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# Great Lakes Prey Fish Populations: A Cross-Basin Overview of Status and Trends Based on Bottom Trawl Surveys, 1978-2015<sup>1</sup>

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## Introduction

The assessment of Great Lakes prey fish stocks have been conducted annually with bottom trawls since the 1970s by the Great Lakes Science Center, sometimes assisted by partner agencies. These stock assessments provide data on the status and trends of prey fish that are consumed by important commercial and recreational fishes. Although all these annual surveys are conducted using bottom trawls, they differ among the lakes in the proportion of the lake covered, seasonal timing, trawl gear used, and the manner in which the trawl is towed (across or along bottom contours). Because each assessment is unique, population indices were standardized to the highest value for a time series within each lake for the following prey species: Cisco (*Coregonus artedii*), Bloater (*C. hoyi*), Rainbow Smelt (*Osmerus mordax*), Alewife (*Alosa pseudoharengus*), and Round Goby (*Neogobius melanostomus*). In this report, standardized indices are presented in graphical form along with synopses to provide a short, informal cross-basin summary of the status and trends of principal prey fishes.

## Methods

For each lake, standardized relative indices of biomass for age-1 and older fishes were calculated as the observed value divided by the maximum value observed in the times series. Standardized relative indices of year-class strengths were calculated from densities of juvenile fishes. In each lake, juvenile year-classes that best reflected the magnitude of future recruitment were used to index year-class strength. Differences in the timing of surveys across lakes and differences in methodology used to distinguish juvenile age classes resulted in adopting different age-classes (age-0, age-1, age-3) to index year-class strength for each species and lake. Year-class strengths were based on age-correlated size classes of Cisco, Bloater, and Rainbow Smelt in Lake Superior and Alewife in Lake Michigan. For other species and lakes, age-classes were assigned based on fish length cut-offs.

The Kendall coefficient of concordance ( $W$ ) was calculated to determine if the time series of relative abundances for a given species was statistically “concordant” across 3 or more lakes.  $W$  can range from 0 (complete discordance or disagreement) to 1 (complete concordance or agreement). For statistical comparisons between two lakes, Spearman’s correlation  $r$  was used assess concordance of ranks, ranging from 0 (complete discordance or disagreement) to 1 (complete concordance or agreement). Concordance can be expressed as either a fraction or percent. A smaller  $P$ -value for  $W$  and  $r$  indicates a greater probability of agreement in comparison of trends.

When making statistical comparisons of trends among lakes, data were restricted to years when all or a group of lakes were sampled. For all lakes, data from 1992, 1993, 1998, and 2000 were omitted from statistical comparisons because missing or atypical data were collected in one or more lakes. Comparisons with Lake Erie

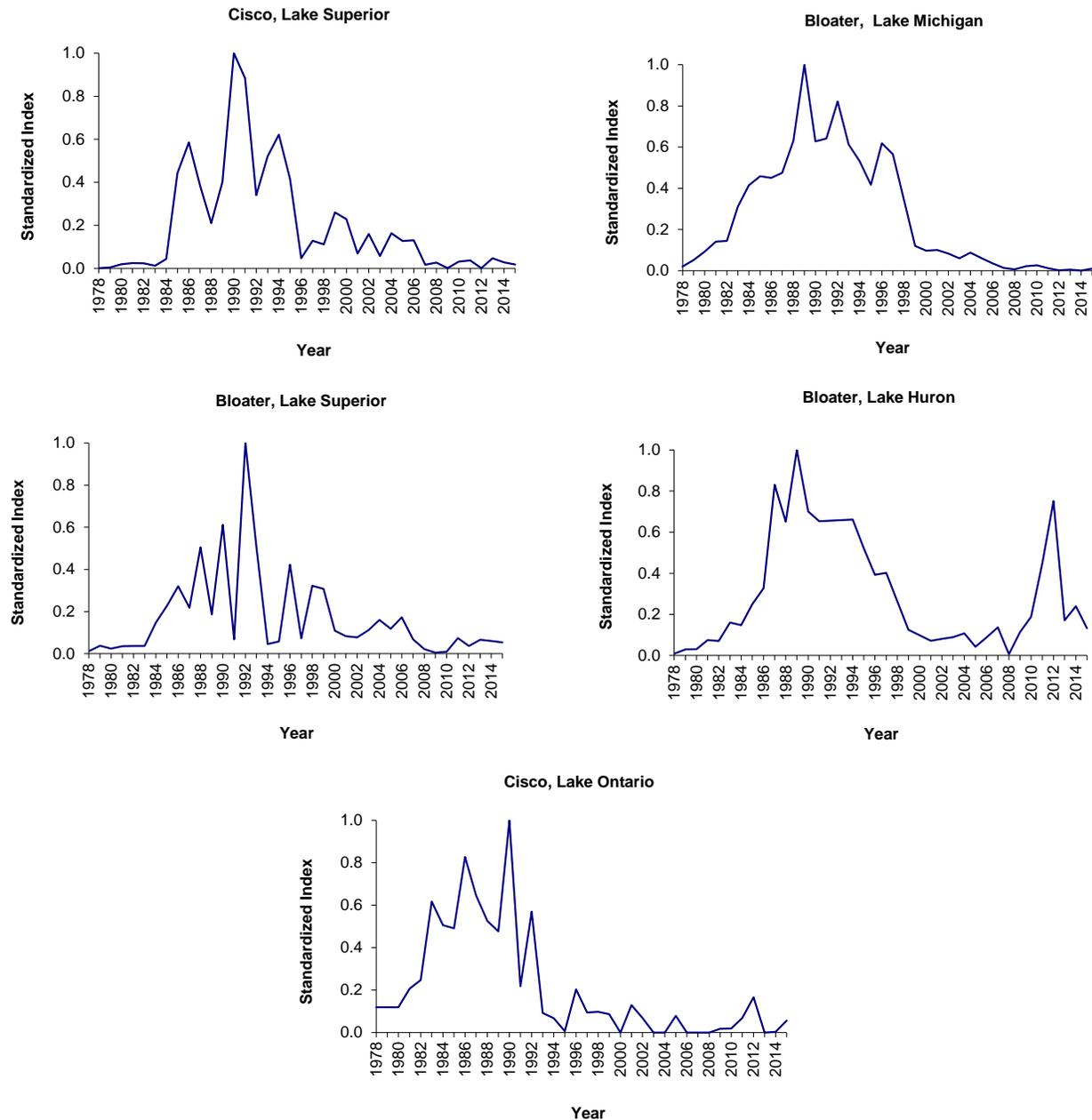
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<sup>1</sup> Prepared for: Great Lakes Fishery Commission  
Upper Lakes Committee Meetings  
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were restricted to 1990-2015, years when multi-agency surveys with a consistent sample design were conducted. Beginning with the 2010 report, a complete data series from Lake Huron was made available for comparison with other lakes because fishing power corrections to the Huron data were developed to account for the use of a larger bottom trawl to conduct surveys during 1992-2013. Assessment of cross-basin trends for Round Goby begins with 1994, the first year that these fish were detected in bottom trawl surveys in the Great Lakes.

## Results

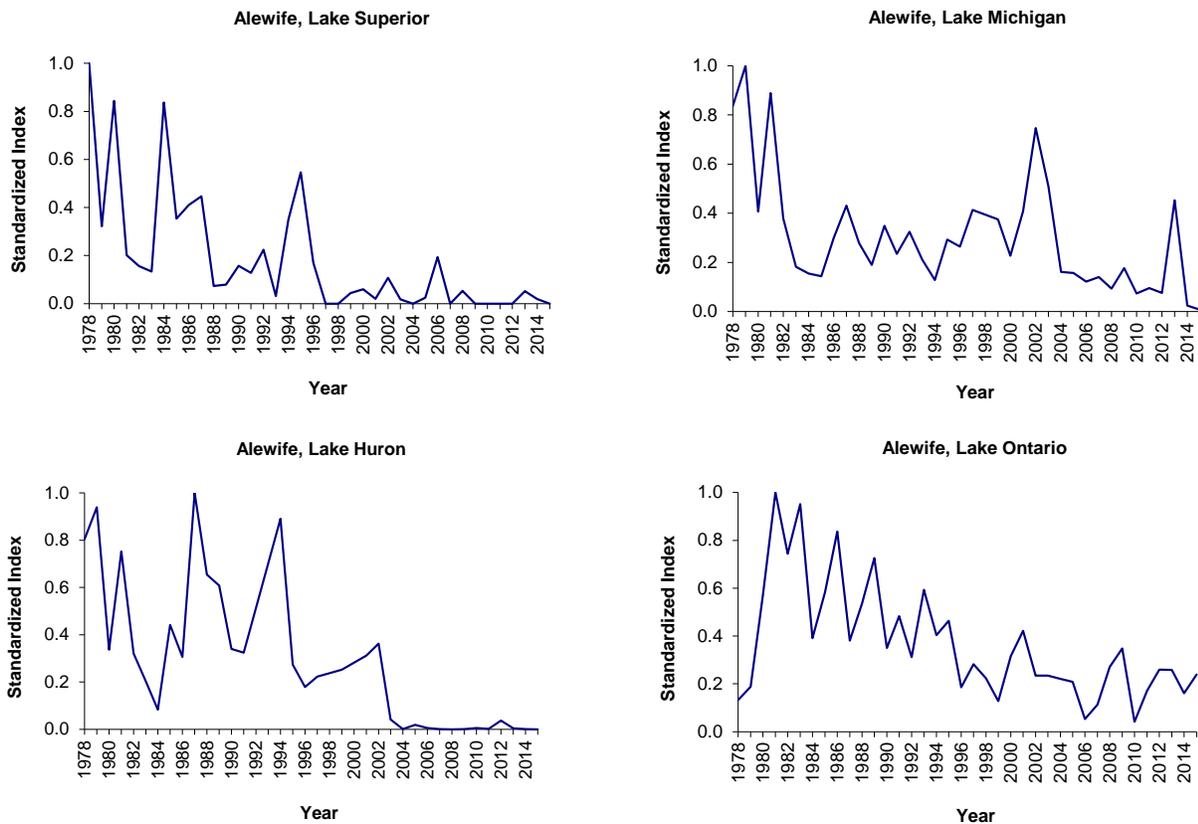


**Figure 1.** – Standardized indices of biomass for age-1 and older Cisco in Lakes Superior and Ontario and age-1 and older Bloater in Lakes Superior, Michigan, and Huron, 1978-2015.

### *Relative Biomass, Age-1 and Older Coregonids*

Trends in relative biomass of age-1 and older coregonids (Cisco in Lake Superior and Bloater in Lakes Superior, Michigan, and Huron) among the 1978-2015 time series were significantly concordant (Fig. 1;  $W = 0.67$ ;  $P < 0.0001$ ). Although Cisco is a rare species in Lake Ontario, (maximum mean biomass of 0.06 kg/ha), it was regularly captured in low numbers throughout the time series. When trends in relative Cisco biomass in

Lake Ontario are included with comparisons of coregonids in the other Lakes, the trends remain significantly concordant (Fig. 1;  $W = 0.60$ ;  $P < 0.0001$ ). Comparison of trends in biomass of Bloater in Lakes Superior, Michigan, Huron, showed significant concordance ( $W = 0.65$ ;  $P < 0.001$ ). Trends in Cisco and Bloater biomass in Lake Superior showed strong agreement ( $r = 0.70$ ,  $P < 0.01$ ), but trends in biomass of age-1 and older Cisco in Lakes Superior and Ontario were not concordant ( $r = 0.23$ ,  $P = 0.22$ ). In all four lakes, coregonid biomass reached peak levels in the late 1980s through the early 1990s. Afterwards, coregonid biomass declined and reached historically low levels in Lakes Superior and Michigan in 2007-2011. Cisco biomass in Lake Ontario declined after 1992 and remained low for the remainder of the time series. In difference to trends in the other lakes, biomass of Bloater in Lake Huron rebounded following a record low in 2008 to 75% of peak biomass in 2012, due to the recruitment and growth of strong 2005 and 2007 and moderate 2008 and 2011 year-classes (Figs. 1, 5). Bloater were absent from survey catches in Lakes Erie and Ontario, and Cisco were rarely encountered in Lakes Michigan, Huron, and Erie.

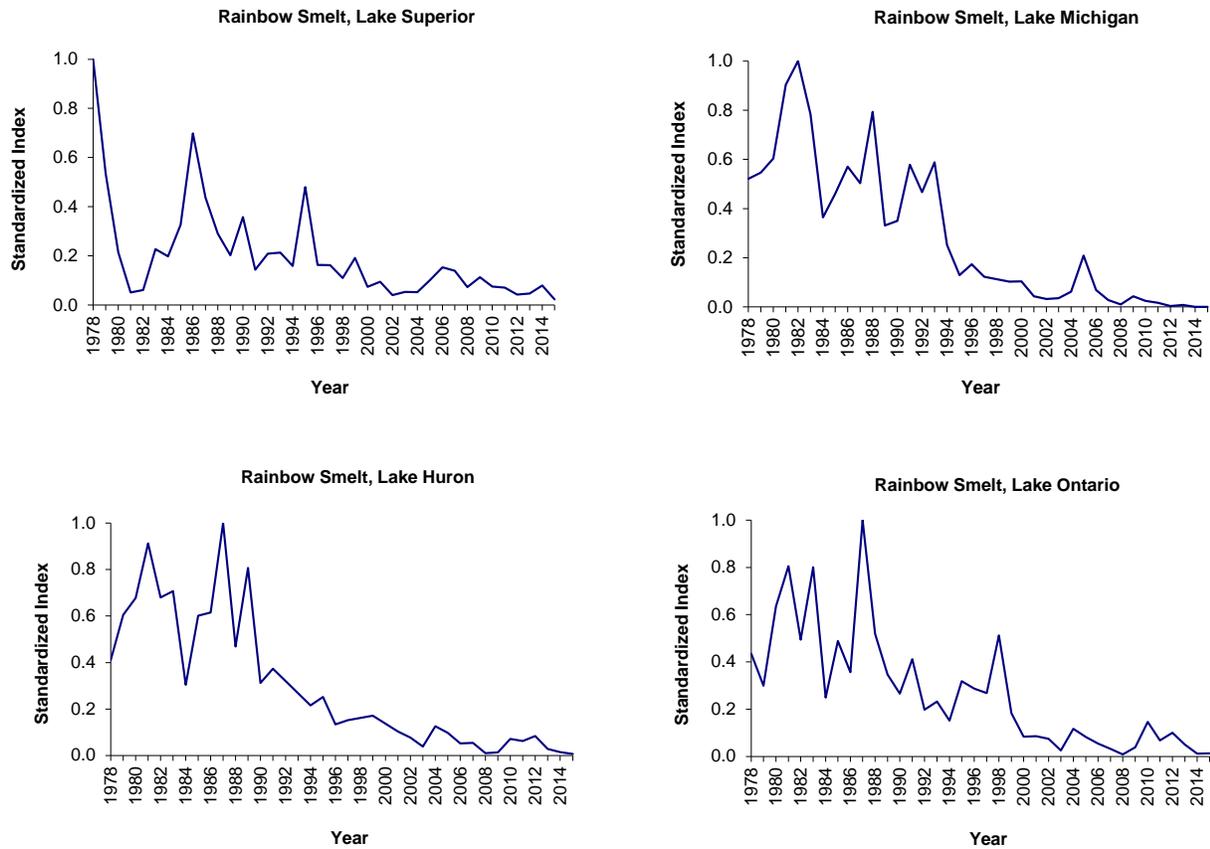


**Figure 2.** – Standardized indices of biomass for age-1 and older Alewife in Lakes Superior, Michigan, Huron, and Ontario, 1978-2015.

### ***Relative Biomass, Age-1 and older Alewife***

Trends in relative biomass of age-1 and older Alewife across Lakes Superior, Michigan, Huron, and Ontario were variable, though biomass was generally higher early in the time series and lower in more recent years (Fig. 2). For all four lakes, there was moderate concordance ( $W = 0.60$ ;  $P < 0.0001$ ) among the 1978-2015 time series. In Lake Michigan, biomass of Alewife was high in the late 1970s and rapidly declined to lower levels by the mid-1980s. After a minor peak in 2002, the result of recruitment of the extremely large 1998 year-class, Alewife biomass remained relatively low during the late 1980s, 1990s, and early 2000s. After 2002, Alewife biomass continued to decline but the trend was punctuated by a minor peak in 2013 that was due to a very large Alewife catch at the 9-m station at Saugatuck. Consequently, there was a high degree of uncertainty associated with this 2013 observation, which was resolved by sharp declines afterwards, reaching near-zero in 2015. In Lake Huron, biomass of Alewife was high in the beginning of the time series, declined to low levels in the mid-1980s, but unlike Lake Michigan, fluctuated widely in the late 1980s – mid 1990s with peaks in 1987

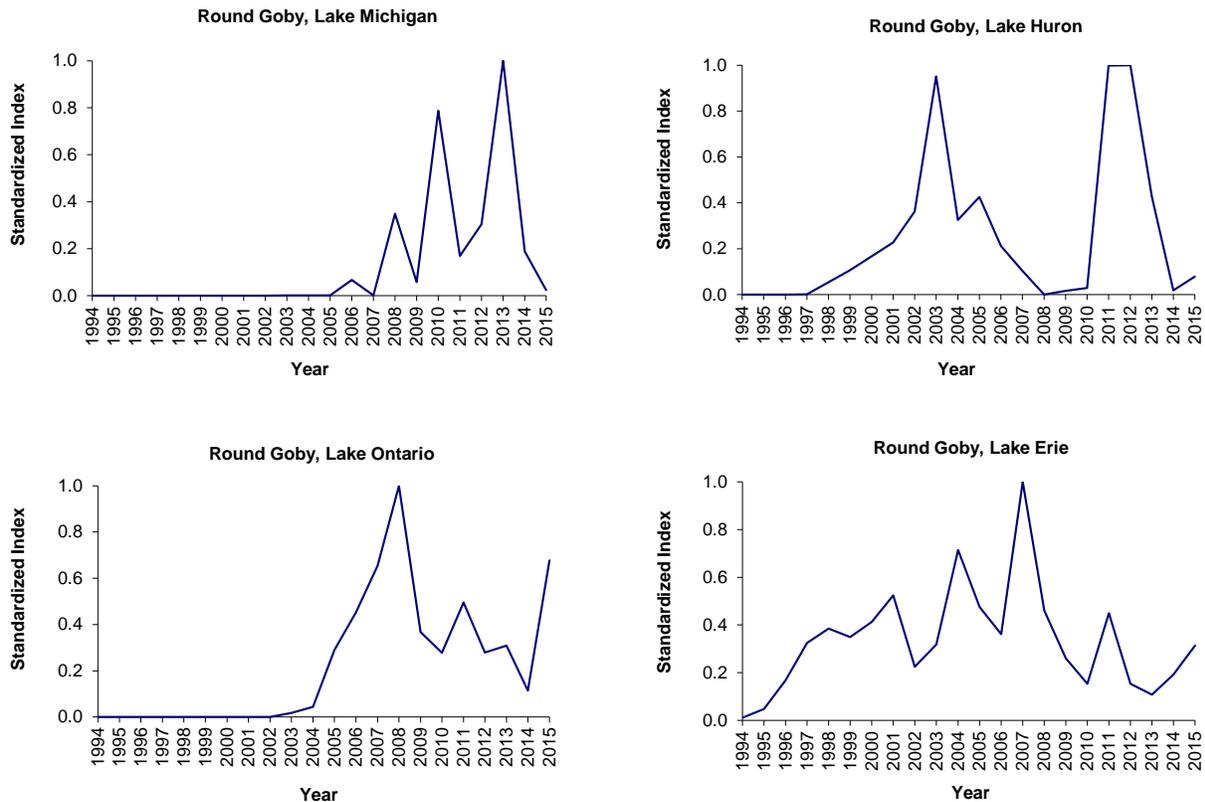
and 1994 and an intervening low in 1990-1991. After 1994, biomass declined to 18% of peak abundance in 1996, rebounded to 36% in 2002 and afterwards declined to near-zero levels in 2004-2011 and 2013-2014 and zero in 2015. In Lake Ontario, biomass of Alewife has declined step-wise since 1980. Although Alewife is a rare species in Lake Superior, the pattern of biomass decline follows that of other Great Lakes; once Lake Trout populations were fully recovered in the late 1990s, relative biomass has remained low. Survey data for Alewife in Lake Erie were not available for this comparison.



**Figure 3.** – Standardized indices of biomass for age-1 and older Rainbow Smelt in Lakes Superior, Michigan, Huron, and Ontario, 1978-2015.

### ***Relative Biomass, Age-1 and Older Rainbow Smelt***

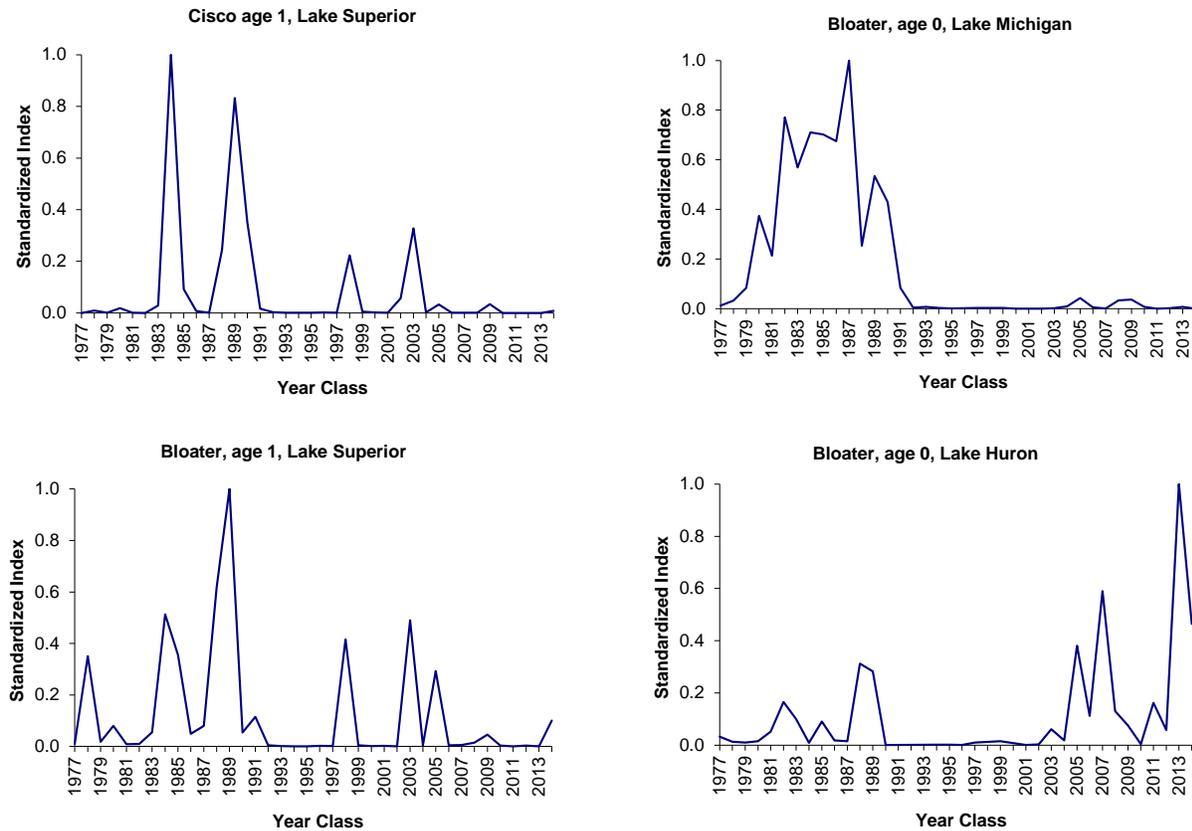
Age-1 and older Rainbow Smelt in Lakes Superior, Michigan, Huron, and Ontario showed a highly concordant trend of fluctuating but declining relative biomass during 1978-2015 (Fig. 3;  $W = 0.82$ ;  $P < 0.0001$ ). In Lake Superior, biomass was at or near-record lows in 2002-2004, recovered to 15% of peak biomass by 2006, and then declined afterwards, reaching near-record lows in 2012 and 2013 and a record low in 2015. Similarly, biomass in Lake Michigan was near record lows during 2001-2003, rose nearly 4-fold in 2005, and then declined to record lows in 2012-2014 and near-zero in 2015. Mirroring the Michigan pattern, biomass in Lake Huron declined to near-record lows in 2002-2003, increased to 13% in 2004 and then declined to record lows in 2008-2009, but differing from the Michigan pattern, biomass increased to 6-8% of peak biomass in 2010-2012. In 2013-2014, biomass dropped again, reaching a record low in 2015. A similar pattern was observed in Lake Ontario where biomass reached a near-record low in 2003 and was followed by two cycles of weak recovery and decline to near record lows in 2014-2015. Survey data for age-1 and older Rainbow Smelt in Lake Erie were not available for this comparison.



**Figure 4.** – Standardized indices of abundance for Round Goby in Lakes Michigan, Huron, Ontario, and Erie, 1994-2015. Indices are computed from number caught in Lake Erie and weight caught in all other lakes.

***Relative Abundance, Age-0 and older Round Goby***

Moderate agreement in trends in relative biomass of age-0 and older Round Goby ( $W = 0.48$ ;  $P < 0.009$ ) was observed among lakes where this species has become established (Lakes Michigan, Huron, Erie, and Ontario; Fig. 4). Further agreement in trends among lakes was hindered by the desynchronized expansion of Round Goby populations. The first records occurred in Lake Erie, followed by Lake Huron and then by Lakes Ontario and Michigan. Following several peaks in 2001, 2004, and 2007, biomass of Round Goby in Lake Erie in 2010-2015 declined to the lowest levels since the initial stages of expansion but was punctuated by small peaks in 2011 and 2015. After what appears to have been a similar pattern of expansion and decline in Lake Huron, biomass of Round Goby spiked to record levels in 2011 and 2012 and then declined 98% by 2014. The peak in biomass of Round Goby observed in 2013 in Lake Michigan was followed by a 98% decline by 2015. Round Goby biomass in Lake Ontario declined in steps from a maximum in 2008 to 11% by 2014 and then rebounded to 68% of maximum in 2015. Round Goby biomass showed a considerable amount of year-to-year variability in these lakes, suggesting that these populations have not reached equilibrium levels. Round Goby have not been caught in annual bottom trawl surveys in Lake Superior.



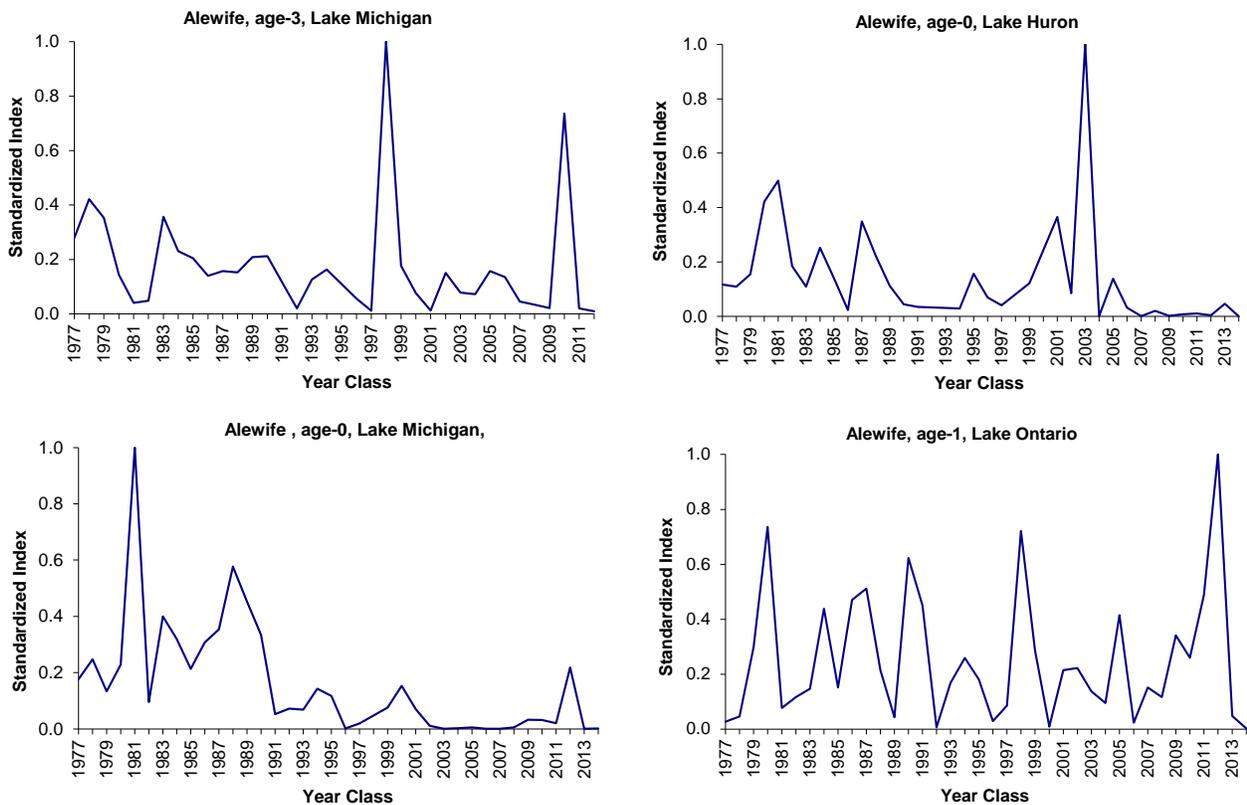
**Figure 5.** – Standardized indices of densities for age  $\leq 1$  ciscoes (Cisco and Bloater) in Lakes Superior, Michigan, and Huron, 1977-2014.

### *Year-Class Strengths, Coregonids*

Trends in relative strengths of 1977-2014 coregonid year-classes showed moderate agreement ( $W = 0.48$ ;  $P = 0.001$ ) among Lakes Superior, Michigan, and Huron (Fig. 5). Restricting the comparison to Bloater also yielded moderate agreement ( $W = 0.55$ ;  $P = 0.01$ ). All lakes shared a general pattern of stronger year-classes in the 1980s and weaker year-classes in the 1990s. Trends in relative year-class strengths of coregonids among the three upper Lakes showed higher concordance before the advent of a succession of strong and moderate year-classes in Lake Huron after 2004 (1977-2004;  $W = 0.57$ ;  $P < 0.0004$ ). Bloater were absent from survey catches in Lakes Erie and Ontario and Cisco are rarely encountered outside of Lake Superior.

### *Year-Class Strengths, Alewife*

Using relative abundances of Alewife at age-3 in Lake Michigan, age-0 in Lake Huron, and age-1 in Lake Ontario to assess year-class strengths, there was no agreement in trends ( $W = 0.38$ ;  $P = 0.29$ ) among the Lakes for 1977-2012 year-classes (Fig. 6). Agreement remained nonsignificant when relative abundances of Alewife at age-0 in Lake Michigan (1977-2012 year classes) were substituted in the comparison ( $W = 0.47$ ;  $P = 0.07$ ). But when the comparison was expanded to 1977-2014 year classes there was significant agreement in trends ( $W = 0.52$ ;  $P = 0.02$ ). Comparison of relative abundances of age-0 Alewife (1977-2014 year classes) in Lakes Michigan and Huron was also significant ( $r = 0.44$ ;  $P < 0.01$ ). However, paired comparisons of relative abundances of age-1 Alewife in Lake Ontario with age-0 Alewife in Lakes Michigan and Huron showed no agreement ( $r = 0.32, 0.06$ ;  $P > 0.27, 0.21$ , respectively). Alewife densities were too low in Lake Superior to assess year-class strengths.



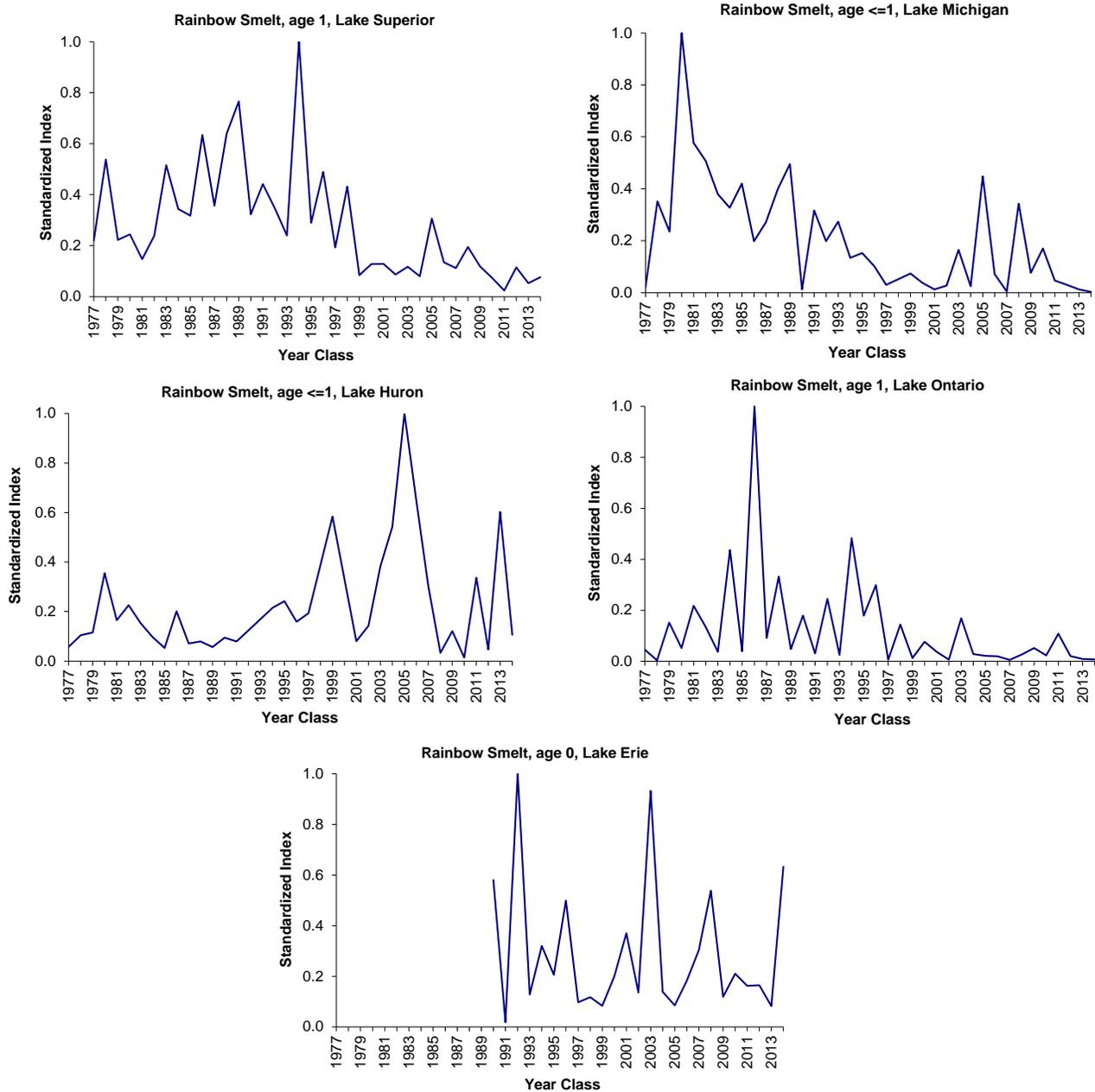
**Figure 6.** – Standardized indices of Alewife densities measured at age 0, 1 or 3 in Lakes Michigan, Huron, and Ontario, 1977-2014.

Comparisons of recruitment trends in Alewife at different ages are problematic because abundances at age-0, age-1, and age-3 are affected by differential survivorship. Thus it is not surprising that comparison of trends in relative year-class strengths of Alewife across the three lakes showed no agreement when these ages were considered. Paired comparisons showed moderate agreement between Lakes Michigan and Huron but no agreement with trends in Lake Ontario. Trends in year-class strengths in Ontario were highly variable with no discernible trends. However, the 2012 year-class was the strongest on record. In Lakes Michigan and Huron, year-class strengths based on abundance of age-0 fish were variable but at intermediate levels through the 1980s. After 1990, year-class strengths declined in Lake Michigan, and were negligible after 2001 and reached zero in 2015 surveys. In Lake Huron, year-class strengths remained variable after 1990, and after producing its strongest year-class in 2003, subsequent year-classes were negligible, reaching zero in the 2015 survey. Alewife is a rare species in Lake Superior and survey data for Lake Erie were not available for this comparison.

### ***Year-Class Strengths, Rainbow Smelt***

Trends in relative strengths of Rainbow Smelt year-classes across Lakes Superior, Michigan, Huron, and Ontario from 1977 to 2014 showed weak agreement (Fig. 7;  $W = 0.38$ ;  $P = 0.03$ ). When the comparison was limited to Lakes Superior, Michigan, and Huron, the agreement remained nonsignificant ( $W = 0.38$ ;  $P = 0.28$ ). Paired comparisons among the three lakes showed agreement between Lakes Superior and Michigan ( $r = 0.57$ ;  $P < 0.01$ ), Michigan and Ontario ( $r = 0.37$ ;  $P < 0.05$ ), and Huron and Ontario ( $r = 0.52$ ;  $P < 0.01$ ). In Lake Superior, year-class strengths varied from moderate to strong during 1977-1996, subsequently declined to weak levels in 1999-2002, and varied from weak to moderate in 2003-2009 and reached a record low in 2011 and near-record lows in 2010 and 2013-2014. In Lake Michigan, year-class strengths declined steadily from 1980 to 2001; afterwards the downward trend was punctuated by moderately strong year-classes in 2005 and 2008, and achieved a near-record low in 2007 and a record low in 2014. In contrast, year-class strengths in Lake Huron were moderate to weak over the first 26 years of the 37-year time series, and then increased rapidly to a peak in 2005 followed by a steep decline to record lows in 2008 and 2010 and then rebounded to 34% of the record in

2011, plunged to 5% in 2012, and rebounded to 60% in 2013 only to decline to 11% in 2014. In Lake Ontario, year-class strengths prior to 1999 exhibited a clear “saw-tooth” pattern caused by alternating strong and weak year-classes. This pattern was not discernible during 1999-2014 due to a succession of weak year classes punctuated by moderate year classes in 2003 and 2011. To include Lake Erie in our analysis, the comparison was restricted to the 1990-2014 year-classes. Concordance in trends in relative year-class strengths among all lakes remained nonsignificant ( $W = 0.28$ ;  $P = 0.10$ ) and paired comparisons showed agreement only between Lakes Ontario and Superior ( $r = 0.50$ ;  $P < 0.05$ ). Agreement between Lakes Ontario and Superior appears due to concordance in higher year-class strengths between 1990 and 1997 and variable but lower year-class strengths afterwards (Fig. 7).



**Figure 7.** – Standardized indices of Rainbow Smelt densities measured at age-1 in Lakes Superior and Ontario and at age-0 in Lakes Michigan, Huron and Erie, 1977-2014.

## Summary

There was basin-wide agreement in the trends of age-1 and older biomass for all prey species, with the highest concordance occurring for coregonids and Rainbow Smelt, and weaker concordance for Alewife. For coregonids Cisco and Bloater, the highest biomass occurred from the late 1980s to the early 1990s. Rainbow Smelt biomass declined slowly and erratically during the last quarter century. In general, Alewife biomass was substantially higher during the 1980s and 1990s compared with the post-2003 era.

Recently, Lake Huron has shown resurgence in biomass of Bloater, achieving 75% of its maximum record in 2012 due to recruitment of a succession of strong and moderate year-classes that appeared in 2005-2011 and the largest on record in 2013. The resurgence of Bloater in Lake Huron notwithstanding, the general concordance in population trends of Bloater and Cisco across the Great Lakes supports hypotheses for large-scale environmental factors influencing the synchrony of recruitment in Great Lakes coregonids.

In general, trends in year-class strengths of prey fishes were less concordant than population biomass across the basin and only coregonids showed statistical agreement across the upper Great Lakes (data on year-class strengths for Lake Ontario Cisco were not available). The appearance of strong and moderate year-classes of Bloater in Lake Huron in 2005-2013 countered the common trend of continuing weak year-classes of coregonids in Lakes Michigan and Superior. There was no agreement in cross-basin trends in year-class strengths for Rainbow Smelt and Alewife, although there was agreement between pairs of lakes.

Although there was statistical agreement in trends of age-0 and older Round Goby biomass among lakes where this species has successfully invaded (Michigan, Huron, Erie, and Ontario), temporal patterns of biomass in each lake were different. Recent trends in biomass remain highly variable in these lakes, suggesting that these populations have not reached equilibrium levels, despite evidence that Round Goby has become increasingly important in piscivore diets, e.g., Lake Trout, Walleye, Smallmouth Bass, Yellow Perch, and Burbot in Lakes Michigan, Huron, Erie, and Ontario. Round Goby continue to be absent from spring bottom trawl assessments in Lake Superior, but their presence in the harbors and embayments of Duluth and Thunder Bay (U.S. Geological Survey and Ontario Ministry of Natural Resources, unpublished data), suggests that there is potential for future colonization.

## Acknowledgements

USGS scientists and technicians Mark Vinson, Daniel Yule, Lori Evrard, Charles Madenjian, David Bunnell, Timothy DeSorcie, Mellissa Kostich, Edward Roseman, Timothy P. O'Brien, Richard Kraus, and Maureen Walsh contributed to data in this report. New York State Department of Environmental Conservation scientist Michael Connerton participated in Lake Ontario data collection. Participants collaborating in the collation of data from Lake Erie included John Deller and Eric Weimer (Ohio Department of Natural Resources), Jim Markham (New York State Department of Environmental Conservation), Chuck Murray and Mike Hosack (Pennsylvania Fish and Boat Commission), and Justin Trumpickas and Andy Cook (Ontario Ministry of Natural Resources).

## Status and Trends in the Lake Superior Fish Community, 2015

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### Abstract

In 2015, the Lake Superior fish community was sampled with daytime bottom trawls at 76 nearshore and 33 offshore stations. Spring and summer water temperatures in 2015 were colder than average, but warmer than that observed in 2014. In the nearshore zone, a total of 11,882 individuals from 22 species or morphotypes were collected. Nearshore lakewide mean biomass was 1.8 kg/ha, which was near the lowest biomass on record for this survey since it began in 1978. In the offshore zone, a total 12,433 individuals from 8 species or morphotypes were collected lakewide. Offshore lakewide mean biomass was 5.9 kg/ha. The mean of the four previous years was 7.1 kg/ha. The abundance of age-1 Cisco was 14.3 fish/ha which was similar to that measured in 2009. We collected larval *Coregonus* in surface trawls at 94 locations and estimated a nearshore lakewide average density of 1,459 fish/ha which was nearly twice that measured in 2014.

### Introduction

The U.S. Geological Survey Lake Superior Biological Station conducts annual daytime bottom trawl surveys in nearshore (~15-80 m) and offshore (100-300 m) waters of Lake Superior. These surveys provide data for assessment of long-term trends in lakewide fish species occurrences, relative abundance, and biomass. Rather than absolute abundance and biomass estimates, these data have historically been considered population indices. Age and diet analyses are conducted for selected species. The nearshore survey has been conducted in spring since 1978 in U.S. waters and since 1989 in Canadian waters. The offshore survey has been conducted in summer since 2011. We report population biomass estimates for a number of common species and recruitment indices of the density of age-1 fish for selected commercial and recreational species (Rainbow smelt, Cisco, Bloater, Lake Whitefish, and Lake Trout, scientific names are provided in Table 1) from nearshore surveys, and population biomass estimates from offshore surveys. Results presented for age-1 and older fish are based solely on bottom trawl sampling, so fishing gear bias should be considered when interpreting the results of this survey particularly for species with lower vulnerability to daytime bottom trawls, such as adult Cisco, and adult Lake Trout. In addition to benthic fish sampling we collected larval fish near the surface, vertical zooplankton samples, and water profiles for a number of physical and chemical attributes. We report on larval fish collections and water temperatures.

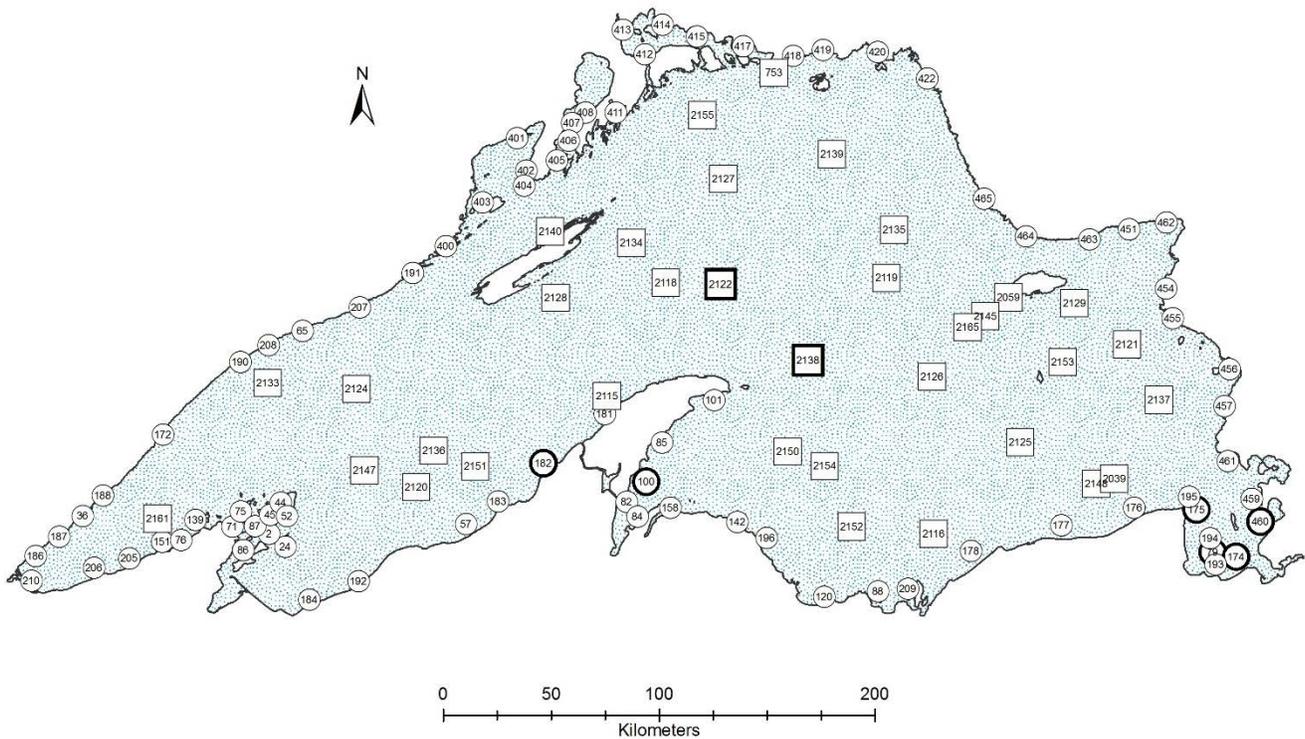
### Methods

#### *Nearshore survey*

Nearshore sites are located around the perimeter of the lake (Figure 1). In 2015, 76 of the 82 long-term sampling locations were sampled between 18 May and 17 June 2015 (Figure 1). Six locations were not sampled due to commercial fishing operations or mechanical problems. At each location, a single bottom trawl tow was conducted with a 12-m Yankee bottom trawl. The median start and end depths for bottom trawl tows were 17 m (range 7-37 m) and 56 m (range 19-140 m), respectively. The median distance trawled was 1.5 km (range 0.5-4.0 km). The median trawl wingspread was 7.3 m (range 6.5-8.9 m). Fish collections were sorted by species, counted, and weighed in aggregate to the nearest g. Total length was measured on a maximum of 50 individuals per species per trawl. Length data for these

<sup>1</sup>Presented at: Great Lakes Fishery Commission, Lake Superior Committee Meeting, 23 March 2016

individuals were then extrapolated to the entire catch. Relative density (fish/ha) and biomass (kg/ha) were estimated by dividing sample counts and aggregate weights by the area of the bottom swept by each trawl tow (ha). Biomass estimates are reported for all species combined and individually for Cisco, Bloater, Rainbow Smelt, Lake Whitefish, Sculpin species (Slimy Sculpin, Spoonhead Sculpin, and Deepwater Sculpin), and hatchery, lean, and siscowet Lake Trout. For Cisco, Bloater, Lake Whitefish, and Rainbow Smelt, age-1 year-class strength was estimated as the mean lakewide relative density for age-1 fish. Age-1 fish designations were based on lengths as follows; Cisco <140 mm, Bloater <130 mm, Lake Whitefish <160 mm, and Rainbow Smelt <100 mm. Lake Trout densities are presented for small, < 226 mm (ca.  $\leq$  age-3) fish.



*Figure 1. Location of 82 nearshore (circles) and 35 offshore (squares) bottom trawl stations established for sampling the Lake Superior fish community. In 2015, 76 nearshore and 33 offshore sites were sampled. Numbers are station numbers. Nearshore and offshore sites that were not sampled in 2015 are shown with bold outlines.*

### **Offshore survey**

Offshore sites are randomly located around the lake using a spatially-balanced, depth-weighted probabilistic sampling design that targets depths >100 m (Figure 1). Sample sites were selected in 2011 and the same sites have been sampled annually thereafter. In 2015, 33 of 35 established trawl locations were sampled during daylight hours between 7 and 22 July. Two sites were not sampled due to mechanical issues. A single bottom trawl tow was conducted at each site using a 12-m Yankee bottom trawl towed on-contour during daylight hours. Station depths ranged from 89 to 315 m. The median trawl distance was 1.4 km (range 1.2-1.6 km). The median trawl wing spread was 8.9 m (range 8.1-10.3 m). Catches

were processed similarly to that described for nearshore trawls. Biomass estimates are presented for all species and individually for Kiyi, Deepwater Sculpin, and siscowet Lake Trout. These three species make up >95% of the total biomass.

### Larval *Coregonus* collections

A paired 1 m<sup>2</sup> 500 micron mesh neuston net was fished at the lake surface (0.5 m depth) for 10 minutes at 118 locations (most sites shown in Figure 1; all sites shown in Figure 7) between 18 May and 22 July 2015. The purpose of this sampling was to describe the spatial distribution of larval *Coregonus*. We think most of these fish are Cisco, other possible species are Bloater and Kiyi. At this time they cannot be differentiated.

## Results

### Nearshore survey

Water temperatures in 2015 were cooler than average and warmer than that observed in 2014. Surface temperature averaged 3.5 C (range = 2.1-15.6 C) and 3.1 C (range = 2.0-3.9 C) at 100 m (Figure 2). The long-term mean (1991-2015) water temperatures for these same locations and dates is 5.8 C at the surface and 3.1 C at 100 m.

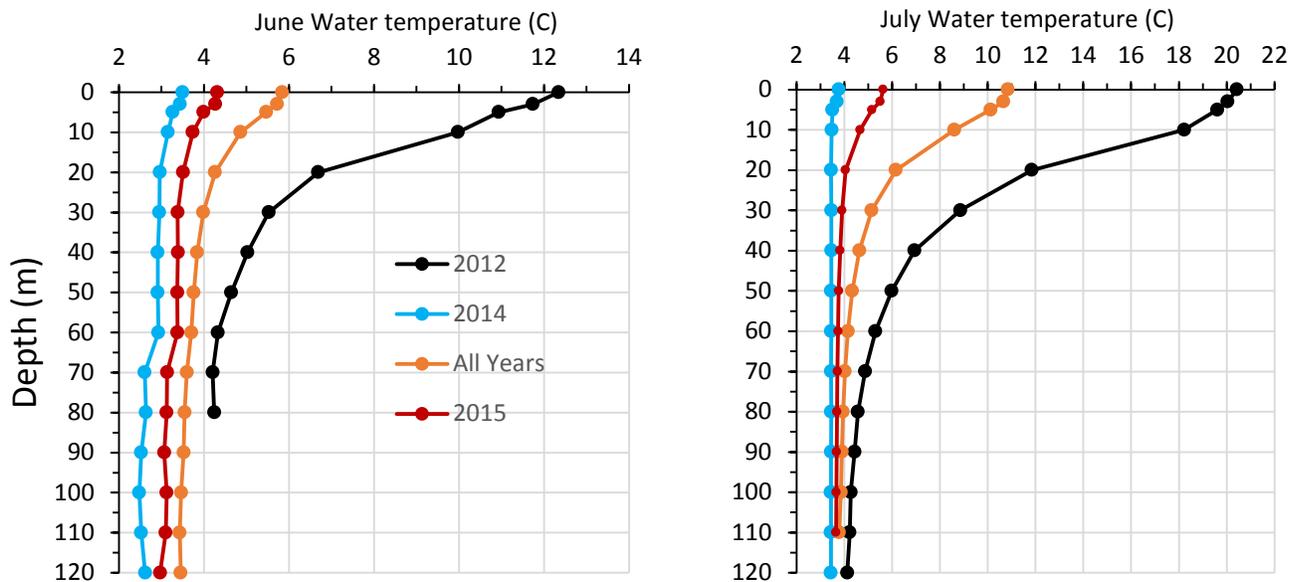


Figure 2 Water temperature profiles for nearshore samples collected in June (left) and for offshore sites collected in July (right). Lines are shown for 2015, 2014 – the coldest year on record, 2012 - the warmest year on record, and the mean for the period of record (1991-2015). For nearshore sites, the mean was calculated for the years 2001-2015. For offshore sites, the mean was calculated for the years 2011-2015.

A total of 11,882 individuals from 22 species or morphotypes were collected (Table 1). The number of species collected at each station ranged from 0 to 15, with a mean of 4.3 and median of 4. Lakewide mean biomass was 1.8 kg/ha, which was one of the lowest values on record and well below the long-term average of 9.0 kg/ha (Table 2, Figure 3). Lakewide median biomass was 0.2 kg/ha in 2015 which was also one of the lowest values on record (Figure 3). Individual station biomass was non-normally

distributed and highly left-skewed (Figure 4). Skewness of the population mean biomass estimates in 2015 was 3.7, which equaled the long-term mean (Figure 4). The highest individual station biomass was estimated for station 76 near Cornucopia, Wisconsin and station 86 near Basswood Island in the Apostle Islands.

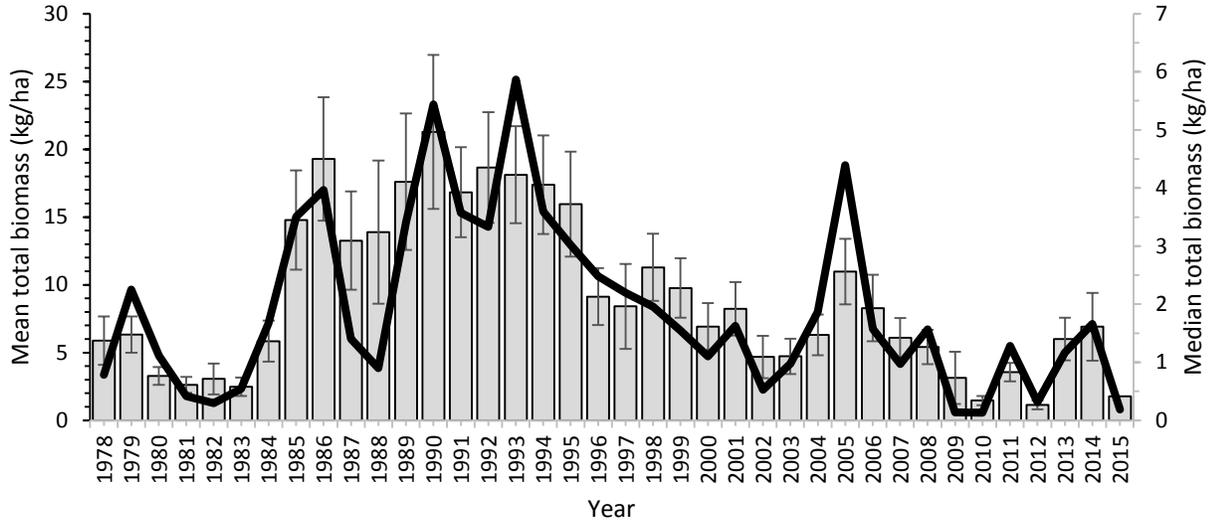


Figure 3. Annual mean  $\pm$  SE (bars, left y-axis) and median (line, right y-axis) lakewide nearshore biomass estimates for all fish species collected in bottom trawls from 1978-2015.

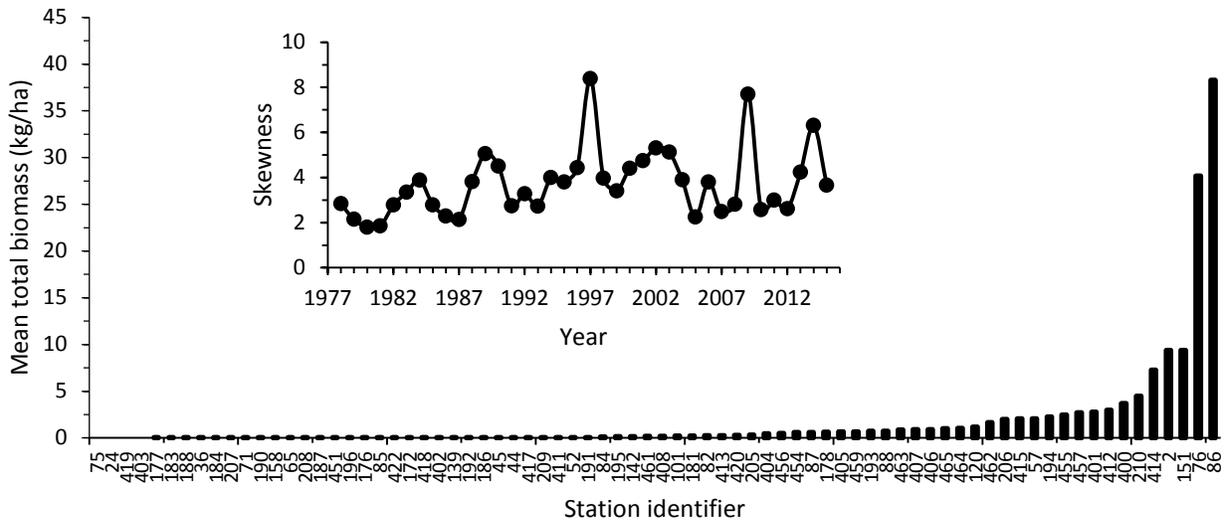


Figure 4. Estimated biomass at individual nearshore sampling stations in 2015. Station locations are shown on Figure 1. The inset plot shows the skewness in the distribution of individual station biomass estimates.

Cisco – Lakewide mean nearshore biomass of Cisco was 0.23 kg/ha in 2015. This was below the long-term average of 2.45 kg/ha and similar to that observed since 2007 (Table 2). Density of age-1 fish was

14.31 fish/ha in 2015, which indicated a small, but measureable recruitment year. This estimate was similar to that observed in 2009. Over the period of record, densities of age-1 Cisco have exceeded 30 fish/ha 8 times and 175 fish/ha 5 times and have been measured as high as 750 fish/ha (Table 3). A density of about 14 age-1 fish/ha (range=11.1-14.3) has been measured in 14 of the 38 years this survey has been conducted.

Bloater – Lakewide mean nearshore biomass for bloater was 0.40 kg/ha in 2015. This was below the long-term average of 1.69 kg/ha (Table 2). Density of age-1 fish was 8.57 fish/ha in 2015. This was the highest density observed since 2005 (Table 3). The highest observed densities of age-1 Bloater is >30 fish/ha.

Lake Whitefish – Lakewide mean nearshore biomass for Lake Whitefish was 0.54 kg/ha in 2015. This was less than the long-term average of 2.14 kg/ha (Table 2). Density of age-1 fish was 1.00 fish/ha in 2015. This was below the long-term average of 7.31 fish/ha (Table 3).

Rainbow Smelt – Lakewide mean nearshore biomass for Rainbow Smelt was 0.22 kg/ha in 2015. This was less than the long-term average of 1.17 kg/ha. This was among the lowest estimates on record for Rainbow Smelt (Table 2). Density of age-1 fish was 30.66 fish/ha in 2015, which is less than the long-term average of 159.01 fish/ ha (Table 3).

Sculpin – Lakewide mean nearshore biomass for Sculpin was 0.02 kg/ha in 2015. This was below the long-term average of 0.06 kg/ha. Sculpin biomass has not exceeded 0.06 kg/ha since 1998 (Table 2).

Other species – The combined mean nearshore lakewide biomass for other species was 0.21 kg/ha in 2015. This was less than the long-term mean of 0.68 kg/ha. Other species include Ninespine Stickleback, Trout-perch, Kiyi, Shortjaw Cisco, Pygmy Whitefish, Round Whitefish, and Longnose Sucker.

Burbot –For the first time since the survey began in 1978, no Burbot were collected in our nearshore survey in 2015. Two Burbot were collected in our offshore survey. Burbot biomass has not exceeded the long-term average of 0.13 kg/ha since 2008 (Table 2).

Lake Trout – No hatchery Lake Trout were collected in our nearshore or offshore survey in 2015. Hatchery Lake Trout biomass has been near zero since 2002 (Figure 5). Lean Lake Trout biomass was 0.08 kg/ha. This was similar to that estimated in 2012. These estimates are the lowest estimates since the early 1980s (Table 2). Siscowet Lake Trout nearshore biomass was 0.08 kg/ha. This was similar to the long-term mean and similar to that observed in 2012, but well below that observed in 2014 (Table 2). Density of age-3 and younger lean and siscowet Lake Trout were 0.14 and 0.06 fish/ha in 2015, respectively. Young lean Lake Trout densities were less than the long-term average and siscowet Lake Trout densities were similar to the long-term average (Table 3).

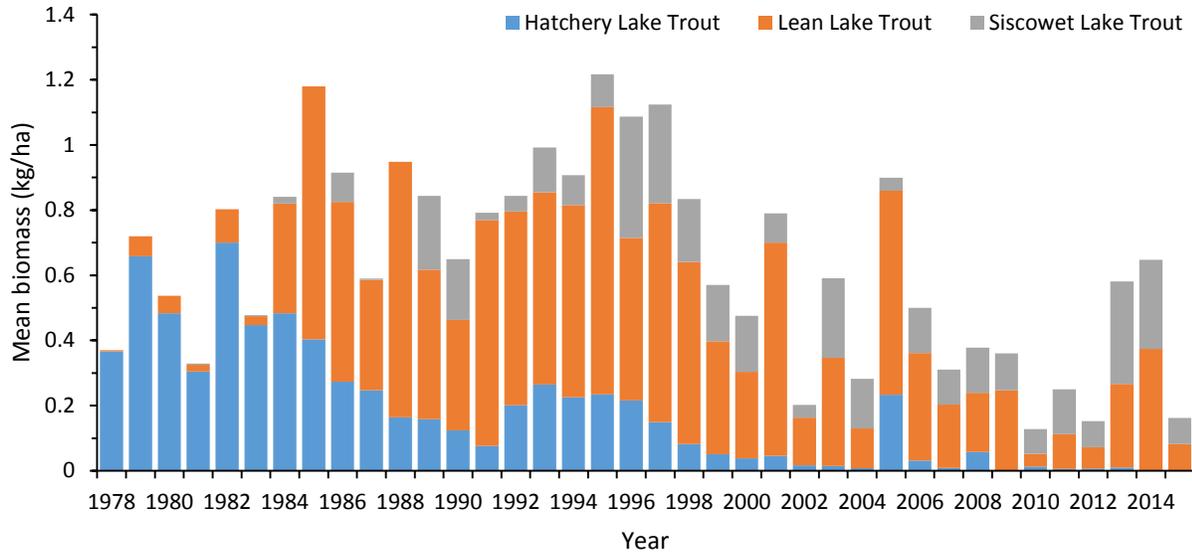


Figure 5. Mean annual lakewide biomass estimates for hatchery, lean, and siscowet Lake Trout estimated from bottom trawls in nearshore locations from 1978-2015.

### Offshore survey

Mean water temperatures throughout the survey period were 5.6 C at the surface and 3.7 C at 100 m (Figure 2). The long-term mean (2011-2015) water temperature at these same locations and dates is 10.8 C at the surface and 3.8 C at 100 m. A total of 12,435 individuals from 9 species were collected lakewide at 33 offshore sites (Table 1). The average and median number of species collected at each station was 3.8 and 4, respectively, and ranged from 1-6. Deepwater Sculpin, Kiyi, and siscowet Lake Trout made up 98% of the total biomass collected in offshore waters at nearly every location (Figure 6). Mean and median lakewide biomass were 5.9 kg/ha and 5.6 kg/ha, respectively (Figure 7). This was less than observed in previous years (Figure 7).

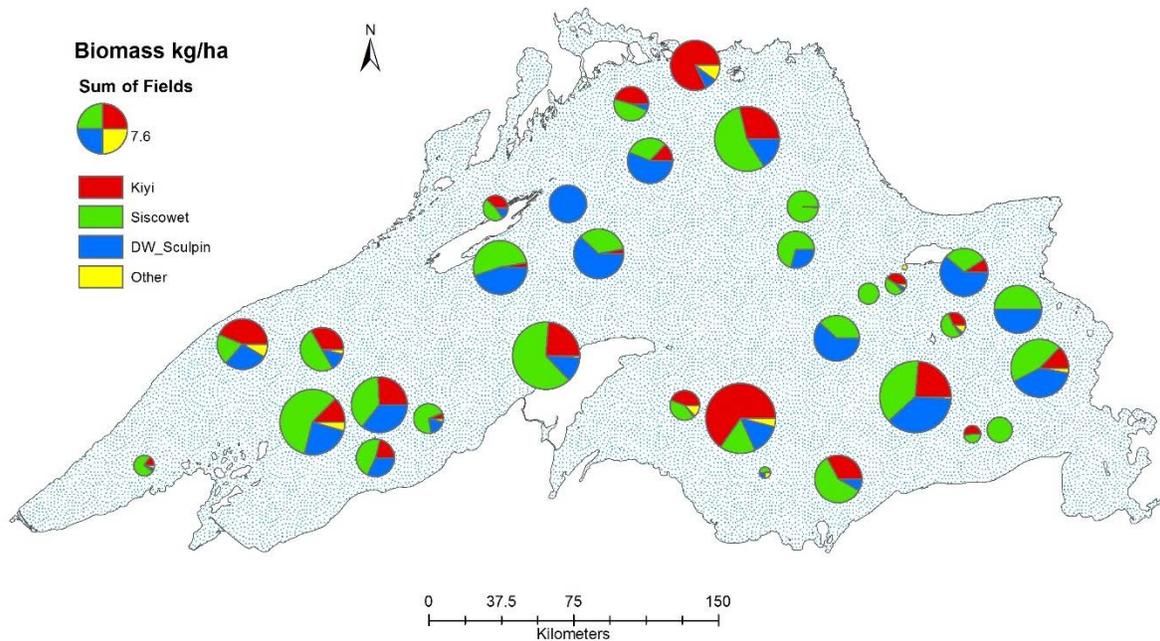


Figure 6. Mean lakewide biomass estimates for Kiyi, siscowet Lake Trout, Deepwater Sculpin, and other species estimated from bottom trawls in offshore locations in 2015. Pie diameter is proportional to the biomass collected at that site and ranged from 0.6-22.1 kg/ha. The pie in the legend is proportional to 7.6 kg/ha with the size of the pies on the map scaled accordingly.

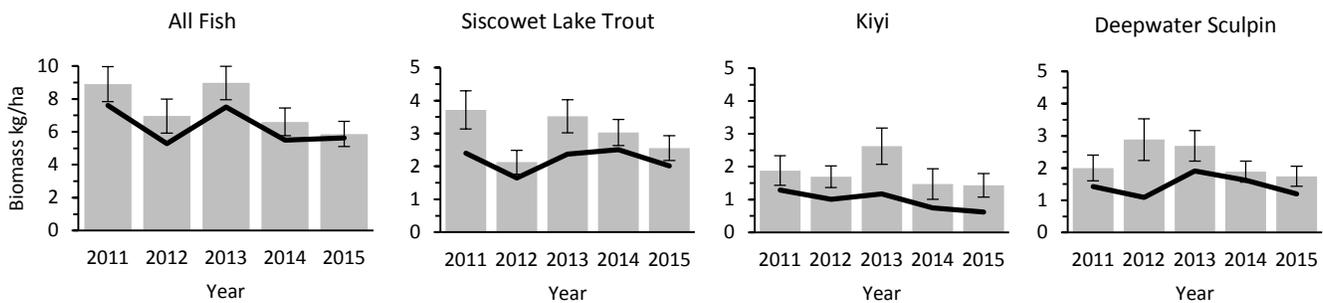


Figure 7. Annual mean  $\pm$  SE (bars) and median (line) lakewide offshore biomass estimates for all species, Kiyi, siscowet Lake Trout, and Deepwater Sculpin collected in bottom trawls from 2011-2015.

Deepwater Sculpin – Lakewide mean offshore biomass of Deepwater Sculpin was 1.7 kg/ha. This was less than observed in previous years (Figure 7).

Kiyi – Lakewide mean offshore biomass of Kiyi was 1.4 kg/ha. This was less than observed in previous years (Figure 7).

Siscowet Lake Trout – Lakewide mean offshore biomass of siscowet Lake Trout was 2.6 kg/ha. This was less than observed in previous years (Figure 7).

### **Larval *Coregonus* collections**

A total of 17,433 larval *Coregonus* were collected. The lakewide nearshore average density was 1,425 fish/ha and ranged from 0-56,747 fish/ha (Figure 8). The lakewide nearshore mean density in 2014 was 577 fish/ha. The total estimated number of larval *Coregonus* lakewide was 26.3 billion with a standard error of  $\pm 1.9$  billion. Larval *Coregonus* collected at the start of the survey on 18 May 2015 were 8-10 mm in length. This suggests a hatch date around mid-May, as this is the length at hatch observed for Cisco raised in the laboratory (Oyadomari and Auer 2008, CJFAS 65:1447-1358). Fish were >20 mm in July. Growth of larval fish (as determined by changes in total length) in 2015 was higher than that observed in 2014 (0.15 mm/day in 2015 and 0.06 mm/day in 2014). We suspect this was related to warmer water in 2014 compared to 2015 (Figure 2).

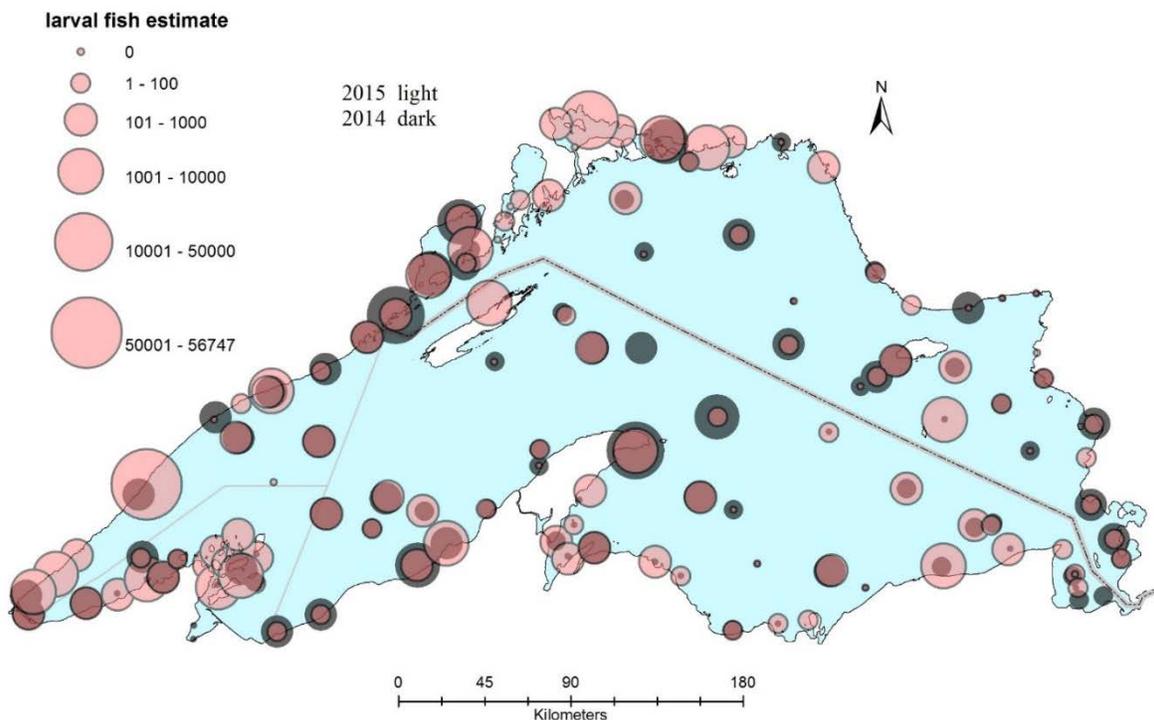


Figure 8. Estimated larval *Coregonus* abundances (number/ha) collected in 2014 and 2015 from surface trawling.

### **Summary**

Over the 38 year history of the nearshore survey, total reported biomass has been largely dependent on recruitment of age-1+ Bloater, Cisco, and Lake Whitefish and survival of Rainbow Smelt to age-3 or older. The lack of significant recruitment of these species in recent years, particularly of Cisco, is of concern to fishery managers. In 2015 we observed a measureable recruitment event of age-1 Cisco and Bloater. For Cisco, the population abundance of this year class was similar to that observed in 2009. For Bloater, it was the highest population recruitment index observed since 2005. Our second year of larval *Coregonus* collections indicated density estimates roughly twice that observed in 2014. Time will tell if this will translate in to a larger age-1 year class in 2016. We plan to continue annual sampling of larval

*Coregonus*. The combination of our near- and offshore bottom and surface trawl surveys provide a lakewide picture of the status and trends of the Lake Superior fish community susceptible to bottom trawls as well as insights into *Coregonus* recruitment dynamics.

**Table 1. Fish species and the number of individuals collected in nearshore and offshore surveys in Lake Superior in 2015. Sampling locations shown on Figure 1.**

Fish	Scientific name	Nearshore	Offshore
Longnose Sucker	<i>Catostomus catostomus</i>	12	0
Unidentified chubs	<i>Coregonus</i>	4	0
Unidentified coregonid	<i>Coregonus</i>	2	0
Cisco	<i>Coregonus artedi</i>	1861	0
Lake Whitefish	<i>Coregonus clupeaformis</i>	380	0
Bloater	<i>Coregonus hoyi</i>	1469	511
Kiyi	<i>Coregonus kiyi</i>	12	1116
Blackfin Cisco	<i>Coregonus nigripinnis</i>	2	0
Shortjaw Cisco	<i>Coregonus zenithicus</i>	102	1
Slimy Sculpin	<i>Cottus cognatus</i>	338	12
Spoonhead Sculpin	<i>Cottus ricei</i>	159	5
Johnny Darter	<i>Etheostoma nigrum</i>	1	0
Ruffe	<i>Gymnocephalus cernuus</i>	7	0
Burbot	<i>Lota lota</i>	0	2
Deepwater Sculpin	<i>Myoxocephalus thompsoni</i>	230	10630
Rainbow Smelt	<i>Osmerus mordax</i>	5531	0
Logperch	<i>Percina caprodes</i>	1	0
Trout-perch	<i>Percopsis omiscomaycus</i>	796	0
Pygmy Whitefish	<i>Prosopium coulteri</i>	458	2
Ninespine Stickleback	<i>Pungitius pungitius</i>	452	0
Lean Lake Trout	<i>Salvelinus namaycush</i>	35	0
Siscowet Lake Trout	<i>Salvelinus namaycush siscowet</i>	19	156
Splake	<i>Salvelinus namaycush X Salvelinus fontinalis</i>	11	0

**Table 2. U.S. Geological Survey spring bottom trawl estimated nearshore mean lakewide biomass (kg/ha) of common fishes in Lake Superior, 1978-2015. Sculpin includes Slimy, Spoonhead, and Deepwater sculpin. All species is the mean and median total biomass for all species. Other species includes Ninespine Stickleback, Trout-Perch, Kiyi, Shortjaw Cisco, Pygmy Whitefish, Round Whitefish, and Longnose Sucker.**

Year	Sites	No fish sites	Number of Species	All species mean	All species median	Rainbow Smelt	Cisco	Lake Whitefish	Bloater	Hatchery Lake Trout	Lean Lake Trout	Siscowet Lake Trout	Burbot	Sculpin	Other. species
1978	43	0	17	5.88	0.78	4.07	0.01	0.70	0.13	0.37	0.00	0.00	0.17	0.14	0.29
1979	49	0	17	6.33	2.25	2.17	0.06	1.27	0.45	0.66	0.06	0.00	0.30	0.20	1.15
1980	48	0	16	3.28	1.11	0.87	0.28	0.58	0.28	0.48	0.05	0.00	0.19	0.19	0.35
1981	48	2	19	2.62	0.42	0.21	0.36	0.67	0.41	0.30	0.02	0.00	0.24	0.18	0.22
1982	32	0	18	3.06	0.29	0.25	0.35	0.85	0.43	0.70	0.10	0.00	0.06	0.03	0.29
1983	50	0	19	2.48	0.54	0.92	0.17	0.20	0.43	0.45	0.03	0.00	0.07	0.06	0.15
1984	53	0	21	5.84	1.67	0.80	0.65	1.30	1.75	0.48	0.34	0.02	0.20	0.06	0.25
1985	53	0	19	14.77	3.50	1.33	6.53	2.14	2.69	0.40	0.78	0.00	0.05	0.08	0.77
1986	53	2	19	19.28	3.97	2.84	8.65	2.65	3.79	0.27	0.55	0.09	0.18	0.07	0.19
1987	53	0	16	13.26	1.40	1.78	5.69	2.00	2.57	0.25	0.34	0.00	0.14	0.07	0.44
1988	53	0	19	13.89	0.90	1.18	3.10	2.40	5.97	0.16	0.78	0.00	0.08	0.04	0.17
1989	76	0	21	17.60	3.41	2.08	6.21	5.54	1.71	0.16	0.46	0.23	0.21	0.08	0.93
1990	81	0	22	21.28	5.44	1.95	10.12	2.36	4.85	0.12	0.34	0.19	0.11	0.08	1.17
1991	84	1	22	16.83	3.57	1.17	10.23	2.74	0.81	0.08	0.69	0.02	0.21	0.10	0.78
1992	85	0	24	18.65	3.33	1.02	3.40	3.70	8.39	0.20	0.59	0.05	0.17	0.07	1.06
1993	87	1	23	18.12	5.86	2.12	4.99	3.67	4.28	0.27	0.59	0.14	0.27	0.08	1.71
1994	87	0	23	17.39	3.59	1.89	7.24	5.42	0.42	0.23	0.59	0.09	0.11	0.08	1.32
1995	87	0	27	15.95	3.02	2.21	3.96	5.84	0.57	0.23	0.88	0.10	0.14	0.09	1.92
1996	87	0	26	9.13	2.48	1.28	1.04	1.63	3.09	0.22	0.50	0.37	0.19	0.11	0.69
1997	85	1	30	8.41	2.20	1.35	1.35	2.77	0.86	0.15	0.67	0.30	0.10	0.06	0.80
1998	87	0	22	11.29	1.95	1.47	1.09	2.26	4.37	0.08	0.56	0.19	0.07	0.07	1.12
1999	83	5	23	9.76	1.54	1.11	2.73	1.28	3.13	0.05	0.35	0.17	0.07	0.04	0.83
2000	85	4	25	6.92	1.10	0.83	2.42	1.60	0.93	0.04	0.27	0.17	0.02	0.04	0.59
2001	83	1	32	8.23	1.63	1.51	1.15	2.78	1.18	0.05	0.65	0.09	0.13	0.04	0.63
2002	84	2	26	4.68	0.53	0.18	1.48	1.69	0.57	0.02	0.15	0.04	0.10	0.02	0.44
2003	86	10	26	4.73	0.98	0.30	0.64	1.84	0.88	0.01	0.33	0.24	0.01	0.02	0.45
2004	75	1	25	6.31	1.87	0.32	1.80	1.88	1.15	0.01	0.12	0.15	0.20	0.03	0.65
2005	52	0	27	10.97	4.39	1.00	2.23	4.37	1.64	0.23	0.63	0.04	0.31	0.01	0.52
2006	55	2	24	8.29	1.57	0.95	2.25	1.70	1.79	0.03	0.33	0.14	0.08	0.02	0.99
2007	56	0	31	6.09	0.97	1.77	0.27	1.86	0.90	0.01	0.19	0.11	0.12	0.02	0.84
2008	59	3	23	5.40	1.57	0.94	0.38	2.37	0.17	0.06	0.18	0.14	0.29	0.02	0.86
2009	64	6	20	3.14	0.14	0.38	0.30	0.15	1.18	0.00	0.25	0.11	0.04	0.02	0.72
2010	76	11	24	1.46	0.13	0.22	0.31	0.27	0.23	0.01	0.04	0.08	0.03	0.05	0.23
2011	82	13	21	3.56	1.28	0.62	0.41	0.94	0.56	0.01	0.11	0.14	0.02	0.05	0.70
2012	72	16	25	1.14	0.31	0.16	0.02	0.15	0.35	0.01	0.07	0.08	0.02	0.03	0.26
2013	79	3	27	6.00	1.17	0.53	0.52	2.98	0.49	0.01	0.26	0.31	0.10	0.02	0.77
2014	73	3	27	6.91	1.66	0.43	0.35	4.31	0.50	0.00	0.37	0.27	0.08	0.02	0.59
2015	76	4	21	1.78	0.19	0.22	0.23	0.54	0.40	0.00	0.08	0.08	0.00	0.02	0.21
Mean	69	2	23	8.97	1.91	1.17	2.45	2.14	1.69	0.18	0.35	0.11	0.13	0.06	0.68

**Table 3. U.S. Geological Survey spring bottom trawl estimated nearshore mean lakewide density (number/ha) of age-1 Cisco, Bloater, Lake Whitefish, and Rainbow Smelt and for small lean and siscowet Lake Trout. Age-1 fish were defined by lengths; Cisco <140 mm, Bloater <130 mm, Lake Whitefish <160 mm, and Rainbow Smelt <100 mm. Lean and siscowet Lake Trout data are for fish <226 mm, ca. < age 3.**

Year class	Sites	Rainbow Smelt	Cisco	Bloater	Lake Whitefish	Lean Lake Trout	Siscowet Lake Trout
1977	43	95.76	0.03	0.82	2.62	0.21	0.00
1978	49	234.14	6.30	30.08	3.90	0.35	0.00
1979	48	96.79	0.11	1.57	1.97	0.25	0.00
1980	48	106.26	13.48	6.85	16.43	0.57	0.07
1981	32	63.81	0.16	0.75	4.16	0.44	0.00
1982	50	103.58	0.05	0.82	0.45	0.41	0.00
1983	53	224.39	21.76	4.74	8.04	1.18	0.00
1984	53	149.51	748.02	44.00	2.47	1.30	0.00
1985	53	150.41	68.92	30.55	3.45	0.86	0.12
1986	53	275.59	5.44	4.23	11.91	0.72	0.04
1987	53	155.27	0.52	6.86	6.11	0.52	0.00
1988	76	274.78	226.80	37.69	36.08	0.26	0.13
1989	81	272.04	425.64	57.26	8.78	0.44	0.05
1990	84	162.03	236.87	11.38	17.54	0.67	0.01
1991	85	176.94	9.08	10.71	11.84	0.81	0.05
1992	87	155.24	3.34	0.22	7.68	0.84	0.20
1993	87	198.62	0.76	0.06	4.95	1.14	0.01
1994	87	401.83	1.47	0.00	13.52	1.71	0.05
1995	87	168.25	0.96	0.05	6.33	2.26	0.21
1996	85	253.04	11.09	0.18	8.80	0.77	0.07
1997	87	145.01	1.18	0.12	7.74	1.21	0.04
1998	83	216.18	90.76	0.40	9.17	0.33	0.10
1999	85	58.40	3.85	0.48	0.77	0.36	0.01
2000	83	256.32	0.83	0.12	2.37	0.52	0.03
2001	84	56.79	0.53	0.12	13.68	0.24	0.06
2002	86	77.83	33.20	0.58	7.74	0.18	0.03
2003	75	70.28	175.34	27.22	6.36	0.25	0.03
2004	52	110.39	8.19	12.07	2.97	0.60	0.07
2005	55	249.56	18.58	13.64	5.51	0.48	0.21
2006	56	360.93	0.41	0.32	19.74	0.10	0.05
2007	59	280.69	0.20	0.28	0.63	0.20	0.09
2008	64	71.64	0.27	0.59	3.00	0.07	0.07
2009	76	45.22	14.03	2.46	6.64	0.03	0.05
2010	82	73.98	0.30	0.75	3.98	0.43	0.03
2011	72	11.05	0.03	0.05	1.90	0.40	0.06
2012	79	142.90	0.17	0.22	5.46	0.36	0.06
2013	73	68.46	0.01	0.06	2.27	0.00	0.06
2014	76	30.66	14.31	8.57	1.00	0.14	0.06
Mean	69	159.07	56.39	8.34	7.31	0.57	0.06

## Status and Trends of Pelagic Prey Fish in Lake Huron, 2015<sup>†</sup>

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### Abstract

The USGS Great Lakes Science Center has conducted integrated acoustic and mid-water trawl surveys of Lake Huron during 1997 and annually from 2004-2015. The 2015 survey was conducted during September and included transects in Lake Huron's main basin, Georgian Bay, and North Channel. Mean lake-wide total pelagic fish density was 1,313 fish/ha and mean total pelagic fish biomass was 10.7 kg/ha in 2015, which represents 77% and 92%, respectively of the long-term mean. Mean lake-wide biomass was 13% higher in 2015 as compared to 2014. The total estimated lake-wide standing stock biomass of pelagic fish species was ~50 kt, consisting almost entirely of bloater (36.8 kt; 74%) and rainbow smelt (12.5 kt; 25%). No alewives were captured during the 2015 survey. Age-0 rainbow smelt abundance increased from 129 fish/ha in 2014 to 475 fish/ha in 2015. Biomass of age-1+ rainbow smelt decreased from 2.8 kg/ha in 2014 to 2.2 kg/ha in 2015. Age-0 bloater abundance increased from 35 fish/ha in 2014 to 315 fish/ha in 2015. Biomass of age-1+ bloater increased from 6.2 kg/ha in 2014 to 7.1 kg/ha in 2015. Emerald shiner density increased from 0.1 fish/ha in 2014 to 37 fish/ha in 2015 and biomass increased from < 0.001 kg/ha in 2014 to 0.02 kg/ha in 2015. Bloater and rainbow smelt will continue to be the primary pelagic species available to offshore predators in coming years, with reduced numbers of rainbow smelt if recruitment to older ages remains poor. Pelagic fish biomass in Lake Huron is greater than that observed in recent lake-wide acoustic surveys of Lake Michigan and Lake Superior, but species composition differs among the three lakes. Of the three upper Great Lakes, Lake Superior had the greatest pelagic prey fish diversity and occurrence of native species, while Lake Michigan had the lowest species diversity and lowest native fish prevalence, whereas Lake Huron was intermediate in regards to both.

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<sup>†</sup>Presented at: Great Lakes Fishery Commission  
Lake Huron Committee Meeting  
Milwaukee, WI, March 21, 2016

## **Introduction**

The U.S. Geological Survey's Great Lakes Science Center (GLSC) has conducted bottom trawl surveys of the Lake Huron fish community since the 1970s. These surveys have tracked broad-scale changes in the fish community and provided valuable information on prey fish dynamics to fishery managers tasked with balancing predatory demand by native and introduced salmonines. Although bottom trawling has been an important tool for monitoring long-term trends in fish populations, integrated acoustic and mid-water trawl surveys were implemented because it was recognized that a substantial proportion of the prey fish biomass was distributed in pelagic zones, which could not be measured using bottom trawl gear. Recent research has further shown that acoustic and mid-water trawling methods are better at assessing species or life stages that are pelagic, particularly over lake areas with rough bottom (Fabrizio et al. 1997, Stockwell et al. 2007, Yule et al. 2008). Acoustic surveys were first conducted during the 1970s, but the first lake-wide acoustic survey that included all of Lake Huron's distinct basins was conducted in 1997. Annual surveys have been conducted since 2004; however, only the main basin was sampled during 2006. The purpose of this report is to provide abundance and biomass estimates for major pelagic offshore prey fish species in Lake Huron which constitute the bulk of prey resources for introduced and native piscivores.

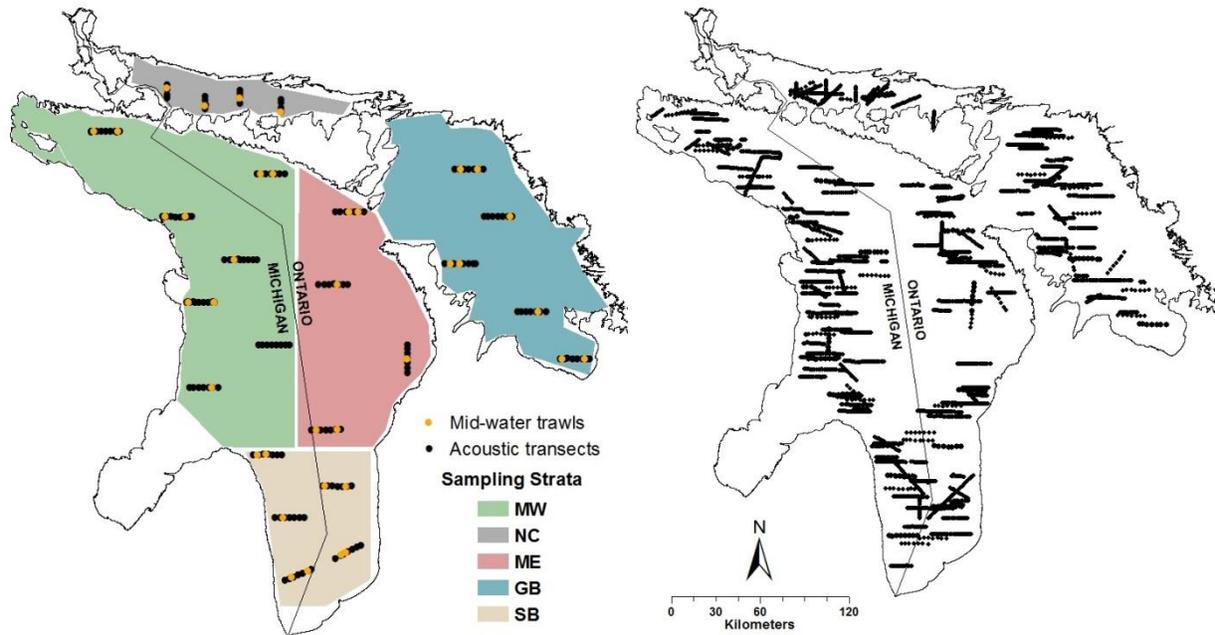
## **Survey and analytical methods**

The pelagic prey fish survey in Lake Huron is based on a stratified-random design with acoustic transects in five geographic strata: eastern main basin (ME), western main basin (MW), southern main basin (SB), Georgian Bay (GB), and the North Channel (NC) (Figure 1). Saginaw Bay was omitted because of its shallow depth and its prey fish community is surveyed by other methods (Fielder and Thomas 2014). Within each stratum, the first transect was selected randomly each year based on latitude and longitude; subsequent transects were spaced evenly around the first. Effort (transects per stratum) was allocated based on stratum area and variability of total biomass in each stratum from previous surveys (Adams et al. 2006). For analysis, each transect was divided into 10 m bottom contour intervals and 5-10 m depth layers (1997), 1,000 m distance intervals and 10 m depth layers (2004-2011), or 3,000 m distance units and 10 m depth layers (2012-2015).

The 2015 pelagic fisheries survey was completed from 8-29 September. Sampling was conducted by both the GLSC (R/V *Sturgeon*) and USFWS (M/V *Spencer F. Baird*). Twenty-five acoustic transects were sampled, resulting in approximately 460 km of acoustic data. Thirty-seven mid-water trawl tows were conducted in conjunction with acoustic data collection.

Fish species were collected using a 15-m headrope mid-water trawl (USGS) and a 21-m headrope mid-water trawl (USFWS). Mid-water trawl locations and depths were chosen to target fish aggregations, but multiple tows per transect were conducted when fish were present so that trawl data within a stratum were available from each scattering layer formed by fish. At a minimum, a single mid-water trawl was conducted on each transect except in rare instances when very few fish targets were detected. Trawl fishing depth was monitored using a Netmind™ system (GLSC) and a Simrad PI44 catch monitoring system (USFWS). In 2015, trawling depths ranged from 4 to 70 m (mean = 28 m, mode = 20 m). Most mid-water trawl tows were of 20 minutes duration, with tow times extended up to 25 or 30 minutes when few fish were present. All fish captured in the mid-water trawl tows were identified, counted, and weighed in aggregate

(g) by species. Total length in millimeters was measured on a random subsample (100-200 fish) per species per tow. Individual fish were assigned to age categories (age-0 or age 1+) based on the following length cutoffs: alewife *Alosa pseudoharengus* = 100 mm; rainbow smelt *Osmerus mordax* = 90 mm; bloater *Coregonus hoyi* = 120 mm. Based on previous age estimates for these species, these lengths approximate the lengths of the smallest age-1 fish of these species.



**Figure 1. Location of acoustic transects and mid-water trawls, and delineation of sampling strata in Lake Huron during 2015 (left) and location of acoustic transects during surveys in 2004-2014 (right).**

Density (fish/ha) of individual species was estimated for each transect as the product of acoustic fish density and the proportion of each species (by number) in the mid-water trawl catches at that location. Total density per species was subdivided into age-0 and age-1+ age-classes by multiplying total density by the numeric proportions of each age group. Biomass (kg/ha) of each species was estimated for each transect as the product of density and size-specific mean mass estimated from fish lengths in trawls, and length-weight relationships. The arithmetic mean and standard error are presented for total and species specific density and biomass estimates for the survey area.

Mean, standard error, and confidence limits for density and biomass for the entire survey area (all three basins pooled) were estimated using stratified cluster analysis methods in SAS (SAS Institute Inc. 2007). Cluster sampling techniques are appropriate for acoustic data, which represent a continuous stream of autocorrelated data (Williamson 1982, Connors and Schwager 2002). Density and biomass values for each elementary sampling unit (ESU) in each stratum were weighted by dividing the stratum area by the number of ESUs in the stratum.

Acoustic equipment specifications, software versions, single target detection parameters, noise levels, and detection limits can be found in appendices 1 and 2. Supplemental methods on acoustic analysis methods and acoustic equipment can be found in appendix 3.

## RESULTS

### Density and biomass by species

Alewife – During 2015, no alewives were caught in mid-water trawls that sampled a broad range of depths in Lake Huron. Alewife densities estimated in 1997, 2005-2006, 2008, and 2013 were considerably higher than other years in the time series. However, we note that density differences, though substantial, did not mean that alewives have been especially abundant in any survey year (Figure 2). During 1997, the year of highest abundance, alewives were only 3.1% of total fish density.

Acoustic estimates of alewife biomass have remained low for the last decade despite large fluctuations in density during 2004-2013 (Figure 2). Temporal biomass differences were largely due to differences in size and age structure between 1997 and other years. In 1997, age 1+ alewife was captured, but low biomass during 2004-2014 was the result of trawl catches dominated by age-0 fish (Figure 2). Since 2004, alewives have never comprised more than 2 % of pelagic fish biomass. Although mid-water trawl catches of age-0 alewives occurred during some acoustic surveys, recruitment has been limited and alewives have shown no sign of returning to higher abundance. Our findings are consistent with results from annual bottom trawl surveys (Roseman et al. 2015), which indicated that alewife density and biomass remain low in the open waters of Lake Huron (i.e., < 1 fish/ha, < 1kg/ha, respectively).

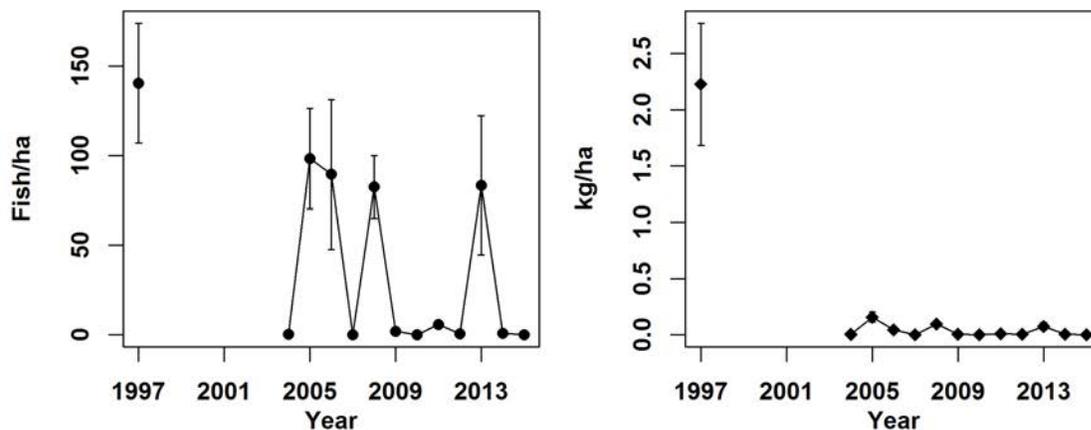


Figure 2. Acoustic and mid-water trawl estimates of alewife numeric density (fish/ha; left panel) and biomass (kg/ha; right panel) in Lake Huron, 1997-2015. Error bars represent  $\pm 1$  standard error.

Rainbow smelt – During 2015, age-0 rainbow smelt density increased from 2014 estimates to 66% of the long-term mean (Figure 3). Age-0 rainbow smelt populations are considerably less than the high observed in 1997, but there has been no clear trend in abundance since 2004. Age 1+ rainbow smelt biomass decreased from 2.8 kg/ha in 2014 to 2.2 kg/ha in 2015. This was roughly 50% of the long-term mean of 4.4 kg/ha (Figure 3) and substantially less than that observed in 1997.

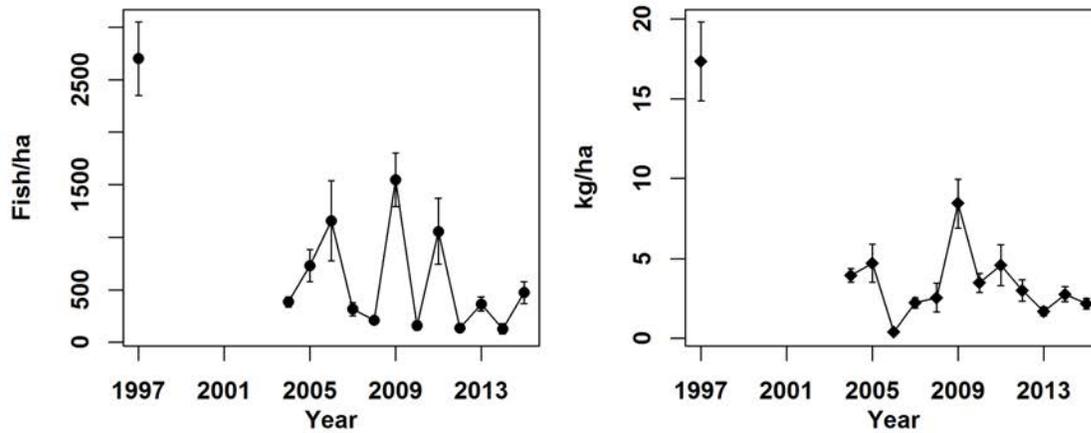


Figure 3. Acoustic and mid-water trawl estimates of rainbow smelt age-0 numeric density (fish/ha; left panel) and age-1+ biomass (kg/ha; right panel) in Lake Huron, 1997-2015. Error bars represent  $\pm 1$  standard error.

Bloater – Estimates of age-0 bloater numeric density showed a nine-fold increase between 2014 and 2015 (Figure 4). Estimated biomass of age-1+ bloater increased from 6.2 kg/ha in 2014 to 7.1 kg/ha in 2015 (Figure 4) however, the standard error around this estimate was large, indicating lower precision. Acoustic estimates of age-0 bloater were low during 1997 (<4 fish/ha, Figure 4). Similar to results from bottom trawl surveys, age-0 bloater density was variable but increased during 2004-2014 (average density > 160 fish/ha). Biomass of age-1+ bloater showed an increasing trend from 2004-2008, followed by a decrease from 2009-2010. Abundance of age-1+ bloater remained relatively unchanged during 2011-2013. Although we have seen increased bloater biomass during the past two years, relative standard error for these estimates ranged from 40-50% indicating low equitability in distribution of biomass throughout Lake Huron. Much of the biomass is driven by bloater aggregations in the southern main basin.

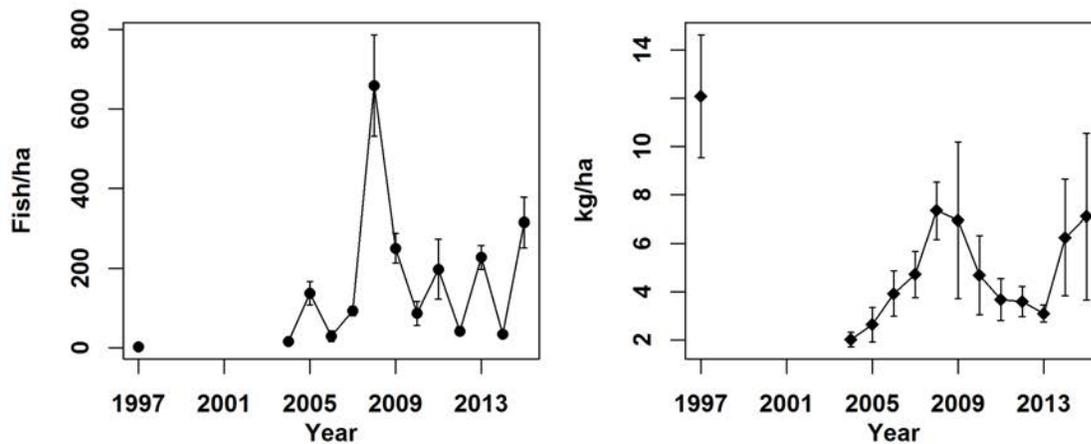


Figure 4. Acoustic and mid-water trawl estimates of bloater age-0 numeric density (fish/ha; left panel) and age-1+ biomass (kg/ha; right panel) in Lake Huron, 1997-2015. Error bars represent  $\pm 1$  standard error.

Emerald shiner – In 2015, emerald shiner biomass increased from 2014 estimates and was 24% of the long-term mean of 0.10 kg/ha (Figure 5). Mean biomass of emerald shiner was estimated to be < 0.01 % of total pelagic fish biomass in 2014, but increased to 0.22 % of total biomass in 2015. Emerald shiner biomass averaged 1.6% of total fish biomass during 2004-2014, but with the exception of 2006, rarely exceeded 1% of total fish biomass in a given year.

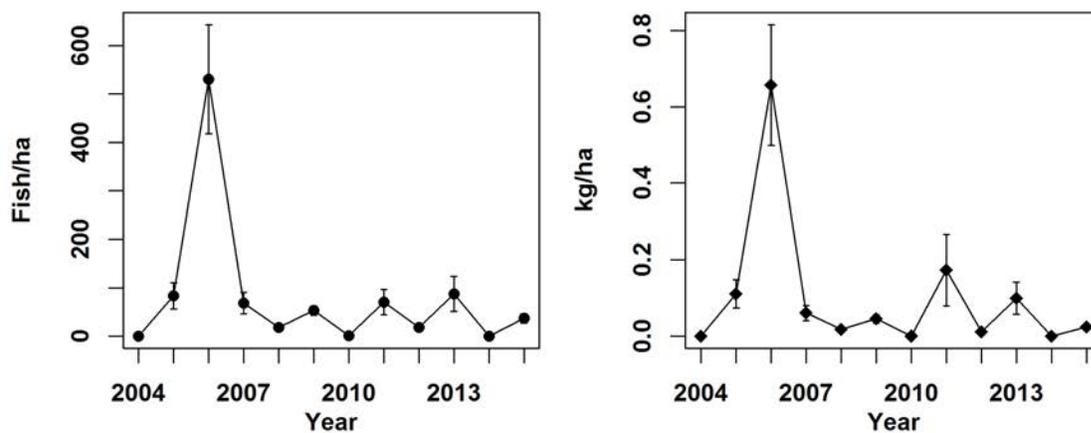


Figure 5. Acoustic and mid-water trawl estimates of emerald shiner numeric density (fish/ha; left panel) and biomass (kg/ha; right panel) in Lake Huron, 2004-2014. Error bars represent  $\pm 1$  standard error.

Other species - Other species captured during acoustic and mid-water trawl surveys included threespine stickleback *Gasterosteus aculeatus*, lake whitefish *Coregonus clupeaformis*, lake trout *Salvelinus namaycush*, and cisco *Coregonus artedi*. These species compose a small proportion of the mid-water trawl catch. In the case of cisco, catches have occurred in most years during acoustic surveys but their density remains low in open waters of the lake during September and October. During October in northern Lake Huron, cisco are primarily distributed in shallow, near shore areas (M.P. Ebener, Chippewa Ottawa Resource Authority, personal communication). Our acoustic and mid-water trawl surveys primarily operate in deeper waters (>15 m) during the fall, and therefore do not effectively sample cisco that are likely more concentrated in nearshore areas. Cisco are occasionally caught in mid-water trawls but catches are too sporadic to be able to use trawl proportions to apportion acoustic densities. During 2015, several small cisco (< 200 mm TL) were caught in the North Channel and two larger cisco (441 mm and 376 mm TL) were caught offshore in Georgian Bay. During 2004-2014, catches of cisco were similarly low during acoustic surveys.

### **Among-basin comparisons of fish biomass**

In 2015, pelagic fish biomass increased in the main basin and decreased in both the North Channel and Georgian Bay. Biomass in the North Channel (12.1 kg/ha) was roughly 63% of the long-term mean and decreases were driven by lower biomass of both age-1+ rainbow smelt and bloater (Figure 6.). Main basin biomass (12.9 kg/ha) showed a 28% increase from 2014 due to increases in age-1+ bloater and a slight increase in age-0 rainbow smelt. Biomass in Georgian Bay (4.1 kg/ha) declined to 37% of the long-term mean due to decreases in age-1+ rainbow smelt. Bloater biomass increased slightly in Georgian Bay during 2015 (Figure 6). In addition to differences in fish biomass, the three basins have had different temporal trends in biomass and community composition. In both Georgian Bay and the main basin, fish biomass has declined relative to 1997, but there is no evidence of a declining trend in the North Channel (Figure 6). Community composition differences are predominantly the result of variation in the proportion of biomass comprised by rainbow smelt and bloater. Most biomass in Georgian Bay has been in the form of rainbow smelt (54% average), while biomass in the main basin has consisted of varying proportions of rainbow smelt and bloater. Since 2012, bloater has been the dominant contributor in the main basin, averaging 72% of pelagic fish biomass (Figure 6). In the North Channel rainbow smelt have comprised 73% of biomass on average.

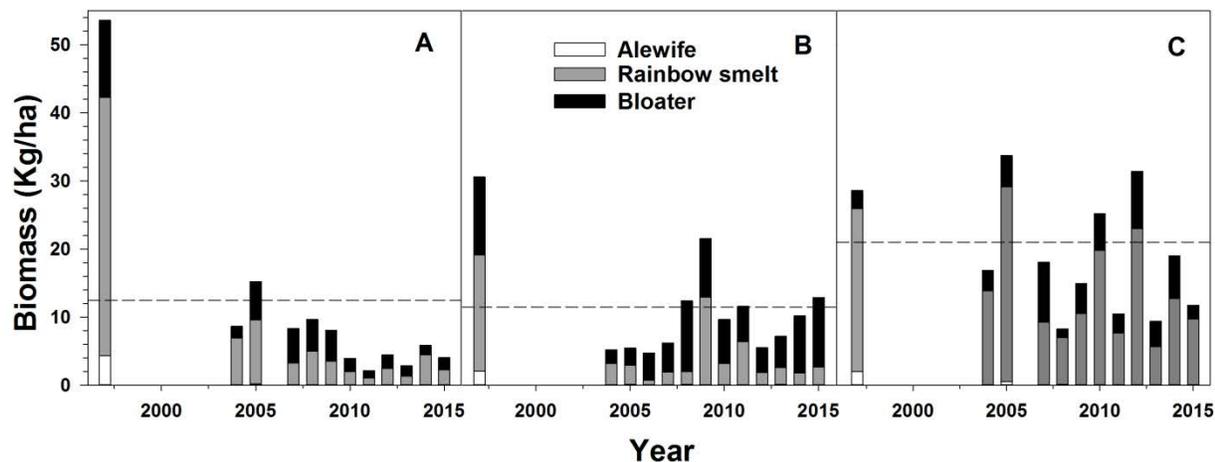


Figure 6. Biomass (kg/ha) of major pelagic fish species in Georgian Bay (panel A), main basin (panel B), and North Channel (panel C) during 1997-2015. Horizontal lines denote 1997-2014 mean density.

### Lake-wide fish density and biomass

Lake-wide mean pelagic fish density increased from 729 fish/ha in 2014 to 1,313 fish/ha in 2015, representing 77% of the long-term mean (Figure 7). The 2015 pelagic fish density estimate represented 26% of that observed in 1997. The 2015 lake-wide mean pelagic fish biomass estimate was 10.6 kg/ha, a 12.5% increase from 2014. Total standing stock biomass in 2015 was estimated at 50 kt (SE 16.3 kt) (Figure 7). This was slightly greater than that observed in 2014 (Figure 7) and was driven by higher biomass of age-1+ bloater in the main basin. In general, acoustic estimates of pelagic fish biomass in Lake Huron have shown no consistent trend between 2004 and 2015. However, biomass has been considerably lower than in 1997 when rainbow smelt and bloater were more abundant in Georgian Bay and the main basin, and alewife was more abundant throughout the lake.

Estimates derived from the lake-wide acoustic survey, as with any other type of fishery survey, include assumptions about the sampling and data analysis techniques. For example, we assumed that the areas sampled were representative of the respective basins. This survey sampled areas of Lake Huron from 10 to 250 m in depth. This depth range encompasses about 85% of the total surface area of Lake Huron. However, nearshore zones and large shallow embayments, especially Thunder Bay, Saginaw Bay, and Parry Sound, are not sampled. These areas could be responsible for high rates of pelagic fish production (Fielder and Thomas 2014, Höök et al. 2001, Klumb et al. 2003), but could not be sampled safely due to the draft of our research vessel (3 m). Given the small surface areas of these shallow-water embayments relative to the total surface area, densities would need to be considerable to influence the lake-wide mean. We conducted sufficient mid-water trawls to achieve an acceptable degree of confidence in fish community composition, according to guidelines in Warner et al. (2012). An additional assumption was that fish size was a reasonable proxy for age-0 or age-1+ groupings. We used size to assign age and assumed no overlap in age among size classes. This assumption was likely violated, especially for rainbow smelt. While this might have slight effects on our estimates of age-0 versus age-1+ density and biomass, it would have no impact on our estimates of total density or biomass for a species.

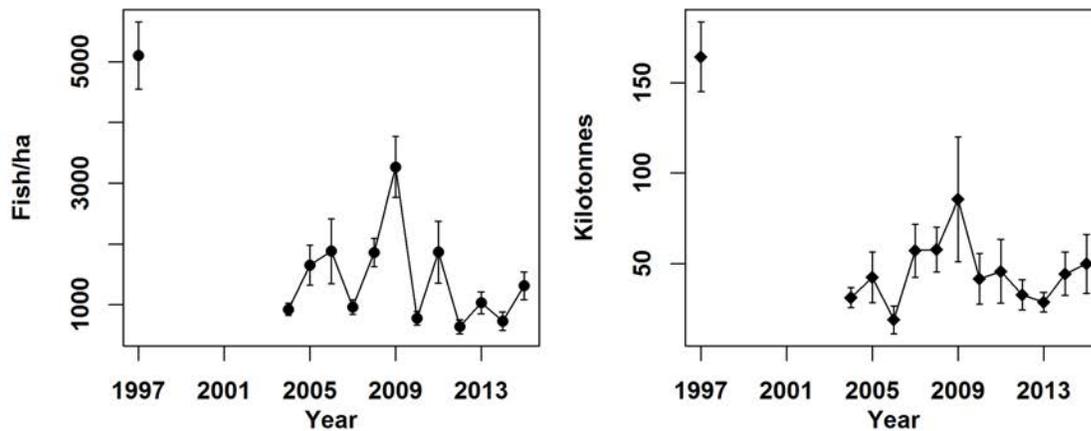


Figure 7. Acoustic and mid-water trawl estimates of lake-wide numeric density (fish/ha; left panel) and standing stock biomass (kilotonnes; right panel) in Lake Huron, 1997-2015. Error bars represent  $\pm 1$  standard error.

## CONCLUSIONS

Higher age-0 production and adult biomass during 2015 indicate bloater will continue to be the most available pelagic prey species in the offshore zone of Lake Huron. Although lake-wide preyfish biomass increased in 2015, we note that biomass was only 30% of the 1997 estimate. This decline is primarily due to reduced biomass of rainbow smelt, which in 2015 was only 13% of the 1997 estimate of 21 kg/ha. Biomass of rainbow smelt in the main basin will likely remain low during 2016 given recent declining trends in recruitment for this species (O'Brien et al. 2014) and lower adult biomass in 2015. During 2016, pelagic prey available to piscivores will likely be similar to that seen in recent years, although offshore predators such as lake trout will have increased numbers of adult bloater available as forage.

Lake-wide pelagic biomass in Lake Huron during 2015 was higher than that estimated for Lake Michigan during 2015 (4.2 kg/ha, Warner et al. 2016) and Lake Superior during 2011 (6.8 kg/ha, Yule et al. 2013). In addition to differences in lake-wide biomass in recent years, pelagic fish community composition differs considerably between the three lakes. In Lake Michigan, alewife is still prevalent and comprises about 70% of the pelagic biomass, while in lakes Huron and Superior, the biomass of this species is negligible. Additionally, native coregonines and other species are at historic low levels in Lake Michigan. Native species constitute much higher proportions of total biomass in lakes Huron and Superior. In the case of Lake Superior, kiyi (*Coregonus kiyi*) are numerically dominant at depths > 100 m, while cisco are most of the biomass (Yule et al. 2013). In Lake Huron, rainbow smelt are numerically more abundant, while rainbow smelt and bloater have been alternating roles as the dominant contributor to total biomass, with bloater contributing more in recent years. Additionally, there have been relatively consistent (but low) catches of emerald shiner and cisco in Lake Huron mid-water trawling. In the case of emerald shiner, it is likely that their reappearance was the result of a release from predation on fry following the collapse of alewife (Madenjian et al. 2008; Schaeffer et al. 2008).

To provide accurate estimates of available prey fish resources in Lake Huron, the continuation of acoustic surveys will be instrumental in assessing the pelagic component of the prey fish community, while complementing bottom trawl surveys that better estimate benthic prey resources. The information gathered from acoustic surveys that sample areas where bottom trawling is not feasible will increase our understanding of variation in prey fish biomass across large temporal and spatial scales (i.e., all of Lake Huron's basins). As no single gear is best for assessing all species, life stages, or habitats, estimates of fish biomass from multiple gear types will lead to a better understanding of ecosystem dynamics.

**Acknowledgements:** We thank the vessel crews and biologists of the R/V *Sturgeon*, R/V *Grayling*, and M/V *Spencer Baird* for their assistance with the night field surveys. We thank Capt. Shawn Parsons, Lyle Grivicich, Erin Grivicich, and Deirdre Jordan for their support of 2015 field operations. Scott Nelson, Dan Benes, and Limei Zhang provided computer and database support. Mark Vinson and Chris Davis provided helpful reviews of this report. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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### Appendix 1. Single target detection parameters used in acoustic data analyses in 2015.

Parameter	Value
TS threshold (dB)	-77 <sup>1</sup>
Pulse length determination level (dB)	6
Minimum normalized pulse length	0.7
Maximum normalized pulse length	1.5
Maximum beam compensation (dB)	6
Maximum standard deviation of minor-axis angles	0.6
Maximum standard deviation of major-axis angles	0.6

<sup>1</sup> Only targets  $\geq -60$  dB were included in analysis

### Appendix 2. Noise levels, detection limits, and acoustic equipment specifications in Lake Huron, 2015.

Vessel	R/V Sturgeon	M/V Spencer Baird
Collection software	Visual Acquisition 6.0	ER60 2.2
Transducer beam angle (3dB)	8.46° split beam	6.18° split beam
Frequency (kHz)	120	120
Pulse length (ms)	0.4	0.256
Sv noise at 1 m (dB)	-125	-125
2 way equivalent beam angle	-19.39	-20.50
Detection limit (m) for -60 dB target <sup>2</sup>	>100	>100

<sup>2</sup> Assuming 3 dB signal-to-noise ratio.

### Appendix 3. Supplement to methods

Acoustic data collected in 1997 were analyzed using custom software (Argyle et al. 1998). Data collected in 2004 and later years were analyzed using Echoview<sup>TM</sup> software, which provided fish density estimates for each sampling unit. Fish density was calculated as:

$$Density (fish / ha) = 10^4 \cdot \frac{ABC}{\sigma}$$

where  $ABC$  was the area backscattering coefficient ( $m^2 / m^2$ ) of each 10 m high by 1000-3,000 m long cell, and  $\sigma$  was the mean backscattering cross section ( $m^2$ ) of all targets between -60 and -30 dB in each cell. The lower threshold should have included any age-0 alewives present (Warner et al. 2002), but may have underestimated age-0 rainbow smelt density (Rudstam et al. 2003). The upper threshold excluded fish larger than our species of interest.

In 1997, a BioSonics model 102 dual-beam echosounder was used to collect acoustic data during pelagic fish surveys. During 2004-2005 and 2007-2008 acoustic data were collected during

September through early October with a BioSonics split-beam 120 kHz echosounder deployed from the Research Vessel (R/V) *Sturgeon*. During 2006, acoustic data were collected during August with a 70 kHz echosounder and a transducer deployed via towfish from the R/V *Grayling*. During 2009, the survey was performed with a 38 kHz echosounder because the 120 kHz transducer failed field calibration tests. In 2010-2015, we used both a 38 and 120 kHz echosounder to facilitate frequency comparisons, but with the exception of 2009, only 120 kHz data are presented in this report. Comparison of paired 120 kHz and 38 kHz data revealed that a) density estimates from 38 kHz are higher than from 120 kHz, b) this difference does not vary among fish species, and c) fish density estimates from the two frequencies are highly correlated ( $r^2 = 0.77$ ). In order to provide estimates for 2009 that would have been equivalent to 120 kHz, we predicted the 2009 fish density estimates using the 38 kHz estimates and a regression model relating the two from data collected in subsequent years. Additionally, studentized residual plots indicated that the model was acceptable. During 2011-2012 and 2014-2015, the survey was carried out jointly between GLSC and the United States Fish and Wildlife Service (USFWS). USFWS used 70 kHz and 120 kHz split-beam echosounders (Simrad EK60) to sample transects located in the MW stratum. In all years, sampling was initiated one hour after sunset and ended no later than one hour before sunrise. A threshold equivalent to uncompensated target strength (TS) of -70 decibels (dB) was applied to  $S_v$  data.

In order to assign fish species and size composition to acoustic data, we used a technique described by Warner et al. (2009), with different approaches depending on the vertical position in the water column. For cells with depth < 40 m, mid-water trawl and acoustic data were matched according to transect, depth layer (0-10, 10-20 m, etc., depending on headrope depth and upper depth of the acoustic cell), and by bottom depth. For acoustic cells without matching trawl data, we assigned the mean of each depth layer and bottom depth combination from the same transect. If acoustic data still had no matching trawl data, we assigned the mean of each depth layer and bottom depth combination within the same geographic stratum. Finally, if acoustic data still had no matching trawl data, we used a lake-wide mean for each depth layer. Mean mass of species/size groups at depths < 40 m were estimated using weight-length equations from mid-water trawl data. For depths  $\geq$  40 m, we assumed that acoustic targets were large bloater if mean TS was > -45 dB (TeWinkel and Fleischer 1999). Mean mass of bloater in these cells was estimated using the mass-TS equation of Fleischer et al. (1997). If mean TS was  $\leq$  -45 dB, we assumed the fish were large rainbow smelt and estimated mean mass from mean length, predicted using a TS-length equation (Rudstam et al. 2003).

As recommended by the Great Lakes Acoustic Standard Operating Procedures (Parker-Stetter et al. 2009, Rudstam et al. 2009), we used a number of techniques to assess or improve acoustic data quality. We used the  $N_v$  index of Sawada et al. (1993) to determine if conditions in each acoustic analysis cell were suitable for estimation of *in situ* TS. We defined suitability as an  $N_v$  value < 0.1 and assumed mean TS in cells at or above 0.1 were biased. We replaced mean TS in these cells with mean TS from cells that were in the same depth layer and transect having  $N_v$  < 0.1. To help reduce the influence of noise, we estimated  $S_v$  noise at 1 m on each transect using either passive data collection or echo integration of data below the bottom echoes. We then used noise at 1 m to estimate noise at all depths, which we subtracted from the echo integration data. Additionally, we estimated the detection limit (depth) for the smallest targets we include in our analyses.

## Status and Trends of Prey Fish Populations in Lake Michigan, 2015<sup>1</sup>

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### Abstract

The U.S. Geological Survey Great Lakes Science Center has conducted lake-wide surveys of the fish community in Lake Michigan each fall since 1973 using standard 12-m bottom trawls towed along contour at depths of 9 to 110 m at each of seven index transects. The resulting data on relative abundance, size and age structure, and condition of individual fishes are used to estimate various population parameters that are in turn used by state and tribal agencies in managing Lake Michigan fish stocks. All seven established index transects of the survey were completed in 2015. The survey provides relative abundance and biomass estimates between the 5-m and 114-m depth contours of the lake (herein, lake-wide) for prey fish populations, as well as burbot, yellow perch, and the introduced dreissenid mussels. Lake-wide biomass of alewives in 2015 was estimated at 0.5 kilotonnes (kt, 1 kt = 1000 metric tonnes), which was a record low. Age distribution of alewives remained truncated with no alewife exceeding an age of 6. Record low biomass was also recorded for slimy sculpin (0.05 kt), deepwater sculpin (0.4 kt) and ninespine stickleback (0.001 kt). Bloater biomass increased ninefold from 0.3 kt in 2014 to 2.8 kt in 2015. Round goby biomass decreased from 2.0 kt in 2014 to 0.3 kt in 2015. Rainbow smelt biomass was estimated at 0.06 kt in 2015. Burbot lake-wide biomass (0.5 kt in 2015) has remained below 3 kt since 2001. Age-0 yellow perch abundance was estimated to be 0.3 fish per ha, which is indicative of a weak year-class. Lake-wide biomass estimate of dreissenid mussels in 2015 was 2.4 kt. Overall, the total lake-wide prey fish biomass estimate (sum of alewife, bloater, rainbow smelt, deepwater sculpin, slimy sculpin, round goby, and ninespine stickleback) in 2015 was 4.0 kt, a record low. In 2015, bloater and deepwater sculpin, two native fishes, constituted over 78% of this total.

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The U.S. Geological Survey Great Lakes Science Center (GLSC) has conducted daytime bottom trawl surveys in Lake Michigan during the fall annually since 1973. Estimates from the 1998 survey are not reported, however, given the trawls were towed at non-standard speeds. From these surveys, the relative abundance of the prey fish populations are measured, and estimates of lake-wide biomass available to the bottom trawls (for the region of the main basin between the 5-m and 114-m depth contours) can be generated (Hatch et al. 1981; Brown and Stedman 1995). Such estimates are critical to fisheries managers making decisions on stocking and harvest rates of salmonines and allowable harvests of fish by commercial fishing operations.

The basic unit of sampling in our surveys is a 10-minute tow using a bottom trawl (12-m headrope, 25 to 45-mm bar mesh in net body, 6.4-mm bar mesh in cod end) dragged on contour at 9-m (5 fathom) depth increments. At most survey locations, towing depths range from 9 or 18 m to 110 m. In 2013, we began adding tows at deeper depths (i.e., 128-135 m), when logistics permitted, in an attempt to assess the extent to which populations of deepwater sculpins and bloater have migrated outside of our traditional survey range. Since then, we have sampled deeper depths offshore of Manistique (N=2), Frankfort (N=3), Ludington (N=1), Saugatuck (N=1), Port Washington (N=3), and Sturgeon Bay (N=1).

Ages were estimated for alewives (*Alosa pseudoharengus*, using otoliths) and bloaters (*Coregonus hoyi*, using scales) from our bottom trawl catches (Madenjian et al. 2003; Bunnell et al. 2006a). Although our surveys have included as many as nine index transects in any given year, we have consistently conducted the surveys at seven transects. These transects are situated off Manistique, Frankfort, Ludington, and Saugatuck, Michigan; Waukegan, Illinois; and Port Washington and Sturgeon Bay, Wisconsin (Figure 1).

All seven transects were completed in 2015.

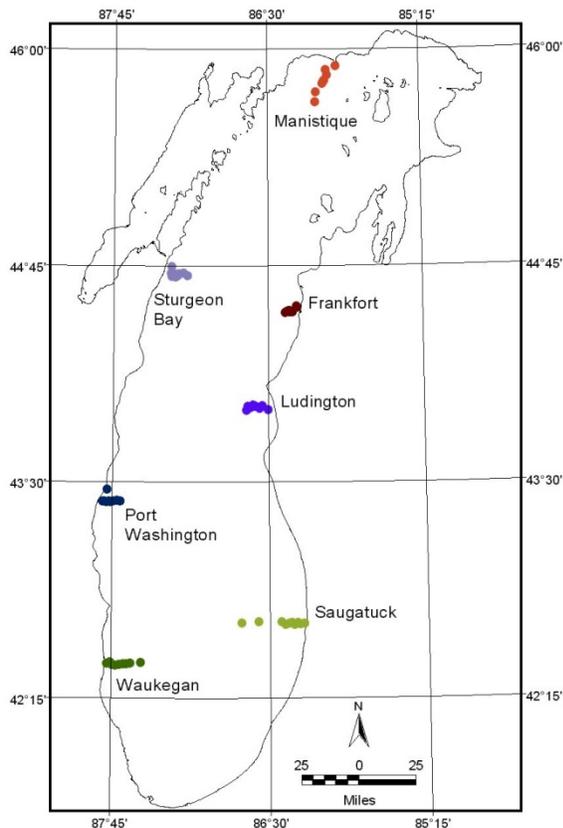


Figure 1. Established sampling locations for GLSC bottom trawls in Lake Michigan.

Lake-wide estimates of fish biomass require (1) accurate measures of the surface areas that represent the depths sampled and (2) reliable measures of bottom area swept by the trawl. A complete Geographical Information System (GIS) based on depth soundings at 2-km intervals in Lake Michigan was developed as part of the acoustics study performed by Argyle et al. (1998). This GIS database was used to estimate the surface area for each individual depth zone surveyed by the bottom trawls. Trawl mensuration gear that monitored net configuration during deployment revealed that fishing depth ( $D$ , in meters) influenced the bottom area swept by the trawl. We have corrected the width ( $W$ , in meters) of the area sampled according to  $W = 3.232 + 7.678(1 - e^{-0.044*D})$ , as well as the actual time ( $AT$ , in minutes) spent on the bottom according to  $AT = \text{tow time} - 0.945 + (0.056D)$ , based on trawl measurements made during June 2009 (Madenjian et al. 2010a). These relationships, along with boat speed, were used to estimate bottom area swept.

In 2015, the R/V Arcticus was used to perform the bottom trawl survey for the first time. Owing to winches that operated at a faster speed, the bottom trawl was lowered to the bottom and retrieved from the bottom at faster rates in 2015 than in the past. The effect of these faster rates on AT has yet to be determined. For purposes of completing this report, we used the above-mentioned relationship to calculate AT. We will attempt to directly estimate AT during 2016, and then adjust the AT estimator, if needed. Thus, our estimates for 2015 may have to be revised in preparation of our next annual report.

We estimate both numeric (fish per hectare [ha]) and biomass (kg per ha) density, although we display graphical trends mostly in biomass for brevity. A weighted mean density over the entire range of depths sampled (within the 5-m to 114-m depth contours) was estimated by first calculating mean density for each depth zone, and then weighting mean density for each depth zone by the proportion of lake surface area assigned to that depth zone. Standard error (SE) of mean density was estimated by weighting the variances of fish density in each of the depth zones by the appropriate weight (squared proportion of surface area in the depth zone), averaging the weighted variances over all depth zones, and taking the square root of the result.

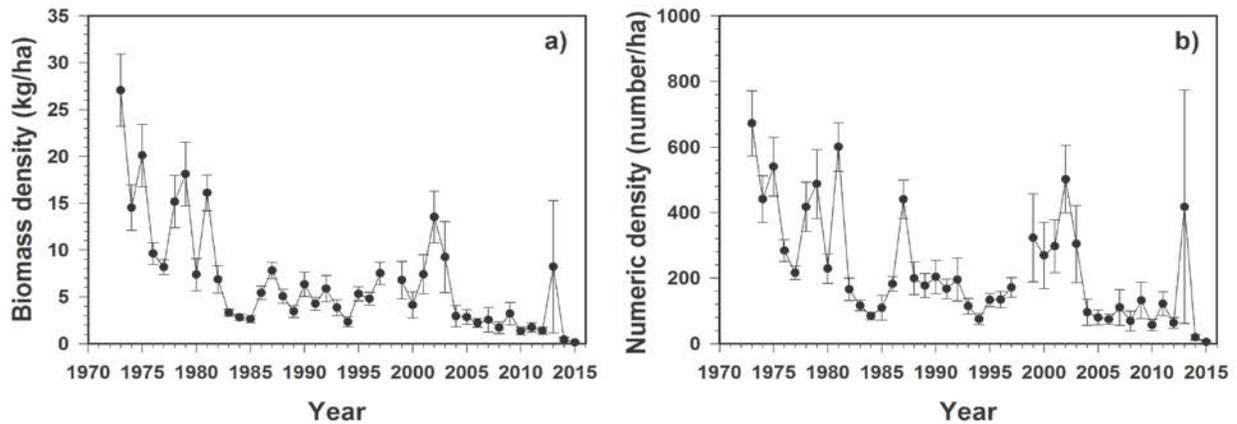
#### *NUMERIC AND BIOMASS DENSITY BY SPECIES*

By convention, we classify "adult" prey fish as age 1 or older, based on total length (TL): alewives  $\geq 100$  mm, rainbow smelt (*Osmerus mordax*)  $\geq 90$  mm, bloaters  $\geq 120$  mm, and yellow perch (*Perca flavescens*)  $\geq 100$  mm. We assume all fish smaller than the above length cut-offs are age-0; length cut-offs are also aided by aging of alewife (by otoliths) and bloater (by scales). Catches of age-0 alewife are not reliable indicators of future year-class strength (Madenjian et al. 2005a), because their position in the water column makes them less vulnerable to bottom trawls. Catches of age-0 bloater, though biased low, can be used as an index of relative abundance given the positive correlation between density of age-0 bloater and density of age-3 bloater (the age at which catch curves reveal full recruitment to our gear, Bunnell et al. 2006a, 2010). Catch of age-0 ( $< 100$  mm TL) yellow perch is likely a good indicator of year-class strength, given that large catches in the bottom trawl during the 1980s corresponded to the strong yellow perch fishery. At the end of this report, we present densities of age-0 yellow perch and other bottom-dwelling species such as burbot (*Lota lota*) and dreissenid mussels that are not necessarily "prey fish" but are caught in sufficient numbers to index. Unfortunately lake whitefish (*Coregonus clupeaformis*) are only rarely sampled in our trawl and the resultant trends are not meaningful.

Alewife – Since its establishment in the 1950s, the alewife has become a key member of the fish community. As a larval predator, adult alewife can depress recruitment of native fishes, including burbot, deepwater sculpin (*Myoxocephalus thompsonii*), emerald shiner (*Notropis atherinoides*), lake trout (*Salvelinus namaycush*), and yellow perch (Smith 1970; Wells and McLain 1973; Madenjian et al. 2005b, 2008; Bunnell et al. 2006b). Additionally, alewife has remained the most important constituent of salmonine diet in Lake Michigan for the last 45 years (Jude et al. 1987; Stewart and Ibarra 1991; Warner et al. 2008; Jacobs et al. 2013). Most of the alewives consumed by salmonines in Lake Michigan are eaten by Chinook salmon (*Oncorhynchus tshawytscha*, Madenjian et al. 2002; Tsehaye et al. 2014). A commercial harvest was established in Wisconsin waters of Lake Michigan in the 1960s to make use of the then extremely abundant alewife that had become a nuisance and health hazard along the lakeshore. In 1986, a quota was implemented, and as a result of these restrictions, the estimated annual alewife harvest declined from about 7,600 metric tons in 1985 to an incidental harvest of only 12 metric tons after 1990 (Mike Toneys, Wisconsin Department of Natural Resources, Sturgeon Bay, personnel communication). Lake Michigan currently has no commercial fishery for alewives.

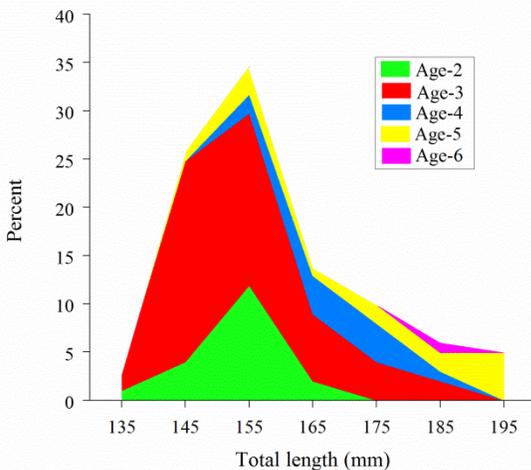
According to the bottom trawl survey results, adult alewife biomass density equaled 0.14 kg per ha in 2015, a record low (Figure 2a). Likewise, adult alewife numeric density in 2015 equaled a record-low estimate of 5 fish per ha (Figure 2b).

This continued depression of adult alewife abundance likely reflects an intensified amount of predation exerted on the alewife population by salmonines since the late 1990s due to six factors: (1) a relatively high percentage of wild Chinook salmon in Lake Michigan (averaging 50% age-1 individuals between 2006-2010, Williams 2012), (2) increased migration of Chinook salmon from Lake Huron in search of alewives (Adlerstein et al. 2007; R. Clark, Michigan State University Quantitative Fisheries Center, personal communication), (3) increased importance of alewives in the diet of Chinook salmon in Lake Michigan between the mid-1990s and the 2000s (Jacobs et al. 2013), (4) a decrease in the energy density of adult alewives during the late 1990s (Madenjian et al. 2006), (5) a reduction in the effects of bacterial kidney disease on Chinook salmon survival after 2003 (R. Clark, personal communication), and (6) a recent increase in lake trout abundance due to increased rates of stocking and natural reproduction (FWS/GLFC 2016; Lake Michigan LTWG 2016). The long-term temporal trends in adult alewife biomass, as well as in alewife recruitment to age 3, in Lake Michigan are attributable to consumption of alewives by salmonines (Madenjian et al. 2002, 2005a; Tsehaye et al. 2014).



**Figure 2. Density of adult alewives as biomass (a) and number (b) per ha (+/- standard error) in Lake Michigan, 1973-2015.**

In 2015, 53% of the adult alewives were age-3 (2012 year-class) fish, while age-2 (2013 year-class), age-5 (2010 year-class), and age-4 (2011 year-class) fish represented 21%, 14%, and 11%, respectively, of the adult alewives (Figure 3). Only 1% of the adult alewives were age-6 fish, and no alewives older than age 6 were caught. Thus, the recent trend of age truncation in the alewife population continued through 2015. Prior to 2008, age-8 alewives were routinely captured.

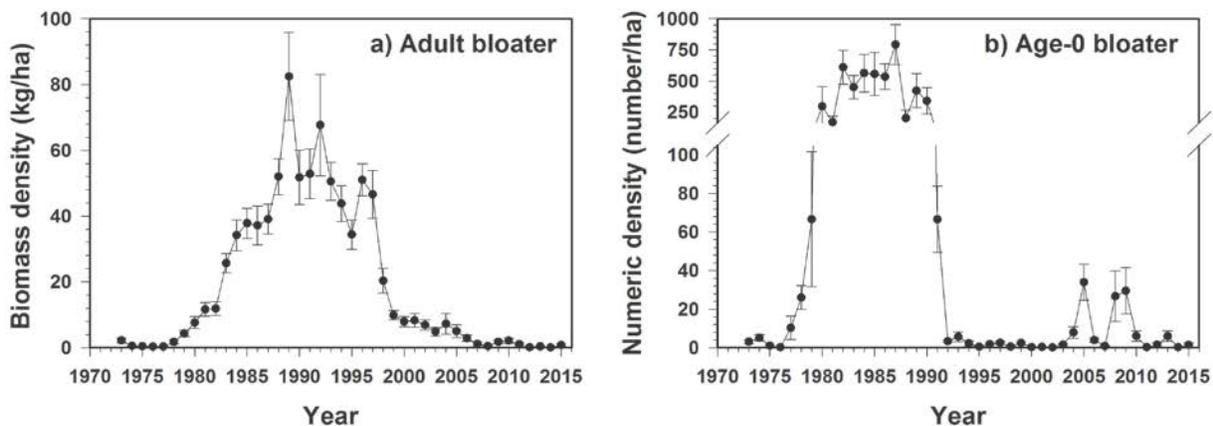


**Figure 3. Age-length distribution of alewives  $\geq 100$  mm total length caught in bottom trawls in Lake Michigan, 2015. No alewives  $< 100$  mm total length were captured in the bottom trawl survey during 2015.**

Our results for temporal trends in adult alewife density were in general agreement with results from the lake-wide acoustic survey, which indicated that biomass of adult alewife during 2004-2015 was relatively low compared with biomass during 1994-1996 (Warner et al. 2016). For adult alewife biomass density, the acoustic estimate exceeded the bottom trawl estimate by a factor of 2.4, on average. However, in 2015, the acoustic estimate (3.16 kg per ha) was more than 20 times greater than the bottom trawl estimate (0.14 kg per ha), although both estimates indicated low biomass of adult alewives. Bottom trawl survey results indicated a 68% decrease in adult alewife biomass density between 2014 and 2015, while acoustic survey results indicated a 32% decrease in adult alewife biomass density between 2014 and 2015.

**Bloater** - Bloaters are eaten by salmonines in Lake Michigan, but are far less prevalent in salmonine diets than alewives (Warner et al. 2008; Jacobs et al. 2010, 2013). For large ( $\geq 600$  mm) lake trout, over 30% of the diets offshore of Saugatuck and on Sheboygan Reef were composed of adult bloaters during 1994-1995, although adult bloaters were a minor component of lake trout diet at Sturgeon Bay (Madenjian et al. 1998). For Chinook salmon, the importance of bloater (by wet weight) in the diets has declined between 1994-1995 and 2009-2010. For small ( $< 500$  mm) Chinook salmon the proportion declined from 9% to 6% and for large Chinook salmon the proportion declined from 14% to  $<1\%$  (Jacobs et al. 2013). The bloater population in Lake Michigan also supports a valuable commercial fishery, although its yield has generally been declining since the late 1990s.

Adult bloater biomass density in our survey has been  $< 10$  kg per ha since 1999 (Figure 4a). In 2015, bloater biomass equaled 0.78 kg per ha. Numeric density of age-0 bloaters ( $< 120$  mm TL) was 1 fish per ha in 2015 (Figure 4b), suggesting continued poor bloater recruitment, aside from 2005, 2008, and 2009 when age-0 bloater abundance exceeded 25 fish per ha.



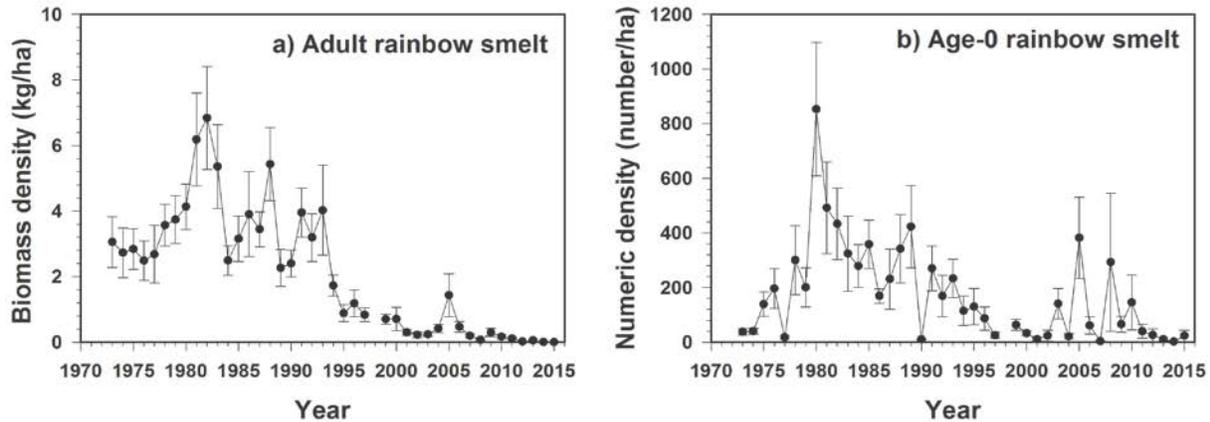
**Figure 4. Panel (a) depicts biomass density (+/- standard error) of adult bloater in Lake Michigan, 1973-2015. Panel (b) depicts numeric density (+/- standard error) of age-0 bloater in Lake Michigan, 1973-2015.**

The exact mechanisms underlying the relatively poor bloater recruitment since 1992 (Figure 4b), and the low biomass of adult bloater since 2007 (Figure 4a), remain unknown. Madenjian et al. (2002) proposed that the Lake Michigan bloater population may be cycling in abundance, with a period of about 30 years, although the exact mechanism by which recruitment is regulated remains unknown. Of the mechanisms that have been recently evaluated, reductions in fecundity associated with poorer condition (Bunnell et al. 2009a) and egg predation by slimy and deepwater sculpins (Bunnell et al. 2014a) are likely contributing to the reduced bloater recruitment, but none is the primary regulating factor.

An important consideration when interpreting the bottom trawl survey results is that bloater catchability may have decreased in recent years, in response to the proliferation of quagga mussels and the associated increased water clarity and decreased *Diporeia* spp. densities. One hypothesis is that some portion of the bloater population has shifted to waters deeper than those typically surveyed by the GLSC. In support of this contention, we note that bloomers have exhibited plasticity in the bottom depths that they occupy, as the depth at which their peak densities occurred increased from 50 m in the 1930s to 85-110 m by 2004-2007 (Bunnell et al. 2012). In addition, commercial fishers have reported an increase in the depth at which they catch bloomers in Lake Michigan during the past 5 to 10 years, with the bulk of the catch from waters deeper than 130 m in recent years (M. LeClair, Susie-Q Fish Market, Two Rivers, WI, personal communication; D. Vanorman, Big Stone Bay Fishery, Inc., Carp Lake, MI, personal communication). Our exploratory sampling at deeper depths (i.e., 128-135 m) revealed that bloater biomass was highest at the deepest depth only about 10% of the time. In addition, results from the acoustic survey (which regularly samples deeper waters than the bottom trawl survey) do not support the deeper water hypothesis; Warner et al. (2016) observed no trend in mean depth of capture between 2005 and 2015, and determined that 95% of all large bloomers were at depths < 130 m. Hence this hypothesis still requires additional evaluation. An alternative hypothesis is that the bloater population remains largely within our sampling area, but bloomers (both age-0 and adult) are less vulnerable to our bottom trawls either owing to behavioral changes (more pelagic during the day) or increased ability to avoid the net while on the bottom (due to clearer water).

A comparison of the two surveys revealed that the bloater biomass estimate from the bottom trawl survey was 79% higher, on average, than that from the acoustic survey during 1992-2006. Since 2007, however, the biomass estimate for the acoustic survey was 57% higher, on average, than that for the bottom trawl survey. Nonetheless, the adult bloater biomass density estimate for the bottom trawl survey (0.78 kg per ha) exceeded that for the acoustic survey (0.60 kg per ha) in 2015. Temporal trends were similar between the two surveys, with adult bloater biomass density decreasing by an order of magnitude between 1992-1996 and 2001-2014. Results from both surveys indicated that age-0 bloater abundance increased between the 1992-1996 and 2005-2015 periods. However, whereas both surveys yielded similar estimates of age-0 bloater abundance during 1992-1996, acoustic survey estimates of age-0 bloater abundance averaged more than 20 times higher than those from the bottom trawl survey during 2005-2015. One plausible explanation for these inconsistent relative differences in results between the two surveys over time is that bloater catchability with the bottom trawl survey decreased sometime during the 2000s.

Rainbow smelt – Adult rainbow smelt have been an important part of the diet for intermediate-sized (400 to 600 mm) lake trout in the nearshore waters of Lake Michigan (Stewart et al. 1983; Madenjian et al. 1998; Jacobs et al. 2010). For Chinook salmon, rainbow smelt comprised as much as 18% in the diets of small individuals in 1994-1996, but that dropped precipitously to 2% in 2009-2010 and rainbow smelt has been consistently rare in the diets of larger Chinook salmon since 1994 (Jacobs et al. 2013). The rainbow smelt population supports commercial fisheries in Wisconsin and Michigan waters (Belonger et al. 1998; P. Schneeberger, Michigan Department of Natural Resources, Marquette, MI, personal communication).



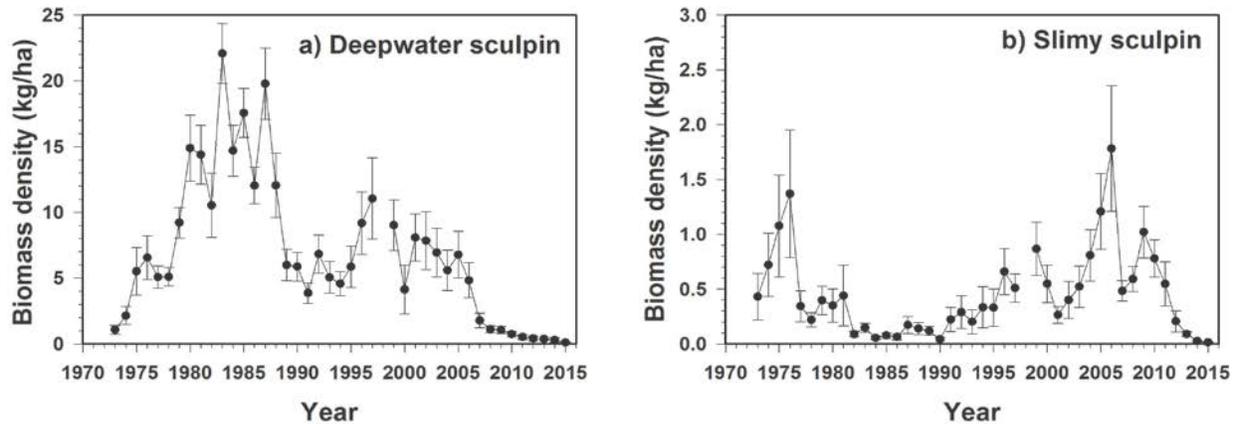
**Figure 5. Biomass density (+/- standard error) of adult (a) and age-0 (b) rainbow smelt in Lake Michigan, 1973-2015.**

Adult rainbow smelt biomass density has remained at low levels since 2001, aside from a relatively high estimate in 2005 (Figure 5a). Biomass density in 2015 equaled a record-low 0.0001 kg per ha. Age-0 rainbow smelt numeric density has been highly variable since 1999 (Figure 5b), but equaled only 23 fish per ha in 2015, marking five consecutive year-classes with <40 fish per ha. Causes for the general decline in rainbow smelt biomass and production remain unclear. Consumption of rainbow smelt by salmonines was higher in the mid-1980s than during the 1990s (Madenjian et al. 2002), yet adult and age-0 (< 90 mm TL) rainbow smelt abundance remained high during the 1980s (Figure 5b). Results from a recent population modeling exercise suggested that predation by salmonines was not the primary driver of long-term temporal trends in Lake Michigan rainbow smelt abundance (Tsehaye et al. 2014). Furthermore, a recent analysis of our time series suggested that the productivity of the population has actually increased since 2000 (relative to 1982-1999), yet those recruits do not appear to be surviving to the adult population (Feiner et al. 2015).

A comparison of the two surveys revealed that the rainbow smelt biomass estimate from the acoustic survey always exceeds that of the bottom trawl survey, on average by a factor of 5. This difference is not surprising given that rainbow smelt tend to be more pelagic than other prey species during the day. In 2015, the estimate for the acoustic survey (0.0080 kg per ha, Warner et al. 2016) was 84 times greater than that of the bottom trawl survey (0.0001 kg/ha). Just as the case for the bottom trawl estimates, biomass density also reached a record low in 2015 for the acoustic estimates. The two surveys detected similar temporal trends, with adult rainbow smelt attaining biomass densities an order of magnitude higher during 1992-1996 than during 2001-2014 for both surveys.

**Sculpins** – From a biomass perspective, the cottid populations in Lake Michigan have been dominated by deepwater sculpins, and to a lesser degree, slimy sculpins (*Cottus cognatus*). Spoonhead sculpins (*Cottus ricei*), once fairly common, suffered declines to become rare to absent by the mid-1970s (Eck and Wells 1987). Spoonhead sculpins were encountered in small numbers in our survey between 1990 and 1999 (e.g., Potter and Fleischer 1992), but have not been sampled since 1999.

Slimy sculpin is a favored prey of juvenile lake trout in nearshore regions of the lake (Stewart et al. 1983; Madenjian et al. 1998), but is only a minor part of adult lake trout diets. When abundant, deepwater sculpin can be an important diet constituent for burbot in Lake Michigan, especially in deeper waters (Van Oosten and Deason 1938; Brown and Stedman 1995; Fratt et al. 1997).



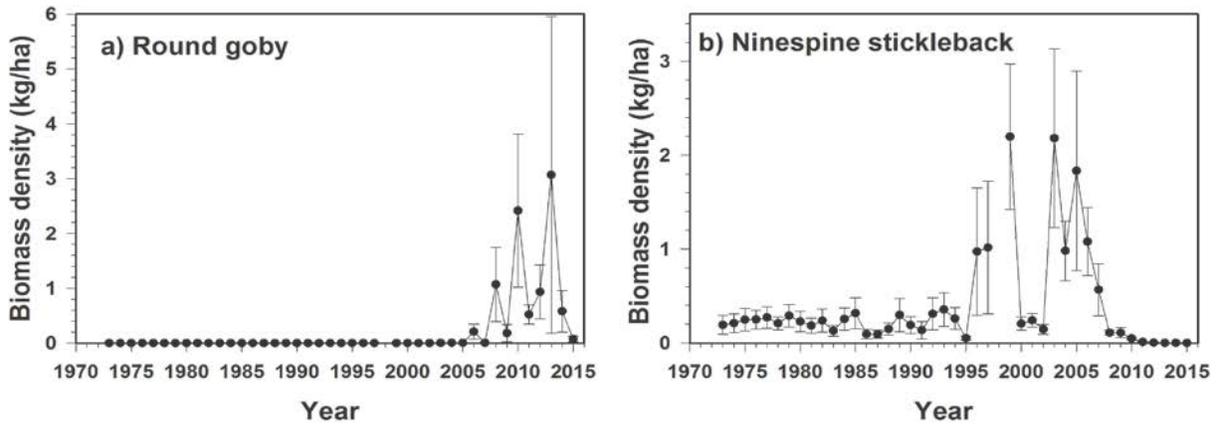
**Figure 6. Biomass density (+/- standard error) for deepwater (a) and slimy sculpin (b) in Lake Michigan, 1973-2015.**

Deepwater sculpin biomass density in 2015 was at a record-low 0.11 kg per ha (Figure 6a). For every year since 2009, this biomass estimate has reached a record low. Previous analysis of the time series indicated deepwater sculpin density is negatively influenced by alewife (predation on sculpin larvae) and burbot (predation on juvenile and adult sculpin, Madenjian et al. 2005b). Based on bottom trawl survey results, neither alewife nor burbot significantly increased in abundance during 2007-2015 to account for this decline in deepwater sculpins. Following no clear trend between 1990 and 2005, the biomass of deepwater sculpin sampled in the bottom trawl has declined precipitously since 2005. Madenjian and Bunnell (2008) demonstrated that deepwater sculpins have been captured at increasingly greater depths since the 1980s. Therefore, one potential explanation for the recent declines in deepwater sculpin densities is that an increasing proportion of the population is now occupying depths deeper than those sampled by our survey (i.e., 110 m), perhaps in response to the decline of *Diporeia* and proliferation of dreissenid mussels. Furthermore, because the deepwater sculpin has historically occupied deeper depths than any of the other prey fishes of Lake Michigan, a shift to waters deeper than 110 m would seem to be a reasonable explanation for the recent declines in deepwater sculpin densities. Our exploratory sampling at deeper depths (i.e., 128-135 m) was supportive of this hypothesis: deepwater sculpin biomass was highest at the deepest depth 64% of the time.

Slimy sculpin biomass density has continued to decline over the past six years, reaching a record-low 0.01 kg per ha in 2015 (Figure 6b). Slimy sculpin abundance in Lake Michigan appeared to be regulated, at least in part, by predation from juvenile lake trout (Madenjian et al. 2005b). We attribute the slimy sculpin recovery that occurred during the 1990s to, in part, the 1986 decision to emphasize stocking lake trout on offshore reefs (as opposed to the areas closer to shore where our survey samples, Madenjian et al. 2002). Likewise, the slimy sculpin decline since 2009 coincided with a substantial increase in the rate of stocking juvenile lake trout into Lake Michigan and an increase in natural reproduction by lake trout (FWS/GLFC 2016; Lake Michigan LTWG 2016).

**Round goby** – The round goby (*Neogobius melanostomus*) is an invader from the Black and Caspian Seas. Round gobies have been observed in bays and harbors of Lake Michigan since 1993, and were captured in the southern main basin of the lake as early as 1997 (Clapp et al. 2001). Round gobies were not captured in the GLSC bottom trawl survey until 2003; our survey likely markedly underestimates round goby abundance given their preferred habitat includes rocky and inshore (i.e., < 9 m bottom depth) areas that we do not sample. By 2002, round gobies had become an integral component of yellow perch diets at nearshore sites (i.e., < 15 m depth) in southern Lake Michigan. Recent studies have revealed

round gobies are an important constituent of the diets of Lake Michigan burbot (Hensler et al. 2008; Jacobs et al. 2010), yellow perch (Truemper et al. 2006), smallmouth bass (*Micropterus dolomieu*, T. Galarowicz, Central Michigan University, personal communication), lake trout (McKenna 2014), and even lake whitefish (S. Hansen, Wisconsin DNR, personal communication).



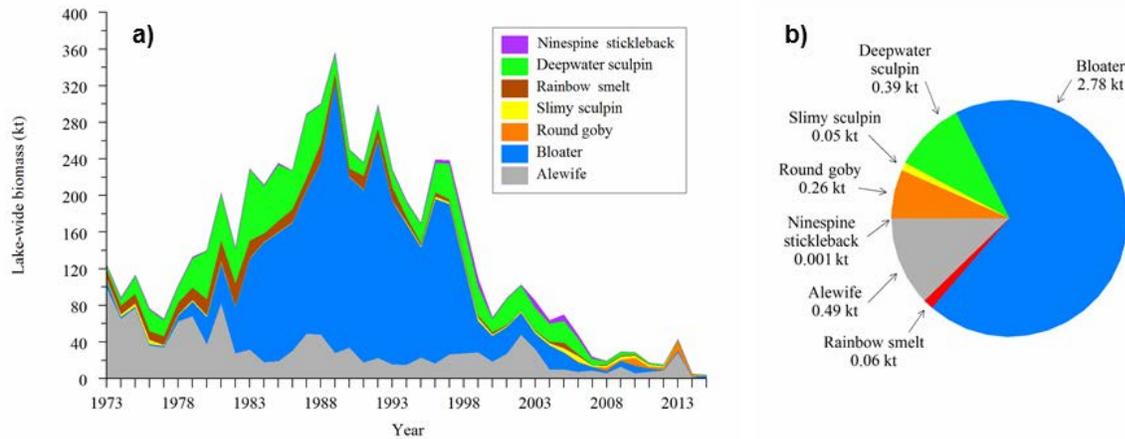
**Figure 7. Biomass density (+/- standard error) of round goby (a) and ninespine stickleback (b) in Lake Michigan, 1973-2015.**

Round goby biomass density equaled 0.07 kg per ha in 2015 (Figure 7a). Round goby abundance in Lake Michigan appears to be leveling off, or perhaps even declining, in response to control by piscivores. This hypothesis was supported by recent estimates of annual mortality rates of between 79 and 84% (Huo et al. 2014), which are comparable to the mortality rates currently experienced by Lake Michigan adult alewives (Tsehaye et al. 2014).

Ninespine stickleback – Two stickleback species occur in Lake Michigan. Ninespine stickleback (*Pungitius pungitius*) is native, whereas threespine stickleback (*Gasterosteus aculeatus*) is non-native and was first collected in the GLSC bottom trawl survey during 1984 (Stedman and Bowen 1985), but has been extremely rare in recent sampling years. Biomass density of ninespine stickleback in 2015 was only 0.2 g per ha, a record low (Figure 7b). Biomass of ninespine stickleback remained fairly low from 1973-1995 and then increased dramatically through 2007, perhaps attributable to dreissenid mussels enhancing ninespine stickleback spawning and nursery habitat through proliferation of *Cladophora* (Madenjian et al. 2010b). Since 2008, however, biomass has been maintained at or near record-low levels. One plausible explanation for the low ninespine stickleback abundance during 2008-2015 is that piscivores began to incorporate ninespine sticklebacks into their diets as the abundance of alewives has remained at a low level. For example, Jacobs et al. (2013) found ninespine sticklebacks to show up in large Chinook salmon diets (i.e., 2% occurrence) during 2009-2010 after 0% occurrence in 1994-1996.

#### LAKE-WIDE BIOMASS

We estimated a total lake-wide biomass of prey fish available to the bottom trawl in 2015 of 4 kilotonnes (kt) (1 kt = 1000 metric tons) (Figure 8a, Appendix 1). Total prey fish biomass was the sum of the population biomass estimates for alewife, bloater, rainbow smelt, deepwater sculpin, slimy sculpin, ninespine stickleback, and round goby. Total prey fish biomass in Lake Michigan has trended downward since 1989, primarily due to a dramatic decrease in bloater biomass (Figure 8a). Total biomass first dropped below 30 kt in 2007, and has since remained below that level with the exception of 2013 (when the biomass estimates for alewife and round goby were highly uncertain).



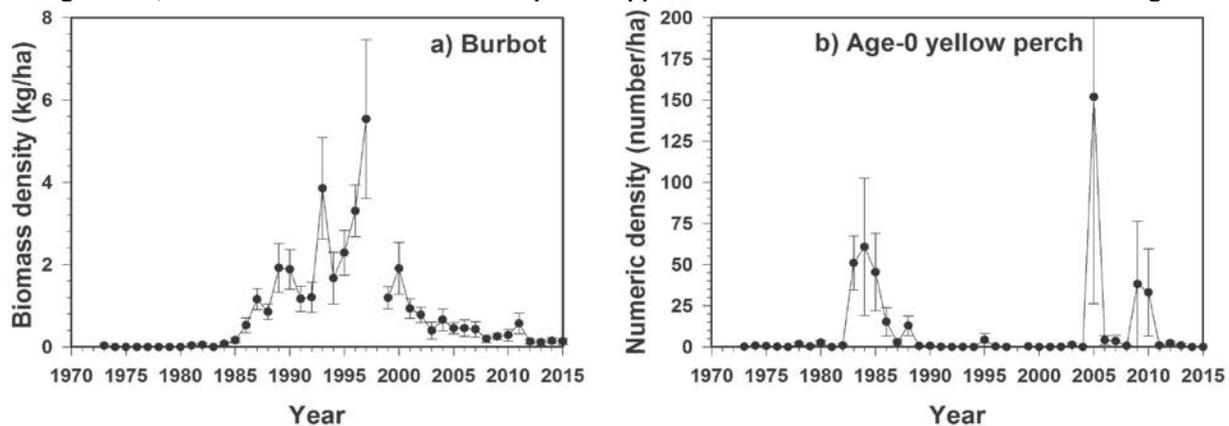
**Figure 8. Estimated lake-wide (i.e., 5-114 m depth region) biomass of prey fishes in Lake Michigan, 1973-2015 (a) and species composition in 2015 (b).**

As Figure 8b depicts, the 2015 prey fish biomass was apportioned as: bloater 68.9% (2.78 kt), alewife 12.2% (0.49 kt), deepwater sculpin 9.6% (0.39 kt), round goby 6.4% (0.26 kt), rainbow smelt 1.6% (0.06 kt), slimy sculpin 1.3% (0.05 kt), and ninespine stickleback 0.02% (0.001 kt).

#### *OTHER SPECIES OF INTEREST*

**Burbot** – Burbot and lake trout represent the native top predators in Lake Michigan. The decline in burbot abundance in Lake Michigan during the 1950s has been attributed to sea lamprey predation (Wells and McLain 1973). Sea lamprey control was a necessary condition for recovery of the burbot population in Lake Michigan, however Eshenroder and Burnham-Curtis (1999) proposed that a reduction in alewife abundance was an additional prerequisite for burbot recovery.

Burbot collected in the bottom trawls are typically large individuals (>350 mm TL); juvenile burbot apparently inhabit areas not usually covered by the bottom trawl survey. Burbot biomass density was 0.13 kg per ha in 2015, which was 46% of the average biomass since 2005. After a period of low numeric density in the 1970s, burbot showed a strong recovery in the 1980s (Figure 9a). Densities increased through 1997, but declined thereafter. Perhaps the apparent decrease in burbot abundance during 2007-



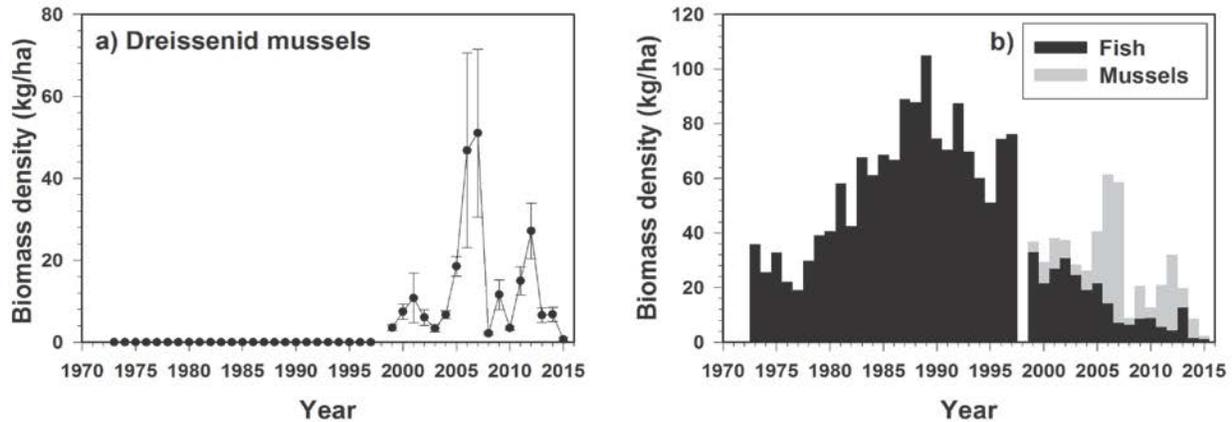
**Figure 9. Biomass density (+/- standard error) of burbot (a) and numeric density (+/- standard error) of age-0 yellow perch (b) in Lake Michigan, 1973-2015.**

2015 was due to a portion of the burbot population moving to waters deeper than 110 m in response to a movement of deepwater sculpins, favored prey of burbot (Van Oosten and Deason 1938; Gamble et al. 2011), to deeper waters. Our exploratory sampling at deeper depths (i.e., 128-135 m) has not provided any support for this hypothesis yet. On the other hand, recent bycatch of burbot in commercial gill nets set for bloaters in northern Lake Michigan has indicated presence of burbot in waters deeper than 130 m (D. Vanorman, personal communication).

Age-0 yellow perch – The yellow perch population in Lake Michigan has supported valuable recreational and commercial fisheries (Wells 1977). GLSC bottom trawl surveys provide an index of age-0 yellow perch numeric density, which serves as an indication of yellow perch recruitment success. The 2005 year-class of yellow perch was the largest ever recorded (Figure 9b) and the 2009 and 2010 year-classes also were higher than average. In 2015, age-0 yellow perch abundance was only 0.3 fish per ha, which is indicative of a weak year-class.

Dreissenid mussels – The first zebra mussel (*Dreissena polymorpha*) noted in Lake Michigan was found in May 1988 in Indiana Harbor at Gary, Indiana. By 1990, adult mussels had been found at multiple sites in the Chicago area, and by 1992 were reported to range along the eastern and western shoreline in the southern two-thirds of the lake, as well as in Green Bay and Grand Traverse Bay (Marsden 1992). In 1999, catches of dreissenid mussels in our bottom trawls became significant and we began recording biomass for each tow. Lake Michigan dreissenid mussels include two species: the zebra mussel and the quagga mussel. The quagga mussel is a more recent invader to Lake Michigan than the zebra mussel (Nalepa et al. 2001). According to the GLSC bottom trawl survey, biomass density of dreissenid mussels was highest in 2007 (Figure 10a), which followed an exponential like increase between 2004 and 2006 (Bunnell et al. 2009b). The biomass density of dreissenid mussels in 2015 was 0.69 kg per ha, which was 90% lower than the 2014 biomass density of 6.79 kg per ha (Figure 10a). Interannual variability in dreissenid mussel density following 2007 is difficult to explain. The exceptionally high densities in 2006 and 2007 were attributable to the expansion of quagga mussels into deeper (> 60 m) waters of Lake Michigan. However, there was no clear explanation for the drastic drop in dreissenid mussel biomass density between 2007 and 2008, as lakewide quagga mussel densities continued to increase through 2010 (Nalepa et al. 2014). Similarly, reasons for the drastic decline in dreissenid mussel biomass density between 2014 and 2015 were not clearly evident.

Over this same period of dreissenid mussel increases, prey fish biomass was declining, which led to a dramatic increase in the percentage of dreissenids in the total bottom trawl catch (Figure 10b). Some authors have attributed the recent decline in prey fish to food-web changes induced by the expansion of dreissenids (Nalepa et al. 2009). However, Bunnell et al. (2009b) proposed that the bulk of the decline in total prey fish biomass may be better explained by factors other than food-web-induced effects by dreissenids, including poor fish recruitment (that preceded the quagga mussel expansion), shifts in fish habitat, and increased predation on prey fish by Chinook salmon and lake trout.



**Figure 10. Panel (a) depicts biomass density (+/- standard error) of dreissenid mussels in the bottom trawl in Lake Michigan between 1999 (first year mussels were weighed) and 2015. Panel (b) depicts biomass of dreissenids and total fish biomass estimated by the bottom trawl between 1973 and 2015.**

A comparison of the biomass density of dreissenid mussels (0.69 kg per ha) with biomass density of all species of fish (1.37 kg per ha) caught in the bottom trawl in 2015 indicated that 33% of the daytime benthic biomass available to the bottom trawl was dreissenid mussels (Figure 10b).

## CONCLUSIONS

Total prey fish biomass estimated by the bottom trawl has revealed a record-low number every year since 2010, with the exception of 2013 when locally high catches of alewife and round goby caused a relatively high estimate (e.g., 43 kt) with high uncertainty. In 2015, total prey fish biomass was estimated to be only 4 kt. Prudently, we conclude that, based on the bottom trawl survey results, total prey fish biomass in Lake Michigan has remained at a low level since 2007.

This low level of prey fish biomass can be attributable to a suite of factors, two of which can be clearly identified: (1) a prolonged period of poor bloater recruitment since 1992 and (2) intensified predation on alewives by salmonines during the 2000s and 2010s. Adult alewife density has been maintained at a relatively low level over the last 11 years and the age distribution of the adult alewife population has become especially truncated in recent years. As recent as 2007, alewives as old as age 9 were sampled in this survey, whereas the oldest alewife sampled in 2013-2014 was age 5 and the oldest alewife sampled in 2015 was age 6.

In addition to the importance of top-down forces, prey fishes also may be negatively influenced by reduced prey resources (i.e., “bottom-up” effects). For example, several data sets are indicating a reduction in the base of the food-web- particularly for offshore total phosphorus and phytoplankton- as a consequence of long-term declines in phosphorus inputs and the proliferation of dreissenid mussels (Evans et al. 2011; Bunnell et al. 2014b). Grazing of phytoplankton by dreissenid mussels appeared to be the primary driver of the 35% decline in primary production in offshore waters between the 1983-1987 and 2007-2011 periods (Madenjian et al. 2015). The evidence for declines in “fish food” (e.g., zooplankton, benthic invertebrates) in offshore waters of Lake Michigan is somewhat less clear. *Diporeia* has undoubtedly declined in abundance (Nalepa et al. 2014), but whether or not crustacean zooplankton and mysids have declined depends on which data set is examined (e.g., Pothoven et al. 2010; Bunnell et al. 2014; Madenjian et al. 2015). Crustacean zooplankton biomass density in nearshore waters appeared to decrease during 1998-2010, likely due to a reduction in primary production mainly stemming from grazing of phytoplankton by dreissenid mussels. The above-mentioned decline in *Diporeia* abundance

appeared to have led to reductions in growth, condition, and/or energy density of lake whitefish, alewives, bloaters, and deepwater sculpins during the 1990s and 2000s (Pothoven et al. 2011, 2012; Madenjian et al. 2015). Of course, decreases in growth, condition, and energy density do not necessarily cause declines in fish abundance. The challenge remains to quantify bottom-up effects on prey fish abundances and biomasses in Lake Michigan. Given the complexities of the food web, disentangling the effects of the dreissenid mussel invasions and the reduction in nutrient loadings from other factors influencing the Lake Michigan food web will require a substantial amount of ecological detective work.

Whether or not the alewife population in Lake Michigan will undergo a complete collapse in coming years (similar to what occurred in Lake Huron) ultimately depends on the consumptive demand of the salmonines, and this estimate is based on many inputs (stocking rates, wild recruitment rates, immigration rates from Lake Huron). Lake Michigan managers reduced Chinook salmon stocking lakewide by 50% from 2012 baseline values beginning in 2013 to lower salmon consumption on alewives and try to maintain predator:prey balance (Lake Michigan Committee 2014). In addition, alewife sustainability will depend on the ability of the alewife spawning stock to produce another strong year-class, which will at least partially depend on appropriate environmental conditions being met (Madenjian et al. 2005b).

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Appendix 1. Mean numeric and biomass density, as well as lake-wide biomass (defined as biomass available to the bottom trawls for the region of the main basin between the 5-m and 114-m depth contours) estimates for various fishes and dreissenid mussels in Lake Michigan during 2015. Estimates are based on the bottom trawl survey. Standard error enclosed in parentheses. NA denotes that estimate is not available.

Taxon	Numeric density (fish per ha)	Biomass density (kg per ha)	Lake-wide biomass (kt)
age-0 alewife	0.00 (0.00)	0.0000 (0.0000)	0.0000 (0.0000)
adult alewife	5.19 (3.88)	0.1399 (0.0978)	0.4928 (0.3445)
age-0 bloater	1.39 (1.18)	0.0095 (0.0081)	0.0335 (0.0285)
adult bloater	14.69 (5.47)	0.7800 (0.3115)	2.7469 (1.0971)
age-0 rainbow smelt	23.47 (20.81)	0.0181 (0.0167)	0.0636 (0.0589)
adult rainbow smelt	0.01 (0.01)	0.0001 (0.0001)	0.0004 (0.0004)
deepwater sculpin	10.46 (3.03)	0.1099 (0.0389)	0.3870 (0.1371)
slimy sculpin	1.80 (0.62)	0.0148 (0.0057)	0.0520 (0.0202)
ninespine stickleback	0.21 (0.21)	0.0002 (0.0002)	0.0008 (0.0008)
burbot	0.08 (0.04)	0.1319 (0.0691)	0.4644 (0.2432)
age-0 yellow perch	0.27 (0.27)	0.0005 (0.0005)	0.0019 (0.0019)
round goby	8.01 (5.31)	0.0731 (0.0502)	0.2576 (0.1768)
dreissenid mussels	NA	0.6883 (0.3411)	2.4238 (1.2011)

# Status and Trends of the Lake Huron Offshore Demersal Fish Community, 1976-2015<sup>1</sup>

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## Abstract

The USGS Great Lakes Science Center has conducted trawl surveys to assess annual changes in the offshore demersal fish community of Lake Huron since 1973. Sample sites include five ports in U.S. waters with less frequent sampling near Goderich, Ontario. The 2015 fall bottom trawl survey was carried out between 14 and 28 October and included all U.S. ports, as well as Goderich, ON. The 2015 main basin prey fish biomass estimate for Lake Huron was 19.4 kilotonnes, a decline of about 50 percent from 2014. This estimate is the second lowest in the time series, and is approximately 5 percent of the maximum estimate in the time series observed in 1987. No adult alewife were collected in 2015 and YOY alewife was the second lowest in the time series, up slightly from the record low in 2014. The estimated biomass of yearling and older rainbow smelt also decreased and was the lowest observed in the time series. Estimated adult bloater biomass in Lake Huron declined to about half of the 2014 estimate. YOY alewife, rainbow smelt, and bloater abundance and biomass decreased over 2014. Biomass estimates for deepwater sculpins declined while trout-perch and ninespine stickleback increased over 2014 values, but all remained low compared to historic estimates. The 2014 biomass estimate for round goby increased from 2014 but remains at only 7 percent of the maximum observed in 2003. Wild juvenile lake trout were captured again in 2015, suggesting that natural reproduction by lake trout continues to occur.

<sup>1</sup>Prepared for the Great Lakes Fishery Commission Lake Huron Committee Meeting, Milwaukee, WI, March 21, 2016.

## Introduction

Lake Huron supports valuable recreational and commercial fisheries that may be at risk due to recent widespread ecological changes in the lake (Bence and Mohr 2008; Riley et al. 2013). Recent major ecosystem changes in Lake Huron include the invasion of dreissenid mussels and drastic declines in the abundance of the native amphipod *Diporeia* spp. (McNickle et al. 2006; Nalepa et al. 2003, 2005, 2007), decreases in lake whitefish *Coregonus clupeaformis* and Chinook salmon *Oncorhynchus tshawytscha* catches (Mohr and Ebener 2005; Bence and Mohr 2008), significant changes in the abundance and species composition of the zooplankton community (Barbiero et al. 2009), the invasion of the round goby *Neogobius melanostomus*, and the collapse of the offshore demersal fish community (Riley et al. 2008).

The USGS Great Lakes Science Center (GLSC) began annual bottom trawl surveys on Lake Huron in 1973, and the first full survey with ports covering the Michigan waters of the lake was conducted in 1976. These surveys are used to examine relative abundance, size and age structure, and species composition of the offshore demersal fish community. The purpose of this report is to present estimates of the abundance and biomass of offshore demersal fish species that are important as prey to common predators in the lake (i.e., lake trout, *Salvelinus namaycush*, and Chinook salmon).

## Methods

The GLSC has monitored fish abundance annually from 1973-2015 using 12-m headrope (1973-1991) and 21-m headrope (1992-2015) bottom trawls at fixed transects at up to eleven depths (9, 18, 27, 36, 46, 55, 64, 73, 82, 92, and 110 m) at five ports (Detour, Hammond Bay, Alpena, Au Sable Point, and Harbor Beach) in the Michigan waters of Lake Huron (Fig. 1). Both trawls used a 4.76 mm square mesh cod end. The same fixed transects were sampled each year from the USGS R/V *Kaho* during 1973-1977, the USGS R/V *Grayling* during 1978-2014, and the USGS R/V *Arcticus* in 2015; some transects were fished from the USGS R/V *Cisco* in 1990. The first year that all of the Michigan ports were sampled was 1976. Sampling has been intermittently conducted at Goderich (Ontario) since 1998 using the same trawling protocols as U.S. ports; this port was sampled in 2015.

Single 10-min trawl tows were conducted during daylight at each transect every year. Tow duration was occasionally less than 10 min due to large catches or obstacles in the tow path; catches for these tows were corrected to be equivalent to 10-min tows (see formula below). Trawl catches were sorted by species and each species was counted and weighed in aggregate. Large catches (> ca. 20 kg) were subsampled; a random sample was sorted, counted, and weighed, and the remainder of the catch was weighed for extrapolation of the sample.

We applied correction factors to standardize trawl data among depths, as the actual time on bottom for each trawl increased with depth (Fabrizio et al. 1997). Relative abundance was standardized to CPE (catch per 10 min on bottom) as

$$C_t = \frac{10N}{K_t T},$$

where  $C_t$  is the catch per 10 min (CPE) on bottom for trawl type  $t$ ,  $N$  is the catch,  $T$  is tow time, and  $K_t$  is a correction factor that varies with fishing depth ( $D$  in m) and trawl type such that  $K_{12} = 0.00400D + 0.8861$  for the 12-m trawl and  $K_{21} = 0.00385D + 0.9149$  for the 21-m trawl. Catches were expressed in terms of density and biomass (number/ha and kg/ha) by dividing the CPE by the area swept by the trawl.

The area swept was estimated as the product of the distance towed (speed multiplied by tow time) and the trawl width. Trawl width estimates were depth-specific and were based on trawl mensuration data collected from the R/V *Grayling* in 1991, 1998, and 2005 (USGS unpublished data). Catches were weighted by the area of the main basin of Lake Huron that occurred in each depth range. Lakewide biomass was estimated as the sum of the biomass of the common species sampled in the survey, and is not a true “lakewide” estimate, as sampling is conducted only to a depth of 110 m.

We partitioned the catches of alewife *Alosa pseudoharengus*, rainbow smelt *Osmerus mordax*, and bloater *Coregonus hoyi* into size-based age classes. To do this, year-specific length cutoffs were predetermined from length-frequency data and then used to apportion the catches into YOY fish (young-of-the-year, or YOY) and those age-1 or older (yearling and older, or YAO).

To make density estimates from the 12 m headrope (1973-1991) and 21 m headrope (1992-2014) trawls comparable, we multiplied density estimates from the 12-m trawl (1976-1991) by species-specific fishing power corrections (FPCs) developed from a comparative trawl experiment (Adams et al. 2009). We applied FPCs greater than 1.0 to the density and biomass of alewife, rainbow smelt (YAO only), bloater, and FPCs less than 1.0 to the density and biomass of deepwater sculpin *Myoxocephalus thompsonii*. Catches of trout-perch *Percopsis omiscomaycus* were not significantly different between the two trawls. Insufficient data were available to estimate FPCs for ninespine stickleback *Pungitius pungitius* and YOY rainbow smelt; density estimates were not corrected for these species.

Trawl surveys on Lake Huron are typically conducted between 3 October and 15 November. In 1992 and 1993, however, trawl surveys occurred in early- to mid-September, and these data were not used in this report because the distribution of many offshore species in the Great Lakes is highly seasonally variable (Dryer 1966; Wells 1968) and data collected in September may not be comparable to the rest of the time series. In 1998, sampling was conducted in a non-standard manner, and these data were also excluded. The fall survey was not conducted in 2000 and was not completed in 2008. We did not use data prior to 1976 because all ports and depths in Lake Huron were not consistently sampled until 1976.

## Results

The 2015 Lake Huron fall bottom trawl survey was conducted between 14 and 28 October. Forty-three trawl tows were completed and all standard ports were sampled, including Goderich, Ontario. Seventeen fish species were captured in the 2015 survey: rainbow smelt, alewife, bloater, deepwater sculpin, trout-perch, lake whitefish, round whitefish *Prosopium cylindraceum*, ninespine stickleback, three-spine stickleback, lake trout, round goby, yellow perch *Perca flavescens*, walleye *Sander vitreus*, white bass *Morone chrysops*, Gizzard shad *Dorosoma cepedianum*, sea lamprey *Petromyzon marinus*, and common carp *Cyprinus carpio*.

Alewife abundance in Lake Huron remained low in 2015. YAO alewife were not collected in 2015 for the first time in the history of the survey (Fig. 2). YOY alewife density and biomass during 2015 were the second lowest in the time series (Fig. 2). YAO rainbow smelt density in Lake Huron in 2015 was the lowest observed in the time series (Fig. 3). Young-of-the-year rainbow smelt abundance and biomass were similar to 2014 values. YAO bloater density and biomass decreased in 2015 (Fig. 4).

Abundance and biomass estimates for deepwater sculpins in Lake Huron in 2015 were also lower than the previous four years and remained relatively low compared to historic estimates (Fig. 5). The 2015 abundance and biomass estimates for ninespine stickleback and trout-perch increased slightly from

previous years (Fig. 6). Round goby abundance and biomass estimates for 2015 increased over 2014 levels but was well below levels observed during 2001-06 and 2011-13 (Fig. 7).

The total main basin prey biomass estimate (5 - 114 m) in 2015 was 19.4 kilotonnes, a decrease of about 50% from the 2014 estimate (Fig. 8). This estimate is the second lowest observed in the time series and is similar to the extreme low estimates that occurred during 2009 and represents approximately 5 percent of the maximum lakewide biomass estimate observed in 1987. Approximately two-thirds of the 2015 biomass estimate was composed of YAO bloater.

## Discussion

Despite collecting 6 more fish species than in 2014, overall abundances were still low. The abundance of prey fish in Lake Huron has remained at very low levels since the collapse of the offshore demersal fish community in 2004 (Riley et al. 2008), although survey catches in 2012 suggested that several species were beginning to increase in abundance. The estimated lakewide biomass of prey fish in 2012 was the highest observed since 2001, while the 2013 estimate was approximately half as high as 2012; 2014 and 2015 were even lower. The estimated biomass of YAO rainbow smelt and alewife in 2015 were lower than in 2014 and remained low compared to earlier data. The reduction in the abundance of these exotic species is consistent with fish community objectives for Lake Huron (DesJardine et al. 1995), but does not bode well for Chinook salmon populations in the lake (Roseman and Riley 2009), which rely almost solely on these species as prey.

YAO bloater showed a consistent positive trend in biomass for 2009-2012, but the 2013 estimate was much reduced from 2012. In 2014, a modest increase over the 2013 levels occurred, but then declined again in 2015. The abundance of this native species is currently at a moderate level, higher than the extreme low estimates observed in 2001-2006. Bloater are one of the only species that has increased in abundance in recent years and continued monitoring of this species will determine whether conditions in the lake are conducive to the survival and recruitment of native coregonines.

Prior to the invasion of alewife and rainbow smelt, deepwater sculpins, slimy sculpins, and trout-perch were likely an important diet of lake trout in the Great Lakes (e.g., Van Oosten and Deason 1938), however in recent years have become only a minor component of lake trout diets (Diana 1990; Roseman et al. 2014). As the prey fish community continues to change, including a reduction in numbers of alewife and rainbow smelt in the system and proliferation of round goby (Schaeffer et al. 2005), monitoring these species continues to be important to understand food availability to lake trout. In 2015, biomass estimates for deepwater sculpins, sticklebacks, and trout-perch were lower than in recent years and remained relatively low compared to historical peak estimates.

Round goby have become a significant part of lake trout diets in some areas of the Great Lakes (Dietrich et al. 2006), including Lake Huron (Ji He, MDNR Alpena, pers. comm.; Roseman et al. 2014). Round goby were first captured in the Lake Huron trawl survey in 1997, reached peak abundance in 2003 (Schaeffer et al. 2005), and declined in abundance until 2011. Our results suggest that they are currently at a moderate to low level of abundance in the offshore waters of Lake Huron, although sharp fluctuations in the time series indicate that abundance estimates for this species may be particularly sensitive to various environmental factors. Additionally, because our survey samples on smooth bottom areas of the lake, and because round goby are known to prefer rocky substrates with interstitial spaces (MacInnis and Corkum 2000; Ray and Corkum 2001), our bottom trawl estimates of abundance and distribution likely do not reflect true round goby population demographics. New research is being proposed by USGS GLSC and partner agencies in 2017 to address these deficiencies.

The estimated lakewide biomass of common offshore prey species in Lake Huron increased from 2009 - 2012, but then decreased in 2013, 2014, and 2015. The peak estimated biomass of prey fish in Lake Huron occurred in the late 1980s, and has declined steadily since then; a similar decline has occurred in Lake Michigan (Madenjian et al. 2014). These declines are possibly associated with the invasion of the lakes by several exotic species, including the spiny water flea (*Bythotrephes*), zebra mussels, quagga mussels, and round gobies, all of which have been introduced since the mid-1980s. However, similar declines in some species (particularly coregonines) have occurred in Lake Superior (Gorman and Bunnell 2009; Gorman et al. 2009), which has a lessened impact from invasive species.

Fish abundance estimates reported here are likely to be negatively biased, primarily due to variability in the catchability of fish by the trawl, which may reflect the vulnerability of fish to the gear and/or the distribution of fish off the bottom. Many individuals of some demersal species may be pelagic at certain times and not available to our trawls, particularly young-of-the-year alewife, rainbow smelt, and bloater. Results reported here should therefore not be interpreted as absolute abundance estimates for any species.

Some of the fluctuations in the estimated abundance of individual species may be a result of changes in catchability caused by altered fish distributions. For example, catchability of a given species might differ from year to year due to changes in temperature or food distribution, and observed changes in abundance might result from fish becoming less vulnerable to bottom trawls in recent years. The invasion of Lake Huron by dreissenid mussels may also have affected the efficiency of the trawl, as has been observed in Lake Ontario (O’Gorman et al. 2005). Data reported here were collected at a restricted range of depths in areas that were free of obstructions and were characterized by sandy or gravel substrates, and it is therefore possible that USGS trawl data do not fully characterize the offshore demersal fish community. There are no other published long-term data on offshore demersal fish abundance in Lake Huron that would allow us to investigate the representativeness of the trawl data. Despite the foregoing constraints, however, these data are currently the best available to assess trends in the Lake Huron offshore demersal fish community.

The results of this survey demonstrate that there has been great variability in the abundance or biomass of a number of fish species (YOY benthopelagic planktivores, round goby) over the last decade. Low levels of prey fish abundance have persisted since approximately 2006, although the 2012-2015 surveys provided evidence that the abundance of some species (e.g. YAO bloater) may be starting to rebound. These results, along with other analyses (Riley and Adams 2010), may indicate that the offshore demersal fish community in Lake Huron is currently in an unstable state. This survey provides the Great Lakes scientific community with the opportunity to monitor and help explain the changes occurring in the Lake Huron food web.

## **Acknowledgments**

We thank Capt. Joe Bergan, MMR Dave Paavola, and mate Deirdre Jordan for their seamanship and dedication to completing the survey. S. Nelson, L. Zhang, and D. Benes provided database and computer support. S. Riley, R. DeBruyne, and N. Godby provided useful reviews of this report.

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## Figures



Figure 1. Bottom trawl sampling locations in Lake Huron.

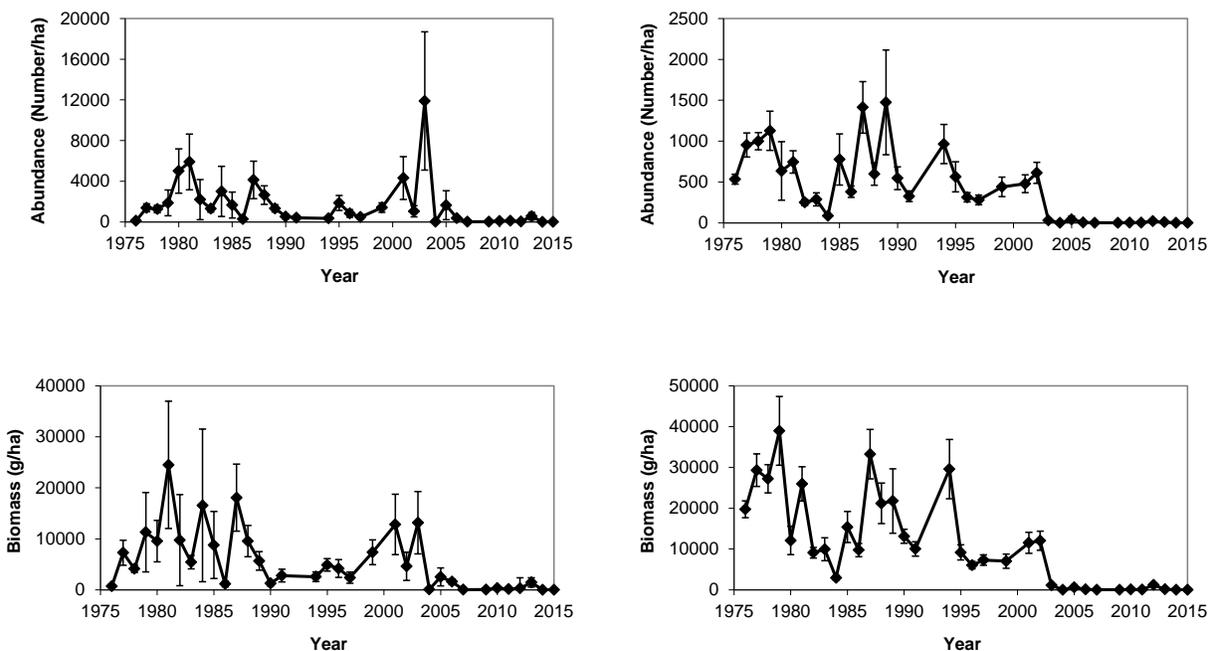


Figure 2. Density of young-of-the-year (YOY: left panels) and adult (YAO: right panels) alewives as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2015. 1976-1991 estimates were corrected using fishing power corrections developed by Adams et al. (2009). Error bars are 95% confidence intervals.

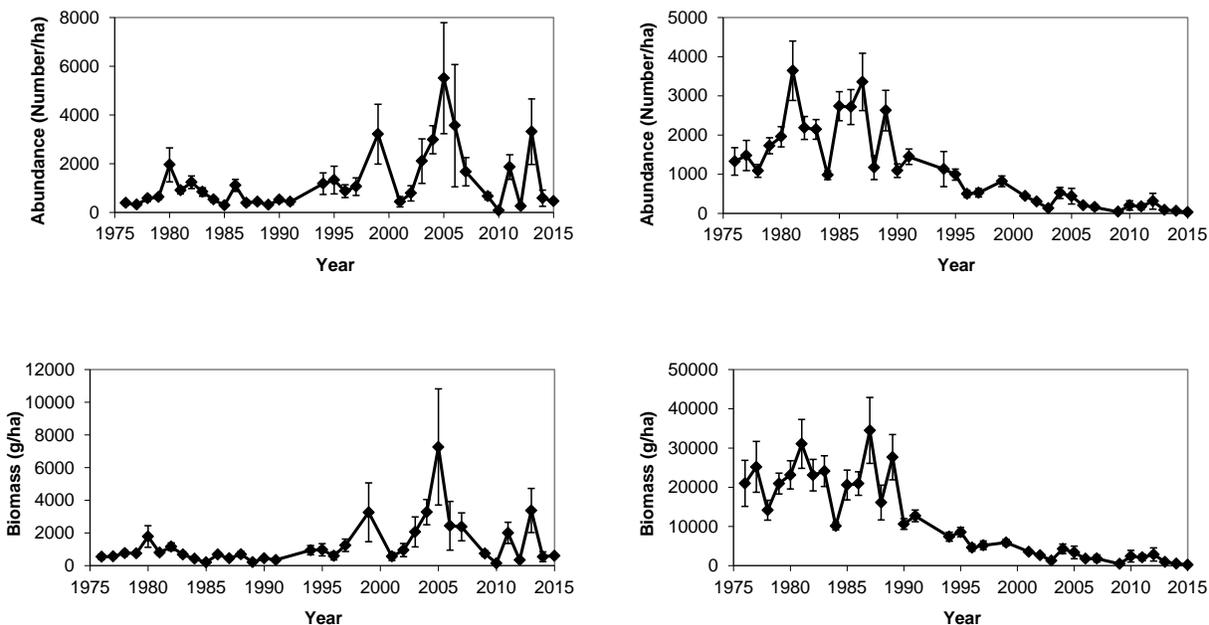


Figure 3. Density of young-of-the-year (YOY: left panels) and adult (YAO: right panels) rainbow smelt as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2015. 1976-1991 estimates for YAO were corrected using fishing power corrections developed by Adams et al. (2009); YOY data are uncorrected. Error bars are 95% confidence intervals.

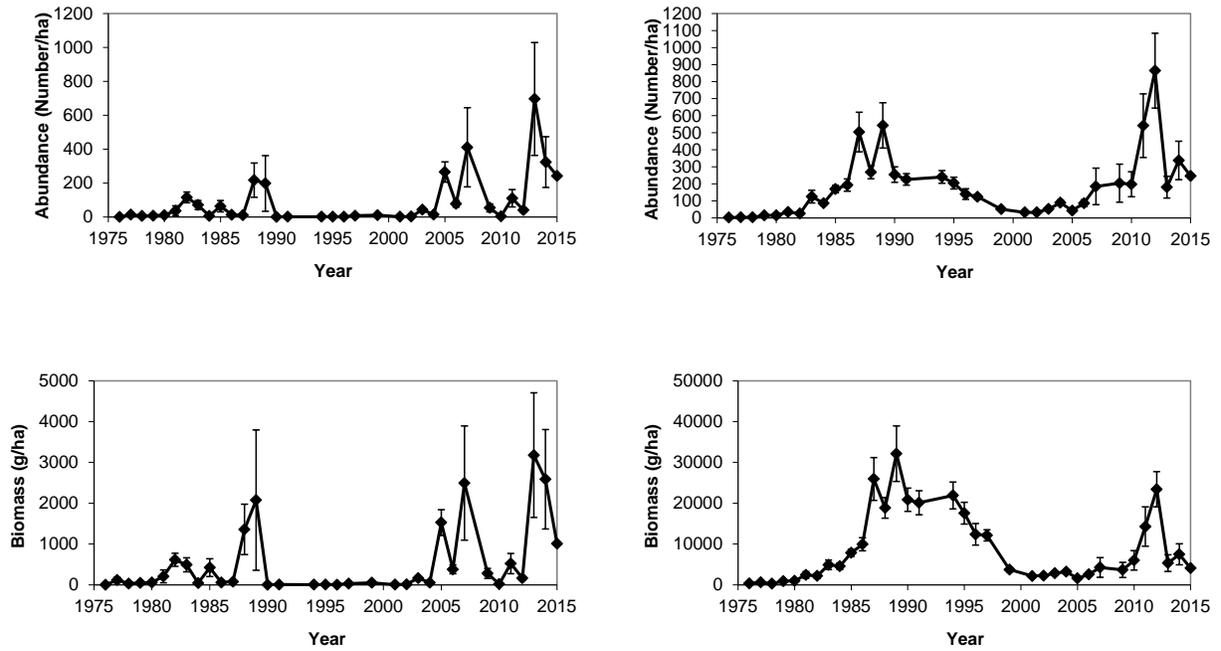


Figure 4. Density of young-of-the-year (YOY: left panels) and adult (YAO: right panels) bloater as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2015. 1976-1991 estimates were corrected using fishing power corrections developed by Adams et al. (2009). Error bars are 95% confidence intervals.

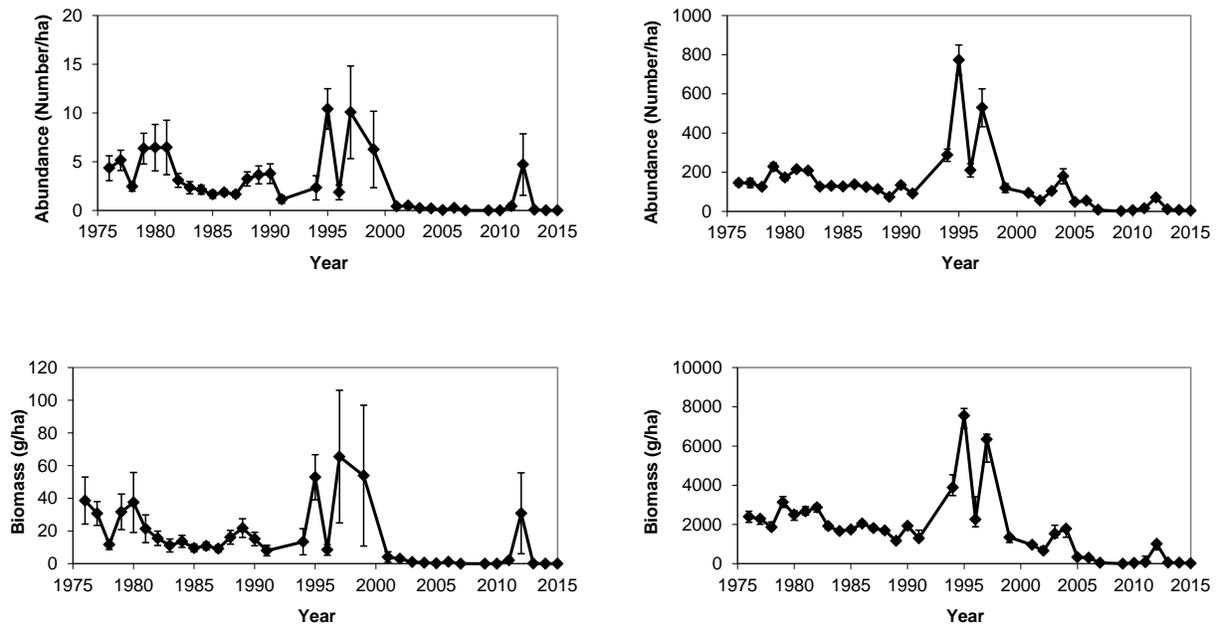


Figure 5. Density of slimy (left panels) and deepwater (right panels) sculpins as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2015. 1976-1991 estimates were corrected using fishing power corrections developed by Adams et al. (2009). Error bars are 95% confidence intervals.

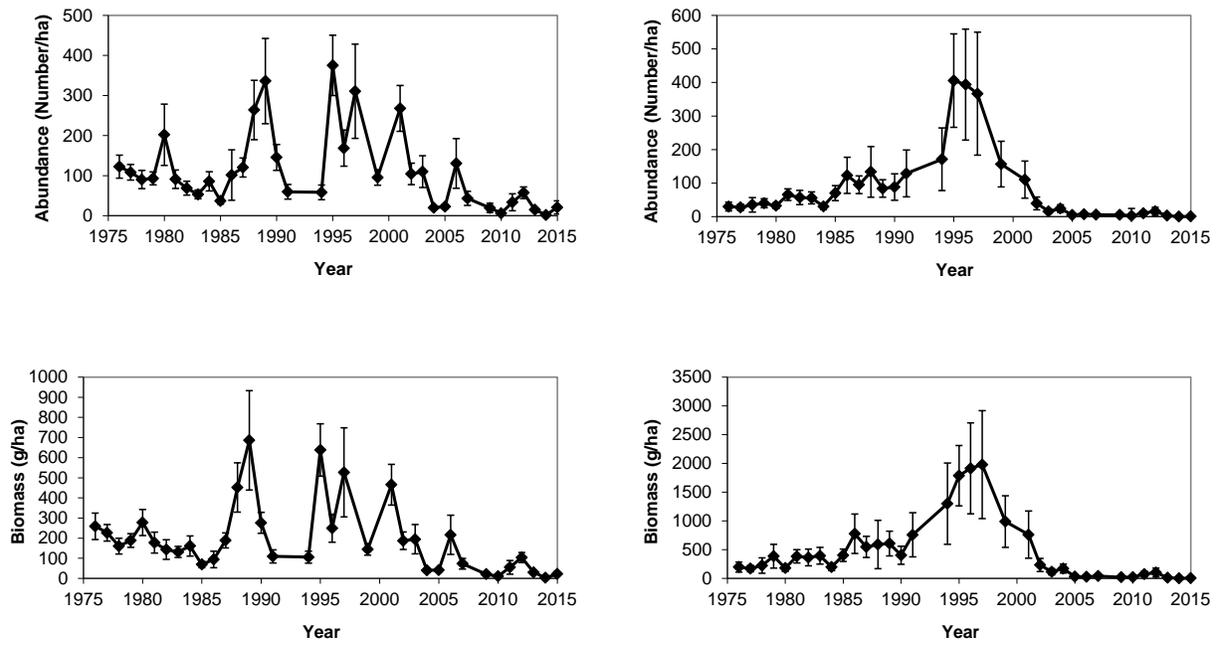


Figure 6. Density of ninespine stickleback (left panels) and trout-perch (right panels) as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2015. Error bars are 95% confidence intervals.

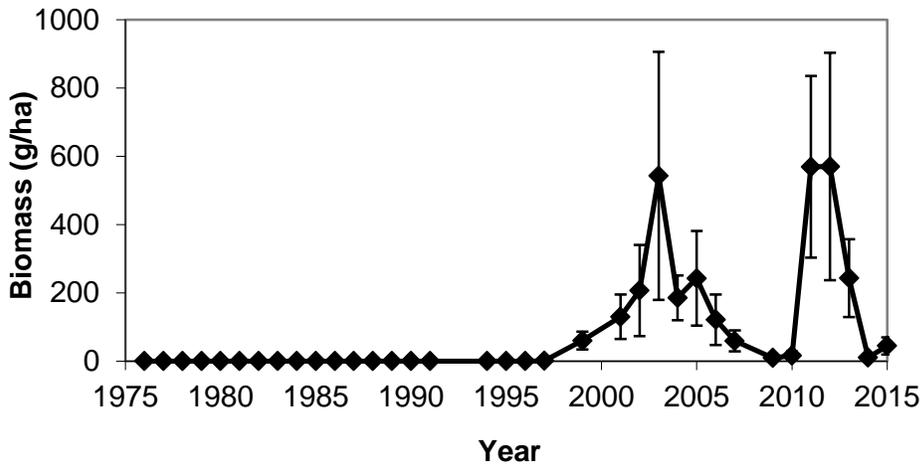
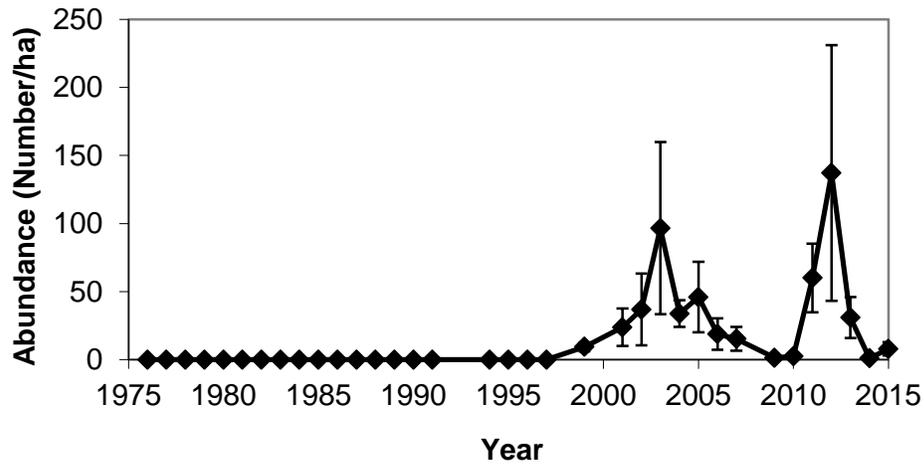


Figure 7. Density of round goby as number (top panel) and biomass (bottom panel) of fish per hectare in Lake Huron, 1976-2015.

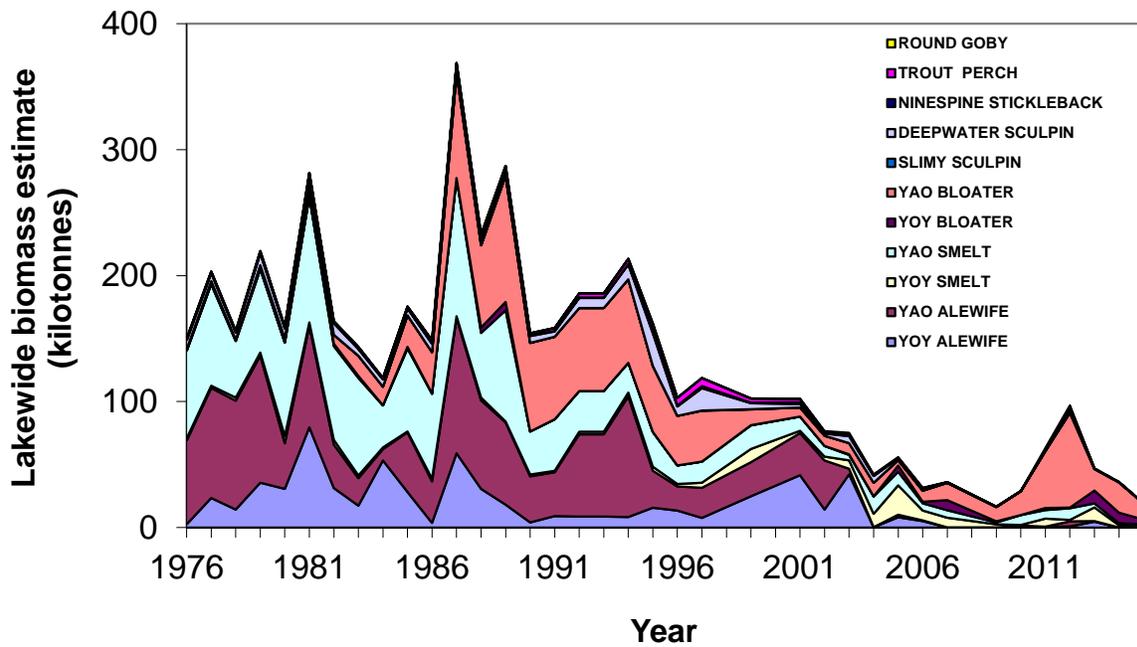


Figure 8. Offshore demersal fish community biomass in the main basin of Lake Huron, 1976-2015. Valid data were not collected in 1992, 1993, 1998, 2000, and 2008; biomass estimates for those years represent interpolated values.

## Status of Pelagic Prey Fishes in Lake Michigan, 2015<sup>1</sup>

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### ABSTRACT

Acoustic surveys were conducted in late summer/early fall during the years 1992-1996 and 2001-2015 to estimate pelagic prey fish biomass in Lake Michigan. Midwater trawling during the surveys as well as target strength provided a measure of species and size composition of the fish community for use in scaling acoustic data and providing species-specific abundance estimates. The 2015 survey consisted of 27 acoustic transects (580 km total) and 31 midwater trawl tows. Four additional transects were sampled in Green Bay but were not included in lakewide estimates. Mean prey fish biomass was 4.2 kg/ha [20.3 kilotonnes (kt = 1,000 metric tons)], equivalent to 44.8 million pounds, which was 36% lower than in 2014 (31.7 kt) and 17% of the long-term (20 years) mean. The numeric density of the 2015 alewife year-class was 25% of the time series average and nearly 9 times the 2014 density. This year-class contributed 8% of total alewife biomass (3.4 kg/ha). In 2015, alewife comprised 82.5% of total prey fish biomass, while rainbow smelt and bloater were <1% and 16.9% of total biomass, respectively. Rainbow smelt biomass in 2015 (0.02 kg/ha) was 74% lower than in 2014, <1% of the long-term mean, and lower than in any previous year. Bloater biomass in 2015 was 0.7 kg/ha and 8% of the long-term mean. Mean density of small bloater in 2015 (489 fish/ha) was slightly lower than peak values observed in 2008-2009 but was more than three times the time series mean (142 fish/ha).

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## INTRODUCTION

Annual evaluation of long-term data on prey fish dynamics is critical in light of changes to the Lake Michigan food web during the last 40 years (Madenjian et al. 2002) and continued restructuring due to exotic species, pollution, fishing, and fish stocking. Alewives are the primary prey in Lake Michigan and of especial importance to introduced salmonines in the Great Lakes (Elliott 1993; Rybicki and Clapp 1996; Warner et al. 2008; Jacobs et al. 2013), however they are also predators of larval fish and are tied to thiamine deficiencies that contribute to recruitment bottlenecks in native fishes including lake trout (*Salvelinus namaycush*). As such, alewives constitute an important component of the food-web. The traditional Great Lakes Science Center (GLSC) prey fish monitoring method (bottom trawl) is inadequate for fish located off bottom (Fabrizio et al. 1997). In particular, bottom trawls provide particularly biased estimates for age-0 alewives (*Alosa pseudoharengus*) based on catchability estimates from stock assessment modeling (Tsehaye et al. 2014). Much of the alewife biomass will not be recruited to bottom trawls until age-3 (Madenjian et al. 2005), but significant predation by salmonines may occur on alewives  $\leq$  age-2 (Warner et al. 2008). Alewife abundance patterns are largely driven by the year-classes that are not effectively sampled by bottom trawls; total alewife density is highly correlated with the density of alewife  $\leq$  age-2 (Warner et al. 2008). Because of the ability of acoustic equipment to count organisms far above bottom, this type of sampling is ideal for highly pelagic fish like age-0 alewives, rainbow smelt (*Osmerus mordax*), and bloater (*Coregonus hoyi*) and is a valuable complement to bottom trawl sampling. Further, these two long-term surveys have enabled the development of a stock assessment model for alewife (Tsehaye et al. 2014).

## METHODS

### *Sampling Design*

The initial Lake Michigan survey adopted by the Lake Michigan Technical Committee (Fleischer et al. 2001) was a stratified quasi-random design with three strata (north, south-central, and west) and unequal effort allocated among strata. The location of strata and number of transects within each stratum was determined from a study of geographic distribution of species and the variability of fish abundance within strata (Adams et al. 2006). A modified design was developed in 2004 (Warner et al. 2005), which included two additional strata (north and south offshore). The initial three strata were retained, but their size was modified based on data collected in 2003 as well as NOAA Coast Watch Great Lakes node maps of sea surface temperature from 2001-2003. In 2007-2015, the number of transects in each stratum was optimized based on stratum area and standard deviation of biomass using methods in Adams et al. (2006). The collection and analytical approach for 2015 acoustic and midwater trawl data was similar to that in 2004-2013. For a detailed description of the methods see Warner et al. (2009) and Warner et al. (2014). In short, each survey vessel samples along transects using scientific echosounders for estimation of total fish density. While sampling those transects, we use midwater trawls to collect fish to determine species, size, and age (in the case of alewife) composition. The numeric density of fish [fish per hectare (ha)] is split among the species captured in the trawls.

## RESULTS

The 2015 acoustic survey of Lake Michigan was conducted by USGS, USFWS, and MDNR. The main basin sampling consisted of 28 transects (Figure 1) for a total transect distance of 580 km, which was similar to the sampling distance in Lake Huron in 2015 (O'Brien et al. 2016). The bottom range over which acoustic data were collected was 12-230 m (39-755 ft), and the mean bottom depth of sampling was 94 m (308 ft). In addition to the main basin effort, USFWS collected data from three transects in Green Bay.

Alewife – The numeric density of the 2015 alewife year-class in 2015 was more than 8 times higher than the density of the 2014 year-class in 2014. At 277 fish/ha, the 2015 estimate was 25% of the long-term mean. While well below average, the numeric density of age-0 alewife in 2015 was the highest since 2012. The biomass density of age-1 or older alewife was 3.2 kg/ha (Figure 2), which was 32% of the

long-term mean of 10 kg/ha and 32% lower than biomass density in 2014. The biomass of alewife  $\geq$  age-1 was predominantly the 2012 (48%), 2011 (19%), 2013 (17%), and 2010 year-classes (15%), respectively. The 2014 and 2009 year classes together made up less than 1% of biomass density, indicating that the 2014 year-class was very weak. The acoustic biomass density estimate for age-1 or older alewife (3.2 kg/ha) was nearly 23 times the bottom trawl estimate (0.14 kg/ha) in 2015 and over the time series (years in which both surveys took place), the acoustic estimates have been 5.5 times the bottom trawl estimates. Although we observed lower than average density of alewife in Lake Michigan, the density is still much higher than the density of alewife in Lake Huron (O'Brien et al. 2016), as no alewife were caught during the Lake Huron acoustic survey and only 30 caught in the Lake Huron bottom trawl survey (E.G. Roseman, USGS GLSC unpublished data).

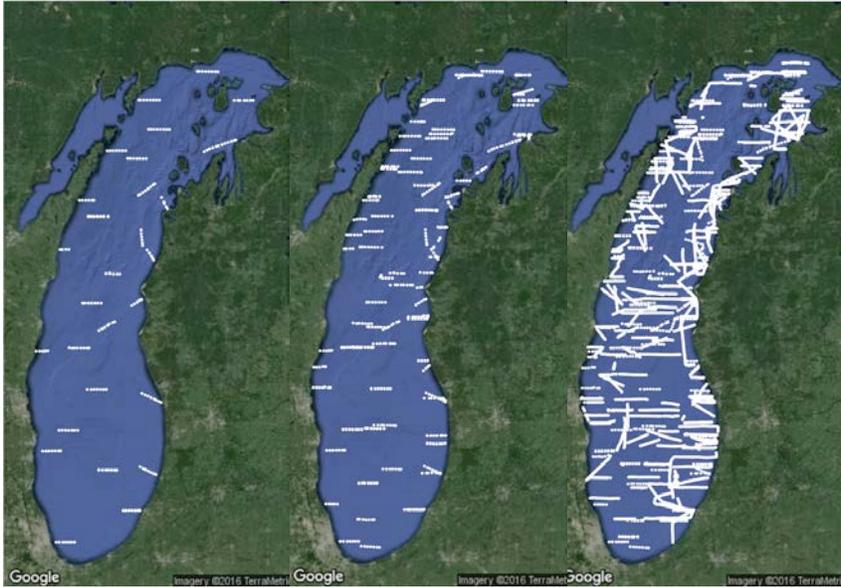


Figure 1. Map of the 2015 acoustic survey track (left panel), the 2013-2015 surveys (center panel), and the 2004-2015 acoustic survey tracks (right panel).

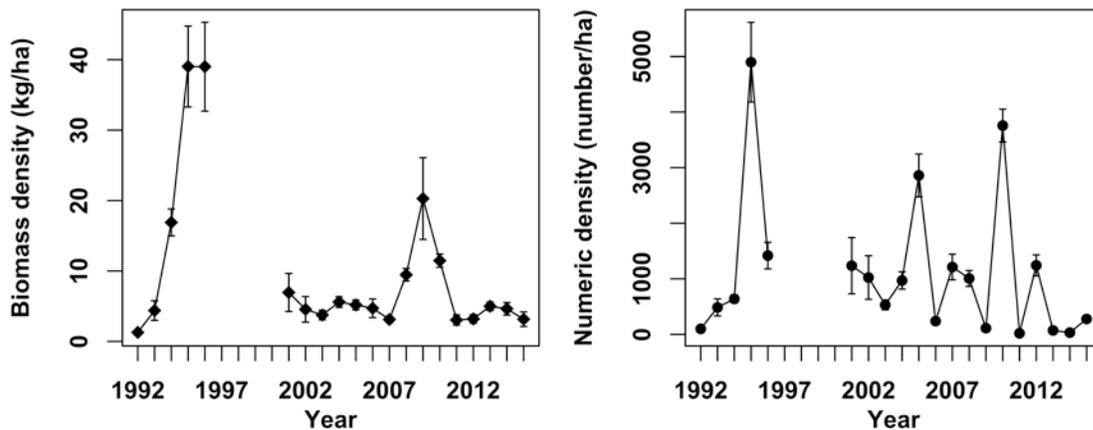


Figure 2. Biomass density of age-1 or older alewife (left panel) and Numeric density of age-0 alewife (right panel) in Lake Michigan during 1992-1996 and 2001-2016. Error bars show one standard error.

Rainbow smelt –At 35 fish/ha, numeric density of small rainbow smelt (<90 mm) in 2015 (Figure 3) was the third lowest in the time series (the lowest was 2002). This density was 17% of the time series mean of 205 fish/ha. Similarly, at 0.008 kg/ha, biomass density of large rainbow smelt ( $\geq 90$  mm) was the lowest in the 20 year survey time series and was <1% of the time series mean, indicating that smelt biomass remains low relative to the early years of the acoustic survey (1992-1996). Even though acoustic biomass density estimates of large smelt have always exceeded bottom trawl estimates, both surveys show there has been an order of magnitude decrease from 1992-1996 to 2001-2014 (Bunnell et al. 2015). Recent low biomass is in stark contrast to observations from the late 1980s (Argyle 1992) but are consistent with the findings of Warner et al. (2012), who reported a shift in the pelagic fish community away from rainbow smelt dominance in the mid-1990s. In addition to highlighting the large decline in rainbow smelt biomass in Lake Michigan, data from recent years provide strong evidence that biomass density in Lake Michigan is lower than in Lake Huron, where the 2014 acoustic estimate of large rainbow smelt biomass density was 34 times that in Lake Michigan (O'Brien et al. 2015).

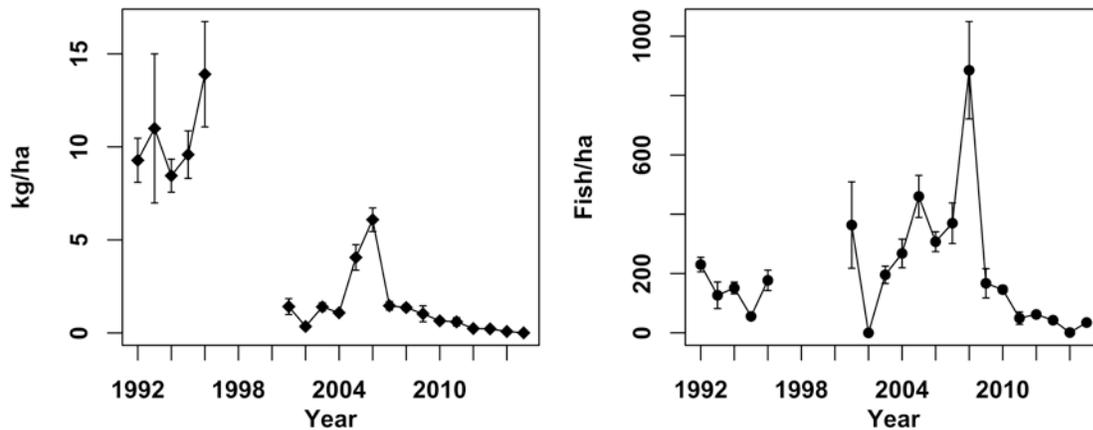


Figure 3. Biomass density of large rainbow smelt ( $\geq 90$  mm, left panel) and numeric density of small rainbow smelt (<90 mm, left panel) in Lake Michigan during 1992-1996 and 2001-2015. Error bars show one standard error.

Bloater –Densities of both small and large bloater have been  $\geq$  variable in 2001-2015. Mean numeric density of small bloater in 2015 (468 fish/ha) was 3.4 times the time series mean of 142 fish/ha (Figure 4). Biomass density of large bloater in 2015 was 0.7 kg/ha, which was only 34% of the 2014 value, 7% of the time series mean, and 2% of the mean in 1992-1996. Bloater biomass has been only 16% of total prey fish biomass density in 2001-2015, on average. This is in contrast to the 1992-1996 period, when bloater made up 48% of total prey fish biomass density. For much of the acoustic time series (1992-2006), estimates of biomass density of large bloater were lower than estimates from the bottom trawl survey. From 2007-2014, acoustic estimates have been nearly five times bottom trawl estimates, on average (Bunnell et al. 2015) but in 2015, the estimates were similar (0.6-0.8 kg/ha). Bunnell et al. (2013) suggested that the continued decrease in bottom trawl biomass density of bloater might be the result of a shift in bloater bathymetric distribution to depths that are now deeper than the bottom trawl sampling. Support for this conclusion includes the fact that bloaters have shown plasticity in bottom depths occupied, with an increase from the 1930s to 2004-2007 (Bunnell et al. 2012) as well as observations from commercial fishermen that the depth at which they capture bloaters has increased (Bunnell et al. 2013).

## DISCUSSION

The results of the 2015 Lake Michigan acoustic survey indicate continued variability in alewife recruitment, persistently low biomass of rainbow smelt and bloater, and continued low abundance of native species. Peak alewife biomass occurred in 1995 and 1996 ( $\approx 40$  kg/ha), and the two highest values during 2001-2015 (2009-2010) were only half as high as in 1995-1996. Total prey fish biomass in 2014 was the lowest observed in the acoustic survey. Total pelagic fish biomass in Lake Michigan (4.2 kg/ha) was lower than in Lake Huron in 2014 (9.5 kg/ha, O'Brien et al. 2014) but similar to Lake Superior in 2011 (6.8 kg/ha, Yule et al. 2013).

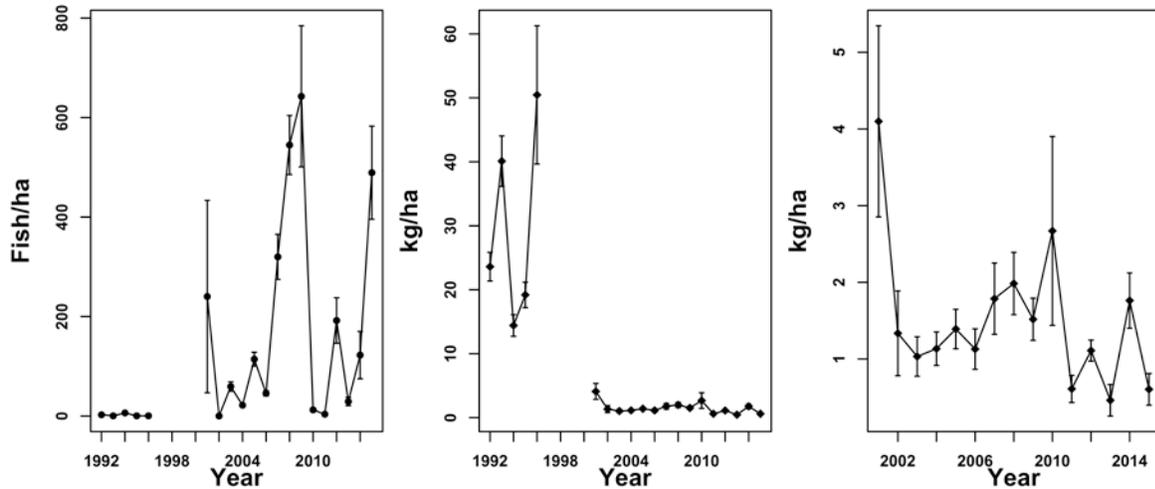


Figure 4. Biomass density of large bloater ( $\geq 120$  mm, left panel) from 1992-2015 (left panel), biomass density of large bloater for the years 2001-2015 (middle panel), and numeric density of small bloater ( $< 120$  mm, right panel) in Lake Michigan. Error bars show one standard error.

As with any survey, it is important to note that trawl or acoustic estimates of fish density are potentially biased and, when possible, we should describe the effects of any bias when interpreting results. With acoustic sampling, areas near the surface (upper blind zone 0-4 m) or near the bottom (bottom dead zone, bottom 0.3-1 m) are not sampled well or at all. The density of fish in these areas therefore is unknown. Recent technological advances allow for acoustic sampling of the upper blind zone over large spatial areas but the cost of this technology has been prohibitive. While our highest alewife and rainbow smelt catches and catch-per-unit-effort with midwater tows generally occur near the thermocline in Lake Michigan (Warner et al. 2008; Warner et al. 2012), it is possible that some are located in the top 4 m and can't be captured with trawls because the ship displaces this water and the fish.

We are less concerned with bias in alewife and rainbow smelt densities attributable to ineffective acoustic sampling of the bottom because of their pelagic distribution at night, when our sampling occurs. In Lake Michigan, day-night bottom trawling was conducted at numerous locations and depths in 1987 (Argyle 1992), with day and night tows occurring on the same day. These data indicate that night bottom trawl estimates of alewife density in August/September 1987 were only 6% of day estimates (D.M. Warner, unpublished data). Similarly, night bottom trawl estimates of rainbow smelt density were  $\approx 6\%$  of day estimates. However, bloaters tend to be more demersal; in Lake Superior, night acoustic/midwater trawl sampling may detect only 60% of bloater present (Yule et al. 2007). The day-night bottom trawl data from Lake Michigan in 1987 suggested that the availability of bloater to acoustic sampling at night was somewhat higher (mean = 76%, D. M. Warner, unpublished data). Slimy sculpins (*Cottus cognatus*) and deepwater sculpins (*Myoxocephalus thompsonii*) are poorly sampled acoustically and we must rely on

bottom trawl estimates for these species (Yule et al. 2008). We also assumed that our midwater trawling provided accurate estimates of species and size composition. Based on the relationship between trawling effort and uncertainty in species proportions observed by Warner et al. (2012), this assumption was likely reasonable.

We made additional assumptions about acoustic data not described above. For example, we assumed that all targets below 40 m with mean TS > -45 dB were bloater. It is possible that this resulted in a slight underestimation of rainbow smelt density. We also assumed that conditions were suitable for use of *in situ* TS to estimate fish density, which could also lead to biased results if conditions are not suitable for measuring TS (Rudstam et al. 2009; Sawada et al. 1993) and biased TS estimates are used. However, we used the Nv index of Sawada et al. (1993) to identify areas where bias was likely. We assumed that noise levels did not contribute significantly to echo integration data and did not preclude detection of key organisms. This assumption was supported by our estimates of noise (Appendix 2). Detection limits were such that the smallest fish were detectable well below the depths they typically occupy. Finally, we have assumed that the estimates of abundance and biomass are relative and do not represent absolute measures. This assumption is supported by recent estimates of catchability derived from a multispecies age structured stock assessment model (Tsehaye et al. 2014).

Prey fish biomass in Lake Michigan remains at levels much lower than in the 1990s, and the estimate of total lakewide biomass (20.4 kt) from acoustic sampling was the lowest in the time series. This is in contrast to 2008-2010, when biomass was relatively high (but still lower than in the 1990s). The recent decline, resulting primarily from decreased alewife biomass, demonstrates the dynamic nature of the pelagic fish community in Lake Michigan. The large difference between prey fish biomass in the 1990s and the 2000s resulted primarily from a decrease in large bloater abundance, but alewife and rainbow smelt declined as well. Bloater densities showed an increasing trend 2001-2009, driven primarily by increases in small bloater. A similar pattern was observed in Lake Huron (Schaeffer et al. 2012), but only in Lake Huron has there been any evidence of increased abundance resulting from recruitment to larger sizes, as bottom trawl estimates of large bloater density have increased in recent years in Lake Huron but not in Lake Michigan (Madenjian et al. 2012; Schaeffer et al. 2012). Alewife were the dominant component of pelagic prey fish biomass in 2015 (Table 1). Limited recruitment of small bloater, numerical dominance of alewife, along with the continued absence of other native species, suggests that little progress is being made toward meeting the Fish Community Objective (FCO, Eshenroder et al. 1995) of maintaining a diverse planktivore community, particularly relative to historical diversity. Bloater and emerald shiner (*Notropis atherinoides*) were historically important species, but bloater currently exist at low biomass levels and emerald shiner have not been captured in Lake Michigan by GLSC surveys since 1962 (D.M. Warner, unpublished data). Similarly, kiyi (*Coregonus kiyi*) are absent from offshore regions of Lake Michigan, which is in stark contrast to Lake Superior, where Yule et al. (2013) found kiyi to be the most numerous species in 2011. As a result, large areas of Lake Michigan which were formerly occupied by kiyi are now devoid of fish, and movement of energy and nutrients through diel vertical migration has essentially disappeared. In Lake Huron, collapse of the alewife population in 2003-2004 was followed by resurgence in emerald shiner abundance in 2005-2006 (Schaeffer et al. 2008) and by increased abundance of cisco [*Coregonus artedii*, (Warner et al. 2009)]. Given evidence from acoustic surveys from lakes Michigan and Huron as well as the evidence provided by Madenjian et al. (2008), it appears that emerald shiners are suppressed by all but the lowest levels of alewife abundance.

While it is clear that abundance patterns for alewife have been driven in large part by continued high predation pressure (Tsehaye et al. 2014), it is not clear what led to the drastic decline in bloater abundance from the 1980s to present. Recent stock-recruit modeling for bloater in Lakes Michigan and Huron indicated that bloater sex ratio and alewife abundance were related to recruitment (Collingsworth et al. 2014). It is also possible that predation on small bloater by salmonines could be an important limit to

recruitment at times (see Warner et al. 2008) as these small fish are found in the same location as alewife and at times can be important to some predators (Elliott 1993; Rybicki and Clapp 1996; Warner et al. 2008). Both Lake Michigan surveys suggest that recruitment in Lake Michigan is much more limited than in Lake Huron, where high densities of small bloater in 2007-2008 preceded increases in the abundance of larger bloater (Schaeffer et al. 2012). However, the increase in biomass of large bloater in 2014 may be a sign that recruitment has improved over the past few years.

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Table 1. Numeric or biomass density, RSE, and 95% CI for age-0, YAO, total alewife, rainbow smelt, and bloater estimated from acoustic and midwater trawl data collected in Lake Michigan in 2015. The numbers in parentheses following the density values are the value for the previous year.

Species	Density	RSE (%)	95% CI
Total alewife	3.4 kg/ha (4.6)	31	(1.6, 5.3)
Age-0 alewife	278 fish/ha (32)	16	(197, 358)
YAO alewife	3.2 kg/ha (4.6)	33	(1.4, 4.9)
Rainbow smelt	40 fish/ha (35)	22	(26, 55)
Bloater	0.7 kg/ha (1.8)	28	(0.4, 1.0)
Total	4.2 kg/ha (6.5)	25	(2.4, 6.0)

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Appendix 1. Single target detection parameters used in acoustic data analyses in 1992-1996, 2001-2005, and 2015.

Parameter	Dual beam 1992-1996	Dual beam 2001-2005 <sup>1</sup>	2015 Split <sup>2</sup>
TS threshold (dB)	-60	-77 <sup>3</sup>	-77
Pulse length determination level (dB)	6	6	6
Minimum normalized pulse length	0.32	0.8	0.7
Maximum normalized pulse length	0.72	1.8	1.5
Maximum beam compensation (dB)	6	6	6
Maximum standard deviation of minor-axis angles	NA	NA	0.6
Maximum standard deviation of major-axis angles	NA	NA	0.6
Over-axis angle threshold (dB)	NA	-1.0	NA

<sup>1</sup>Dual beam system was only used on the MDNR vessel Steelhead in 2001-2005.

<sup>2</sup>Split beam systems were used on all vessels in 2006-2014.

<sup>3</sup>Although a lower threshold was used in 2001-2014 only targets  $\geq -60$  dB were included in analyses. The lower threshold was used in the event that efforts were made to include smaller fish.

Appendix 2. Noise levels (mean and range of Sv at 1 m), detection limits, and acoustic equipment specifications in 2015 for the R/V Sturgeon, S/V Steelhead, and M/V Spencer F. Baird.

Vessel	R/V Sturgeon	S/V Steelhead	M/V Spencer F. Baird
Collection software	Visual Acquisition	Visual Acquisition	ER60 2.2
	6.0	6.0	
Transducer beam angle (3dB)	8.3° split beam	6.9° split beam	6.18 ° split beam
Frequency (kHz)	120	123	120
Pulse length (ms)	0.4	0.4	0.256
Two-way equivalent beam angle (dB)	-19.34	-20	-20.5
Sv detection limit (m) for -60 dB target <sup>1</sup>	>100	>100	>100 m

<sup>1</sup> Assuming 3 dB signal-to-noise ratio.