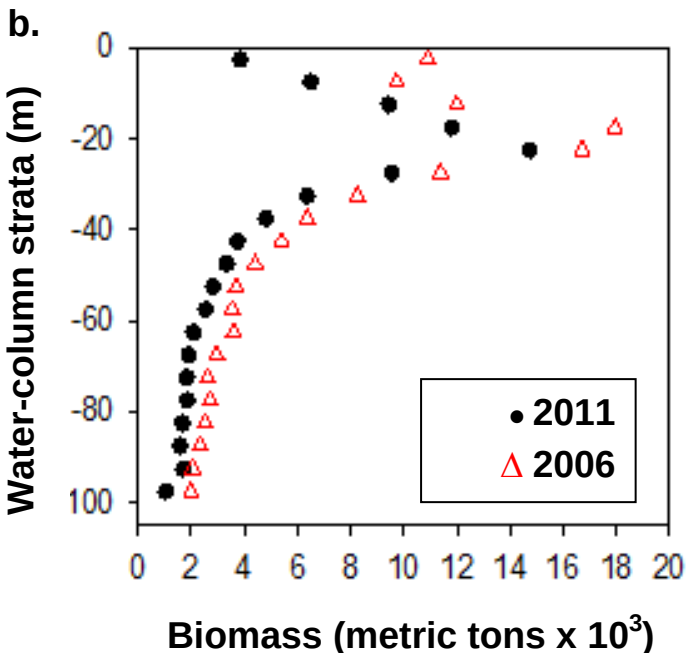


Fig. 6. Lakewide zooplankton biomass (metric tons) by (a) bottom depth and (b) depth-strata in water column estimated for U.S. waters of Lake Superior less than 100-m deep based on Laser-Optical Plankton Counter (LOPC) tows in 2006 (Δ) and 2011 (●).

a.


Biomass (metric tons x 10^3)
10
8
6
4
2
0
0
100
200
300
400
Bottom depth (m)
2011
2006



With the new LOPC technology, concentration profiles were available for the water column, and, by integrating biomass across water-column strata or bottom-depth strata, it was possible to get a relative depiction of the importance of spatial distribution in total zooplankton biomass for the whole lake (Fig. 6b). This biomass integration indicated that the region of highest total zooplankton biomass was 15-25 m below the surface between bottom-depth contours of approximately 50 and 250 m.

A few major taxa comprised the majority of zooplankton biomass across all stations (Table 3). No substantial changes occurred between 2006 and 2011 in the spatial distribution of major species (sites at which present). Some species were widely distributed in the lake, notably most calanoid copepods, some cyclopoids, *Bosmina*, *Daphnia galeata*, *Bythotrephes*, and *Holopedium*.

Table 3. Zooplankton taxonomy, number of stations where present, and average biomass ($mg \cdot m^{-3}$) density across stations in vertical net tows in Lake Superior in 2006 (Yurista et al. 2009) and 2011.

Group	Species	2006		2011	
		Stations Present	**Biomass $mg \cdot m^{-3}$**	**Stations Present**	**Biomass $mg \cdot m^{-3}$**
Adult calanoids	*Diaptomus ashlandi*	2	0.1	0	0.0
	Diaptomus minutus	11	71.9	8	47.3
	Diaptomus oregonensis	14	362.5	7	20.7
	Diaptomus sicilis	50	619.6	51	631.5
	Epischura lacustris	50	257.4	49	129.3
	Limnocalanus macrurus	48	4,942.2	53	3,183.2
	Senecella calanoides	2	0.7	5	3.7
Adult cyclopoids	*Cyclops bicuspidatus thomasi*	52	601.8	53	507.8
	Mesocyclops edax	14	416.8	11	3.2
	Tropocyclops prasinus mexicanus	6	178.2	1	0.1
Bosminids	*Bosmina longirostris*	46	632.5	49	292.8
Daphnids	*Daphnia galeata mendotae*	51	1,366.3	52	2,018.3
	Daphnia longiremis	2	0.1	0	
	Daphnia retrocurva	6	2,836.7	12	65.1

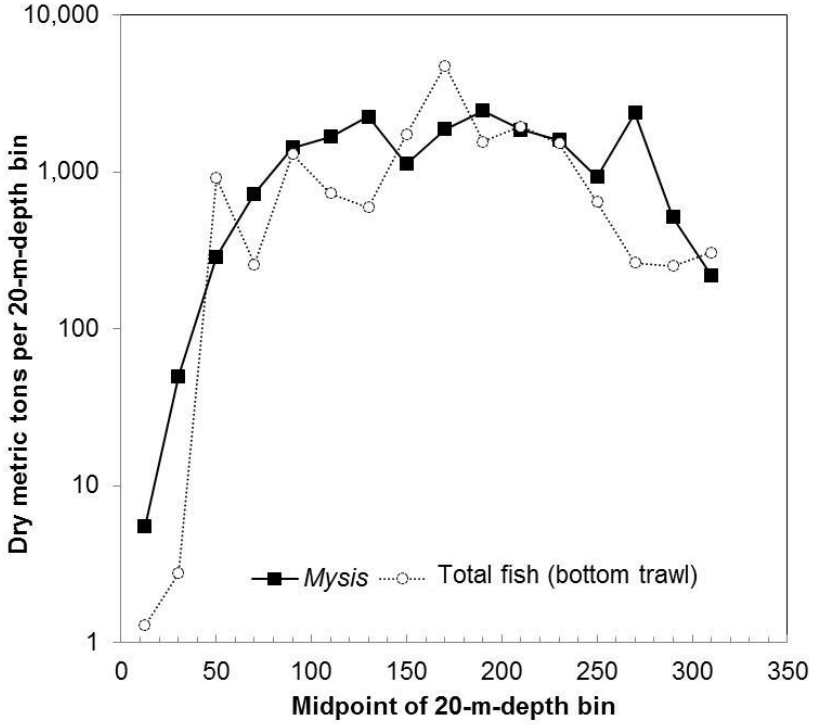
Table 3, continued

Group	Species	2006		2011	
		Stations Present	**Biomass mg·m^{-3}**	**Stations Present**	**Biomass mg·m^{-3}**
Immature calanoids	*Diaptomus copepodites*	52	9,000.6	53	9,356.9
	Epischura copepodites	50	434.4	44	44.6
	Limnocalanus copepodites	9	7.9	8	21.9
	Senecella copepodites	43	239.3	30	79.3
	Cyclops copepodites	52	944.7	53	303.5
	Mesocyclops copepodites	16	279.3	12	2.1
	Tropocyclops copepodites	8	80.9	0	0.0
Other cladocerans	*Bythotrephes longimanus*	52	676.4	50	462.4
	Ceriodaphnia lacustris	4	1,211.6	1	0.2
	Ceriodaphnia reticulata	1	121.3	0	
	Ceriodaphnia spp.	3	270.0	0	
	Chydorus gibbus	1	0.0	0	
	Chydorus sphaericus	1	0.2	1	0.3
	Diaphanosoma birgei	7	2,474.7	6	2.7
	Holopedium gibberum	52	3,253.9	51	3,131.1
	Leptodora kindtii	5	87.9	0	

Macroinvertebrates

Whole-lake estimates of *Diporeia* spp. and *Mysis* in 2011 were 68 trillion (95% CI 46-90) and 9.9 trillion (95% CI 6.6-13.3), respectively. Overall, water quality and plankton showed minor horizontal (inshore to offshore) variability as indicated by low confidence intervals for seston and zooplankton (Fig. 3). Abundance of seston and plankton spatial variability relates principally to the vertical structure of summer stratification and the influence of light and thermocline structure on chemistry and biology. In contrast, abundance of macroinvertebrates and fishes increased or decreased as a function of water depth. For example, *Diporeia* spp. abundance peaked in waters <100 m in depth. *Mysis* showed a general increase from nearly zero at the shallowest nearshore stations to the highest levels in deep offshore waters (Fig. 7). *Mysis* abundance has been reported only intermittently for Lake Superior; whole-lake estimates exist for the 1970s (Carpenter et al. 1974), the 2005-2006 CSMI period (Isaac 2010; Kelly et al. 2011), and now 2011. *Mysis* depth distribution and movement patterns in 2011 were generally similar to those measured in previous periods.

Fig. 7. Biomass (dry metric tons) of *Mysis* and benthic fishes in 2011 estimated for 20-m-depth bins at depths from 5 to 320 m, which encompasses ~97% of the benthic area of Lake Superior.



When considering the virtual depletion of *Diporeia* spp. from the other Great Lakes, the continued vibrancy and a possible increase of *Diporeia* spp. (an important prey source) in Lake Superior is notable. For years, surveys missed the large biomass of *Diporeia* spp., which represents about 60% of the total benthos biomass in the nearshore zone, because the nearshore zone was not sampled regularly until 2011 (Scharold et al. 2004; Barbiero et al. 2011; Kelly et al. 2011). Whole-lake estimates of *Diporeia* spp. for 2005 and 2006 pilot/demonstration surveys, using a similar statistical approach to the 2011 survey, averaged about 40 trillion (Kelly et al. 2011), approximately 33% below the 2011 estimate. Analyses are still in progress to statistically assess differences in lower food-web components during 2005-2011.

Food-Web Dynamics

The 2005-2006 and 2011 CSMI surveys provided new insights into the structure and function of the Lake Superior food web. Yurista et al. (2014) used results of lakewide remote sensing surveys (including Coulter counts for phytoplankton, optical plankton counts for zooplankton, and acoustic methods for pelagic prey fish) to inform a biomass size-spectrum ecosystem model. There did not appear to be any change in the overall lakewide spectrum over the five-year interval (2005-2006 versus 2011), indicating a stable ecosystem. When data from the 2005-2006 and 2011 surveys were combined, observed levels of pelagic prey-fish biomass were generally lower than levels predicted based on the biomass and size structure of zooplankton. This pattern is consistent with a system where top-level piscivores like lake trout are likely exerting top-down control of prey-fish populations. The fact that acoustic surveys tend to underestimate prey-fish biomass (Yule et al. 2007) likely contributed to the discrepancy.

Sierszen et al. (2014), utilizing stable-isotope samples from the 2005-2006 CSMI, determined that the overall importance of benthic food-web pathways to fish was highest in nearshore species, whereas the importance of planktonic pathways was highest in offshore species. Cisco and rainbow smelt obtained most of their nutrition from pelagic pathways, while pygmy whitefish and slimy and spoonhead sculpins obtained most of their nutrition from benthic pathways. Both pathways were important to bloater, lake whitefish, deepwater sculpin, and kiyi. The benthic pathway was more important to siscowet lake trout because of their reliance on kiyi and

deepwater sculpin, while lean lake trout obtained more nutrition from the pelagic pathway because of their high utilization of rainbow smelt and cisco. Sierszen et al. (2014) concluded that Lake Superior was an exemplar system showing trophic linkages among pelagic, profundal, and littoral habitats that are likely integral to the productivity of large lake ecosystems.

Conclusions and Recommendations

Contaminant levels in fish remained relatively stable between 2005-2006 and 2011 as did the distribution, abundance, and biomass of the lower food web, notwithstanding an apparent modest increase in abundance of *Diporeia* spp.. Conversely, the ongoing higher mean water temperatures and decreases in ice cover hint that profound changes in the physical properties of the lake with potential to destabilize the food web lie ahead. Determining whether the productive capacity of the lake to produce fish (the FCO) is being achieved given its broad scope remains challenging (Table 1). The productive capacity of nearshore (15-80-m depths) and offshore (>80-m depths) habitats has remained relatively consistent, allowing many of the FCOs for nearshore and offshore species to be achieved. However, concerns are still apparent for fishes reliant on inshore (<15-m depths) and tributary habitats (Superior Work Group of the Lake Superior Lakewide Action and Management Plan 2015), and agencies continue to require fish-consumption advisories due to fish-contaminant burdens. Agencies should continue to support the five-year CSMI monitoring cycle and the efforts to protect or restore aquatic habitats, particularly those in tributaries and inshore areas that have been most impacted by humans.

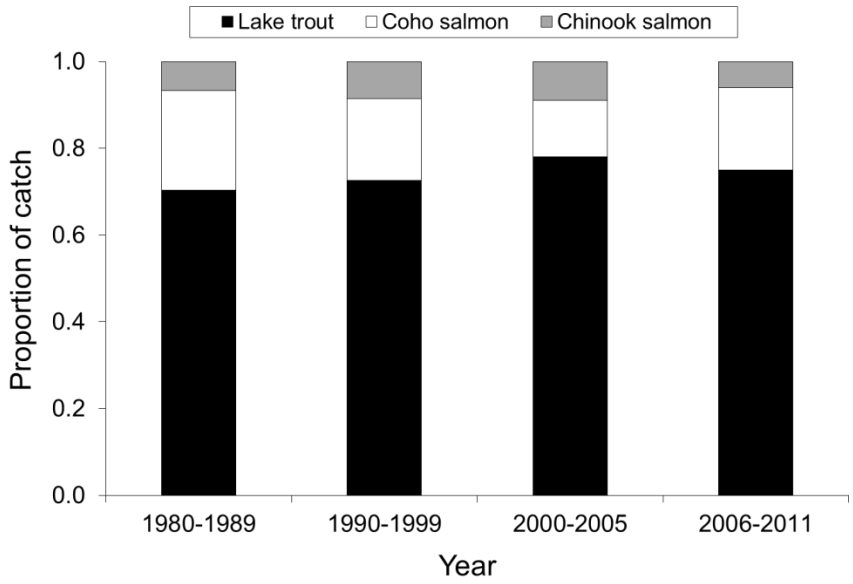
INSHORE, EMBAYMENT AND TRIBUTARY FISHES

Pacific Salmon, Rainbow Trout, Brown Trout

The introduction and naturalization of non-indigenous salmonines has had a major impact on angling in tributaries and in inshore and nearshore habitats. All agencies that stock trout and salmon monitor, to some extent, their relative abundance and the contribution of stocked fish to the fishery. Creel surveys targeting the spring-summer (April-September) open-water lake fishery, and, in some jurisdictions, ice fisheries are used to assess angler catch and catch rate of salmonines in U.S. waters.

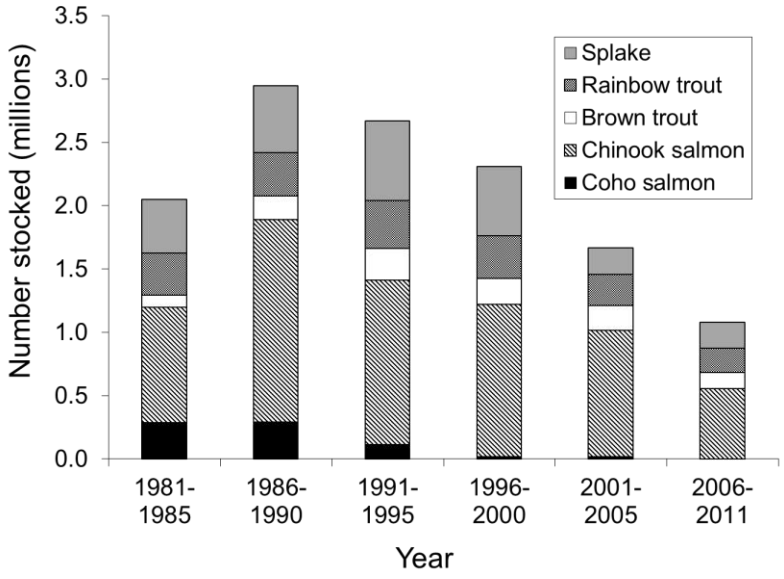
Of the total angler catch of salmonines (in numbers of fish), ~29% were non-indigenous species and the remainder (71%) were indigenous species during 2006-2011. The harvest of indigenous salmonines comprised lake trout and a few brook trout. The catch of non-indigenous salmonines was mainly coho salmon (62%), followed by Chinook salmon (20%), splake (9%), rainbow trout (5%), pink salmon (3%), and brown trout (1%). Despite the many changes that have occurred in the fish community since the early 1980s, the proportion of the two major non-indigenous salmonine species in the total angler harvest has remained relatively consistent (Fig. 8).

Fig. 8. Proportional catch of major salmonines in the Lake Superior sport fishery in U.S. waters, 1980-2011.



Non-indigenous salmonines play a relatively minor role in the Lake Superior fish community (Kitchell et al. 2000; Bronte et al. 2003). Thermal limitations relegate non-indigenous salmonines to the inshore zone and to pelagic portions of the nearshore and offshore zones (Schreiner et al. 2010). Non-indigenous salmonines may benefit if surface water temperatures continue to increase (Austin and Colman 2008). However, increased summer stream temperatures and more variable stream flows may counteract the benefit of warmer lake-surface waters.

Fig. 9. Number of non-indigenous salmonines stocked in Lake Superior, 1981-2011.

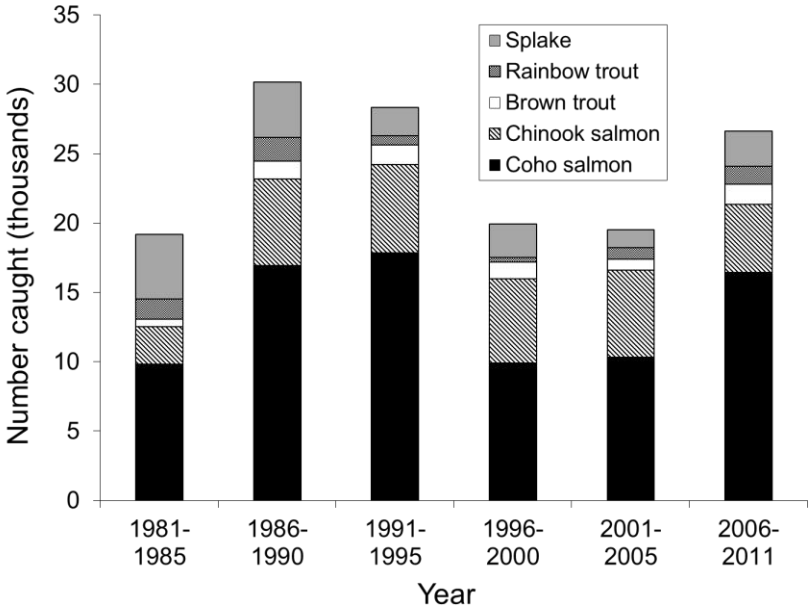


Conclusions and Recommendations

The fish community objective for non-indigenous salmonines is being realized (Table 1). Most of the introduced salmonines in Lake Superior are self-sustaining (naturalized) at relatively high levels and support productive sport fisheries. The naturalization of non-indigenous salmonines has provided diversity to the Lake Superior fishery and can be considered a success by anglers and management agencies. Because most species of interest have naturalized, there is minimal need for stocking. The total number of fish stocked has been reduced by over 50% since the late 1980s, yet angler catch remains relatively stable with some species near all-time highs (Fig. 10). Only in very specific and limited geographic areas do agencies continue to rely on stocking to sustain a handful of "specialized" fisheries for purely recreational purposes (brown trout in Chequamegon Bay,

Wisconsin; Kamloops rainbow trout in Minnesota; and splake in Michigan and Wisconsin).

Fig. 10. Angler catch (number of fish) of non-indigenous salmonines in U.S. waters of Lake Superior, 1981-2011.



The desired balance between indigenous and non-indigenous salmonines continues to be debated among agencies and between agencies and their constituents. However, because most non-indigenous salmonines are naturalized, agencies have limited control over their abundance. That said, agencies should develop a standardized database for creel information to inform future management decisions. Owing to naturalization, further

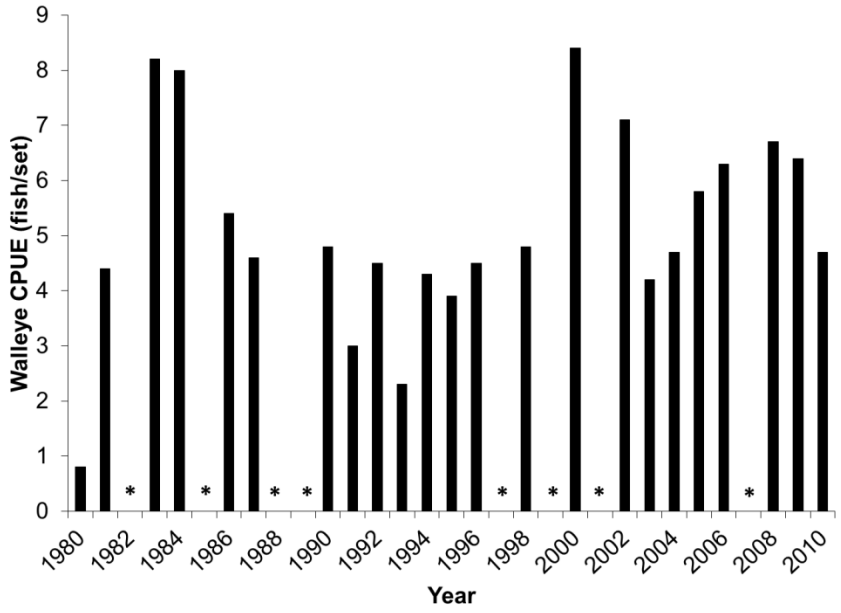
reductions in stocking non-indigenous salmonines are tenable since stocking is expensive, is largely without benefit, and is potentially a source for introduced diseases and genetic risks to native and naturalized populations (Krueger et al. 1994; Miller et al. 2004; Negus et al. 2012). In addition, non-indigenous salmonines may compete with brook trout for spawning and nursery habitat in the nearshore zone and in tributaries (Fausch and White 1986; Huckins et al. 2008; Schreiner et al. 2008), but further research is needed to assess any interaction. Efforts by management agencies to inform the public of the cost-effectiveness and risks of stocking should be continued.

Walleye

Many walleye populations in Lake Superior continue to be maintained or enhanced through stocking. During 2006-2011, approximately 53 million larvae and fingerlings were stocked, which was similar to the ~50 million stocked during the previous reporting 2000-2005 period. Contributions of stocked walleye to fisheries have rarely been evaluated (Schram et al. 2010). However, fingerling stocking in the Waishkey River during 2009-2011 contributed substantially to a popular sport fishery in the St. Marys River (M.P. Ebener, Chippewa Ottrawa Resource Authority, unpublished data).

The St. Louis River walleye population in western Lake Superior remains the only population known to be near historical abundance levels. Supplemental stocking occurred during previous reporting periods but was discontinued after 2005, and since then natural reproduction alone supports the population and popular angler fishery in the river and in the adjacent lake waters. Year-class strength has been variable since the 1980s, yet relative abundance has remained relatively stable (Fig. 11). The fish community of the St. Louis River estuary has changed dramatically since the 1980s due to improved water quality and the invasion of non-native species, including ruffe, white perch, and round goby. Thus far, these changes in the fish community do not appear to have negatively impacted the walleye population. Successful rehabilitation of this population has been attributed to improved water quality and conservative fishing regulations (Schram et al. 1992).

Fig. 11. Walleye relative abundance in the St. Louis River estuary based on catch-per-unit effort (CPUE) from graded-mesh gillnet surveys conducted by the Minnesota DNR, 1980-2010. Asterisks indicate years with no survey conducted.



Efforts to rehabilitate the Black Bay walleye population, mainly stocking and fishery closures, have met with limited success (Wilson et al. 2007). The walleye population in Black Bay collapsed in the mid-1960s due to overfishing and habitat degradation (Colby and Nepszy 1981; Furlong et al. 2006). The lack of sufficient spawning habitat in Black Bay and its largest tributary, the Black Sturgeon River, inhibits rehabilitation. Providing fish passage at a downstream dam would increase spawning habitat and likely improve reproduction (Furlong et al. 2006; Schram et al. 2010). However, debate over the dam's removal continues due to the extensive amount of sea

lamprey reproductive habitat that would become accessible were the dam removed. The potential for increased sea lamprey production, the increased cost of treating the newly exposed habitat with lampricide, the effect of chemical treatment on populations of northern brook lamprey, and other potential unintended consequences of fish passage are being evaluated against the benefit of potential walleye rehabilitation (McLaughlin et al. 2012). Since 2006, multiple workshops and meetings with stakeholder groups were held to assess management options and their anticipated benefits and risks. Ultimately, an advisory council produced two management options: remove the dam and replace it with an upstream barrier or add a trap-and-sort fishway to the existing dam. The Province of Ontario is soliciting further public input on the proposed actions as both the existing dam and the site of the proposed new sea lamprey barrier are within the boundaries of the Black Sturgeon River Provincial Park.

Conclusions and Recommendations

As of 2011, the FCO for walleye in Lake Superior (Table 1) is not being met. Despite fishery regulation and stocking, all but one walleye population likely remains below historical abundance levels (Hoff 2003). The impediments to successful rehabilitation continue to be limited data for most populations, habitat loss, and inherent life-history constraints, including highly variable recruitment and slow growth (Schram et al. 2010). Agencies continue to address these impediments through strategies described in the walleye rehabilitation plan for Lake Superior (Hoff 2003), especially strategies to improve and protect the quality and quantity of spawning habitat. Given the number of walleye stocked into Lake Superior, the efficacy of stocking should be assessed.

Lake Sturgeon

The Lake Superior population of lake sturgeon was listed as “Threatened” by the Province of Ontario (as are the other Great Lakes populations in Ontario) and is recommended for listing as Threatened under the federal Canadian Species-At-Risk Act by the Committee on the Status of Endangered Wildlife in Canada, although no time frame was identified for a listing decision. Twenty-one basin tributaries and Lake Nipigon supported

lake sturgeon populations historically. Populations persist or have been re-established in 10 Lake Superior tributaries and throughout Lake Nipigon (Holey et al. 2000; Auer 2003; Pratt 2008; Quinlan et al. 2010). Two populations (Bad River, Wisconsin, and Sturgeon River, Michigan) currently meet self-sustaining criteria described in the Lake Sturgeon Rehabilitation Plan for Lake Superior (Auer 2003; Schloesser and Quinlan 2010; Hayes and Caroffino 2012). The 2010 spawning-run estimate for the Bad River was 844 (95% CI 607-1,081) individuals (Schloesser and Quinlan 2010), and the adult population in the Sturgeon River was estimated at 1,808 individuals (Hayes and Caroffino 2012). The Kaministiquia, Goulais, Pic, and White Rivers in Ontario meet most rehabilitation criteria, but additional assessment is needed (Friday 2008; Pratt 2008; Ecclestone 2012).

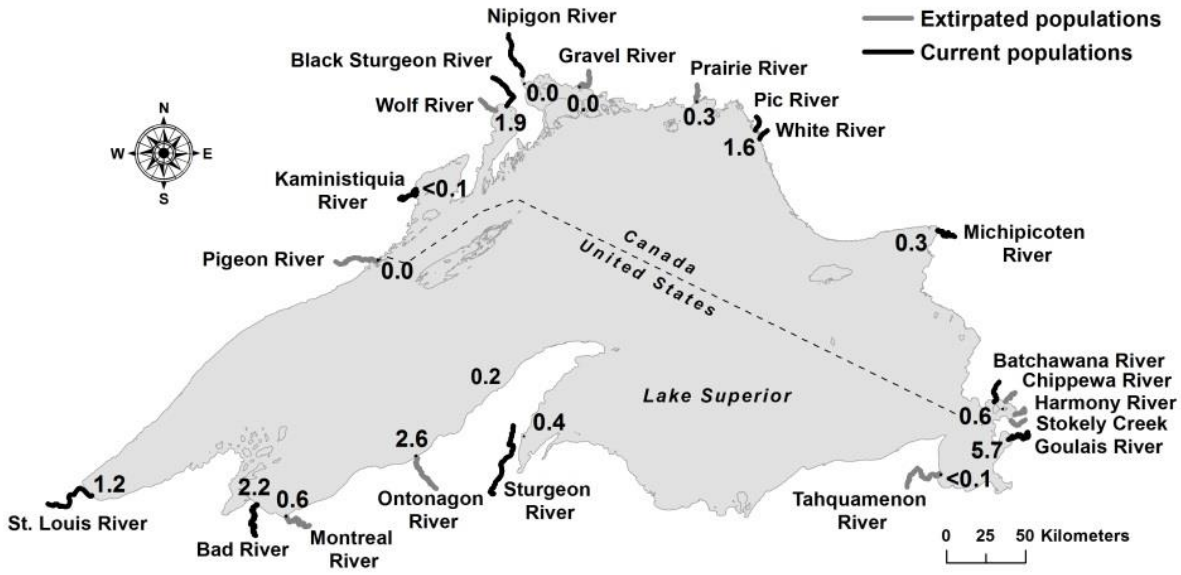
Assessments during 2006-2011 confirmed that natural reproduction is occurring in the Kaministiquia, Black Sturgeon, Nipigon, Pic, White, Batchawana, and Goulais Rivers of Ontario and in the Sturgeon, Bad, and St. Louis Rivers in the U.S. (Pratt 2008; Eccelstone 2012; Schloesser et al. 2014; B. Borkholder, Fond du Lac Band of Chippewa, pers. comm.). Lake sturgeon were reintroduced via stocking to the lower and upper St. Louis River and the Ontonagon River in the U.S. (Schram et al. 1999; Wilson 2008; B. Borkholder, Fond du Lac Band of Chippewa, personal communication, 2011). Natural reproduction in the lower St. Louis River culminates a 30-year effort to restore lake sturgeon through stocking, habitat restoration, and protective regulations (Schram et al. 1999; J. Lindgren, Minnesota DNR, personal communication, 2011). Hydropower operations and dams or barriers limit rehabilitation progress in the Michipicoten, Black Sturgeon, Wolf, Pic (Black), St. Louis, and Bad (White) Rivers.

In 2011, as part of the Lake Superior Binational Program Cooperative Science and Monitoring Initiative (CSMI) (Richardson et al. 2012), a lakewide lake sturgeon survey was initiated in inshore waters, including embayments, associated with all historical lake sturgeon populations. Twenty-two agencies contributed to the CSMI effort, which addresses assessment needs identified in the rehabilitation plan (Auer 2003). Surveys were completed at all locations, except Black Bay (Black Sturgeon and Wolf Rivers), which was not completed due to bycatch concerns (Schloessser et al 2014). Goulais Bay had the highest sturgeon catch-per-unit effort, 2.5 times higher than the Pic and Ontonagon Rivers and nearly three times higher than the Bad River (Fig. 12).

Conclusions and Recommendations

The FCO for lake sturgeon was only partially met (Table 1). Few Lake Superior lake sturgeon populations are considered fully rehabilitated. Protective harvest regulations should remain in place until evidence suggests more liberalized harvests can be sustained while rehabilitation is in progress. Impediments to successful rehabilitation continue to be limited data for most populations, which hinders optimal allocation of effort; habitat loss due primarily to hydropower operations and barriers; a life history strategy that favors late maturation and intermittent spawning; and low lakewide abundance, which limits range expansion into unoccupied, historically used habitat. Agencies should continue to support the five-year CSMI sturgeon survey to assess rehabilitation progress.

Fig. 12. Catch-per-unit effort (number·305 m gillnet) of lake sturgeon in inshore waters and embayments surveyed in 2011 as part of the Cooperative Science and Monitoring Initiative. Surveys were associated with tributaries where lake sturgeon currently or historically spawned. Current population designation indicates evidence of natural reproduction.


Extirpated populations
Current populations
Nipigon River
Black Sturgeon River
Gravel River
Prairie River
Wolf River
Pic River
White River
Kaministiquia River
Pigeon River
Michipicoten River
Canada
United States
Lake Superior
Batchawana River
Chippewa River
Harmony River
Stokely Creek
Goulais River
Ontonagon River
Sturgeon River
Tahquamenon River
St. Louis River
Bad River
Montreal River
0.0
0.0
1.9
0.3
1.6
<0.1
0.0
0.3
0.2
2.6
0.4
0.6
5.7
<0.1
1.2
2.2
0.6
N
W
E
S
0 25 50 Kilometers

Brook Trout

Coaster brook trout abundance remains extremely low lakewide with adult population estimates for individual tributaries ranging from tens to several hundred of individuals (Ward 2008; Bobrowski et al. 2011; C. Huckins, Michigan Technological University, personal communication, 2011). In Lake Nipigon, in Minnesota tributaries to Lake Superior, and at Tobin Harbor, Isle Royale, coaster brook trout abundance and size structure increased along with a range expansion during 2006-2011 (Ward 2008; Bobrowski et al. 2011).

During 2006-2011, over 1.7 million brook trout were stocked in U.S. waters at the Grand Portage (Minnesota), Red Cliff (Wisconsin), and Keweenaw Bay (Michigan) Indian reservations and by the Michigan DNR. Life stages stocked included larvae, small fingerlings, fall fingerlings, yearlings, and adults. Most stocked fish originated from Lake Superior-basin strains. Agencies that stock brook trout monitor, to various degrees, the relative abundance and contribution of stocked fish to the fishery.

Catch and release angling regulations were enacted in 2005 at Isle Royale, Michigan, and possession was limited to one fish over 56 cm in Ontario for all of its waters, including tributaries and Lake Nipigon. At Isle Royale, relative abundance of coasters in tributaries increased from 1.3 per km (1997-2005) to 3.2 per km during 2006-2011 (HRQ, unpublished data). In South Bay and West Bay, Lake Nipigon, the proportion of adults over 56 cm in length increased by 43% and 59%, respectively, likely as a result of the regulation change, and abundance increased over 40% after 2005 (Bobrowski et al. 2011). Likewise, in the Nipigon River and Nipigon Bay, the proportion of brook trout over 56 cm in length increased by 22% and 17%, respectively. Despite increased protection and increasing abundance, adult abundance was 4.5% to 25% below management targets (Bobrowski et al. 2011), and catch rates for anglers targeting brook trout, although improved, remained below the management objective of one brook trout for every two hours of angling (OMNR 2004).

Studies of coaster and resident (non-migratory) brook trout populations suggest similar age and size structure prior to migration (Kusnierz et al.

2009; Bobrowski et al. 2011), but, thereafter, coasters grew faster and lived longer than stream-resident fish (Robillard et al. 2011). Genetic studies show that remnant coaster populations form discrete stocks at Isle Royale, Salmon Trout River, Nipigon Bay, and Lake Nipigon (Wilson et al. 2008; Stott et al. 2010; Scribner et al. 2012). Populations along the north shore of Minnesota are also genetically distinct from each other and from coaster populations elsewhere (Stott et al. 2010). These results indicate low levels of straying among populations.

Conclusions and Recommendations

The brook trout FCO is not being fully achieved (Table 1), although progress is being realized in some areas. Protective regulations in both stream and lake environments have led to increased abundance. Impediments to further recovery continue to be a lack of protective regulations in some areas, habitat loss, excessive sedimentation, high sand bed loads, loss of channel complexity, and unsuitable water temperatures. Non-indigenous salmonines have the potential to compete with brook trout for spawning and nursery habitat in the nearshore zone and in tributaries (Fausch and White 1986; Huckins et al. 2008; Schreiner et al. 2008), and further research should be undertaken to determine if negative effects are being realized. A standardized sampling protocol and development of routine reporting measures are needed to assess progress toward the FCO.

NEARSHORE FISHES

Progress in achievement of the fish community objectives (FCOs) for lean lake trout and lake whitefish is based on interagency gillnet assessments whereas those for major prey fishes and species diversity (Table 1) are based on abundance trends in daytime bottom trawling conducted during May-June 1978-2011 by the Great Lakes Science Center (GLSC) (for methods, see Stockwell et al. 2007; Yule et al. 2007). The subset of nearshore fishes vulnerable to trawling included cisco, bloater, shortjaw cisco, lake whitefish, rainbow smelt, longnose sucker, slimy sculpin, spoonhead sculpin, ninespine stickleback, and pygmy whitefish. Not all species inferred in the species diversity FCO, such as minnows (Cyprinidae), are assessed or reported owing to logistical constraints.

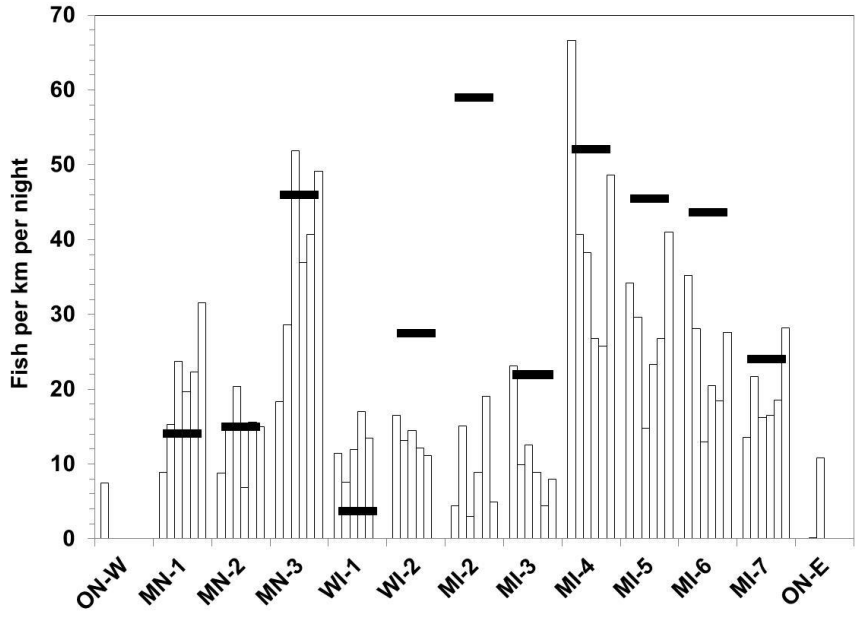
Lean Lake Trout

Abundance and Stocking

During 2006-2011, in response to an increase in abundance of wild lean lake trout, a limited commercial fishery was implemented in Minnesota units MN-3 (2007) and MN-2 (2010) (see Fig. 1 for unit locations; Figs. 13, 14). Wild lake trout comprise nearly 90% of Minnesota populations such that stocking has been discontinued in MN-2 and 3 and greatly reduced in MN-1. Stocking likely will be discontinued in MN-1 within the next five years if the current increases in abundance continue. In western Wisconsin waters (WI-1 and 2), wild lake trout abundance was lower in 2006-2011 than during the previous reporting period (2001-2005) due to higher levels of fishery exploitation (Fig. 13). Stocking continues in WI-1 and was higher during 2006-2011 than 2001-2005. Hatchery fish comprise about 50% of lake trout in WI-1 and less than 10% in WI-2. In Michigan units west of the Keweenaw Peninsula (MI-2 and 3), wild lake trout abundance has declined since 2001-2005 (Fig. 13). In units east of the Keweenaw Peninsula (MI-4 through MI-7), considered to be in a post-rehabilitated state, wild lake trout abundance has generally declined from peak recovery levels observed in the mid-to-late 1990s. In MI-2 to MI-7, hatchery fish made up less than 10% of lean lake trout populations during 2006-2011 and comprised 1% in 2011. In Whitefish Bay (MI-8), wild lake trout recovery was set back due to earlier decisions to defer rehabilitation in Michigan waters such that now hatchery

fish continue to make up the bulk of the population, but, nonetheless, abundance of wild fish has increased since 2005. Ontario ceased stocking in Whitefish Bay because of the lack of progress in rehabilitation, and stocking in adjacent U.S. waters was discontinued under the terms of a Consent Decree signed in 2000 between certain Indian tribes and the state of Michigan. Survey data for western and central Ontario waters are scant such that wild lean lake trout populations in those areas are assumed to mirror the trends in adjoining U.S. waters.

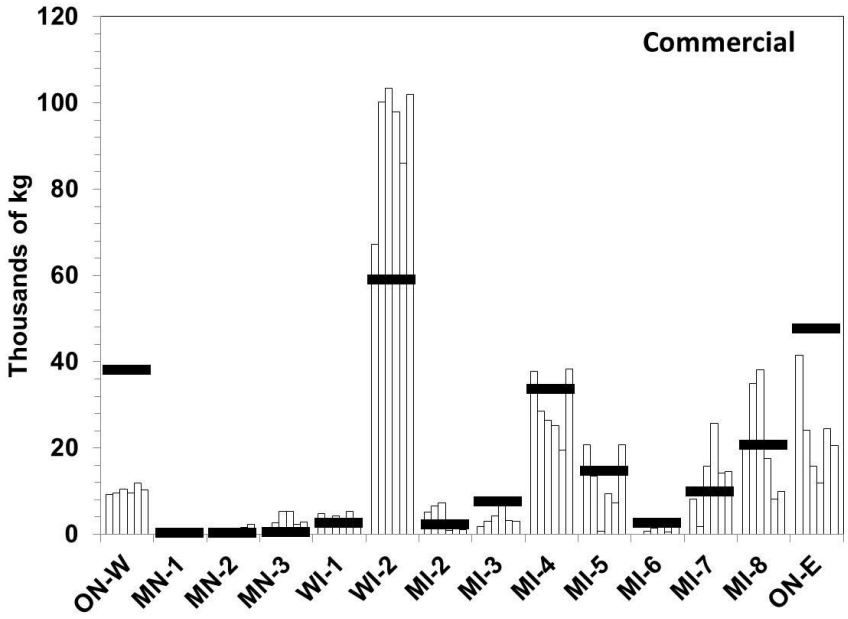
Fig. 13. Relative abundance of wild lean lake trout in management units of Lake Superior expressed as the annual geometric mean number caught per km of gillnet per night fished (catch-per-unit effort = fish·km^{-1}·night^{-1}) from standardized spring (April-June) bottom-set gillnet surveys during 2006-2011 (vertical bars in chronological order). Horizontal bars represent the geometric mean catch-per-unit effort during 2001-2005 (Sitar et al. 2010). There were no data for 2007-2011 in ON-W; 2011 in WI-1 and 2; and 2006 and 2009-2011 in ON-E .

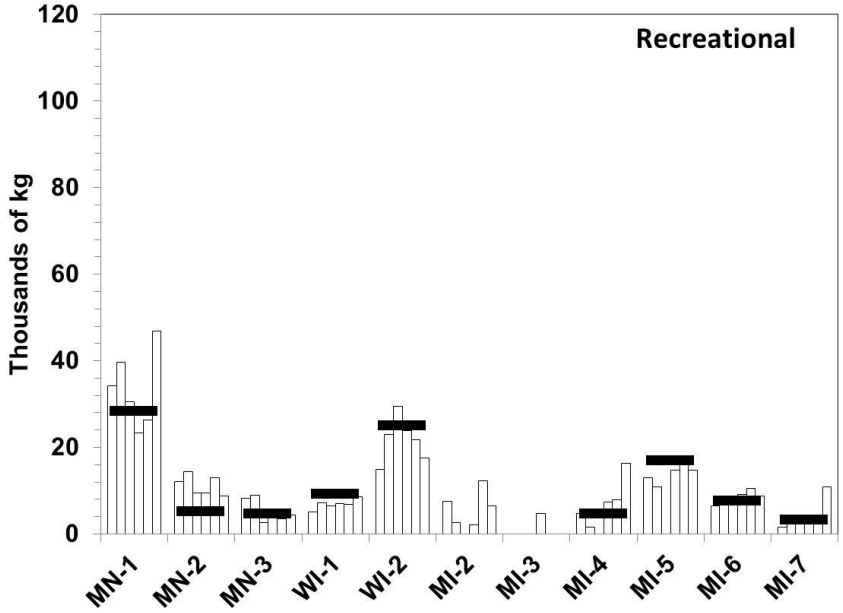


Harvest

The greatest commercial harvest of lean lake trout during 2006-2011 continued to be in WI-2 (92,800 kg·yr^{-1}), MI-4 (29,300 kg·yr^{-1}), MI-8 (21,400 kg·yr^{-1}), and ON-23 to ON-34 (23,100 kg·yr^{-1}). Commercial harvest during 2006-2011 in all districts declined or was similar to that in 2001-2005, except in WI-2 and MI-7 where harvest was higher (Fig. 14). Angler harvest of lean lake trout was highest in MN-1 (average 33,500 kg·yr^{-1}) and WI-2 (21,700 kg·yr^{-1}) and has increased since 2001. In contrast, angler harvest was much lower in Michigan and has generally declined since 2001-2005 in all management units, except MI-4 (Fig. 14).

Fig. 14. Annual commercial and recreational yields (kg) of lean lake trout in Lake Superior management areas during 2006-2011 (vertical bars in chronological order) based on creel-survey and commercial reports. Horizontal black bars are the mean commercial and recreational yield between 2001 and 2005. There were no recreational data for 2008 in MI-2; 2006-2007 and 2010-2011 in MI-3, and 2008 in MI-5, 6, and 7.

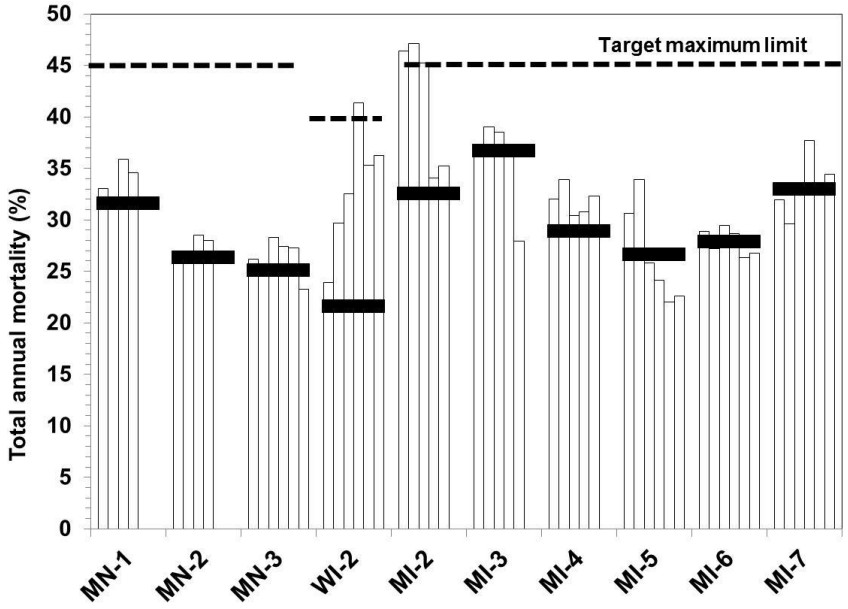




Mortality and Growth

Lake trout populations have been managed for the most part based on a target-total-annual-mortality-rate maximum of between 40% and 45% (Hansen 1996; Wisconsin State-Tribal Biological Committee 2007; Technical Fisheries Committee 2012). Mortality rates during 2006-2011 were estimated using statistical catch-at-age (SCAA) models for most U.S. management units (Fig. 15). The SCAA models for MI-2, 3, and 4 are still in development, and, therefore, the estimates for these units are provisional. No models have yet been developed for WI-1, MI-1 and 8, and Canadian waters.

Fig. 15. Total annual mortality (%) of age-6 and older lake trout in U.S. waters of Lake Superior during 2006-2011 (vertical bars in chronological order) and average for 2001-2005 (horizontal black bars). Dashed lines represent the target maximum limit established for each lake trout management unit. Mortality rates were estimated from a statistical catch-at-age analysis for each management unit. There were no estimates for 2010-2011 in MN-1 and 2; and 2011 in MI-2, 3, and 4.

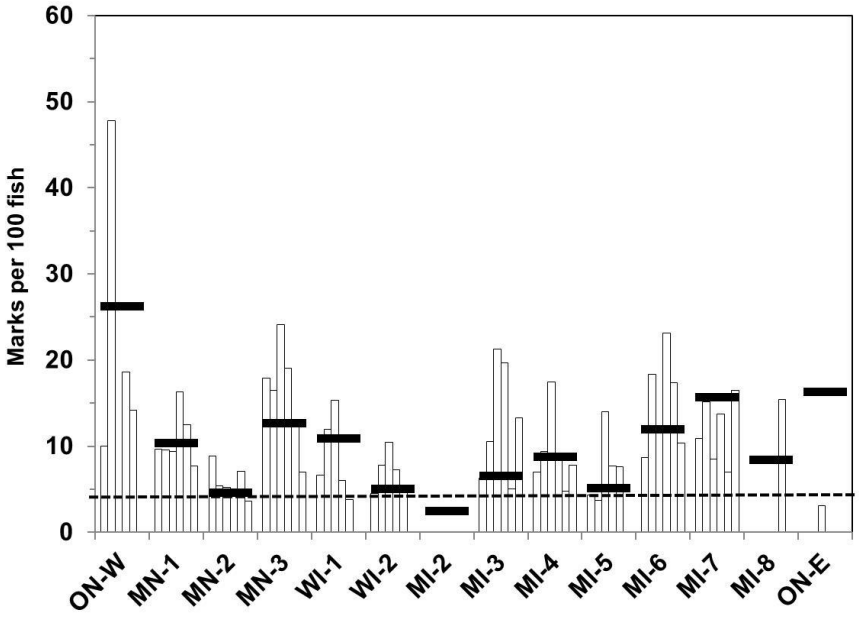


Total annual mortality rates in most U.S. waters in 2006-2011 were generally slightly higher than or comparable to rates in 2001-2005 except in WI-2 and MI-2 (Fig. 15). In WI-2, mortality increased substantially from 23.9% in 2006 to 36.3% in 2011 and, in 2009 exceeded the lower bound of the maximum limit (40%); the average of 33.2% for 2006-2011 was higher than the average during 2001-2005 (21.6%). A near doubling of commercial harvest in WI-2 was driven by more liberal fishing policies that were a response to SCAA model overestimates of abundance and biomass. The

model has been recalibrated and total allowable catches have subsequently fallen. In MI-2, total mortality during 2006-2011 reached 41.6 %, which was slightly above the lower bound of the maximum limit (40%) and 32.6% higher than in 2001-2005. Mortality in MI-2 was likely affected by more intensive fishing in the adjoining district, WI-2. In MI-5, 6, and 7, average total mortality rates (for ages 6-11) during 2006-2011 ranged from 26.5% to 33.4% and were about equal to the 2001-2005 average of 26.7-33.0%.

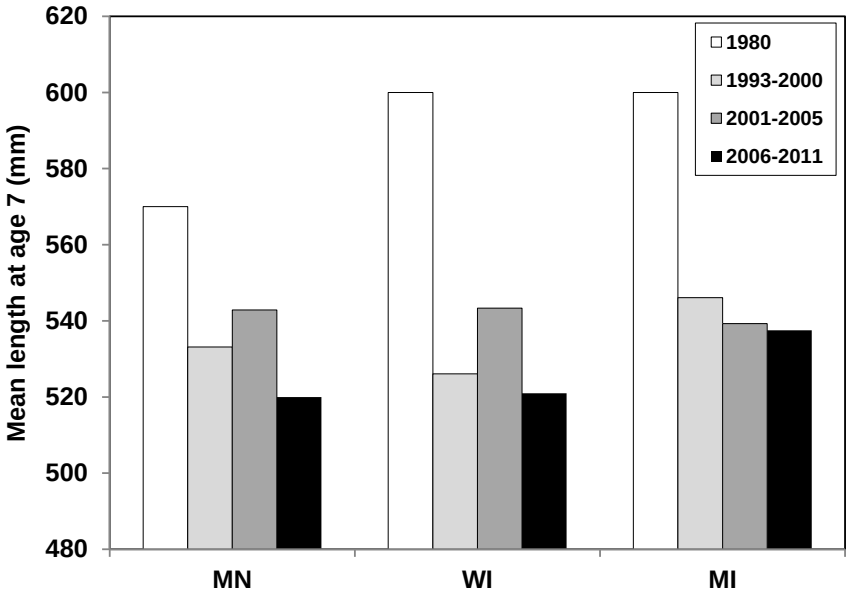
Sea lamprey predation continues to be a major source of lake trout mortality, matching or exceeding in many management units mortality from angling and commercial fishing combined. Annual trends in sea lamprey marking rates have been variable across Lake Superior and have exceeded the maximum limit of 5.0 Type A, Stages I-III, marks per 100 fish (mark classification as per Ebener et al. 2006) in all management units, except MI-2 (Fig. 16). Compared to 2001-2005, major increases in marking rates were observed only in MN-3 and MI-3. The populations with the highest sea lamprey marking rates were in western Ontario waters (MN-3 and MI-3, 6, and 7).

Fig. 16. Annual sea lamprey marking rates for lean lake trout >533 mm total length in Lake Superior management units during 2006-2011 (vertical bars in chronological order) and average marking during 2001-2005 (horizontal black bars). Marking rates were the total number of Type A, Stages I-III, marks per 100 lake trout. The dashed horizontal line is the maximum marking-rate limit established for Lake Superior lean lake trout (5 per 100 fish). Canadian management units 1-22 were pooled as ON-W and units 23-34 were pooled as ON-E. There were no data for 2008 and 2011 in ON-W; 2006-2009 and 2011 in MI-8; and 2006-2007 and 2009-2011 in ON-E.



Growth of lean lake trout continues to decline in U.S. waters (Fig. 17). Mean length of age-7 lake trout during 2006-2011 has reached the lowest levels since 1980. The average length at age 7 in Minnesota, Wisconsin, and Michigan waters was greater than 560 mm in 1980 but averaged less than 540 mm during 2006-2011. Increased abundance of lake trout coupled with decreased abundance of prey fishes are believed to be the major causes of the growth decline.

Fig. 17. Lean lake trout mean length (mm) at age 7 in U.S. waters of Lake Superior in 1980, 1993-2000, 2001-2005, and 2006-2011. Data are from standardized spring (April-June) bottom-set gillnet surveys.



Conclusions and Recommendations

Based on several indicators, the lake trout FCO (Table 1) is believed to have been met at a lakewide level, notwithstanding a need for further progress in western U.S. waters. In eastern U.S. waters, lake trout abundance levels peaked during the 1990s and have since undergone post-recovery density-dependent declines as have growth and recruitment. In western and central Canadian waters, population status is assumed to be similar to the trends observed in eastern U.S. waters. In WI-2 and MI-2, 3, and 8, lean lake trout populations are a concern due to high mortality rates or low abundance levels. SCAA models have been developed to assess populations and develop harvest quotas for most U.S. management units (e.g., Linton et al. 2007; Wisconsin State-Tribal Biological Committee 2007; Technical Fisheries Committee 2012). These models provide feedback needed to guide fishery management and sea lamprey control. In the future, agencies should model the relationship between habitat and fish production to evaluate the

productivity and sustainability of lake trout under current and projected climates. Modification of the long-term spring lake trout assessment to allow for incorporation of multiple-mesh gear with improved selectivity while retaining compatibility with existing data would add an important capability for assessing lean lake trout.

Lake Whitefish

Abundance

Landings of lake whitefish during 2006-2011 remained high, consistent with an upward trend that began in the early 1960s and leveled off in the mid-1980s (Fig. 18). Currently, the only lakewide index of abundance of adult lake whitefish is catch-per-unit effort (CPUE) from the bottom-set gillnet fishery. The SCAA models, which estimate abundance and biomass, have been developed only for Michigan waters within the 1836 Treaty-ceded area (MI-5, 6, 7, and 8; Fig. 1). The CPUE in the commercial fishery averaged 164 $kg \cdot km^{-1}$ during 2006-2011, which is 31% higher than during the 2001-2005 reporting period (average 125 $kg \cdot km^{-1}$) and higher still than the 1990-1999 FCO target range of 65-137 $kg \cdot km^{-1}$ (Fig. 19). The SCAA models, in contrast, indicate that abundance in the ceded area has remained unchanged or declined slightly. Insomuch as the abundance estimates are for different areas, the discrepancy between them may be due to simply geography.

Fig. 18. Commercial-fishery harvest (metric tons) of lake whitefish from Lake Superior during 1867-2011.

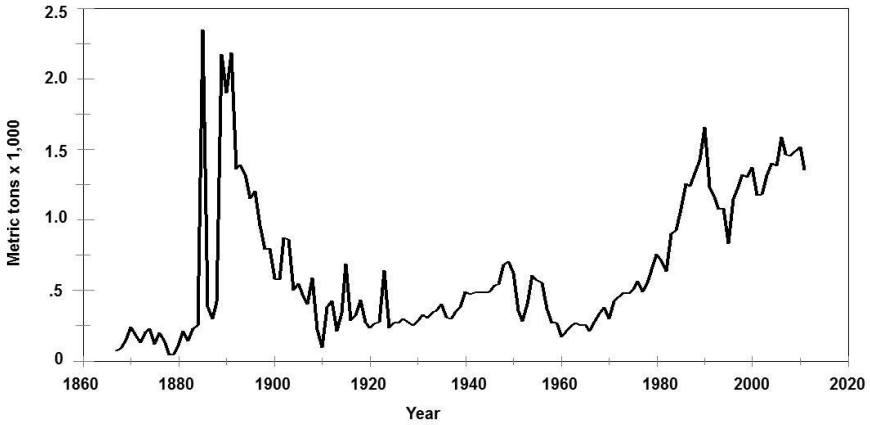
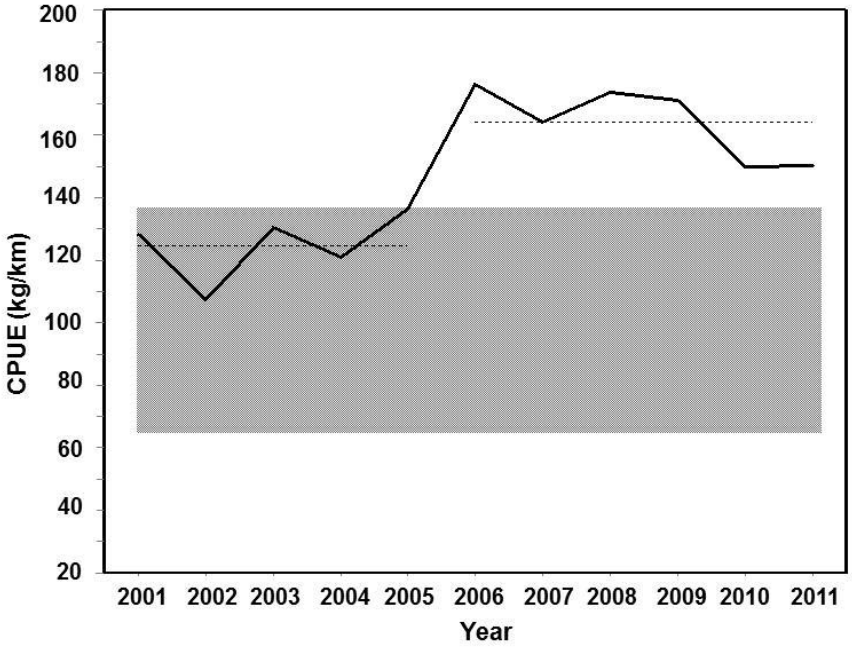


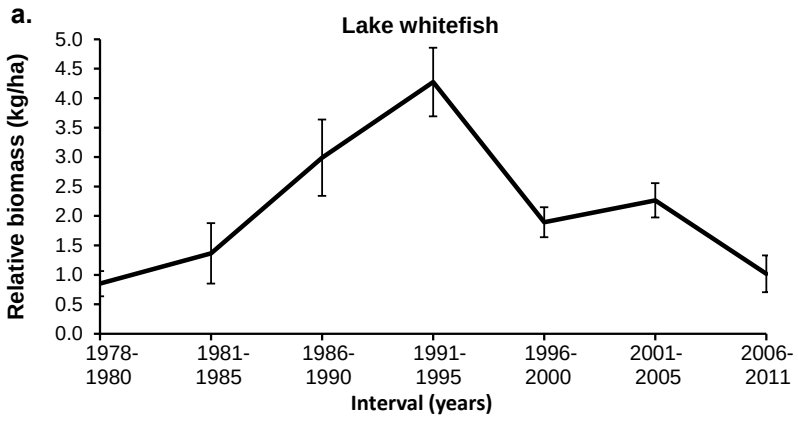
Fig. 19. Lake whitefish relative abundance based on gillnet CPUE (CPUE = $kg \cdot km^{-1}$ of gillnet) in the Lake Superior commercial fishery, 2001-2011. Dashed lines show the average CPUE during 2001-2005 and 2006-2011, and the shaded area shows the range of CPUEs during 1990-1999, which is the fish community objective target.



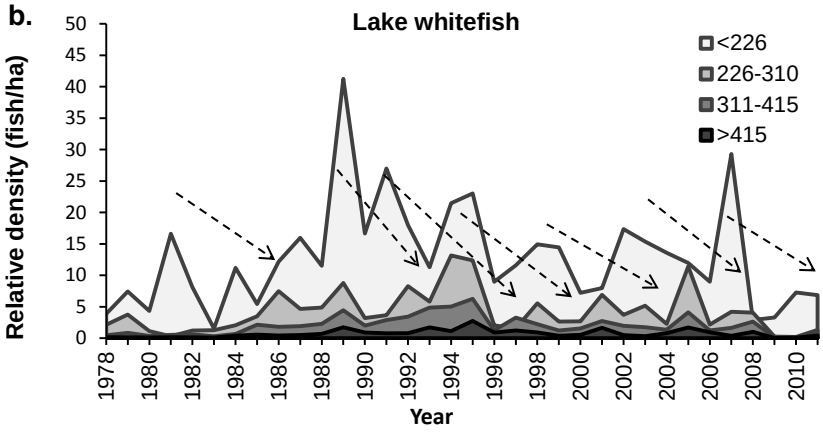
Estimates of lake whitefish fishable abundance (numbers of fish) and biomass in 1836 Treaty-ceded waters declined 8.2 and 1.5%, respectively, from 2001-2005 (Ebener et al. 2005) to 2006-2011. Fishable abundance and biomass during 2006-2011 averaged 1.64 million fish and 1.21 million kg. These estimates remain unchanged from those for 1990-2004, but they are substantially lower than those for 1986-1990 when abundance and biomass averaged 2.61 million fish and 1.83 million kg, respectively. These trends

are reasonably consistent with relative biomass estimates from U.S. Geological Survey (USGS) bottom-trawl surveys of 1978-2011 (Fig. 20a).

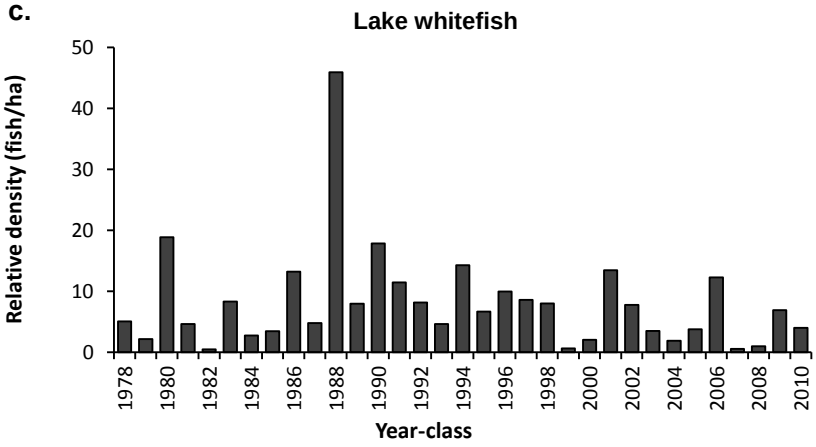
Fig. 20. Relative biomass (a), relative density of size-classes (mm) (b), and year-class strength (density of age-1 fish) (c) for lake whitefish and rainbow smelt based on annual spring lakewide U.S. Geological Survey bottom-trawl surveys of nearshore waters of Lake Superior, 1978-2011. Error bars represent ±1 standard error. Size-classes (mm) (b) are ordered from smallest to largest and correspond to ages 1-2, 3-4, 5-7, and >7 for lake whitefish and ages 1, 2, 3, and >3 for rainbow smelt. Arrows indicate recruitment to larger (and older) size-classes.

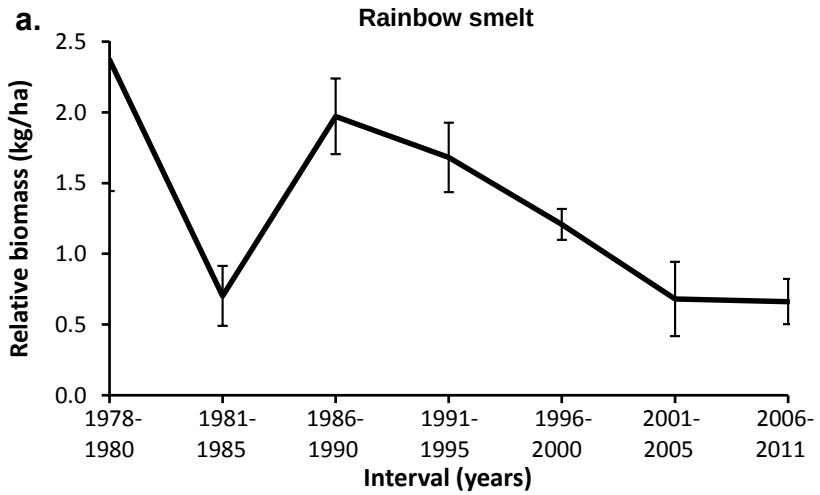


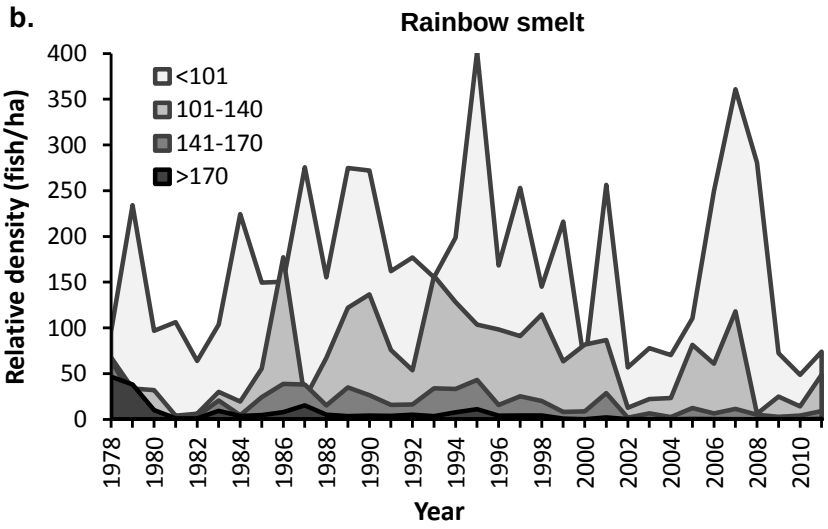
b.

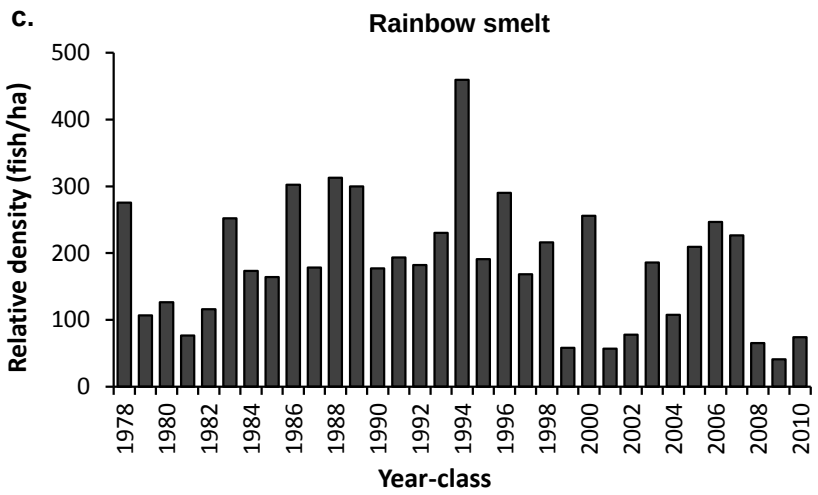

Lake whitefish
<226
226-310
311-415
>415
Relative density (fish/ha)
Year

c.


Lake whitefish
Relative density (fish/ha)
Year-class


a.
Rainbow smelt
Relative biomass (kg/ha)
2.5
2.0
1.5
1.0
0.5
0.0
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)


b.
Rainbow smelt
Relative density (fish/ha)
400
350
300
250
200
150
100
50
0
<101
101-140
141-170
>170
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year



Changes in abundance and biomass in the 1836 Treaty-ceded waters of Michigan have been driven largely by patterns in recruitment. Recruitment of age-4 fish declined 16% from 2001-2005 to 2006-2011. Recruitment averaged 439,000 age-4 fish during 2006-2011 with the 2007 year-class (317,000) being the least abundant. The highest levels of recruitment occurred in western waters of Whitefish Bay (MI-8), which accounted for 29-57% of total recruitment in ceded waters during 2006-2011.

USGS-GLSC bottom-trawl data indicated moderate-to-strong year-classes of lake whitefish in 1980, 1986, 1988, 1990, 1994, 1996, 1998, 2001, and 2006 (Fig. 20c). Variation in lake whitefish year-class strength was much lower than in some other coregonines (e.g., cisco and bloater). The ratio of the five weakest to the five strongest year-classes was 1:25, making the tracking of individual year-classes less clear (Fig. 20b). Nevertheless, the contributions of larger year-classes resulted in increased densities of larger size-classes and total biomass; this pattern was especially visible for the 1988, 1990, and 1994 year-classes. The fates of the first and last moderate-to-strong year-classes, 1980 and 2006, demonstrate the range of change in the lake whitefish population over the 35-year time series. The 1980 year-class gave rise to a rapid increase in density of larger size-classes and total biomass

through the late-1980s, whereas the 2006 year-class gave rise to the lowest densities of larger size-classes and the lowest biomass (Fig. 20b). The low recruitment of whitefish from the moderate 2006 year-class coupled with very weak year-classes in 2007 and 2008 resulted in the lowest total biomass in 2011.

Management

In Wisconsin waters, harvest by gillnets is limited by an effort limitation applied to each fisher. In addition, there are set seasons and limited entry to the fishery. In western Michigan 1842 Treaty-ceded waters, harvest is limited seasonally and by limited entry. In Ontario and in Michigan 1836 Treaty-ceded waters, lake whitefish management is based on limiting the total weight that can be harvested each year (harvest quotas). In Ontario, management unit-specific harvest quotas are developed and each fisher is given an individual transferable quota (ITQ) that represents some portion of the overall management-unit-specific quota (Ebener et al. 2008). Individual fishers can buy and sell their ITQ to other fishers within the unit. Provincial managers and representatives of the commercial-fishing industry discuss annually the status of lake whitefish populations in each management unit, and ITQs are adjusted accordingly, typically by no more than 10-15% (Mohr and Ebener 2005). In 1836 Treaty-ceded waters, management-unit-specific harvest limits are estimated each year using SCAA estimates of abundance, mortality, and growth (Ebener et al. 2005). In two management units where state-licensed and tribal commercial fisheries share the catch, SCAA-generated total allowable catches (TACs) are usually accepted as the harvest limit. In the three exclusive tribal commercial-fishing zones, SCAA models also are used to estimate harvest limits, but the tribes themselves establish harvest limits they deem appropriate based upon the model projections and characteristics of the fishery.

Harvest and Effort

Harvest of lake whitefish since the mid-1980s has been sustained at levels comparable to those seen in the late 1800s (Fig. 18) despite the current observations of low, lakewide biomass (Fig. 20a). Lakewide harvest ranged from 1.17 to 1.59 million $kg \cdot yr^{-1}$ during 2001 to 2011. Average annual harvest (nearshore zone only) during 2006-2011 (1.48 $kg \cdot ha^{-1}$, range 1.35-

1.59 kg·ha^{-1}) was 0.19 million kg·ha^{-1}more than during 2001-2005 (1.29 kg·ha^{-1}, range 1.17-1.40 kg·ha^{-1}). The lake whitefish fishery consists mainly of a trapnet and a bottom-set gillnet fishery. The angler fishery, although present in some areas of the lake, makes inconsequential harvests. The number of trapnet lift-days ranged from about 2,800 to 4,100 during 2001-2011 and averaged 3,162 during 2001-2005 and 3,552 during 2006-2011. Gillnet effort ranged from 5,214 km to 6,834 km during 2001-2011 and averaged 6,354 km during 2001-2005 and 5,872 km during 2006-2011. Bottom-set gillnets are commonly used in U.S. waters and exclusively used in Canadian waters.

Conclusions and Recommendations

The lake whitefish FCO (Table 1) is being achieved. Lake whitefish are resilient to exploitation, are self-sustaining, and comprise many spatially segregated stocks. Commercial fishing began in the 1830s and increased in intensity over the 19th century. Poorly managed fishing by "aggressive and enterprising commercial fisheries" produced the destabilizing effects of intense size-selective mortality (Lawrie and Rahrer 1972). After a 60-yr lull (1900-1960), harvest increased through the 1990s and thereafter leveled off (Fig. 18). Recent estimates of abundance from both commercial catch data and SCAA models indicate that current populations are within the range observed during 1990-1999, thus meeting the FCO. Where possible, agencies should improve stock assessment models to better estimate abundance, to partition mortality, and to develop fishery-independent surveys to provide a check on the current fishery-based estimates.

Rainbow Smelt

Rainbow smelt are the staple prey of lean lake trout in Lake Superior since at least the 1960s, but their contribution to the lake trout diet declined from roughly 80% in 1986 to 60% by 2001 (Dryer et al. 1965; Conner et al. 1993; Ray et al. 2007). Rainbow smelt produced moderately strong year-classes in 2005, 2006, and 2007, and variation in year-class strength (ratio of the five weakest to the five strongest year-classes was 1:5.6) has been much lower than for cisco and bloater (Fig. 20c; Gorman 2007). However, rainbow smelt are shorter-lived than ciscoes and require frequent strong year-classes to

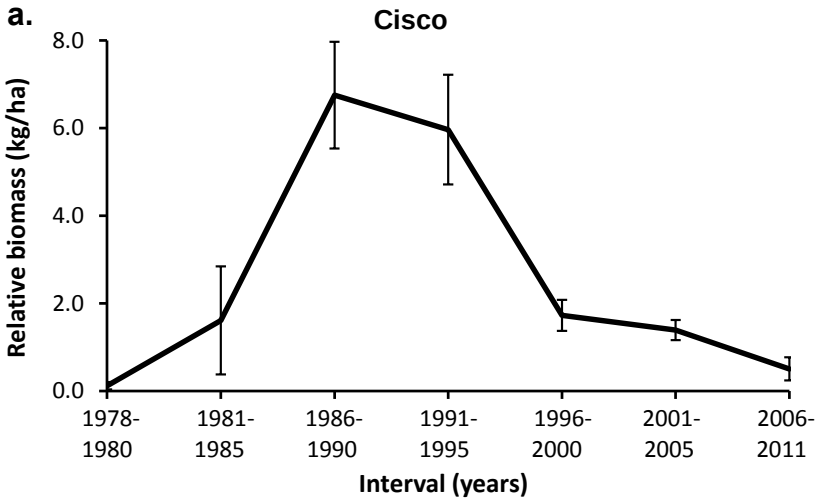
maintain abundance. During 1978-1979, rainbow smelt biomass was relatively high, and the population was dominated by large age-3+ individuals, but since then population structure has shifted to smaller age-1-2 fish (Fig. 20a, 20b; Gorman 2007). Of 35 rainbow smelt year-classes that have been measured, the eight weakest have occurred in the last 13 years (Fig. 20c). Despite the appearance of moderate year-classes in 2005-2007, little recruitment to larger size-classes was evident, resulting in low biomass since 2001 (Fig. 20; Gorman 2007). This pattern is consistent with increasing predation pressure (Gorman 2012) and suggests that rainbow smelt biomass will remain low into the foreseeable future.

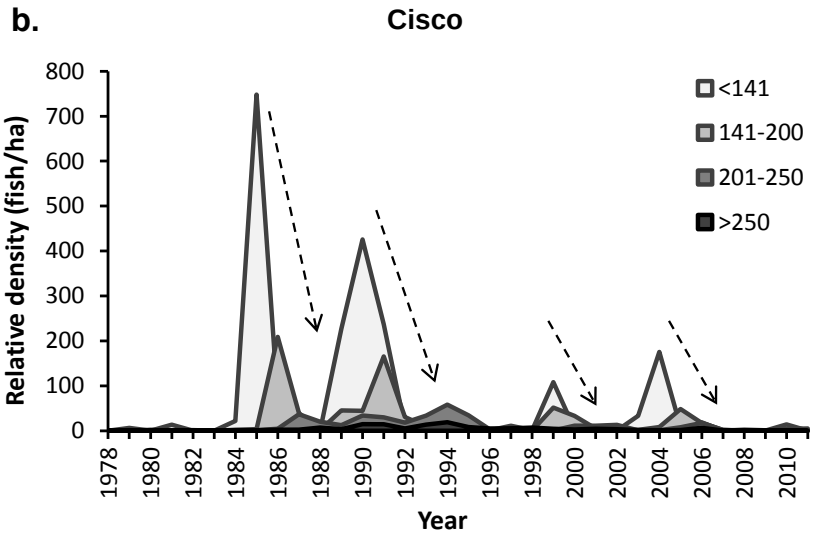
Cisco

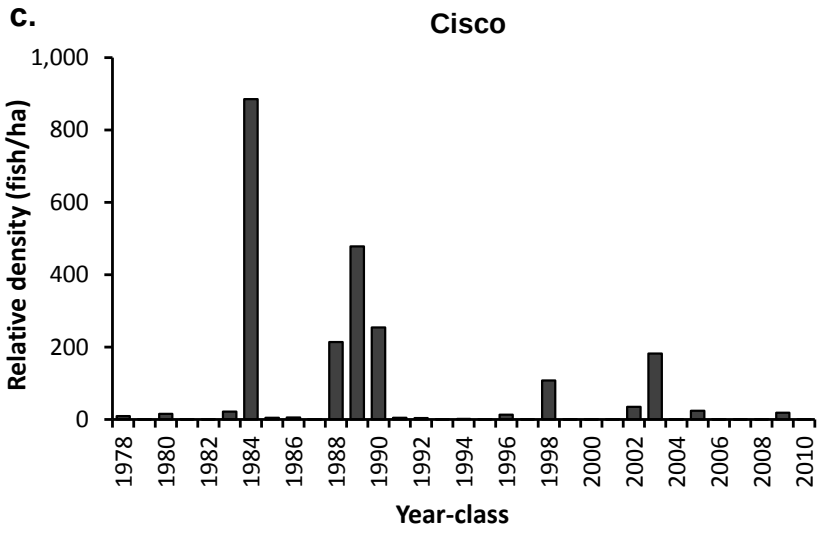
Abundance

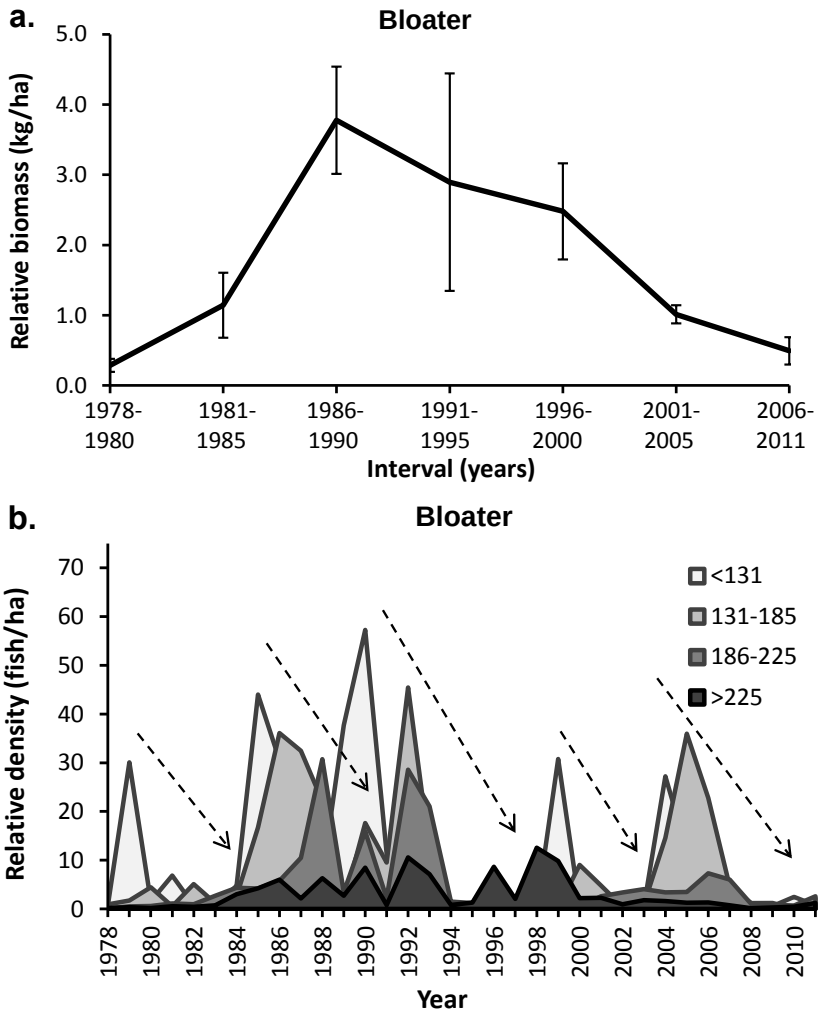
Year-class strength was highly variable during 1977-2011—the ratio of the five weakest to the five strongest was 1:6,000. Strong year-classes of cisco were produced in 1984, 1988, 1989, 1990, 1998, and 2003, which subsequently resulted in increased biomass and density of larger size-classes (Fig. 21). These increases in biomass appeared to dwindle after 4 years, but this was in part an apparition, the result of cisco becoming more pelagic with increasing age and size and thus no longer vulnerable to bottom trawls (Stockwell et al. 2006; Yule et al. 2008a; Gorman et al. 2012a). The tracking of year-classes over time (Fig. 21b) suggests that cisco require 3-4 years to reach adult size (>250 mm TL), which is in agreement with published studies of cisco growth and age (Stockwell et al. 2009). Cisco year-classes have been weaker since 1990, resulting in lower densities of juveniles and adults in trawl catches and in smaller adult spawning populations (Gorman et al. 2012b, 2012c; Yule et al. 2012, 2013).

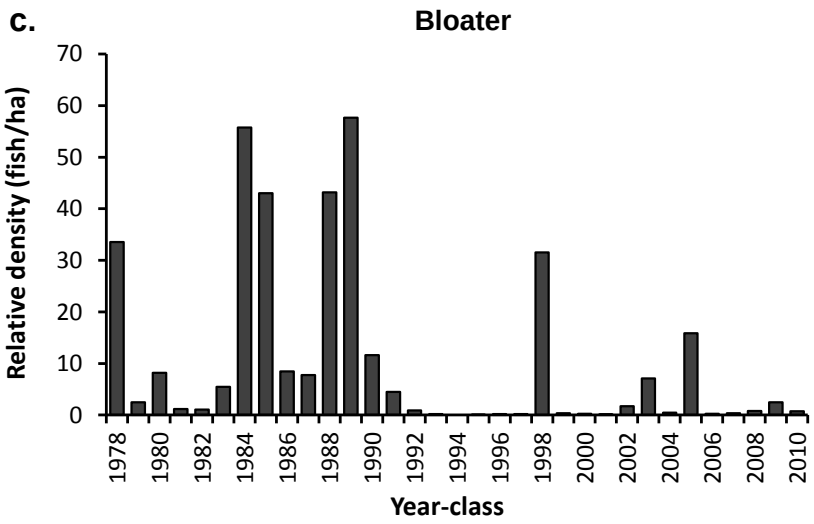
Fig. 21. Relative biomass (a), relative density of size-classes (mm) (b), and year-class strength (relative density of age-1 fish) (c) for cisco and bloater captured in annual spring lakewide U.S. Geological Survey bottom-trawl surveys of nearshore waters of Lake Superior, 1978-2011. Error bars represent ±1 standard error. Size-classes (mm) (b) are ordered from smallest to largest and correspond to ages 1, 2-3, 4-5, >5, respectively. Arrows indicate recruitment to larger (and older) size-classes.




b.
Cisco
Relative density (fish/ha)
800
700
600
500
400
300
200
100
0
<141
141-200
201-250
>250
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year


c.
Cisco
Relative density (fish/ha)
1,000
800
600
400
200
0
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year-class


a.
Bloater
Relative biomass (kg/ha)
5.0
4.0
3.0
2.0
1.0
0.0
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)
b.
Bloater
Relative density (fish/ha)
70
60
50
40
30
20
10
0
<131
131-185
186-225
>225
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Year

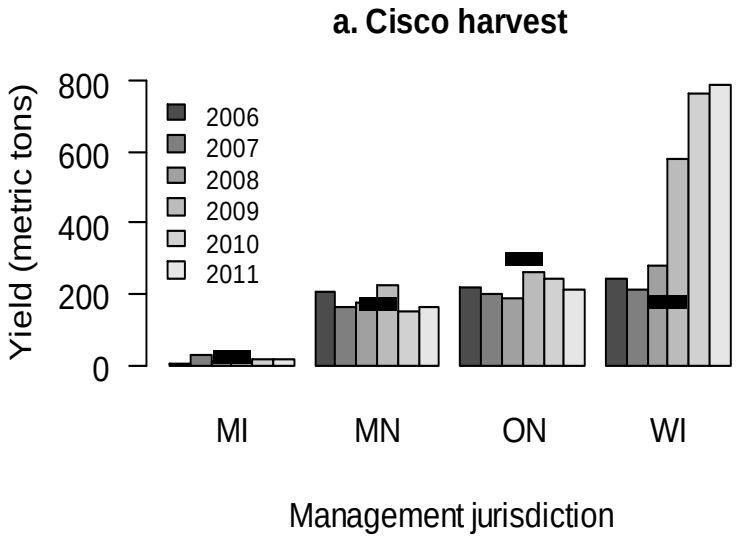


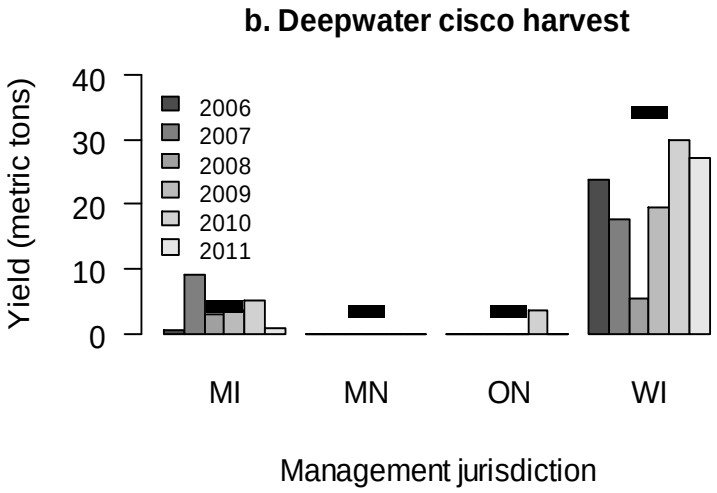
Management and Harvest

Following a series of successful recruitment events in the late 1970s and early 1980s, cisco began to recover from the population collapse of the mid-1960s. Commercial harvest of cisco was modest from 1990 to 2005 with an average annual lakewide yield of 687 metric tons (Baldwin et al. 2009). However, declines in Baltic Sea vendace (*Coregonus albula*) led to increased demand for cisco roe, which serves as a substitute for the Scandinavian delicacy "löjrom." The lucrative roe market has motivated commercial operators, especially those in Wisconsin, to invest more resources at targeting spawning aggregations of cisco. The commercial fishing fleet operating in Wisconsin waters of Lake Superior is large compared to other jurisdictions. A total of 23 large-boat (defined as a vessel with a powered net lifter) and 25 small-boat commercial licenses were issued in 2011 between the Wisconsin DNR, the Red Cliff Band of Lake Superior Chippewa, and the Bad River Band of Lake Superior Chippewa. High commercial fishing capacity in Wisconsin waters combined with a limited degree of regulation resulted in a swift increase in fishing effort and harvest in response to market demand. In 2011, some 1,165 km of gillnet

were set for cisco, resulting in a targeted catch of 764 metric tons, which, when compared to 2006, represented a 5-fold increase in effort and over a 2-fold increase in catch (Fig. 22a). Yule et al. (2013) recently estimated lakewide biomass of cisco at 44,000 metric tons, suggesting that, on a lakewide scale, exploitation is low (<3%). However, exploitation actually occurs at smaller spatial scales. The exploitation rate of adult cisco was estimated to be 3% at Bayfield, Wisconsin, in 2004 (Yule et al. 2006) and 8.5% in Thunder Bay, Ontario, in 2005 (Yule et al. 2008b). Although overall harvest is low, exploitation at specific spawning locations can be much higher, as it surely is in Wisconsin waters, and may be harmful to specific stocks.

Fig. 22. Annual commercial yield (round weight metric tons) of cisco (a) and deepwater ciscoes (b) from jurisdictional waters of Lake Superior during 2006-2011. Horizontal black bars represent the average annual yield during 1990-2005. Cisco yield in round weight was derived from reported dressed weight using a factor of 1.2 in Michigan and Minnesota and 1.4 in Wisconsin. Ontario cisco yields were reported as round weight. Yield of deepwater ciscoes in round weight was derived from dressed weight using a factor of 1.2 in Wisconsin. The remaining jurisdictions reported deepwater cisco yield as round weight.


a. Cisco harvest
Yield (metric tons)
800
600
400
200
0
2006
2007
2008
2009
2010
2011
MI
MN
ON
WI
Management jurisdiction


b. Deepwater cisco harvest
Yield (metric tons)
40
30
20
10
0
2006
2007
2008
2009
2010
2011
MI
MN
ON
WI
Management jurisdiction

Food-Web Dynamics

Cisco are an important prey fish (Stockwell et al. 2009), but what fraction of the population can be consumed by top predators is unresolved. Stockwell et al. (2010), applying a model that predicted the maximum prey sizes that could be ingested by salmonines, suggested that cisco ≥300 mm TL are too large for most siscowet lake trout to consume, but Negus et al. (2008) had argued earlier against this premise. Negus et al. (2008) also evaluated sources of cisco mortality in the western arm of Lake Superior and found that commercial yield in 2004 was trivial compared to consumption by piscivores. Predation pressure on coregonines appears to be especially high in nearshore regions, such as that studied by Negus et al. (2008) where 50% or more of the available coregonine biomass may be consumed annually. Declining cisco abundance could negatively affect lake whitefish that feed on cisco eggs in winter (Stockwell et al. 2009). Conversely, the invasive and carnivorous cladoceran, *Bythotrephes*, could benefit from declining cisco abundance (Keeler et al., in press).

Conclusions and Recommendations

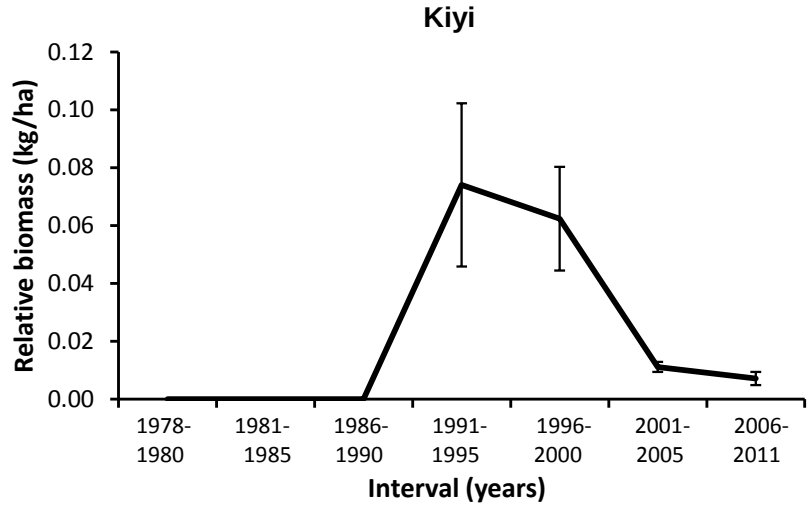
Despite there being no specific FCO for cisco, the species is important to the commercial fishery and the ecosystem. Cisco does fit within the Prey-Fishes FCO (Table 1), where it meets the objective of a self-sustaining population that currently meets ecosystem needs and supports commercial fishing. Given its importance (ecologically and commercially), any future revisions to Lake Superior's FCOs should include a specific objective for cisco. Evidence of increased rates of both natural and fishing mortality combined with poor recruitment in recent years accentuates the need for regular monitoring of cisco populations and a more restrictive commercial harvest. Recent increases in exploitation mean that agencies should work collaboratively to evaluate the long-term sustainability of current harvest rates employing fishery-independent surveys.

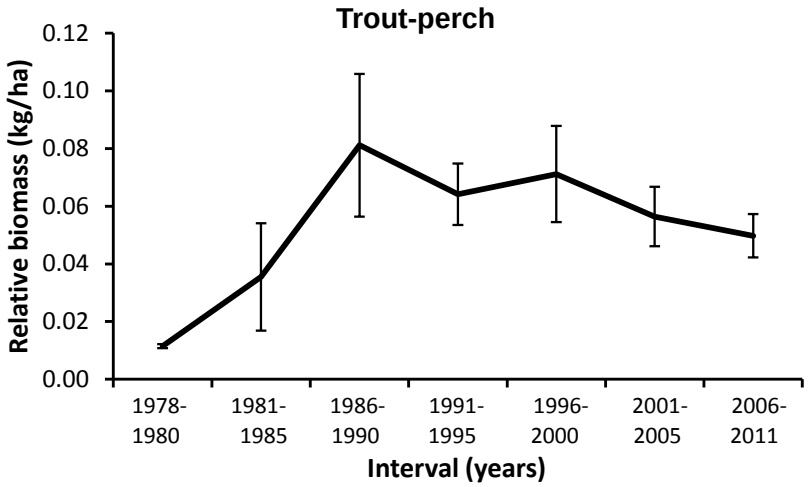
Deepwater Ciscoes

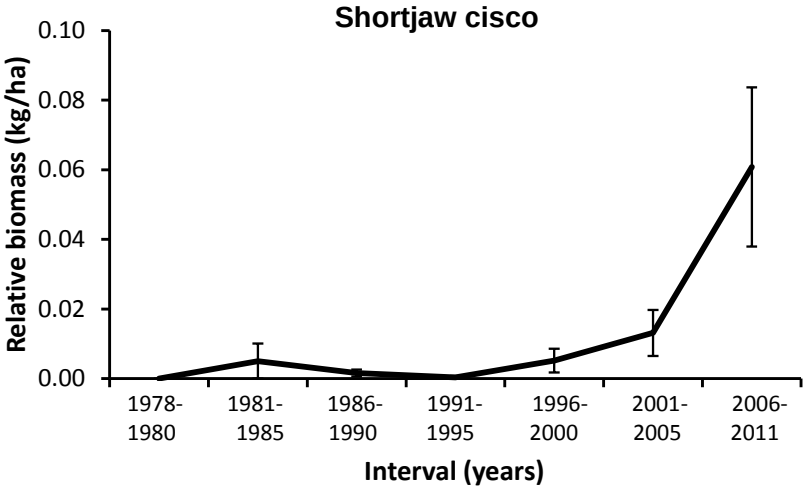
Abundance

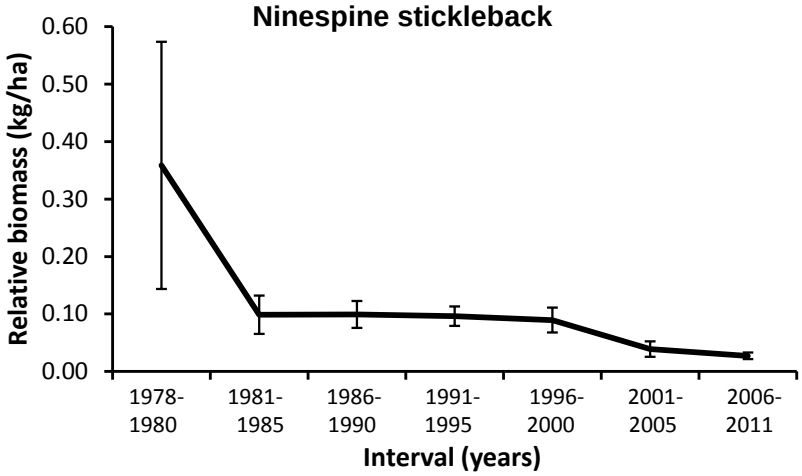
Prior to 1980, the deepwater ciscoes (i.e., bloater, kiyi, and shortjaw cisco; marketed as chubs) were a major target of the commercial fishery. Bloater is the most common nearshore deepwater cisco, whereas kiyi is found primarily offshore, and shortjaw cisco is now relatively rare, making up <10% of the deepwater cisco complex (Gorman and Todd 2007; Gorman 2012; Pratt and Chong 2012). Strong year-classes of bloater appeared in 1978, 1984, 1985, 1988, 1989, 1998, and 2005 and, as was the case for cisco, resulted in sequential increases in biomass and density of larger-sized fish (Fig. 21). Variation in bloater year-class strength was less variable than in cisco–the ratio of the five weakest to the five strongest bloater year-classes during 1977-2011 was just over 500-fold. Increases in biomass following strong year-classes were detected beyond 4 years (Fig. 21b), a result of bloater remaining at least partially vulnerable to bottom trawls with increasing size and age (Gorman et al. 2012a). Bloater biomass and abundance of larger bloaters (>185 mm TL) declined markedly after 2000 and remains low as recruitment was dependent on only two strong year-classes (1998 and 2005), which were spaced seven years apart (Figs. 21a, b). Kiyi biomass in nearshore bottom trawls declined after 1991-1995 and stayed low in 2006-2011, whereas shortjaw cisco biomass increased sharply in the current reporting period (Fig. 23). The substantial increase was largely the result of recruitment from strong 2003 and 2005 year-classes.

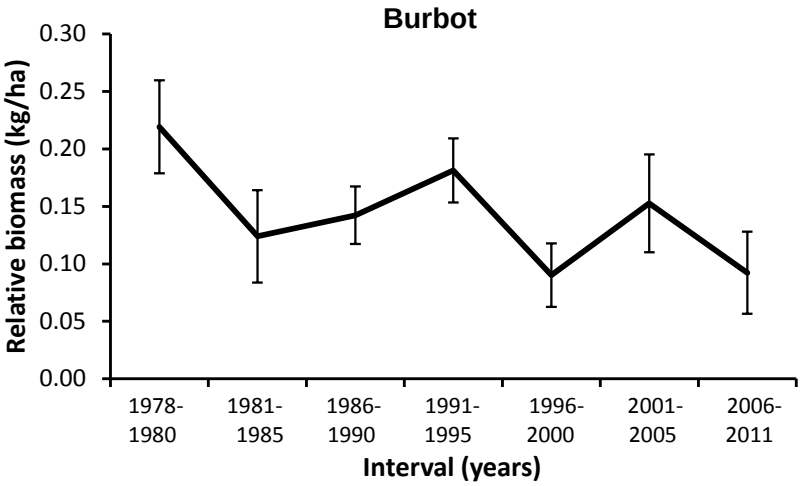
Fig. 23. Relative biomass of “other” prey species (kiyi, trout-perch, shortjaw cisco, ninespine stickleback, burbot, longnose sucker, pygmy whitefish, and all sculpins combined) based on spring annual lakewide U.S. Geological Survey bottom-trawl surveys of nearshore waters of Lake Superior, 1978-2011. Error bars represent ±1 standard error.

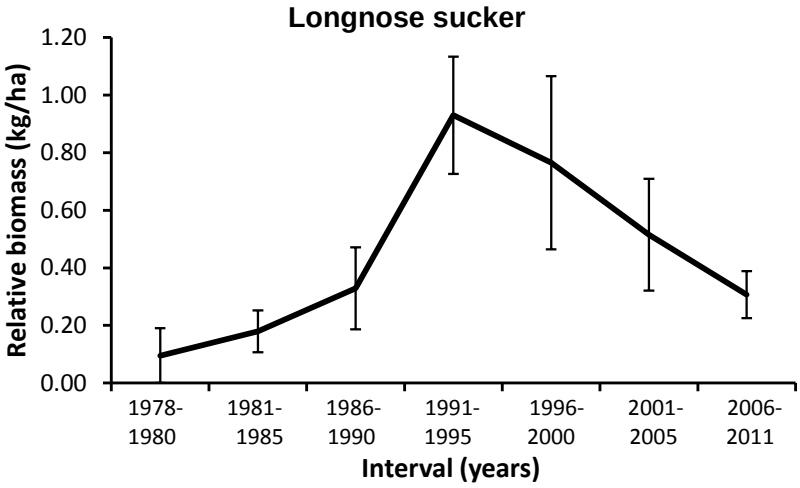

Kiyi
Relative biomass (kg/ha)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)

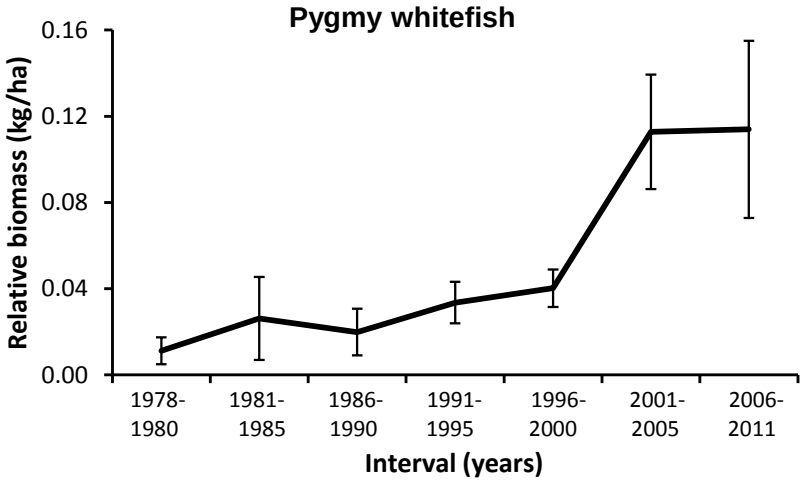

Trout-perch
Relative biomass (kg/ha)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)

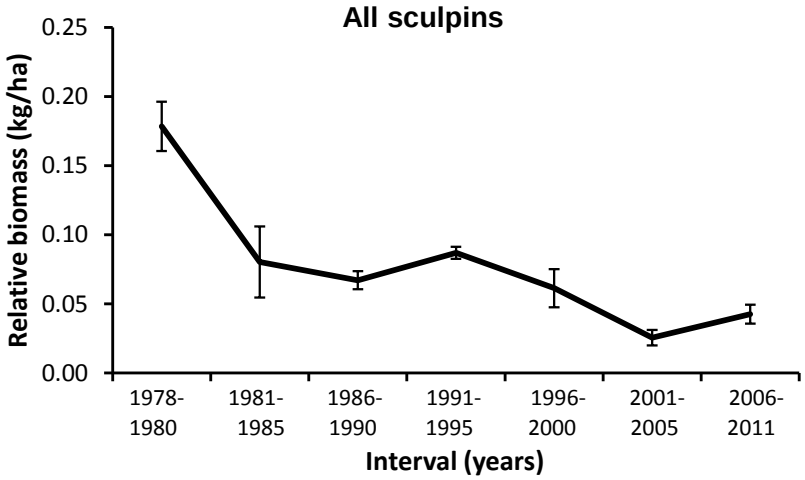

Shortjaw cisco
Relative biomass (kg/ha)
0.10
0.08
0.06
0.04
0.02
0.00
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)


Ninespine stickleback
Relative biomass (kg/ha)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)


Burbot
Relative biomass (kg/ha)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)


Longnose sucker
Relative biomass (kg/ha)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)


Pygmy whitefish
Relative biomass (kg/ha)
0.16
0.12
0.08
0.04
0.00
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)


All sculpins
Relative biomass (kg/ha)
0.25
0.20
0.15
0.10
0.05
0.00
1978-1980
1981-1985
1986-1990
1991-1995
1996-2000
2001-2005
2006-2011
Interval (years)

Harvest

Current commercial yield of deepwater ciscoes is only a fraction of historical levels (>692 metric tons during 1960s-early 1970s) with average annual yields of 46 metric tons during 1990-2005 (Baldwin et al. 2009) and 25 metric tons during 2006-2011. Although harvest is currently low, it remains important for several operators, especially in Wisconsin (Fig. 22b). In 2011, 81% of the lakewide yield of deepwater ciscoes was taken by two commercial licenses in Wisconsin waters. Despite limited participation, CPUE in the Wisconsin commercial fishery has declined from 175 $kg \cdot km^{-1}$ in 1993 to only 50 $kg \cdot km^{-1}$ in 2011.

Food-Web Dynamics

Deepwater ciscoes play a pivotal role in both the nearshore and offshore food webs of Lake Superior by linking invertebrate production to piscivore production (Gamble et al. 2011a; 2011b). The diversity of ecological niches filled by this species complex facilitates the movement of benthic energy into pelagic pathways (Gorman et al. 2012a; 2012b). Negus et al. (2008) found that more than 50% of the coregonine biomass in nearshore areas could be consumed annually by piscivores. This observation of elevated predation is consistent with the decline in commercial CPUE for deepwater ciscoes and is likely the result of the recovery of lean and siscowet lake trout in combination with the decline of rainbow smelt (Gorman 2007, 2012). Negus et al. (2008) cautioned that Lake Superior could be at or near its carrying capacity for predators and that the forage base should be monitored closely.

Other Prey Fishes

Of those species classified here as other prey species, only shortjaw cisco and pygmy whitefish displayed relatively consistent increases in biomass over successive time intervals during the 1978-2011 bottom-trawl time series. Three species (kiyi, trout-perch, and longnose sucker) displayed increasing biomass in middle intervals and a decline in later intervals. The remaining species (ninespine stickleback, burbot, and all sculpins) displayed declining trends in biomass (Fig. 23). The decline in sculpin biomass was

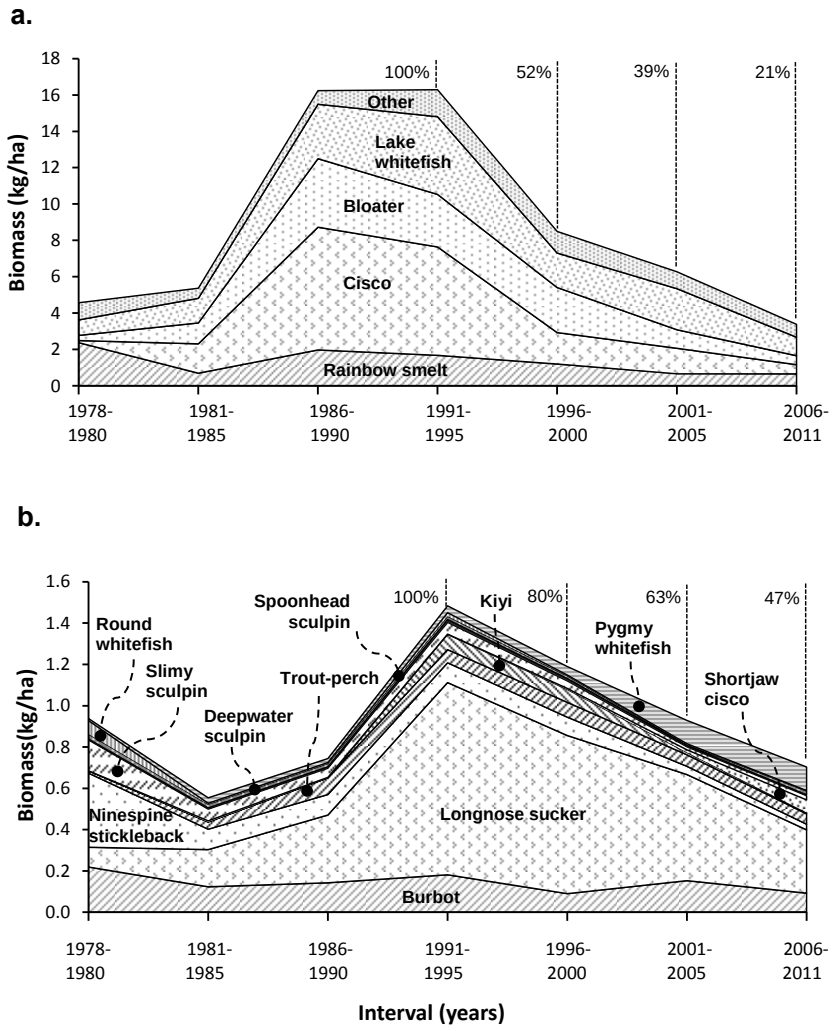
due mainly to a decline of slimy sculpin, which was dominant, and, to a lesser extent, a decline of spoonhead sculpin in later years.

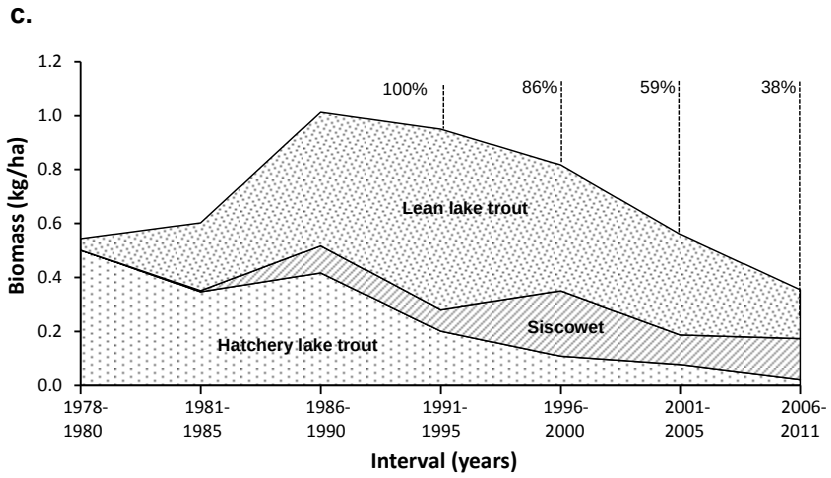
Sculpins (all species) represented about 10% of the biomass consumed by lake trout in recent years (Ray et al. 2007), which may account for the decline in sculpin biomass. Burbot account for 12.3% of lean lake trout diet by weight in central Michigan waters (SPS, unpublished data). Predation by lean and siscowet lake trout resulted in a decline in burbot populations in Lake Superior after the 1980s largely by preferential predation on smaller-size burbot (Gorman and Sitar 2013). Trout-perch, ninespine stickleback, and longnose sucker, all found in the diet of lake trout, also showed declines in biomass consistent with predation after the mid-1980s (Ray et al. 2007; SPS, unpublished data). In particular, ninespine stickleback declined in response to stocked lake trout in the late 1970s-early 1980s and then declined even more in response to wild lake trout, which began a strong recovery during 1981-1985 (Madenjian et al. 2010). In contrast to other prey species, biomass of pygmy whitefish increased after 2000. Pygmy whitefish appear to remain in the demersal stratum (Yule et al. 2007; Gorman et al. 2012a), which may reduce their encounter rates with lake trout as compared to other prey species that at night undergo diel vertical migration from the bottom up into the water column.

Nearshore Community Trends

The composition of the nearshore fish community changed radically during 1978-2011 (Fig. 24). In 1978-1980, hatchery lake trout dominated the predator population, representing 93% of lake trout biomass, and rainbow smelt dominated the prey-fish community, representing 52% of (total) prey-fish biomass. At the same time, biomass of cisco, bloater, and lake whitefish were at their lowest levels, comprising 28% of prey-fish biomass, while biomass of burbot, slimy sculpin, ninespine stickleback, and round whitefish was at its highest level representing 17% of prey-fish biomass in the aggregate.

Fig. 24. Composition and relative biomass for major prey-fish species (a), other prey-fish species (b), and lake trout (c) in the Lake Superior nearshore fish community as assessed by annual spring lakewide U.S. Geological Survey bottom-trawl surveys, 1978-2011. Percentages next to vertical dashed lines represent the amount of biomass in relation to that in 1991-1995.





After 1980, the fish community began a transition toward a state dominated by native species (Fig 24). In 1981-1985, wild lean lake trout biomass increased to 42% of total lake trout biomass; rainbow smelt decreased to 13% of prey-fish biomass; and the biomass of cisco, bloater, and lake whitefish combined increased to 77% of prey-fish biomass. Although biomass of rainbow smelt, round whitefish, slimy sculpin, and ninespine stickleback declined sharply, prey-fish biomass increased from 4.6 kg·ha^{-1} in 1978-1980 to 5.4 kg·ha^{-1} in 1981-1985 (Fig. 24).

Biomass of the native fish community increased and achieved its highest levels during 1986-1995 (Fig. 24). Strong year-classes of cisco and bloater appeared in 1984, 1988, 1989, and 1990 (Fig. 21c) and contributed greatly to the increase. The combined biomass of cisco, bloater, and lake whitefish represented more than 80% of prey-fish biomass (Fig. 24). Total prey-fish biomass peaked at 16.3 kg·ha^{-1} during 1991-1995, and, by then, wild lean and siscowet lake trout represented 79% of lake trout biomass.

Total prey-fish biomass declined after 1995 and was driven by declines in all component species, except pygmy whitefish and shortjaw cisco (Fig. 24). Despite the appearance of moderate-to-strong year-classes of cisco and bloater in 1998, 2003, and 2005 (Fig. 21c), by 2006-2011, the combined biomass of cisco, bloater, and lake whitefish, which represented 60% of prey-fish biomass, declined to its lowest level (3.4 $kg \cdot ha^{-1}$). Wild lean and siscowet lake trout biomass during 2006-2011 represented more than 94% of lake trout biomass and was 56% lower than the 1991-1995 peak in lake trout biomass.

Conclusions and Recommendations

As called for in the Prey-Fish FCO, the prey-fish community remains dominated by indigenous fishes capable of supporting desired populations of predators and a managed commercial fishery. Although this objective currently is being met in Lake Superior (Table 1), management agencies are concerned about the declines in abundance of major prey fishes that began after 1995 so nearshore community dynamics should be watched closely.

OFFSHORE FISHES

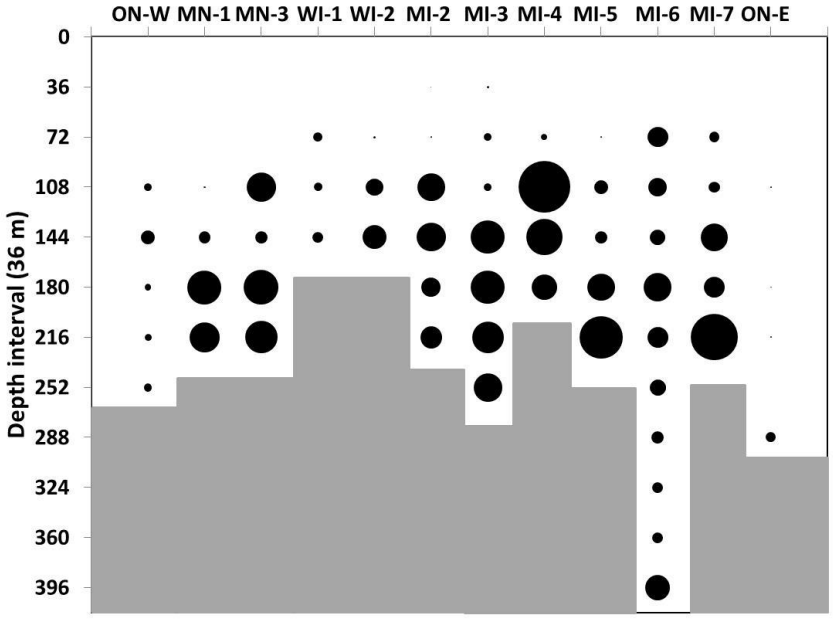
Siscowet Lake Trout

Since 2005, the study and description of lake trout morphotypes in Lake Superior and other large lakes has received increased emphasis (e.g., Zimmerman et al. 2006; Bronte and Moore 2007; Goetz et al. 2010). These studies utilized modern approaches in genetics, physiology, and morphometrics to characterize lake trout populations that resulted in an improved ability to better differentiate forms and provided insightful information on life-history attributes for the lean, siscowet, and humper forms. Due to an emerging interest in harvesting siscowet for extraction of omega-3 oils, a better understanding of siscowet life history and ability to sustain a fishery is needed (Bronte and Sitar 2008).

Abundance and Age Structure

Relative abundance of siscowet, based on catch-per-unit effort (CPUE) in coordinated gillnet surveys during 2006-2011 was highest at depths of 110-219 m (Fig. 25). Few siscowets were caught in the shallowest sampling stratum (0-37 m) where lean lake trout were most prevalent. At depths >37 m, siscowet CPUE (geometric mean) was much higher than that of lean lake trout CPUE. Mean siscowet CPUE across all depths was highest in Unit MI-4 (45.1 fish·km^{-1}·night^{-1}) and lowest in western Ontario (1.2 fish·km^{-1}·night^{-1}). In contrast, lean lake trout CPUE across all depths ranged from <0.01 fish·km^{-1}·night^{-1} in MI-3 to 12.9 fish·km^{-1}·night^{-1} in MN-1. The average ratio of siscowet to lean lake trout across all depths and management units during 2006-2011was 15:1. Since the start of the coordinated surveys in 1996, siscowet CPUE has generally declined in most units (Fig. 26). At the same time, older siscowets have represented more of the age distribution. The proportion of age-20+ siscowets was less than 5% in 1996 but increased to 18.3% in 2006.

Fig. 25. Relative abundance of siscowet (top panel) and lean lake trout (bottom panel) by 36-m depth intervals in Lake Superior management areas during 2006-2011. Black circles represent the geometric mean catch-per-unit effort (GMCPUE = fish·km^{-1}·night^{-1}) and size of circle is scaled proportional to GMCPUE. Canadian management units 1-22 are pooled as ON-W, and units 23-34 are pooled as ON-E. The top of shaded columns indicates maximum depth for that management unit.



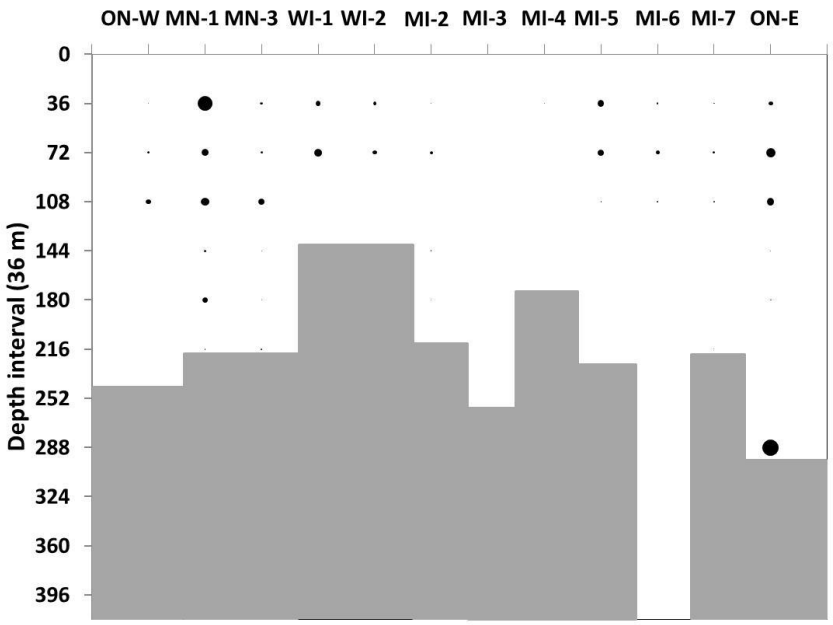
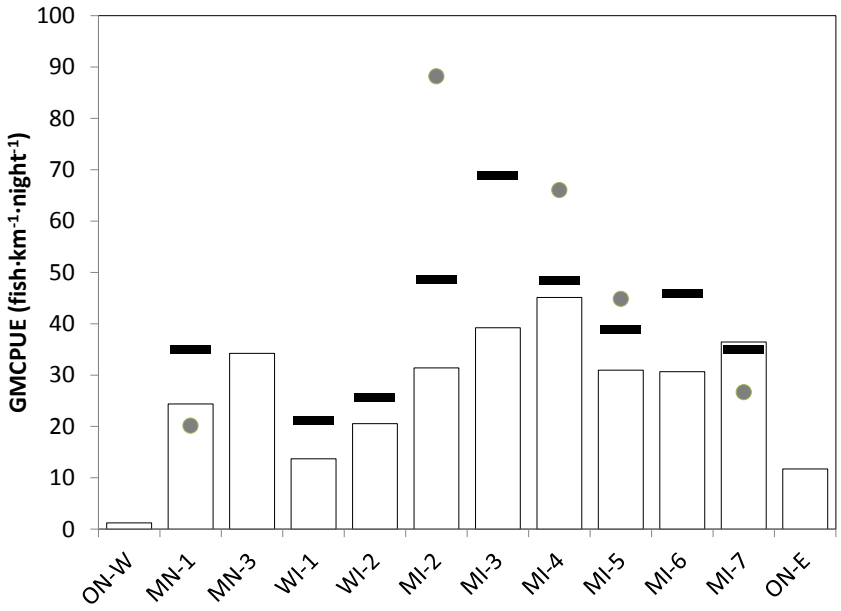


Fig. 26. Relative abundance of siscowet lake trout based on geometric mean catch-per-unit effort (GMCPUE = fish·km^{-1}·night^{-1}) in management units of Lake Superior during 2006-2011 (vertical bars), during 2001-2005 (horizontal black bars), and in 1996 (gray circles). Canadian management units 1-22 are pooled as ON-W, and units 23-34 are pooled as ON-E.



Fishery Yield

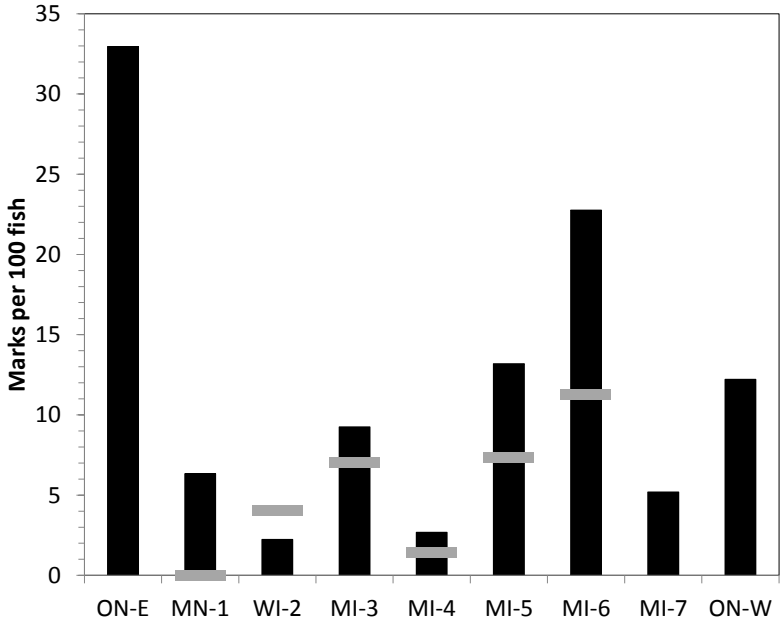
Presently there are no targeted siscowet fisheries in Lake Superior. However, siscowets are often harvested incidentally in both commercial and recreational fisheries. Since the 1980s, siscowets have been distinguished from lean lake trout in the U.S. commercial harvest but not in the Ontario commercial harvest. Average siscowet commercial harvest in U.S. waters has increased 58%—from 34,900 kg·yr^{-1} during 2001-2005 to 55,100 kg·yr^{-1} during 2006-2011. Recreational yield in U.S. waters averaged 8,000 kg·yr^{-1} during 2006-2011, which is an increase of 20% from 2001-2005.

Sea Lamprey Predation

Sea lamprey marks were prevalent on siscowets at all depths sampled in coordinated surveys conducted between 2006 and 2011. Average marking rates on siscowets (11.9 Type A, Stages I-III, marks per 100 fish) were

higher during 2006-2011 than during 2001-2005 (5.2 marks per 100 fish) (Fig. 27) and were similar to or higher than marking rates on lean lake trout (Fig. 16). Despite the high marking rates observed on siscowets, the lethality of sea lamprey attacks on siscowets is lower than for leans (Moody et al. 2011). Given that abundance and marking rates on siscowets are higher than on lean lake trout, siscowets likely buffer sea lamprey predation on lean lake trout and other fishes (Moody et al. 2011).

Fig. 27. Sea lamprey marking rates for siscowet lake trout >533 mm total length in Lake Superior management units during 2006-2011 (vertical columns) and during 2001-2005 (horizontal bars). Marking rates were the total number of Type A, Stages I-III, marks per 100 lake trout. Canadian management units 1-22 are pooled as ON-W and units 23-34 are pooled as ON-E.



Growth and Reproduction

In addition to their function in growth and reproduction, lipids in siscowets play a role in buoyancy and aid in vertical migration (Henderson and Anderson 2002; Hrabik et al. 2006; Jensen et al. 2006). As abundance of siscowets increased since the mid-1900s, percent body fat has declined. Average percent body fat for 500-620-mm siscowet measured in 1953 and 1960 was 36% (Thurston 1962; Eschmeyer and Phillips 1965), whereas recent estimates of percent body fat were 8.5% in 1991 (Zabik et al. 1996) and 10% in 2009 (R.E. Kinnunen, Michigan Sea Grant, unpublished data).

Until recently, siscowet reproduction was presumed to be similar to that of lean lake trout. Goetz et al. (2011) measured reproductive timing in southern Lake Superior during 2006-2008 by measuring reproductive hormone levels and histological staging of gonadal tissue and found temporal overlap in spawning time of leans and siscowets. They also observed that a proportion of adult siscowets and leans skip spawning (not spawning every year), and, in a follow-up study in 2010-2011, determined that 12% of lean females and 60% of siscowet females skipped spawning. Further, skipped spawning in siscowets was prevalent across a wide range of sizes (ages) but was only exhibited in smaller (younger) leans (Sitar et al. 2014).

Conclusions and Recommendations

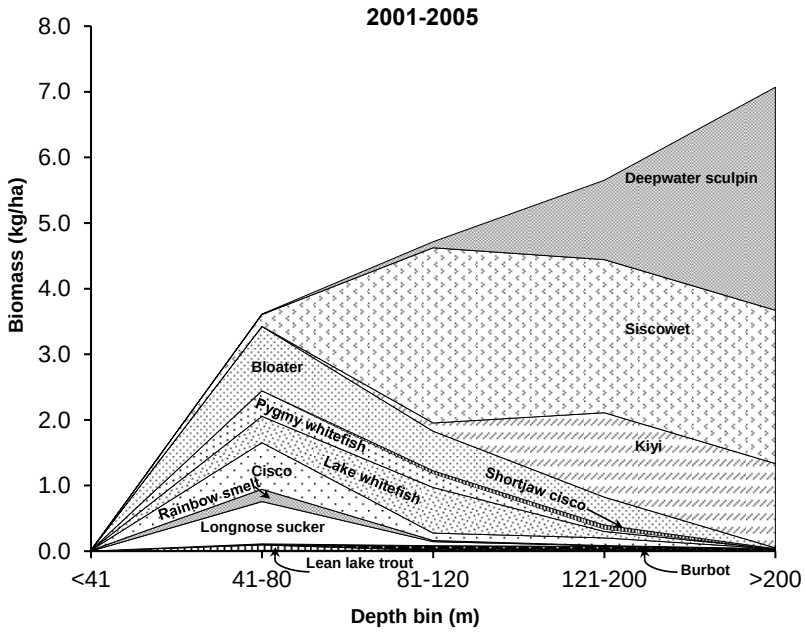
The previous state-of-the-lake report (Ebener et al. 2010) indicated that the FCO for siscowet (Table 1) had been achieved, and this finding is not changed here. Siscowets are still the most abundant lake trout form and are completely self-sustaining, but indications of density dependence are evident: older age structure, decreased percent body fat, and some populations with high incidence of skipped spawning. Although the standing stock of siscowets is high, their resiliency to modest commercial exploitation is unknown. Given their late age at maturity and the likelihood that a sizeable portion of the population does not spawn each year, production potential may be limited as compared with lean lake trout. Sustainability of siscowet populations should be evaluated closely as exploitation is increased.

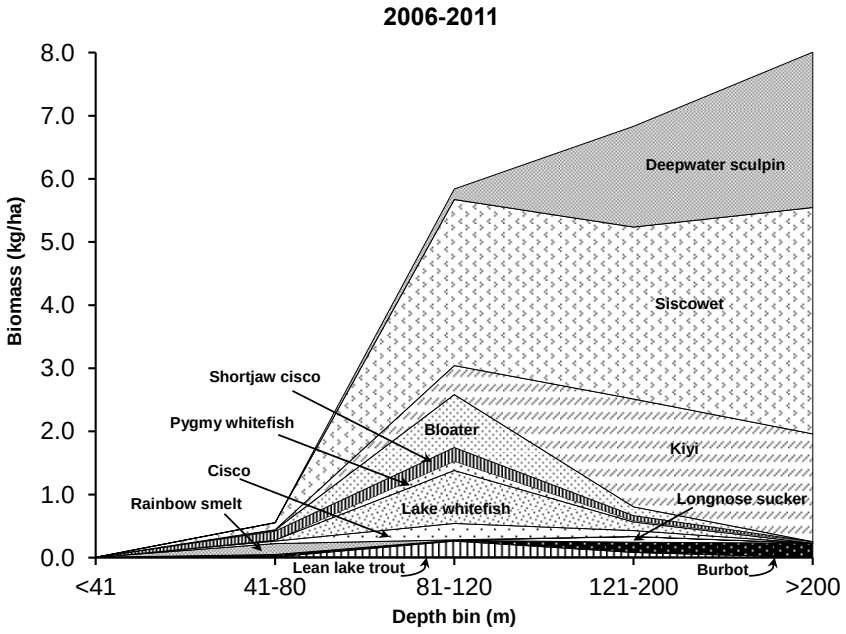
Offshore Prey Fishes

Trends in abundance of offshore prey fishes were determined mainly from offshore bottom-trawl surveys conducted at >80-m depths in June-August 2001-2011 (no survey in 2007). Biomass of kiyi in the deepest depth stratum (>200 m) was assigned biomass recorded from the 121-200-m depth stratum as kiyi tend to be suspended off the bottom at depths >200 m making this fraction of the population less vulnerable to bottom trawling (Gorman et al. 2012b). Cisco is common in the offshore zone but, being pelagic, is not well represented in bottom-trawl catches at depths >80; the biomass of cisco in deep waters (Fig. 28) is an underestimate (Stockwell et al. 2006, 2007; Yule et al. 2007; Gorman et al. 2012a).

During 2001-2005, bloater and lake whitefish dominated prey-fish biomass in the 81-120-m depth stratum (1.3 $kg \cdot ha^{-1}$), siscowet lake trout dominated piscivore biomass (2.7 $kg \cdot ha^{-1}$), and total community biomass was 4.7 $kg \cdot ha^{-1}$ (Fig. 28). In the 121-200-m and >200-m depth strata, the community was dominated by kiyi, deepwater sculpin, and siscowet lake trout, and total community biomass was near or at 7 $kg \cdot ha^{-1}$. In 2006-2011, total community biomass in the 81-120-m depth stratum was 5.0 $kg \cdot ha^{-1}$, slightly higher than in 2001-2005, due mainly to increased kiyi biomass (Fig. 28). The biomass of cisco, bloater, lake whitefish, and shortjaw cisco combined in 2006-2011 peaked at the 81-120-m depth stratum whereas, in 2001-2005, it peaked at 41-80 m suggesting a recent offshore shift in distribution. Similar shifts were evident for pygmy whitefish, longnose sucker, and lean lake trout. The offshore fish community exhibited remarkable stability during 2001-2005 and 2006-2011 due mainly to the relatively unchanging biomass of its principal deepwater fishes: kiyi, deepwater sculpin, and siscowet (Fig. 28).

Fig. 28. Composition and relative biomass of the Lake Superior fish community for two periods, 2001-2005 and 2006-2011. All species were assessed by U.S. Geological Survey offshore bottom trawls (see text for methodological references). Results are presented as average biomass by depth bins. Very few fish were enumerated at depths <41 m.





Hydroacoustic surveys conducted in 2005 and 2011 provide snapshots of the offshore fish community that suggest that lakewide biomass of prey fishes has declined substantially, down 45% from 99.4 kt in 2005 to 54.9 kt in 2011 (Gorman et al. 2012b; Yule et al. 2013). Individually, lakewide hydroacoustic biomass estimates of cisco declined 48%, down from 84.7 kt to 44.0 kt; kiyi declined 39%, down from 9.9 kt to 6.0 kt; bloater declined 62%, down from 2.9 kt to 1.1 kt; but rainbow smelt increased 79%, up from 1.9 kt to 3.4 kt (Gorman et al. 2012b; Yule et al. 2013). These results bolster the hypothesis that predation by fully recovered lean and siscowet lake trout populations coupled with a lack of recruitment of cisco, bloater and kiyi underlies the declines in biomass of prey fishes.

Conclusions and Recommendations

In contrast to the nearshore fish community, the offshore fish community during 2001-2011 appears to be relatively stable. Given that ~81% of fish community biomass inhabits offshore waters (Gorman et al. 2012b) and is dominated by native species, the offshore community appears healthy and is likely to remain stable in the near future. However, the lack of moderate-to-strong year-classes of cisco after 2003 has resulted in small spawning populations.

As is consistent with the Prey Species (FCO) (Table 1), the prey assemblage continues to be dominated by indigenous species, as it has for more than 30 years. Although prey-fish populations have declined in nearshore waters, they do not appear to have declined in offshore waters that contain, based on raw bottom-trawl data, 81% of fish biomass. However, the lack of substantial year-classes of cisco after 2003 and bloater and kiyi after 2005 raises a flag of caution. Current populations of these indigenous prey fishes are comprised mainly of older fish. Agencies should consider conserving spawning stock to improve the prospects that reproductive capacity is maintained.

AQUATIC NUISANCE SPECIES

The fish community objective for nuisance species has three sub-objectives: to prevent the introduction of non-indigenous aquatic species, prevent or delay their spread, and to eliminate or reduce their populations where possible (Table 1). Depreciation of native fish populations in the Great Lakes caused by non-indigenous nuisance species, such as the sea lamprey, zebra mussel (*Dreissena polymorpha*), and round goby has been extensive. Moreover, the Great Lakes continue to remain vulnerable to new aquatic invasions, such as the current threat posed by Asian carps (i.e., silver carp and bighead carp). Currently, Lake Superior contains at least 97 non-indigenous aquatic species, 19 of which are fish (Trebitz et al. 2009). Prior to 2008, monitoring of aquatic non-indigenous nuisance species in Lake Superior was either single-species focused or was secondary to other research and monitoring efforts. The U.S. Fish and Wildlife Service's (FWS) ruffe surveillance program ended in 2007 after which focus shifted toward implementing a more comprehensive early-detection program for non-indigenous fishes in general, based on a need identified by the Lake Superior Binational Program (2008).

To provide for early detection, Trebitz et al. (2009) developed and Hoffman et al. (2011) refined a sampling approach to monitor invasion-vulnerable areas of the Great Lakes using the St. Louis River at Duluth, Minnesota, as a case study. While conducting this case study in 2005-2007, several previously undetected invasive species were collected in the St. Louis River estuary, including quagga mussel (*Dreissena bugensis*), pea clam (*Pisidium henslowanum*), two oligochaete worms (*Paranais frici* and *Pristina acuminate*), an amphipod (*Echinogammarus ischnus*), and New Zealand mud snail (*Potamopyrgus antipodarum*) (Trebitz et al. 2009). The recommended fish sampling approach developed by Trebitz et al. (2009) was adopted by the FWS in 2008 and is being continued in the St. Louis River estuary. Other sampling efforts include early detection and monitoring of non-native mollusks at eight marinas in and around Chequamegon Bay, Wisconsin, and early detection of invasive fish also in Chequamegon Bay, the upper St. Marys River, and Thunder Bay, Ontario. All three locations were selected for monitoring because they host large volumes of shipping traffic. No new non-native fish species were detected at any location through

2011, but, in 2010, faucet snails (*Bithynia tentaculata*) were collected from Chequamegon Bay, the first confirmed detection of this non-native invertebrate species in Lake Superior.

In 2010, the Lake Superior Binational Program's Lake Superior Work Group completed a Lake Superior Aquatic Invasive Species Complete Prevention Plan (Lake Superior Binational Program 2014). The plan outlines new recommended actions to be implemented by state, tribal, provincial, and federal U.S. and Canadian agencies, in addition to existing efforts to prevent new aquatic invasive species from entering and becoming established in Lake Superior. Implementation of this plan calls for periodic reporting via updates disseminated from the Lake Superior Lakewide Management Plan (Lake Superior Binational Program 2008).

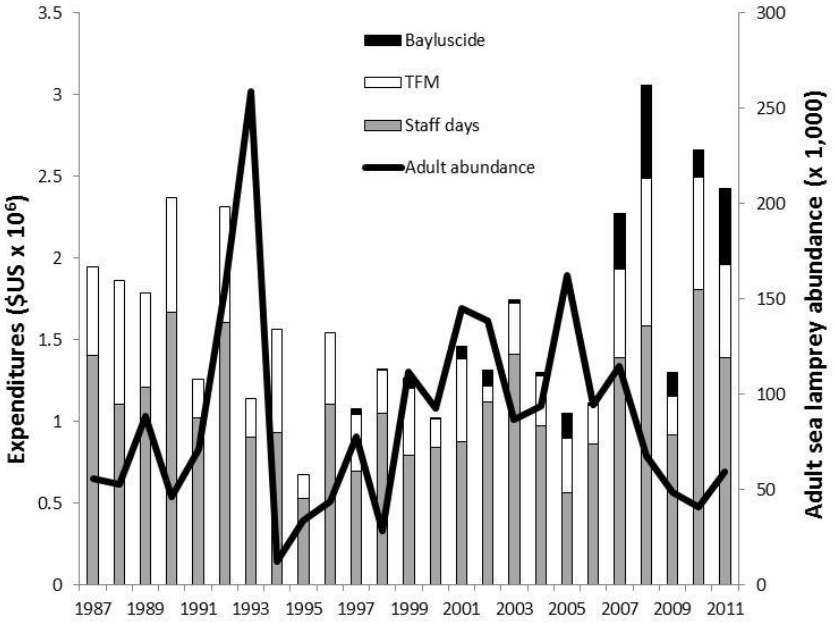
Conclusions and Recommendations

The FCO for nuisance species (Table 1) has not been fully achieved. No new non-native fish species were detected during this reporting period, and one new non-native invertebrate species was detected. New introductions of non-native and potentially invasive species remain a threat to the inshore fish communities of Lake Superior. In response, agencies have shifted from a single-species surveillance effort in local areas to one that is more systematic and comprehensive. Detecting a new species early and while still geographically limited allows for the possibility of preventing range expansion. Agencies should continue to implement and, where possible, expand comprehensive early-detection and monitoring efforts for non-native fishes in those areas most vulnerable to new introductions. Agencies should also implement the actions recommended in the Lake Superior Aquatic Invasive Species Complete Prevention Plan (Lake Superior Binational Program 2014).

SEA LAMPREY

The population of spawning sea lampreys during 2006-2011 averaged 58,000, slightly more than the upper bound of the allowable maximum of 56,000 (point estimate of allowable maximum, 37,000 ± 95% CI of 19,000). Although larger than desired, the spawning population during 2006-2011 was reduced considerably from the previous reporting period, 2001-2005, when the spawning population averaged 105,000 (Fig. 29; Steeves et al. 2010). Sea lamprey control, based mainly on lampricide (3-trifluoromethyl-4-nitrophenol (TFM) and Baylucide) treatments of streams and embayments harboring larvae, began in Lake Superior in 1958 in response to sea lamprey predation on lake trout, following the establishment of the sea lamprey in the late 1930s (Hansen et al. 1995). Subsequently, stream treatments were refocused from an even distribution of effort within a lake to a basin-wide distribution based on cost effectiveness or cost/kill (Heinrich et al. 2003). Beginning in 2005, over half of the streams treated were selected based on expert judgement, geographic cluster optimization, and other criteria such as large-scale treatment strategies (a large-scale treatment strategy will be deployed on Lake Superior tributaries in 2016). The remainding treatments during this period continued to be selected based on cost/kill. A combination of increased treatment effort allocated using a combination of these tactics accounts apparently in the lower abundance of sea lampreys in this reporting period.

Fig. 29. Expenditures ($US) on granular Bayluscide (vertical bars), 3-trifluoromethyl-4-nitropheno (TFM), and staff days to control sea lamprey in Lake Superior and corresponding annual estimates of spawning sea lamprey abundance (line) from 1985 through 2011. The effects of sea lamprey control efforts do not affect the estimates of spawner abundance for at least two years.



The average annual cost for lampricide application effort (staff days), TFM usage, and Bayluscide usage all increased between 2001-2005 and 2006-2011 (Fig. 29). The average amount of TFM (and cost) used annually to treat Lake Superior tributaries increased from 6,440 kg ($0.3 million) during 2001-2005 to 10,905 kg ($0.5 million) during 2006-2011 (Fig. 29). Lampricide usage has also increased during 2006-2011, both in the application of TFM to tributaries and Bayluscide to embayments. The use of Bayluscide to assess the distribution of larval sea lamprey in embayments or lentic areas increased starting in 2004. Use of RoxAnn™ technology, beginning in 2005, has resulted in sonar-based quantification of embayment substrates and a more efficient evaluation of the distribution of larvae within these substrates. These assessments have resulted in the treatment of 26 lentic areas (435 ha) with Bayluscide during 2006-2011.

As of 2011, there were 16 low-head barriers on Lake Superior tributaries built specifically to block adult sea lampreys from migrating further upstream to spawning habitats. These barriers eliminate the need for upstream lampricide applications, although the use of barriers reduces fish-species richness above barrier sites (Dodd et al. 2003). The 16 barriers include 12 conventional (no fish passage), two with fishways, one with a variable-crest, and a modification of a conventional dam (Black Sturgeon River, Ontario). Barriers constructed since 1990 have either been of a variable-crest design (Big Carp River, Canada) where the barrier crest can be lowered to the stream bed to enable fish passage when sea lampreys are not migrating or have incorporated trap-and-sort fishways to provide for selective passage of other fishes (Brule River, Wisconsin, and Big Carp River, Ontario). Two low-head barriers (Stokely Creek and Gimlet Creek, a Pancake River tributary) were refurbished, and one barrier (Sheppard Creek, a Goulais River tributary) was decommissioned during 2006-11.

Conclusions and Recommendations

The Sea Lamprey FCO that calls for suppression to levels that cause only insignificant mortality on lake trout (Table 1) is not being met. While adult sea lamprey abundance targets were met during 2009-2011, marking rates remained high, and models indicate that sea lampreys remain a major source of mortality on lean lake trout. Further work remains to evaluate the extent and effects of sea lamprey attacks on other hosts (e.g. siscowet lake trout, lake whitefish, and cisco). The control agents should continue to monitor tributaries after treatment to detect recolonization and/or unexpectedly large numbers of treatment survivors and to search for lentic areas that require control.

ACKNOWLEDGMENTS

We are grateful for the contributions of the following persons: C. Abel, J.M. Barber, E. Berglund, T. Billehus, M.J. Brouder, S.C. Chong, A.M. Cotter, M. Defoe, M.P. Ebener, L. Everard, A.E. Gamble, C.A. Goldsworthy, J.C. Hoffman, T.R. Hrabik, E.J. Isaac, J.R. Kelly, R.E. Kinnunen, J. Lindgren, G.Mensch, S.B. Michaels, S. Miller, S.K. Moses, J. Ross, S. Sapper, J. Scharold, J.T. Schloesser, M.J. Siefkes, M.E. Sierszen,T.B. Steeves, P. Stevens, J.D. Stockwell, J. Van Alstine, and M. Vinson.

REFERENCES

Auer, N.A. [ED.]. 2003. A lake sturgeon rehabilitation plan for Lake Superior [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/2003_02.pdf [accessed 24 October 2015].

Austin, J.A., and Colman, S.M. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: a positive ice-albedo feedback. Geophys. Res. Lett. **34**(6): 1-5. doi:10.1029/2006GL029021.

Austin, J.A., and Colman, S.M. 2008. A century of temperature variability in Lake Superior [online]. Available from: http://www.aslo.org/lo/toc/vol_53/issue_6/2724.html [accessed 24 October 2015].

Baldwin, N.A., Saalfeld, R.W., Dochoda, M.R., Buettner, H.J., and Eshenroder, R.L. 2009. Commercial fish production in the Great Lakes 1867-2006 [online]. Available from: http://www.glfc.org/databases/commercial/commerc.php [accessed 24 October 2015].

Barbiero, R.P., Schmude, K., Lesht, B.M., Riseng, C.M., Warren, G.J., and Tuchman, M.L. 2011. Trends in *Diporeia* populations across the Laurentian Great Lakes, 1997-2009. J. Great Lakes Res. **37**(1): 9-17. doi:10.1016/j.jglr.2010.11.009.

Berger, S.A., Diehl, S., Stibor, H., Trommer, G., and Ruhenstroth, M. 2010. Water temperature and stratification depth independently shift cardinal events during plankton spring succession. Global Change Biology 16(7): 1954-1965. doi: 10.1111/j.1365-2486.2009.02134.x.

Bhavsar, S.P., Jackson, D.A., Hayton, A., Reiner, E.J., Chen, T., and Bodnar, J. 2007. Are PCB levels in fish from the Canadian Great Lakes still declining? J. Great Lakes Res. **33**(3): 592-605. doi: 10.3394/0380-1330(2007)33[592:APLIFF]2.0.CO;2.

Bhavsar, S.P., Awad, E., Fletcher, R., Hayton, A., Somers, K.M., Kolic, T., MacPherson, K., and Reiner, E.J. 2008. Temporal trends and spatial distribution of dioxins and furans in lake trout or lake whitefish from the Canadian Great Lakes. Chemosphere **73**(1): S158-S165. doi:10.1016/j.chemosphere.2007.05.100.

Bhavsar, S.P., Gewurtz, S.B., McGoldrick, D.J., Keir, M.J., and Backus, S.M. 2010. Changes in mercury levels in Great Lakes fish between 1970s and 2007. Environ. Sci. Technol. **44**(9): 3273-3279. doi:10.1021/es903874x.

Bobrowski, R.J., Chase, M., Swainson, R., Vanogtrop, A., Bobrowicz, S., Cullis, K., and Sobchuk, M. 2011. Update on brook trout rehabilitation in the Ontario waters of Lake Superior, Lake Nipigon, and the Nipigon River, Public Workshop Proceedings [online]. Available from: http://www.thegreaterlakesuperiorfoundation.org/pdf/2011CoasterWorkshopProceedingsFINAL.pdf [accessed 24 October 2015].

Bronte, C.R., and Moore, S.A. 2007. Morphological variation of siscowet lake trout in Lake Superior. Trans. Am. Fish. Soc. **136**(2): 509-517. doi:10.1577/T06-098.1.

Bronte, C.R., and Sitar, S.P. 2008. Harvest and relative abundance of siscowet lake trout in Michigan waters of Lake Superior, 1929-61. Trans. Am. Fish. Soc. **137**(3): 916-926. doi:10.1577/T07-096.1.

Bunnell, D.B., Barbiero, R.P., Ludsin, S.A., Madenjian, C.P., Warren, G.J., Dolan, D.D., Brenden, T.O., Briland, R., Gorman, O.T., He, J.X., Johengen, T.H., Lantry, B.F., Lesht, B.M., Nalepa, T.F., Riley, S.C., Riseng, C.M., Treska, T.J., Tsehaye, I., Walsh, M.G., Warner, D.M., and Weidel, B.C. 2014. Ecosystem-level trends within the Laurentian Great Lakes: implications for the stability of the world's inland seas. BioScience **64**(1): 26-39. doi: 10.1093/biosci/bit001.

Carlson, D.L., and Swackhamer, D.L. 2006. Results from the U.S. Great Lakes fish monitoring program and effects of lake processes on bioaccumulative contaminant concentrations [online]. Available from: http://www3.epa.gov/greatlakes/glindicators/fishtoxics/Carlson_&_Swackhamer_JGLR_090205_GLFMP.pdf [accessed 24 October 2015].

Carlson, D.L., De Vault, D.S., and Swackhamer, D.L. 2010. On the rate of decline of persistent organic contaminants in lake trout (*Salvelinus namaycush*) from the Great Lakes, 1970-2003. Environ. Sci. Technol. **44**(6): 2004-2010. doi: 10.1021/es903191u.

Carpenter G.F., Mansey, E.I., and Watson, N.H.F. 1974. Abundance and life history of *Mysis relicta* in the St. Lawrence Great Lakes. J. Fish. Res. Board Can. **31**(3): 319-325. doi:10.1139/f74-051.

Colby, P.J., and Nepszy, S.J. 1981. Variation in among stocks of walleye (*Stizostedion vitreum vitreum*): management implications. Can. J. Fish. Aquat. Sci. **38**(12): 1814-1831. doi: 10.1139/f81-228.

Conner, D.J., Bronte, C.R., Selgeby, J.H., Collins, H.L., 1993. Food of salmonine predators in Lake Superior, 1981-1987. [online]. Available from: http://www.glfc.org/pubs/TechReports/Tr59.pdf [accessed 17 November 2015].

Desai, A.R., Austin, J.A., Bennington, V., and McKinley, G.A., 2009. Stronger winds over a large lake in response to weakening air-to-lake temperature gradient. Nature Geoscience **2**: 855-858. doi:10.1038/ngeo693.

Dobiesz, N.E., McLeish, D.A., Eshenroder, R.L., Bence, J.R., Mohr, L.C., Ebener, M.P., Nalepa, T.F., Woldt, A.P., Johnson, J.E., Argyle, R.L., and Makarewicz, J.C. 2005. Ecology of the Lake Huron fish community, 1970-1999. Can. J. Fish. Aquat. Sci. **62**(6): 1432-1451. doi:10.1139/f05-061.

Dodd, H.R., Hayes, D.B., Baylis, J.R., Carl, L.M., Goldstein, J.D., McLaughlin, R.L., Noakes, D.L.G., Porto, L.M., and Jones, M.L. 2003. Low-head lamprey barrier effects on stream habitat and fish communities in the Great Lakes basin. J. Great Lakes Res. **29**(Suppl. 1): 386-402. doi:10.1016/S0380-1330(03)70502-4.

Dryer, W.R., Erkkila, L.F., and Tezloff, C.L. 1965. Food of lake trout in Lake Superior. Trans. Am. Fish. Soc. **94**(2): 169-176. doi:10.1577/1548-8659(1965)94[169:FOLTIL]2.0.CO;2.

Ebener, M.P., Bence, J.R., Newman, K.R., and Schneeberger, P.J. 2005. Application of statistical catch-at-age models to assess lake whitefish stocks in the 1836 treaty-ceded waters of the upper Great Lakes [online]. Available from: http://www.glfc.org/pubs/TechReports/Tr66.pdf [accessed 24 October 2015].

Ebener, M.P., King, E.L., Jr., Edsall, T.A. 2006. Application of a dichotomous key to the classification of sea lamprey marks on Great Lakes fish [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/2006-02.pdf [accessed 23 November 2015].

Ebener, M.P., Kinnunen, R.E., Mohr, L.C., Schneeberger, P.J., Hoyle, J.A., and Peeters, P. 2008. Management of commercial fisheries for lake whitefish in the Laurentian Great Lakes of North America [online]. Available from: http://www.miseagrant.umich.edu/downloads/research/journals/08-310.pdf [accessed 24 October 2015].

Ebener, M.P., Sitar, S.P., Mattes, W.P., Hrabik, T.R., and Mata, M.T. 2010. Offshore fish community: siscowet [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/Sp10_1.pdf [accessed 24 October 2015].

Ecclestone, A. 2012. Movement patterns, habitat utilization, and spawning habitat of lake sturgeon (*Acipenser fulvescens*) in the Pic River, a northeastern Lake Superior tributary in Ontario, Canada. M.Sc. thesis, Trent Univ., Peterborough, ON.

Eschmeyer, P.H., and Phillips, A.M. 1965. Fat content of the flesh of siscowets and lake trout from Lake Superior. Trans. Am. Fish. Soc. **94**(1): 62-74. doi:10.1577/1548-8659(1965)94[62:FCOTFO]2.0.CO;2.

Fausch, D.F., and White, R.J. 1986. Competition among juveniles of coho salmon, brown trout and brook trout in a laboratory stream, and implications for Great Lakes tributaries. Trans. Am. Fish. Soc. **115**(3): 363-381. doi:10.1577/1548-8659(1986)115<363:CAJOCS>2.0.CO;2.

Friday, M.J. 2008. The migratory and reproductive response of spawning lake sturgeon to controlled flows over Kakabeka Falls on the Kaministiquia River, 2008. Ont. Min. Nat. Resour. Upper Great Lakes Management Unit Lake Superior Tech. Rep. 2008.01.

Furlong, P.D., Foster, R.F., Colby, P.J., and Friday, M.J. 2006. Black Sturgeon River dam: a barrier to the rehabilitation of Black Bay walleye [online]. Available from: http://www.thunderbayfishing.com/blacksturgeonreport.pdf [accessed 24 October 2015].

Gamble, A.E., Hrabik, T.R., Yule, D.L., and Stockwell, J.D. 2011a. Trophic connections in Lake Superior part I: the offshore fish community. J. Great Lakes Res. **37**(3): 541-549. doi:10.1016/j.jglr.2011.06.003.

Gamble, A.E., Hrabik, T.R., Yule, D.L., and Stockwell, J.D. 2011b. Trophic connections in Lake Superior part II: the nearshore fish community. J. Great Lakes Res. **37**(3): 550-560.

GLFC (Great Lakes Fishery Commission). 2007. A joint strategic plan for management of Great Lakes fisheries (adopted in 1997 and supersedes 1981 original). [online]. Available from: http://www.glfc.org/fishmgmt/jsp97.pdf [accessed 24 October 2015].

Goetz, F., Rosauer, D., Sitar, S., Goetz, G., Simchick, C., Roberts, S., Johnson, R., Murphy, C., Bronte, C.R., and MacKenzie, S. 2010. A genetic basis for the phenotypic differentiation between siscowet and lean lake trout (*Salvelinus namaycush*) [online]. Available from: http://onlinelibrary.wiley.com/doi/10.1111/j.1365-294X.2009.04481.x/epdf [accessed 24 October 2015]. doi:10.1016/j.jglr.2011.06.008.

Goetz, F., Sitar, S., Rosauer, D., Swanson, P., Bronte, C.R., Dickey, J., and Simchick, C. 2011. The reproductive biology of siscowet and lean lake trout in southern Lake Superior. Trans. Am. Fish. Soc. **140**(6): 1472-1491. doi:10.1080/00028487.2011.630276.

Goldman, J.C., and Carpenter, E.J. 1974. A kinetic approach to the effect of temperature on algal growth. Limnol. Oceanogr. **19**(5): 756-66. doi:10.4319/lo.1974.19.5.0756.

Gorman, O.T. 2007. Changes in a population of exotic rainbow smelt in Lake Superior: boom to bust, 1974-2005. J. Great Lakes Res. **33**(Suppl. 1): 75-90. doi:10.3394/0380-1330(2007)33[75:CIAPOE]2.0.CO;2.

Gorman, O.T. 2012. Successional change in the Lake Superior fish community: population trends in ciscoes, rainbow smelt, and lake trout, 1958-2008. Advanc. Limnol. **63**: 337-362. doi:10.1127/advlim/63/2012/337.

Gorman, O.T., and Todd, T.N. 2007. History of the shortjaw cisco (*Coregonus zenithicus*) in Lake Superior, 1895-2003. Advanc. Limnol. **60**: 433-458. doi:10.1127/advlim/60/2007/433.

Gorman, O.T., and Sitar, S.P. 2013. Ups and downs of burbot and their predator lake trout in Lake Superior, 1953-2011. Trans. Amer. Fish. Soc. **142**(6): 1757-1772. doi:10.1080/00028487.2013.824918.

Gorman, O.T., Yule, D.L., and Stockwell, J.D. 2012a. Habitat use by fishes of Lake Superior. I. Diel patterns of habitat use in nearshore and offshore waters of the Apostle Islands region of Lake Superior. Aquat. Ecosyst. Health Manage. Soc. **15**(3): 333-354. doi:10.1080/14634988.2012.715972.

Gorman, O.T., Yule, D.L., and Stockwell, J.D. 2012b. Habitat use by fishes of Lake Superior. II. Consequences of diel habitat use for habitat linkages and habitat coupling in nearshore and offshore waters. Aquat. Ecosyst. Health Manage. Soc. **15**(3): 355-368. doi:10.1080/14634988.2012.711664.

Gorman, O.T., Evrard, L.M., Cholwek, G.A., Yule, D.L., and Vinson, M.R. 2012c. Status and trends of the nearshore fish community of Lake Superior, 2011 [online]. Available from: http://www.glsc.usgs.gov/sites/default/files/product_files/2011LakeSuperiorPreyfish.pdf [accessed 24 October 2015].

Gronewold, A.D., Fortin, V., Lofgren, B.M., Clites, A.H., Stow, C.A., and Quinn, F.H., 2013. Coasts, water levels, and climate change: a Great Lakes perspective. Clim. Change **120**(4): 697-711. doi:10.1007/s10584-013-0840-2.

Hansen, M.J. 1996. A lake trout restoration plan for Lake Superior [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/LakeTroutRepSup.pdf [accessed 24 October 2015].

Hansen, M.J., Peck, J.W., Schorfhaar, R.G., Selgeby, J.H., Schreiner, D.R., Schram, S.T., Swanson, B.L., MacCallum, W.R., Burnham-Curtis, M.K., Curtis, G.L., Heinrich, J.W., and Young, R.J. 1995. Lake trout (*Salvelinus namaycush*) populations in Lake Superior and their restoration in 1959-1993. J. Great. Lakes Res. **21**(Suppl. 1): 152-175. doi:10.1016/S0380-1330(95)71088-7.

Hayes, D.B., and Caroffino, D.C. [EDS]. 2012. Michigan's lake sturgeon rehabilitation strategy [online]. Available from: http://www.michigandnr.com/PUBLICATIONS/PDFS/ifr/ifrlibra/Special/Reports/sr62/SR62.pdf [accessed 24 October 2015].

Heinrich, J.W., Mullett, K.M., Hansen, M.J., Adams, J.V., Klar, G.T., Johnson, D.A., Christie, G.C., and Young, R.J. 2003. Sea lamprey abundance and management in Lake Superior, 1957-1999. J. Great. Lakes Res. **29**(Suppl. 1): 566-583. doi:10.1016/S0380-1330(03)70517-6.

Henderson, B.A., and Anderson, D.M. 2002. Phenotypic differences in buoyancy and energetics of lean and siscowet lake charr in Lake Superior. Environ. Biol. Fishes. **64**(1-3): 203-209. doi:10.1023/A:1016023027437.

Herman, A.W., Beanlands, B., and Phillips, E.F. 2004. The next generation of optical plankton counter: the laser-OPC. J. Plankton Res. **26**(10): 1135-1145. doi:10.1093/plankt/fbh095.

Hoff, M.H. [ED.] 2003. A rehabilitation plan for walleye populations and habitats in Lake Superior [online]. Available from: www.glfc.org/pubs/SpecialPubs/2003_01.pdf [accessed 24 October 2015].

Hoffman, J.C., Kelly, J.R., Trebitz, A.S., Peterson, G.S., and West, C.W. 2011. Effort and potential efficiencies for aquatic non-native species early detection. Can. J. Fish. Aquat. Sci. **68**(12): 2064-2079. doi:10.1139/f2011-117.

Holey, M.E., Baker, E.A., Thuemler, T.F., and Elliott, R.F. 2000. Research and assessment needs to restore lake sturgeon in the Great Lakes: results of a workshop sponsored by the Great Lakes Fishery Trust [online]. Available from: https://glft.org/system/cms/attachments/29/2000_lake_sturgeon_workshop.pdf [accessed 24 October 2015].

Horns, W.H., Bronte, C.R., Busiahn, T.R., Ebener, M.P., Eshenroder, R.L., Gorenflo, T., Kmiecik, N., Mattes, W., Peck, J.W., Petzold, M., and Schreiner, D.R. 2003. Fish-community objectives for Lake Superior [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/Sp03_1.pdf [accessed 24 October 2015].

Hrabik, T.R., Jensen, O.P., Martell, S.J.D., Walters, C.J., and Kitchell, J.F. 2006. Diel vertical migration in the Lake Superior pelagic community. I. Changes in vertical migration of coregonids in response to varying predation risk. Can. J. Fish. Aquat. Sci. **63**(10): 2286-2295. doi:10.1139/f06-124.

Huckins, C.J., Baker, E.A., Fausch, K.D., and Leonard J.B.K. 2008. Ecology and life history of coaster brook trout and potential bottlenecks in their rehabilitation. North Am. J. Fish. Manage. **28**(4): 1321-1342. doi:10.1577/M05-191.1.

Isaac, E.J. 2010. An evaluation of the importance of *Mysis relicta* to the Lake Superior fish community. M.Sc. thesis, Univ. Minn., Duluth, MN.

Jensen, O.P., Hrabik, T.R., Martell, S.J.D., Walters, C.J., and Kitchell, J.F. 2006. Diel vertical migration in the Lake Superior pelagic community. II. Modeling trade-offs at an intermediate trophic level. Can. J. Fish. Aquat. Sci. **63**(10): 2296-2307. doi:10.1139/f06-125.

Keeler, K.M., Bunnell, D.B., Diana, J.S., Adams, J.V., Mychek-Londer, J.G., Warner, D.M., Yule, D.L., and Vinson, M.R. In press. Evaluating the importance of abiotic and biotic drivers on *Bythotrephes* biomass in Lakes Superior and Michigan. J. Gt. Lakes Res. doi:10.1016/j.jglr.2015.07.010.

Kelly, J.R., Yurista, P.M., Miller, S.E., Cotter, A.C., Corry, T.C., Scharold, J.S., Sierszen, M.E., Isaac, E.J., and Stockwell, J.D. 2011. Challenges to Lake Superior's condition, assessment, and management: a few observations across a generation of change. Aquat. Ecosyst. Health Manag. **14**(4): 332-344. doi:10.1080/14634988.2011.626753.

Kitchell, J.F., Cox, S.P., Harvey, C.J., Johnson, T.B., Mason, D.M., Schoen, K.K., Aydin, K., Bronte, C., Ebener, M., Hansen, M., Hoff, M., Schram, S., Schreiner, D., and Walters, C.J. 2000. Sustainability of the Lake Superior fish community: interactions in a food web context. Ecosystems **3**(6): 545-560. doi:10.1007/s100210000048.

Krueger, C.C., Perkins, D.L., Everett, R.J., Schreiner, D.R., and May, B. 1994. Genetic variation in naturalized rainbow trout (*Oncorhynchus mykiss*) from Minnesota tributaries to Lake Superior. J. Great Lakes Res. **20**(1): 299-316. doi:10.1016/S0380-1330(94)71149-7.

Kusnierz, P.C., Stimmell, S.P., and Leonard, J.B.K. 2009. Movement and growth indicators in resident and adfluvial coaster brook trout (*Salvelinus fontinalis*) in the Hurricane River, Lake Superior, Michigan, USA. J. Great Lakes Res. **35**(3): 385-391. doi:http://dx.doi.org/10.1016/j.jglr.2009.04.004.

Lake Superior Binational Program. 2008. Lake Superior lakewide management plan (LaMP) 2008 [online]. Available from: http://www3.epa.gov/greatlakes/lakesuperior/lake-superior-lamp-2008.pdf#_ga=1.160916857.518025883.1445874871 [accessed 20 April 2015].

Lake Superior Binational Program. 2012. Lake Superior lakewide management plan: 1990-2010 critical chemical reduction milestones [online]. Available from: http://www3.epa.gov/greatlakes/lakesuperior/2010/2010-lamp.pdf#_ga=1.231558619.518025883.1445874871 [accessed 24 October 2015].

Lake Superior Binational Program. 2014. Lake Superior aquatic invasive species complete prevention plan [online]. Available from: http://www3.epa.gov/greatlakes/lakesuperior/lake-superior-ais-prevention-plan-201401.pdf#_ga=1.62867816.518025883.1445874871 [accessed 24 October 2015].

Lawrie, A.H., and Rahrer, J.F. 1972. Lake Superior: effects of exploitation and introductions on the salmonid community. J. Fish. Res. Board Can. **29**(6): 765-776. doi:10.1139/f72-121.

Linton, B.C., Hansen, M.J, Schram, S.T., and Sitar, S.P. 2007. Dynamics of a recovering lake trout population in eastern Wisconsin waters of Lake Superior, 1980-2001. North Am. J. Fish. Manage. **27**(3): 940-954. doi:10.1577/M06-042.1.

Madenjian, C.P., Bunnell, D.B., and Gorman, O.T. 2010. Ninespine stickleback abundance in Lake Michigan: increases after invasion of Dreissenid mussels. Trans. Am. Fish. Soc. **139**(1): 11-20. doi:10.1577/T09-005.1

Madenjian, C.P., Yule, D.L., Chernyak, S.M., Begnoche, L.J., Berglund, E.K., and Isaac, E.J. 2014. Males exceed females in PCB concentrations of cisco (*Coregonus artedi*) from Lake Superior. Sci. Total Environ. **493**: 377-383. doi:10.1016/j.scitotenv.2014.06.007.

McGoldrick, D., Clark, M., and Murphy, E. 2013. Contaminants in whole fish. *In* State of the Great Lakes 2011. *Edited by* Environment Canada and U.S. Environmental Protection Agency [online]. Available from: http://binational.net/wp-content/uploads/2014/11/sogl-2011-technical-report-en.pdf [accessed 24 October 2015].

McLaughlin, R.L., Smyth, E.R.B, Castro-Santos, T., Jones, M.L., Koops, M.A., Pratt, T.C., and Velez-Espino, L-A. 2012. Unintended consequences and trade-offs of fish passage. Fish Fisheries **14**(4): 580-604. doi: 10.1111/faf. 12003.

Miller L., Close, T., and Kapuscinski, A.R. 2004. Lower fitness of hatchery and hybrid rainbow trout compared to naturalized populations in Lake Superior tributaries. Mol. Ecol. **13**(11): 3379-3388. doi: 10.1111/j.1365-294X.2004.02347.x.

Mills, E.L., Casselman, J.M., Dermott, R., Fitzsimons, J.D., Gal, G., Holeck, K.T., Hoyle, J.A., Johannsson, O.E., Lantry, B.F., Makarewicz, J.C., Millard, E.S., Munawar, I.F., Munawar, M., O'Gorman, R., Owens, R.W., Rudstam, L.G., Schaner, T., and Stewart, T.J. 2003. Lake Ontario: food web dynamics in a changing ecosystem (1970-2000). Can. J. Fish. Aquat. Sci. **60**(4): 471-490. doi:10.1139/f03-033.

Mohr, L.C., and Ebener, M.P. 2005. Evaluation of two harvest policies for managing lake whitefish (*Coregonus clupeaformis*) populations in a Laurentian Great Lake, Lake Huron. Arch. Hydro. Spec. Issue Advanc. Limnol. **60**: 471-483.

Moody, E.K., Weidel, B.C., Ahrenstorff, T.D., Mattes, W.P., and Kitchell, J.F. 2011. Evaluating the growth potential of sea lampreys (*Petromyzon marinus*) feeding on siscowet lake trout (*Salvelinus namaycush*) in Lake Superior. J. Great Lakes Res. **37**(2): 343-348. doi:10.1016/j.jglr.2011.01.007.

Negus, M.T., Schreiner, D.R., Halpern, T.N., Schram, S.T., Seider, M.J., and Pratt, D.M. 2008. Bioenergetics evaluation of the fish community in the western arm of Lake Superior in 2004. North Am. J. Fish. Manage. **28**(6): 1649-1667. doi:10.1577/M07-176.1.

Negus, M.T., Schreiner, D.R., Ward, M.C., Blankenheim, J.E., and Staples, D.F. 2012. Steelhead return rates and relative costs: a synthesis of three long-term stocking programs in two Minnesota tributaries of Lake Superior. J. Great Lakes Res. **38**(4): 653-666. doi:10.1016/j.jglr.2012.09.010.

OMNR (Ontario Ministry of Natural Resources). 2004. Lake Nipigon basin signature site: park management parent plan [online]. Available from: http://files.ontario.ca/environment-and-energy/parks-and-protected-areas/mnr_bpp0166.pdf [accessed 24 October 2015].

Peck, J.W. 1992. The sport fishery and contribution of hatchery trout and salmon in Lake Superior and tributaries at Marquette, Michigan, 1984-87. Mich. Dept. Nat. Resour. Fish. Res. Rep. 1975.

Peck, J.W., Jones, T.S., MacCallum, W.R., and Schram, S.T. 1999. Contribution of hatchery-reared fish to Chinook salmon populations and sport fisheries in Lake Superior. North Am. J. Fish. Manage. **19**(1): 155-164. Doi:10.1577/1548-8675(1999)019<0155:COHRFT>2.0.CO;2.

Pratt, T.C., 2008: Population status and threats of lake sturgeon in designatable unit 8 (Great Lakes/St. Lawrence River watersheds) [online]. Available from: http://www.dfo-mpo.gc.ca/Library/334960.pdf [accessed 24 October 2105].

Pratt, T.C., and Chong, S.C. 2012. Contemporary life history characteristics of Lake Superior deepwater ciscoes. Aquat. Ecosyst. Health Manage. **15**(3): 322-332. doi:10.1080/14634988.2012.708639.

Quinlan, H.R., Pratt, T.C., Friday, M.J., Schram, S.T., Seider, M.J., and Mattes, W.P. 2010. Inshore fish community: lake sturgeon [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/Sp10_1.pdf [accessed 24 October 2015].

Ray, B.A., Hrabik, T.R., Ebener, M.P., Gorman, O.T., Schreiner, D.R., Schram, S.T., Sitar, S.P., Mattes, W.P., and Bronte, C.R. 2007. Diets and prey selection by Lake Superior lake trout during spring, 1986-2001. J. Great Lakes Res. **33**(1): 104-113. doi:10.3394/0380-1330(2007)33[104:DAPSBL]2.0.CO;2.

Richardson, V., Warren, G.J., Nielson, M., and Horvatin, P.J. 2012. Cooperative science and monitoring initiative (CSMI) for the Great Lakes—Lake Ontario 2008. J. Great Lakes Res. **38**(Suppl. 4): 10-13. doi:10.1016/j.jglr.2012.07.00.

Robillard, M.M., McLaughlin, R.L., and Mackereth, R. 2011. Diversity in habitat use and trophic ecology of brook trout in Lake Superior and tributary streams revealed through stable isotopes. Trans. Am. Fish. Soc. **140**(4): 943-953. doi:10.1080/00028487.2011.601219.

Scharold, J.V., Lozano, S.J., and Corry, T.D. 2004. Status of the amphipod *Diporeia* spp. in Lake Superior, 1994-2000. J. Great Lakes Res. **30**(Suppl. 1): 360-368. doi:10.1016/S0380-1330(04)70397-4.

Schertzer,W.M., and Rao, Y.R., 2009. An overview of the characteristics of Lake Superior meteorology, hydrology and physical limnology. *In* State of Lake Superior. *Edited by* M. Munawar and I.F. Munawar. EcovisionWorld Monograph Series, Aquat. Ecosyst. Health Manage. Soc., Burlington, ON, Canada. pp. 3-50.

Schloesser, J., and Quinlan, H. 2010. Status of the 2010 lake sturgeon spawning population in the Bad and White Rivers, Wisconsin [online]. Available from: http://www.fws.gov/midwest/sturgeon/documents/bad-white-rivers-2010-spawn-assmt.pdf [accessed 24 October 2015].

Schloesser, J.T., Quinlan, H.R., Pratt, T.C., Baker, E.A., Adams, J.V., Mattes, W.P., Greenwood, S., Chong, S., Berglund, E., Gardner, W.M., Lindgren, J.P., Palvere, C.R., Stevens, P., Borkholder, B.D., Edwards, A.J., Mensch, G., Isaac, E.J., Moore, S.A., Abel, C., Wilson, T., Ripple, P., and Ecclestone, A. 2014. Lake Superior lake sturgeon index survey: 2011 status report. U.S. Fish Wildl. Serv., Ashland Fish and Wildlife Conservation Office, Ashland, WI.

Schram, S.T., Lindgren, J., and Evrard, L.M. 1999. Reintroduction of lake sturgeon in the St. Louis River, western Lake Superior. North Am. J. Fish. Manage. **19**(3): 815-823. doi:10.1577/1548-8675(1999)019<0815:ROLSIT>2.0.CO;2

Schram, S.T., Seider, M.J., Furlong, P.D., and Friday, M.J. 2010. Status of walleye in Lake Superior [online]. Available from: http://glfc.org/pubs/TechReports/Tr69.pdf [accessed 24 October 2015].

Schreiner, D.R., Ostazeski, J.J., Halpern, T.N., and Geving, S.A. 2006. Fisheries management plan for the Minnesota waters of Lake Superior [online]. Available from: http://files.dnr.state.mn.us/areas/fisheries/lakesuperior/lsmpfinalplan2006.pdf [accessed 24 October 2015].

Schreiner, D.R., Cullis, K.I., Donofrio, M.C., Fisher, G.J., Hewitt, L., Mumford, K.G., Pratt, D.M., Quinlan, H., and Scott, S.J. 2008. Management perspectives on coaster brook trout rehabilitation in the Lake Superior basin. North Am. J. Fish. Manage. **28**(4): 1350-1364. doi:10.1577/M05-173.1.

Schreiner, D.R., Seider, M.J., Sitar, S.P., and Chong, S.C. 2010. Nearshore fish community: Pacific salmon, rainbow trout, and brown trout [online]. Available from: http://www.glfc.org/pubs/SpecialPubs/Sp10_1.pdf [accessed 24 October 2015].

Scribner, K., Huckins, C., Baker, E., and Kanefsky, J. 2012. Genetic relationships and gene flow among resident and migratory brook trout in the Salmon Trout River. J. Great Lakes Res. **38**(1): 152-158. doi:10.1016/j.jglr.2011.11.009.

Sierszen, M.E., Kelly, J.R., Corry, T.D., Scharold, J.V., and Yurista, P.M. 2011. Benthic and pelagic contributions to *Mysis* nutrition across Lake Superior. Can. J. Fish. Aquat. Sci. **68**(6): 1051-1063. doi:10.1139/f2011-033.

Sierszen, M.E., Hrabik, T.R., Stockwell, J.D., Cotter, A.M., Hoffman, J.C., and Yule, D.L. 2014. Depth gradients in food-web processes linking habitats in large lakes: Lake Superior as an exemplar ecosystem. Freshwater Biology **59**(10): 2122-2136. doi:10.1111/fwb.12415.

Sitar, S.P., Chong, S.C., Ebener, M.P., Halpern, T.N., Mattes, W.P., Seider, M.J., and Symbal, M.J. 2010. Nearshore fish community: lake trout. *In* The state of Lake Superior in 2005. *Edited by* O.T. Gorman, M.P. Ebener, and M.R. Vinson [online]. Available from http://www.glfc.org/pubs/SpecialPubs/Sp10_1.pdf [accessed 23 November 2015].

Sitar, S.P., Jasonowicz, A.J., Murphy, C.A., and Goetz, F.W. 2014. Estimates of skipped spawning in lean and siscowet lake trout in southern Lake Superior: implications for stock assessment. Trans. Am. Fish. Soc. **143**(3): 660-672. doi:10.1080/00028487.2014.880745.

Sterner, R.W. 2010. In situ-measured primary production in Lake Superior. J. Great. Lakes Res. **36**: 139-149. doi:10.1016/j.jglr.2009.12.007.

Stevens, D.L., Jr., and Olsen, A.R. 1999. Spatially restricted surveys over time for aquatic resources. J. Agric. Biol. Environ. Stat. **4**(4): 415-428. doi:10.2307/1400499.

Stevens, D.L., Jr., and Olsen, A.R. 2003. Variance estimation for spatially balanced samples of environmental resources. Environmetrics **14**: 593-610. doi:10.1002/env.606.

Stockwell, J.D., Yule, D.L., Gorman, O.T., Isaac, E.J., and Moore, S.A. 2006. Evaluation of bottom trawls compared to acoustics to assess adult lake herring (*Coregonus artedi*) abundance in Lake Superior. J. Great Lakes Res. **32**(2): 280-292. doi:10.3394/0380-1330(2006)32[280:EOBTAC]2.0.CO;2.

Stockwell, J.D., Yule, D.L., Hrabik, T.R., Adams, J.V., Gorman, O.T., and Holbrook, B. 2007. Vertical distribution of fish biomass in Lake Superior: implications for day bottom trawl surveys. North Am. J. Fish. Manage. **27**(3): 735-749. doi:10.1577/M06-116.1.

Stockwell, J.D., Ebener, M.P., Black, J.A., Gorman, O.T., Hrabik, T.R., Kinnunen, R.E., Mattes, W.P., Oyadomari, J.K., Schram, S.T., Schreiner, D.R., Seider, M.J., Sitar, S.P., and Yule, D.L. 2009. A synthesis of cisco recovery in Lake Superior: implications for native fish rehabilitation in the Laurentian Great Lakes. North Am. J. Fish. Manage. **29**(3): 626-652. doi:10.1577/M08-002.1.

Stockwell, J.D., Hrabik, T.R., Jensen, O.P., Yule, D.L., and Balge, M. 2010. Empirical evaluation of predator-driven diel vertical migration in Lake Superior. Can. J. Fish. Aquat. Sci. **67**(3): 473-485. doi:10.1139/F09-198.

Stott, W.L., Quinlan, H.R., Gorman, O.T., King, T.L. 2010. Genetic structure and diversity among brook trout from Isle Royale, Lake Nipigon, and three Minnesota tributaries of Lake Superior. North Am. J. Fish. Manage. **30**(2): 400-411. doi:10.1577/M08-213.1.

Superior Work Group of the Lake Superior Lakewide Action and Management Plan. 2015. A biodiversity conservation assessment for Lake Superior [online]. Available from: http://www.natureconservancy.ca/assets/documents/on/lake-superior/A-Biodiversity-Conservation-Assessment-for-Lake-Superior-Vol-1-Final-Draft-Updated-March2015.pdf [accessed 20 April 2015].

Technical Fisheries Committee. 2012. Technical fisheries committee administrative report 2012: status of lake trout and lake whitefish populations in the 1836 treaty-ceded waters of Lakes Superior, Huron, and Michigan, with recommended yield and effort levels for 2012. [online]. Available from: http://www.michigan.gov/documents/dnr/2012StatusStocksReport_403608_7.pdf [accessed 26 March 2013].

Thurston, C.E. 1962. Physical characteristics and chemical composition of two subspecies of lake trout. J. Fish. Res. Board. Can. **19**(1): 39-44. doi:10.1139/f62-002.

Trebitz, A.S., Kelly, J.R., Hoffman, J.C., Peterson, G.S., and West, C.W. 2009. Exploiting habitat and gear patterns for efficient detection of rare and non-native benthos and fish in Great Lakes coastal ecosystems [online]. Available from: http://www.aquaticinvasions.net/2009/AI_2009_4_4_Trebitz_etal.pdf [accessed 24 October 2015].doi:10.3391/ai.2009.4.4.10.

Urban, N.R., Auer, M.T., Green, S.A., Lu, X., Apul, S., Powell, K.D., and Bub, L. 2005. Carbon cycling in Lake Superior. J. Geophys. Res. **110**: C06S90. doi:10.1029/2003JC002230.

Vollenweider, R.A., Munawar, M., and Stadelmann, P. 1974. A comparative review of phytoplankton and primary production in the Laurentian Great Lakes. J. Fish. Res. Board Can. **31**(5): 739-762. doi:10.1139/f74-100.

Ward, M. 2008. Status of brook trout in the Minnesota waters of Lake Superior. Minn. Dept. Nat. Resour. Fish. Div., Lake Superior Area. Minnesota F-29-R(P)-28.

Wilson, C.C., Lavender, M., and Black, J. 2007. Genetic assessment of walleye (*Sander vitreus*) restoration efforts and options in Nipigon Bay and Black Bay, Lake Superior. J. Great Lakes Res. **33**(Suppl. 1): 133-144. doi:http://dx.doi.org/10.3394/0380-1330(2007)33[133:GAOWSV]2.0.CO;2.

Wilson, C.C., Stott, W., Miller, L., D'Amelio, S., Jennings, M.J., and Cooper, A.M. 2008. Conservation genetics of Lake Superior brook trout: issues, questions, and directions. North Am. J. Fish. Manage. **28**(4): 1307-1320. doi:10.1577/M05-190.1.

Wisconsin State-Biological Technical Committee. 2007. Lake Superior fishing agreement 2005-2015 [online]. Available from: http://dnr.wi.gov/topic/fishing/documents/lakesuperior/lakesuperiorfishingagreement0515.pdf [accessed 24 October 2015].

Xia, X., Hopke, P.K., Crimmins, B.S., Pagano, J.J., Milligan, M.S., and Holsen, T.M. 2012. Toxaphene trends in Great Lakes fish. J. Great Lakes Res. **38**(1): 31-38. doi:10.1016/j.jglr.2011.11.001.

Yule, D.L., Stockwell, J.D., Cholwek, G.A., Evrard, L.M., Schram, S., Seider, M., and Symbal, M. 2006. Evaluation of methods to estimate lake herring spawner abundance in Lake Superior. Trans. Am. Fish. Soc. **135**(3): 680-694. doi:10.1577/T05-203.1.

Yule, D.L., Adams, J.V., Stockwell, J.D., and Gorman, O.T. 2007. Using multiple gears to assess acoustic detectability and biomass of fish species in Lake Superior. North Am. J. Fish. Manage. **27**(1): 106-126. doi:10.1577/M06-090.1.

Yule, D.L., Adams, J.V., Stockwell, J.D., and Gorman, O.T. 2008a. Factors affecting bottom trawl catches: implications for monitoring the fishes of Lake Superior. North Am. J. Fish. Manage. **28**(1): 109-122. doi:10.1577/M06-289.1.

Yule, D.L., Stockwell, J.D., Black, J.A., Cullis, K.I., Cholwek, G.A., and Myers, J.T. 2008b. How systematic age underestimation can impede understanding of fish population dynamics: lessons learned from a Lake Superior cisco stock. Trans. Am. Fish. Soc. **137**(2): 481-495. doi:10.1577/T07-068.1.

Yule, D.L., Berglund, E.K., Evrard, L.M., Cullis, K.I., and Cholwek, G.A. 2010. 2009 spawning cisco investigations in the Canadian waters of Lake Superior [online]. Available from: http://www.glsc.usgs.gov/sites/default/files/product_files/2009SpawningCisco.pdf [accessed 24 October 2015].

Yule, D.L., Schreiner, D.R., Addison, P.A., Seider, M.J., Evrard, L.M., Geving, S.A., and Quinlan, H.R. 2012. Repeat surveys of spawning cisco (*Coregonus artedi*) in western Lake Superior: timing, distribution and composition of spawning stocks. Advanc. Limnol. **63**: 65-87. doi:10.1127/advlim/63/2012/65.

Yule, D.L., Adams, J.V., Hrabik, T.R., Vinson, M.R., Woiak, Z., Ahrenstorff, T.D. 2013. Use of classification trees to apportion single echo detections to species: application to the fish community of Lake Superior. Fish. Res. **140**: 123-132. doi:10.1016/j.fishres.2012.12.012.

Yurista, P.M., Kelly, J.R., and Miller, S. 2009. Lake Superior zooplankton biomass: alternate estimates from a probability-based net survey and spatially extensive LOPC surveys. J. Great Lakes Res. **35**(3): 337-346. doi:10.1016/j.jglr.2009.03.004.

Yurista, P.M., Yule, D.L., Balge, M., Van Alstine, J.D., Thompson, J.A., Gamble, A.E., Hrabik, T.R., Kelly, J.R., Stockwell, J.D., and Vinson, M.R. 2014. A new look at the Lake Superior biomass size spectrum. Can. J. Fish. Aquat. Sci. **71**(9): 1324-1333. doi:10.1139/cjfas-2013-0596.

Zabik, M.E., Booren, A., Zabik, M.J., Welch, R., and Humphrey, H. 1996. Pesticide residues, PCBs and PAHs in baked, charbroiled, salt boiled and smoked Great Lakes lake trout. Food Chem. **55**(3): 231-239.

Zanaski, T.J., Holsen, T.M., Hopke, P.K., and Crimmins, B.S. 2011. Mercury temporal trends in top predator fish of the Laurentian Great Lakes. Ecotoxicology **20**(7): 1568-1576. doi: 10.1007/s10646-011-0751-9.

Zimmerman, M.S., Krueger, C.C., and Eshenroder, R.L. 2006. Phenotypic diversity of lake trout in Great Slave Lake: differences in morphology, buoyancy, and habitat depth. Trans. Am. Fish. Soc. **135**(4): 1056-1067. doi:10.1577/T05-237.1.

88-3 Age structured stock assessment of Lake Erie walleye (report of the July 22-24, 1986 Workshop). 1988. R. B. Deriso, S. J. Nepszy, and M. R. Rawson.

88-4 The international Great Lakes sport fishery of 1980. 1988. D. R. Talhelm.

89-1 A decision support system for the integrated management of sea lamprey. 1989. J. F. Koonce and A. B. Locci-Hernandez.

90-1 Fish community objectives for Lake Superior. 1990. Edited by T. R. Busiahn.

90-2 International position statement and evaluation guidelines for artificial reefs in the Great Lakes. 1990. Edited by J. E. Gannon.

90-3 Lake Superior: the state of the lake in 1989. 1990. Edited by M. J. Hansen.

90-4 An ecosystem approach to the integrity of the Great Lakes in turbulent times (proceedings of a 1988 workshop supported by the Great Lakes Fishery Commission and the Science Advisory Board of the International Joint Commission). 1990. Edited by C. J. Edwards and H. A. Regier.

91-1 Status of walleye in the Great Lakes: case studies prepared for the 1989 workshop. 1991. Edited by P. J. Colby, C. A. Lewis, and R. L. Eshenroder.

91-2 Lake Michigan: an ecosystem approach for remediation of critical pollutants and management of fish communities (report of a round table sponsored in 1990 by the Great Lakes Fishery Commission, the Science Advisory Board of the International Joint Commission, and the Lake Michigan Federation). 1991. Edited by R. L. Eshenroder, J. H. Hartig, and J. E. Gannon.

91-3 The state of the Lake Ontario fish community in 1989. 1991. S. J. Kerr and G. C. LeTendre.

93-1 Great Lakes fish disease control policy and model program. 1993. Edited by J. G. Hnath. 38 p. Protocol to minimize the risk of introducing emergency disease agents with importation of salmonid fishes from enzootic areas. 1993. Edited by R.W. Horner and R. L. Eshenroder.

94-1 The state of Lake Superior in 1992. 1994. Edited by M. J. Hansen.

94-2 An introduction to economic valuation principles for fisheries management. L.G. Anderson.

95-1 Fish-community objectives for Lake Huron. 1995. R. L. DesJardine, T. K. Gorenflo, R. N. Payne, and J. D. Schrouder.

95-2 The state of Lake Huron in 1992. Edited by M. P. Ebener.

95-3 Fish-community objectives for Lake Michigan. R.L. Eshenroder, M.E. Holey, T.K. Gorenflo, and R.D. Clark, Jr.

99-1 Fish-community objectives for Lake Ontario. T.J. Stewart, R.E. Lange, S.D. Orsatti, C.P. Schneider, A. Mathers, M.E. Daniels.

03-01 Fish-community objectives for Lake Superior. W.H. Horns, C.R. Bronte, T.R. Busiahn, M.P. Ebener, R.L. Eshenroder, T. Gorenflo, N. Kmiecik, W. Mattes, J.W. Peck, M. Petzold, D.R. Schreiner.

03-2 Fish-community goals and objectives for Lake Erie. P.A. Ryan, R. Knight, R. MacGregor, G. Towns, R. Hoopes, W. Culligan.

05-01 The state of Lake Michigan in 2000. Edited by M.E. Holey and T.N. Trudeau.

05-02 The state of Lake Huron in 1999. Edited by M.P. Ebener.

07-01 The state of Lake Ontario in 2003. Edited by B.J. Morrison and S. R. LaPan.

07-02 The state of Lake Superior in 2000. Edited by M.P. Ebener.

08-01 The state of Lake Huron in 2004. Edited by J.R. Bence and L.C. Mohr.

08-02 The state of Lake Michigan in 2005. Edited by D.F. Clapp and W. Horns.

09-01 Standard operating procedures for fisheries acoustic surveys in the Great Lakes. S.L Parker-Stetter, L.G. Rudstam, P.J. Sullivan, and D. M. Warner.

09-02 The state of Lake Erie in 2004. Edited by J.T. Tyson, R.A. Stein, and J.M. Dettmers.

10-01 The state of Lake Superior in 2005. Edited by O.T. Gorman, M.P. Ebener, and M.R. Vinson.

12-01 The state of Lake Michigan in 2011. Edited by David B. Bunnell.

13-01 The state of Lake Huron in 2010. Edited by Stephen C. Riley.

14-01 The state of Lake Ontario in 2008. Edited by Angela C. Adkinson and Bruce J. Morrison.

14-02 Model program for fish health management in the Great Lakes. Kenneth A. Phillips, Andrew Noyes, Ling Shen, and Gary Whelan

Special Publications

79-1 Illustrated field guide for the classification of sea lamprey attack marks on Great Lakes lake trout. 1979. E. L. King and T. A. Edsall.

82-1 Recommendations for freshwater fisheries research and management from the Stock Concept Symposium (STOCS). 1982. A. H. Berst and G. R. Spangler.

82-2 A review of the adaptive management workshop addressing salmonid/lamprey management in the Great Lakes. 1982. Edited by J. F. Koonce, L. Greig, B. Henderson, D. Jester, K. Minns, and G. Spangler.

82-3 Identification of larval fishes of the Great Lakes basin with emphasis on the Lake Michigan drainage. 1982. Edited by N. A. Auer. (Cost: $10.50 U.S., $12.50 CAN)

83-1 Quota management of Lake Erie fisheries. 1983. Edited by J. F. Koonce, D. Jester, B. Henderson, R. Hatch, and M. Jones.

83-2 A guide to integrated fish health management in the Great Lakes basin. 1983. Edited by F. P. Meyer, J. W. Warren, and T. G. Carey.

84-1 Recommendations for standardizing the reporting of sea lamprey marking data. 1984. R. L. Eshenroder and J. F. Koonce.

84-2 Working papers developed at the August 1983 conference on lake trout research. 1984. Edited by R. L. Eshenroder, T. P. Poe, and C. H. Olver.

84-3 Analysis of the response to the use of "Adaptive Environmental Assessment Methodology" by the Great Lakes Fishery Commission. 1984. C. K. Minns, J. M. Cooley, and J. E. Forney.

85-1 Lake Erie fish community workshop (report of the April 4-5, 1979 meeting). 1985. Edited by J. R. Paine and R. B. Kenyon.

85-2 A workshop concerning the application of integrated pest management (IPM) to sea lamprey control in the Great Lakes. 1985. Edited by G. R. Spangler and L. D. Jacobson.

85-3 Presented papers from the Council of Lake Committees plenary session on Great Lakes predator-prey issues, March 20, 1985. 1985. Edited by R. L. Eshenroder.

85-4 Great Lakes fish disease control policy and model program. 1985. Edited by J. G. Hnath.

85-5 Great Lakes Law Enforcement/Fisheries Management Workshop (report of the 21, 22 September 1983 meeting). 1985. Edited by W. L. Hartman and M. A. Ross.

85-6 TFM vs. the sea lamprey: a generation later. 1985.

86-1 The lake trout rehabilitation model: program documentation. 1986. C. J. Walters, L. D. Jacobson, and G. R. Spangler.

87-1 Guidelines for fish habitat management and planning in the Great Lakes (report of the Habitat Planning and Management Task Force and Habitat Advisory Board of the Great Lakes Fishery Commission). 1987.

87-2 Workshop to evaluate sea lamprey populations "WESLP" (background papers and proceedings of the August 1985 workshop). 1987. Edited by B. G. H. Johnson.

87-3 Temperature relationships of Great Lakes fishes: a data compilation. 1987. D. A. Wismer and A. E. Christie.

88-1 Committee of the Whole workshop on implementation of the Joint Strategic Plan for Management of Great Lakes Fisheries (reports and recommendations from the 18-20 February 1986 and 5-6 May 1986 meetings). 1988. Edited by M. R. Dochoda.

88-2 A proposal for a bioassay procedure to assess impact of habitat conditions on lake trout reproduction in the Great Lakes (report of the ad hoc Committee to Assess the Feasibility of Conducting Lake Trout Habitat Degradation Research in the Great Lakes). 1988. Edited by R. L. Eshenroder.