# Status of Pelagic Prey Fishes in Lake Michigan, 2012[1]

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**ABSTRACT**

Acoustic surveys were conducted in late summer/early fall during the years 1992-1996 and 2001-2012 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 2012 survey consisted of 26 acoustic transects (576 km total) and 31 midwater tows. Mean total prey fish biomass was 6.4 kg/ha (relative standard error, RSE = 15%) or 31 kilotonnes (kt = 1,000 metric tons), which was 1.5 times the estimate for 2011 and 22% of the long-term mean. The increase from 2011 resulted from increased biomass of age-0 alewife, age-1 or older alewife, and large bloater. The abundance of the 2012 alewife year class was similar to the average, and this year-class contributed 35% of total alewife biomass (4.9 kg/ha, RSE = 17%), while the 2010 alewife year-class contributed 58%. The 2010 year class made up 89% of age-1 or older alewife biomass. In 2012, alewife comprised 77% of total prey fish biomass, while rainbow smelt and bloater were 4 and 19% of total biomass, respectively. Rainbow smelt biomass in 2012 (0.25 kg/ha, RSE = 17%) was 40% of the rainbow smelt biomass in 2011 and 5% of the long term mean. Bloater biomass was much lower (1.2 kg/ha, RSE = 12%) than in the 1990s, and mean density of small bloater in 2012 (191 fish/ha, RSE = 24%) was lower than peak values observed in 2007-2009. In 2012, pelagic prey fish biomass in Lake Michigan was similar to Lake Superior and Lake Huron. Prey fish biomass remained well below the Fish Community Objectives target of 500-800 kt, and key native species remain absent or rare.

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## INTRODUCTION

In light of changes in the Lake Michigan food web during the last 40 years (Madenjian et al. 2002) and the continued restructuring due to exotic species, pollution, fishing, and fish stocking, regular evaluation of long-term data on prey fish dynamics is critical. 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*). 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), and, as such, constitute an important food web component. Alewife dynamics can reflect occurrences of strong year-classes because total alewife density is highly correlated with the density of alewife ≤ age-2 (Warner et al. 2008). 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 ≤ 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.

## 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 (Argyle et al. 1998). A modified design (Figure 1) 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 2007-2012, the number of transects in each stratum was optimized based on stratum area and standard deviation of total biomass using methods in Adams et al. (2006). In 2012, the acoustic survey consisted of 26 transects with a total sampled distance of 576 km accompanied by 31 midwater trawls.

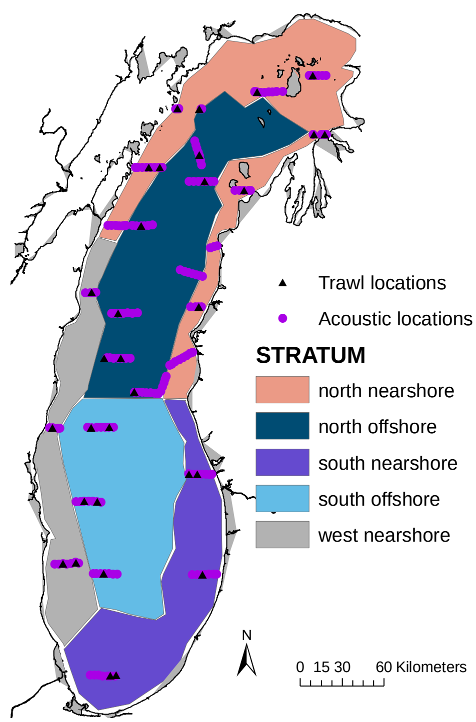


Figure 1. Map of Lake Michigan showing strata used in design and analysis of the lakewide acoustic. Symbols represent acoustic and midwater trawl locations for 2012.

*Fish Data Collection and Processing*

The lakewide acoustic survey has been conducted as a cooperative effort in the majority of the surveys. In 2012, three agencies (United States Geological Survey, U.S.G.S., Michigan Department of Natural Resources, M.D.N.R., and United States Fish and Wildlife Service U.S.F.W.S.) contributed to the completion of the survey. Annual sampling has been conducted between August and November, with acoustic data collection initiated ≈ 1 hour after sunset and ending ≈1 hour before sunrise. Several different vessels, 10-32 m in length and with sampling speeds ranging from 5-11 km/hour, have been used. Different echosounders have been used through the years (Biosonics 102 dual beam, DE5000 dual beam, DT split beam, DT-X split beam and Simrad EK60 split beam). However, acoustic data have always been collected using echosounders with a nominal frequency of 120 kilohertz. With the exception of one unit used in 2001, echosounders have been calibrated during the survey using methods described in Foote et al. (1987) and MacLennan and Simmonds (1992). Transducer deployment techniques have included a towfish, sea chests (Fleischer et al. 2002), hull mounting, and sonar tubes. With the exception of the towfish, a portion of the upper water column remains unsampled because the transducer is deeper. Fish density estimates in the area of the water column sampled with all deployment techniques however are comparable.

Midwater trawls were employed to identify species in fish aggregations observed with echosounders and to provide size composition data. Tows targeted aggregations of fish observed in echograms while sampling, and typically trawling locations were chosen when there was uncertainty about the composition of fish aggregations observed acoustically. Cod end mesh on all trawls was 6.35 mm. A trawl with a 5-m headrope was fished from the S/V Steelhead in 1992-2009. In 2010-2012, a larger trawl (12 m headrope) was used on the S/V Steelhead. On the U.S.G.S. vessel R/V Grayling, a variety of trawls were used (Argyle et al. 1998). On the U.S.G.S. vessels R/V Siscowet, R/V Kiyi and R/V Sturgeon (2001 to present), a trawl with ≈15 m headrope was used. On the U.S.F.W.S. vessel, a 21-m trawl was used. In the 1990s, trawl depth was monitored using net sensors. Similar sensors were used in 2001-2005 (except 2002 on U.S.G.S. vessel, 2001-2004 on M.D.N.R. vessel). In cases without trawl sensors, warp length and angle were used to estimate fishing depth. From 2005 onward, trawl sensors have been used on all trawls. Given the size of fish present, we expect little influence of trawl size on species and size composition data.

Fish were measured as total length (mm) either in the field or frozen in water and measured upon return to the laboratory. Lengths of fish in large catches of a given species (> 100 fish) were taken from a random subsample (typically 50-100 fish). Fish were weighed in groups (total catch weight per species, nearest 2 g) in the field or individually in the laboratory (nearest 0.1 g). Total catch weight was recorded as the sum of weights of individual species. Rainbow smelt were assigned to two size categories (< 90 mm, ≥ 90 mm), while the size cutoff for bloater was < or ≥ 120 mm. The small size category for these two species is predominantly age-0, while the large size category consists of fish that are predominantly age-1 or older. Alewives in each midwater tow were assigned to age classes using year-specific age-length keys with age estimated from sagittal otoliths for a subsample of alewife each year. Age-length keys were available for each year except 1992. The key for 1992 was constructed by averaging the 1991 and 1993 keys.

*Estimates of Fish Abundance and Biomass*

Transect data were subdivided into elementary distance sampling units (EDSU) consisting either of horizontal intervals between adjacent 10 m bottom contours that were 5 or 10 m deep (1990s) or of 1,000-3,000 m intervals that consisted of 10 m layers (2000s). Data collected at bottom depths > 100 m were defined as offshore strata. Data from the 1990s were analyzed using custom software (Argyle et al. 1998). Data collected from 2001-2012 were analyzed with Echoview 4.8 and 5.0 software.

An estimate of total fish density for data from 2001-2012 was made using the formula

$$(1)\quad Total\ density\ (fish/ha) = 10^4 \times \frac{ABC}{\sigma}$$

where $10^4$ = conversion factor ($m^2 \cdot ha^{-1}$), *ABC* = area backscattering coefficient ($m^2 \cdot m^2$) and σ = the mean backscattering cross section ($m^2$) of all targets between -60 and -30 dB. An echo integration threshold equivalent to a target strength of -70 dB was applied to *ABC* data. Based on a target strength (TS) – length relationship for alewives (Warner et al. 2002), the applied lower threshold should have allowed detection of our smallest targets of interest (≈20 – 30 mm age-0 alewife). This threshold may have resulted in underestimation of rainbow smelt density given expected target strengths (Rudstam et al. 2003).

In order to assign species and size composition to acoustic data, we used a technique described by Warner et al. (2009), with different approaches depending on the vertical position in the water column. For cells with depth < 40 m, midwater trawl and acoustic data were matched according to transect, depth layer (0-10, 10-20 m, etc., depending on headrope depth and upper depth of the acoustic cell), and by bottom depth. For acoustic cells without matching trawl data, we assigned the mean of each depth layer and bottom depth combination from the same transect. If acoustic data still had no matching trawl data, we assigned the mean of each depth layer and bottom depth combination within geographic strata. If acoustic data still had no matching trawl data, we used a lakewide mean for each depth layer. Mean mass of species/size groups at depths < 40 m were estimated using weight-length equations from midwater trawl data. In 2001, trawl data were only available for the north nearshore and north offshore strata. To provide an estimate of species composition and size for other strata, the mean of catch proportions and sizes from 2002-2003 were used. For depths ≥ 40 m, we assumed that acoustic targets were large bloater if mean TS was > -45 dB (TeWinkel and Fleischer 1999). Mean mass of bloater in these cells was estimated using the mass-TS equation of Fleischer et al. (1997). If mean TS was ≤ -45 dB, we assumed the fish were large rainbow smelt and estimated mean mass from mean length, predicted using a TS-length equation (Rudstam et al. 2003).

As recommended by the the Great Lakes acoustic SOP (Parker-Stetter et al. 2009; Rudstam et al. 2009), we used a number of techniques to assess or improve acoustic data quality. We used the $N_v$ index of Sawada et al. (1993) to determine if conditions in each acoustic analysis cell were suitable for estimation of *in situ* TS. We defined suitability as an $N_v$ value < 0.1 and assumed that mean TS in cells at or above 0.1 was biased. We replaced mean TS in these cells with mean TS from cells that were in the same depth layer and transect with $N_v$ < 0.1. We also estimated noise at 1 m using ambient noise from each transect using either passive data collection or echo integration of data below the bottom echo. To help reduce the influence of noise, we subtracted an estimate of noise which was estimated from ambient noise measurements for each transect. Additionally, we estimated the detection limit (depth) for the smallest targets we include in our analyses. Acoustic equipment specifications, software versions, single target detection parameters, noise levels, and detection limits can be found in Appendices 1 and 2.

Densities (fish/ha) of the different species were estimated as the product of total fish density and the proportion by number in the catch at that location. Total alewife, rainbow smelt, and bloater density was subdivided into size- or age class-specific density by multiplying total density for these species by the numeric proportions in each age or size group. Biomass (kg/ha) for the different groups was then estimated as the product of density in each size or group and size or age-specific mean mass as determined from fish lengths in trawls (except as described for depths ≥ 40 m).

Mean and relative standard error (RSE = (SE/mean) x 100) for density and biomass in the survey area were estimated using stratified cluster analysis methods featured in the statistical routine SAS PROC SURVEYMEANS (SAS Institute Inc. 2004). 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 ESDU in each stratum were weighted by dividing the stratum area (measured using GIS) by the number of ESDUs in the stratum.

## RESULTS

Alewife – Alewife density in 2012 (1,410 fish/ha, RSE = 15%) was five times that observed in 2011 and was similar to the long-term (1992-2011) mean of 1,770 fish/ha. This increase was primarily the result of higher density of age-0 alewife. Alewife biomass (4.9 kg/ha, RSE = 17%) in 2012 was 35% of the long-term mean of 14.2 kg/ha but was the fourth lowest in the time series. Age-0 alewife density (1,242 fish/ha, RSE = 15%, Figure 2), was similar to the long-term mean of 1,282 fish/ha. Age-1 or older (YAO) alewife biomass was highly variable in the 1990s but the highest values of the time series were in 1995 and 1996. The high biomass in 1996 was in large part the result of a very strong year class in 1995. Biomass of this age group was relatively constant from 2001-2007 (Figure 3), increased in 2008-2010, and then declined by 69% from 2010 to 2011. In 2012 biomass of the YAO group was 3.2 kg/ha (RSE = 20%), which consisted of fish from the 2007-2010 year-classes (Figure 4). Mean age of YAO increased from 1.3 years in 2011 to 2.1 years in 2012 (Figure 5). Estimated density of spawners (age-3 and older surveyed in 2012) was the second lowest in the time series. Acoustic and bottom trawl results both indicated that biomass of YAO alewife in 2012 was similar to that in 2011 and both surveys indicated that age-2 alewife (2010 year class) made up most of the population in both numbers and biomass (Bunnell et al. 2013). However, the acoustic estimate of YAO alewife biomass was more than twice the bottom trawl estimate.

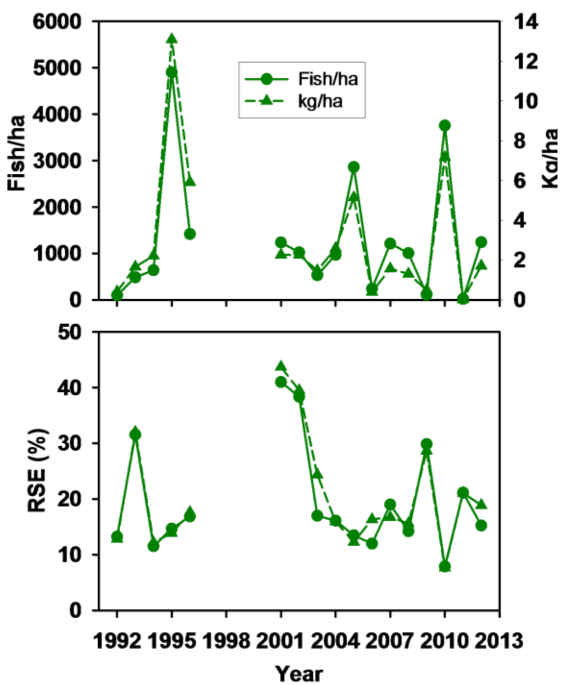


Figure 2. Acoustic estimates of age-0 alewife density and biomass in Lake Michigan, 1992-2012 (upper panel) shown with relative standard error of the estimates (RSE, lower panel).

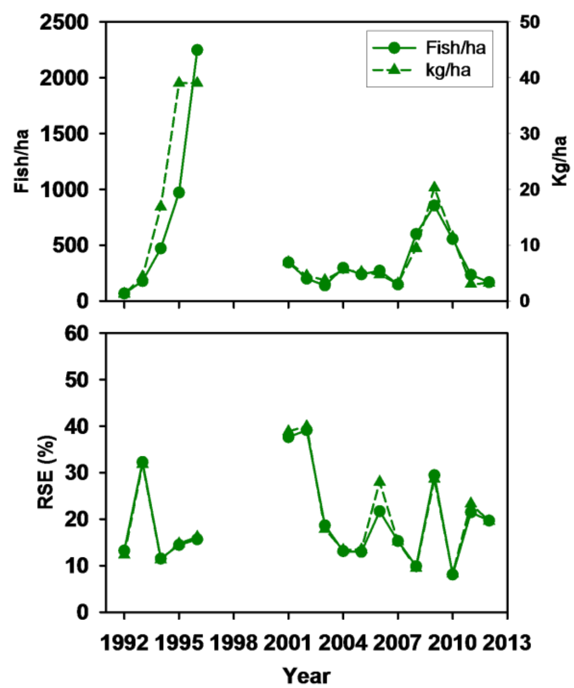


Figure 3. Acoustic estimates of age-1 or older alewife density in Lake Michigan, 1992-2012 (upper panel) shown with relative standard error of the estimates (RSE, lower panel).

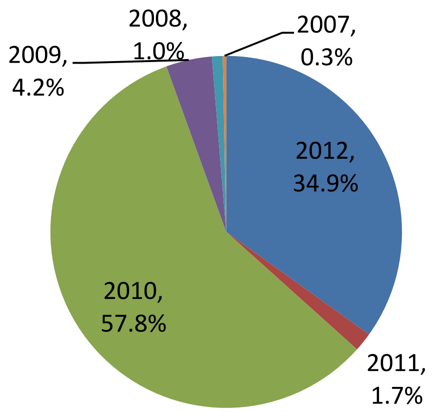


Figure 4. Percent contribution of alewife year-classes to alewife biomass during 2012. Labels show year class and percent of alewife biomass.

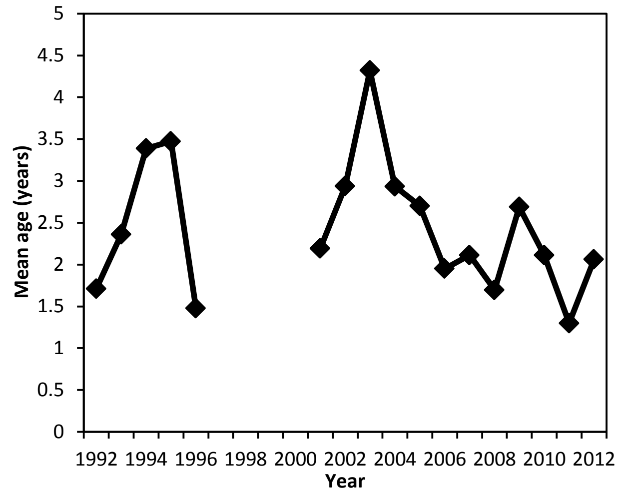


Figure 5. Mean age of YAO alewife in Lake Michigan in 1992-2012.

Rainbow smelt – Density of rainbow smelt generally increased from 2002-2008 (Figure 6), before declining to much lower levels in 2009-2012. However, biomass has been consistently low since 2007. Rainbow smelt density in 2012 (196 fish/ha, RSE = 25%) was the second lowest in the time series. Biomass of rainbow smelt (0.25 kg/ha, RSE = 19%) was 20% of the 2011 biomass and was only 4% of the long term mean. Rainbow smelt > 90 mm in length constituted roughly 60% of the population and 65% of biomass. Both acoustic and bottom trawl survey results showed biomass in 2012 was similar to 2011, but the acoustic biomass estimate was nearly five times the bottom trawl estimate (Bunnell et al. 2013). The decrease in biomass has been accompanied by an increase in RSE.

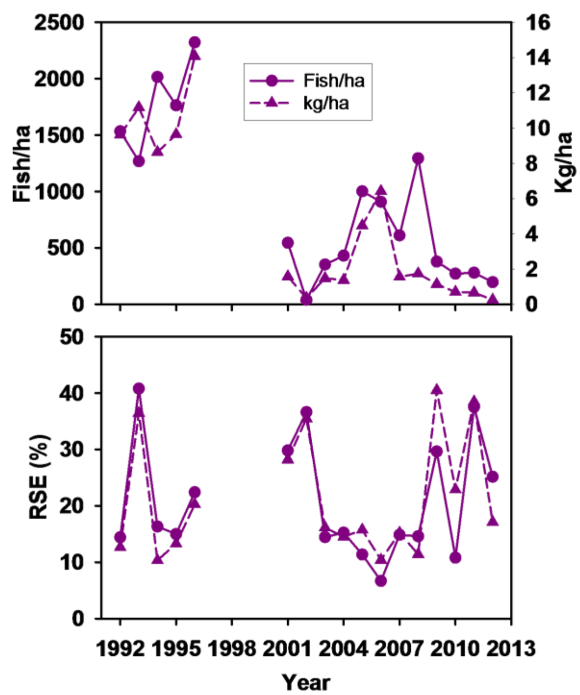


Figure 6. Acoustic estimates of rainbow smelt density and biomass in Lake Michigan in fall 1992-2012 (upper panel) shown with relative standard error of the estimates (RSE, lower panel).

Bloater – Bloater continue to be present at low densities relative to the 1990s. Mean density of all bloater in 2012 (232 fish/ha, RSE = 20%) was higher than in 2011, as was total bloater biomass (1.2 kg/ha, RSE = 12%). Small bloater showed an increasing trend from 2001-2009 (Figure 7), while large bloater showed no trend during this period (Figure 8). Acoustic results for small bloater were consistent with bottom trawl results, as density and biomass increased for this size group in both surveys. However, results were not consistent for larger bloater; the acoustic estimate of biomass nearly doubled from 2011-2012, while the bottom trawl biomass estimate in 2012 was only 10% of the 2011 estimate. Neither acoustic or bottom trawl estimates for large bloater show any evidence of increased abundance resulting from recruitment of fish hatched in the previous 10 years.

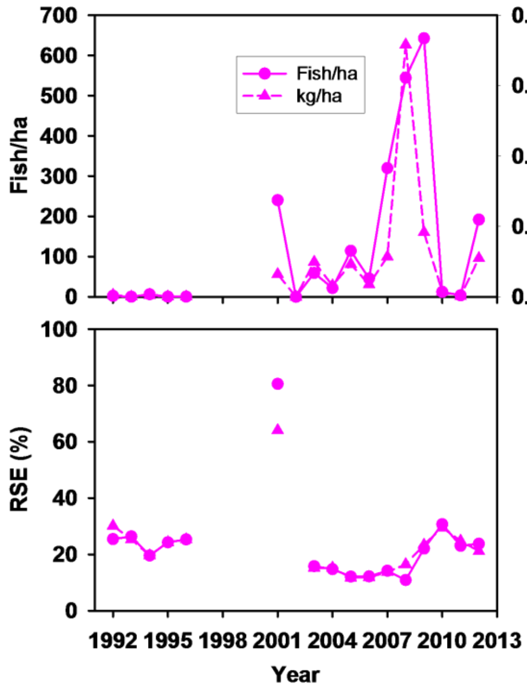


Figure 7. Acoustic estimates of small bloater density and biomass in Lake Michigan in fall 1992-2012 (upper panel) shown with relative standard error of the estimates (RSE, lower panel).

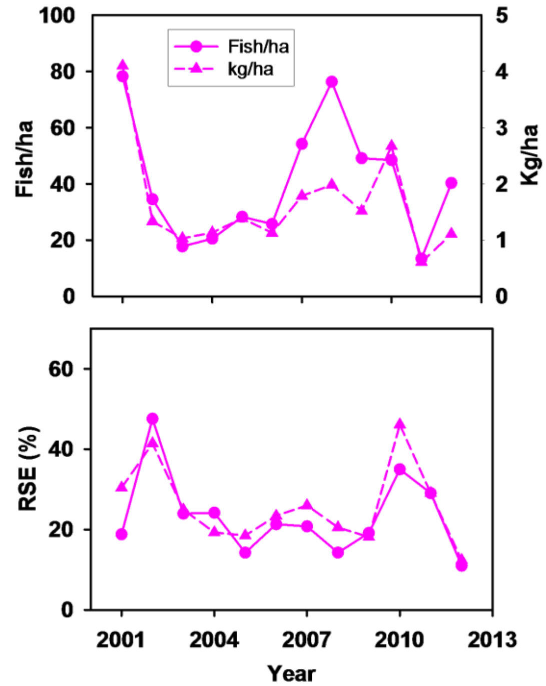


Figure 8. Acoustic estimates of large bloater density and biomass in Lake Michigan in fall 2001-2012 (upper panel) shown with relative standard error of the estimates (RSE, lower panel).

## DISCUSSION

The results of the 2012 Lake Michigan acoustic survey indicate continued variability in alewife biomass as well as persistently low biomass of rainbow smelt and bloater. Peak alewife biomass occurred in 1995 and 1996 (≈40 kg/ha), and the two highest values during 2001-2012 (2009-2010) were only half as high as in 1995-1996. Total prey fish biomass in 2012 was the second lowest ever observed (Figure 9).

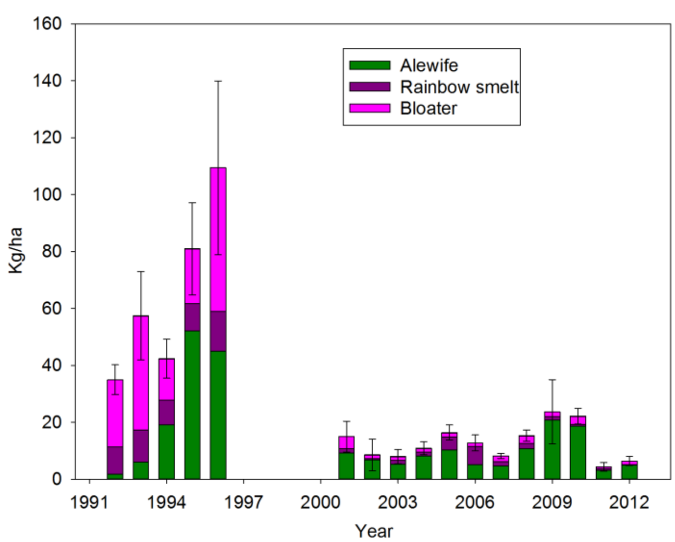


Figure 9. Acoustic estimates of total prey fish biomass in Lake Michigan, 1992-2012.

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 bottom (bottom 0.3-1 m) and the surface (0-3 m) are not sampled well or at all. The density of fish in these areas therefore is unknown. Air-water interface problems, technology limitations, as well as time limitations preclude the use of upward or side-looking transducers. If one assumes that fish available to a bottom trawl with ≈ 1 m fishing height at night are not available to acoustic sampling, it is doubtful that the bottom deadzone contributes much bias for alewife and rainbow smelt because of their pelagic distribution at night. 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. After examining these data we found 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 ≈ 6% of day estimates. Evidence suggests bloater tend to be more demersal; in Lake Superior, night acoustic/midwater trawl sampling may detect only 60% of bloater present (Yule et al. 2007). 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). Alewife and rainbow smelt (primarily age-0) may occupy the upper 3 m of the water column and any density calculation in this area results in underestimation of water column and mean lakewide density. Depending on season, in inland New York lakes and Lake Ontario, 37-64% of total alewife catch in gill nets can occur in the upper-most 3 m (D.M. Warner, unpublished data). However, 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). We also assumed that our midwater trawling provided accurate estimates of species and size composition. Based on the relationship between trawling effort and uncertainty in species proportions observed by Warner et al. (2012), this assumption was likely reasonable.

We made additional assumptions about acoustic data not described above. For example, we assumed that all targets below 40 m with mean TS > -45 dB were bloater. It is possible that this resulted in a slight underestimation of rainbow smelt density. We also assumed that conditions were suitable for use of *in situ* TS to estimate fish density, which could also lead to biased results if conditions are not suitable for measuring TS (Rudstam et al. 2009) and biased TS estimates are used. However, we identified areas where TS was biased and replaced these biased values with unbiased values from nearby areas in the same depth layer. Finally, 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 and detection limits for targets of interest (Appendix 2).

Prey fish biomass in Lake Michigan remains at levels much lower than in the 1990s, and the estimate of total lakewide biomass (31 kt) from acoustic sampling was the 2$^{nd}$ lowest in the time series. This is in contrast to 2008-2010, when biomass was relatively high (but still lower than in the 1990s). This recent decline, resulting primarily from decreased alewife biomass, demonstrates the dynamic nature of the pelagic fish community in Lake Michigan. The large difference in prey fish biomass in the 1990s and 2000s resulted primarily from the decrease in large bloater abundance, but alewife and rainbow smelt declined as well. Bloater densities showed an increasing trend 2001-2009, with most of the increase driven by increases in small bloater. A similar pattern has been observed in Lake Huron (Schaeffer et al. 2012), but only in Lake Huron has there been any evidence of increased abundance resulting from recruitment to larger sizes, as bottom trawl estimates of large bloater density have increased in recent years in Lake Huron but not in Lake Michigan (Madenjian et al. 2012; Schaeffer et al. 2012). Pelagic fish biomass was not evenly split among the species present in 2012 (Table 1), and limited recruitment of small bloater, along with the continued absence of other native species, suggests that little progress is being made toward meeting the Fish Community Objectives (FCO, Eshenroder et al. 1995) of maintaining a diverse planktivore community, particularly relative to historical diversity. Bloater and emerald shiner (*Notropis atherinoides*) were historically important species, but bloater currently exist at low biomass levels and emerald shiner have not been captured in Lake Michigan by GLSC surveys since 1962 (D.M. Warner, unpublished data). Similarly, kiyi (*Coregonus kiyi*) are absent from offshore regions of Lake Michigan, which is in stark contrast to Lake Superior, where Yule et al. (2013) found kiyi to be the most numerous species in 2011. As a result, large areas of Lake Michigan which were formerly occupied by fish are devoid of fish, and movement of energy and nutrients through diel vertical migration has essentially disappeared. In Lake Huron, collapse of the alewife population in 2003-2004 was followed by resurgence in emerald shiner abundance in 2005-2006 (Schaeffer et al. 2008) and by increased abundance of cisco [*Coregonus artedi*, (Warner et al. 2009)]. Given evidence from acoustic surveys from lakes Michigan and Huron as well as the evidence provided by Madenjian et al. (2008), it appears that emerald shiners are suppressed by all but the lowest levels of alewife abundance. In 2012 total pelagic fish biomass in Lake Michigan (6.4 kg/ha) was similar to that in Lake Huron in 2012 (6.3 kg/ha, Warner et al. 2013) as well as Lake Superior in 2011 (6.8 kg/ha, Yule et al. 2013). Prey biomass based on the acoustic survey data collected in 2012 (95% CI = 23 – 39 kt) was low relative to the FCO, which calls for biomass levels matched to primary production and predator demand (500-800 kt) and maintenance of a diverse planktivore community. With sculpin biomass from the bottom trawl survey (Bunnell et al. 2013) added to the acoustic biomass of other species, estimated lakewide biomass (33 kt) is still well below the recommended FCO range.

It is not clear what led to the drastic decline in bloater abundance from the 1980s to present. Madenjian et al. (2002) proposed that bloater recruitment and abundance are regulated by internal cycling, and Bunnell et al. (2006) found that during periods of low abundance and recruitment, the sex ratio of bloater is predominantly female, while during periods of high abundance and recruitment sex ratio is more balanced. Based on ages of bloater captured in the bottom trawl survey, relatively high levels of age-0 bloater in 2007-2009 (Figure 7) are reflected in age composition of YAO bloaters in recent years, as 71% of the larger bloater aged in 2009-2011 were hatched in 2007-2009, adding support to the belief that bloater become fully recruited to the bottom trawl by age-3 (Bunnell et al. 2006). Data from both acoustic and bottom trawl surveys suggest that recruitment has not been sufficient to offset mortality. We hypothesize that predation on small bloater by salmonines could be an important limit to recruitment at times (see Warner et al. 2008) as these small fish are found in the same location as alewife and at times can be important to some predators (Elliott 1993; Rybicki and Clapp 1996; Warner et al. 2008). Both Lake Michigan surveys suggest that recruitment in Lake Michigan is much more limited than in Lake Huron, where high densities of small bloater in 2007-2008 preceded increases in the abundance of larger bloater (Schaeffer et al. 2012).

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Table 1. Biomass, 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 2012.

| Species | Biomass (kg/ha) | RSE (%) | 95% CI |
|---|---|---|---|
| Total alewife | 4.9 | 17.4 | (3.4, 6.4) |
| Age-0 alewife | 1.7 | 18.9 | (1.2, 2.3) |
| YAO alewife | 3.2 | 19.5 | (4.3, 19.5) |
| Rainbow smelt | 0.3 | 17.1 | (0.2, 0.3) |
| Bloater | 1.2 | 11.8 | (1.0, 1.5) |
| Total | 6.4 | 14.8 | (4.8, 8.0) |

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Appendix 1. Single target detection parameters used in acoustic data analyses in 1992-1996 and 2012.

| Parameter | Dual beam 1992-1996 | Dual beam 2001-2005 | Split[1] |
|---|---|---|---|
| TS threshold (dB) | -60 | -77 | -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 |

[1]Although a lower threshold was used in 2001-2012, only targets ≥-60 dB were included as in analyses of the 1990s data.

Appendix 2. Noise levels (mean and range of Sv and TS at 1 m), detection limits, and acoustic equipment specifications in 2012 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) | 8.2º split beam | 6.9º split beam | 6.49 º x 6.53 º split beam |
| Frequency (kHz) | 120 | 123 | 120 |
| Pulse length (ms) | 0.4 | 0.4 | 0.256 |
| Mean of Sv noise at 1 m (dB) | -127 | -117 | -120 |
| Mean of TS noise at 1 m (dB) | -154 | -144 | -147 |
| Two-way equivalent beam angle (dB) | -19.34 | -20 | -20.1 |
| Detection limit (m) for -60 dB target[1] | ≥90 | ≥55 | ≥63 |

[1] Assuming 15 dB signal-to-noise ratio.