Status and Trends of Pelagic and Benthic Prey Fish Populations in Lake Michigan, 2021[1,2]

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[1] The data associated with this report are currently under review and will be publicly available in 2022 at the following location: https://doi.org/10.5066/P9XVOLR1. Previous versions of the data may be accessed at U.S. Geological Survey, Great Lakes Science Center, 2019, Great Lakes Research Vessel Operations 1958-2018. (ver. 3.0, April 2019): U.S. Geological Survey data release, https://doi.org/10.5066/F75M63X0. Please direct questions to our Data Management Librarian, Sofia Dabrowski, at sdabrowski@usgs.gov.

[2] 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).

Abstract

Lake wide acoustic (AC) and bottom trawl (BT) surveys are conducted annually to generate indices of pelagic and benthic prey fish densities in Lake Michigan. The BT survey has been conducted each fall since 1973 using 12-m trawls at depths ranging from 9 to 110 m and includes 70 fixed locations distributed across seven transects; this survey estimates densities of seven prey fish species [i.e., alewife (*Alosa pseudoharengus*), bloater (*Coregonus hoyi*), rainbow smelt (*Osmerus mordax*), deepwater sculpin (*Myoxocephalus thompsonii*), slimy sculpin (*Cottus cognatus*), round goby (*Neogobius melanostomus*), ninespine stickleback (*Pungitius pungitius*)] as well as for age-0 yellow perch (*Perca flavescens*) and large (> 350 mm) burbot (*Lota lota*). The AC survey has been conducted each late summer/early fall since 2004, and the 2021 survey consisted of 25 transects [507 km total (315 miles)] covering bottom depths ranging from 15 to 235 m and 42 midwater trawl tows covering bottom depths ranging 13 to 215 m; this survey estimates densities of three prey fish species (i.e., alewife, bloater, and rainbow smelt). The data generated from these surveys are used to estimate various population parameters that are, in turn, used by state and tribal agencies in managing Lake Michigan fish stocks.

For the BT survey, total biomass density of prey fish equaled only 2.4 kg/ha, the 5th lowest estimate of the time series and well below the long-term average total biomass of 34.28 kg/ha. For the AC survey, total biomass density of prey fish equaled 6.61 kg/ha, 50% higher than the long-term average total biomass of 4.28 kg/ha.

The AC survey reported bloater to be the dominant species (by biomass) among prey fishes, while the BT survey reported co-dominance of alewife, bloater, and round goby. Mean biomass of yearling and older (YAO) alewives in 2021 was 1.71 kg/ha in the AC survey and 0.504 kg/ha in the BT survey. Catchability of YAO alewives continues to be substantially lower for the BT survey since 2014.

Comparing the acoustic estimate to previous years, YAO alewife biomass was 10% higher than the 2019 estimate and less than the average from 2004-2019. Numeric density of age-0 alewife from the AC survey was 352 fish/ha in 2021, which is 71% of the long-term mean of 499 fish/ha. The alewife age distribution remained truncated, with age-0 fish and age-1 fish dominating the population. Biomass density of YAO bloater was 3.7 kg/ha in the AC survey and 0.43 kg/ha in the BT survey- each at least an order of magnitude lower than what was estimated by the BT survey between 1981 and 1998. Numeric density of age-0 bloater was the highest ever measured for the AC survey at 1,037 fish/ha while for the BT survey, it was 20 fish/ha. Biomass density of YAO rainbow smelt was 0.13 kg/ha in the AC survey and 0.005 kg/ha in the BT survey, continuing the trend of low rainbow smelt biomass that has been observed since 2001. Numeric density of age-0 rainbow smelt was 84 fish/ha in the AC survey and 1.9 fish/ha in the BT survey, indicating a weak year-class. All four prey fish species sampled only by the BT survey indicated below average biomass densities. Deepwater sculpin was estimated at 0.45 kg/ha, which makes 11 of the past 12 years when biomass was <1 kg/ha. Slimy sculpin was estimated at 0.05 kg/ha, the sixth lowest density ever measured. Round goby was estimated at 0.63 kg/ha, which was below the average biomass of 0.84 kg/ha since 2008. Ninespine stickleback density was < 1 fish/ha. Burbot biomass remained near record low levels, and only three age-0 yellow perch were caught in all trawls, indicating a weak yellow perch year-class in 2021.

Introduction

Annual evaluation of prey fish dynamics is critical to understand changes to the Lake Michigan food web during the last 40 years (e.g., Madenjian et al. 2002, 2015) and continued restructuring due to exotic species, changing nutrient inputs, changing climate, and management levers including fishing mortality and fish stocking. Nonindigenous alewives (*Alosa pseudoharengus*) are a key prey fish in the Lake Michigan food web because they serve as the primary prey for Lake Michigan salmonines (Elliott 1993; Rybicki and Clapp 1996; Warner et al. 2008; Jacobs et al. 2013). Alewife also help structure the food web because they are predators of native larval fish [e.g., lake trout (*Salvelinus namaycush*), emerald shiner (*Notropis atherinoides*), Madenjian et al. (2008)] and contribute to recruitment bottlenecks. Bloater (*Coregonus hoyi*, commonly known as "chub") is a native coregonine prey fish that dominated the community biomass in the 1980s and 1990s. Nonindigenous rainbow smelt (*Osmerus mordax*) is another abundant planktivorous prey fish species since its introduction into Lake Michigan in the early 20th century. Alewife, bloater, and rainbow smelt supported commercial fisheries in the 1980s, but these fisheries have either been closed (alewife) or now have limited participation (bloater, smelt) owing to low fish densities in recent decades. Key native benthic species include deepwater and slimy sculpin (*Myoxocephalus thompsonii* and *Cottus cognatus*, respectively). Since 2004, nonindigenous benthic round goby (*Neogobius melanostomus*) has become abundant in Lake Michigan and another key player in the food web given their importance as prey for lake trout, brown trout (*Salmo trutta*), and smallmouth bass (*Micropterus dolomieu*), but also for their ability to consume nonindigenous dreissenid mussels and “return” that energy back into the food web. At the same time, round goby can negatively affect native fishes by consuming their eggs (e.g., Chotkowski and Marsden 1999; Steinhart et al. 2004).

Lakewide monitoring of prey fish began in 1973 with a bottom trawl (BT) survey that samples the bottom ~1.5 m of water over soft or sandy substrates during the daytime. Although many adult prey fishes occupy the bottom of the lake during the day, presumably to avoid predation, scientists recognized that the survey provided a relative (not absolute) density index because some proportion of adult alewife, bloater, and rainbow smelt remain pelagic during the day. In addition, age-0 alewives are mostly above the thermocline, rather than below, during the day (Brandt 1980). To provide a complementary relative index of prey fish abundance, Lake Michigan scientists began conducting nighttime AC (acoustic) survey in the early 1990s, and an interagency, lake wide, annual survey was formalized in 2004. Together, these two annual surveys have enabled the development of a stock assessment model for alewives (Tsehaye et al. 2014) that is used to inform annual agency stocking decisions of Chinook salmon, lake trout, steelhead (*Oncorhynchus mykiss*), brown trout, and coho salmon (*Oncorhynchus kisutch*) in Lake Michigan; each survey provides unique data. The BT survey provides abundance indices for benthic species such as deepwater sculpin, slimy sculpin, round goby, ninespine stickleback (*Pungitius pungitius*), and even age-0 yellow perch (*Perca flavescens*). The BT survey has also traditionally indexed burbot (*Lota lota*). In turn, the AC survey provides abundance indices for age-0 alewife, which is an early indicator of alewife year-class strength (Warner et al. 2008). Given that cisco (*Coregonus artedi*) are also resurging in Lake Michigan (Claramunt et al. 2019), it is also conceivable—based on Lake

Superior sampling—that a spring BT survey could index yearlings cisco (see Yule et al. 2008) and the AC survey could index adult ciscoes (see Stockwell et al. 2006).

Since the 2019 field season, we have combined the results of both surveys in one report, which is consistent with one synthetic oral presentation that has been delivered to the Lake Michigan Technical Committee for the past several years. Our goal is to provide a synthetic and relatively concise report that emphasizes the complementarity of the two surveys. For methodological details, we invite readers to consult the previous separate survey reports published in 2019 and earlier (see Bunnell et al. 2019a; Warner et al. 2019). We provide a high-level overview of both methods below.

Methods

For the BT survey, the basic unit of sampling is a 10-min tow using a "Yankee" trawl (12-m headrope, 25- to 45-mm bar mesh in net body, 6.4-mm bar mesh in cod end) dragged along depth contours at 9 m (5 fathom) depth increments. At most survey transects, towing depths range from 9 or 18 m to 110 m. Depths shallower than 9 m cannot be sampled at most sites because the draft of the research vessel (i.e., vertical distance between the waterline and the bottom of the hull) prevents safe navigation while trawling. In 2013 we began adding tows at deeper depths (i.e., 128 m) to assess the extent to which some species (e.g., deepwater sculpins, bloater) have migrated outside of our traditional survey range. In 2021, we also added three additional deepwater tows at 146 (Frankfort and Sturgeon Bay) and 165 m (Ludington). Since 2016, we have directly estimated time on bottom for each tow with a head-rope depth sensor that provides

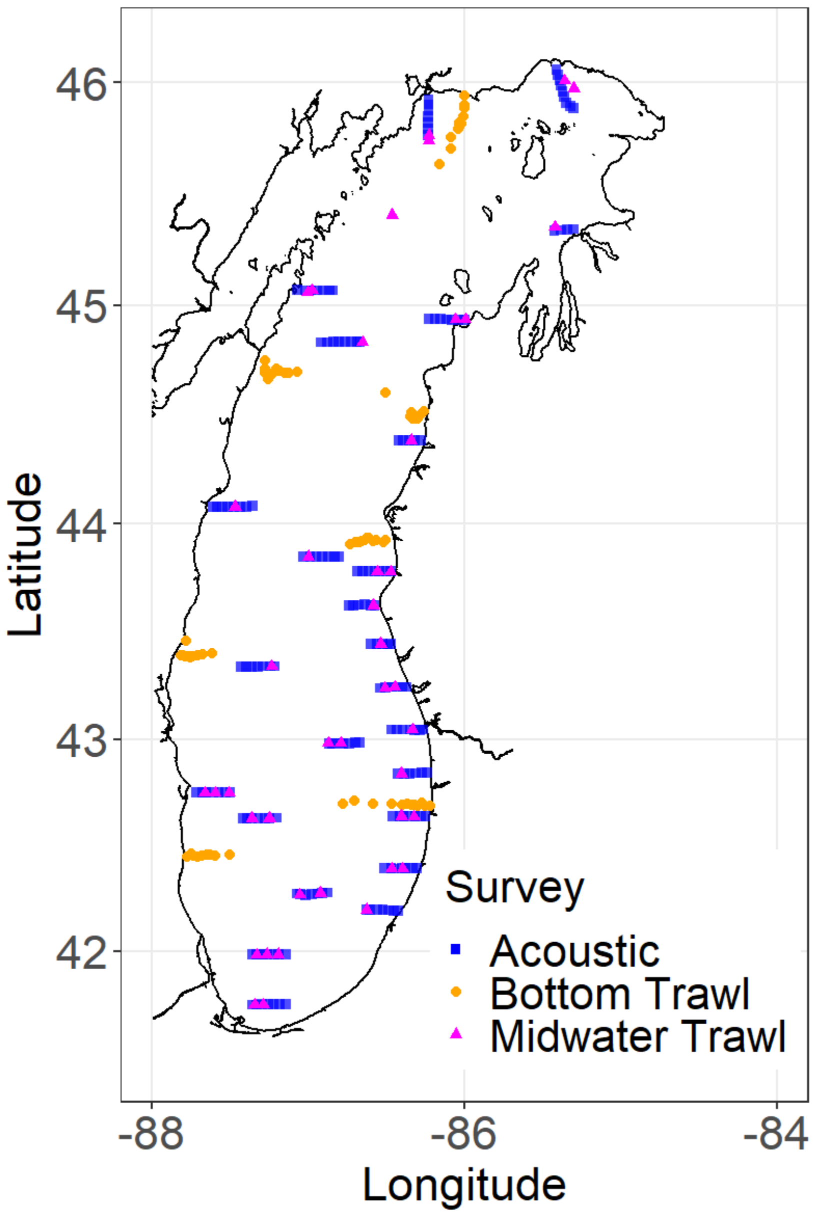

Figure 1. Map of sampling locations for the Lake Michigan bottom trawl and acoustic surveys in 2021. Blue squares represent acoustic transects, orange circles represent bottom trawl samples, and magenta triangles represent midwater trawl locations..

a more accurate estimate of area (ha) swept. In 2021, we transitioned to a new head-rope depth sensor that allows for live-monitoring of net depth and position. During each survey, seven transects are sampled offshore of Manistique, Frankfort, Ludington, and Saugatuck, Michigan (MI); Waukegan, Illinois (IL); and Port Washington and Sturgeon Bay, Wisconsin (WI) (see Fig. 1). However, in 2020 COVID-19 pandemic severely limited research efforts; while the AC survey was not conducted, three of seven standard BT transects (Saugatuck, Waukegan and Port Washington) were completed during an abbreviated survey. The 2021 sample season represented a return to normalcy and each survey was completed in its entirety.

We estimate both numeric (fish per hectare [fish/ha]) and biomass (kg/ha) density with lakewide means and variances calculated using a stratified design (BT) and a stratified cluster design (AC).

For the AC survey, split beam transducers with a nominal frequency of 120 kHz (range 120-129) are used to estimate numeric fish density along each of the 25 transects sampled in 2021 (see Fig. 1). While sampling those transects, midwater trawls are deployed to sample fish, enabling estimation of species and size composition of fish for the numeric fish density data. Acoustic estimates for the upper part of the water column (<40 m) were derived using the NearD method (Yule et al. 2013). Briefly, numeric fish density estimates were generated using the function estimateLake()in The EchoNet2Fish package for R (Adams 2018), with consideration of the five geographic strata (north nearshore, north offshore, south nearshore, south offshore, west nearshore, see Warner et al. 2019) and vertical depth layer. This function calculates numeric fish density estimates and apportions them to user-defined fish groups using the midwater catch data. Fish density in the <40 m layer was apportioned to fish categories (age or size groups within species) using the catch from the nearest trawl (Euclidean distance). Fish density in the >40 m layer was apportioned to fish categories (age or size groups within species) using acoustic target strength (TS) and prior information about the composition of midwater trawl catch in this layer (Adams et al. 2006; Warner et al. 2012). For additional details regarding assignment assumptions in this deep layer see Warner et al. (2019). Lake wide average numeric and biomass density is estimated using the stratClust() function from Adams (2018) which calculates the population mean for a single stage stratified cluster estimator with known stratum sizes.

Given the importance of the alewife age distribution for the stock assessment model, sagittal otoliths were removed from alewives in both surveys. Otoliths were mounted and the number of annual rings was read independently up to three times by two readers. If consensus on the number of annual rings could not be reached, the otolith age was determined to be unknown. In 2021, ages from 326 otoliths were successfully estimated from alewife sampled in the BT survey and ages from 256 otoliths were successfully estimated from alewife sampled in the AC survey. An age-length key was derived for each survey. The age-length key for AC included fish from both the AC and BT surveys, while the age-length key for the BT survey included only fish caught by bottom trawling. By convention, we classified alewife, bloater, rainbow smelt, and yellow perch as either age-0 or yearling and older (YAO) based on total length (TL) cutoffs (where YAO includes the noted size): alewife= 100 mm, bloater = 120 mm, rainbow smelt = 90 mm, yellow perch = 100 mm. In the case of alewife from the acoustic survey, we used actual age to identify age-0 fish.

Results

Alewife

Biomass density of YAO alewife in 2021 was estimated as 1.7 kg/ha in the AC survey and only 0.5 kg/ha in the BT survey (Fig. 2a). Between 2004 and 2013, the standard error (SE) of the means for the two surveys overlapped each year except 2005 (BT higher) and 2008 (AC higher). But from 2014-2019, the SE of the means never overlapped and the mean biomass estimated from the AC survey was always at least an order of magnitude higher than that of the BT survey. Standard errors of the means again did not overlap between the two surveys in 2021, with the AC mean biomass 3.4 times that of the BT.

Assuming the AC survey more accurately indexes YAO alewife biomass since 2014, alewife biomass estimated from the AC survey during the last five years (averaging 2.3 kg/ha) is still markedly lower than the mean biomass estimated by the BT survey in the 1970s (16.1 kg/ha), 1980s (6.1 kg/ha), and 1990s (6.0 kg/ha). For the AC time series, the 2021 estimate is 9% higher (0.14 kg/ha) than what was measured in 2019 (the last year the survey was conducted) but was 0.47 kg/ha less than the mean biomass from 2004-2019.

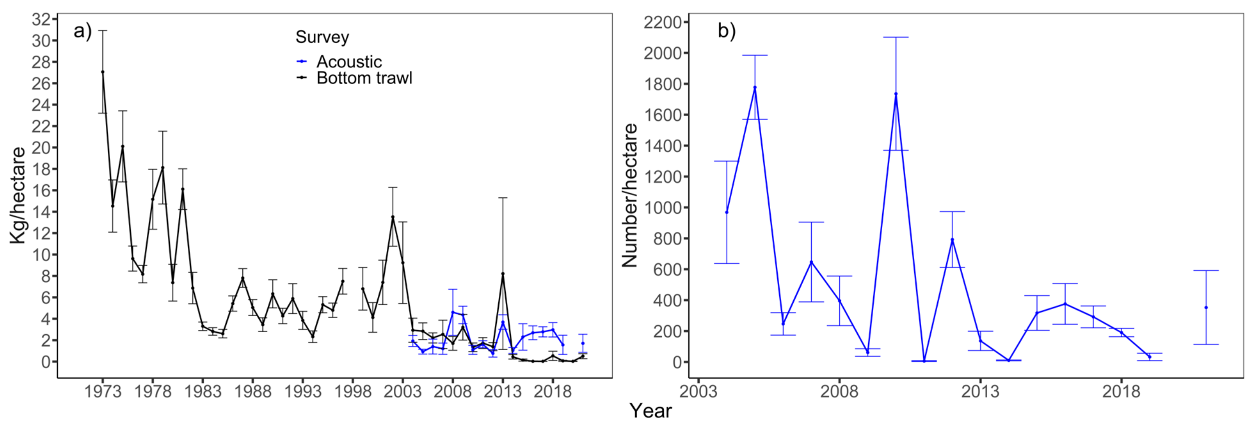

Figure 2. Density of yearling and older (YAO) alewives as biomass density (a) and of age-0 alewives as numeric density (b) in Lake Michigan, 1973-2021. Error bars in both panels are +/- standard error.

Numeric density of age-0 alewives estimated by the AC survey was 352 fish/ha in 2021 (Fig. 2b), the strongest year-class indexed since 2016. However, the strongest year-classes indexed by the AC survey occurred in 2005, 2010, and 2012, and the slightly below average year-class in 2021 follows the pattern of average or weak-year classes measured since 2013.

YAO alewife achieved the highest densities in southwestern Lake Michigan, but moderately high densities were also observed in the central basin on the eastern and western shores (Fig. 3a, left panel). Age-0 alewife were largely concentrated in the southern half of the lake, with the highest densities consistently along the eastern shoreline (Fig. 3b, right panel). Age-0 alewife in the AC survey were largely absent from northern Lake Michigan.

Age distribution of alewife was dominated by age-0 and age-1 fish (Fig. 4). Age truncation in the alewife population continued through 2021, as the maximum age was six (only two fish). Prior to 2010, age-7 or older alewives were captured routinely, while none have been captured since 2009. Reduced longevity is likely due to increased predation pressure. An alternative hypothesis

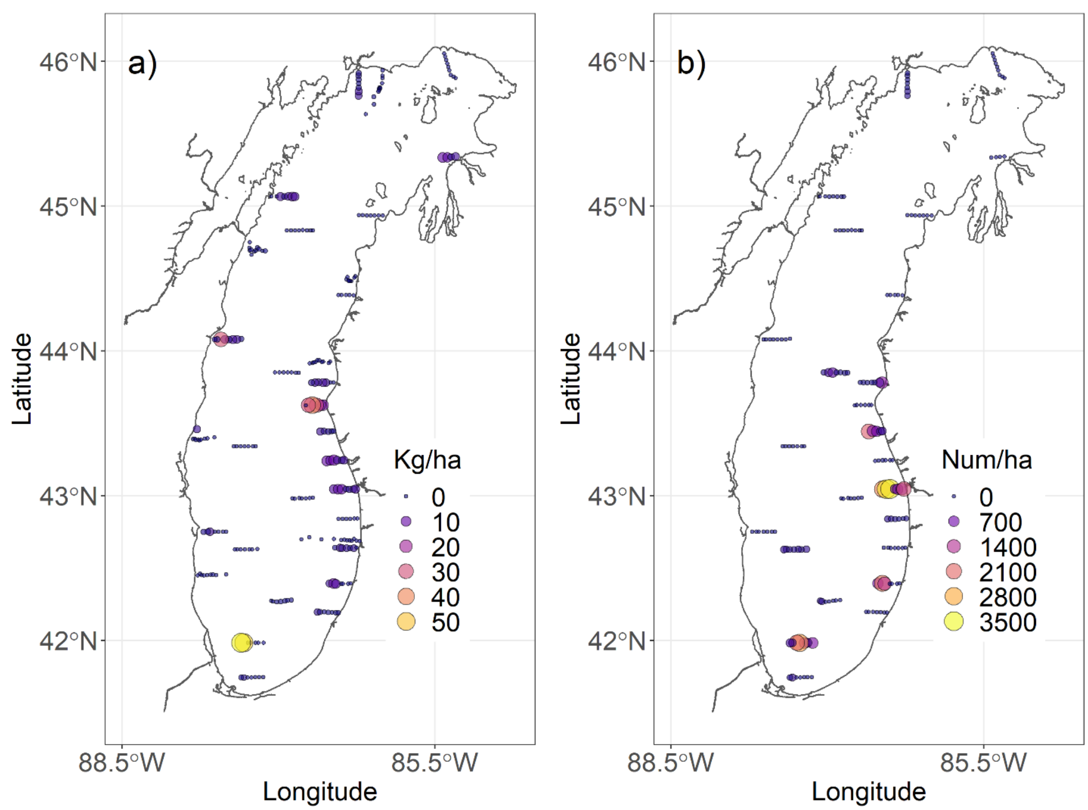

Figure 3. Map of biomass density of alewife ≥ age-1 (a) and numeric density of age-0 alewife (b) observed during the Lake Michigan acoustic survey and bottom trawl surveys, 2021.

of reduced survival owing to starvation as juveniles and adults is not supported given that their energetic density is relatively unchanged between 2002-2004 and 2015 (Bunnell et al. 2019b) and predicted weight of a 175-mm alewife has increased since 1996 (Bunnell et al. 2019a). Lower levels of alewife biomass in the 2000s relative to the 1990s and earlier are attributable primarily to high levels of consumption by salmonines (Madenjian et al. 2002, 2005a; Tsehaye et al. 2014), despite declines in Chinook salmon stocking in 2006, 2013, and 2017-2018. Factors that have maintained high predation pressure include a relatively high abundance (i.e., at least 50%) of wild Chinook salmon in Lake Michigan (Williams 2012; Tsehaye et al. 2014), increased migration of Chinook salmon from Lake Huron in search of alewives (Clark et al. 2017), increased importance

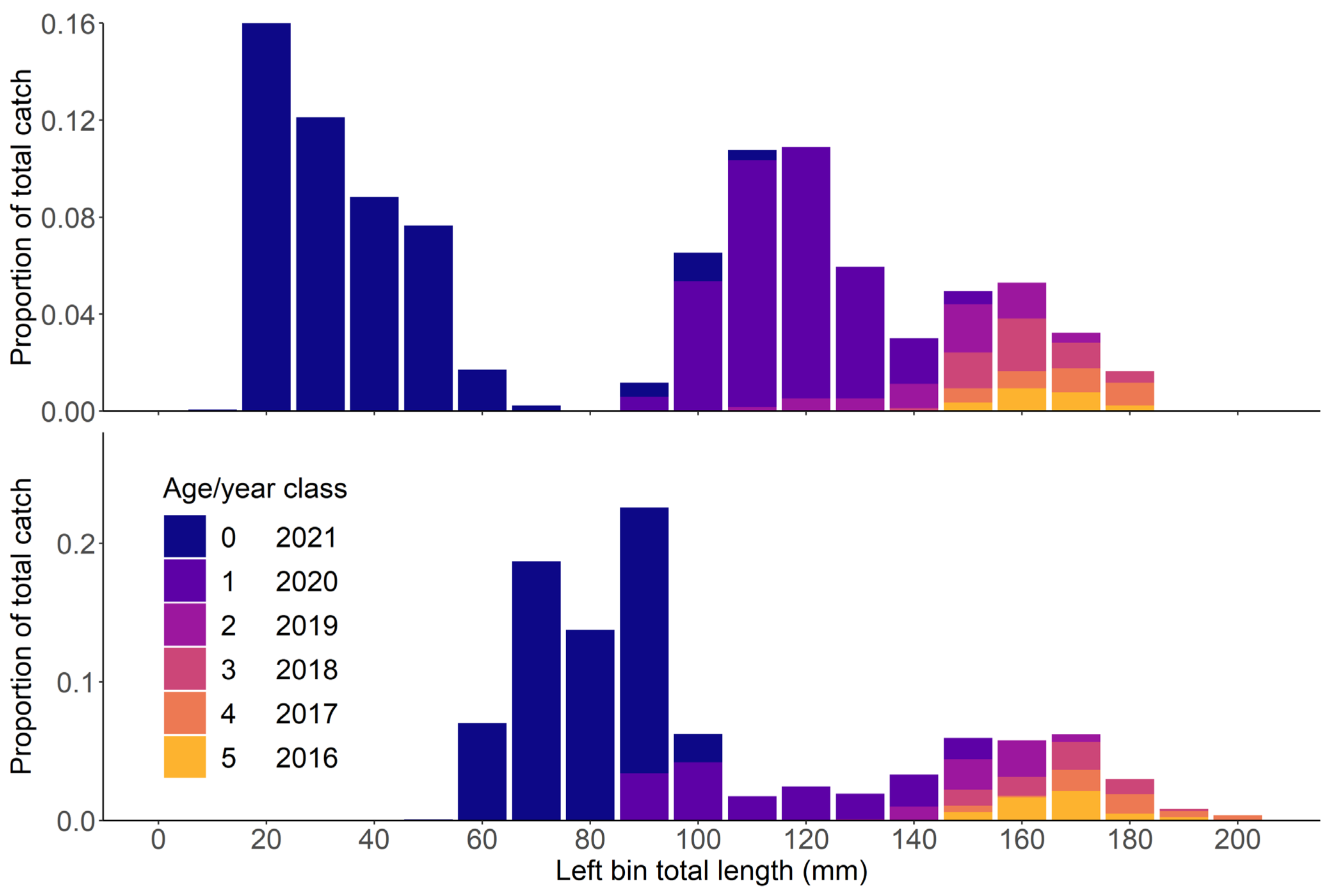

Figure 4. Age-at-length composition of Lake Michigan alewife, as indexed by the acoustic (upper panel) and bottom trawl (lower panel) surveys in 2021.

of alewives in the diet of Chinook salmon in Lake Michigan (Jacobs et al. 2013), a decrease in the energy density of adult alewives between 1979 and 2004 (Madenjian et al. 2006), and potential increases in consumption by a growing lake trout population (FWS/GLFC 2017; Lake Michigan LTWG 2019). Beyond predation, numbers of alewife may be reduced by declines in the number of spawning adults and long-term declines in productivity that could reduce fecundity and larval growth rates (see Bunnell et al. 2018; Eppehimer et al. 2019).

Bloater

Biomass density of YAO bloater in 2021 was estimated as 3.7 kg/ha in the AC survey and 0.43 kg/ha in the BT survey (Fig. 5a). Between 2004 and 2019, the SE of the means for the two surveys overlapped in only 2 years: 2015 and 2018. From 2004-2011 and 2017, the mean from the BT survey was higher. Alternatively, the mean from the AC survey has tended to be higher in more recent years: 2012-2014, 2016, 2019, and 2021. Regardless, the maximum biomass density measured from any survey from the 2004-2019 period was 7.26 kg/ha, which is an order of magnitude lower than the biomass measured in every year between 1981 and 1998.

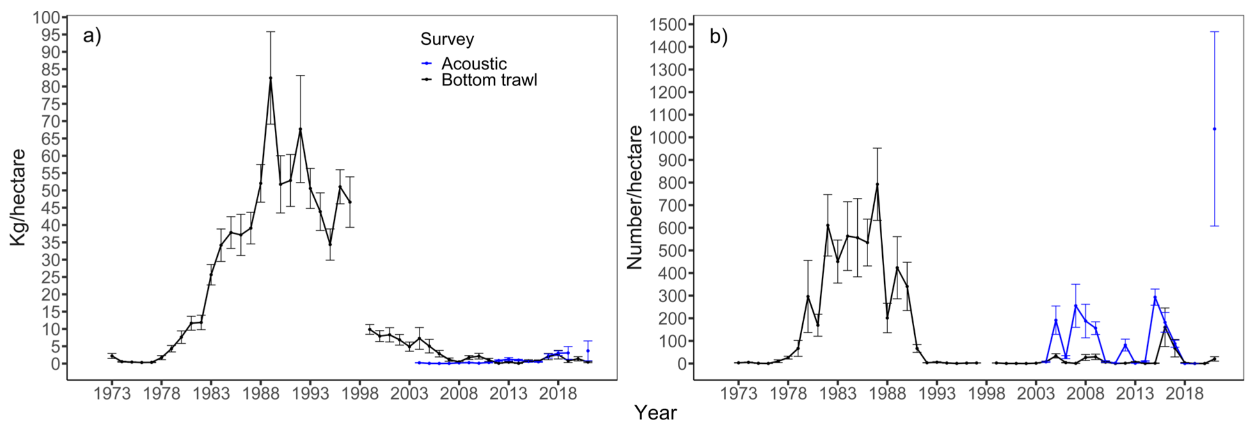

Figure 5. Density of yearling and older (YAO) bloater as biomass density (a) and of age-0 bloater as numeric density b) in Lake Michigan, 1973-2021. Error bars in both panels are +/- standard error.

Numeric density of age-0 bloater for the AC survey went from the lowest ever measured in 2019 (0 fish/ha) to the highest observed in 2021 (1037 fish/ha, Fig. 5b). A similar large increase was observed in the BT, with density in 2021 (20 fish/ha) being three orders of magnitude greater than in 2020 (0.02 fish/ha). Based on the BT survey, the buildup of adult biomass during the 1980s and 1990s was due to 11 consecutive years of age-0 bloater density > 100 fish/ha from 1980-1990. Following 13 years of weak production (i.e., <10 fish/ha) from 1992-2004, six year-classes with more than 100 age-0 bloater/ha were detected by at least one of the surveys between 2005 and 2016. But 2018 and 2019 revealed two consecutive year-classes with near record lows of age-0 bloater production.

The exact mechanisms underlying the apparently poor bloater recruitment from 1992-2004 period, and the resultant low YAO biomass remain unknown. Of the mechanisms that have been recently evaluated, reductions in fecundity associated with poorer condition (Bunnell and Madenjian 2009) and egg predation by slimy and deepwater sculpins (Bunnell et al. 2014) may be contributing to the reduced bloater recruitment, but neither one is the primary regulating factor.

YAO bloater attained the highest densities along the eastern shoreline (Fig. 6a, left panel), and at sites farther from shore as would be expected. Age-0 bloater were primarily observed in the southern half of the lake (Fig. 6b, right panel).

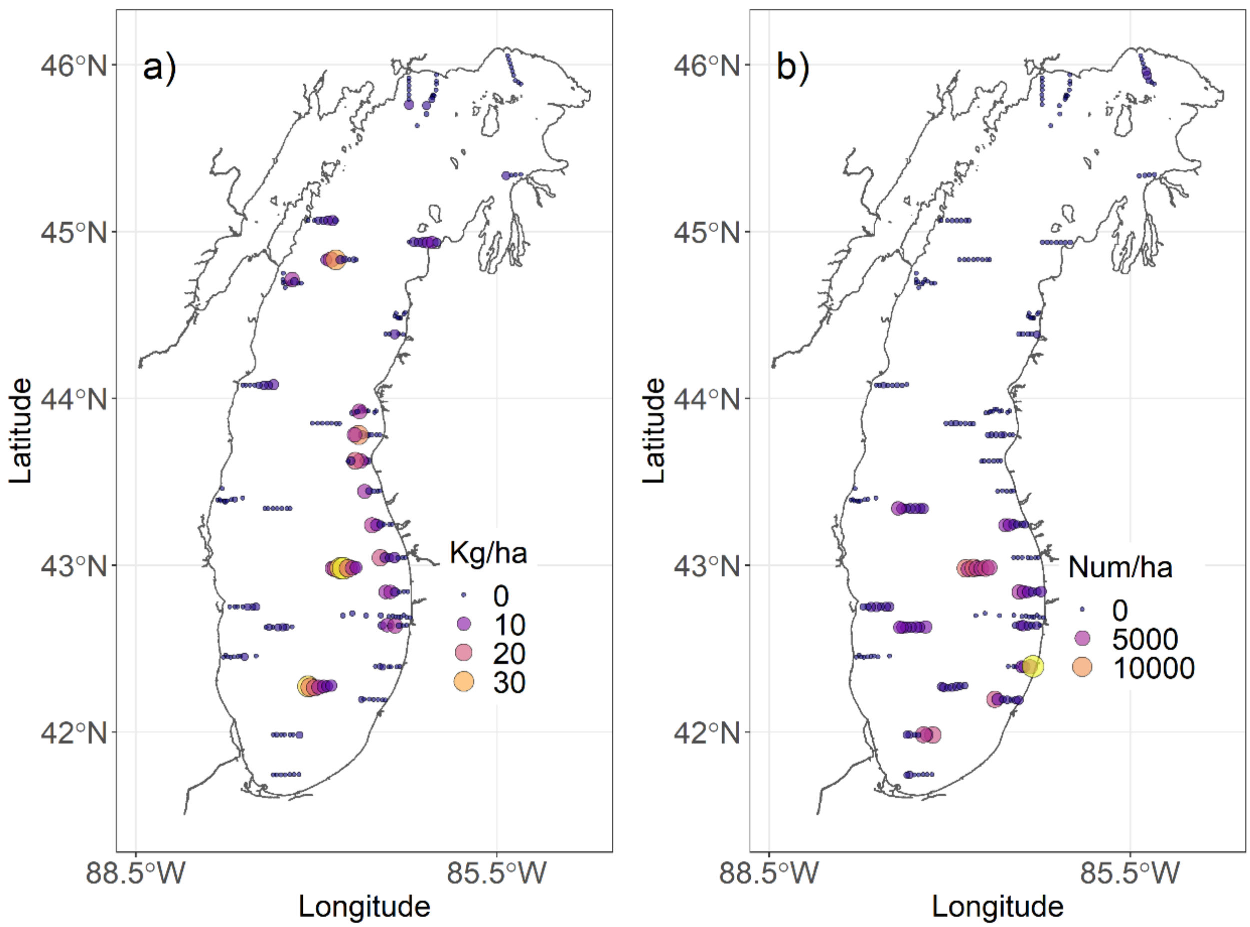

Figure 6. Map of biomass density of bloater ≥ age-1 (a) and of numeric density of age-0 bloater (b) observed during the Lake Michigan acoustic survey and bottom trawl surveys, 2021.

Rainbow smelt

Biomass density of YAO rainbow smelt estimated by the AC survey in 2021 was 0.13 kg/ha and 0.005 kg/ha in the BT survey (Fig. 7a). Survey estimates have been similar in 12 of the previous 16 years as the SE of the means for the two surveys overlapped. Biomass density of YAO rainbow smelt has been <2 kg/ha since 1994, following the 1973-1993 era when rainbow smelt density averaged 3.71 kg/ha.

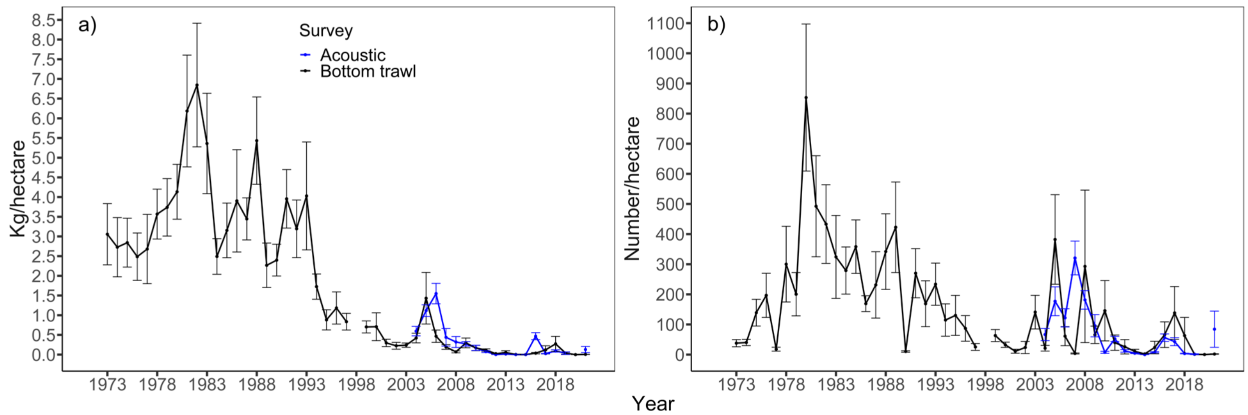

Figure 7. Density of yearling and older (YAO) rainbow smelt as biomass density (a) and of age-0 rainbow smelt (b) as numeric density (right panel) in Lake Michigan, 1973-2021. Error bars in both panels are +/- standard error.

Numeric density of age-0 rainbow smelt estimated by the AC survey in 2021 was 84 fish/ha, whereas it was only 1.9 fish/ha by the BT survey (Fig. 7b). As indexed by the AC survey, rainbow smelt in 2021 produced the strongest year-class since 2009.

YAO rainbow smelt attained the highest densities near the Upper Peninsula of Michigan (Fig. 8a, left panel). Age-0 rainbow smelt were more widespread, with highest density observed near Two Rivers, WI (Fig. 8b, right panel).

Causes for the long-term decline in rainbow smelt biomass since 1993 remain unclear. Consumption of rainbow smelt by salmonines was higher in the mid-1980s than during the 1990s (Madenjian et al. 2002), yet rainbow smelt abundance remained high. Results from a recent analysis 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 time series analysis through 2012 suggested that the production of age-0 fish relative to the number of spawners had actually increased since 2000 (relative to 1982-1999), yet those age-0 fish do not appear to be surviving to to adulthood (Feiner et al. 2015).

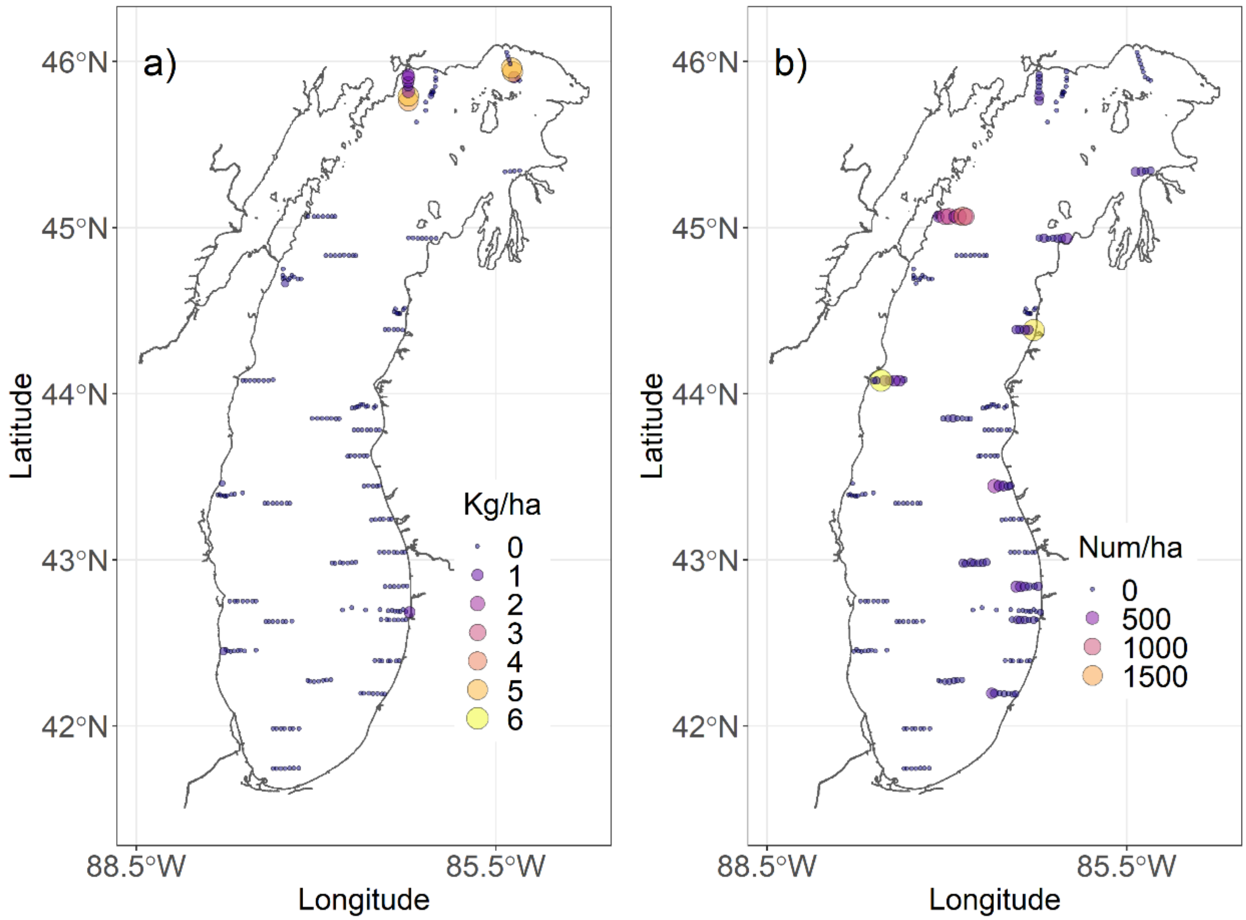

Figure 8. Map of biomass density of a) rainbow smelt ≥ age-1 and b) numeric density of age-0 rainbow smelt observed during the Lake Michigan acoustic survey and bottom trawl surveys, 2021.

Slimy sculpin

Biomass density of slimy sculpin measured by the BT in 2021 was only 0.05 kg/ha, the fifth lowest density measured in the 49-year time series (Fig. 9a). In 2013, slimy sculpin biomass density declined below 0.25 kg/ha and has not rebounded. Previous analyses have revealed that slimy sculpin abundance is regulated, at least in part, by predation from juvenile lake trout (Madenjian et al. 2005b). In fact, slimy sculpin biomass began declining in 2010, which coincides 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 2017; Lake Michigan LTWG 2019). When the

128-m tows are analyzed, slimy sculpin still occur in about 50% of them, but their densities are nearly an order of magnitude lower than what is estimated at 73, 82, 91, and 110 m sites. Hence, we do not believe the decline in slimy sculpins is an artifact of only sampling to a depth of 110 m for our standard tows.

Deepwater Sculpin

Biomass density of deepwater sculpin in 2021 estimated by the BT survey was 0.45 kg/ha, which makes 11 of the past 12 years when biomass was <1 kg/ha (Fig. 9b). Deepwater sculpin remain at relatively low levels since 2007 (mean = 0.64 kg/ha). 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); because neither of these species have increased since 2007, these mechanisms likely do not underlie the recent downward trend. A more likely explanation is that some proportion of the deepwater sculpin population has shifted to waters deeper than 110 m (the deepest depth for the standard trawling sites). In support of this, Madenjian and Bunnell (2008) found that deepwater sculpins have been captured at

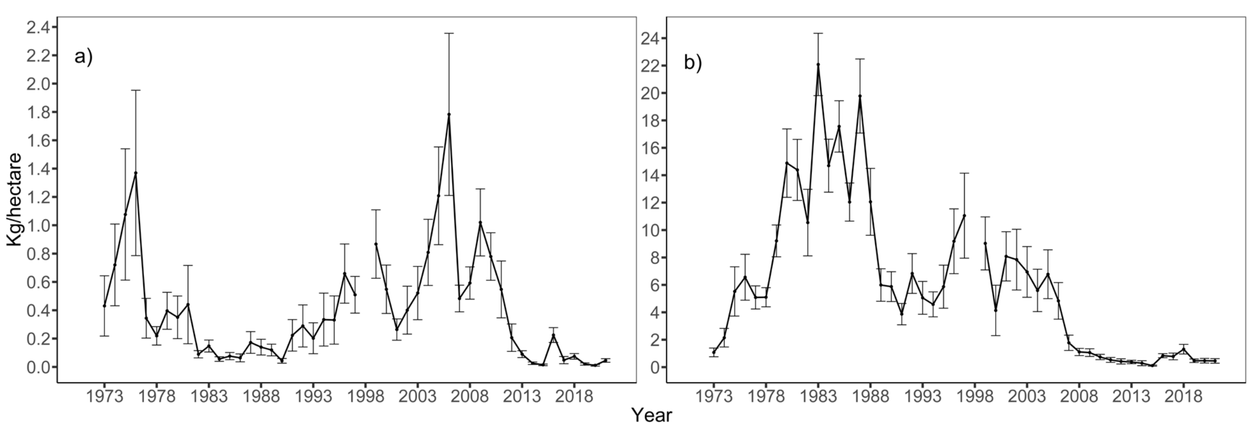

Figure 9. Biomass density of a) slimy sculpin and b) deepwater sculpin in Lake Michigan, 1973-2021, as measured by the bottom trawl survey. Error bars in both panels are +/- standard error.

increasingly greater depths since the 1980s. The data collected from the 128 m sites since 2013 also clearly demonstrate increasing biomass density with depth (Madenjianet al. 2022. Future research could sample at even greater depths to determine the depth at which deepwater sculpin biomass peaks.

Ninespine stickleback

Two stickleback species occur in Lake Michigan. Ninespine stickleback is native, whereas threespine stickleback (*Gasterosteus aculeatus*) is non-native and was first collected in the BT survey during 1984 (Stedman and Bowen 1985) but has been extremely rare in recent sampling years. Biomass density of ninespine stickleback has also been extremely low (i.e., <0.5 kg/ha) since 2007. The densities in 2021 were a record low (<0.001 kg/ha, Fig. 10a), with only 22 ninespine sticklebacks caught in the entire BT survey. Biomass of ninespine stickleback remained 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. 2010). Since 2011, ninespine stickleback have declined, likely because piscivores began to incorporate ninespine sticklebacks into their diets as alewives declined. Jacobs et al. (2013) found ninespine sticklebacks in large Chinook salmon diets (i.e., 2% occurrence) during 2009-2010 after 0% occurrence in 1994-1996.

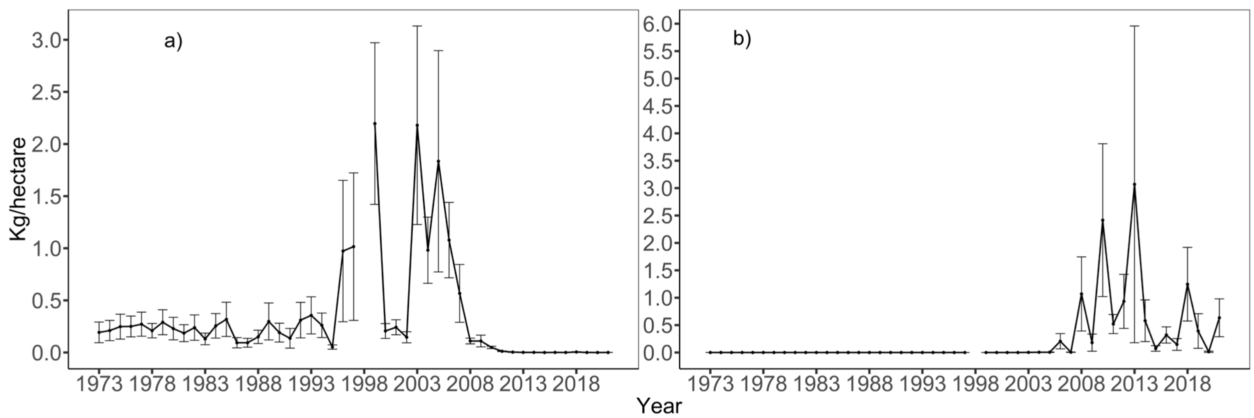

Figure 10. Biomass density of a) ninespine stickleback and b) round goby in Lake Michigan, 1973-2021, as measured by the bottom trawl survey. Error bars in both panels are +/- standard error.

Round goby

Nonindigenous round gobies were first detected in bays and harbors of Lake Michigan in 1993 (Clapp et al. 2001) but were not widespread enough to be sampled in our BT survey until 2003. As our survey samples only soft substrates deeper than 9 m, our estimate is biased low because we are not sampling their preferred habitat in September (rocky substrate and shallow [< 9 m] depths). Round goby biomass density was 0.63 kg/ha in 2021 (Fig. 10b), which is nearly identical to the average biomass of 0.62 kg/ha over the 2008-2020 period.

While round gobies were sampled at all seven BT transects in 2021 (Fig. 11), biomass was low at almost all locations except for two near Waukegan, IL and one near Port Washington, WI. One potential explanation for higher densities on the western side of the lake is rockier habitat relative to the eastern side of the lake (Janssen et al. 2005). Round goby are consumed by diverse fish including smallmouth bass (*Micropterus dolomieu,* Crane and Einhouse, 2016), yellow perch (Truemper et al. 2006), burbot (Jacobs et al. 2010), lake trout (Luo et al. 2019), lake whitefish (*Coregonus clupeaformis*, Pothoven and Madenjian, 2013), cisco (Breaker et al, 2020), as well as brown trout, rainbow trout (*Onchorhynchus mykiss*), coho salmon (*O. kisutch*), and Chinook salmon (O. *tshawytscha*) (Turschak et al. 2021). We hypothesize that round goby abundance in Lake Michigan is controlled by predation, given that annual mortality rates range from 79 to 84% (Huo et al. 2014), comparable to estimates for adult alewives (Tsehaye et al. 2014).

Prey fish community trends

The prey fish community sampled by the BT survey includes alewife, bloater, rainbow smelt, deepwater sculpin, slimy sculpin, ninespine stickleback, and round goby. In 2021, this survey estimated a total biomass density of prey fish equal to 2.4 kg/ha (Fig. 12), the 5th lowest estimate of the time series and well below the long-term (i.e., 1972-2019) average total biomass of 34.9 kg/ha. Total biomass density first dropped below 10 kg/ha in 2007 and has since remained below

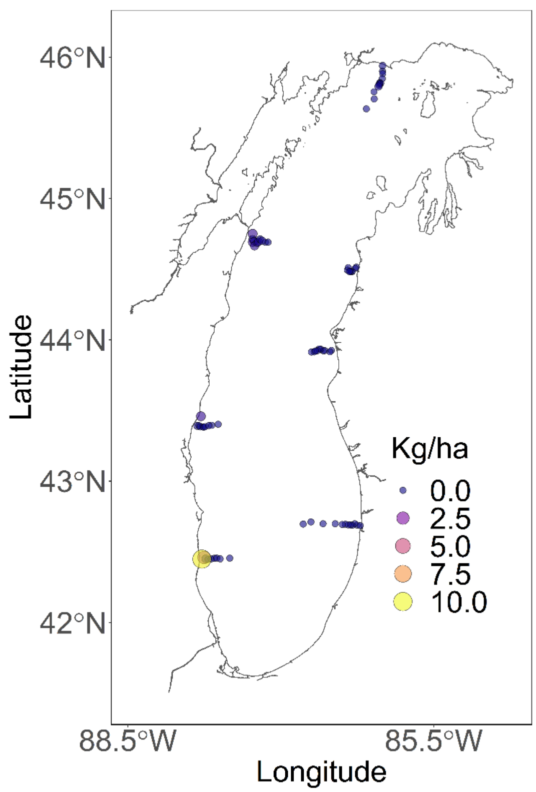

Figure 11. Map of round goby biomass estimates in Lake Michigan as measured by the bottom trawl survey in 2021.

that level except in 2013, when the biomass estimates for alewife and round goby were highly uncertain. For the first time in six years, the composition of the 2021 prey fish community was dominated by species other than just bloater, with nearly equal contributions from alewife (28%), bloater (24%), and round gobies (27%).

The prey fish community sampled by the AC survey includes alewife, bloater, rainbow smelt, and cisco (with only one captured in 2021). In 2021, this survey estimated a total biomass density of 6.6 kg/ha (Fig. 13), 50% higher than the long-term (i.e., 2004-2019) average total biomass of 4.4 kg/ha. Total biomass density has exhibited no strong trend since 2004. Unlike the BT survey, the AC survey found that the dominant species in the prey fish community was bloater (67%). This is only the second time since 2004 that bloater biomass, and not alewife biomass, has dominated the prey fish community as measured by the AC survey and nearly 60% of the increase in bloater biomass was the result of high abundance of YOY bloater.

Other species of interest

Burbot - Burbot and lake trout represent the native top predators in Lake Michigan. The recovery of burbot during the 1980s was attributable to reduction in sea lamprey (Wells and McLain 1973) and perhaps even alewife, which can feed on burbot larvae (Eshenroder and Burnham-Curtis 1999; Madenjian et al. 2008). Burbot collected in the BT survey are typically large individuals (>350 mm TL); juvenile burbot typically do not inhabit areas sampled by the BT survey. Burbot biomass density was 0.01 kg/ha in 2021, consistent with extremely low estimates since 2012 (Fig. 14a). It is unclear why burbot catches in the BT survey have remained low in the face of relatively low densities of sea lamprey and alewife over the past decade.

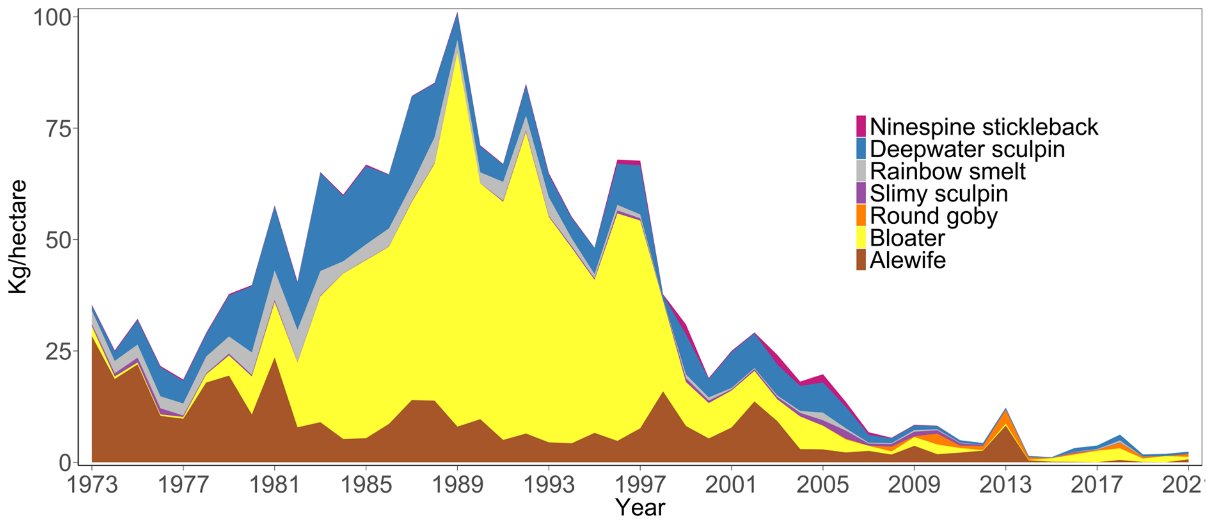

Figure 12. Estimated biomass of prey fishes sampled in the bottom trawl survey, 1973-2021.

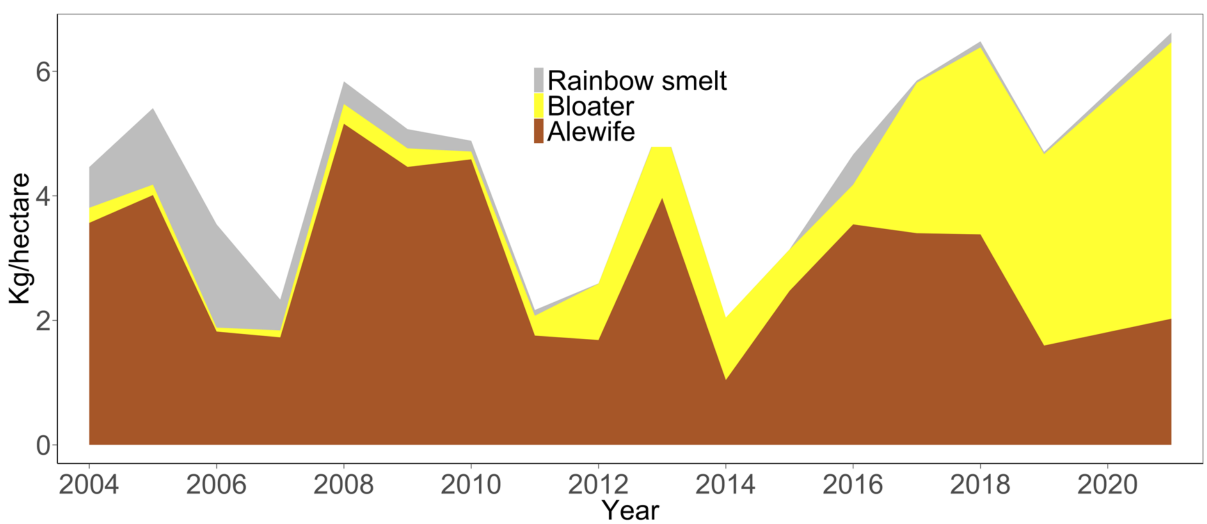

Figure 13. Estimated biomass of prey fishes sampled in acoustic survey, 2004-2021.

<u>Age-0 yellow perch</u> - The yellow perch population in Lake Michigan has supported valuable recreational and commercial fisheries (Wells 1977). The BT survey provides 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 (Fig. 14b) and the 2009 and 2010 year-classes also were higher than average. In 2021, three age-0 yellow perch were caught, indicating a weak year-class. In 2005, a year with a strong year-class, nearly 1,700 were captured.

Conclusions

The year 2021 was an average-to-poor recruitment year for three species that are indexed as age-0: alewife, rainbow smelt, and yellow perch. However, comparing 2021 estimates of prey fish biomass to previous years depends on the temporal perspective. Focusing on the AC survey results that date back to 2004, total prey fish biomass was higher than the long-term average, although the 2021 YAO alewife biomass estimate is 21% lower than the long-term average. Comparing the 2021 acoustic estimates of YAO fish to the mean YAO biomass from the 1970s-1990s (in the BT survey), however, reveals substantial long-term declines. Alewife 2021 biomass was only 18% of the 1970s-1990s mean. Bloater 2021 biomass was only 11% of the 1970s-1990s mean. Finally, rainbow smelt 2021 biomass was only 1% of the 1970s-1990s mean. Hence the AC survey indicates relative stability and a modest decline for alewife biomass in 2021, relative to surveys since 2004. But longer-term comparisons to the results from the BT survey reveal considerable declines during the 1990s or early 2000s for these three key species.

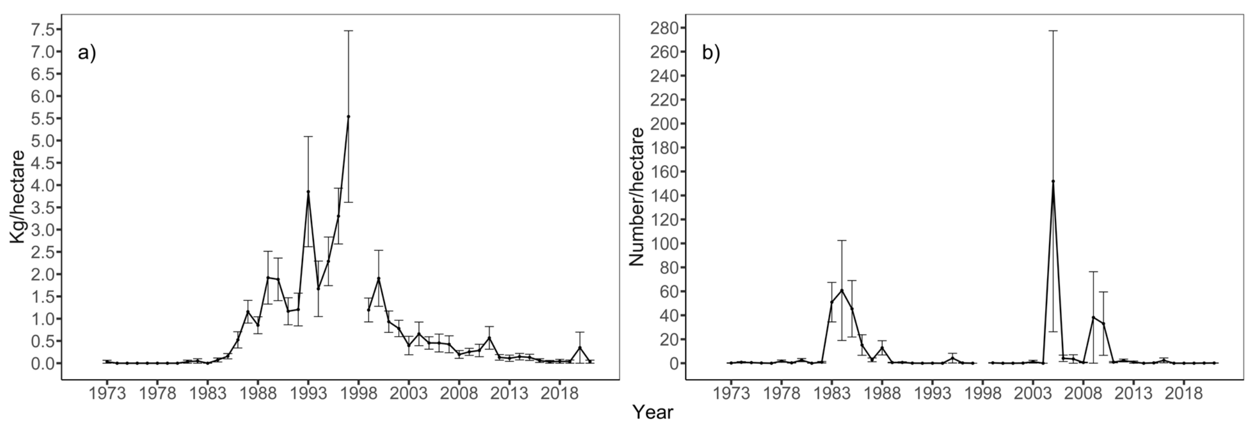

Figure 14. Biomass density of a) burbot and b) numeric density of age-0 yellow perch in Lake Michigan, 1973-2021, as measured by the bottom trawl survey. Error bars in both panels are +/- standard error.

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