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Great Lakes Prey Fish Populations: A Cross-Basin Overview of Status and Trends Based on Bottom Trawl Surveys, 1978-2016¹

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Introduction

Assessments of Great Lakes prey fishes have been conducted annually with bottom trawls since the 1970s by the Great Lakes Science Center and in some lakes in cooperation with partner agencies. These assessments provide data on the status and trends of prey fishes 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 (Figure 1), seasonal timing, trawl gear used, and the manner in which the trawl is towed (across or along bottom contours). To reduce potential bias associated with different sampling designs, population indices for prey fish were standardized to the highest value for a time series within each lake for the following species: Cisco (*Coregonus artedii*), Bloater (*C. hoyi*), Rainbow Smelt (*Osmerus mordax*), Alewife (*Alosa pseudoharengus*), and Round Goby (*Neogobius melanostomus*). In this report, standardized population indices are presented in graphical form along with synopses to provide a short, informal cross-basin summary of the status and trends for principal prey fishes.

Methods

For lakes Superior, Huron, Michigan and Ontario, standardized relative indices of biomass for age-1 and older fishes (Cisco, Bloater, Alewife, Rainbow Smelt) were calculated as the observed value divided by the maximum value observed over a 1978-2016 times series. For Round Goby, standardized relative indices for age-0 and older fishes were calculated from biomass for all lakes but Erie where the relative index was based on available density data. Thus, cross-lake trends in Round Goby were represented by measures of relative abundance.

For each lake, standardized relative indices of density of the juveniles of each species present (Cisco, Bloater, Alewife, Rainbow Smelt) were calculated as the observed value divided by the maximum value observed over the 1978-2016 times series. In each lake, densities of juvenile age-classes that best predicted the magnitude of future recruitment are used to index year-class strengths. Differences in the timing of surveys across lakes and differences in methodology used to distinguish juvenile age classes resulted in adopting different age-classes (e.g., 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 2 or more lakes. W can range from 0 (complete discordance or disagreement) to 1 (complete concordance or agreement). Concordance can be expressed as

¹ Presented at: Great Lakes Fishery Commission, Lake Committees Meeting, 20-24 March 2017. The data associated with this report have not received final approval by the U.S. Geological Survey (USGS) and are currently under review. The Great Lakes Science Center is committed to complying with the Office of Management and Budget data release requirements and providing the public with high quality scientific data. We plan to make all USGS research vessel data collected between 1958 and 2016 publicly available from the GLSC website later in 2017. The anticipated citation will be <http://doi.org/10.5066/F75M63X0>. Please direct any immediate questions to our Information Technology Specialist, Scott Nelson, at snelson@usgs.gov.

either a fraction or percent. A smaller P -value for W 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 were restricted to 1990-2016, years when multi-agency surveys with a consistent sample design were conducted. 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.



Figure 1. – Array of bottom trawl sampling locations for prey fish surveys in the Great Lakes used in this report. Records of biomass of age-1 and older fish and densities of age-0, age-1 and age-3 fish used for indexing year classes from these locations were used for cross-lake comparisons.

Results

Relative Biomass, Prey Fish

Relative combined biomass of pelagic prey fish (Cisco, Bloater, Rainbow Smelt, Alewife) in lakes Superior, Michigan, Huron and Ontario for the 1978-2016 time series trended downward, but were weakly concordant (Fig. 2; $W = 0.42$; $P < 0.01$). However, there were no pair-wise agreements in trends with Ontario and other lakes ($P > 0.72$). When the comparison is limited to lakes Superior, Michigan and Huron, the concordance in trends increases substantially ($W = 0.79$; $P < 0.0001$). Comparisons of combined prey fish biomass with Lake Erie over 1990-2016 were not concordant ($W = 0.21$; $P > 0.40$).

Composition of the prey fish assemblages in the lakes varied over the time series. In Lake Superior, Rainbow Smelt dominated the assemblage early in the time series and following resurgence of coregonids in the early 1980s, Cisco and Bloater dominated the assemblage thereafter. Early in the Lake Michigan time series, Alewife dominated the assemblage and Bloater dominated the assemblage through the late 1990s. Although Rainbow Smelt resurged in the early 1980s, they were a relatively minor component of the Michigan assemblage through the mid-1990s and declined to low levels thereafter. In the 2000s, Round Goby became a minor component of the assemblage and by 2015 Rainbow Smelt and Alewife reached very low levels. Trends in the Lake Huron

prey fish assemblage contrasted somewhat with that of Michigan. Alewife and Rainbow Smelt dominated the assemblage through the 1990s, though Bloater became an important component of the assemblage in the 1990s following resurgence in the early 1980s. After 2002, prey fish biomass declined sharply. Following a nadir in 2008, the prey fish assemblage recovered somewhat but Bloater now dominated the assemblage, the result of recruitment from a succession of new cohorts. By 2013, Alewife and Rainbow Smelt had become rare components of the prey fish assemblage. The Lake Ontario prey fish assemblage was consistently dominated by Alewife over the time series. Rainbow Smelt, a minor component in the assemblage, declined to low levels after 2000 while Round Goby became a minor component of the assemblage. Without the provisional correction applied to data after 1996, the biomass trend in Ontario was downward through the time series (dashed line, Figure 2). In Lake Erie, Rainbow Smelt was the dominant component of the prey fish assemblage over the 1990-2016 time series. Following the appearance of Round Goby in the mid-1990s, this species expanded to become a co-dominant component of the assemblage through 2008. Afterwards, abundance of Rainbow Smelt increased relative to Round Goby.

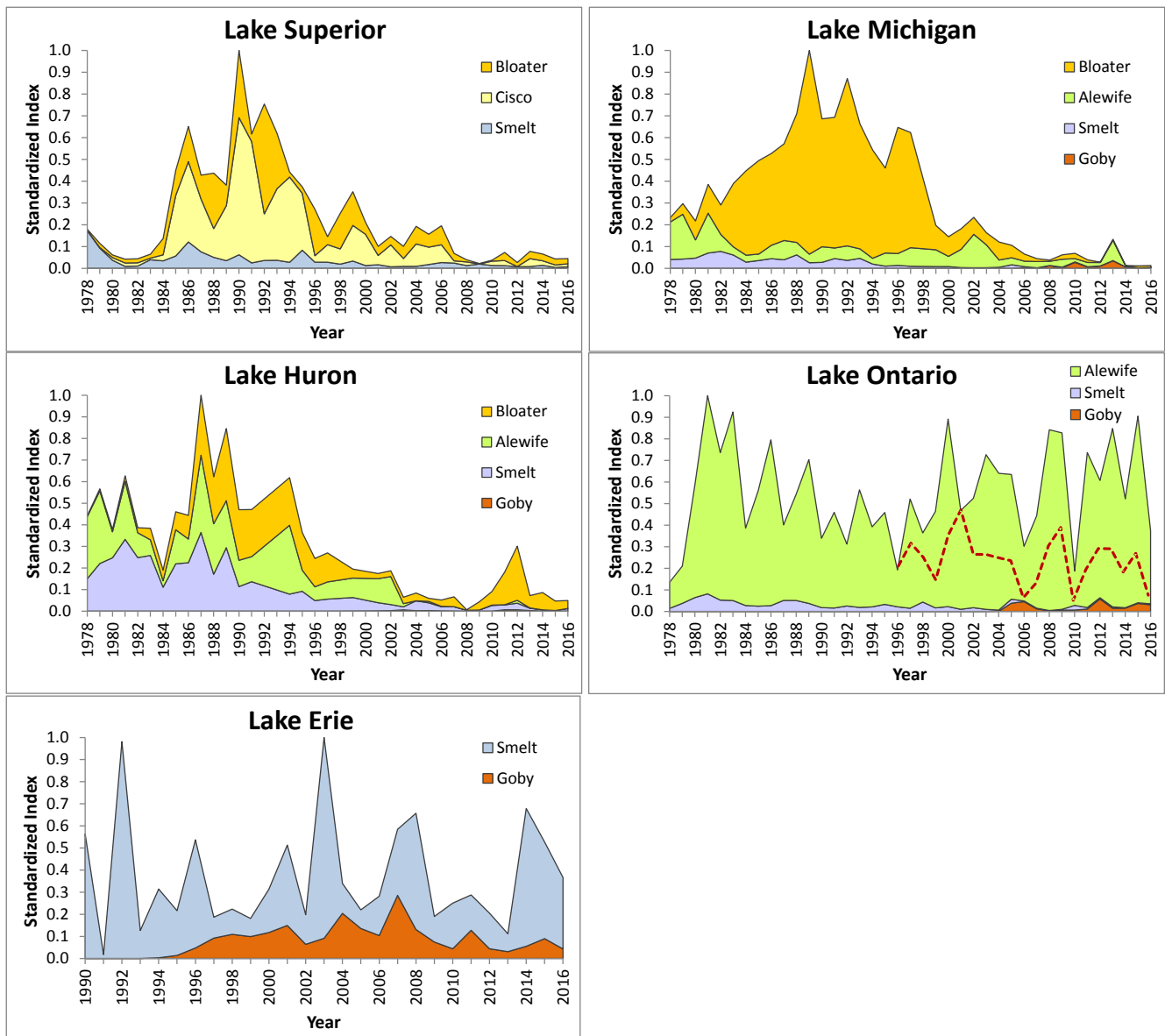


Figure 2. – Standardized indices of total biomass of pelagic prey fish (Cisco, Bloater, Rainbow Smelt, Alewife, and Round Goby) in lakes Superior, Michigan, Huron and Ontario for 1978-2016 and 1990-2016 for Lake Erie. Dashed line in the Lake Ontario panel shows total predicted total relative prey fish biomass without application of corrections after 1996 (Weidel et al. 2017a ,b).

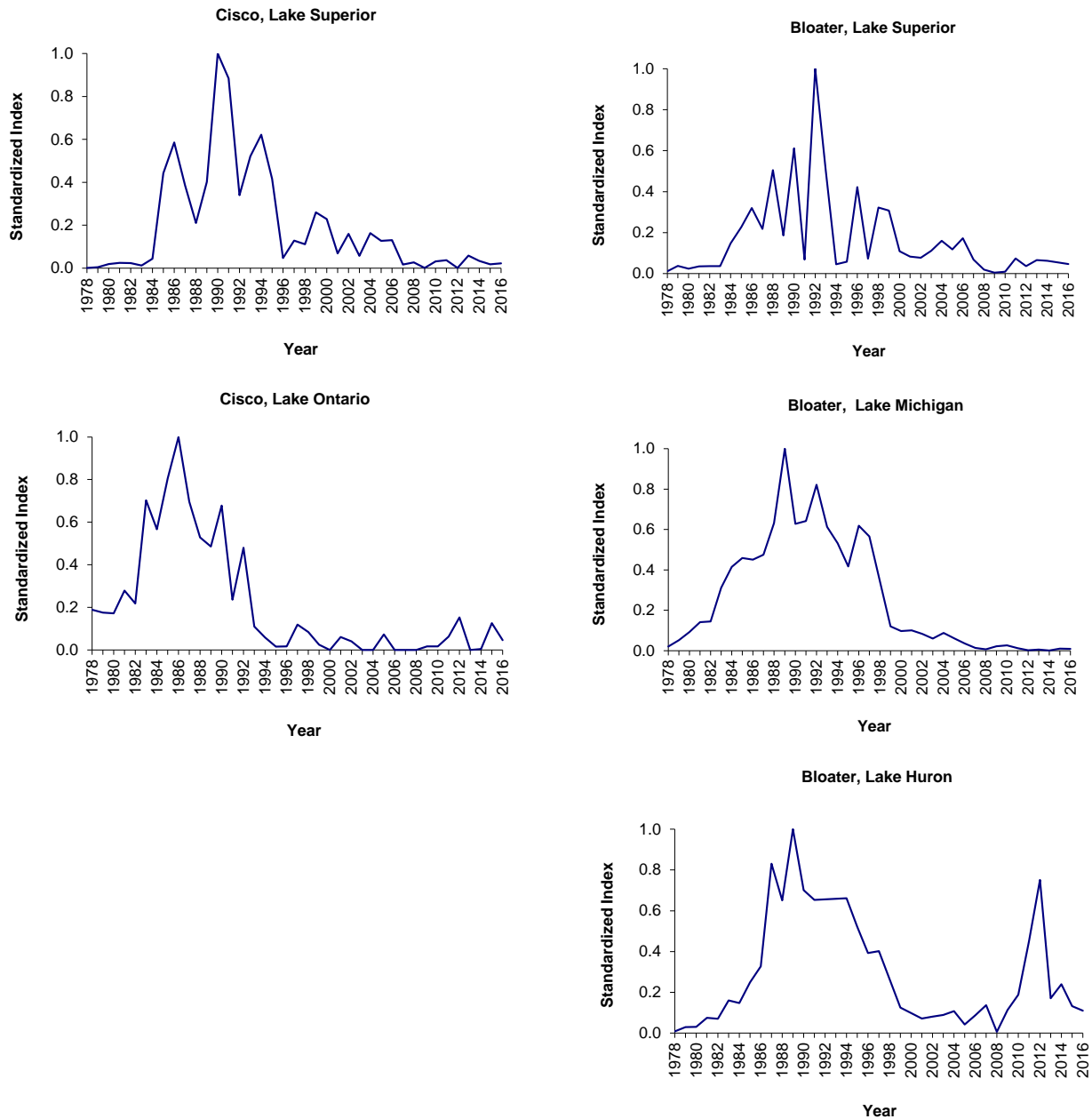


Figure 3. – Standardized indices of biomass for age-1 and older coregonids (Cisco in lakes Superior and Ontario and Bloater in lakes Superior, Michigan, and Huron), 1978-2016.

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 1978-2016 time series were significantly concordant (Fig. 3; $W = 0.67$; $P < 0.0001$). Although Cisco is a rare species in Lake Ontario (maximum mean biomass, density, 1986: 0.89 kg/ha; 0.08 fish/ha; minimums are zero), it was regularly captured in low numbers throughout the time series. When the Lake Ontario Cisco relative biomass trends are included in a comparison of trends in the lakes, the trends remain significantly concordant (Fig. 3; $W = 0.56$; $P < 0.0001$), but is not concordant with the trend in Lake Superior Cisco ($P > 0.21$). 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 ($r = 0.72$, $P < 0.01$).

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 was initially higher than in other lakes (before 1982) and declined sooner (after 1992) than in the other lakes, a difference that contributed to a lack of concordance with other lakes. 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. 3, 7). Although Huron's Bloater biomass has trended downward since the 2012 peak, recruitment from a record 2013 year class and moderate 2014 and 2015 year classes may boost future biomass. Bloater were absent from survey catches in lakes Erie and Ontario, and Cisco were rarely encountered in lakes Michigan, Huron, and Erie.

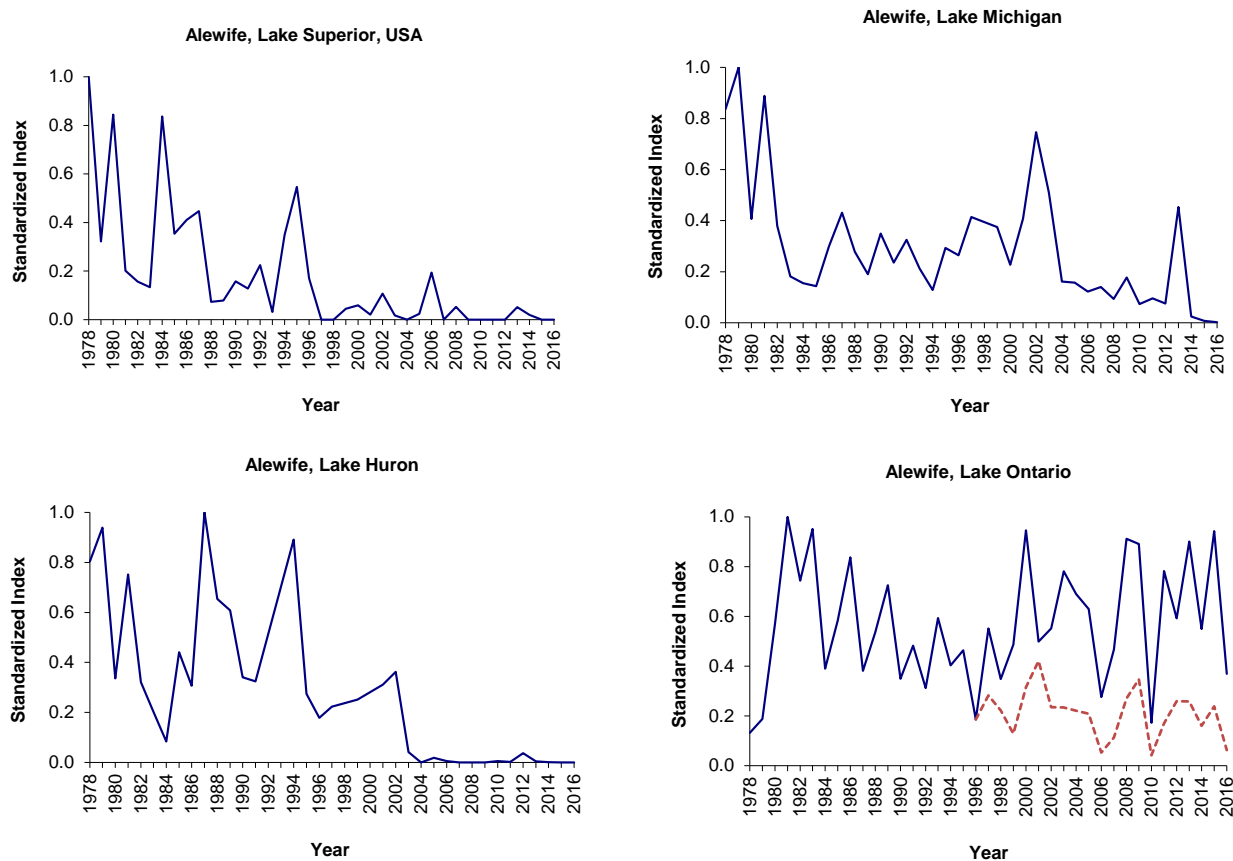


Figure 4. – Standardized indices of biomass for age-1 and older Alewife in lakes Superior, Michigan, Huron, and Ontario, 1978-2016. Dashed line in the Ontario panel shows predicted relative biomass without application of provisional corrections to data after 1996.

Relative Biomass, Age-1 and older Alewife

Trends in relative biomass of age-1 and older Alewife across lakes Superior, Michigan, and Huron were variable, though biomass was generally higher early in the time series and lower in more recent years (Fig. 4). For these three lakes, there was strong concordance ($W = 0.73$; $P < 0.0001$) among the 1978-2016 time series. There was no concordance in trends of Alewife in Lake Ontario and other lakes (Fig. 4; $W < 0.5$; $P > 0.5$). A change in depth distribution of Alewife in Ontario after 1996 necessitated a correction in estimated biomass; a provisional correction was implemented for the 2016 analysis (Weidel et al. 2017a,b).

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 (Madenjian et al. 2014). 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 and 2016. 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, 2013-2014, zero in 2015, and near zero in 2016. Following the application of provisional corrections to data collected after 1996, Alewife biomass in Lake Ontario appeared to be highly variable with no apparent trend. To put the trends in Alewife abundance in lakes Michigan, Huron and Ontario in perspective, it should be noted that during the mid-1960s Alewife abundances were much higher than shown in the current time series (Madenjian et al, 2005). Although Alewife is a rare species in Lake Superior, the pattern of biomass decline followed that of other Great Lakes; once Lake Trout populations were fully recovered in the late 1990s, relative biomass has remained low. For Lake Superior, maximum reported Alewife biomass and density, 1978: 0.14 kg/ha and 0.01 fish/ha; minimums are zero. Survey data for Alewife in Lake Erie were not available for this comparison.

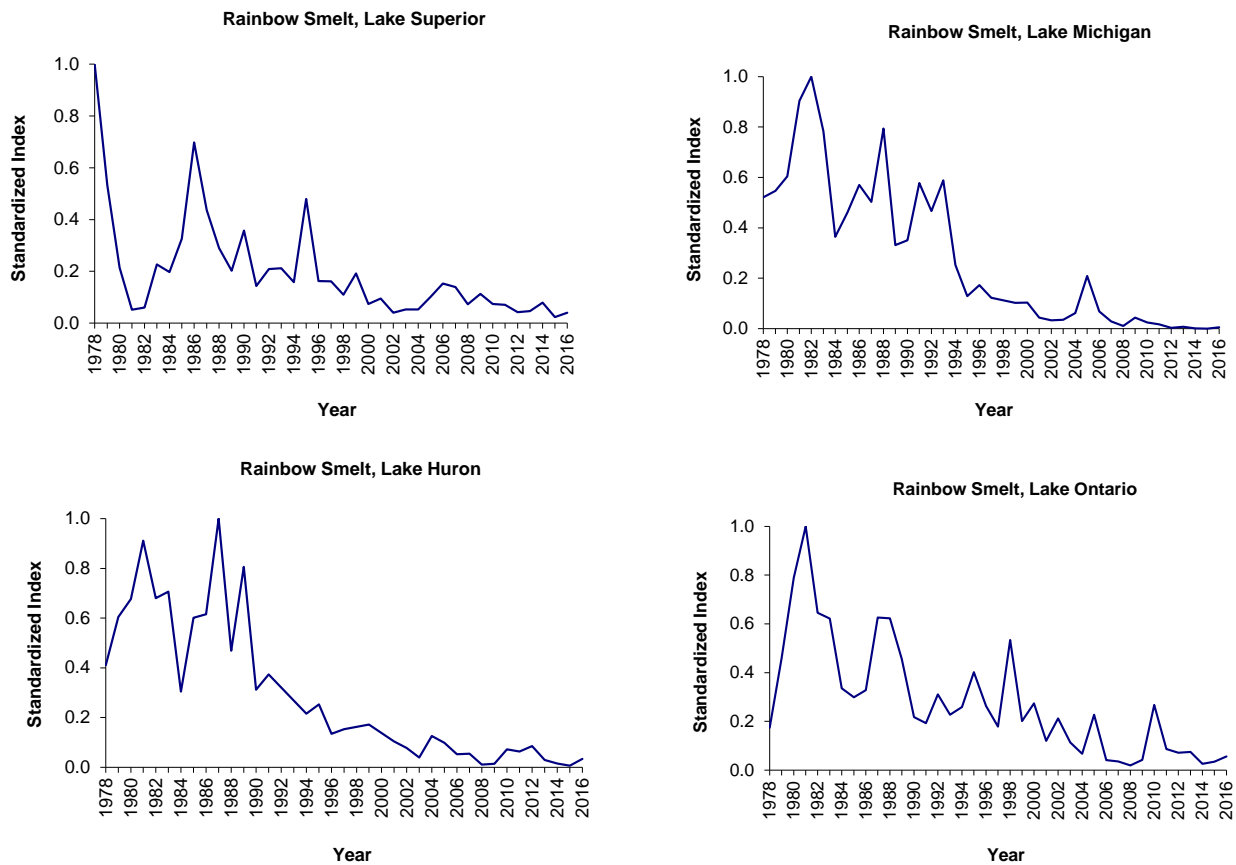


Figure 5. – Standardized indices of biomass for age-1 and older Rainbow Smelt in lakes Superior, Michigan, Huron, and Ontario, 1978-2016.

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 1978-2016 (Fig. 5; $W = 0.80$; $P < 0.0001$). 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, 2013, 2016 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, 2016 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. Then in 2013-2014, biomass dropped again, reaching a record low in 2015 and recovering slightly in 2016. A similar pattern was observed in Lake Ontario where biomass reached a near-record lows in 2006-

2009 and was followed by a weak recovery 2010, and decline to near record lows in 2014-2016. Survey data for age-1 and older Rainbow Smelt in Lake Erie were not available for this comparison.

Relative Abundance, Age-0 and older Round Goby

Weak agreement in trends in relative abundance of age-0 and older Round Goby ($W = 0.46$; $P = 0.01$) was observed among lakes where this species has become established (lakes Michigan, Huron, Erie, and Ontario; Fig. 6). Increased 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, relative abundance of Round Goby in Lake Erie in 2010-2016 declined to the lowest levels since the initial stages of expansion but was punctuated by small peaks in 2011 and 2015; this pattern is suggestive of nearing equilibrium. After what appears to have been a similar pattern of expansion and decline in Lake Huron, relative abundance of Round Goby spiked to record levels in 2011 and 2012 and then declined > 90% thereafter. The peak in relative abundance of Round Goby observed in 2013 in Lake Michigan was followed by $\geq 90\%$ decline afterwards. Round Goby relative abundance in Lake Ontario was highly variable over the time series; after initial detection in 2003, abundance increased rapidly, peaking in 2006 but then underwent a series of peaks and declines thereafter. Round Goby relative abundance showed a considerable year-to-year variability in lakes Michigan, Huron, and Ontario, suggesting that impending population equilibrium remains uncertain. Round Goby have not been caught in annual bottom trawl surveys in Lake Superior.

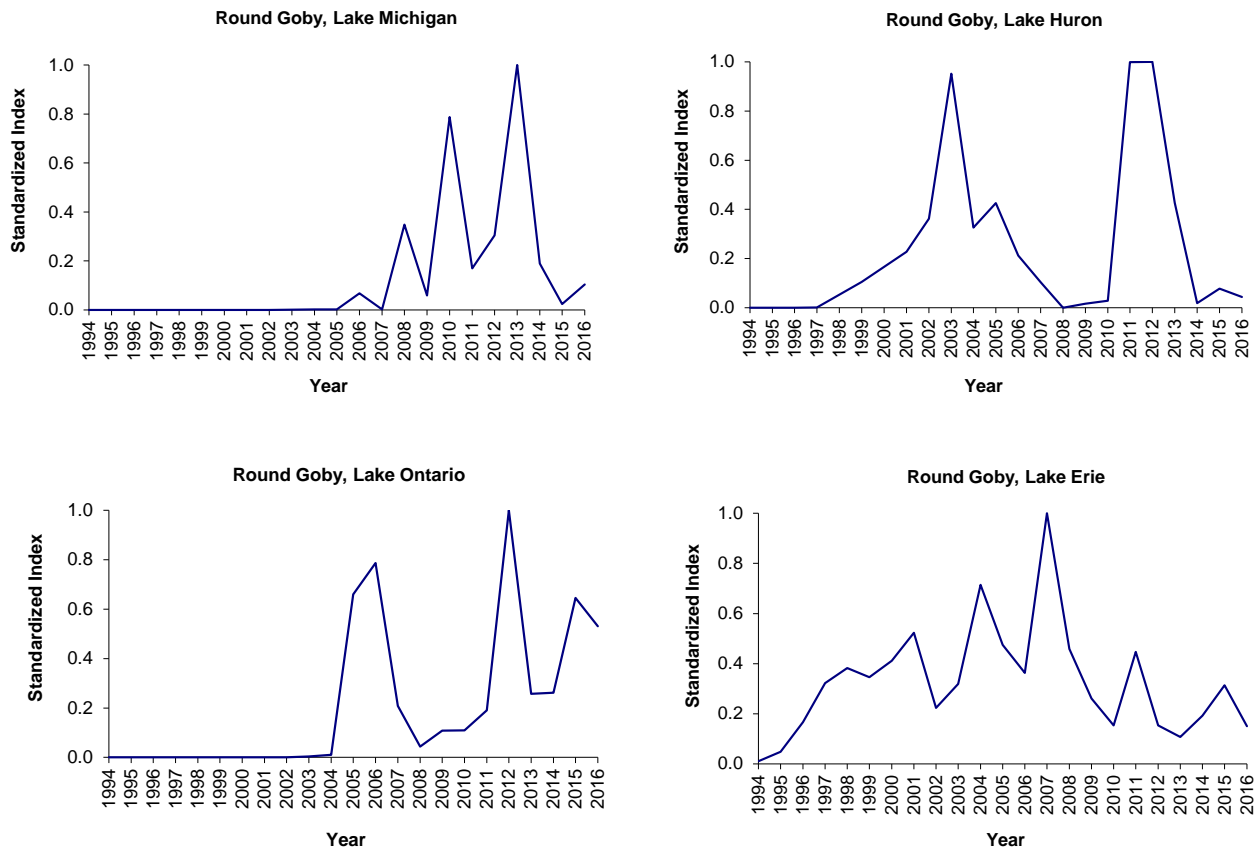


Figure 6. – Standardized indices of abundance for Round Goby in lakes Michigan, Huron, Ontario, and Erie, 1994-2016. Indices are computed from number caught in Lake Erie and weight caught in all other lakes.

Year-Class Strengths, Coregonids

Trends in relative strengths of 1977-2015 coregonid year-classes showed weak to moderate agreement ($W = 0.47$; $P = 0.001$) among lakes Superior, Michigan, and Huron (Fig. 7). Superior Cisco and Bloater trends were

highly correlated ($W = 0.83$; $P < 0.01$). Restricting the comparison to Superior vs. Michigan Bloater yielded strong agreement ($W = 0.80$; $P = 0.01$); no other inter-lake comparisons showed significant agreement.

Lakes Superior, Huron and Michigan shared a common pattern of stronger year-classes in the 1980s and weaker year-classes in the 1990s. Lake Superior was unique in have moderate year-classes of coregonids in 1998 and 2003. Trends in relative year-class strengths of coregonids among these lakes showed higher concordance before the advent of a succession of strong and moderate year-classes in Lake Huron after 2004 (1977-2004; $W = 0.57$; $P < 0.0004$). The appearance of small 2014 and 2015 Bloater year classes in Lake Superior is notable as is the appearance of a moderate 2016 Bloater year class in Lake Michigan. Bloaters were absent from survey catches in lakes Erie and Ontario and Cisco are rarely encountered outside of Lake Superior.

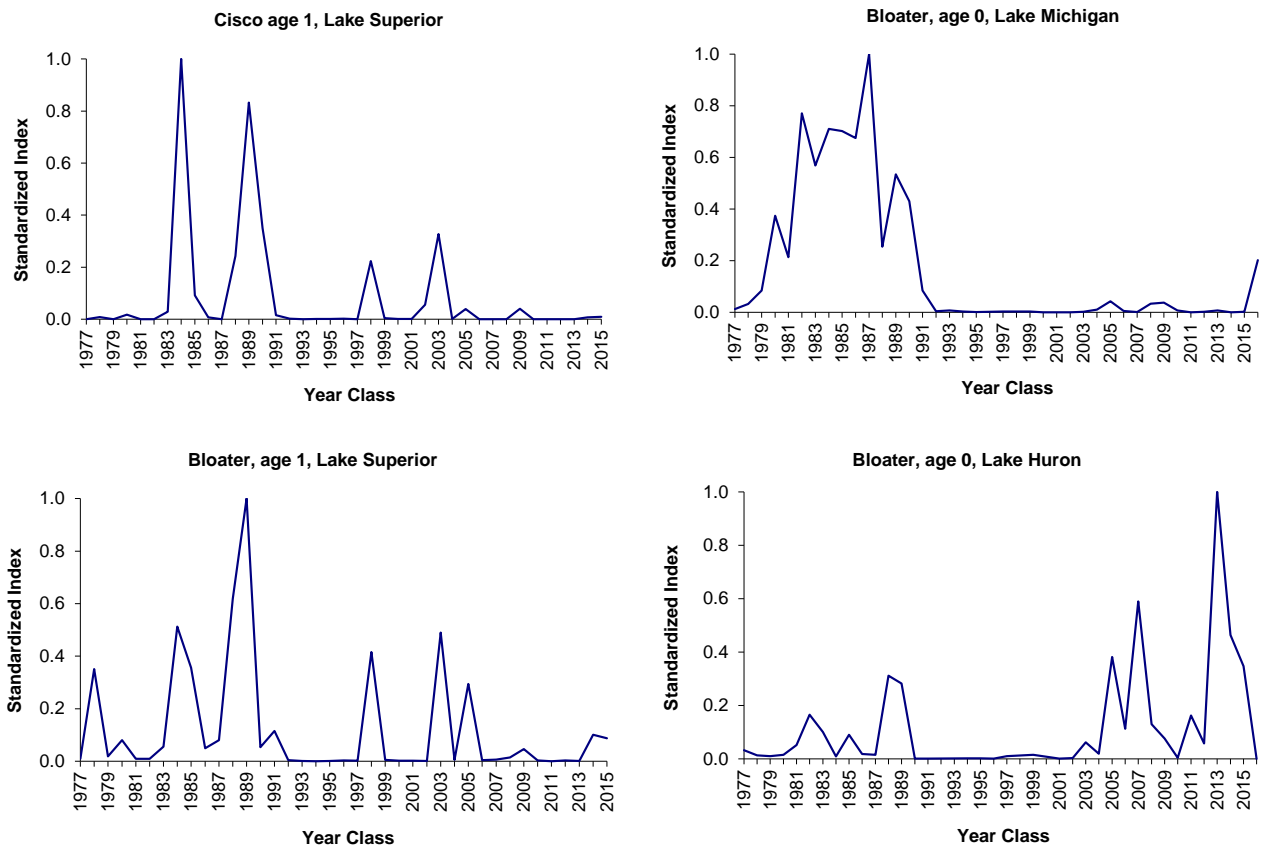


Figure 7. – Standardized indices of densities for age ≤ 1 Ciscoes (Cisco and Bloater) in lakes Superior, Michigan, and Huron, 1977-2016 year classes.

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 (the accepted age groups for indexing year-class strengths in these lakes), there was no agreement in trends ($W = 0.38$; $P = 0.56$) among the 1977-2013 year-classes (Fig. 8). Agreement remained nonsignificant when relative abundances of Alewife at age-0 in Lake Michigan (1977-2015 year classes) were substituted in the comparison ($W = 0.40$; $P = 0.20$). But when this comparison limited to Michigan and Huron 1977-2015 age-0 year classes, there was significant agreement in trends ($W = 0.75$; $P = 0.03$). However, this concordance is likely an artifact of decreased catchability of age-0 Alewife in Michigan after 1990, due in part to shifting fall sampling to an earlier date (Madenjian et al. 2005). Low abundances of age-0 Alewife in Huron after 2003 can be explained by very low abundances of adults after 2004 (Figure 4). Declines in adult Alewife biomass in Michigan after 2013 will likely lead to very low abundances of juveniles in the future. No other inter-lake comparisons showed agreement in trends. Alewife densities were too low in Lake Superior to assess year-class strengths.

Trends in abundances of age-0 fish in lakes Michigan were higher but variable prior to 1991 and afterwards fluctuated about near-zero levels. As mentioned previously this decline was likely the result of a shift in fall sampling to an earlier date when age-0 fish were smaller and less vulnerable to bottom trawls. Trends in abundance of age-3 Alewife in Michigan remained variable over the time series with spikes in 1998 and 2010 and ending with three successive years of very low abundances in 2011-2013. Trends in abundance of age-0 fish in Huron were variable until 2003 when a record year-class appeared; afterwards abundances were low and fluctuated about near-zero levels. As noted previously, this shift appears tied to the near-disappearance of adult Alewife in Huron in 2004. Trends in year-class strengths in Ontario were variable with no discernible trends, although the application of provisional corrections to data after 1996 resulted in reduced relative densities of year-class strengths prior to 1997 (Figure 8). However, beginning with the record 1998 year class, a series of near-record year classes were produced in 2005, 2009, 2012. Alewife is a rare species in Lake Superior and survey data for Lake Erie were not available for this comparison.

Comparisons of densities of different ages of juvenile Alewife are problematic because abundances at age-0, age-1, and age-3 are affected by differential survivorship, and as mentioned, the timing of sampling of age-0 fish can greatly affect their vulnerability to bottom trawls. For this reason age-3 Alewife are used to assess year class strengths in Lake Michigan (Madenjian et al. 2005, 2015). Thus it is not surprising that comparison of trends in relative abundances of juvenile Alewife across the three lakes showed no agreement when mixed ages were considered.

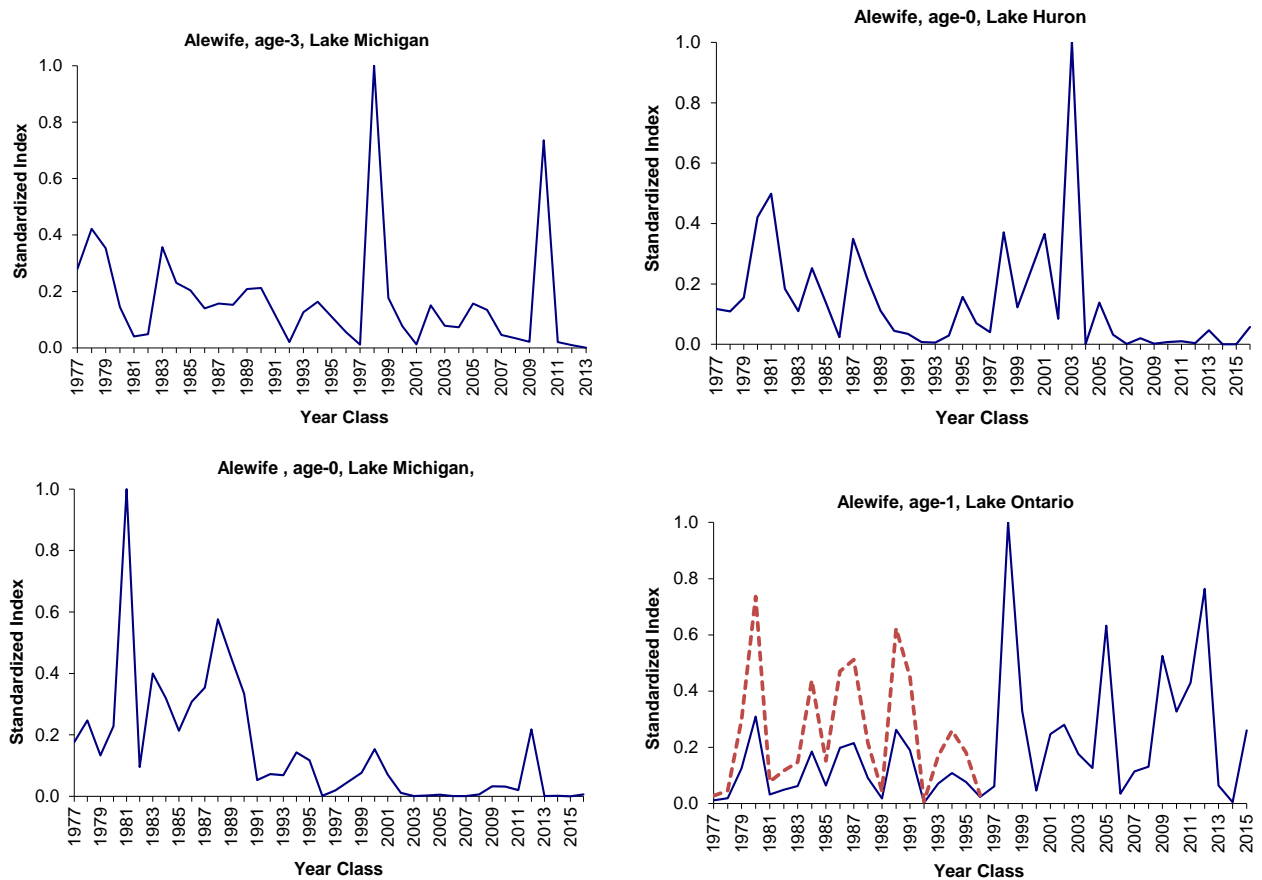


Figure 8. – Standardized indices of Alewife densities measured at age 0, 1 or 3 in lakes Michigan, Huron, and Ontario, 1977-2016 year classes. Dashed line in the Lake Ontario panel shows predicted relative densities without application of provisional corrections to data after 1996 (Weidel et al. 2017a, b).

Year-Class Strengths, Rainbow Smelt

Trends in relative strengths of Rainbow Smelt year-classes across lakes Superior, Michigan, Huron, and Ontario from 1977 to 2015 showed weak but significant agreement (Fig. 9; $W = 0.38$; $P < 0.03$). When the comparison was limited to lakes Superior, Michigan, and Huron, the agreement was nonsignificant ($W = 0.39$; $P = 0.24$). Paired comparisons among the lakes showed agreement between lakes Superior and Michigan ($W = 0.79$; $P < 0.02$), Superior and Ontario ($W = 0.77$; $P < 0.03$), and Michigan and Ontario ($W = 0.67$; $P < 0.09$).

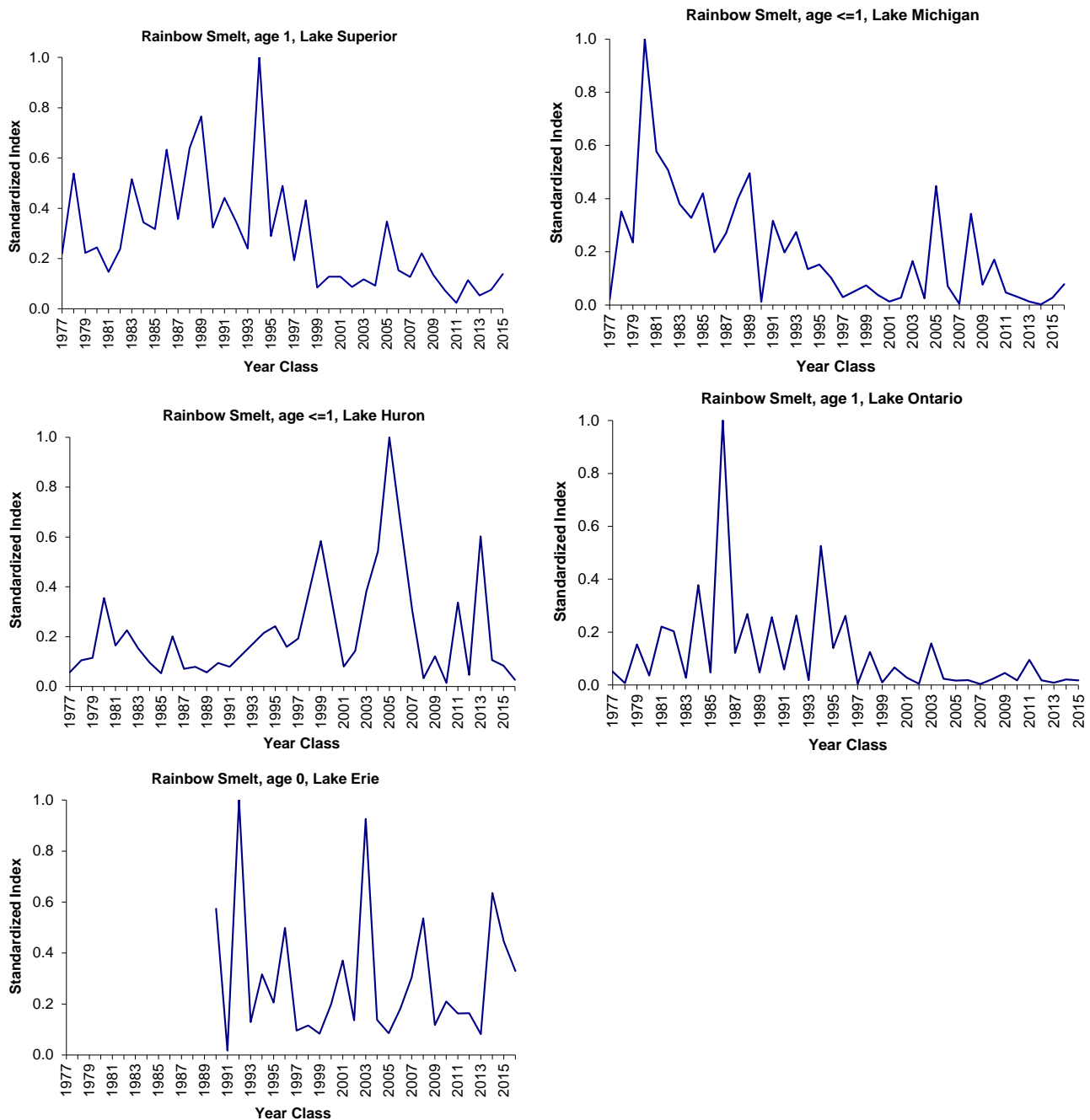


Figure 9. – Standardized indices of Rainbow Smelt densities measured at age-1 in lakes Superior and Ontario and at age ≤ 1 in lakes Michigan, Huron and Erie, 1977-2016 year classes.

In Lake Superior, year-class strengths of Rainbow Smelt 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. A small uptick to 8% of maximum was achieved in 2016. In contrast, year-class strengths in Lake Huron were moderate to weak over the first 21 years of the 37-year time series, and beginning with 1999 an alternating series of moderate to strong and weak year classes emerged; 2005 marked the strongest year class and 2010 and 2016 marked the weakest year classes on record. In Lake Ontario, year-class strengths prior to 1999 exhibited a “saw-tooth” pattern caused by alternating strong and weak year-classes. This pattern was not discernible during 1999-2015 due to a succession of weak year classes punctuated by moderate year classes in 2003 and 2011.

Summary

Among lakes Superior, Huron, Michigan, and Ontario, there was agreement in the trends of age-1 and older biomass for all prey species, however, prey fish biomass trends in Ontario were not concordant with other lakes. That discord follows the application of a provisional correction in 2016 to Lake Ontario prey fish biomass data collected after 1996; in prior cross-basin reports there was general concordance in trends in prey fish biomass with lakes Superior, Michigan and Huron. When trends for individual species among the lakes are compared, the concordance was greatest for coregonids and Rainbow Smelt, and weak concordance for Alewife. For coregonids, the highest biomass occurred from the late 1980s to the early 1990s and relatively low biomass after 2000 (with Huron as the exception). Rainbow Smelt biomass declined slowly and erratically during the last quarter century and reached record low levels in the 2000s. In general, Alewife biomass in lakes Huron and Michigan was substantially higher during the 1980s and 1990s compared with the post-2003 era, when biomass declined to record low levels. In contrast, Alewife biomass in Lake Ontario was highly variable but without an evident trend. This result for Lake Ontario also contrasts with previous reports and comes as the result of applying a provisional correction in 2016 to prey fish data collected after 1996 (Weidel et al. 2017a, b).

Recently, Lake Huron has shown resurgence in Bloater biomass, 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. With favorable recruitment of the moderate 2014-2015 year classes, biomass may be sustained in the near future, though the decline in recent increases in biomass remains unexplained. 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 densities of juvenile 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 2005-2015 countered the common trend of weak year-classes of coregonids in lakes Michigan and Superior. However, the appearance of a moderate year-class of Bloater in Michigan in 2016 is the largest since the 1990 year-class. 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 for Rainbow Smelt.

Although there was statistical agreement in trends of age-0 and older Round Goby relative abundance among lakes where this species has successfully invaded (Michigan, Huron, Erie, and Ontario), temporal patterns were different in each lake. Recent trends in relative abundance of gobies remain highly variable in lakes Huron, Michigan and Ontario, suggesting that impending population equilibrium in these lakes remains uncertain. The pattern of increase, peak and decline of goby abundance in Lake Erie suggests an approaching equilibrium. Although the recent trends in goby abundance among these lakes is mixed, there is mounting evidence that Round Goby has become increasingly important in the diets of Lake Whitefish and typical piscivores, e.g., Lake Trout, Walleye, Smallmouth Bass, Yellow Perch, Lake Whitefish, and Burbot in lakes Michigan, Huron, Erie, and Ontario (He et al. 2015). 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.

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All GLSC sampling and handling of fish during research are carried out in accordance with guidelines for the care and use of fishes by the American Fisheries Society (<http://fisheries.org/docs/wp/Guidelines-for-Use-of-Fishes.pdf>).

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Status and Trends in the Lake Superior Fish Community, 2016¹

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Abstract

In 2016, the Lake Superior fish community was sampled with daytime bottom trawls at 76 nearshore and 35 offshore stations. Spring and summer water temperatures in 2016 were warmer than average and considerably warmer than observed in 2014 and 2015. In the nearshore zone, a total of 17,449 individuals from 20 species or morphotypes were collected. Nearshore lakewide mean biomass was 2.2 kg/ha, which was near the lowest biomass on record for this survey since it began in 1978. In the offshore zone, a total 8,487 individuals from 16 species or morphotypes were collected lakewide. Offshore lakewide mean biomass was 4.5 kg/ha, which was the lowest biomass recorded since the offshore survey began in 2011. The density of age-1 Cisco was 5.0 fish/ha, which was 35% of that measured in 2015. Larval *Coregonus* were collected in surface trawls at 144 locations lakewide from May to July. The average nearshore lakewide larval *Coregonus* density estimate was 1,630 fish/ha, which was similar to that estimated in 2015.

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. 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 at each station, we conducted surface trawls for larval fish, epilimnetic (30 m) and whole water column (100 m) zooplankton collections, and an electronic water profile that collected depth, temperature, specific conductance, pH, dissolved oxygen, chlorophyll a, photosynthetic active radiation (PAR), and beam transmission data. Herein we report on bottom and surface trawl collections and water temperatures.

¹Presented at: Great Lakes Fishery Commission, Lake Superior Committee Meeting, 21 March 2017. The data associated with this report have not received final approval by the U.S. Geological Survey (USGS) and are currently under review. The Great Lakes Science Center is committed to complying with the Office of Management and Budget data release requirements and providing the public with high quality scientific data. We plan to make all USGS research vessel data collected between 1958 and 2016 publicly available from the GLSC website later in 2017. The anticipated citation will be <http://doi.org/10.5066/F75M63X0>. Please direct any immediate questions to our Information Technology Specialist, Scott Nelson, at snelson@usgs.gov.

Methods

Nearshore survey bottom trawling

Nearshore sites are located around the perimeter of the lake (Figure 1). In 2016, 76 of the 82 long-term sampling locations were sampled between 16 May and 16 June (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 16 m (range 10-34 m) and 54 m (range 20-143 m), respectively. The median distance trawled was 1.5 km (range 0.6-4.0 km). The median trawl wingspread was 8.3 m (range 7.4-9.6 m). Fish collections were sorted by species, counted, and weighed in aggregate to the nearest gram. Total length was measured on a maximum of 50 individuals per species per trawl. Length data for these individuals were then extrapolated to the entire catch, if necessary. 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 Burbot, 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 species-specific lengths; Cisco <140 mm, Bloater <130 mm, Lake Whitefish <160 mm, and Rainbow Smelt <100 mm. Young Lake Trout densities are presented for small, < 226 mm (ca. \leq age-3) fish. Age-1 size cutoffs were based on past unpublished aging analyses and are approximate and are known to vary among years.

Offshore survey bottom trawling

Offshore sites are located around the lake and were selected using a spatially-balanced, depth-weighted probabilistic sampling design that targets depths >90 m (Figure 1). Sample sites were selected in 2011 and the same sites have been sampled annually thereafter. In 2016, 35 locations were sampled during daylight hours between 27 June and 25 July. 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 92 to 315 m. The median trawl distance was 1.6 km (range 1.8-2.3 km). The median trawl wing spread was 9.8 m (range 8.3-11.4 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 made up >93% of the total biomass.

Surface water trawling

A paired 1 m² 500 micron mesh neuston net was fished at the lake surface (0.5 m depth) for 10 minutes at 144 locations lakewide from 5 May to 25 July 2016. The purpose of this sampling was to describe the spatial distribution and abundance of larval *Coregonus*. Larval *Coregonus* were not identified to species, so it is assumed these fish are a mix of Cisco, Bloater, and Kiyi. In addition to *Coregonus* species, a few Sculpin and Pacific Salmon are also collected.

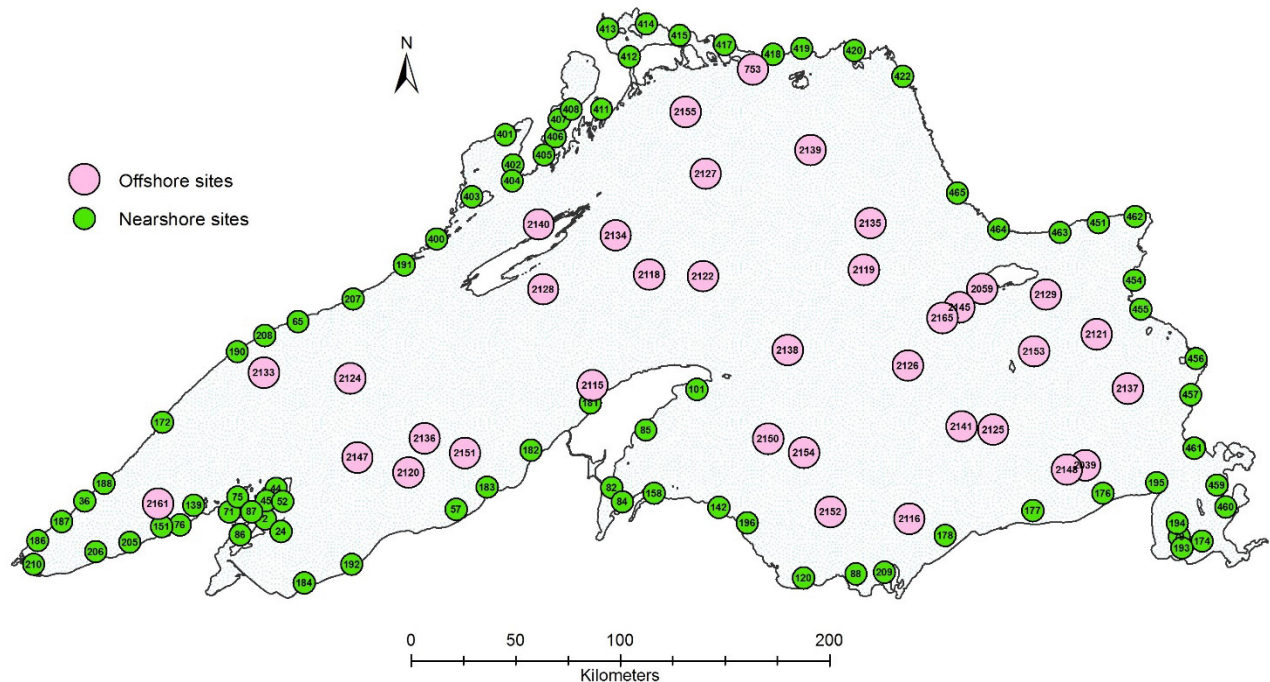


Figure 1. Location of 76 nearshore (green circles) and 35 offshore (pink circles) stations sampled May-July 2016. Samples collected at each location included bottom trawls for demersal fish, surface trawls for larval fish, epilimnetic (30 m) and whole water column (100 m) zooplankton collections, and an electronic water profile that collected data on depth, temperature, specific conductance, pH, dissolved oxygen, Chl a, PAR, and beam transmission. An additional 32 locations not shown on the map were sampled for larval fish, zooplankton, and water profile attributes.

Results

Nearshore survey

Nearshore water temperatures in 2016 were warmer than the long-term average and much warmer than observed in 2014 and 2015 (Figure 2a). Nearshore temperatures in June averaged 7.1 °C (range = 4.7-14.3 °C) at the surface and 4.0 °C (range = 3.8-5.0 °C) at 100 m. The long-term average (1991-2016) water temperatures for these same locations and dates is 5.9 °C at the surface and 3.5 °C at 100 m.

A total of 17,449 individual fish from 20 species or morphotypes were collected (Table 1). The number of species collected at each station ranged from 0 to 13, with a mean of 4.7 and median of 4. Lakewide mean biomass was 2.2 kg/ha, which was one of the lowest values on record and well below the long-term average of 9.1 kg/ha (Table 2, Figure 3). Lakewide median biomass was 0.2 kg/ha which was also one of the lowest values on record (Figure 3).

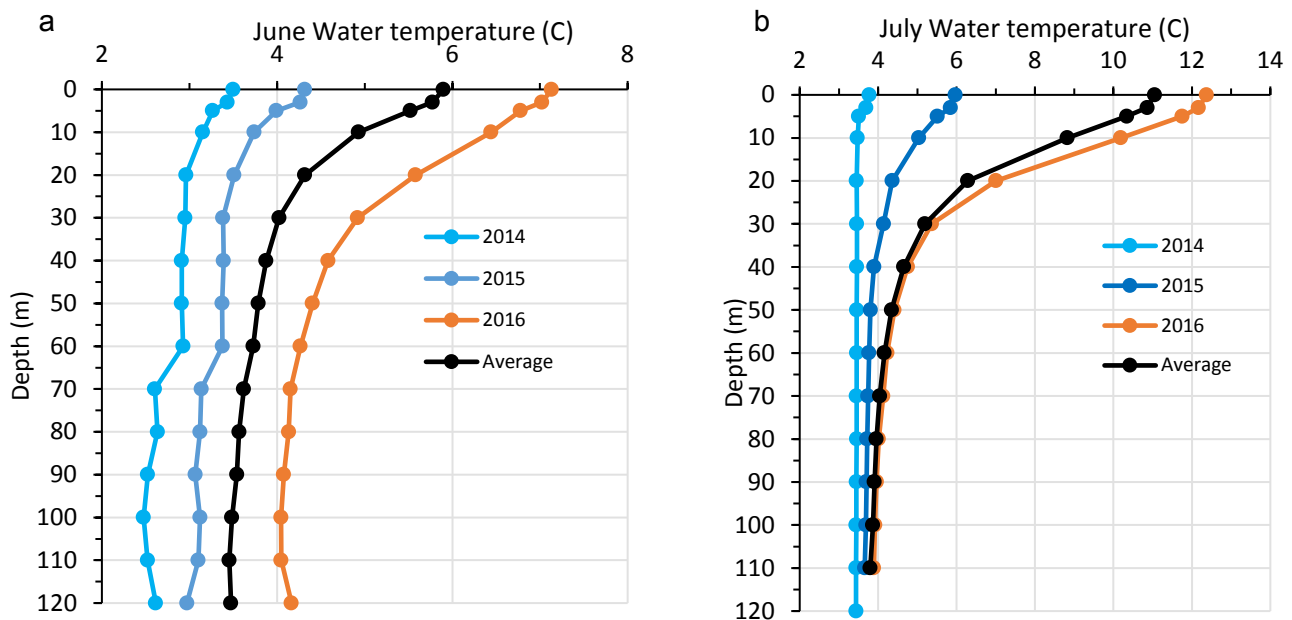


Figure 2. a) Average nearshore water temperature profiles collected in June. B) Average offshore water temperatures collected in July. Lines are shown for 2016, 2015, and 2014 – the coldest year on record. Nearshore June water temperatures have been collected since 1991 and offshore July temperatures since 2011.

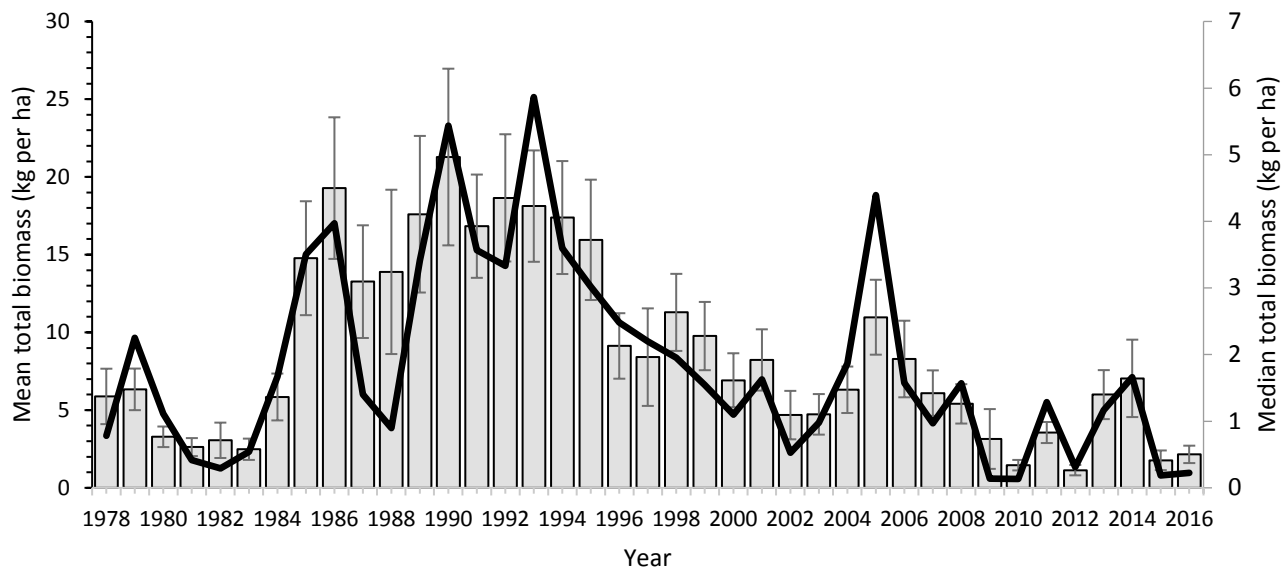


Figure 3. Annual mean \pm SE (bars, left y-axis) and median (line, right y-axis) lakewide nearshore biomass estimates for all fish species collected in bottom trawls from 1978-2016.

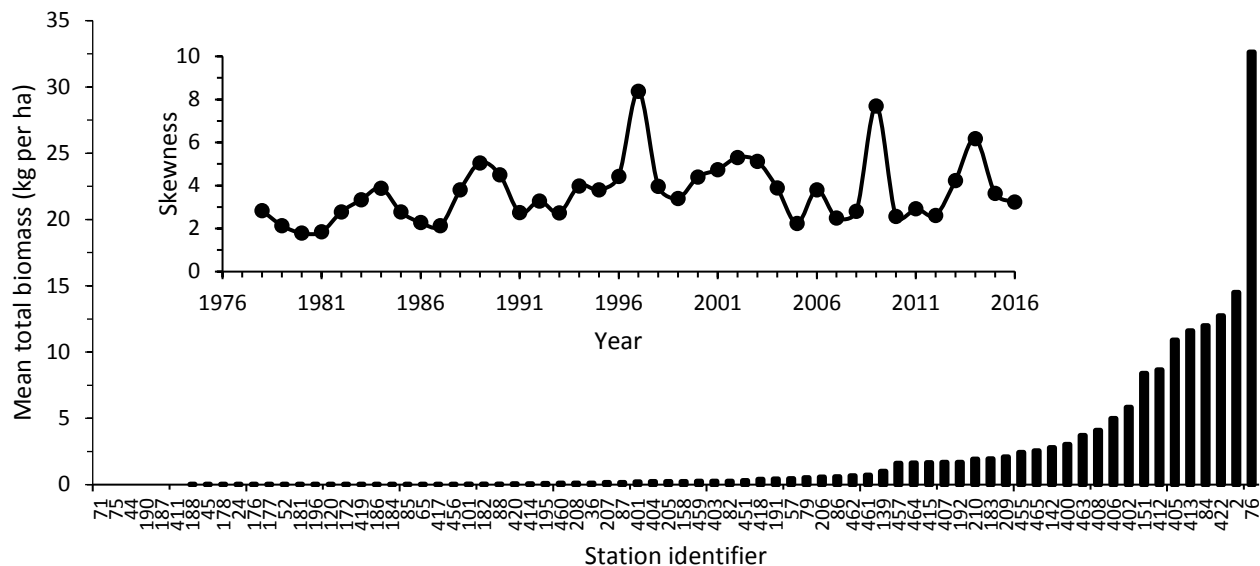


Figure 4. Estimated biomass at individual nearshore sampling stations in 2016. Station locations are shown in Figure 1. The inset plot shows the annual skewness in the distribution of individual station biomass estimates. Higher skewness values indicate greater differences in fish biomass among sampling locations.

Individual station biomass was non-normally distributed and highly left-skewed (Figure 4). The skewness of the distribution of individual station biomass estimates in 2016 was 3.2, which was less than long-term mean of 3.7 (Figure 4). The highest individual station biomass was estimated for station 76 near Cornucopia, Wisconsin.

Cisco – Lakewide mean nearshore biomass of Cisco was 0.2 kg/ha in 2016. This was below the long-term average of 2.4 kg/ha and similar to that observed since 2007 (Table 2). Density of age-1 Cisco was 4.99 fish/ha in 2016, which indicated a small, but measureable recruitment year. This estimate was less than the 14.31 fish/ha observed in 2015. Over the course of the nearshore survey’s history, densities of age-1 Cisco have exceeded 30 fish/ha eight times and 175 fish/ha five times and have been measured as high as 750 fish/ha (Table 3). Age-1 Cisco density of 5 fish/ha has a two-year recurrence interval and this density has been exceeded 18 times in the 39 year survey period.

Bloater – Lakewide mean nearshore biomass for Bloater was 0.4 kg/ha in 2016. This was below the long-term average of 1.7 kg/ha (Table 2). Age-1 Bloater density was 9.76 fish/ha in 2016, the highest density observed since 2006 (Table 3). The highest observed densities of age-1 Bloater is >30 fish/ha.

Lake Whitefish – Lakewide mean nearshore biomass for Lake Whitefish was 0.5 kg/ha in 2016. This was similar to that observed in 2015 and less than the long-term average of 2.1 kg/ha (Table 2). Age-1 Lake Whitefish density was 1.57 fish/ha in 2016, which was below the long-term average of 7.17 fish/ha (Table 3).

Rainbow Smelt – Lakewide mean nearshore biomass for Rainbow Smelt was 0.4 kg/ha in 2016. This was similar to that observed in 2015 and less than the long-term average of 1.2 kg/ha. Rainbow Smelt biomass has been less than the long-term mean since 2007 (Table 2). Age-1 Rainbow Smelt density was 82.71 fish/ha in 2016, which was about half of the long-term average of 157 fish/ ha (Table 3).

Sculpin – Lakewide mean nearshore biomass for Sculpin was 0.02 kg/ha in 2016. 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 all other species was 0.3 kg/ha in 2016. This was less than the long-term mean of 0.68 kg/ha. Species include Ninespine Stickleback, Trout-perch, Kiyi, Shortjaw Cisco, Pygmy Whitefish, Round Whitefish, and Longnose Sucker.

Burbot – Lakewide mean nearshore biomass for Burbot was 0.05 kg/ha. Burbot biomass has not exceeded the long-term average of 0.13 kg/ha since 2008 (Table 2).

Lake Trout – Four hatchery Lake Trout were collected during the nearshore survey. Hatchery Lake Trout biomass has been near zero since 2002, with the exception of 2005 (Figure 5). Lean Lake Trout biomass was 0.1 kg/ha. This was less than the long-term average of 0.3 kg/ha (Table 2). Siscowet Lake Trout nearshore biomass was 0.1 kg/ha, which was similar to the long-term average (Table 2). Densities of age-3 and younger lean and siscowet Lake Trout were 0.19 and 0.04 fish/ha in 2016, respectively. Young lean Lake Trout densities were less than the long-term average while young siscowet Lake Trout densities were similar to the long-term average (Table 3).

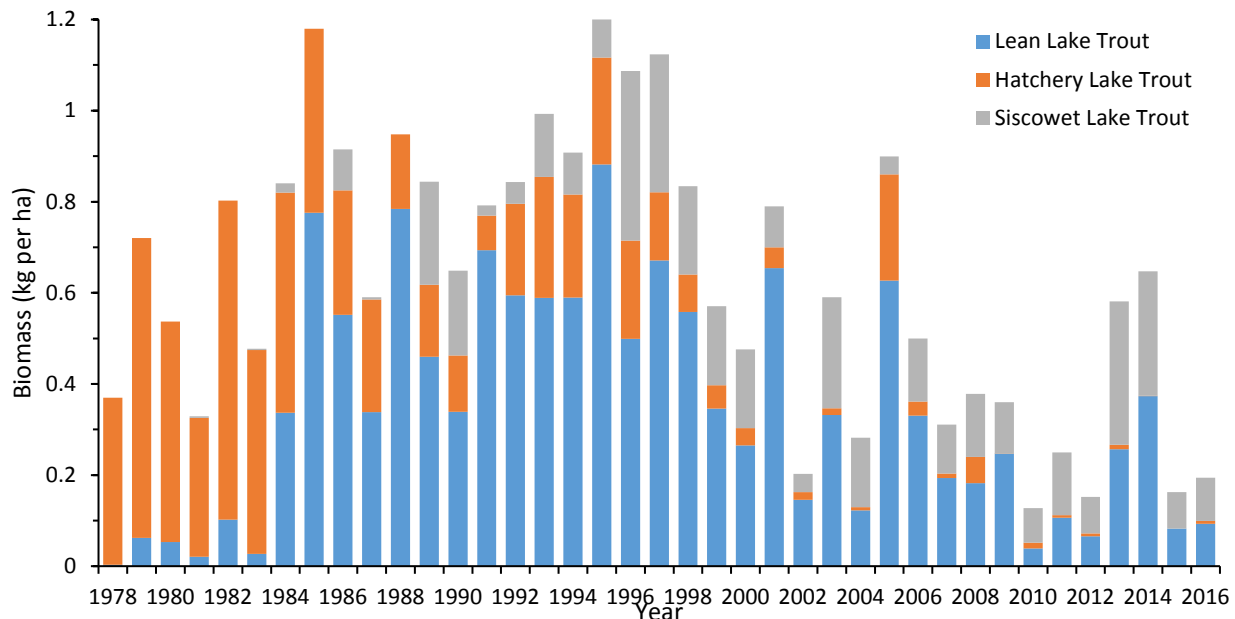


Figure 5. Mean annual lakewide biomass estimates for hatchery, lean, and siscowet Lake Trout estimated from bottom trawls in nearshore locations from 1978-2016.

Offshore survey

Similar to the nearshore, offshore water temperatures were warmer than average (2011-2016) and much warmer than observed in 2014 and 2015. Offshore temperatures in July averaged 13.2 °C (range = 7.5-18.7 °C) at the surface and 3.9 °C (range = 3.8-4.4 °C) at 100 m (Figure 2).

A total of 10,375 individuals from 14 species were collected lakewide at 35 offshore sites (Table 1). The average and median observed species richness at each station was 3.9 and 4 species, respectively, and ranged from 1 to 8 species. Deepwater Sculpin, Kiyi, and siscowet Lake Trout made up 93% of the total biomass collected in offshore waters (Figure 6). Bloater and Pygmy Whitefish were the most common other species collected, but both species were generally limited to depths <110 m. Mean and median lakewide biomass was 4.5 kg/ha and 3.0 kg/ha, respectively (Figure 7). This was less than observed in previous years (Figure 7).

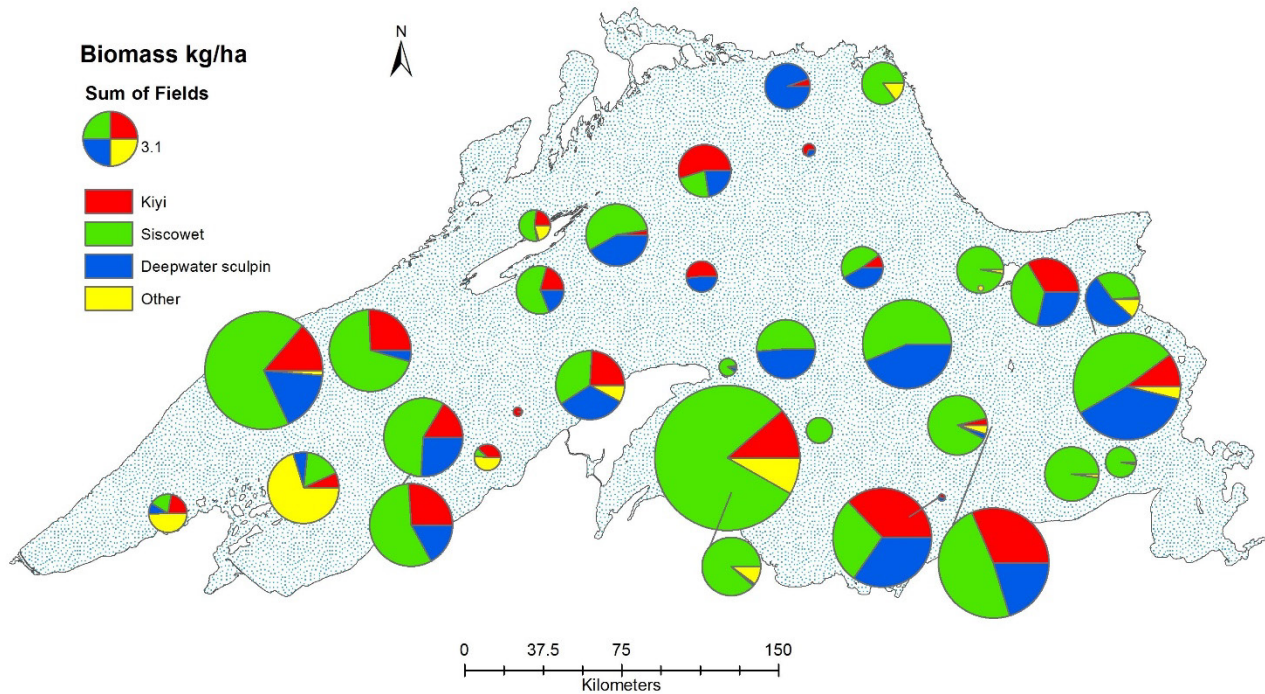


Figure 6. Mean lakewide biomass estimates for Kiyi, siscowet Lake Trout, Deepwater Sculpin, and other species estimated from offshore bottom trawls in 2016. Pie diameter is proportional to the biomass collected at that site, which ranged from 0-22 kg/ha. The pie in the legend is scaled to 3.1 kg/ha with the size of the pies on the map scaled accordingly to that reference.

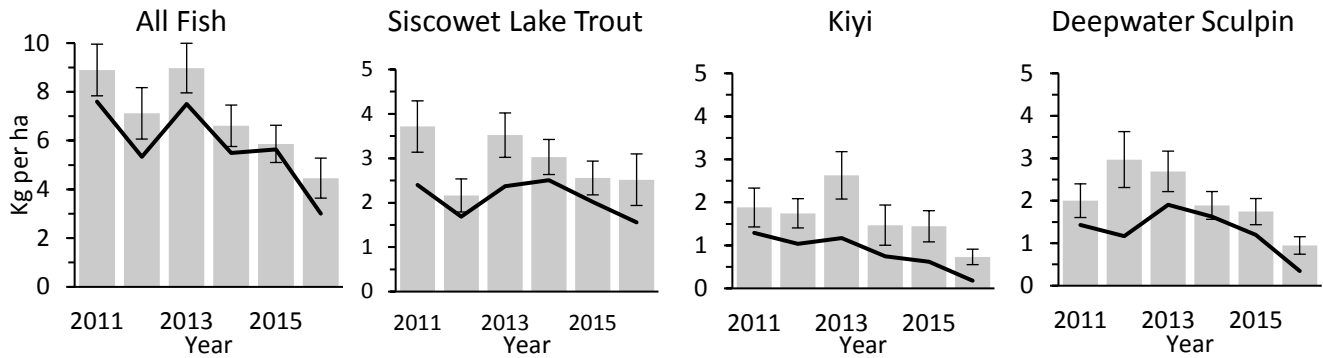


Figure 7. Annual mean \pm SE (bars) and median (line) lakewide offshore biomass estimates for all species, siscowet Lake Trout, Kiyi and Deepwater Sculpin collected in bottom trawls from 2011-2016.

Siscowet Lake Trout – Lakewide mean offshore biomass of siscowet Lake Trout was 2.5 kg/ha. This was similar to that observed in 2015, but generally less than previous years (Figure 7).

Kiyi – Lakewide mean offshore biomass of Kiyi was 0.7 kg/ha. This was 50% of that observed in 2015. With the exception of 2013, there has been a steady decline in Kiyi biomass since 2011 (Figure 7).

Deepwater Sculpin – Lakewide mean offshore biomass of Deepwater Sculpin was 0.9 kg/ha. This was 54% of that estimated in 2015. Deepwater Sculpin biomass has declined steadily since 2012 (Figure 7).

Larval *Coregonus* collections

A total of 22,097 *Coregonus* individuals were collected from May-July 2016. The lakewide nearshore average density between 16 May and 16 June was 1,630 fish/ha and ranged from 0-21,910 fish/ha. For comparison, the lakewide nearshore mean density during these same dates in 2014 and 2015 was 1,425 and 787 fish/ha, respectively (Figure 8a). Larval *Coregonus* were first collected on 4 May 2016 and were 9-10 mm in length. This suggests a hatch date around the first week of May, as this is the length at hatch observed for Cisco raised in the laboratory (Oyadomari and Auer 2008, CJFAS 65:1447-1358). Estimated hatch dates were mid-May in 2015 and the end of May in 2014. Growth of larval fish, as determined by the change in total length over time was greatest in 2016 and least in 2014 (Figure 8b). We suspect this was related to the earlier hatch date and warmer water in 2016 as compared to 2014 and 2015 (Figure 2).

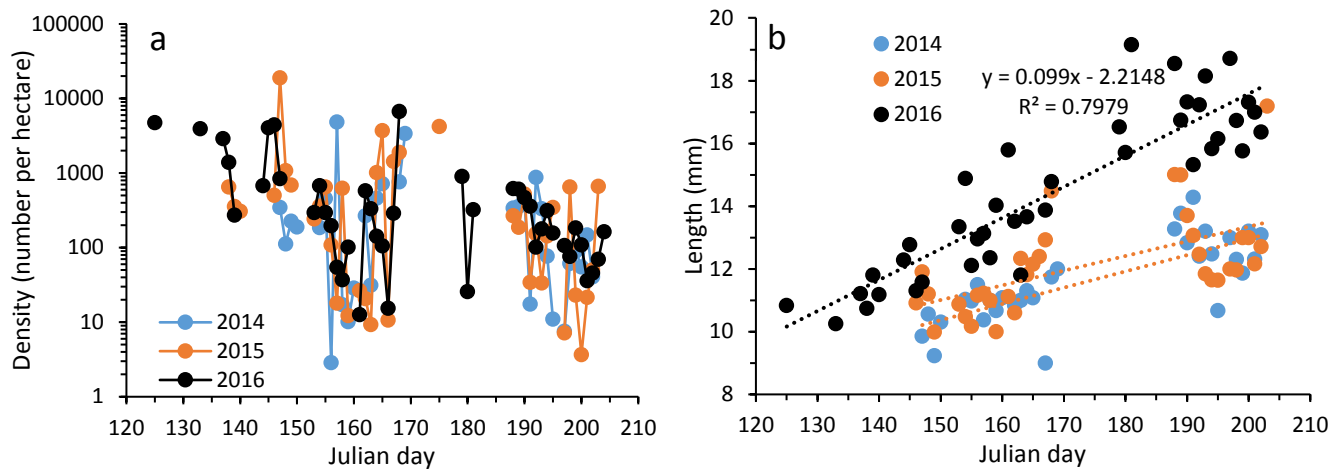


Figure 8. a) Mean daily estimated larval *Coregonus* densities (fish/ha) collected in 2014, 2015, and 2016 from surface trawling. The number of locations sampled each day ranged from 1-5. b) Mean larval length for each trawl collected in 2014, 2015, and 2016. A maximum of 50 individuals were measured from each trawl. The slope of the lines were 0.1 mm per day in 2016 and 0.05 mm per day in 2014 and 2015.

Summary

Over the 39-year history of the Lake Superior nearshore survey, total reported biomass has been largely dependent on recruitment of age-1+ Bloater, Cisco, and Lake Whitefish populations as well as 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 and 2016 we observed small but measureable recruitment of age-1 Cisco, Bloater, and Kiyi. Larval *Coregonus* density estimates in 2016 were similar to that observed in 2015 and roughly twice that observed in 2014. Larval *Coregonus* summer growth in 2016 was twice that observed in 2014 and 2015. Time will tell if this will translate to a larger age-1 year class in 2017. Offshore demersal fish biomass, principally Deepwater Sculpin, Kiyi, and siscowet Lake Trout, was lower than that observed in previous years. The cause of this 5-year decline is not well understood, but may be driven by consumption of these species by large siscowet Lake Trout. 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. We plan to continue these surveys into the future.

Note: All GLSC sampling and handling of fish during research are carried out in accordance with guidelines for the care and use of fishes by the American Fisheries Society (<http://fisheries.org/docs/wp/Guidelines-for-Use-of-Fishes.pdf>).

Table 1. *Fish species and the number of individuals collected in nearshore and offshore bottom trawl surveys in Lake Superior in 2016. Sampling locations shown in Figure 1.*

Fish	Species name	Nearshore	Offshore
Rainbow Smelt	<i>Osmerus mordax</i>	11002	6
Bloater	<i>Coregonus hoyi</i>	1957	80
Cisco	<i>Coregonus artedii</i>	1001	3
Pygmy Whitefish	<i>Prosopium coulteri</i>	935	59
Ninespine Stickleback	<i>Pungitius pungitius</i>	821	10
Trout-perch	<i>Percopsis omiscomaycus</i>	496	0
Slimy Sculpin	<i>Cottus cognatus</i>	448	14
Lake Whitefish	<i>Coregonus clupeaformis</i>	347	1
Spoonhead Sculpin	<i>Cottus ricei</i>	117	8
Deepwater Sculpin	<i>Myoxocephalus thompsoni</i>	86	7044
Lean lake Trout	<i>Salvelinus namaycush</i>	47	1
Shortjaw Cisco	<i>Coregonus zenithicus</i>	45	5
Kiyi	<i>Coregonus kiyi</i>	43	1011
Siscowet Lake Trout	<i>Salvelinus namaycush siscowet</i>	37	235
Longnose Sucker	<i>Catostomus catostomus</i>	31	0
Blackfin Cisco	<i>Coregonus nigripinnis</i>	9	0
Common Shiner	<i>Notropis cornutus</i>	8	0
Burbot	<i>Lota lota</i>	7	4
Hatchery Lake Trout	<i>Salvelinus namaycush</i>	4	0
Alewife	<i>Alosa pseudoharengus</i>	3	0
Unidentified coregonid	<i>Coregonus</i>	5	5

Table 2. Lake Superior nearshore bottom trawl lakewide mean biomass (kg/ha) estimates of common fishes, from 1978-2016. Sculpin includes Slimy, Spoonhead, and Deepwater sculpin. Mean and median total biomass includes all species. Other species includes Ninespine Stickleback, Trout-Perch, Kiyi, Shortjaw Cisco, Pygmy Whitefish, Round Whitefish, and Longnose Sucker.

Year	Sites	Number of species	Mean total biomass	Median total biomass	Rainbow Smelt	Cisco	Lake Whitefish	Bloater	Hatchery Lake Trout	Lean Lake Trout	Siscowet Lake Trout	Burbot	Sculpin	Other species
1978	43	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	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	27	7.04	1.66	0.43	0.35	4.31	0.50	0.00	0.37	0.27	0.08	0.02	0.72
2015	76	21	1.77	0.19	0.22	0.23	0.54	0.40	0.00	0.08	0.08	0.00	0.02	0.19
2016	76	20	2.15	0.23	0.44	0.22	0.53	0.38	0.01	0.09	0.10	0.05	0.02	0.33
Mean	69	22.7	8.79	1.87	1.15	2.39	2.10	1.66	0.17	0.34	0.11	0.13	0.06	0.68
Median	76	23.0	6.92	1.57	1.00	1.09	1.86	0.88	0.12	0.33	0.09	0.11	0.05	0.69

Table 3. Lake Superior nearshore bottom trawl lakewide mean age-1 density (number/ha) estimates of Cisco, Bloater, Lake Whitefish, and Rainbow Smelt and for small lean and siscowet Lake Trout. Age-1 fish were defined by species-specific 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	Year Class	Sites	Rainbow Smelt	Cisco	Bloater	Lake Whitefish	Kiyi	Lean Lake Trout	Siscowet Lake Trout
1978	1977	43	95.76	0.02	0.82	2.62	0.00	0.11	0.00
1979	1978	49	234.14	6.31	30.08	3.90	0.00	0.17	0.00
1980	1979	48	96.79	0.10	1.57	1.97	0.00	0.12	0.00
1981	1980	48	106.26	13.42	6.85	16.43	0.00	0.28	0.03
1982	1981	32	63.81	0.19	0.75	4.16	0.00	0.22	0.00
1983	1982	50	103.58	0.06	0.82	0.45	0.00	0.20	0.00
1984	1983	53	224.39	21.72	4.74	8.04	0.00	0.59	0.00
1985	1984	53	149.51	748.04	44.00	2.47	0.00	0.65	0.00
1986	1985	53	150.41	68.94	30.55	3.45	0.00	0.43	0.06
1987	1986	53	275.59	5.43	4.23	11.91	0.00	0.36	0.02
1988	1987	53	155.27	0.53	6.86	6.11	0.01	0.26	0.00
1989	1988	76	274.78	226.75	37.69	36.08	0.00	0.13	0.07
1990	1989	81	272.04	425.63	57.26	8.78	0.01	0.22	0.02
1991	1990	84	162.03	236.85	11.38	17.54	0.00	0.33	0.01
1992	1991	85	176.94	9.05	10.71	11.84	0.06	0.40	0.02
1993	1992	87	155.24	3.32	0.22	7.68	0.02	0.42	0.10
1994	1993	87	198.62	0.79	0.06	4.95	0.02	0.57	0.01
1995	1994	87	401.83	1.48	0.00	13.52	0.02	0.86	0.02
1996	1995	87	168.25	0.97	0.05	6.33	0.01	1.13	0.10
1997	1996	85	253.04	11.08	0.18	8.80	0.00	0.39	0.04
1998	1997	87	145.01	1.20	0.12	7.74	0.02	0.60	0.02
1999	1998	83	216.18	90.76	0.40	9.17	0.05	0.16	0.05
2000	1999	85	58.40	3.86	0.48	0.77	0.26	0.18	0.01
2001	2000	83	256.32	0.82	0.12	2.37	0.00	0.26	0.02
2002	2001	84	56.79	0.54	0.12	13.68	0.00	0.12	0.03
2003	2002	86	77.83	33.20	0.58	7.74	0.01	0.09	0.01
2004	2003	75	70.28	175.37	27.22	6.36	0.11	0.12	0.01
2005	2004	52	110.39	8.23	12.07	2.97	0.12	0.30	0.03
2006	2005	55	249.56	18.64	13.61	5.51	0.13	0.24	0.10
2007	2006	56	360.93	0.43	0.32	19.74	0.01	0.05	0.03
2008	2007	59	280.69	0.19	0.28	0.63	0.00	0.10	0.04
2009	2008	64	71.64	0.27	0.59	3.00	0.00	0.04	0.03
2010	2009	76	45.22	14.01	2.46	6.64	0.01	0.02	0.02
2011	2010	82	73.98	0.29	0.76	3.98	0.01	0.22	0.01
2012	2011	72	11.05	0.03	0.06	1.90	0.00	0.20	0.03
2013	2012	79	142.90	0.17	0.22	5.46	0.00	0.18	0.03
2014	2013	73	68.46	0.01	0.06	2.27	0.00	0.00	0.03
2015	2014	76	30.66	14.31	8.57	1.00	0.09	0.07	0.03
2016	2015	76	82.71	4.99	9.76	1.57	0.12	0.19	0.04
Mean		69	157.11	55.08	8.37	7.17	0.03	0.28	0.03
Median		76	149.51	3.86	0.82	5.51	0.00	0.22	0.02

Status and Trends of Pelagic Prey Fish in Lake Huron, 2016^{†1}

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Abstract

The U.S. Geological Survey Great Lakes Science Center has conducted integrated acoustic and mid-water trawl surveys of Lake Huron during 1997 and annually from 2004-2016. The 2016 survey was conducted during September and early October and included transects in Lake Huron's main basin, Georgian Bay, and North Channel. Mean lake-wide pelagic fish density was 824 fish/ha and mean pelagic fish biomass was 9.0 kg/ha in 2016, which represents 58% and 77% of the long-term mean respectively. Mean lake-wide biomass was 15% lower in 2016 as compared to 2015. The total estimated lake-wide standing stock biomass of pelagic fish species was ~42 kt (\pm 9.8 kt), consisting almost entirely of bloater (28.7 kt; 68%) and rainbow smelt (13 kt; 31%). No alewives were captured during the 2016 survey. Age-0 rainbow smelt abundance decreased from 475 fish/ha in 2015 to 173 fish/ha in 2016. Biomass of age-1+ rainbow smelt increased from 2.2 kg/ha in 2015 to 2.6 kg/ha in 2016. Age-0 bloater abundance decreased from 315 fish/ha in 2015 to 103 fish/ha in 2016. Biomass of age-1+ bloater decreased from 7.1 kg/ha in 2015 to 5.6 kg/ha in 2016. Emerald shiner density increased from 37 fish/ha in 2015 to 45 fish/ha in 2016 and biomass remained unchanged between the two years. 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.

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Lake Huron Committee Meeting
Ypsilanti, MI, March 21, 2017

¹ The data associated with this report have not received final approval by the U.S. Geological Survey (USGS) and are currently under review. The Great Lakes Science Center is committed to complying with the Office of Management and Budget data release requirements and providing the public with high quality scientific data. We plan to make all USGS research vessel data collected between 1958 and 2016 publicly available from the GLSC website later in 2017. The anticipated citation will be <http://doi.org/10.5066/F75M63X0>. Please direct any immediate questions to our Information Technology Specialist, Scott Nelson, at snelson@usgs.gov.

Introduction

The U.S. Geological Survey 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 benthic fish community and provided valuable information on prey fish dynamics to fishery managers tasked with balancing predatory demand by native and introduced salmonines. 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 (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 present 2016 abundance and biomass estimates for major pelagic offshore prey fish species in Lake Huron and compare these estimates to previous years.

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). Within each stratum, the first transect is selected randomly each year based on latitude and longitude; subsequent transects are spaced relatively uniformly around the first. Effort (transects per stratum) is reallocated each year based on stratum area and variability of total biomass in each stratum from previous surveys (sampling design described in Adams et al. 2006). For analyses, 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 (2012-2016). These comprise the elementary sampling units (ESUs) within which fish density is summarized along transects.

The 2016 pelagic fisheries survey was completed from 7 September to 3 October. Sampling was conducted by both the GLSC (R/V *Sturgeon*) and US Fish and Wildlife Service (USFWS; M/V *Spencer F. Baird*). Twenty-six acoustic transects were sampled, resulting in approximately 480 km of acoustic data. Forty-five mid-water trawl tows were conducted in conjunction with acoustic data collection.

Fish were collected using a 16.5-m headrope mid-water trawl with 76, 38, 25, and 6.35 mm stretch meshes (USGS) and a 19.8-m headrope mid-water trawl with 200, 150, 100, 75, 50, and 38 mm stretch mesh with a cod-end liner having 3.175 mm stretch mesh (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 NetmindTM (2004-2015) and Marport M3 (2016) systems (USGS) and a Simrad PI44 catch monitoring system (USFWS). In 2016, trawling depths ranged from 5 to 71 m (mean = 29 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 fishes 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 fishes 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. These lengths approximate the lengths of the smallest age-1 fish of these species (GLSC unpublished data).

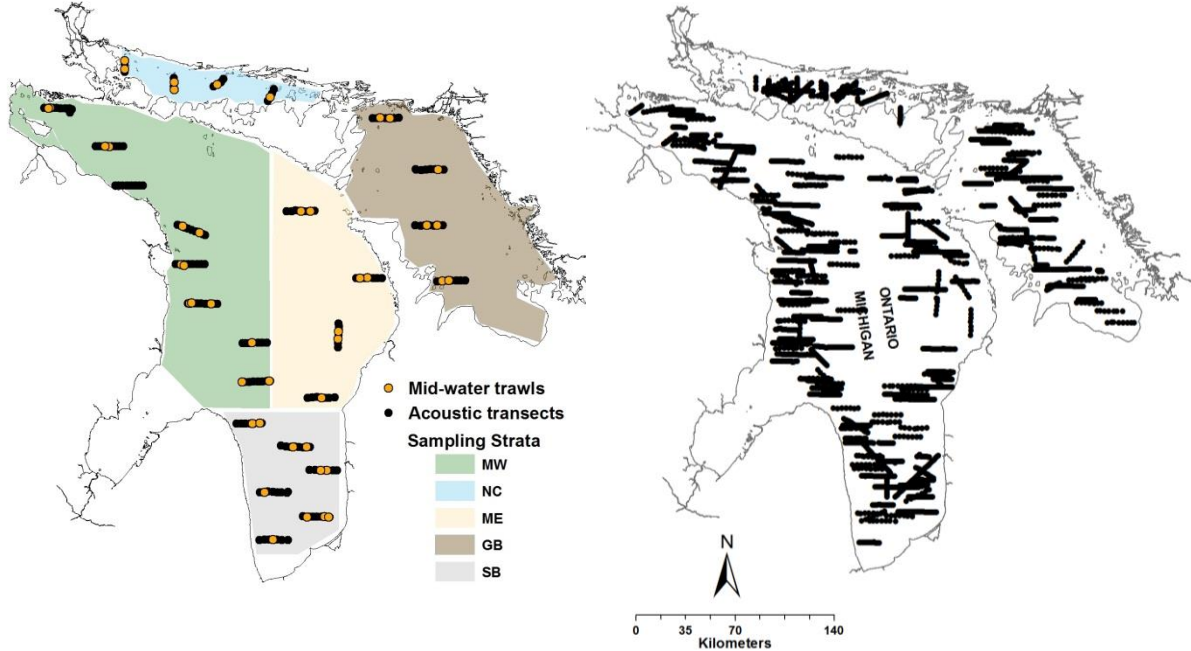


Figure 1. Location of acoustic transects and mid-water trawls within sampling strata in Lake Huron during 2016 (left), and location of acoustic transects during surveys in 2004-2015 (right).

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 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 and Discussion

Density and biomass by species

Alewife – During 2016, no alewives were captured. 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 were especially abundant in any survey year (Figure 2). During 1997, the year of highest abundance, alewives were only 3.1% of total fish density.

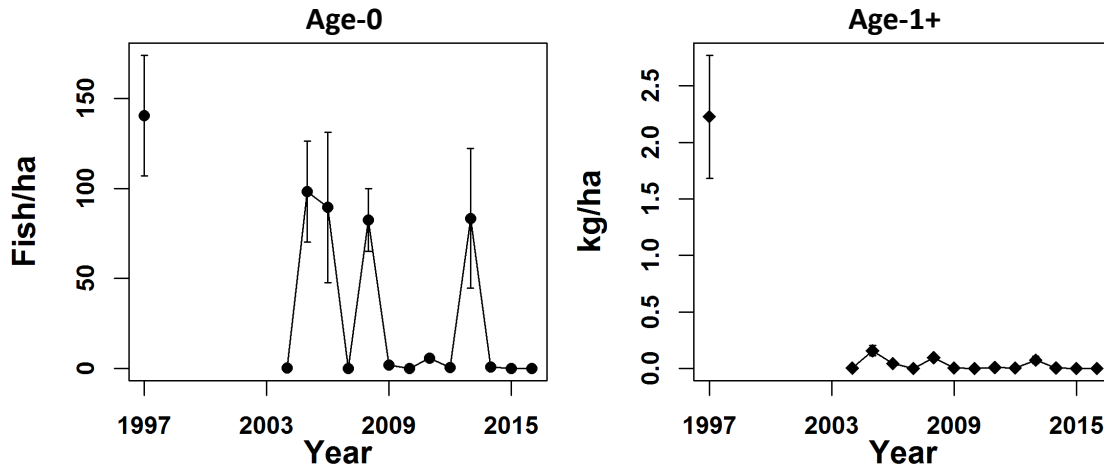


Figure 2. Acoustic and mid-water trawl estimates of alewife numeric density (fish/ha; left panel) and biomass (kg/ha; right panel) in Lake Huron, 1997-2016. Error bars represent ± 1 standard error.

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. High biomass in 1997 was due to age 1+ alewife and 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. These findings differ from that observed in the 2016 bottom trawl survey (Riley et al. 2017), which found high numbers of young-of-year alewife in several trawl catches near the ports of Alpena and Hammond Bay. However, abundance and biomass of both young-of-year and yearling-and-older alewife remain low relative to previous decades (Riley et al. 2017). Overall trends between acoustic and bottom trawl surveys have typically been similar with respect to alewife abundance since populations crashed in 2004.

Rainbow smelt – During 2016, age-0 rainbow smelt density decreased from 2015 estimates by nearly a factor of 3 to 24% 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 increased from 2.2 kg/ha in 2015 to 2.6 kg/ha in 2016. This is roughly 60% of the long-term mean of 4.3 kg/ha (Figure 3) and

substantially less than that observed in 1997. Rainbow smelt were most abundant in the North Channel and Georgian Bay respectively (Figure 4).

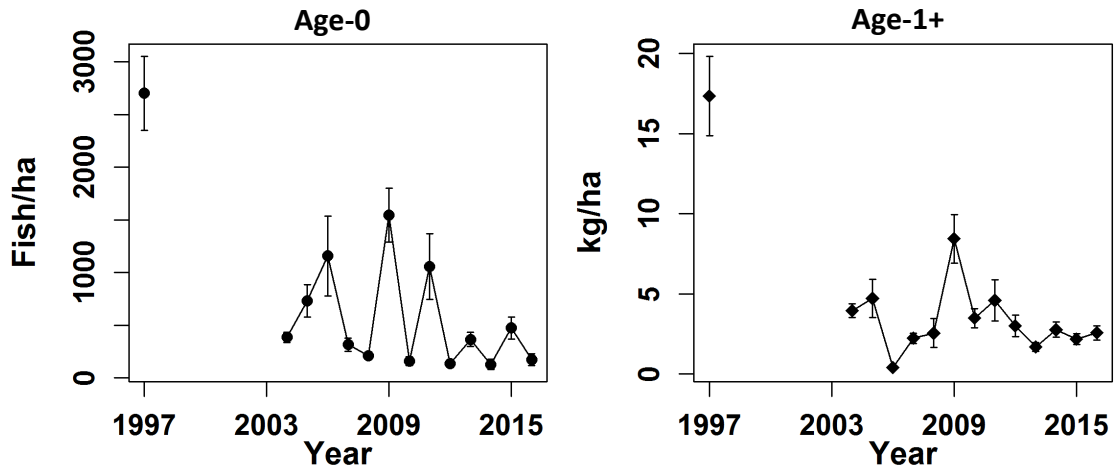


Figure 3. Acoustic and mid-water trawl estimates of rainbow smelt age-0 numeric density (fish/ha; left panel) and age-1+ biomass (kg/ha; right panel) in Lake Huron, 1997-2016. Error bars represent ± 1 standard error.

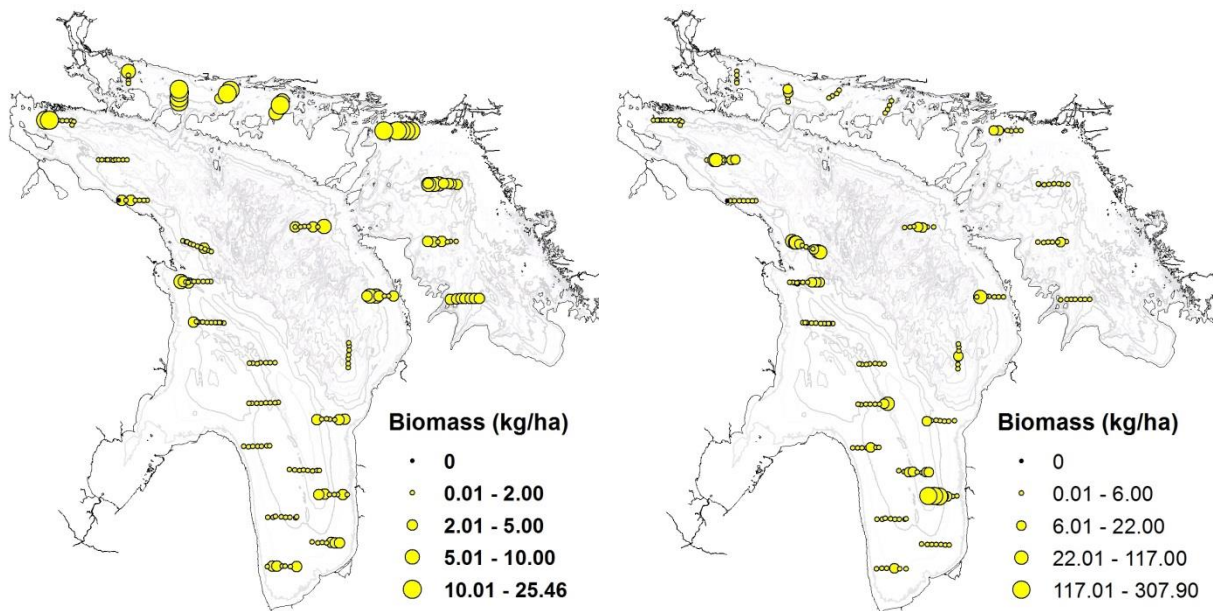


Figure 4. Geographic distribution of rainbow smelt (left) and bloater (right) biomass summarized within elementary sampling units (dots). Gray lines are 20 m depth intervals.

Bloater – Estimates of age-0 bloater numeric density in 2016 were 33% of estimated densities for 2015 (Figure 5). Estimated biomass of age-1+ bloater decreased from 7.1 kg/ha in 2015 to 5.6 kg/ha in 2016 (Figure 5). However, the standard error around this estimate was large, indicating low precision. Similar to results from bottom trawl surveys, age-0 bloater density was variable, but increased during 2004-2015 (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 bloater biomass increase during the past three years, relative standard error for these estimates ranged from 36-48% indicating low equitability in distribution of biomass throughout Lake Huron. Much of the biomass is driven by bloater aggregations in the southern and northwestern main basin (Figure 4).

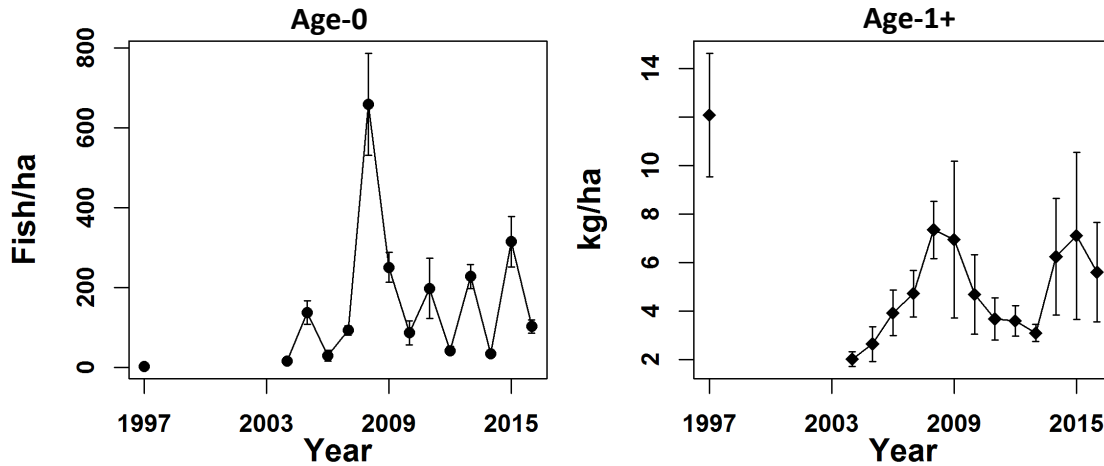


Figure 5. Acoustic and mid-water trawl estimates of bloater age-0 numeric density (fish/ha; left panel) and age-1+ biomass (kg/ha; right panel) in Lake Huron, 1997-2016. Error bars represent ± 1 standard error.

Emerald shiner – In 2016, emerald shiner biomass remained unchanged relative to 2015 and was 24% of the long-term mean of 0.10 kg/ha (Figure 6). In 2015, mean biomass of emerald shiner was estimated to be 0.22% of total pelagic fish biomass, compared to 0.27% in 2016. 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.

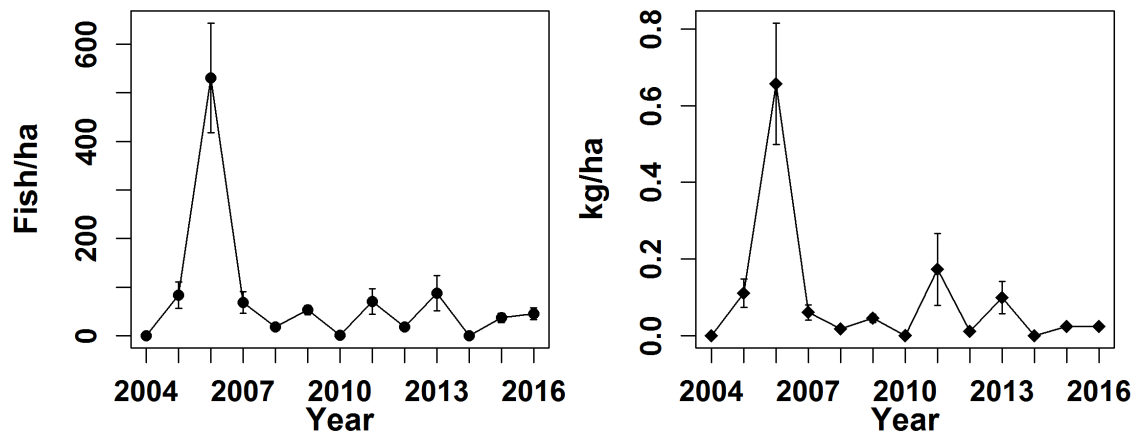


Figure 6. Acoustic and mid-water trawl estimates of emerald shiner numeric density (fish/ha; left panel) and biomass (kg/ha; right panel) in Lake Huron, 2004-2016. Error bars represent ± 1 standard error.

Other pelagic species - Other species captured during acoustic and mid-water trawl surveys included threespine stickleback *Gasterosteus aculeatus*, ninespine stickleback *Pungitius pungitius*, chinook salmon *Oncorhynchus tshawytscha*, lake whitefish *Coregonus clupeaformis*, lake trout *Salvelinus namaycush*, and cisco *Coregonus artedii*. These species typically 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 may not effectively sample cisco that are moving into shallower areas prior to spawning. Cisco are occasionally caught in mid-water trawls but catches are too sporadic to use trawl proportions to apportion acoustic densities. During 2016, sixteen cisco (> 300 mm TL) were captured. Three of these were captured in the North Channel, seven in Georgian Bay and six in the main basin near the Straights of Mackinaw. These specimens were captured at a mean fishing depth of 19.5 m and mean water temperature of 17°C. This pattern in depth distribution is typical for cisco captured in the September acoustic surveys, with fish foraging in offshore areas at or near the thermocline.

Among-basin comparisons of fish biomass

In 2016, pelagic fish biomass decreased in the main basin and increased in both the North Channel and Georgian Bay. Biomass in the North Channel (13.3 kg/ha) was roughly 70% of the long-term mean and increases were driven by higher biomass of both age-1+ rainbow smelt and bloater (Figure 7). Mean main basin biomass (10.45 kg/ha) showed a 19% decrease from 2015 primarily due to decreases in age-1+ bloater. Biomass in Georgian Bay (8.5 kg/ha) showed a two-fold increase to 76% of the long-term mean due to increases in age-0 and age-1+ rainbow smelt, and to a lesser extent, age-0 and age-1+ bloater (Figure 7). 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 remains lower than in 1997,

but there is no clear evidence of a declining trend in the North Channel (Figure 7). Community composition differences are predominantly the result of variation in the proportion of biomass comprised by rainbow smelt and bloater, the two most dominant species.

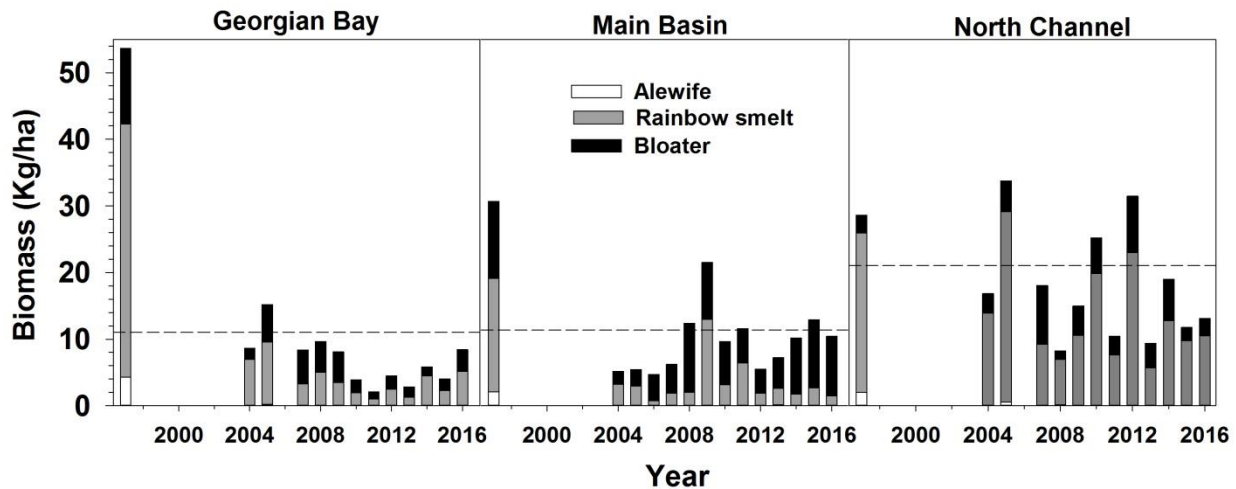


Figure 7. Biomass (kg/ha) of major pelagic fish species in Georgian Bay, main basin, and North Channel during 1997-2016. Horizontal lines denote 1997-2015 mean density.

Most biomass in Georgian Bay is rainbow smelt (60% 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 73% of pelagic fish biomass (Figure 8). In the North Channel rainbow smelt have comprised 73% of biomass on average.

Lake-wide fish density and biomass

Lake-wide mean pelagic fish density decreased from 1,313 fish/ha in 2015 to 824 fish/ha in 2016, representing roughly 60% of the long-term mean (Figure 8). The 2016 pelagic fish density estimate represented 16% of that observed in 1997. The 2016 lake-wide mean pelagic fish biomass estimate was 9.0 kg/ha, a 15% decrease from 2015. Total standing stock biomass in 2016 was estimated at 42 kt (SE 9.8 kt) (Figure 8). The decline in total standing stock biomass was driven primarily by lower 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 2016. 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.

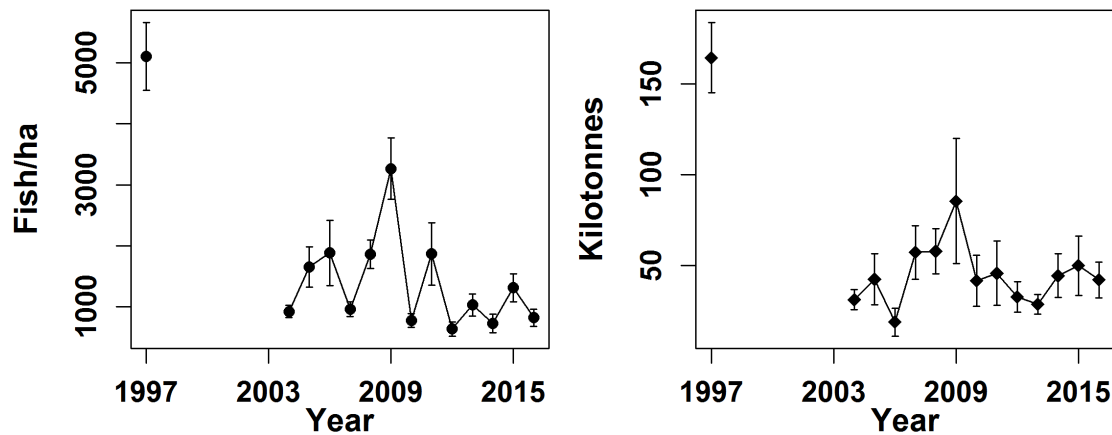


Figure 8. Acoustic and mid-water trawl estimates of lake-wide numeric density (fish/ha; left panel) and standing stock biomass (kilotonnes; right panel) in Lake Huron, 1997-2016. Error bars represent ± 1 standard error.

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. These depths encompass 85% of the range of depths in Lake Huron, although sampling is limited in shallower (<20 m) areas of the lake. For example, 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.

Conclusions

Relatively high adult bloater biomass during 2016 indicates that this species will continue to be the most available pelagic prey species in the offshore zone of Lake Huron. Although lake-wide preyfish biomass decreased in 2016 due to reduced biomass of bloater, preyfish stocks in Georgian Bay increased relative to 2015, and have maintained relatively high productivity in the North Channel through time. Biomass of rainbow smelt in the main basin will likely remain low during 2017 given recent trends in low recruitment for this species (O'Brien et al. 2014) and

relatively low adult biomass in 2016. During 2017, pelagic prey available to piscivores will likely be similar to that seen in recent years.

Lake-wide pelagic biomass in Lake Huron during 2016 (9.7 kg/h) was higher than that estimated for Lake Michigan during 2016 (5.5 kg/ha, Warner et al. 2017) 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 between the three lakes. In Lake Michigan, alewife is still prevalent and comprises about 72% 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 and cisco is dominant by 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.

Acknowledgments

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Appendix 1. Single target detection parameters used in acoustic data analyses in 2016.

Parameter	Value
TS threshold (dB)	-77 ¹
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

¹ Only targets ≥ -60 dB were included in analysis

Appendix 2. Noise levels, detection limits, and acoustic equipment specifications in Lake Huron, 2016.

Vessel	R/V Sturgeon	M/V Spencer Baird
Collection software	Visual Acquisition 6.0	ER60 2.2
Transducer beam angle (3dB)	8.28° split beam	6.53° 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	-19.78	-21
Detection limit (m) for -60 dB target ²	>100	>100

² 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 EchoviewTM 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 σ 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

Status and Trends of Prey Fish Populations in Lake Michigan, 2016^{1,2}

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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 2016. 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. Lake-wide biomass of alewives in 2016 was estimated at 0.35 kilotonnes (kt, 1 kt = 1000 metric tonnes), which was a record low, and 30% lower than in 2015. Age distribution of alewives remained truncated with no alewife exceeding age 4. Bloater biomass increased twofold from 2.8 kt in 2015 to 5.9 kt in 2016. Round goby biomass increased fourfold from 0.3 kt in 2015 to 1.1 kt in 2016. Rainbow smelt biomass also increased fourfold up to 0.3 kt in 2016, but it was still the seventh straight year under 1 kt. Both sculpin species also were estimated higher in 2016 relative to 2015: slimy sculpins were estimated at 0.8 kt (highest since 2011) and deepwater sculpins were estimated at 3.0 kt (highest since 2009). Ninespine stickleback remained at near record low levels of biomass (0.003 kt). Burbot lake-wide biomass (0.2 kt in 2016) has remained below 3 kt since 2001. Age-0 yellow perch abundance was estimated to be 2.4 fish per ha, which is indicative of a relatively weak year-class. 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 2016 was 11.4 kt, nearly a threefold increase over 2015 but still the third lowest estimate in the 44-year time series. In 2016, bloater and deepwater sculpin, two native fishes, constituted 78% of this total.

¹ Presented at Great Lakes Fishery Commission, Lake Michigan Committee Meeting, Ypsilanti, MI on March 20, 2017

²The data associated with this report have not received final approval by the U.S. Geological Survey (USGS) and are currently under review. The Great Lakes Science Center is committed to complying with the Office of Management and Budget data release requirements and providing the public with high quality scientific data. We plan to make all USGS research vessel data collected between 1958 and 2016 publicly available from the GLSC website later in 2017. The anticipated citation will be <http://doi.org/10.5066/F75M63X0>. Please direct any immediate questions to our Information Technology Specialist, Scott Nelson, at snelson@usgs.gov.

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 m) 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 all ports except Waukegan, for a total of 17 “deep” tows. To maintain time series consistency, these tows are not included in our time series results but are specifically noted for some species.

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, only data from those transects are reported herein. 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 2016.

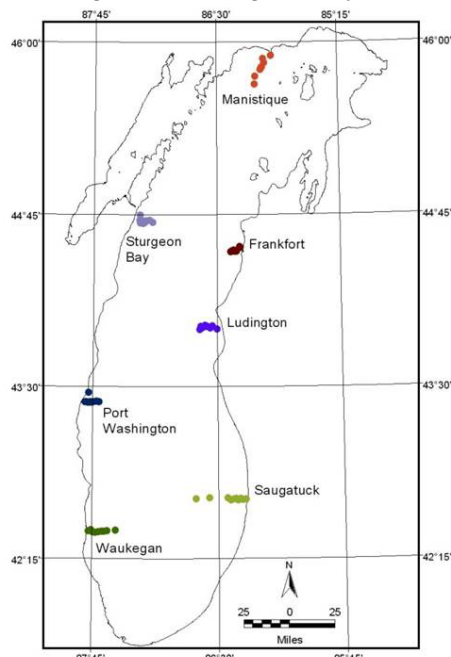


Figure 1. Established sampling locations for GLSC bottom trawls in Lake Michigan.

Indices of lake-wide biomass of fishes vulnerable to the bottom trawl require accurate measures of (1) the surface areas that represent the depths sampled and (2) 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. In June 2009, we used trawl mensuration gear to monitor net configuration during deployment. It provided specific correction factors for width of the net and actual time on bottom when sampling at 2.1 mph (Madenjian et al. 2010a) that were applied to all years through 2015.

We revisited these relationships in June 2016 given that we switched to the R/V Arcticus, which has a wider beam than the previously used R/V Grayling. In addition to trawl mensuration gear, we also used a go-pro camera and adjusted the number of chain links that connect the door to the bridle to improve the angle upon which the doors fish the net. We found that the relationship between bottom depth, D , and width of the net, W ,

needed to be updated for the R/V Arcticus: $W = 6.43 + 6.55(1 - e^{-0.074 * D})$. On average, the trawl fished

about 2.9 m wider on the R/V Arcticus compared to what we measured on the R/V Grayling in 2009. In 2016, we also began directly estimating time on bottom for each tow with an RBR sensor that was attached to the head rope, and which estimates sensor depth every second. After every tow, we plotted time versus depth to determine when the net settled on the bottom and when it came off the bottom. We only applied these changes (new width prediction, empirical time on bottom) in 2016, even though the R/V Arcticus was first used in 2015- largely because the chain link adjustments were not made in 2015.

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 ≥ 100 mm, rainbow smelt (*Osmerus mordax*) ≥ 90 mm, bloaters ≥ 120 mm, and yellow perch (*Perca flavescens*) ≥ 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 also present densities of age-0 yellow perch and other bottom-dwelling species such as burbot (*Lota lota*) 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. Since 1999, dreissenid mussels sampled in the trawl have also been sorted and weighed (but not counted), and their biomass is reported in the Appendix. Beginning this year, we do not report the time series for dreissenid mussel biomass because the annual estimate is extremely sensitive to our ability to retrieve hundreds of pounds of mussels in the trawl on to the boat, often times with assistance of the crane on the back deck. Because we retrieved all but one tow this year (the cod end came undone owing to a large mussel load at Ludington 73 m in 2016), the mussel biomass estimate was extremely large. In contrast, during 2011-2014 on the R/V Grayling, most large mussel hauls were not retrieved because its crane was underpowered.

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 after 1990. Lake Michigan currently has no commercial fishery for alewives.

According to the bottom trawl survey results, adult alewife biomass density equaled 0.03 kg per ha in 2016, a record low (Figure 2a). Likewise, adult alewife numeric density in 2016 equaled a record-low estimate of 2.5 fish per ha (Figure 2b). In 2016, 84% of tows and four ports failed to sample any alewife (Figure 3). Since 2013, alewives have been sampled in 10 of 17 deep tows. For 7 of them, alewife biomass density at 128 m was higher than at 110 m, suggesting that some proportion of the alewife population is in waters deeper than 110 m.

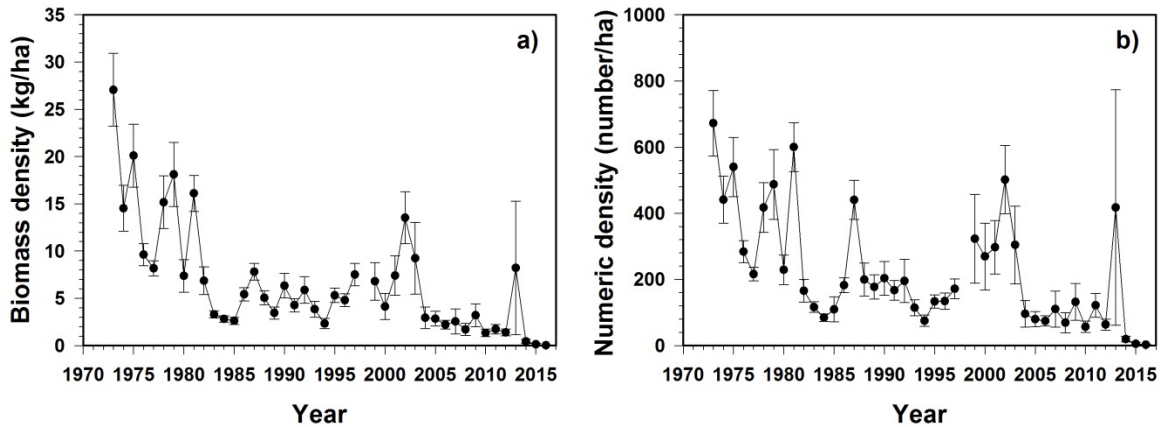


Figure 2. Density of adult alewives as biomass (a) and number (b) per ha (+/- standard error) in Lake Michigan, 1973-2016.

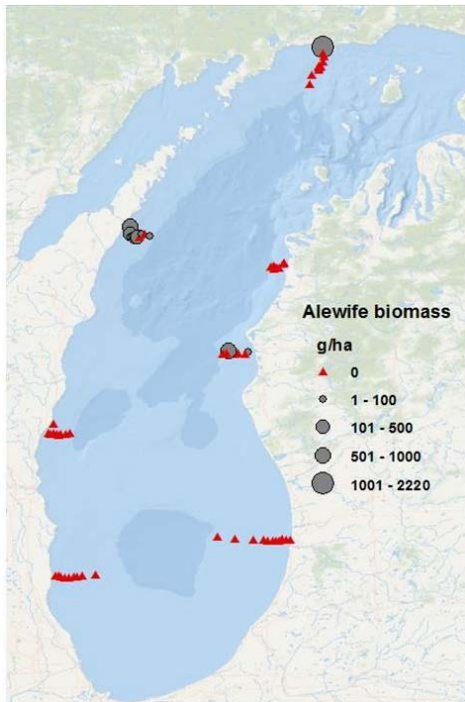


Figure 3. Scaled-symbol plot showing the biomass of alewife sampled at each of the 2016 bottom trawl sites.

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). Several factors have likely maintained this high predation pressure in the 2000s including: a relatively high percentage (>50%) of wild age-1 Chinook salmon in Lake Michigan (Williams 2012), 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), increased importance of alewives in the diet of Chinook salmon in Lake Michigan (Jacobs et al. 2013), a decrease in the energy density of adult alewives (Madenjian et al. 2006), and increases in lake trout abundance due to increased rates of stocking and natural reproduction (FWS/GLFC 2016; Lake Michigan LTWG 2016).

In 2016, the bottom trawl survey only captured 36 “adult” (i.e., ≥ 100 TL) alewives for which we typically construct an age-length distribution. The age composition of these fish was

dominated by age-1 (48%, 2015 year-class) and age-4 (31%, 2012 year-class) fish. The age-0 (2016 year-class), age-3 (2013 year-class), and age-2 (2014 year-class) fish represented 10%, 7%, and 4%, respectively (Figure 4). No alewives older than age 4 were caught in the survey, thus, the recent trend of age truncation in the alewife population continued through 2016. Prior to 2008, age-8 alewives were routinely captured.

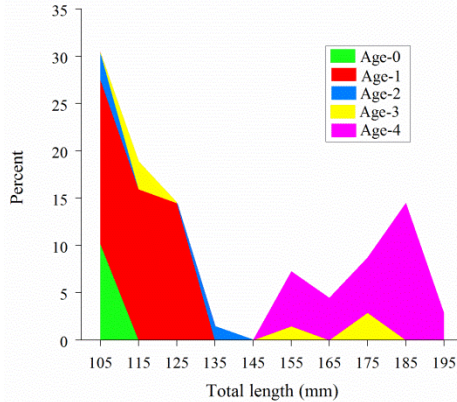


Figure 4. Age-length distribution of alewives ≥ 100 mm total length caught in bottom trawls in Lake Michigan, 2016.

Both the acoustic and bottom trawl survey time series for total alewife biomass are in general agreement, indicating that biomass during 2004-2016 was relatively low compared with biomass during 1994-1996 (Warner et al. 2017). Across the 21 years, however, the acoustic estimate has been higher than the bottom trawl survey estimate 81% of the time. The discrepancy between the two estimates has increased between 2014 and 2016, with the acoustic estimate being 10-40 times higher. The acoustic survey likely provides a less biased estimate of younger (age 3 and younger) alewives, owing to their pelagic orientation. Thus, this recent higher discrepancy between the two surveys may have been partly due to the alewife population in the lake becoming younger in recent years, but other factors were also likely involved. In addition, the acoustic survey reported a 14% increase in total alewife biomass in 2016, relative to 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 (≥ 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 declined sharply since the late 1990s.

Adult bloater biomass density in our survey has been < 10 kg per ha since 1999 (Figure 5a). In 2016, bloater biomass equaled 0.74 kg per ha, very similar to the 2015 estimate. Numeric density of age-0

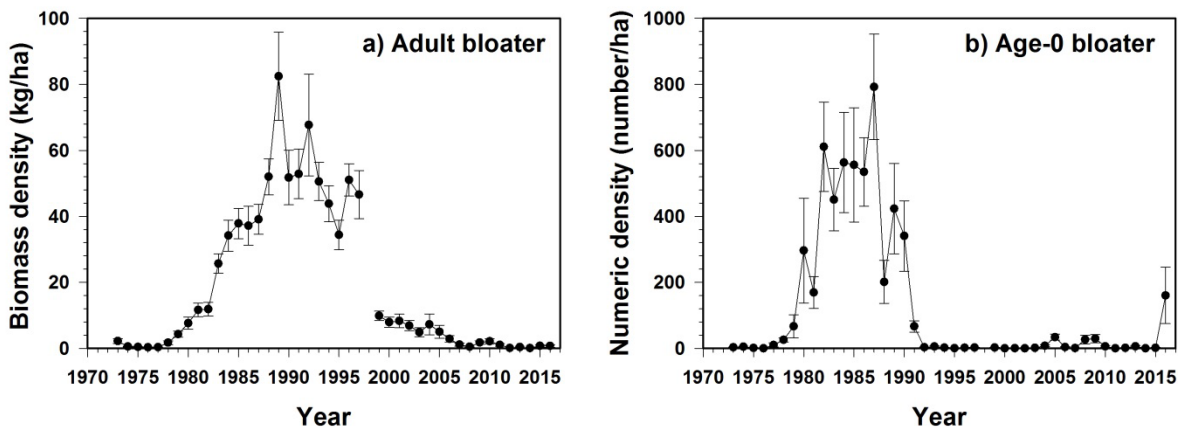


Figure 5. Panel (a) depicts biomass density (+/- standard error) of adult bloater in Lake Michigan, 1973-2016. Panel (b) depicts numeric density (+/- standard error) of age-0 bloater in Lake Michigan, 1973-2016.

bloaters (< 120 mm TL), however, were 160 per ha, which was the highest estimate since 1990 (Figure 5b). Bloaters were sampled in all seven ports in 2016 (Figure 6), with the highest mean biomass at Port Washington and Ludington. Since 2013, bloaters have been sampled in 7 of 17 deep tows. For only 3 of them, bloater biomass density at 128 m was higher than at 110 m, suggesting that a relatively small proportion of the bloater population is in waters deeper than 110 m.

The exact mechanisms underlying the relatively poor bloater recruitment since 1992 (Figure 5b), and the low biomass of adult bloater since 2007 (Figure 5a), 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. 2009) 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.

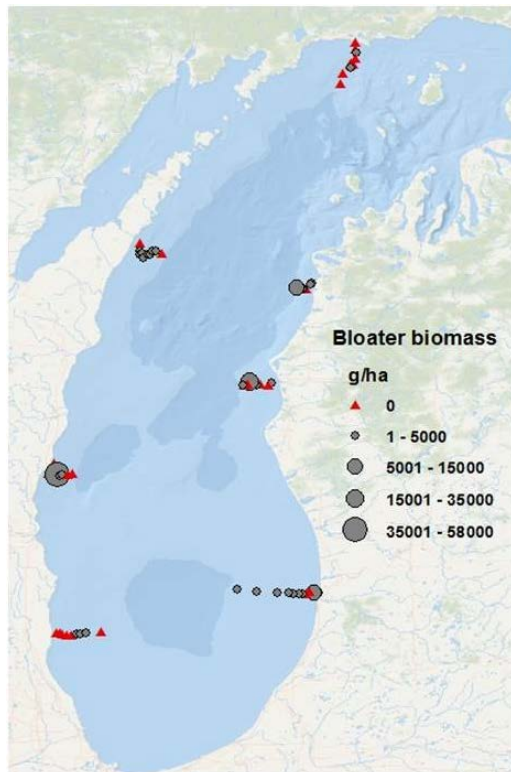


Figure 6. Scaled-symbol plot showing the biomass of bloater sampled at each of the 2016 bottom trawl sites.

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, which could be responsible for a shift to the more pelagic calanoid copepods in their diets (Bunnell et al. 2015). Hence, one hypothesis is that bloaters are less vulnerable to our daytime 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). If increased ability to avoid the net underlies changing catchability for bloater, it also raises the possibility that this factor is affecting other species, such as alewife.

Both the acoustic and bottom trawl survey report that biomass of bloater was at least an order of magnitude higher during 1992-1996 than during 2001-2016. A comparison of the two surveys during 1992-2006 revealed that the biomass estimate from the bottom trawl survey was always higher (79%, on average) than the acoustic survey estimate. Since 2007, which survey yielded the highest estimate has been more variable. In 2016, total biomass density estimated for bloater was twice as high in the bottom trawl survey (1.66 kg per ha) than in the acoustic survey (0.79 kg per ha). Age-0 bloater trends also have revealed differences between surveys through time. During 1992-1996, both surveys

reported age-0 bloater per ha to range between 0.3 and 6.2 fish per ha. Since 2001, however, the acoustic survey has reported nine years where age-0 bloater per ha exceeded 100 per ha; the bottom trawl survey has only reported one such year- 2016. One potential explanation for these inconsistent differences in survey results over time is that catchability of age-0 bloater with the bottom trawl 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 has traditionally supported commercial fisheries in Wisconsin and Michigan waters (e.g., Belonger et al. 1998), but its yields have also declined through time. Between 1971 and 1999, more than 1.3 million pounds were annually harvested on average. Between 2000 and 2011, the annual average dropped to about 375,000 pounds. Since 2013, less than 2,000 pounds have been harvested per year.

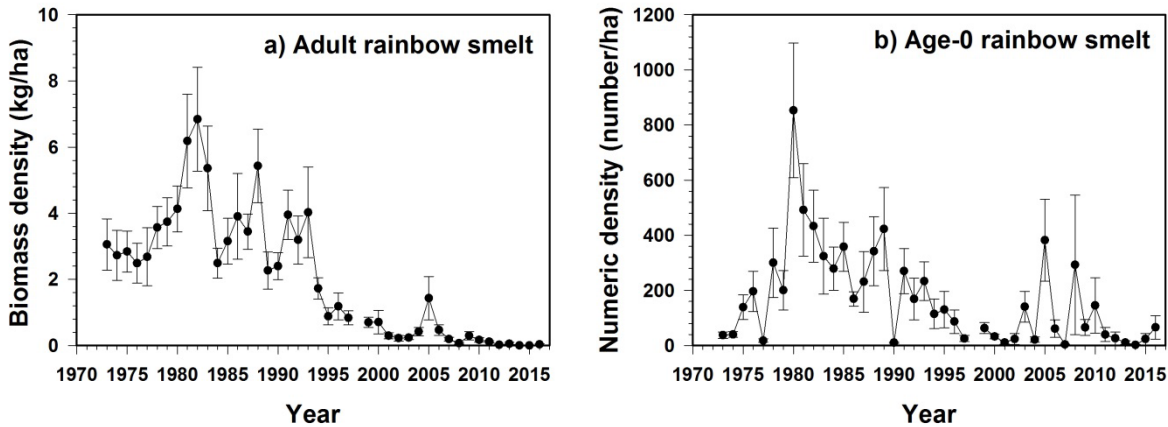


Figure 7. Biomass density (+/- standard error) of adult (a) and age-0 (b) rainbow smelt in Lake Michigan, 1973-2016.

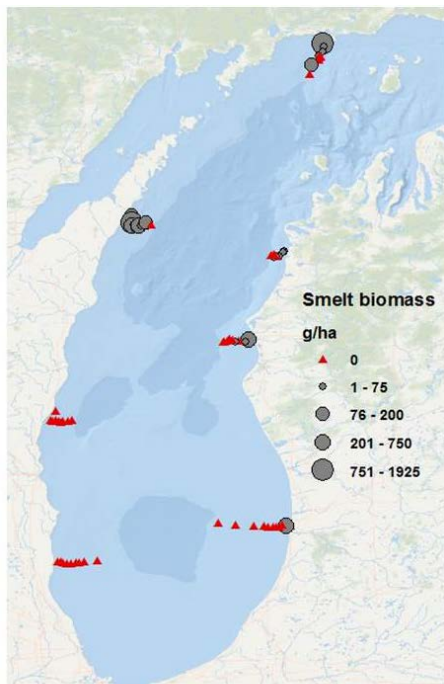


Figure 8. Scaled-symbol plot showing the biomass of rainbow smelt sampled at each of the 2016 bottom trawl sites.

Similar to the commercial yields, adult rainbow smelt biomass density in the bottom trawl has remained at low levels since 2001, aside from a relatively high estimate in 2005 (Figure 7a). Biomass density in 2016 was 0.04 kg per ha. Age-0 rainbow smelt numeric density has been highly variable since 1999 (Figure 7b), but equaled only 66 fish per ha in 2016, marking six consecutive year-classes with <100 fish per ha. Rainbow smelt were sampled in five of seven ports in 2016 (Figure 8), with the highest mean biomass at the northern ports of Manistique and Sturgeon Bay. 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 7b). 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).

The bottom trawl and acoustic surveys detected similar temporal trends, with biomass densities an order of magnitude higher, on average, during 1992-1996 than during 2001-2014. A comparison of the two survey estimates revealed that acoustic survey always exceeds that of the bottom trawl survey, on average by a factor of 6. This difference is not surprising given that rainbow smelt tend to be more pelagic than other prey species during the day. In 2016, the total biomass estimate for all rainbow smelt was 0.76 kg per ha for the acoustic survey (Warner et al. 2017), which was more than 9 times greater than the bottom trawl survey estimate (0.08 kg/ha).

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).

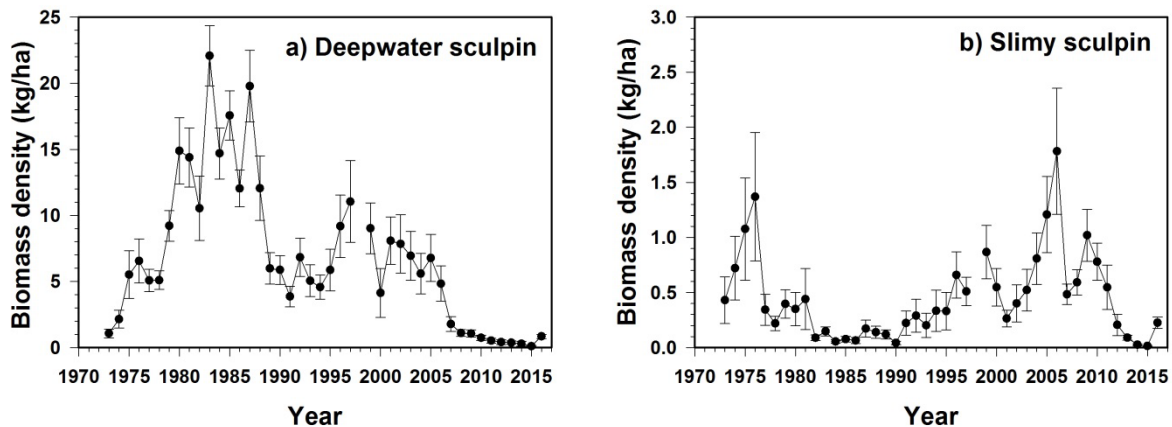


Figure 9. Biomass density (+/- standard error) for deepwater (a) and slimy sculpin (b) in Lake Michigan, 1973-2016.

Deepwater sculpin biomass density in 2016 was 0.85 kg per ha, a nearly 8-fold increase over 2015 and the highest estimate since 2009 (Figure 9a). 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 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 sampling at deeper depths has been supportive of this hypothesis. Since 2013, deepwater sculpins have been sampled in all 17 deep tows. For 13 of them,

deepwater sculpin biomass density at 128 m was higher than at 110 m, suggesting that a relatively large proportion of the population is in waters deeper than 110 m.

Slimy sculpin biomass density was 0.23 kg per ha in 2016, a significant increase over 2015. In fact, slimy sculpin had been declining between 2009 and 2015, although this followed several “sawtooth” patterns in slimy sculpin biomass since around 1995 (Figure 9b). Slimy sculpin abundance in Lake Michigan is 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 (outside of our sampling area, Madenjian et al. 2002). Likewise, the slimy sculpin decline that began in 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). Since 2013, slimy sculpins have been sampled in 11 out of 17 deep tows. For only 4 of them, however, slimy sculpin biomass density at 128 m was higher than at 110 m, suggesting that a relatively small proportion of the population is in waters deeper than 110 m.

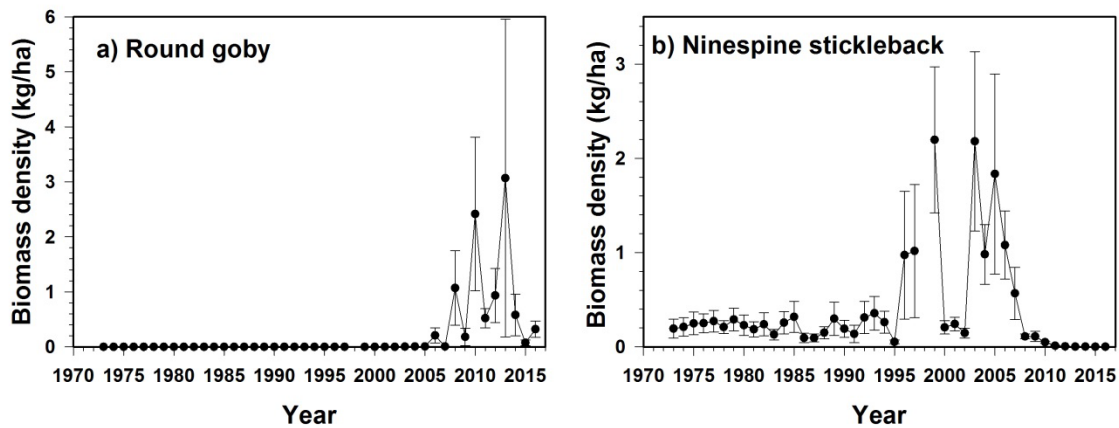


Figure 10. Biomass density (+/- standard error) of round goby (a) and ninespine stickleback (b) in Lake Michigan, 1973-2016.

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).

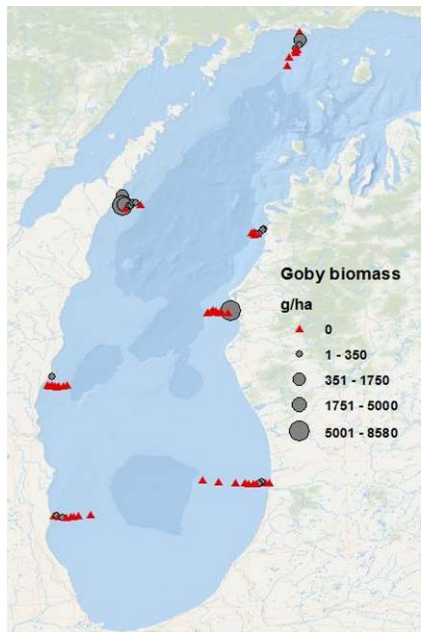


Figure 11. Scaled-symbol plot showing the biomass of round goby sampled at each of the 2016 bottom trawl sites.

Round goby biomass density equaled 0.32 kg per ha in 2016 (Figure 10a). Since 2011, round goby biomass has ranged between 0.30 and 1.0 kg per ha in every year except for 2013 (due to a few extraordinarily large catches inflating the mean and causing high uncertainty) and 2015 (due to consistently low catches). Round goby were sampled in all seven ports in 2016 (Figure 11), with the highest mean biomass at Sturgeon Bay. We hypothesize that round goby abundance in Lake Michigan is being controlled by predation. 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 2016 was only 0.8 g per ha, the second lowest estimate ever recorded (Figure 10b). 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 2008-2016 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 2016 of 11.4 kilotonnes (kt) (1 kt = 1000 metric tons) (Figure 12a, 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 12a). 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).

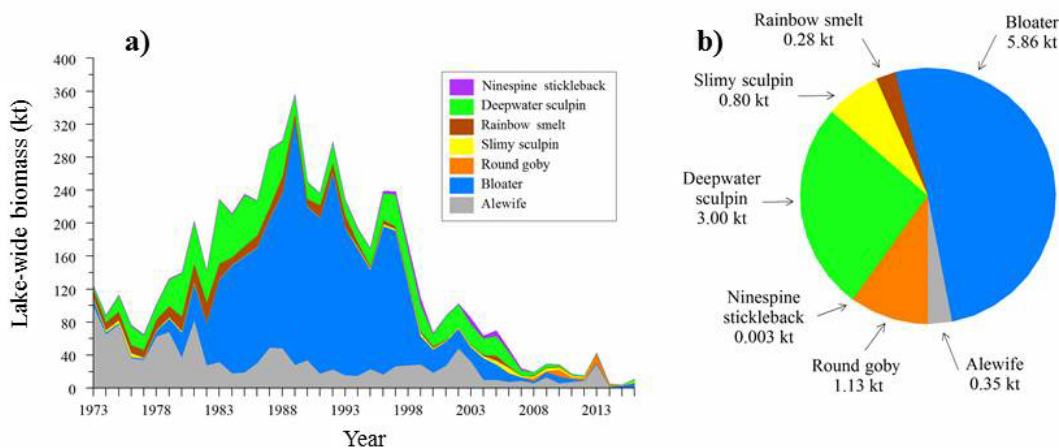


Figure 12. Estimated lake-wide (i.e., 5-114 m depth region) biomass of prey fishes in Lake Michigan, 1973-2016 (a) and species composition in 2016 (b).

As Figure 12b depicts, the 2016 prey fish biomass was apportioned as: bloater 51.3% (5.86 kt), deepwater

sculpin 26.3% (3.0 kt), round goby 9.9% (1.13 kt), slimy sculpin 7.0% (0.80 kt), alewife 3.0% (0.35 kt), rainbow smelt 2.5% (0.28 kt), and ninespine stickleback 0.02% (0.003 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 0.06 kg per ha in 2016, the lowest estimate since 1983 when none were captured. After a period of low numeric density in the 1970s, burbot showed a strong recovery in the 1980s (Figure 13a). Densities increased through 1997, but declined thereafter. It is unclear why burbot catches in the bottom trawl survey have declined in the face of relatively low alewife densities.

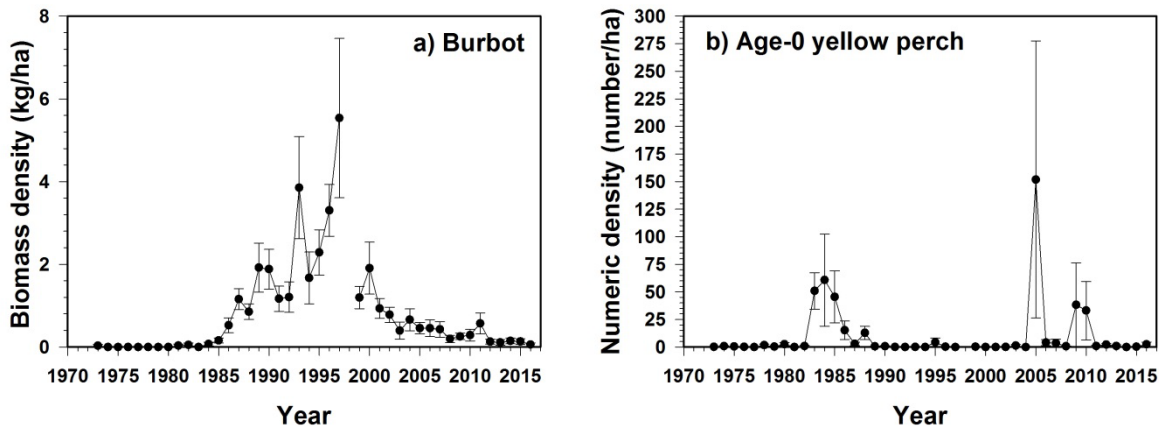


Figure 13. Biomass density (+/- standard error) of burbot (a) and numeric density (+/- standard error) of age-0 yellow perch (b) in Lake Michigan, 1973-2016.

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 13b) and the 2009 and 2010 year-classes also were higher than average. In 2016, age-0 yellow perch abundance was only 2.4 fish per ha, which is indicative of a weak year-class.

CONCLUSIONS

In 2016, total prey fish biomass was estimated to be 11.4 kt, a 275% increase over 2015. This increase cannot be attributable to the new estimation for calculating area swept in 2016. The trawl widths that we measured while deploying the bottom trawl from the R/V Arcticus during June 2016 were 30% greater than those measured off the R/V Grayling, whereas time on bottom measured during June 2016 with the R/V Arcticus was 24% less than that measured previously off the R/V Grayling. Thus, the increase in trawl width was nearly balanced by the decrease in time on bottom such that the total prey fish biomass

estimated by the swept-area equations corresponding to R/V Grayling operation would have been 11.7 kt, which was very similar to the estimate of 11.4 kt derived from using the swept-area equations corresponding to R/V Arcticus operation. Relative to previous years in the time series, however, total prey fish biomass for 2016 was still relatively low- the third lowest estimate ever.

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 2016 was age 4.

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. 2014b; 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.

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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 2016. 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	22.05 (20.79)	0.067 (0.062)	0.238 (0.218)
adult alewife	2.50 (1.42)	0.031 (0.014)	0.108 (0.048)
age-0 bloater	160.29 (85.33)	0.928 (0.488)	3.266 (1.719)
adult bloater	32.80 (18.38)	0.736 (0.364)	2.590 (1.283)
age-0 rainbow smelt	66.23 (42.62)	0.044 (0.030)	0.156 (0.106)
adult rainbow smelt	3.68 (1.81)	0.036 (0.016)	0.125 (0.058)
deepwater sculpin	146.02 (24.07)	0.851 (0.160)	2.998 (0.564)
slimy sculpin	42.23 (7.69)	0.226 (0.052)	0.796 (0.184)
ninespine stickleback	0.67 (0.39)	0.0008 (0.0004)	0.003 (0.001)
burbot	0.06 (0.03)	0.059 (0.042)	0.209 (0.148)
age-0 yellow perch	2.39 (2.04)	0.011 (0.009)	0.037 (0.033)
round goby	47.96 (23.38)	0.321 (0.149)	1.129 (0.524)
dreissenid mussels	NA	60.935 (16.473)	214.591 (58.013)

Status and Trends of the Lake Huron Offshore Demersal Fish Community, 1976-2016^{1,2}

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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 more recent sampling near Goderich, Ontario. The 2016 fall bottom trawl survey was carried out between 19 and 31 October at all ports. The 2016 main basin prey fish biomass estimate for Lake Huron was 26.7 kilotonnes, an increase of about 37 percent from 2015. This estimate is the fourth-lowest in the time series, and is approximately 7 percent of the maximum estimate observed in 1987. Adult alewife abundance was the second-lowest in the time series, but YOY alewife biomass was the highest estimated since 2003, before the alewife crash, although catches varied substantially among ports. The estimated biomass of yearling-and-older rainbow smelt increased from that observed in 2015, but still remained very low compared to historical estimates. YOY rainbow smelt abundance and biomass decreased from that observed in 2015. Estimated adult bloater biomass was slightly less than the 2015 estimate, while the abundance and biomass estimates for YOY bloater were the second-lowest of the time series, and more than an order of magnitude lower than any recent estimate. Biomass estimates for deepwater and slimy sculpins, trout-perch, and ninespine stickleback increased over 2015, but all remained low compared to historic estimates. The 2016 biomass estimate for round goby increased from 2015 but remained at only 7 percent of the maximum observed in 2003.

¹Prepared for the Great Lakes Fishery Commission Lake Huron Committee Meeting, Ypsilanti, MI, March 2017.

²The data associated with this report have not received final approval by the U.S. Geological Survey (USGS) and are currently under review. The Great Lakes Science Center is committed to complying with the Office of Management and Budget data release requirements and providing the public with high quality scientific data. We plan to make all USGS research vessel data collected between 1958 and 2016 publicly available from the GLSC website later in 2017. The anticipated citation will be <http://doi.org/10.5066/F75M63X0>. Please direct any immediate questions to our Information Technology Specialist, Scott Nelson, at snelson@usgs.gov.

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 growth and recruitment of lake whitefish *Coregonus clupeaformis* and Chinook salmon *Oncorhynchus tshawytscha* catches (Mohr and Ebener 2005; Bence and Mohr 2008; Gobin et al. 2015), 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 changes in the distribution and abundance of fish species that make up the offshore demersal fish community (Riley et al. 2008; Riley and Adams 2010).

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 relative 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 1973-2016 using 12-m headrope (1973-1991) and 21-m headrope (1992-2016) 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, Tawas [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 2015-2016; some transects were fished from the USGS R/V *Cisco* in 1990. Sampling has been conducted at Goderich (Ontario) since 1998 using the same trawling protocols as U.S. ports; this port was sampled in 2016.

Single 10-min trawl tows were conducted during daylight at each transect each 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. Lake-wide relative biomass was estimated as the sum of the biomass of the common species sampled in the survey, and is not a true lake-wide estimate, as sampling is conducted only to 110 m and most Ontario waters are not sampled.

We partitioned catches of alewife *Alosa pseudoharengus*, rainbow smelt *Osmerus mordax*, and bloater *Coregonus hoyi* into size-based age classes for analysis. To do this, year-specific length cutoffs were predetermined from length-frequency data and then used to apportion the catches into age-0 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 (1992-2016) 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 2016 Lake Huron fall bottom trawl survey was carried out during 19 - 31 October. Forty-six trawl tows were completed and all standard ports were sampled. Three standard transects (19-37 m transects at Detour) were not sampled this year due to the presence of commercial fishing gear in the trawl path. Fifteen fish species were captured in the 2016 survey: rainbow smelt, alewife, bloater, slimy sculpin *Cottus cognatus*, deepwater sculpin, trout-perch, spottail shiner *Notropis hudsonius*, emerald shiner *Notropis atherinoides*, lake whitefish, ninespine stickleback, lake trout, round goby, yellow perch *Perca flavescens*, white perch *Morone americana*, and white bass *Morone chrysops*.

Alewife abundance in Lake Huron remained relatively low in 2016. The abundance and biomass estimates for yearling and older (YAO) alewife were the second-lowest in the history of the survey (Fig. 2). Age-0 alewife density and biomass during 2016 were the highest estimated since 2003, before the alewife crash, but remained low compared to historic estimates (Fig. 2). YOY alewife catches varied spatially, with the majority of the fish captured at Hammond Bay and Alpena. YAO rainbow smelt abundance and biomass estimates in 2016 increased from 2015 but remained low relative to historical estimates (Fig. 3). YOY rainbow smelt abundance and biomass estimates were among the lowest observed in the time series. YAO bloater abundance and biomass estimates decreased in 2016, and YOY bloater abundance and biomass were the second lowest estimates in the time series (Fig. 4).

Abundance and biomass estimates for deepwater sculpins in 2016 increased over those observed in 2015 and were higher than any observed since 2012 (Fig. 5). Slimy sculpin were not captured by the

survey in 2014 and 2015, and 2016 abundance and biomass estimates remained relatively low compared to historic estimates (Fig. 5). The 2016 abundance and biomass estimates for ninespine stickleback and trout-perch increased slightly from previous years (Fig. 6). Round goby abundance and biomass estimates for 2016 decreased from 2015 levels and remained among the lowest estimates in the time series (Fig. 7).

The total main basin prey biomass estimate (5 - 114 m) in 2016 was 26.7 kilotonnes, an increase of about 37percent from the 2015 estimate (Fig. 8). This estimate is the fourth-lowest observed in the time series, similar to the extreme low estimates that occurred during 2009-2010, and represents approximately 7 percent of the maximum lake-wide biomass estimate observed in 1987. Approximately 42 percent of the 2016 biomass estimate was composed of YAO bloater, and 40 percent of the biomass estimate was made up of YOY alewife. This is the first time that either age class of alewife has made a substantive (>10%) contribution to lake-wide preyfish biomass since 2006.

Discussion

The abundance of prey fish in Lake Huron has remained at 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 lake-wide biomass of prey fish in 2012 was the highest observed since 2001, while the 2013 estimate was approximately half as high as 2012, and the 2014 and 2015 estimates were even lower. The estimated biomass of YAO rainbow smelt and alewife in 2016 were higher than in 2015 but remained among the lowest observed in the history of the survey. The collapse of alewife in the lake may have been precipitated by an extremely cold winter (Dunlop and Riley 2013), but was likely ultimately caused by bottom-up controls due to reduced production at all trophic levels, which may have been related to the invasion of dreissenid mussels, and also by predators such as lake trout and Chinook salmon (Kao et al. 2016). The persistence of low abundance estimates for exotic alewife and rainbow smelt 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 heavily on these species as prey (Roseman et al. 2014).

YAO bloater showed a consistent positive trend in biomass for 2009-2012, but the 2013 estimate was much reduced from 2012, and while 2014 showed a modest increase over the 2013 levels, biomass then declined again in 2015 and 2016. The abundance of this native species is currently at a moderate level, higher than the extreme low estimates observed in 2001-2006. Bloater biomass, however, is currently at low levels comparable to estimates observed during 2001-2006. Decreases in body condition of bloater may be associated with declines in abundance of lipid-rich prey, including *Diporeia* spp., in the lake (Prichard et al. 2016).

Deepwater and slimy sculpins, ninespine sticklebacks, and trout-perch are typically minor components of lake trout diets in the Great Lakes (Diana 1990; Roseman et al. 2014), but were probably more important before the invasion of the lakes by alewife, rainbow smelt and round goby (Van Oosten and Deason 1938). In 2016, biomass estimates for all of these species were greater than in recent years, but remain relatively low compared to historical 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 (Roseman et al. 2014). Round goby were first captured in the Lake Huron trawl survey in 1997, reached a peak in abundance in 2003, and declined in abundance until increasing again in 2011-2012. 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.

Moreover, round gobies primarily inhabit nearshore areas and tend to be most common on rocky substrates, and the Lake Huron bottom trawl survey may not provide a robust estimate of their relative abundance or biomass in the lake.

The estimated lake-wide biomass of common offshore prey species in Lake Huron increased from 2009 - 2012, but then decreased through 2015. The 2016 estimate represents an increase over 2015, but lake-wide biomass is still currently low and similar to the lowest estimates that occurred in 2006-2009. 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 and Lake Ontario (Bunnell et al. 2015; Gorman and Weidel 2016). It is possible that these declines are 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 (Bunnell et al. 2014; Kao et al. 2016). However, similar declines in some species (particularly coregonines) have occurred in Lake Superior (Vinson et al. 2016), which has been less impacted by invasive species.

Three trawl transects (19-37 m at Detour) were not sampled in 2016 due to the presence of commercial fishing gear within the trawl path. Although the GLSC has communicated with commercial fishermen regarding the location of our transects, it is not uncommon for fishing gear to prevent sampling of 1-3 transects per year. Retrospective analysis suggests that missing these transects has a minimal effect on our estimates of relative abundance and biomass (GLSC unpublished data). In future, the GLSC will attempt to locate alternative safe trawl transects near to those that frequently support commercial fishing gear.

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 (see Riley and Dunlop 2016).

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. Time varying catchability is common in survey gear (Wilberg et al. 2010), and understanding how bottom-trawl catchability changes through time may provide great insights into our estimates of prey fish biomass. 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.

Acknowledgments

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Figures



Figure 1. Bottom trawl sampling locations in Lake Huron.

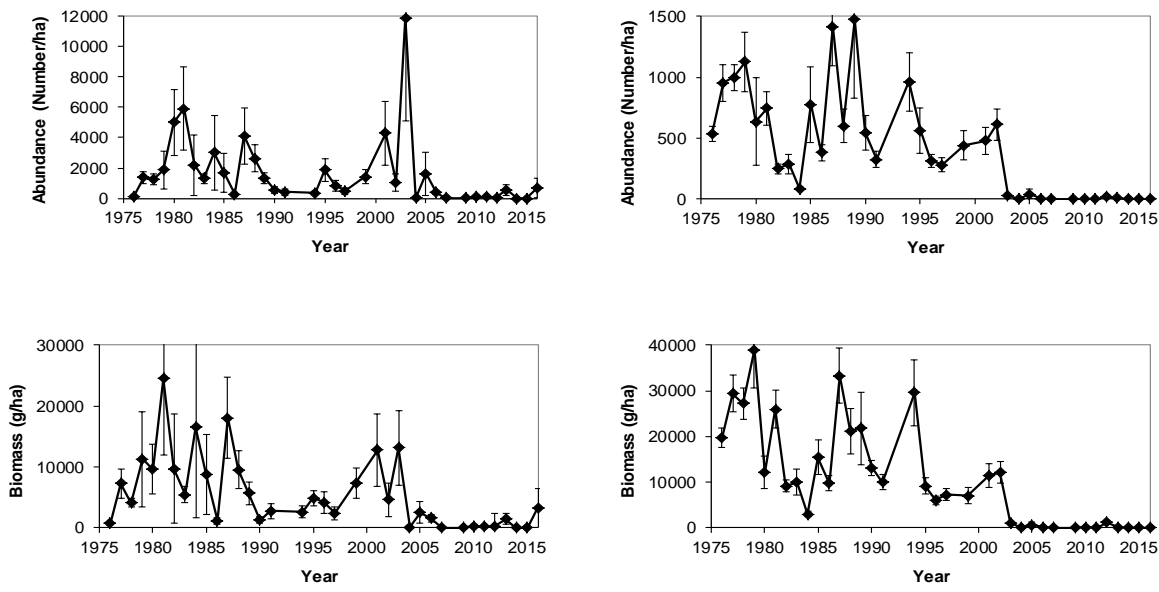


Figure 2. Density of young-of-the-year (YOY: left panels) and adult (YAO: right panels) alewives as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2016. 1976-1991 estimates were corrected using fishing power corrections developed by Adams et al. (2009). Error bars are 95% confidence intervals.

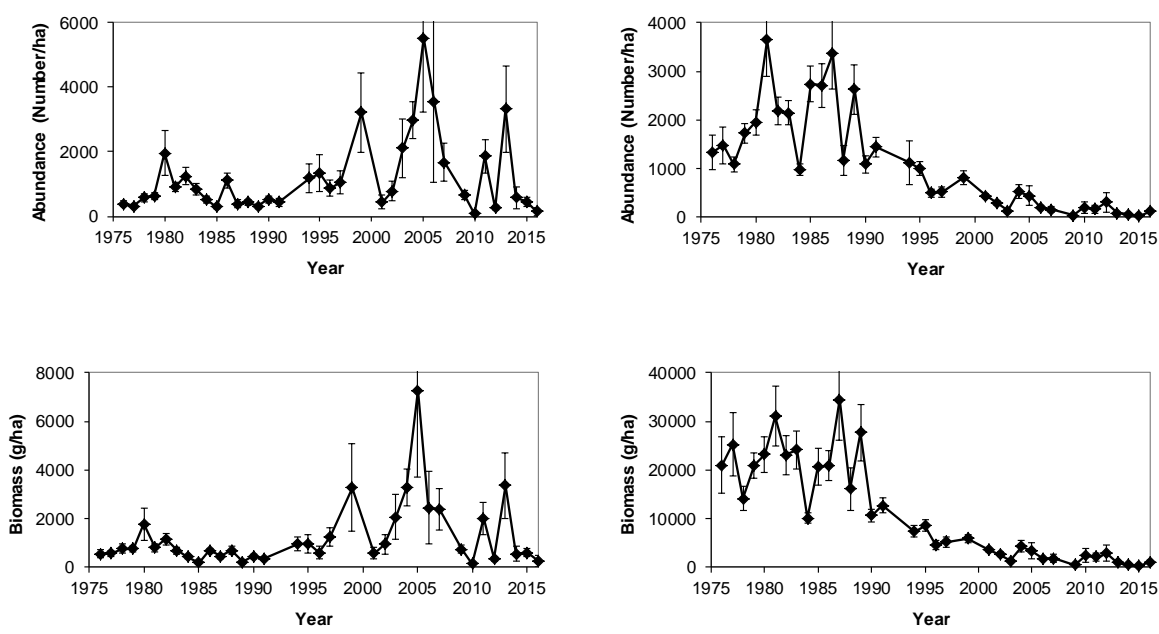


Figure 3. Density of young-of-the-year (YOY: left panels) and adult (YAO: right panels) rainbow smelt as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2016. 1976-1991 estimates for YAO were corrected using fishing power corrections developed by Adams et al. (2009); YOY data are uncorrected. Error bars are 95% confidence intervals.

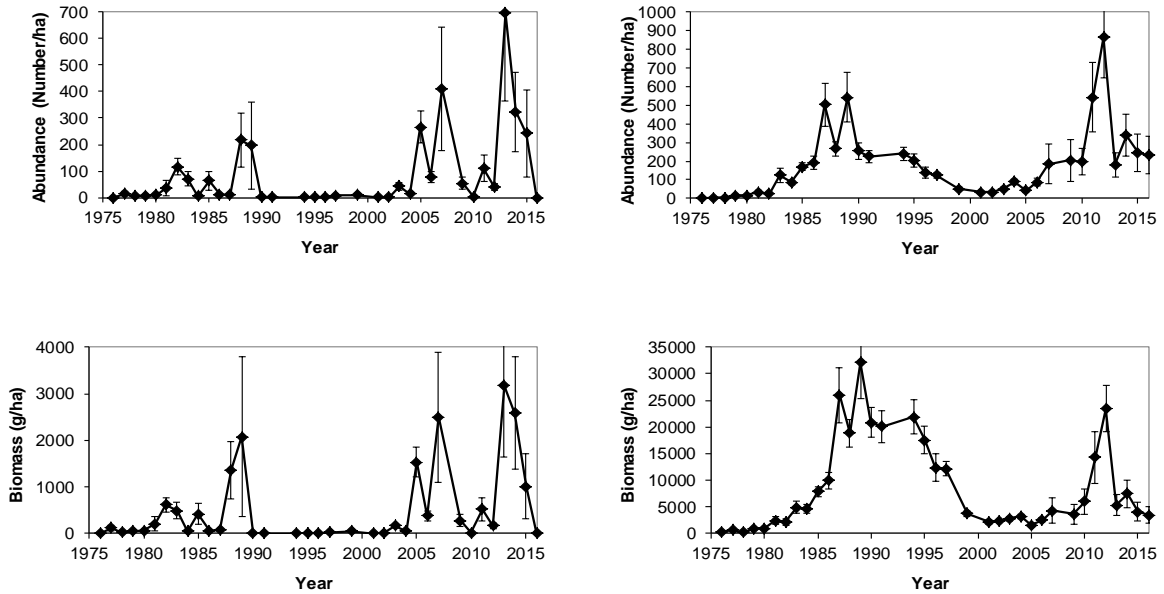


Figure 4. Density of young-of-the-year (YOY: left panels) and adult (YAO: right panels) bloater as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2016. 1976-1991 estimates were corrected using fishing power corrections developed by Adams et al. (2009). Error bars are 95% confidence intervals.

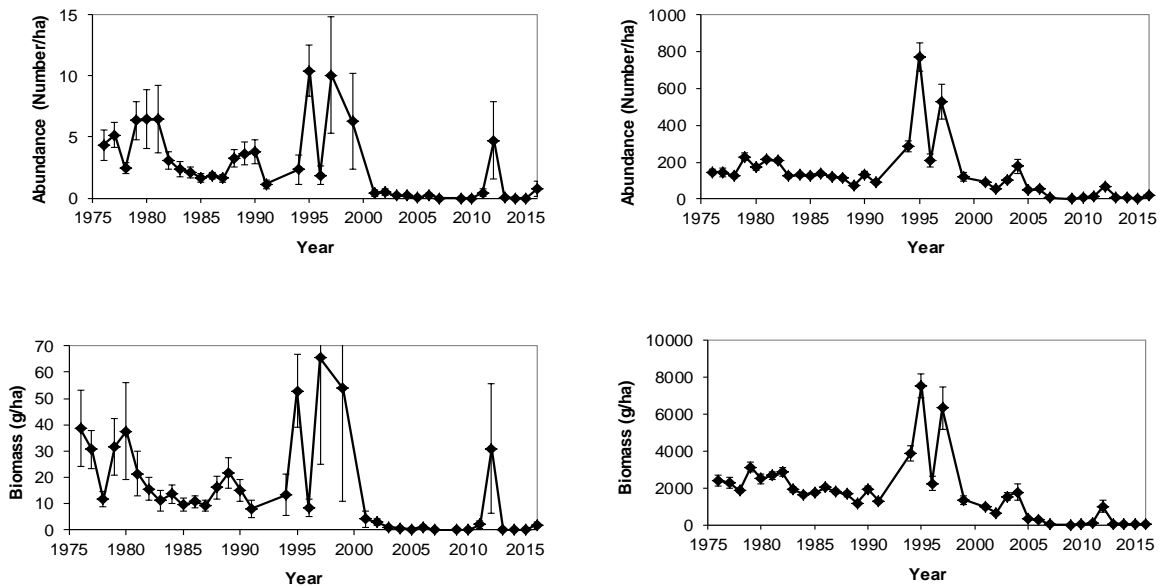


Figure 5. Density of slimy (left panels) and deepwater (right panels) sculpins as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2016. 1976-1991 estimates were corrected using fishing power corrections developed by Adams et al. (2009). Error bars are 95% confidence intervals.

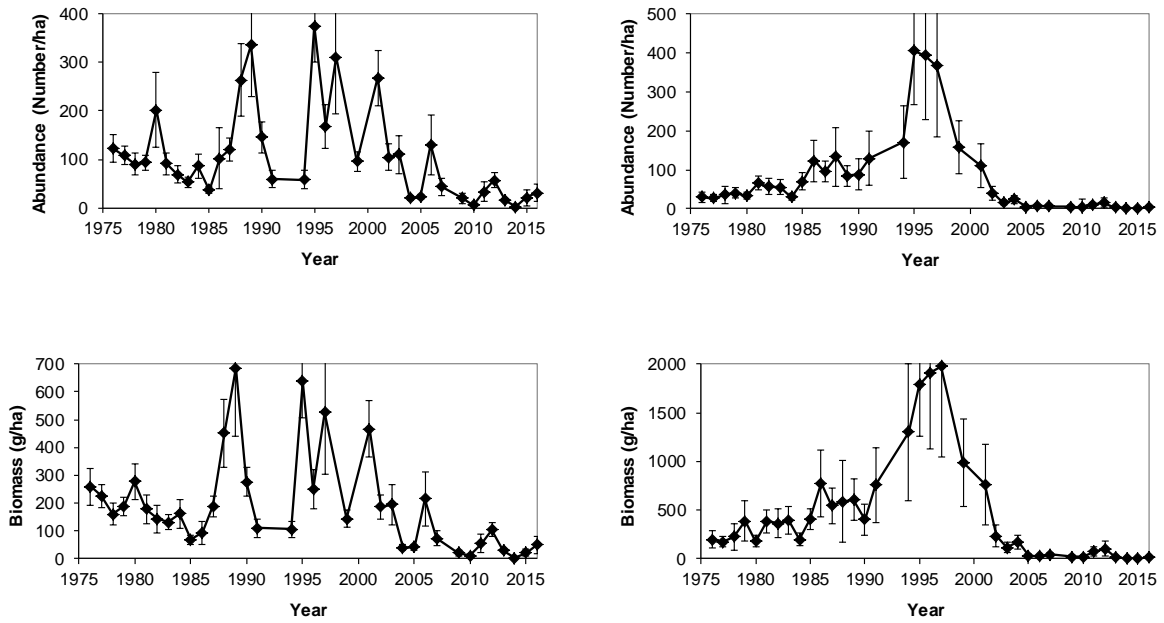


Figure 6. Density of ninespine stickleback (left panels) and trout-perch (right panels) as number (top panels) and biomass (bottom panels) of fish per hectare in Lake Huron, 1976-2016. Error bars are 95% confidence intervals.

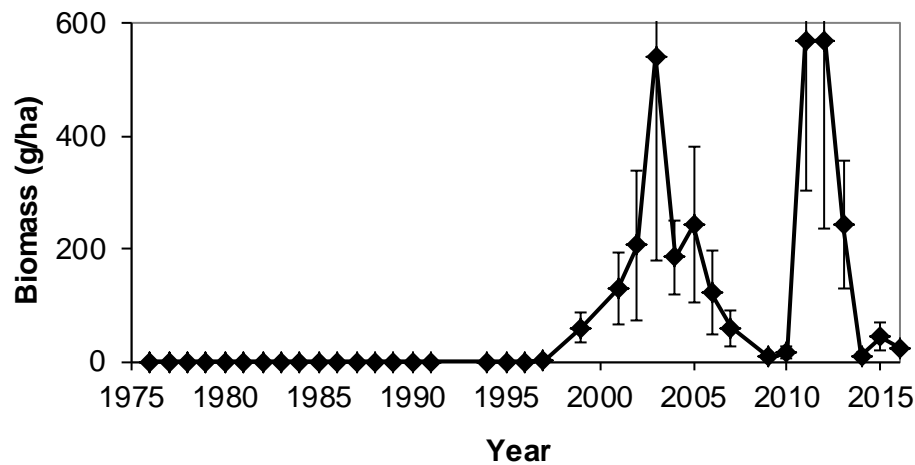
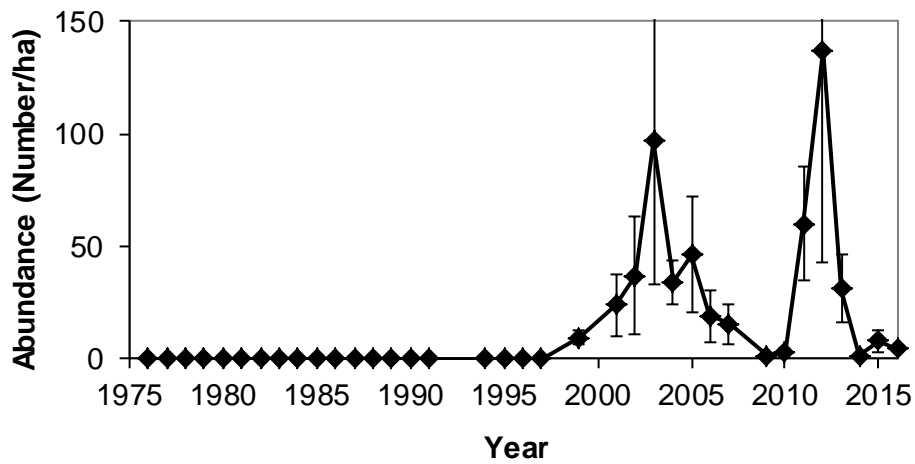


Figure 7. Density of round goby as number (top panel) and biomass (bottom panel) of fish per hectare in Lake Huron, 1976-2016.

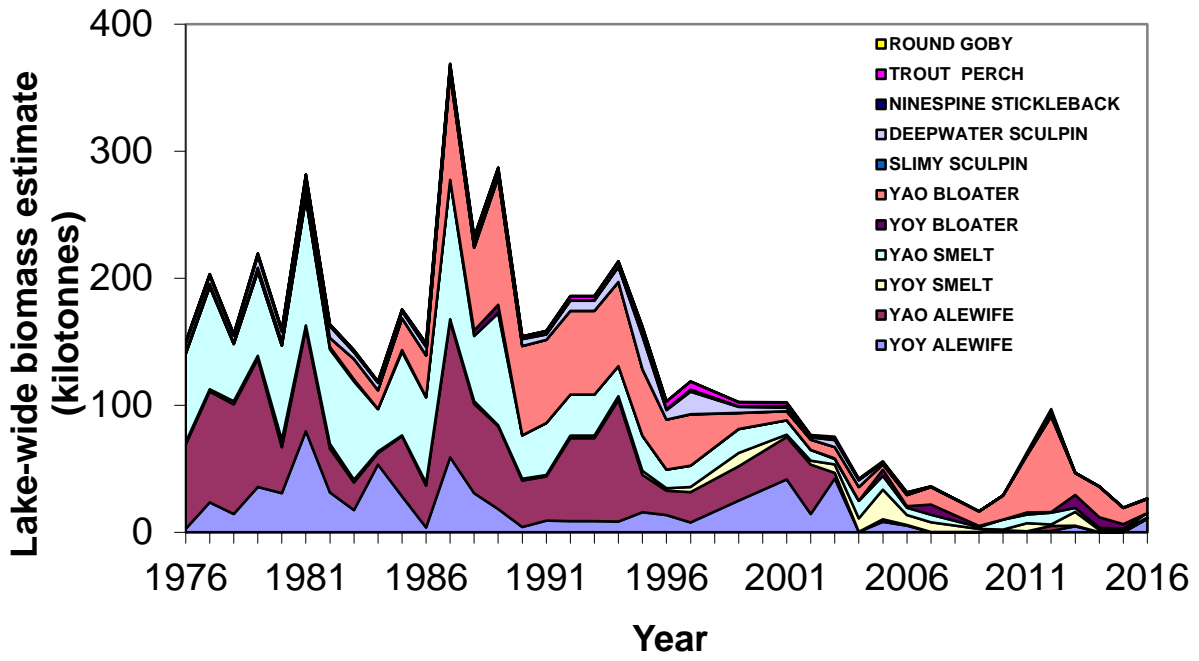


Figure 8. Offshore demersal fish community biomass in the main basin of Lake Huron, 1976-2016. Valid data were not collected in 1992, 1993, 1998, 2000, and 2008; biomass estimates for those years represent interpolated values.

Status of Pelagic Prey Fishes in Lake Michigan, 2016¹

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ABSTRACT

Acoustic surveys were conducted in late summer/early fall during the years 1992-1996 and 2001-2016 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 2016 survey consisted of 34 acoustic transects [655 km total (407 miles)] and 68 midwater trawl tows. Mean prey fish biomass was 5.5 kg/ha [26.7 kilotonnes (kt = 1,000 metric tons)], which was 31% higher than in 2015 and 23% of the long-term (21 years) mean. The numeric density of the 2016 alewife year-class was 44% of the time series average and 1.7 times the 2015 density. This year-class contributed 19% of total alewife biomass (3.9 kg/ha). Survival estimates for age-1 alewife showed above-average survival for the 2013 and 2016 alewife year classes. In 2016, alewife comprised 72% of total prey fish biomass, while rainbow smelt and bloater were both 14% of total biomass. Rainbow smelt biomass in 2016 (0.8 kg/ha) was 21% of the long-term mean and increased for the first time since 2008. Bloater biomass in 2016 was 0.8 kg/ha and 10% of the long-term mean. Mean density of small bloater in 2015 (307 fish/ha) was slightly lower than peak values observed in 2008-2009 but was twice the time series average (150 fish/ha). Although prey fish biomass remains low relative to the 1990s, it did increase in 2016. This increase, along with higher-than-average survival of two recent alewife year classes, are likely a response to reduced predation pressure stemming from a reduction in the abundance of Chinook salmon. Though it is possible these year classes may have had higher survival owing to abundance or timing of zooplankton prey, slow growth of larval alewife in 2015 suggests this was not the case in 2015.

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Lake Michigan Committee Meeting
Ypsilanti, MI, March 20, 2017

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 age-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 2007-2016, 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 2016 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 except in water >40 m below the surface, where species are determined using target strength

RESULTS

The 2016 acoustic survey of Lake Michigan was conducted by the United States Geological Survey (USGS), the United States Fish and Wildlife Service (USFWS), the Michigan Department of Natural Resources (MDNR), and the Little Traverse Bay Band of Odawa Indians (LTTBOI). The main basin sampling consisted of 34 transects for a total transect distance of 655 km, which was similar to the sampling distance in Lake Huron in 2016 (O'Brien et al. 2017). The bottom range over which acoustic data were collected was 4-234 m (13-767 ft). Survey locations are shown in Figure 1.

Alewife – The numeric density of the 2016 alewife year-class in 2016 was more than 1.7 times higher than the density age-0 alewife in 2015. At 468 fish/ha, the 2016 estimate was 44% of the long-term mean. While well below average, the numeric density of age-0 alewife in 2016 was the highest

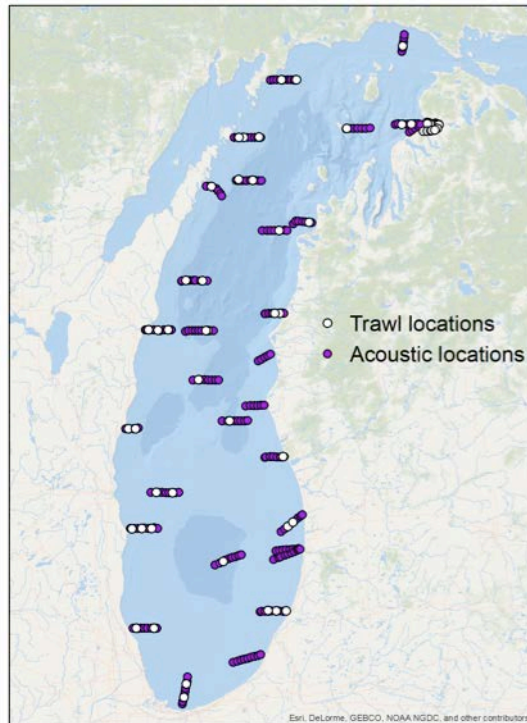


Figure 1. Location of acoustic (purple symbols) and midwater trawl (white symbols) samples in the 2016 acoustic survey of Lake Michigan.

since 2012. The biomass density of age-1 or older alewife was 3.2 kg/ha (Figure 2), which was 33% of the long-term mean and similar to biomass density in 2015. The biomass of alewife \geq age-1 was predominantly the 2015 (48%), 2012 (33%), and 2013 (12%) year classes, respectively. The 2010, 2011, and 2014 year classes together made up the remaining 7%. Although the 2015 alewife year class had below average density in 2015, estimated survival [$0.49, N_{t+1}/N_t$, Ricker 1955]) to age-1 was more than twice the average for other year classes. The acoustic biomass density estimate for all alewife was approximately 40 times the bottom trawl estimate in 2016 (Bunnell et al. 2017) and over the time series (years in which both surveys took place), the acoustic estimates have been greater than the bottom trawl estimates 81% of the time (17 years). During the previous 16 years, acoustic biomass estimates were between 1.2 (2001) and 25 (2015) times the bottom trawl estimate for the same year. 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 as no alewife were caught during the Lake Huron acoustic survey (O'Brien et al. 2017).

Spatial patterns in YOY and YAO alewife appear to be relatively complex (Figure 3). Highest numeric densities of YOY alewife were observed far offshore at a midlake transect but there were also high densities observed in eastern and southern nearshore transects. West nearshore and north nearshore transects densities were generally low. In contrast, YAO alewife numeric densities were highest and similar at a southern nearshore transect north of Holland and northern nearshore transect east of Washington Island, WI but there were also relatively high densities observed at several transects south along the Wisconsin shoreline. Additionally, large alewife (> 100 mm) have become less ubiquitous from 2013 to 2016, with most of the decline in density we have observed occurring offshore (Figure 4). Densities of YAO alewife at bottom depths > 100 m have declined more than at shallower bottom depths (Figure 5)

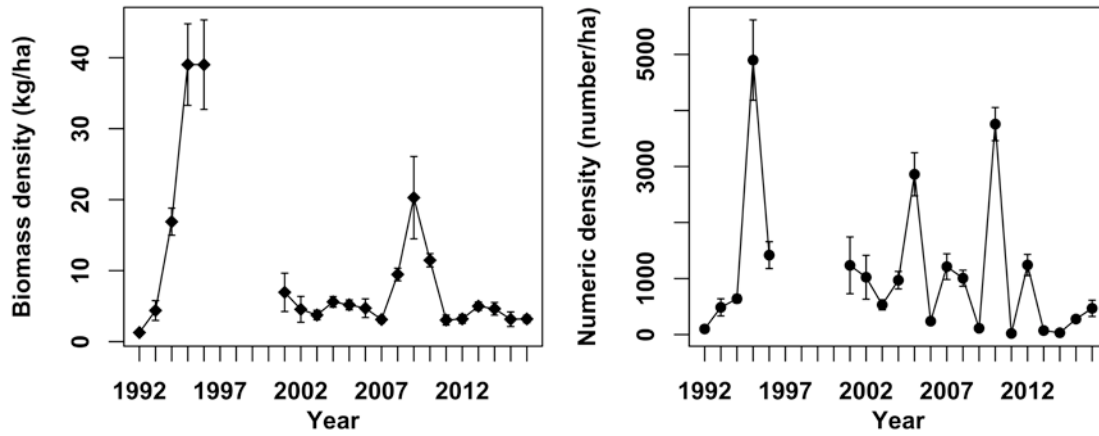


Figure 2. Biomass density of age-1 or older alewife (left panel) and Numeric density of age-0 alewife (right panel) in Lake Michigan during 1992-1996 and 2001-2016. Error bars show one standard error.

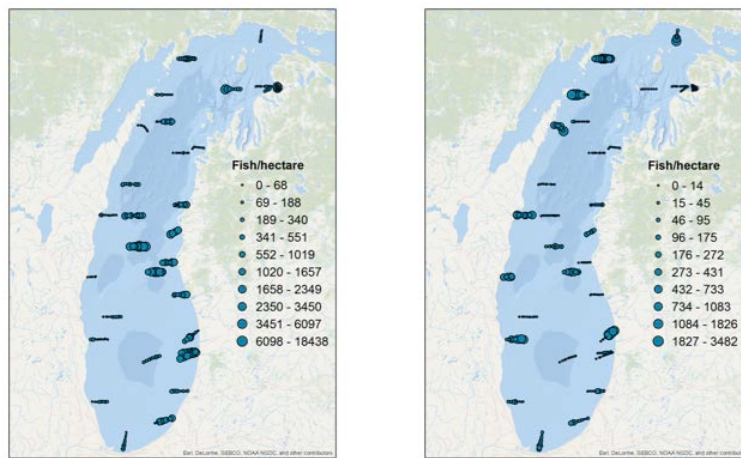


Figure 3. Map of numeric density of YOY alewife (left map) and YAO alewife (right map) during August 2016. Symbol size corresponds to the acoustic estimate of density.

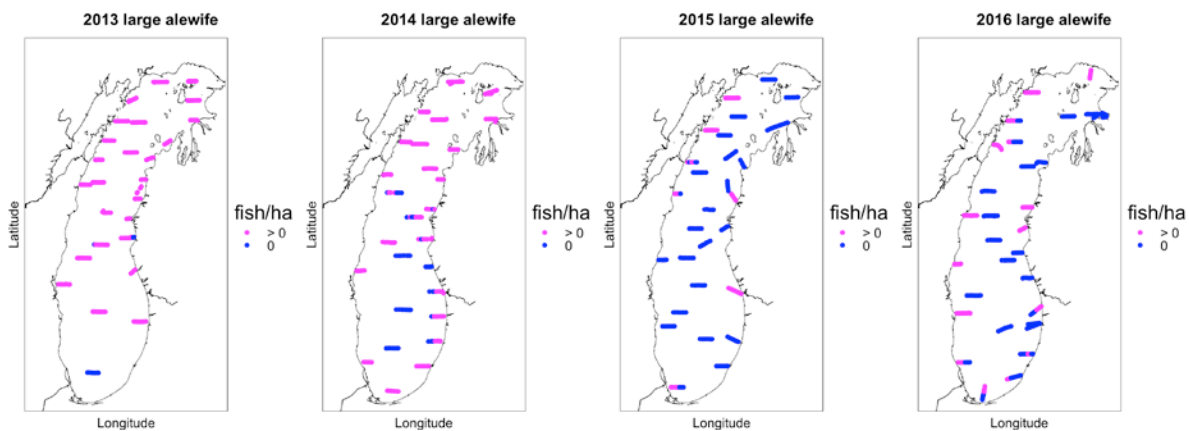


Figure 4. Map of presence and absence of large alewife (>100 mm) in Lake Michigan during the years 2013-2016.

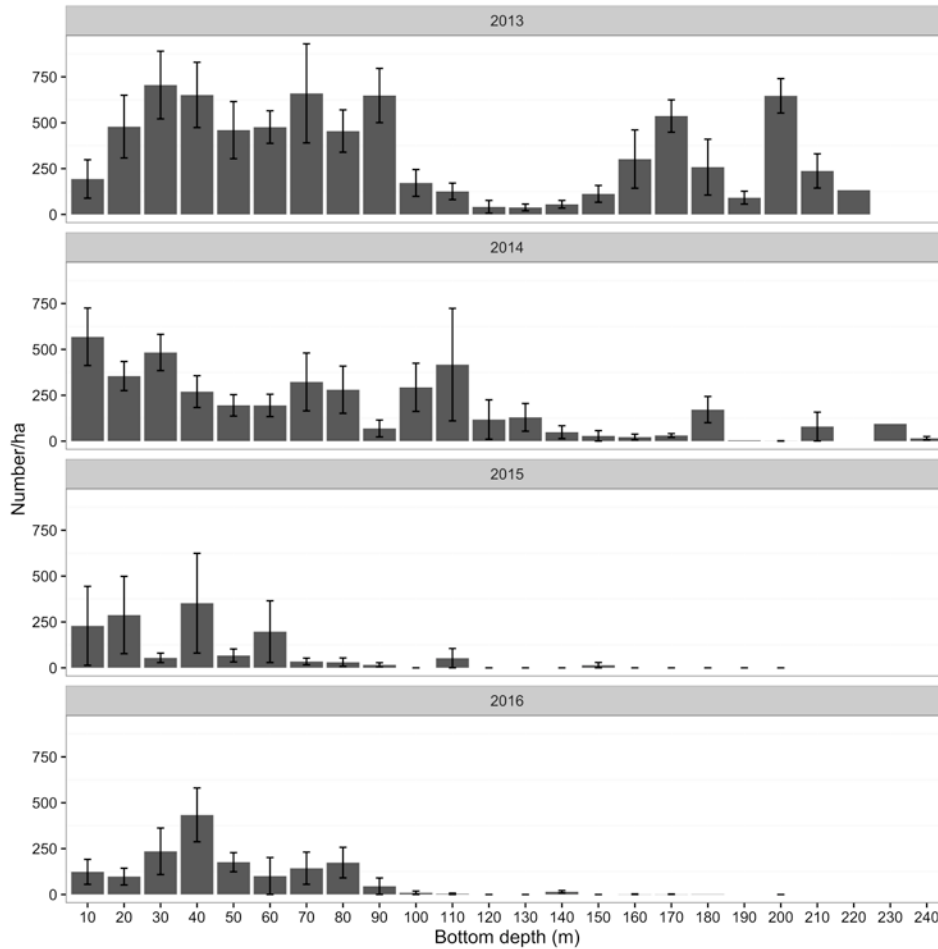


Figure 5. Mean numeric density of YAO alewife in Lake Michigan at a range of bottom depths in the years 2013-2016.

Rainbow smelt –At 178 fish/ha, numeric density of small rainbow smelt (<90 mm) in 2016 (Figure 6) was five times that in 2015. This density was 88% of the time series mean of 203 fish/ha. Similarly, at 0.9 kg/ha, biomass density of large rainbow smelt (≥ 90 mm) increased from that observed in 2015. This was the first increase in the biomass density of larger smelt since 2008. 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 numeric dominance in the mid-1990s following this period of dominance in the late 1980s. 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 2015 acoustic estimate of large rainbow smelt biomass density was 34 times that in Lake Michigan (O'Brien et al. 2016).

Spatial patterns in rainbow smelt density differed from alewife. Throughout much of the southern portion of the lake densities of small rainbow smelt were zero or near zero, but most transects in the northern third of the lake had densities at or near average density and three nearshore transects between Ludington, MI and Grand Haven, MI also had relatively high densities. Densities of large rainbow smelt were zero throughout most of the lake and highest densities were observed in northern nearshore areas (Figure 7).

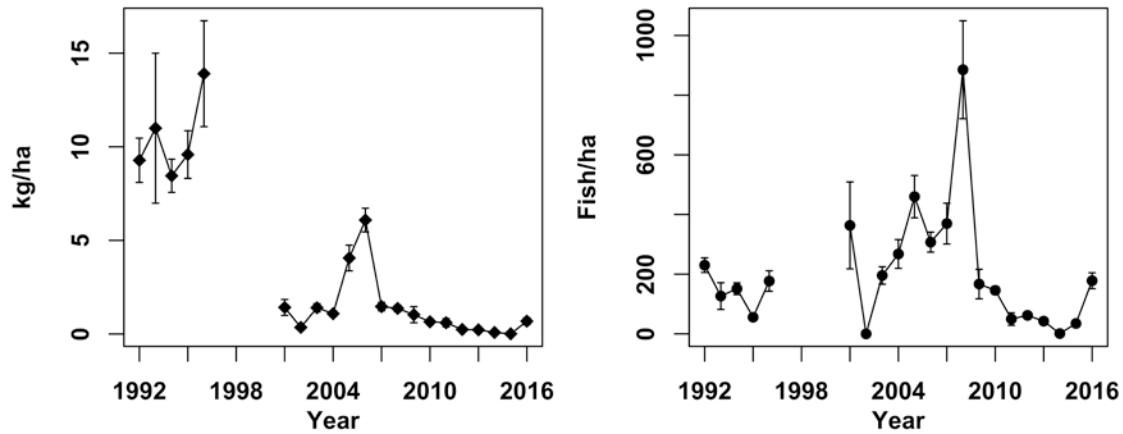


Figure 6. Biomass density of large rainbow smelt (≥ 90 mm, left panel) and numeric density of small rainbow smelt (< 90 mm, right panel) in Lake Michigan during 1992-1996 and 2001-2016. Error bars show one standard error.

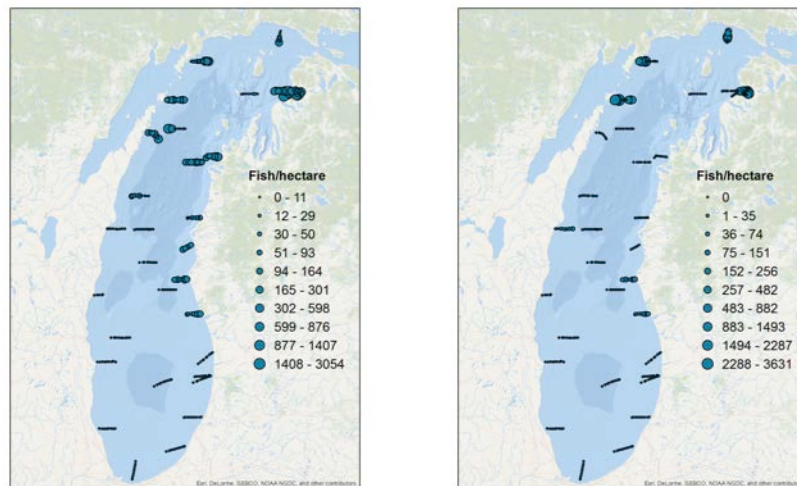


Figure 7. Map of numeric density of small rainbow smelt (< 90 mm total length, left map) and large rainbow smelt (right map) during August 2016. Symbol size corresponds to the acoustic estimate of density.

Bloater –Densities of both small and large bloater have been variable in 2001-2016. Mean numeric density of small bloater in 2016 (307 fish/ha) was 2 times the time series mean (Figure 8). Biomass density of large bloater in 2016 was 0.5 kg/ha, which was 7% of the time series mean, and 2% of the mean in 1992-1996. Bloater biomass has been only 14% of total prey fish biomass density in 2001-2016, 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 2016, the estimates were similar (0.5 kg/ha for the acoustic survey and 0.7 kg/ha for the bottom trawl survey).

Spatial patterns in bloater indicated different distributions for small and large bloater (Figure 9). Highest densities of small bloater were generally in the southern two-thirds of the lake, with the maximum observed north of Holland, MI and average or higher densities at most transects in the southeastern nearshore. However, we also observed densities of a similar magnitude at an offshore transect east of the base of the Door Peninsula in WI, and a southern offshore transect west of Holland, MI. The highest densities of large bloater were generally in the northern half of the lake with many locations in the southern half of the lake near zero. As with small bloater, the maximum density was observed at a southeastern nearshore transect north of Holland, MI.

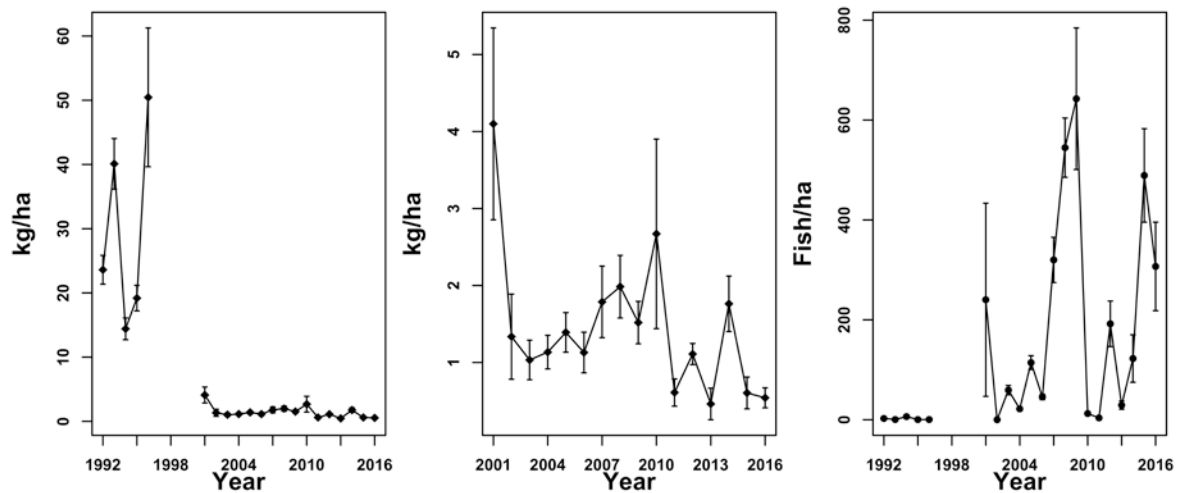


Figure 8. Biomass density of large bloater (≥ 120 mm, left panel) from 1992-2016 (left panel), biomass density of large bloater for the years 2001-2016 (middle panel), and numeric density of small bloater (< 120 mm, right panel) in Lake Michigan. Error bars show one standard error.

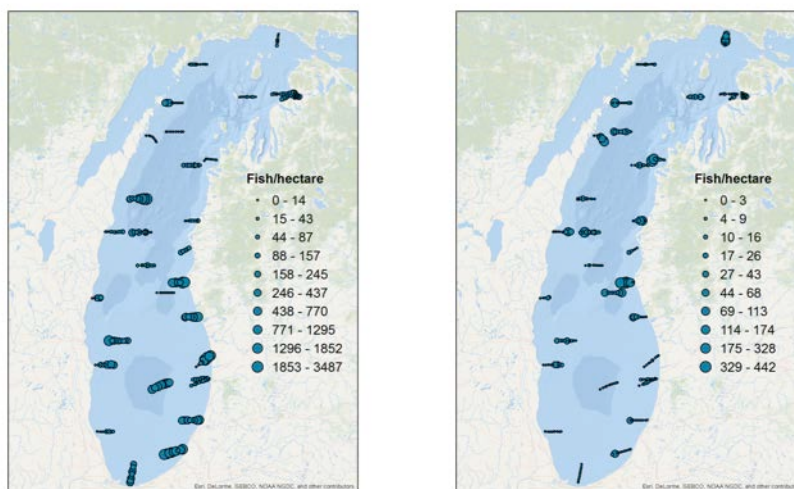


Figure 9. Map of numeric density of small bloater (< 120 mm total length, left map) and large bloater (right map) during August 2016. Symbol size corresponds to the acoustic estimate of density.

ASSUMPTIONS

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 target strength (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). Even though subject to various biases, our stratified random sampling design and use of standardized data processing techniques allow for comparisons of prey fish abundance estimates between years and throughout the time series.

Acknowledgments

We thank the crews of the research vessels M/V Spencer F. Baird, S/V Steelhead, and R/V Sturgeon as well as reviewers for their contributions to this work. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government. A portion of the funding for this work is provided through the Sport Fish Restoration Project #230485.

NOTICE

The data associated with this report have not received final approval by the U.S. Geological Survey (USGS) and are currently under review. The Great Lakes Science Center is committed to complying with the Office of Management and Budget data release requirements and providing the public with high quality scientific data. We plan to make all USGS research vessel data collected between 1958 and 2016 publicly available from the GLSC website later in 2017. The anticipated citation will be <http://doi.org/10.5066/F75M63X0>. Please direct any immediate questions to our Information Technology Specialist, Scott Nelson, at snelson@usgs.gov.

All GLSC sampling and handling of fish during research are carried out in accordance with guidelines for the care and use of fishes by the American Fisheries Society (<http://fisheries.org/docs/wp/Guidelines-for-Use-of-Fishes.pdf>).

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 2016.

Species	Density	RSE (%)	95% CI
Total alewife	3.9 kg/ha	15	(2.9, 5.0)
Age-0 alewife	468 fish/ha	31	(219, 717)
YAO alewife	3.2 kg/ha	17	(2.3, 4.1)
Rainbow smelt	286 fish/ha	15	(212, 361)
Bloater	0.8 kg/ha	21	(0.5, 1.1)
Total	5.5 kg/ha	14	(4.2, 6.8)

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Appendix 1. Single target detection parameters used in acoustic data analyses in 1992-1996, 2001-2005, and 2016.

Parameter	Dual beam 1992-1996	Dual beam 2001-2005 ¹	2016 Split ²
TS threshold (dB)	-60	-77 ³	-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

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

²Split beam systems were used on all vessels in 2006-2014.

³Although a lower threshold was used in 2001-2014 only targets ≥ -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 2016 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 6.0	Visual Acquisition 6.0	ER60 2.2
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 ¹	>100	>100	>100 m

¹ Assuming 3 dB signal-to-noise ratio.