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Spatio-Temporal Dynamics of Yellow Perch-Alewife Interactions in Lake Michigan: Implications for Yellow Perch Recruitment
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# SPATIO-TEMPORAL DYNAMICS OF YELLOW PERCH-ALEWIFE INTERACTIONS IN LAKE MICHIGAN: IMPLICATIONS FOR YELLOW PERCH RECRUITMENT 

By

Matthew P. Balge

## A THESIS

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# ABSTRACT <br> SPATIO-TEMPORAL DYNAMICS OF YELLOW PERCH-ALEWIFE INTERACTIONS IN LAKE MICHIGAN: IMPLICATIONS FOR YELLOW PERCH RECRUITMENT 

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Yellow perch recruitment in Lake Michigan has been extremely low since the early 1990s, prompting intensive research efforts to determine the mechanisms regulating year-class strength. Much is unknown about the earlylife history spatial and temporal distribution of the species, due in part to inefficiencies of traditional sampling gear, which do not capture yellow perch larvae $>8 \mathrm{~mm}$. Additionally, the potential influence of predation, particularly by adult alewives, on early life stage survival of yellow perch has not been determined. This study evaluated the ability of side-looking hydroacoustics to detect and estimate densities of larval yellow perch. Also, the dynamics of spatial and temporal overlap between larval yellow perch and their potential predators in southwestern Lake Michigan from 1999-2001 were explored. Hydroacoustics proved to be highly efficient at detecting larval yellow perch with swim bladders, but field density estimates were extremely sensitive to water surface conditions. The spatial and temporal overlap of larval yellow perch and potential predator distributions varied greatly among years, with highest predation likely occurring in offshore waters in 2000. This study provides insight into new methods for sampling larval yellow perch, and shows that predation on larval yellow perch may be a factor influencing yellow perch year-class strength.

This thesis is dedicated to all of my friends and family who showed enormous support and patience with me through all the stressful days and sleepless nights as I worked toward the highest academic achievement of my life so far.

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## CHAPTER 1

Overview of Yellow Perch in Lake Michigan

## Introduction

Yellow perch (Perca flavescens) is an important ecological and economical species in the Great Lakes. Ecologically, yellow perch is an indigenous species that plays a role in nutrient cycling and energy transfer in nearshore waters (Evans 1986). Additionally, yellow perch is an important link between the nearshore and offshore food webs because they move to shallow waters in the spring to spawn, and post-spawn adults retreat to deeper waters later in the year (Eshenroder et al. 1995). Economically, yellow perch have contributed considerably to the sport and commercial fisheries in Lake Michigan. Yellow perch were the most popular sport fish during the 1980s and 1990s (Bence and Smith 1999) comprising nearly $85 \%$ of the total recreational catch (GLFC 1995, Francis et al. 1996). The combined annual take of yellow perch by recreational and commercial fisheries exceeded 2.5 million pound from 1985 through 1993 in Lake Michigan (GLFC 2000). Recent declines in yellow perch numbers, however, have prompted closed seasons, slot limits, and reduced bag limits for recreational anglers. While the State of Michigan did not previously allow commercial fishing for yellow perch, commercial fishing has been stopped indefinitely for all other states surrounding Lake Michigan, except for an annual harvest of 200,000 pounds in Green Bay, WI (Makauskas and Clapp 2001). The ecological and economical impact of the yellow perch decline has prompted an intensive investigation by researchers to determine the causes for the lack of recruitment, and the potential for the population to recover in the near future.

Yellow perch populations frequently display large fluctuations in year class strength in small lake systems (Forney 1971, Kelso and Ward 1977, Sanderson et al. 1999) as well as in the Laurentian Great Lakes (Hile and Jobes 1940, Eshenroder 1977, Wells 1977, Henderson 1985). Yellow perch populations in Lake Michigan have displayed similar year class strength variation. Yellow perch numbers declined in Lake Michigan in the 1960s, and remained low until strong years classes were produced throughout the 1980s (Wells 1977, Jude and Tesar 1985, Eck and Wells 1987, Makauskas and Clapp 2001). Yellow perch recruitment success began diminishing in the late 1980s, and Lake Michigan has been experiencing extremely poor recruitment since the early 1990s (Makauskas and Clapp 2001).

Very few age-0 yellow perch have been collected for over a decade in summer and fall assessments by any of the state and federal agencies doing research on Lake Michigan (Makauskas and Clapp 2000, Pientka et al. 2001, Allen and Lauer 2002, Hirethota 2002, Makauskas 2002). Near Waukegan, IL, for example, CPUE (number per $1000 \mathrm{~m}^{2}$ using a bottom trawl) of age-0 yellow perch was nearly 7000 in 1988, which dropped to 500 in 1989. CPUE has only reached 50 twice since 1990 (1990 and 1998), with CPUE <4 for all other years within that time period (Makauskas and Clapp 2000, Pientka et al. 2001). The last noteworthy year class was produced in 1998, and was only marginal at best with age-0 abundances at least an order of magnitude lower than those recorded during the 1980s. Individuals from the 1998 year class have dominated the
yellow perch population in Lake Michigan in recent years, comprising up to 94\% of all yellow perch collected (Makauskas and Clapp 2000). Nearly 100\% of the yellow perch collected in Wisconsin and Illinois waters of Lake Michigan in 2002 were $\geq$ age-4 (Hirethota and Thompson 2002, Makauskas 2002).

To assess the decline in yellow perch recruitment since the early 1990s, the Lake Michigan Committee (LMC) of the Great Lakes Fishery Commission (GLFC) formed the Yellow Perch Task Group (YPTG). The LMC was set up to consider issues and problems with fish stocks of Lake Michgian of common concern to Illinois, Indiana, Michigan, Wisconsin, and/or the Chippewa Ottawa Treaty Fishery Management Authority. Additionally, the LMC was instructed to develop and coordinate joint research projects, to be conducted by the Lake Michigan Technical Committee (LMTC), to provide information to the GLFC for resource management direction. The LMC functions also include the formation of necessary task groups to address specific issues outside the scope of the LMTC. The YPTG was formed in 1994, and given the following three charges: (1) Consolidate and assess compatibility of the available data on yellow perch, (2) from this consolidation, evaluate stock discreetness of yellow perch in Lake Michigan, and (3) report progress to the LMTC. However, growing concern over the rapid decline in yellow perch stocks prompted the addition of the following charge in 1995: (4) Expand research on perch by developing a multi-agency initiative to identify the likely causes for the lack of yellow perch recruitment.

Several hypotheses were developed by the YPTG to focus research on the prolonged problem of low yellow perch recruitment in southern Lake Michigan (Makauskas and Clapp 2000). These hypotheses include: contaminants are limiting survival of early life stages; disease is limiting pre-demersal survival; and the stock-recruitment relationship is limiting recruitment. The hypothesis ranked highest in importance however, is that pre-demersal larval yellow perch survival is limiting recruitment. Within this hypothesis are numerous sub-hypotheses, again ranked by the YPTG. The lowest ranked hypotheses which have received little research attention include: gamete quality is limiting recruitment; embryonic mortality is limiting recruitment; post yolk-sac fry survival is limited by lack of swim bladder inflation; reduced primary production affects larval foraging; larval yellow perch are starving to death; and increased water clarity increases alewife (Alosa pseudoharengus) predation on larvae. From these, the only related research showed that some maternal effects on egg production and larval morphology were present in Lake Michigan yellow perch (Heyer et al. 2001). However, the larval traits that translate into increased survival differ from year to year, so the effect of differences in traits on recruitment success could not be determined.

Another sub-hypothesis, ranked with higher importance is that zooplankton density, size and species composition limit recruitment of larval yellow perch, and that inappropriate diet (nutrition) is limiting pre-demersal survival. Near Waukegan, IL there is a strong positive relationship between
young-of-the-year yellow perch CPUE and zooplankton density during the time of larval yellow perch hatch (Pientka et al. 2001). It has also been shown that laval yellow perch may be gape-limited, and that both zooplankton size and taxa likely are important for growth and survival (Bremigan et al., in review). The species composition of the crustacean zooplankton community changed considerably in Lake Michigan from 1983-1992. The large, and previously rare, Daphnia galeta mendota became the dominant cladoceran, and replaced smaller Daphnia species (Makarewicz et al. 1995). The end of this time period corresponds with the beginning of the yellow perch decline, indicating there may be a link between the two, but the extent of this relationship has not been determined.

The limitation of recruitment due to physical lake processes, particularly the transport of larval yellow perch by upwelling/downwelling event and currents, has also been identified as a sub-hypothesis within the early-life stage context. Physical processes may influence survival by transporting larval perch to areas of concentrated or diluted food resources (influenced by the same physical processes), or by increasing the probability of encounter with predators. Lake Michigan generally experiences numerous upwelling and downwelling events during the early life stages of larval yellow perch, providing evidence that the offshore transport of larval fish to offshore waters occurs. For example, as the summer progressed near Waukegan, IL in 2000 and 2001, larval yellow perch were found further offshore in areas of zooplankton densities at least twice as high as nearshore (J. Dettmers, unpublished data). These results suggest that
food resources may not be limiting the growth and survival of larval yellow perch as they are transported offshore.

The sub-hypothesis of alewife predation limiting yellow perch recruitment was ranked with highest importance. This is based on evidence suggesting alewives have played a role in influencing larval yellow perch year class strength in Lake Michigan. Smith (1970) indicated that yellow perch numbers declined abruptly after alewives became abundant in the 1960s. Wells (1977) reported that increasing alewife numbers in the 1960s resulted in declining YOY yellow perch numbers followed by a sharp decline in the adult population. Additionally, Eck and Wells (1987) showed that year class strength of yellow perch has inversely fluctuated with alewife abundance. Most recently, Shroyer and McComish (2000) reported a clear negative relationship between local alewife abundance and yellow perch recruitment (subsequent abundance at age-2) in southern Lake Michigan. These studies led researchers to conclude that alewife predation likely occurs during the early life stages of yellow perch, and may help limit recruitment in Lake Michigan.

Although direct evidence of alewife predation on larval yellow perch has been scarce for Lake Michigan (i.e. Pientka et al. 2001), such predation has been found in other systems. Juvenile and adult alewives feed primarily on zooplankton, but predation on fish eggs and larvae has been observed (Janssen and Brandt 1980, Wells 1980, Brandt et al. 1987, Krueger et al. 1996, Mason and

Brandt 1996, Brooking et al. 1998). Alewife predation on larval yellow perch can be a significant source of larval mortality in Lake Ontario, where individual alewife can consume > 100 larval yellow perch in a single evening (Brandt et al. 1987, Mason and Brandt 1996).

Intuitively, for alewife predation on larval yellow perch to occur, the two species must overlap in space and time. Alewives move inshore in the spring to spawn, and can be present in high densities during the time of yellow perch hatching. Additionally, post-spawn adult alewives move offshore and become abundant in the epilimnion and thermocline (Brown 1972; Argyle 1982; Brandt 1980; Brandt et al. 1980; Crowder and Magnuson 1982). The offshore advection of larval yellow perch has the potential to increase the spatial overlap with these potential predators. Additionally, the duration of the spatial overlap as larval yellow perch move offshore likely would have a large influence on the total amount of predation. Therefore, the ability to determine the degree of spatial and temporal overlap is critical for a full understanding of the potential for predation to be a factor in limiting yellow perch recruitment.

Our current knowledge of the distribution and density of post-hatch larval yellow perch has been greatly limited due to gaps in information of yellow perch life history throughout their first summer. Traditional gear used for larval yellow perch sampling is only effective at catching fish up to approximately 8 mm (Noble 1970, B. Pientka unpublished data). Past this stage in development, yellow
perch currently cannot be effectively sampled until they become demersal and move back nearshore in the fall of their first year where they can be collected using beach seines. If yellow perch year class strength is truly determined between hatching and fall inshore movement as hypothesized by the YPTG, a complete understanding of yellow perch dynamics throughout this entire time period is crucial.

## Thesis Objectives

It is unlikely that one hypothesis can explain the greater than ten-year decline in yellow perch abundance in Lake Michigan. This thesis focused on the predation hypothesis, and will be integrated with results from other studies to further our understanding of predation as a mechanism controlling larval yellow perch year class strength. The specific objectives for this thesis were: (1) To determine the feasibility of hydroacoustics to detect and estimate densities of larval yellow perch in Lake Michigan, (2) to estimate the amount of spatial and temporal overlap of larval yellow perch and their potential predators during their hatch and subsequent offshore advection, and (3) to determine if the summer alewife offshore movement can be related to changes in water temperature.

Chapter 2 presents laboratory and Lake Michigan data, which were used to assess the ability of hydroacoustics to detect larval yellow perch. Controlled laboratory experiments determined acoustic data analysis parameters for field-
collected data, and results were used to compare hydroacoustic density estimates to those obtained from neuston net data. The results address the problem of sampling bias with traditional gear, and offer an alternative method for sampling larval fish to fill in spatial gaps in our knowledge of their distribution.

Chapter 3 presents hydroacoustics data collected near Waukegan, IL which were used to determine the spatial and temporal distribution of potential predators of larval yellow perch. Larval yellow perch distribution data throughout their offshore transport were compared with predator distributions to identify periods of overlap from 1999-2001. The relationship of predator density to changes in water temperature was also explored to determine if predator movements might be predictable. These results were used to assess the hypothesis that predation on larval yellow perch is limiting recruitment by determining the extent to which larval yellow perch encounter predators throughout their advection into offshore waters.

Chapter 4 synthesizes these results in the context of yellow perch management, and examines future directions for the application of hydroacoustics in fisheries science.

## CHAPTER 2

Use of Hydroacoustics To Detect and Estimate Density of Larval Fish In Lake
Michigan


#### Abstract

Recent decline in yellow perch (Perca flavescens) recruitment in Lake Michigan has led researches to examine the mechanisms affecting survival during early life stages. However, sampling biases of traditional gear have severely limited our ability to sample, estimate abundance, and describe spatial distributions of larval yellow perch during their early life history. This study explored the potential of side-looking hydroacoustics to detect and estimate the density and distribution of larval fish in the upper water column. A side-looking 129 kHz split beam transducer was able to detect larval yellow perch with developed swim bladders ( $9-27 \mathrm{~mm}$ ), but was unable to detect any without swim bladders $(6-11 \mathrm{~mm})$. A 418 kHz split beam transducer was able to detect larval perch with and without swim bladders ( $9-17 \mathrm{~mm}$ ). Target strength (TS, in $d B$ ) increased with total length (mm) according to the equation TS=15.996Log(L)84.157. Target strength was also influenced by swim bladder morphology and fish orientation to the transducer. Mobile side-looking hydroacoustic surveys in Lake Michigan were capable of estimating larval fish densities similar to those calculated using neuston net data during sampling periods of calm water. Acoustic noise increased with distance from the transducer during times of surface disturbance, which greatly inflated density estimates. Side-looking hydroacoustic surveys could be useful when lake conditions are conducive to low-noise data collection to help fill spatial and temporal gaps in data created by traditional larval fish collection methods.


## Introduction

Yellow perch (Perca flavescens) recruitment in Lake Michigan has been extremely poor during the last decade. Lake Michigan fisheries managers generally agree that the factors influencing yellow perch recruitment occur during their early life stages, although the specific mechanisms are not known (Makauskas and Clapp 2000). Determination of these mechanisms has thus become a priority, and numerous hypotheses have been presented to explain such low survival rates. One area that has received much attention is the interactions between alewife (Alosa pseudoharengus) and yellow perch. Jude and Tesar (1985) showed an increase in yellow perch CPUE following three years of low alewife CPUE. Shroyer and McComish (2000) showed a negative relationship between alewife abundance and yellow perch abundance two years later in southern Lake Michigan. Such a decline in yellow perch recruitment may be attributed to the feeding habits of adult alewife. Competition for food between alewife and the early life stages of perch has been suggested (Crowder 1980, Jude and Tesar 1985, Eck and Wells 1987). In addition, alewives have a preference for larger zooplankton (Brooks 1968), and this could include larval fish. Juvenile and adult alewives feed primarily on zooplankton, but predation on fish eggs and larvae has also been observed (Jansen and Brandt 1980, Kohler and Ney 1980, Brandt et al. 1987, Krueger et al 1995, Brooking et al. 1998). Mason and Brandt (1996) demonstrated that alewife predation was a significant source of larval yellow perch mortality in an embayment on Lake Ontario. It has
been suggested that alewife predation on larval yellow perch is a mechanism which may significantly affect yellow perch recruitment in the Laurentian Great Lakes (Crowder 1980, Brandt et al 1987, Mason and Brandt 1996).

For alewife and larval yellow perch to interact, these species must overlap both spatially and temporally. Quantification of such interactions must therefore rely on sampling methods that can accurately estimate the densities and spatial distributions of both species. Current sampling methods for larval yellow perch mainly include the use of neuston nets and high-speed Miller samplers. Biases associated with these methods result from the inefficiency of capturing larval fish at all stages of their development. Noble (1970) found that 8mm larvae could avoid a high-speed Miller sampler towed at $3.5-4 \mathrm{~m}^{*} \mathrm{~s}^{-1}$. Additionally, 92.6\% of total larval fish and $97.4 \%$ of larval yellow perch collected by the lllinois Natural History Survey (INHS) in neuston nets (500 or $1000 \mu \mathrm{~m}$ mesh, typically towed at $<1.5 \mathrm{~m}^{*} \mathrm{~s}^{-1}$ ) in southwestern Lake Michigan were $<8 \mathrm{~mm}$ in length (Figure 1, B. Pientka, unpublished data).

Yellow perch larvae occupy the upper portion of the water column (<2 m) during their transport offshore caused by mass water movements (Post and McQueen 1988). Yellow perch become demersal during their first summer after their offshore advection, and migrate back to nearshore waters in the fall. The spatial extent of the offshore transport remains unknown, and there are currently few sampling methods that allow managers to accurately track the distribution


Figure 1. Length frequency distributions of larval fish collected in neuston nets from southwestern Lake Michigan 2000-2001. Outlined bars represent all larval fish collected, solid bars represent all larval yellow perch collected.
and density of yellow perch from the time at which gear avoidance begins ( $\sim 8 \mathrm{~mm}$ ) until the fall inshore migration $(\sim 40 \mathrm{~mm})$. Traditional nets are also limited in the volume of water that can be sampled, and do not allow continuous sampling along a transect of sufficient length to determine the full spatial extent of larval yellow perch distributions. Because of this, any patchiness of larval perch densities in space and time may bias density estimations from net samples. Finding a means to reduce gear avoidance and improve sampling efficiency is necessary if managers wish to more completely understand the mechanisms that influence yellow perch recruitment.

Thorne (1983) suggests that use of hydroacoustics may provide an alternative to traditional gear sampling methods for pelagic fish through the ability to sample much greater volumes of water along continuous transects. Spatial and temporal changes in distributions and densities could thus be more accurately determined than from net sampling alone (Thorne 1983). Mobile sidelooking hydroacoustic surveying of surface waters to quantify distributions and densities of larval fish is an application of this technology that has not been fully tested. The overall objective of this chapter was to assess the feasibility of using hydroacoustics to detect and estimate densities of larval yellow perch. A target strength (TS) to size relationships for larval yellow perch was determined, and this information was used to estimate larval fish abundance and distribution in the field.

## Methods

The TS - length relationship for larval yellow perch over a range sizes and stages of swim bladder development was determined in a laboratory setting. Results from the laboratory experiments were used to determine appropriate single-target detection parameters when processing field collected hydroacoustic data. Average backscattering cross-section ( $\bar{\sigma}_{\mathrm{bs}}$, a measure of the average amount of sound reflected by an individual fish) was calculated from the TS (in dB ) of single targets, and was used in conjunction with the results of echosquared integration to estimate fish density. These density estimates were compared to density estimates calculated from neuston net samples to determine the influence of processing parameters and sea state on acoustic larval yellow perch assessments.

## Target Strength vs. Larval Size

Laboratory work was conducted in July 2001 and August 2002 to assess the ability of hydroacoustic gear to detect lanval yellow perch and develop a TSlength relationship. Target strength is the measure of incident sound energy reflected back to the transducer by an object in the water, corrected for the object's angle off the acoustic axis. A small fiberglass fish run (approximately $0.75 \mathrm{~m} \times 0.75 \mathrm{~m} \times 2 \mathrm{~m}$ ) was cleaned and filled with filtered water (using a $63 \mu \mathrm{~m}$ zooplankton net) pumped directly from Lake Michigan. Filtering the water helped
reduce the risk of acoustic signal contamination that could result from unwanted materials (i.e. suspended particles and zooplankton) in the tank. Water temperature in the tank was $17-18^{\circ} \mathrm{C}$, and was similar to surface temperatures observed on the lake during field data collection $\left(12-21^{\circ} \mathrm{C}\right)$. We used a Biosonics DT6000 129kHz digital split-beam system for laboratory data collection. The transducer was set on its side at one end of each fish run, and aimed so the acoustic cone would run the length of the tank. Fine-tuning adjustments of the transducer (e.g. raising. lowering, tilting, and rotating) minimized noise from sound-cone interaction with the water surface or sides of the tank. System performance was monitored using a frequency-specific tungsten-carbide reference sphere.

Yellow perch egg skeins were collected in spring 2000 and 2001 by the INHS from southwestern Lake Michigan, and were hatched and reared in the laboratory. For hydroacoustic experiments, live larval yellow perch with and without swim bladders were used. Fish without swim bladders ranged from 611 mm , and fish with swim bladders were $10-27 \mathrm{~mm}$. Individual fish were released in the tank at a distance >1m from the transducer face, and hydroacoustic data (10 ping/sec, $0.1-0.3 \mathrm{~ms}$ pulse width, -75 dB minimum raw echo strength (SV) threshold) were collected as the fish swam or sank through the acoustic beam. The range of fish sizes used allowed for target strength estimation of larval yellow perch at different stages of development. Additional variation in the amount of sound reflected may be attributed to the orientation of the fish relative
to the incident sound wave (Love 1977, Foote 1980, Ona 1990, Horne and Clay 1998). To estimate variability in larval yellow perch target strength due to this, orientation of the fish (i.e. broadside, tail-toward or head-toward the transducer face) was recorded when possible.

Because higher frequency transducers are able to detect smaller targets than lower frequency transducers, additional work (using the same methods described above) was conducted using a Biosonics DE6000 418kHz split-beam transducer. This allowed for the comparison of larval yellow perch detection abilities between frequencies, as well as assessed the potential advantages and/or disadvantages of using a 418kHz transducer for larval fish data collection in the field.

The amount of sound reflected back to the transducer from the fish is determined by physical structures with densities differing from the surrounding water. In teleost fish, the swim bladder is the major source of backscattered sound (Foote 1985). To determine if unexpected target strength measurements (i.e. a larger fish with a lower TS than a smaller fish) were a function of swim bladder morphology, measurements of this organ were made using an Optimas microscope measuring system. Measurements made from a side-looking aspect included total fish length, total swim bladder length, and swim bladder height at three evenly spaced locations along the length. From a dorsal aspect, width of


Figure 2. Measurements of larval yellow perch used to approximate air bladder side surface area and volume. Letters represent measurements (mm) used in equation 1.
the swim bladder was measured at the midpoint of the swim bladder length (Figure 2). From these measurements, approximate surface area ( $\mathrm{mm}^{2}$ ) from a side-looking orientation and swim bladder volume ( $\mathrm{mm}^{3}$ ) were calculated using the equations

$$
\begin{equation*}
\text { area }=\left(\frac{1}{4} L * \frac{1}{2} T\right)+\left[\frac{1}{4} L *\left(\frac{1}{2} T+\frac{1}{2} M\right)\right]+\left[\frac{1}{4} L *\left(\frac{1}{2} H+\frac{1}{2} M\right)\right]+\left(\frac{1}{4} L * \frac{1}{2} H\right) \tag{1}
\end{equation*}
$$

volume = area * W
where $L, T, M, H$, and $W$ are as described in Figure 2.

Field Sampling

Mobile side-looking hydroacoustic data were collected near Waukegan Harbor, IL from mid-May through mid-July in 2000 aboard the INHS RN Sculpin. Hydroacoustic data were collected at night concurrently with a towed neuston net. Transects were at four locations along a 6 nautical mile long transect perpendicular to shore which started offshore in 50 m water and terminated nearshore in 10 m water. Additional hydroacoustic and neuston net data were collected nearshore along 0.5 nautical mile transects along 5 m and 10 m depth contours.

A Biosonics DT6000 129 kHz digital split-beam echosounder with a $6.2^{\circ}$ nominal beam width measured at -3 dB off beam axis (equal to $50 \%$ sound intensity loss in the transducer directivity pattern) and a transmit source level of $225 \mathrm{~dB} / \mu \mathrm{Pa}$ was used. The transducer was mounted to the underside of a 4 ft . Biosonics BioFin ${ }^{\mathrm{TM}}$ in a side-looking configuration using an $87^{\circ}$ aluminum bracket, and the towbody was stabilized using a counterbalance to ensure smooth operation (Figure 3). The mounting angle allowed the upper edge of the main acoustic beam to be parallel with the surface of the water. The towbody was suspended off the port side of the vessel and towed at $1-2 \mathrm{~m}$ below the water surface, with tow depths increasing as wave action on the lake increased to keep the transducer underwater. Mounting angle and tow depth were important for reducing the risk of water/air boundary interference with the acoustic signal. Data were collected with Biosonics Visual Acquision v4.0 software, using 3 ping $^{*} \sec ^{-1}, 0.4 \mathrm{~ms}$ pulse width, and a minimum squared voltage (SV) threshold of -80dB (-65dB in July 2000). Maximum range of acoustic data collection was 50 m from the face of the transducer for all dates. A tungstencarbide reference sphere was used for system calibration. All acoustic data were digitally recorded on a laptop computer in the field for later analysis. Water surface condition (wave height and surface smoothness) was also qualitatively observed and recorded along all transects.

Larval fish were directly sampled using a $1 m \times 2 m$ frame neuston net (500 $\mu \mathrm{m}$ mesh May-June, $1000 \mu \mathrm{~m}$ mesh July) for ground truthing of


Figure 3. Side-looking transducer configuration used for mobile hydroacoustic surveys near Waukegan Harbor, Lake Michigan in 2000.
hydroacoustic data (collected simultaneously). Samples were collected using 10 minute neuston net tows at an average speed of $1.1 \mathrm{~m}^{\star} \mathrm{s}^{-1}$, starting at four points along the transect (approximately 7, 5.5, 4 and 2.5 nautical miles offshore moving inshore). A flowmeter recorded the volume of water sampled for each neuston net tow for density calculation. Samples were immediately preserved in 95\% ETOH for later species identification, measurement and density estimation (All sample collection, preservation, and processing was conducted by the INHS).

Hydroacoustic data analysis

Hydroacoustic data were analyzed using Echoview v2.20.52 software (SonarData Pty Ltd 1995-2001). All analyses of laboratory and field data were calibrated for water temperature (sound speed correction), transducer frequency, and nominal beam angle. Echoview requires user defined parameter values for single target detection and echo integration processing. For single target detection of the laboratory larval yellow perch data, the minimum target pulse length, which is the proportion of transmitted pulse length returned by the target, was set to 0.01 . Maximum beam compensation, or the maximum allowed dB increase in target strength for correction of a potential target's depth and angle off axis, was set to 5 dB . This setting helped filter out targets that were not within the nominal beam. The standard deviation of the angle measurement of a target's position off of the acoustic axis is calculated from the location of a
number of digital resamples within a single echo pulse (i.e. echo return for a target in a single ping) for the potential target of interest. A high standard deviation for either the alongship or athwartship angles off axis would indicate an erroneous echo, and would not be accepted as a single target. For analysis, the maximum standard deviation of both alongship and athwartship angles for each potential single target was set to $0.6^{\circ}$. Additionally, Echoview allows the user to set the pulse width determination level (PWDL, in dB ), which is subtracted from the maximum TS of a potential single target to determine where the target pulse length is measured for that target (Figure 4). If the target pulse width is less than the minimum pulse width setting at the measurement point defined by the PWDL, or if the total dB range of a potential single target is less than the PWDL setting, it is not recognized as a single target. For laboratory TS analysis, a PWDL of 1dB was used, which resulted in the greatest number of TS estimations per single track of a larval fish. This setting was appropriate for laboratory data analysis because all identified single targets could be positively identified as either a larval fish or as noise. Target strength is a function of the wavelength of the transmitted pulse and total fish length (Love 1969, 1970 and 1977). Because of this, TS measurements for the 129 kHz and 418 kHz systems were analyzed separately.

For Lake Michigan hydroacoustic data analyses, the PWDL was set at 6dB, 3 dB , and 1 dB to evaluate the effect this parameter has on field identification of targets. The minimum pulse width factor was set to 0.01 to allow for


Figure 4. Example of oscilloscope readings for three potential single targets (bold lines, numbered at right). The solid vertical line represents maximum Sv of each target, and dashed lines represent locations where target pulse widths are measured at pulse width determination levels (PWDL) of 1,3 and 6 dB . A, B, and C show target pulse widths measurements which are used to calculate the pulse length factor (see text) of each individual target using the respective PWDL. If the total Sv range of a potential target is less than the PWDL used, it is not recognized as a target.
recognition of the smallest targets. Only hydroacoustic data that corresponded with neuston net sampling times were used for analysis. Acoustic data were layered into 10 m distance intervals from the face of the transducer ( 5 m intervals for $1-10 \mathrm{~m}$ ) and layers were the length of each neuston net tow. The resulting bins were processed individually, and analysis included echo-squared integration and target strength estimation using the split-beam single target detection algorithm, each using -75dB minimum Sv threshold.

The mean backscattering coefficient ( $\bar{\sigma}_{\mathrm{bs}}$ ) for each layer was calculated from single target data using

$$
\begin{equation*}
\bar{\sigma}_{b s}=\frac{\sum_{i=1}^{n} 10^{\left(\frac{T S_{i}}{10}\right)}}{n} \tag{3}
\end{equation*}
$$

where $\mathrm{TS}_{i}$ is the target strength of individual target $i$, and $n$ is the total number of targets in the bin of interest. Fish density (fish* $\mathrm{m}^{-2}$ ) was then calculated for each layer using

$$
\begin{equation*}
\text { Density }=\frac{10^{\left(\frac{\overline{\mathrm{Sv}}}{10}\right)}}{\bar{\sigma}_{\mathrm{bs}}} \tag{4}
\end{equation*}
$$

where $\overline{\mathrm{Sv}}$ is the mean volume backscattering strength $\left(\mathrm{dB}^{\star} \mathrm{m}^{-2}\right.$ ) for the layer of interest, which is scaled by the backscattering coefficient ( $\bar{\sigma}_{\mathrm{bs}}$ ). This layered
analysis allowed for the determination of proper sampling ranges by assessing potential biases in TS and $\bar{\sigma}_{\mathrm{bs}}$ estimations at increasing distances from the transducer. Additionally, the feasibility of manually selecting areas with high signal-to-noise ratios within portions of echograms that have "patchy" noise (i.e. a number of clean pings preceded and followed by noisy pings) to obtain density estimates from otherwise unusable data was examined. For this selective data analysis, PWDL = 3dB was

## Results

## Lab Results

The 129 kHz system was able to detect all larval yellow perch with swim bladders (10-27mm, $\mathrm{n}=16$ ), but was not capable of detecting fish without a swim bladder (6-11mm, $n=5$ ). For this reason, only fish with swim bladders could be included in analysis of 129 kHz data. Although the 418 kHz system was able to detect all larval perch with and without swim bladders (9-11mm), the total sample size was too small $(n=5)$ for statistical analysis. For fish sampled using $418 \mathrm{kHz}, \overline{T S}$ was -64.2 dB , with a total range of -78.6 dB to -46.5 dB .

Swim bladder side-surface area and volume increased with larval yellow perch length (Figure 5). Linear regression was performed using $\log _{10}$-transformed swim bladder measurement data to predict mean TS:

$$
\begin{gather*}
\overline{\mathrm{TS}}=12.139 \log _{10}(\text { Area })-61.677  \tag{5}\\
\mathrm{R}^{2}=0.66 \quad \mathrm{p}<0.001 \\
\overline{\mathrm{TS}}=7.462 \log _{10}(\text { Volume })-65.416  \tag{6}\\
\mathrm{R}^{2}=0.49 \quad \mathrm{p}=0.004
\end{gather*}
$$

One fish was identified as having a swim bladder side-surface area and volume larger than expected given its length (Figure 5). This point was highly influential in TS-log 10 (length) regression analysis, with a DFFITS value of 1.643 and studentized deleted residual of 6.348 (Bonferroni critical $t$-value of 3.618 , $\alpha=0.10$, two-tailed), and was not included in the final regression equation (Neter et al. 1996). Larval yellow perch lengths were $\log _{10}$-transformed, and used to predict mean TS

$$
\begin{gather*}
\overline{\mathrm{TS}}=15.996 \log _{10}(\mathrm{~L})-84.157  \tag{7}\\
\mathrm{R}^{2}=0.54 \quad \mathrm{p}=0.002
\end{gather*}
$$

for 129 kHz , where L is total length in mm (Figure 7).

Additional variation in TS using the 129 kHZ system was attributed to the fish orientation to the transducer (Figure 8). Highest mean TS measurements were made with the fish broadside to the transducer, and the lowest mean TS
was with the fish in the head-towards the transducer orientation. Mean TS increased with size for the broadside orientation with the equation

$$
\begin{align*}
\overline{\mathrm{TS}} & =26.541 \log _{10}(L)-94.391  \tag{8}\\
r & =0.95 \quad p<0.001
\end{align*}
$$

with total length (L) in mm. Mean TS did not significantly increase with $\log _{10}($ Length $)$ for the tail-toward or head-toward orientation $(r=0.032, p=$ 0.67 and $r=0.55, p=0.20$ respectively). The highest variation in mean TS was with the fish in the tail-towards orientation.


Figure 5. Approximate air bladder area and volume for larval yellow perch used to determine TS-Length relationship. Circled points represent a single fish with larger than expected air bladder size for its length.


Figure 6. Target strength-air bladder morphology relationships for larval yellow perch using a 129 kHz transducer. Circles represent mean TS for individual fish, horizontal ticks are mean $\mathrm{TS} \pm 1$ standard deviation. Solid circle represents fish identified in Figure 5 as having larger than expected air bladder


Figure 7. Log $_{10}$ Length (mm) - Mean Target Strength regression for 129 kHz using larval yellow perch compared to Love's (1971) maximum side-aspect TS of an individual fish and Warner et al. (2002) alewife TS estimation. Vertical lines show total TS range for each fish, and horizontal ticks are mean TS $\pm 1$ standard deviation. Solid circle represents fish identified in Figure 5 as having larger than expected air bladder size, and was not included in regression analysis.


Figure 8. Mean TS for larval yellow perch for different orientations to the face of a 129 kHz transducer compared to Love's (1971) maximum TS for broadside aspect and Warner et al. (2002) alewife TS, with length in mm. Regression line is for broadside aspect. Head- and tail-toward mean TS did not significantly increase with $\log _{10}($ Length ) (p values $0.20,0.67$ respectively)

The pulse width determination level used for analysis had a large influence on the number of single targets detected. PWDL settings of 6 and 3 dB gave similar results regardless of the sea state or distance from the transducer, while PWDL of 1 dB had a greater number of larger targets as both surface disturbance and distance from the transducer increased (Figure 9). Additionally, all three PWDLs increased single target detection of large targets (>-50dB) at ranges $\mathbf{> 1 0 m}$ during times of sea surface disturbance. These results show that PWDL $=1 \mathrm{~dB}$ is not an appropriate setting for analysis, as it would bias density estimates by including noise in the calculation of $\bar{\sigma}_{\mathrm{bs}}$.

A side-looking 129 kHz transducer was effective at detecting individual targets with target strengths similar to those expected from larval yellow perch at a maximum range of approximately 30 m . The minimum detected TS was approximately -70 dB at a distance of 30 m , which increased to -66 dB at 50 m (Figure 9). This pattern was consistent for all dates, PWDLs, and water surface conditions. Based on the $\overline{T S}$ - size relationship, any larval yellow perch $>30 \mathrm{~m}$ from the face of the transducer would not be detectable.
Calm



Figure 9. Comparison of single target detections for (a) calm and (b) ripple/wave conditions for Lake Michigan surface side-looking hydroacoustic data collected on June 6, 2000 for increasing distances from the transducer (5-50m). Effects of using different pulse width determination levels (PWDL, in dB) on number of targets detected is shown (see text for parameter description), as well as a decrease in the minimum TS that can be detected as distance from the transducer increases.

Results of target strength analysis for data collected on Lake Michigan are summarized in Table 1. Mean TS increased with distance from the transducer, a pattern that was similar for all dates and PWDLs. The rate at which mean TS increases as distance from the transducer increases is, however, dependent on sea state. Mean TS increased faster with distance during ripple/wavy surface conditions then during calm/flat conditions. Echograms for data collected during ripple or wavy water surface conditions showed a rapid decrease in the signal-to-noise ratio as range increased (Figure 10). This generally resulted in an increase in the proportion of larger targets (high signal-to-noise) to small targets (low signal-to noise ratio) identified as range increased.

Selective analysis of areas of relatively high signal-to-noise ratios within areas of low signal-to-noise ratios (obtained from data collected during ripple/wavy conditions) gave results similar to calm/flat conditions, with a maximum appropriate analysis range of 30 m . Comparisons of TS analysis results of full bins (including all noisy sections) to the noise-free subsamples selected from within those bins are shown in Table 2.

Hydroacoustic and neuston net density estimates from Lake Michigan in 2000 are summarized in Table 3. Only data analyzed using PWDLs of 3 and6dB, at data collection ranges $<30 \mathrm{~m}$ are reported. Hydroacoustic larval fish density estimates obtained from data collected on calm nights were more similar

Table 1. Mean target strengths for hydroacoustic data collected in Lake Michigan in 2000, analyzed using two pulse width determination levels for single target detection (see text for parameter description). Distance offshore is in nautical miles, and bottom depth is in meters.

## PWDL = 3dB

| Date | Dist. Offshore | Bottom Depth | Mean Target Strength (dB) |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | 1-5m | 5-10m | 10-20m | 20-30m | 30-40 | 0-50m |
| 6/6 | 2.5 | 18 | -67.2 | -67.9 | -66.6 | -62.5 | -56.1 | -58.8 |
|  | 4 | 27 | n/a | -68.1 | -67.9 | -67.8 | -66.9 | -64.8 |
|  | 5.5 | 38 | -73.2 | -64.0 | -70.2 | -69.3 | -66.8 | -64.3 |
|  | 7 | 49 | n/a | -64.0 | -66.6 | -64.8 | -65.9 | -64.6 |
| 6/8 | 1 | 10 | -71.3 | -70.3 | -67.9 | -65.6 | -63.3 | -62.2 |
| 6/15 | 0.5 | 5 | n/a | -70.1 | -71.5 | -69.7 | -66.7 | -64.3 |
|  | 1 | 10 | -74.0 | -73.9 | -70.5 | -63.3 | -62.5 | -60.7 |
| 6/27 | 2.5 | 18 | -70.8 | -66.7 | -63.4 | -66.0 | -63.8 | -62.1 |
|  | 4 | 27 | -70.8 | -66.2 | -52.6 | -46.5 | -43.5 | -47.2 |
|  | 5.5 | 38 | -70.2 | -65.1 | -51.0 | -44.0 | -43.3 | -47.4 |
|  | 7 | 49 | -70.6 | -65.4 | -57.7 | -54.3 | -53.4 | -53.2 |
| 7/13 | 0.5 | 5 | -60.7 | -58.4 | -52.4 | -46.5 | -41.7 | -37.5 |
|  | 1 | 10 | n/a | -58.1 | -54.8 | -54.1 | -48.9 | -42.0 |
|  | 2.5 | 18 | -61.0 | -58.4 | -48.3 | -42.0 | -40.2 | -42.3 |
|  | 4 | 27 | -60.4 | -58.5 | -50.0 | -43.3 | -43.0 | -45.3 |
|  | 5.5 | 38 | -61.3 | -58.4 | -48.7 | -42.1 | -39.0 | -38.5 |
|  | 7 | 49 | -60.8 | -58.7 | -47.6 | -41.3 | -39.2 | -41.8 |


| PWDL= 6dB |  | Bottom <br> Depth | Mean Target Strength (dB) |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Date | Dist. Offshore |  | 1-5m | 5-10m | 10-20m | 20-30m | 30-40m | 40-50m |
| 6/6 | 2.5 | 18 | -68.4 | -69.6 | -68.8 | -67.1 | -60.2 | -61.6 |
|  | 4 | 27 | n/a | -70.4 | -69.4 | -69.4 | -67.0 | -64.9 |
|  | 5.5 | 38 | -73.2 | -64.2 | -72.3 | -69.6 | -67.2 | -64.9 |
|  | 7 | 49 | n/a | -63.6 | -71.3 | -67.7 | -66.5 | -64.7 |
| 6/8 | 1 | 10 | -71.7 | -72.0 | -71.9 | -69.8 | -66.7 | -64.7 |
| 6/15 | 0.5 | 5 | n/a | -70.5 | -71.8 | -70.0 | -67.0 | -65.1 |
|  | 1 | 10 | -72.4 | -71.6 | -71.3 | -68.3 | -66.6 | -64.4 |
| 6/27 | 2.5 | 18 | -71.7 | -70.0 | -69.1 | -68.6 | -66.7 | -64.3 |
|  | 4 | 27 | -71.4 | -70.3 | -60.0 | -53.9 | -57.5 | -60.2 |
|  | 5.5 | 38 | -71.1 | -70.0 | -56.8 | -50.0 | -55.3 | -57.7 |
|  | 7 | 49 | -71.3 | -70.3 | -57.9 | -52.0 | -54.3 | -58.6 |
| 7/13 | 0.5 | 5 | -60.7 | -59.7 | -56.4 | -53.9 | -47.9 | -48.4 |
|  | 1 | 10 | n/a | -59.1 | -58.1 | -58.3 | -57.5 | -52.1 |
|  | 2.5 | 18 | -61.0 | -59.8 | -52.9 | -44.7 | -43.8 | -54.0 |
|  | 4 | 27 | -60.4 | -59.9 | -54.1 | -44.8 | -48.6 | -52.3 |
|  | 5.5 | 38 | -61.3 | -60.0 | -51.9 | -43.3 | -41.0 | -45.2 |
|  | 7 | 49 | -60.8 | -60.1 | -50.9 | -43.5 | -43.9 | -49.0 |



Figure 10. Examples of echograms for different levels of surface water disturbance for Lake Michigan data collected on June 6, 2000. Grayscale bar represents uncorrected target strength in dB , with black as the strongest echo. At distances $>10 \mathrm{~m}$ during wavy/ripple conditions, background noise (i.e. non-fish echoes) was >-50dB.

Table 2. Comparison of $\overline{\mathrm{S}_{\mathrm{V}}}, \overline{\mathrm{TS}}$, and density estimates using full bins (corresponding to an entire neuston net tow) and "noise-free" subsamples from within each bin for data collected in Lake Michigan on June 6, 2000. Bottom depth is in meters, sample range is distance from the transducer, $\overline{\mathbf{S}_{V}}$ is in units of $\mathrm{dB}^{*} \mathrm{~m}^{-3}, \overline{\mathrm{TS}}$ is dB , and density is fish $\mathrm{m}^{*}$.

| Bin \# | $\begin{aligned} & \text { Bottom } \\ & \text { Depth } \\ & \hline \end{aligned}$ | Sample <br> Range | Full Bin |  |  | Acoustic <br> Density | Neuston <br> Denstiy |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | \#pings | $\overline{\mathrm{s}} \mathrm{V}$ | TS |  |  |
| 1 | 18 | 1-10m | 2200 | -69.6 | -69.0 | 0.218 | 0.007 |
| 2 | 18 | 10-20m | 2200 | -62.7 | -68.8 | 0.073 | 0.007 |
| 3 | 18 | 20-30m | 2200 | -59.5 | -67.1 | 0.044 | 0.007 |
| 4 | 27 | 1-10m | 2500 | -81.7 | -70.4 | 0.026 | 0.005 |
| 5 | 27 | 10-20m | 2500 | -74.6 | -69.4 | 0.011 | 0.005 |
| 6 | 27 | 20-30m | 2500 | -73.8 | -69.4 | 0.013 | 0.005 |
| 7 | 27 | $30-40 \mathrm{~m}$ | 2500 | -76.2 | -67.0 | 0.106 | 0.005 |
| 8 | 27 | 40-50m | 2500 | -77.2 | -64.9 | 0.052 | 0.005 |


|  |  |  | Subsample within Bin |  |  | $0.010$ | 0.007 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 18 | 1-10m | 40 | -90.8 | -70.7 |  |  |
| 2 | 18 | 10-20m | 40 | -76.0 | -58.1 | 0.016 | 0.007 |
| 3 | 18 | 20-30m | 40 | -84.7 | -66.3 | 0.015 | 0.007 |
| 4 | 27 | 1-10m | 362 | -81.7 | -62.3 | 0.003 | 0.005 |
| 5 | 27 | 10-20m | 362 | -75.3 | -69.9 | 0.029 | 0.005 |
| 6 | 27 | 20-30m | 362 | -83.4 | -67.5 | 0.028 | 0.005 |
| 7 | 27 | $30-40 \mathrm{~m}$ | 362 | -87.8 | -63.9 | 0.020 | 0.005 |
| 8 | 27 | 40-50m | 362 | -88.0 | -64.4 | 0.017 | 0.005 |

Table 3. Comparison of density estimates obtained from hydroacoustic and neuston net sampling on Lake Michigan in 2000 using two PWDL settings for $\bar{\sigma}_{\mathrm{bs}}$ calculation (see text for parameter description). Bottom depth is in m , sample range is distance from the transducer, and all densities are fish* $\mathrm{m}^{-3}$.

to neuston net density estimates than data collected on nights of rougher sea states. Increased density estimates for nights of wavy conditions were a result of increased amount of backscattered sound (Figure 10). Additionally, density estimates tended to decrease with range for nights of wavy or ripple conditions, with highest density estimates calculated for the $5-10 \mathrm{~m}$ range.

## Discussion

Laboratory work showed that hydroacoustics is efficient at detecting larval yellow perch with inflated swim bladders using a 129 kHz system, and capable of detecting larval perch at all stages of development at 418 kHz . Field sampling of larval fish populations using mobile surface side-looking hydroacoustics may be a viable option for filling in spatial gaps created when using traditional gear. Additionally, acoustics has the ability to detect fish that cannot be collected in traditional gear due to avoidance behavior as fish become larger and more developed.

Comparison of our TS - length relationship with those developed in other studies provided confirmation that the hydroacoustic system used in our study reliably estimated larval yellow perch TS. Maximum observed TS measurements for larval yellow perch were consistent with those expected based on the maximum side aspect TS defined by Love (1971), although the fish used by Love were not as small as those used for this study (Figure 7). Warner et al. (2002)
reported a TS - length relationship for alewives that is slightly higher than that determined by our study (Figure 7). Although Wamer et al. (2002) used a downlooking 70 kHz split-beam system, the fish used to determine the relationship were as small as 8 mm , which is close to the minimum size used in our analysis. Although no TS - length equation was reported, Rudstam et al. (2002) showed TS estimates of larval fish $5-15 \mathrm{~mm}$ (mean 9.5 mm ) were between -76 and -64 dB using a down-looking 70kHz split-beam system. These results were similar to laboratory mean TS estimates for larval yellow perch in our study with mean TS of -67 dB for fish $10-14 \mathrm{~mm}$ (mean 12.3 mm ). For fish $15-25 \mathrm{~mm}$, however, our laboratory mean TS measurements were lower (-64dB, 20.1 mm mean length) than those found by Rudstam et al. (2002, -59dB, 20.3 mm mean length). Although these other studies used down-looking methods for hydroacoustic data collection, the increases in mean TS with fish length show slopes consistent with that determined by analysis of laboratory acoustic data for larval yellow perch in this study. Based on the results of our laboratory TS work, it was determined that a 129 kHz split-beam system would be effective at detecting larval fish with swim bladders in the field, and has the potential to yield reliable and useful information on larval fish densities, distributions, and movement patterns.

Love (1971) showed fish should have greater TS from a side-aspect than a dorsal aspect. Our results of side-aspect analysis show lower mean TS than those found for similar sized fish using dorsal aspect. Measurements of the swim bladders of the larval yellow perch used in this study showed that the
maximum depth of the swim bladder (perpendicular to the length of the fish from a dorsal aspect) was an average of 1.5 times the height of the swim bladder (perpendicular to the length of the fish for a side aspect). This difference would increase the amount of sound reflected by a fish in a dorsal aspect orientation compared to one in a side aspect orientation, resulting in higher TS for dorsal aspect.

Discrepancies between hydroacoustic and neuston net density estimates on calm water nights may be attributed to several factors, including swim bladder inflation and patchiness in horizontal or vertical distribution. Although swim bladder information was not available for larval fish collected in neuston nets in 2000, examination of fish collected in 2001 showed a range of $0-50 \%$ of larval perch had developed air bladders. Assuming similar percentages for larval fish collected in 2000, hydroacoustic density estimates would not have included fish of the same stage of development that estimates from the neuston net would have. Additionally, few fish larger than 8 mm were collected in neuston net samples. If such fish were present, they would have been included in hydroacoustic density estimates.

Patchiness in larval fish distribution may also account for differences in density estimates from neuston net samples and hydroacoustics. Given the volume of water sampled by the neuston net per transect (approximately $15,000 \mathrm{~m}^{3}$ ) compared to that sampled by hydroacoustics (approximately 141,000
$m^{3}$ at 30 m range), such patches may not be accounted for when using neuston samples to estimate density. Additionally, while the neuston net samples a depth of $0-1 \mathrm{~m}$, the transducer was towed at a depth of $1-2 \mathrm{~m}$ to minimize acoustic signal interference with the surface. At a range of 30 m , the lower edge of the acoustic cone would sample a depth range of approximately $1-4 \mathrm{~m}$. While the volume of water sampled using the two techniques is not the same, larval perch are known to occupy the upper region of the water column where both techniques sampled. However, any vertical patchiness within the upper 4 m of the water column could potentially result in differences in density calculations between the two sampling methods.

The most significant limitations of using side-looking hydroacoustics is the dependence of the technique on calm surface conditions, and the maximum distance at which larval fish size targets can be detected. Density estimates on calm days at distances $<30 \mathrm{~m}$ were much closer to neuston net densities on calm days than on rough days. This greatly limits the number of days that can be successfully sampled in a season on large lakes. This study used a limited number of sampling days in 2000, and it was not possible to always choose the best (i.e. most calm) days when determining cruise schedules. Researchers with immediate access to a lake would likely have greater success with this technique by increasing the number of good sampling days per season. Additionally, the application of this technique to simultaneously monitor densities of both larval
and adult fish populations on inland lakes could be beneficial, as potentially more calm days would be available for sampling.

Limitations of the technique also include a minimum depth (1m) at which the transducer must be towed to avoid and water/air boundary interference with the acoustic signal. Signal contamination results from the acoustic side-lobes (an unavoidable property of underwater acoustic cones) coming in contact with the water surface. As such, it is not possible to sample the uppermost portion of the water acoustically and keep the acoustic cone parallel to the water surface.

This study has shown that a 129 kHz split-beam acoustics system is highly proficient in detecting larval yellow perch with swim bladders in the laboratory, and given the right conditions, can yield reasonable density estimates in the field. Although not tested in the field, a 418 kHz system is capable of detecting larval perch at all stages of development. Potential limitations of a 418 kHz system are the potential for this higher frequency to detect zooplankton (which may confound larval fish density estimates), and a reduced sampling range compared to a 129 kHz system. Hydroacoustic technology could prove very useful in helping to determine the distribution of larval yellow perch during and after their post-hatch transport offshore. Hydroacoustics removes many of the limitations of current sampling methods, and may allow for the tracking of yellow perch populations throughout their first summer of growth prior to moving inshore in the fall. Further development of the surface side-looking technique may allow researchers to
track larval yellow perch (or any other species of interest) after gear avoidance begins to bias information gained using traditional sampling methods. Filling in the gap in the knowledge of the spatial distribution of perch during and after their offshore movement is key in determining the factors that influence survival, and in turn regulate recruitment.

## CHAPTER 3

Spatio-Temporal Overlap of Larval Yellow Perch with Potential Predators in Southwestern Lake Michigan


#### Abstract

Alewife (Alosa pseudoharengus) predation on larval yellow perch (Perca flavescens) has been identified as a potential mechanism responsible for the observed declines of yellow perch in Southern Lake Michigan. For predation to occur, alewife must overlap in space and time with larval yellow perch. Thus, understanding the timing and duration of predator-prey overlap is critical for understanding the potential impact alewife may have on larval yellow perch. Here, we used hydroacoustics to track the time-varying distributions and densities of predators in southern Lake Michigan from 1999-2001. These data were used in conjunction with larval yellow perch distribution and density data from neuston net samples to estimate the duration and extent of spatial overlap of larval yellow perch with their potential predators. In addition, temperature was measured to determine if potential predator movement and changes in density were related to thermal changes. Alewives and other potential predators were mostly offshore, with little spatial overlap with immediately post-hatch larval yellow perch. However, predator and larval yellow perch overlap increased with time corresponding with the offshore transport of larvae. Potential predator densities were greatest in 2000, and in 2000 and 2001, predator densities increased offshore with the onset of thermal stratification in early summer. Thus potential for mortality due to predation was greatest in offshore waters of southwestern Lake Michigan in 2000. With observed low larval yellow perch densities in all years, high predation rates in areas of strong overlap would have the potential to play a role in limiting yellow perch recruitment.


## Introduction

Drastic declines in yellow perch (Perca flavescens) recruitment in Lake Michigan since the early 1990s have focused research on determining the factors that regulate survival (Francis et al. 1996). Although the exact mechanisms and their relative impacts have not been determined, it has been generally agreed upon that the controlling of yellow perch recruitment occurs during the early life stages. Much attention has been paid to the role of the alewife (Alosa pseudoharengus) in limiting yellow perch recruitment. Shroyer and McComish (2002) described a clear negative relationship between local alewife abundance and local yellow perch recruitment (abundance at age-2) in southern Lake Michigan. Predation on larval fish by adult alewives has been observed (Jansen and Brandt 1980, Wells 1980, Brandt et al. 1987, Krueger et al. 1995), and can be a significant source of larval yellow perch mortality (Mason and Brandt 1996). Although this study focuses on alewife as the major potential predator, another species present in Lake Michigan, the rainbow smelt (Osmerus mordax), may also prey on larval fish (Crowder 1980; Loftus and Hulsman 1986; Hrabik et al. 1998). Predation on larval yellow perch, particularly by adult alewives, during their post-hatch offshore transport has been identified as having strong potential to impact survival, and in turn, year class strength. Determining the degree to which predation on larval yellow perch is important in regulating recruitment in Lake Michigan is critical for understanding the current status of yellow perch.

For predation to be a factor influencing larval yellow perch survival in Lake Michigan, potential predator populations must overlap in space and time with larval yellow perch distributions. Timing of yellow perch spawning in the spring is a function of winter water temperature, and although slightly variable between years, occurs within a predictable time frame (Hokanson 1977). Post-hatch larval yellow perch are transported offshore in the upper water column (Post and McQueen 1988). Alewives display a highly variable timing of inshore spawning movement, and in Lake Ontario this timing has been shown to vary by as much as 2 months from year-to-year (Mason and Brandt 1996). Predation would likely be strongest when high densities of alewives and other predators are present nearshore in spring when larval yellow perch hatch. Post-spawn adult alewives move offshore and occupy the thermocline during times of thermal stratification in the Great Lakes as the summer progresses (Brown 1972; Argyle 1982; Brandt 1980; Brandt et al. 1980; Crowder and Magnuson 1982). Additional predation may occur throughout the summer in offshore waters if predator movement is coincident with larval perch offshore transport.

The factors influencing the migration patterns of adult alewives are not well understood. Temperature has been shown to influence alewife distribution in Lake Ontario, where the mean depths of alewife capture decreased exponentially with increasing mean temperature near bottom during April-June (O'Gorman et al. 1991). In Lake Michigan, Wells (1968) demonstrated that movement of alewives toward shore in the spring was correlated with the
warming of inshore waters. Mason and Brandt (1996) suggest the key to understanding the interactions between alewives and larval yellow perch lies in our ability to effectively predict alewife movements based on environmental conditions. Quantification of environmental cues such as changes in temperature may be used to help predict the timing and duration of alewife migration inshore in the spring and their subsequent movement offshore in the summer.

The objectives of this study were to: (1) determine the extent of spatial and temporal overlap of larval yellow perch and their potential predators in southwestern Lake Michigan, (2) identify the potential for alewife predation to impact larval yellow perch survival, and (3) explore the potential for water temperature as a cue for the offshore movement patterns of predators. Hydroacoustics data were collected in southwestern Lake Michigan to estimate nearshore densities of potential larval yellow perch predators during the time of larval yellow perch hatch in spring 2000 and 2001. Additional hydroacoustic data were used to track the distribution and density of alewives and other potential predators during their summer migration to offshore waters from 1999-2001. These data were used in conjunction with larval yellow perch distribution and density data (collected using a neuston net) to determine the amount of spatial and temporal overlap that occurred between the two species during sampled years.

## Methods

## Field Sampling

Sampling was done at night on Lake Michigan aboard the Illinois Natural History Survey (INHS) RV Sculpin out of Waukegan Harbor, IL. Trawl sampling and hydroacoustic surveys were conducted simultaneously in 2000 and 2001 along a 0.25 nautical mile $(\mathrm{nm})$ transect along the 10 m depth contour. In addition, 6 nm hydroacoustic transects perpendicular to shore, starting at approximately 8 m and terminating at 50 m depth were used to estimate the spatial distribution of potential larval yellow perch predators (Figure 11). In 1999 hydroacoustic transects were run perpendicular to shore, and no trawl samples were collected (Figure 11).

A bottom trawl $(4.9 \mathrm{~m}$ head rope, 38 mm stretch mesh body, 13 mm cod liner mesh) was used by the INHS in 2000 and 2001 to gather species composition data to ground truth hydroacoustic data. Fish caught were identified to species, measured, and counted. Gear limitations restricted the maximum trawl depth to 10 m . Larval fish were collected by the INHS using a $1 \mathrm{~m} \times 2 \mathrm{~m}$ frame neuston net with $500 \mu \mathrm{~m}$ mesh in June 2000 and 2001, and $1000 \mu \mathrm{~m}$ in July 2000 and 2001. Neuston net tows were 10 min in duration, and were used along trawl transects, and at four evenly spaced points along the offshore transect


Figure 11. Transects used for hydroacoustic, trawl and neuston net sampling in Lake Michigan 1999-2001. No trawl or neuston net samples were taken along any transects in 1999. Circles represent approximate locations of neuston net samples in 2000 and 2001.
(Figure 11). Neuston net sampling was used to determine the density and spatial distribution of larval yellow perch.

Alewife abundance and spatial distribution data were collected using a Biosonics DT6000 129 kHz digital split-beam transducer with a $6.2^{\circ}$ nominal beam angle and a source level of $225 \mathrm{~dB}^{*} \mu \mathrm{~Pa}^{-1}$. Transducer was mounted in the down-looking configuration on a four-foot Biosonics BioFin ${ }^{\text {TM }}$ stable towbody and was towed along side the boat at $1.3-1.8 \mathrm{~m}^{*} \mathrm{~s}^{-1}$ for the trawl transect, and $2.5-3$ $\mathrm{m}^{*} \mathrm{~s}^{-1}$ for the offshore transect. Tow depth was $1-2 \mathrm{~m}$, with tow depth increasing as wave action increased to ensure the transducer remained below the surface. Data collection parameters were set at 5 pings* $\mathrm{sec}^{-1}$ for bottom depths $<30 \mathrm{~m}$ and 3 pings*sec ${ }^{-1}$ for depths $>30 \mathrm{~m}, 0.4 \mathrm{~ms}$ pulse width, and -80 dB minimum volume backscatter (Sv) threshold (-65dB in July 2000). System calibration was performed using a tungsten-carbide reference sphere. All acoustic data were recorded directly to a laptop hard drive for later analysis. A Vemco minilogger was attached to the towbody and recorded surface water temperatures every 5 sec along each transect.

## Data analysis

Hydroacoustic data were analyzed using Echoview v2.20.52 software (SonarData Pty Ltd 1995-2001). All raw acoustic data were corrected for transducer frequency, nominal beam angle, and water temperature (sound speed correction) for both echo integration and single target detection.

Absolute fish density estimation using hydroacoustic data is determined using relative density ( $\overline{S v}$, a measure of the total sound reflected in a volume of sampled water) and the mean backscatter coefficient ( $\bar{\sigma}_{b s}$, an estimate of the amount of sound reflected by an individual fish). Both $\overline{S v}$ and $\bar{\sigma}_{b s}$ must be representative of the size of potential predators to correctly estimate their density. Although this study focused on the role of alewives as the major larval yellow perch predator, rainbow smelt and spottail shiners (Notropis hudsonius) are other potential predators that may also be present (Wells 1968, Crowder et al. 1981). Warner et al. (2002) predicts that a 7 cm alewife (approximately the smallest observed in trawl samples from this study) would have a target strength (TS) of -47 dB . The smallest smelt found in trawl samples were approximately 5 cm . Rudstam et al. (in press) show that 5 cm smelt have a TS of -55 dB , and Fleisher et al. (1997) predict a TS of -55 dB for 7 cm Great Lakes pelagic planktivores. To include all potential predators in analysis, this study used -55db as a minimum threshold for both $\overline{S v}$ and $\bar{\sigma}_{b s}$ calculation.

Echoview requires user-defined parameter settings for single target detection. The minimum pulse length factor was set to 0.25 (proportion of transmitted pulse length), and the maximum standard deviations for alongship and athwartship angles were $1^{\circ}$. The maximum beam compensation was set to 5dB, which allowed single target identification only within the nominal beam, and the pulse length determination level was set to 6 dB (see Chapter 2, Figure 4 for parameter description). All single targets >-55dB were used for $\bar{\sigma}_{b s}$ calculation.

The Echoview bottom detection algorithm was used with the discrimination level set to -50 dB , and a backstep of -0.25 m . All bottoms identified were manually edited to ensure that echoes from the lake bottom were not included in echo integration. If any potential target was located below the bottom line defined by Echoview, but was clearly separated from the bottom, the line was redrawn so the echo would be included in integration. Additionally, any sections of the echogram containing apparent noise were manually isolated and excluded from analysis

Hydroacoustic data were processed to determine relative fish density ( $\overline{S v}$ ) using echo-squared integration. Acoustic data for each sample period along the trawl transect were integrated as one bin, and echo integration included only $\overline{S v}$ values collected $>2 m$ from the face of the transducer. Hydroacoustic data collected along offshore transects were divided into bins by bottom depth, with each bin representing 5 m of depth change (Figure 12). For sections of the transect with bottom depths $<15 \mathrm{~m}$, all $\overline{S v}$ values above the bottom detection line were included in analysis. For transect sections with bottom depths $\mathbf{> 1 5 m}$, echo integration was performed only for the upper 15 m of the water column, which included all fish within the epilimnion and thermocline. The thermocline extended to a depth of approximately 20 m on July 5 and 9,2001 . For these dates echo integration included data to depths of 20 m .


Figure 12. Example of an echogram showing data analysis bins (a-h) used for hydroacoustic predator density estimates, with each bin representing a 5 m change in bottom depth. For July 5 and 9, 2001, a maximum analysis bin depth of 20 m was used.

The mean backscatter coefficient was determined from the results of single target analysis, and $\bar{\sigma}_{b s}$ was calculated for each individual bin processed. Absolute fish density (number* $\mathrm{m}^{-3}$ ) was calculated for each bin for all dates and transects using the equation

$$
\begin{equation*}
\text { Density }=\frac{10^{\left(\frac{\overline{S v}}{10}\right)}}{\bar{\sigma}_{b s}} \tag{1}
\end{equation*}
$$

In addition, mean surface water temperatures for each bin along the offshore transect were calculated.

## Results

1999

## Offshore Transect

The highest densities of predator size targets were in the $10-15 \mathrm{~m}$ depth bin on June 9, with lower densities in the upper 15 m of the water column further offshore (Figure 13). Relatively low densities (maximum 0.005 fish ${ }^{*} \mathrm{~m}^{-3}$ ) were calculated for the entire length of each transect used on June 24 and July 9, with maximum bottom depths of 30 m and 37 m respectively. Relatively high numbers of potential predator size (>-55dB) single targets were identified in the top 15 m of


Figure 13. Hydroacoustic density estimates of potential predator-size targets (>-55dB, approximately 7 cm ) in the upper 15 m of water ( 20 m on July 5 and 9, 2001) along the offshore transect from 1999-2001.
the 10-22m bottom depth range on June 6 (Figure 14). Smaller targets (<-55 dB) represented the majority of single targets along all transects in all depth bins. Target distributions throughout the water column for the entire length of each transect are shown in Figure 15. Again, larger targets were identified in the upper portion of the water column in early June, with few large targets at depths >10m. By early July, few large targets were identified at any depth, and smaller targets were scattered throughout the entire water column. Surface water temperatures for June 24 and July 7 were $>20^{\circ} \mathrm{C}$ along the entire length of each transect (Figure 16). No comparison of larval yellow perch and potential predator distributions could be done using 1999 data because neuston net samples were not collected.


Figure 14. Target strength frequency distributions of targets in the upper 15 m of the water column for nearshore ( $<30 \mathrm{~m}$ bottom depth) and offshore ( $>30 \mathrm{~m}$ ) waters along the offshore transects in 1999. No date were collected in water >29m deep on June 6. Only data >-55dB were used for echo integration (dotted vertical line).


Figure 15. Target strength distributions by depth for the offshore transects in 1999 showing concentrations of targets within the thermocline. Note there is no offshore spatial distribution along the transect represented.


Figure 16. Mean water surface temperature in Lake Michigan along the offshore transects from 1999-2001.

Trawl Transects

Predator-size target densities were greatest in mid-May, lowest in early to mid-June, and increased in late-June along the trawl transect (Figure 17). Species composition of trawl catches indicate alewives were most abundant along this transect in mid-May, with very few caught after May 22, and none caught after June 19 (Figure 18). Low fish densities resulted in few individual targets being identified by single target analysis of hydroacoustic data, which did not allow for target strength distributions to be constructed for comparison to length distributions of trawl-caught fish. Instead, the mean TS of targets >-55dB for each date were calculated (Figure 19). Mean TS for the trawl transect did not significantly change throughout the sampling period in $2000\left(r^{2}=0.034, p=0.73\right)$.

Larval yellow perch were not found in neuston net samples until June 8 (Figure 17). Acoustic and trawl data indicate that alewives likely were not present in high densities during the early stages of the perch hatch inshore. Although potential predator size acoustic targets were identified in late-June, few alewives were collected in trawl samples after June 6, and none were collected after June 15. No neuston net data were collected along the trawl transect after June 19.


Figure 17. Potential larval yellow perch predator (targets $>-55 \mathrm{~dB}$ ) densities using hydroacoustics and larval yellow perch densities calculated from neuston net samples along the trawl transect (nearshore, 10 m bottom depth) in Lake Michigan in 2000-2001. Hollow circles represent dates when alewives were not collected in a bottom trawl towed simultaneously with hydroacoustic data collection.


Figure 18. Species composition of bottom trawl samples collected in 10 m depth in Lake Michigan in 2000 and 2001.


Figure 19. Mean target strength ( $\pm 1 \mathrm{SD}$ ) for targets $>-55 \mathrm{~dB}$ along the Lake Michigan trawl transects in 2000 and 2001. Mean TS did not significantly change for either year ( $p=0.73, p=0.102$ for 2000 and 2001 respectively).

Nearshore, the highest acoustic density of potential predator size targets along with high numbers of alewives caught in trawls were found in mid-May when water surface temperature was $10^{\circ} \mathrm{C}$ (Figure 20). Much lower acoustic densities and numbers of alewife caught in trawls were found as surface temperatures rose through mid-June. No alewives were present in trawls after water surface temperatures reached approximately $17^{\circ} \mathrm{C}$.

## Offshore Transects

From mid-May through mid-June, potential larval yellow perch predator densities were highest in nearshore waters (bottom depth <20m), with very low densities found further offshore (Figure 13). Predator-size target densities increased nearshore by late June, and decreased through July 13 (Figure 13). Highest densities of potential predators were found in the upper 15 m of water where bottom depths were $>20 \mathrm{~m}$ in late-June (Figure 13). By July 13, potential predator size target densities had decreased in waters $<30 \mathrm{~m}$, and were highest in offshore waters (Figure 13). In mid-May, targets of all sizes were detected along the entire length of the transect, but larger targets were not detected from late-May through mid-June (Figure 21). By late-June, the majority of targets identified in offshore waters ( $>30 \mathrm{~m}$ bottom depth) were of potential predator size (Figure 21), and these targets were concentrated in the epilimnion and thermocline (Figure 22).


Figure 20. Acoustic target (>-55dB) density and mean surface temperature along the Lake Michigan trawl transect in 2000 and 2001. Hollow circles represent dates with no alewives collected in bottom trawl samples (collected simultaneously with hydroacoustic data).


Figure 21. TS frequency distributions for targets in the upper 15 m of the water column for nearshore ( $<30 \mathrm{~m}$ bottom depth) and offshore ( $>30 \mathrm{~m}$ ) waters of the offshore transect in Lake Michigan in 2000. No Data <-65dB were collected on July 13. Only data >-55dB were used for echo integration (dotted vertical line).


Figure 22. Target strength distributions by depth for the offshore transects in 2000 showing concentrations of targets within the thermocline. Note there is no offshore spatial distribution along the transect represented.

On June 15, the highest larval yellow perch densities were found in the 15-20m depth bin (Figure 23). Low densities of hydroacoustic targets >-55dB were found in that depth range, however (Figure 21). No hydroacoustic data were collected in water $\mathbf{> 2 2 m}$ on June 15. Larval yellow perch were present in offshore waters during times of thermal stratification in late-June (Figure 23). Hydroacoustic density data show that the distributions of larval yellow perch and their potential predators had a high degree of spatial overlap during the offshore transport of larval yellow perch in late-June through early-July (Figure 23). Additionally, target strengths expected from larval yellow perch (Chapter 1) were located throughout the upper 15 m of water, indicating that spatial overlap may extend vertically throughout the thermocline (Figure 22).

The highest densities of targets >-55dB on May 15 (Figure 13) were found in the warmest water (approximately $10^{\circ} \mathrm{C}$ surface temperature) along the transect, with low densities found in all areas $<10^{\circ} \mathrm{C}$ (Figure 16). From May 22 through mid-June, potential predator densities were low (Figure 13) along the entire offshore transect, with temperatures ranging from $9^{\circ} \mathrm{C}$ to $13^{\circ} \mathrm{C}$ (Figure 16). Potential predator densities along the offshore transect were higher in the upper 15 m of water in bins with bottom depths $\mathbf{> 2 0 m}$ (Figure 13) when the water surface temperature rose over $16^{\circ} \mathrm{C}$ in late-June (Figure 16). By July 13, the highest densities of targets >-55dB were found in bins with bottom depths $>30 \mathrm{~m}$ (Figure 13), when the water temperature along the entire transect was nearly constant at approximately $21^{\circ} \mathrm{C}$ (Figure 16).


Figure 23. Acoustic density of targets $>-55 \mathrm{~dB}$ in the upper 15 m of water along the offshore transect in Lake Michigan in 2000 during times of larval yellow perch presence in neuston net samples.

## Trawl Transect

Equipment failure resulted in no data collected between May 30 and June 28. Alewives were present in trawl samples for all dates sampled in 2001 except June 28 (Figure 18). Densities of predator-size targets were low ( $<0.004^{*} \mathrm{~m}^{-3}$ ) and remained relatively constant for all dates of sampling (Figure 17). The low number of single targets detected for each date in 2001 did not allow TS frequency distributions to be created. Although mean TS for targets >-55dB was greater at the end of the sampling period $(-43 \mathrm{~dB})$ than at the beginning $(-48 \mathrm{~dB})$, the overall increase was not significant $\left(r^{2}=0.64, p=0.102\right)$ (Figure 19).

Larval yellow perch were present in neuston net samples along the trawl transect in 2001 from late-may through early-July (Figure 17). Density estimates along the trawl transect were similar to 2000 for the same time period. Although potential predator size targets were detected during times of larval yellow perch presence, estimated densities were very low. Additionally, the maximum estimated yellow perch density along the trawl transect in 2001 was almost three times lower than the maximum density calculated in 2000.

The mean surface temperature along the trawl transect in 2001 is shown in Figure 20. The disappearance of alewives and most other species from the
trawl sample collected on July 9 coincided with an increase in water temperature from $19^{\circ} \mathrm{C}$ (on July 5 ) to $22^{\circ} \mathrm{C}$. Alewives were again found on July 16 when the mean surface water temperature was $21^{\circ} \mathrm{C}$. No hydroacoustic or trawl sampling was performed after July 16 along the trawl transect.

## Offshore Transect

Hydroacoustic density estimates for potential predators along the offshore transect for 2001 are shown in Figure 13. Based on information from single target distribution (Figure 24), the maximum depth range of data analysis was 20 m for July 5 and 9. The maximum depth of analyzed data for all other dates in 2001 was 15 m . Mean densities of targets >-55dB were an order of magnitude lower than in 1999 and 2000, with a maximum density for all dates in 2001 of $0.012^{*} \mathrm{~m}^{-3}$ (July 9). In late-May 2001, densities were relatively low in the upper 15 m of water along the entire transect, with the exception of a peak in the $20-$ 25 m water depth bin. By late-June, densities had increased further offshore, with the maximum fish density in the $40-45 \mathrm{~m}$ depth bin. Densities along the transect on July 5 show relatively low numbers along the entire transect, with the highest densities found in depth bins $\mathbf{> 2 0 m}$. Densities greatly increased on July 9, with higher densities found in the upper 20 m of water in the $20-40 \mathrm{~m}$ bottom depth bins. By July 16, however, densities had again decreased along the entire transect, with maximum densities found in depth bins $<30 \mathrm{~m}$. Starting in lateJune, targets of all sizes were found throughout the transect, with little difference


Figure 24. Target strength distributions by depth for the offshore transects in 2001 showing concentrations of targets within the thermocline. Note there is no offshore spatial distribution along the transect represented.
between nearshore ( $10-30 \mathrm{~m}$ ) and offshore ( $30-50 \mathrm{~m}$ ) areas (Figure 25). As the thermocline became established by late-June, targets of all sizes (>-75dB) were located in the upper 15 m of the water column (Figure 24). On July 5 and 9, however, the thermocline was not as well defined, and targets of all sizes extended to a depth of 20 m . Targets of all sizes (including larval yellow perch size, see Chapter 2) remained in the thermocline through July 16, 2001.

Larval yellow perch were present in the top 1 m of the water column on June 28, 2001 (Figure 26). Highest larval perch density at this time was found at the furthest offshore point of the transect in approximately 48m water depth. Highest estimated potential predator density was also at the furthest offshore point of the transect during that time. By July 5, larval yellow perch were found along with low predator densities throughout the transect. Low larval yellow perch densities were calculated from neuston net samples collected in the 3540m depth bin on July 9, with the highest potential predator densities found in the 20-40m bins. Although hydroacoustic data were collected on July 16 and show the highest predator density nearshore ( $<30 \mathrm{~m}$ bottom depth), no neuston net samples were collected on this date. Neuston net sampling indicate that larval yellow perch were present along the transect until July 31, 2001.

Temperature data were not collected on May 30. In late-June, surface temperatures were relatively constant along the entire transect at $21^{\circ} \mathrm{C}$ (Figure 16). By July 5 , temperatures decreased to approximately $18^{\circ} \mathrm{C}$ nearshore $(<30 \mathrm{~m}$


Figure 25. Target strength frequency distributions of targets in the upper 15 m (May 30, June 28, July 16) and upper 20 m (July 5, 9) of nearshore and offshore waters along offshore transects in southwestern Lake Michigan in 2001. Only data >-55dB were used for echo integration.


Figure 26. Acoustic density of targets >-55dB in the upper 15 m of water along the offshore transect in Lake Michigan during times of larval yellow perch presence in neuston net samples in 2001.
bottom depth) and $17^{\circ} \mathrm{C}$ further offshore ( $>30 \mathrm{~m}$ ). This decrease in offshore temperature coincided with a decrease in potential predator density in the upper portion of the water column in areas of bottom depths $>30 \mathrm{~m}$ (Figure 13). Temperatures increased to approximately $21^{\circ} \mathrm{C}$ along the entire transect on July 9, at which time potential predator densities also increased along the entire transect. Although surface water temperatures along the transect rose only slightly by July 16 , with a nearly constant temperature of almost $22^{\circ} \mathrm{C}$, predator density decreased along the entire transect.

## Discussion

Yellow perch year class strength is most likely determined during the early life-stages (Forney 1971), and predation during the larval stages can greatly increase mortality rates (Mason and Brandt 1996). In some aquatic systems, predation pressure on larval fish may result in prey behavior modifications (i.e. seeking refuge) that reduce the chance of encounter with predators (Mittlebach 1986). Success with such behavior modification would rely on two factors, first the ability of the prey to determine its location within the water volume, and second the availability of shelter to protect it from a predator. In southwestern Lake Michigan, larval yellow perch are advected offshore with mass water movement due to currents and strong wind events (Clady 1976), indicating the overall inability of larval yellow perch to seek refuge. Additionally, the advection of larval yellow perch offshore completely removes any physical structure that
may aid in predator avoidance. Because of this, larval yellow perch in a largelake system such as Lake Michigan may have a reduced ability to avoid predators compared to their small-lake system counterparts. This apparent inability of larval yellow perch to avoid predation risk during their offshore movement in southwestern Lake Michigan suggests that any spatial and temporal overlap with potential predator distributions could result in a decline in larval yellow perch survival.

The amount of spatial and temporal overlap of potential predators and larval yellow perch in southwestern Lake Michigan varied among years, suggesting that predation pressure differed between years. The highest densities of potential predators in 1999 occurred nearshore in early June, indicating there was the potential for high predation pressure on recently hatched yellow perch. This coincident timing of larval yellow perch hatch and high densities of alewives in nearshore waters (10m bottom depth) was not apparent in 2000 and 2001 suggesting predation pressure on immediately post-hatch larvae was low for these years. In contrast to the timing of predator and prey overlap in nearshore waters, predator and prey overlap in offshore waters appeared reduced in 1999, but higher in 2000 and 2001. This suggests that predation of later stage yellow perch that had been advected offshore likely was lower than inshore predation in 1999, but higher in 2000 and 2001. In addition, potential predator densities were an order of magnitude higher in 2000 than in

1999 and 2001, further suggesting that predation pressure on larval yellow perch in offshore waters was likely highest in 2000.

Although predators overlapped in space and time with larval yellow perch in Lake Michigan during this study, there has been little empirical evidence of larval yellow perch in alewife stomachs. This has made it difficult to estimate larval yellow perch mortality due to predation. There are, however, numerous reasons why lack of empirical evidence should not discount the potential for predation to be a mechanism regulating recruitment. For example, alewives rapidly digest zooplankton, which become unrecognizable within 3.5 hours of consumption (Gannon 1976). Moreover, Brandt et al. (1987) and Pientka et al. (2001) reported that fish larvae in stomachs of alewives collected at dusk were less digested than those collected one or more hours after sunset. For these reasons, alewives must be collected during the short predation window, and have the viscera preserved quickly to increase confidence in diet item identification.

Alewives must also be collected in areas of larval yellow perch presence to determine the rate of predation. Alewives used for stomach content analysis near Waukegan Harbor, IL were collected in 2000 and 2001 using a bottom trawl, and did not contain any larval fish in their stomachs (Pientka et al 2001). Larval yellow perch occupy the upper 2 m of the water column after hatch (Post and McQueen 1988), indicating that alewives collected along the bottom may not have access to larval yellow perch. Additionally, because alewives vertically
migrate at night and are typically found in the water column (Brandt et al. 1980), alewives collected from bottom trawls may not be representative of the alewife population. Acoustic data collected along trawl transects in 10 m water show that many predator-size targets were suspended off the bottom, and would not have been sampled by the trawl used to collect alewives for diet analysis. Moreover, Pientka et al. (2001) found that gill nets set 0.5 m below the surface ( 30 minute set) in southwestern Lake Michigan from 1996 to 2000 showed up to $4.5 \%$ of alewife diets were comprised of larval fish, with two larval yellow perch positively identified in alewife stomachs. The spatial distribution and overlap of predators and prey combined with the short feeding period (early night) and fast digestion, suggests that alewives must be captured in specific areas at specific times in order to directly observe predation. Accurate sampling methods are critical in understanding the full extent to which alewife predation could control yellow perch recruitment in Lake Michigan.

An additional factor contributing to the difficulty in observing larval yellow perch in alewife stomachs is the very low densities at which larval yellow perch occur in Lake Michigan. Maximum larval yellow perch density in southwestern Lake Michigan was $0.25^{*} \mathrm{~m}^{-3}$, but densities were generally much lower for most dates and locations sampled (Figures 17, 23, 26). High alewife densities coupled with low larval yellow perch densities greatly reduces the probability of capturing an individual alewife containing a larval yellow perch as a prey item. Alewives are known to prey on larval yellow perch (Mason and Brandt 1996) and typically
select the larger sized particles in the water column. From this, it can be assumed that any overlap in larval yellow perch and alewife spatial distributions could result in a predation event. Although overall predation rates may be low, the overall impact on the already reduced population of yellow perch has the potential to be significant.

Changes in the vertical distribution of larval yellow perch throughout their offshore movement may increase the probability of encounter with predators. Larval yellow perch distributions for this study were determined using sample data from a neuston net towed at the surface. Because of this, any occurrence of larval perch below $\sim 1 \mathrm{~m}$ water depth could not be directly observed. Larval yellow perch have been collected at depths approaching the thermocline in Lake Michigan near Milwaukee, WI (Richard Fulford, unpublished data). Additionally, this study found larval yellow perch-size targets (Chapter 1) throughout the epilimnion and thermocline during the time of their offshore advection (Figures 14, 15, 21, 22, 24 and 25). These data suggest that larval yellow perch distributions may extend vertically into the thermocline, which would greatly increase the chance for predation mortality due to the high densities of predators found throughout the upper water column (Figures 15, 22, 24).

Mason and Brandt (1996) suggested that the key to fully understanding the potential for predation on larval yellow perch by alewives lies in the understanding of the environmental cues the trigger that spring inshore migration
of adult alewives. Although this study does not have data for the inshore migration of alewives, it does show that temperature may play a role in determining the subsequent late-spring offshore movement of adult alewives. In 2000 and 2001, the greatest numbers of alewives were collected in trawl samples (nearshore, in 10 m water depth) when surface water temperatures were approximately $11^{\circ} \mathrm{C}$. Alewives were not collected after the surface water temperature rose above $17^{\circ} \mathrm{C}$ in 2000 , and very few alewives were collected in 2001 trawl samples as surface temperatures rose above $19^{\circ} \mathrm{C}$ (Figures 18 and 20). The decrease in alewife numbers inshore corresponded with the onset of thermal stratification in offshore waters in 2000 and 2001. This information could be used in conjunction with knowledge of the timing of the hatch and offshore advection rates of larval yellow perch to determine the spatial and temporal extent to which they are exposed to predation risk.

This study has shown that although direct evidence for alewife predation on larval yellow perch has been scarce in Lake Michigan, the potential for predation does exist in southwestern Lake Michigan. Observed low larval yellow perch densities indicate that any increase in mortality, whether due to predation or other factors, has the potential for a profound negative impact on yellow perch year class strength. The quantification of accurate predation rates in areas of simultaneous larval yellow perch and potential predator occurrence remains key to understanding the overall impact that alewives and other predators may have on the health of yellow perch populations in Lake Michigan.

## CHAPTER 4

 PerspectivesAdvancing the knowledge of the early life-history dynamics of yellow perch in Lake Michigan is necessary for fisheries researchers and managers to gain a better understanding of the mechanisms controlling recruitment of the species. The advancement of such knowledge, however, has been slowed due to critical gaps in larval yellow perch distribution and density information. Because of this, identifying and developing sampling methods efficient at filling these gaps must become high priority. This study shows that hydroacoustics has great potential to help determine the full spatial extent of larval yellow perch through their first year of growth, which is currently unknown due to traditional sampling gear biases. Hydroacoustics proved to be more efficient at detecting larger larval yellow perch than traditional sampling gear. Use of a side- looking transducer on Lake Michigan produced reasonable larval fish density estimates when compared to neuston net density estimates, although successful use of the technique was limited to times of calm water surface conditions. The application of both sidelooking and down-looking hydroacoustics may provide insight into the patchiness of larval yellow perch distributions by allowing the collection of continuous information along transects.

The major obstacle to the use of hydroacoustics for tracking larval perch, however, is the current inability to differentiate between species based on singlefrequency data alone. Although remote species identification remains the "Holy Grail" to acoustic researchers (Horne 2000), species-specific research (e.g. Chapter 2) is moving hydroacoustic science closer to that goal. Hydroacoustic
technology has advanced greatly in recent years with improvements in splitbeam data processing and further development of broadband systems (which use a wide range of frequencies transmitted simultaneously). Combining this improved technology with information already known about the life histories of the species of interest will continue to increase the species identifying power of hydroacoustics. Such advances will continue to move hydroacoustic science in the direction of improved accuracy and increased confidence in results, thus providing managers and researchers with more tools to further fisheries science.

Information about the spatial and temporal dynamics of larval yellow perch distributions can be used to determine which mechanisms have the potential to influence survival during the early life-stages. Based on observations in other systems, alewife predation on larval yellow perch is a likely scenario that occurs in Lake Michigan when the two species overlap in space and time. Although ranked high in importance, the alewife predation on larval yellow perch in Lake Michigan hypothesis has been criticized for the lack of supporting empirical evidence (e.g. "if it is true, why are we not finding larval yellow perch in alewife stomachs?"). This argument may not be valid, however, as Chapter 3 shows that predation may be occurring on a much larger scale (both spatial and temporal) than encompassed by current sampling methods used for collection of alewives for diet analysis. The proper sampling of alewives (or other potential predators) is necessary for further exploration of the full impact that predation may have on larval yellow perch survival during times of spatial overlap between the species.

This study provides insight into predation as a factor influencing recruitment of yellow perch, but additional work is necessary for a more complete understanding. Quantification of predation mortality rates during all stages of yellow perch development throughout their first summer is critical. Combining knowledge of alewife predation rates and year-class strength with larval yellow perch distribution information may help in determining the overall mortality rate of age-0 yellow perch. By having a better idea of mortality rates, researchers and managers gain more confidence in their ability to predict yellow perch year-class strength. A better estimate of the size of the yellow perch stock in Lake Michigan helps with the determination of proper harvest limits, which are necessary for the sustainability of the fishery. This study will provide information that can be used to help develop research and management strategies that will ensure the recovery of the highly important indigenous yellow perch in Lake Michigan.

Allen, P. J., and T. E. Lauer. 2002. Preliminary results of 2002 Ball State University yellow perch research in Indiana waters of Lake Michigan. Prepared for the Yellow Perch Task Group. Yellow Perch Task Group Meeting, December 2001. 9 pp.

Argyle, R. L. 1982. Alewives and rainbow smelt in Lake Huron: midwater and bottom aggregations and estimates of standing stocks. Transactions of the American Fisheries Society 111:267-285.

Bence, J. R. and Smith, K. D. 1999. An overview of recreational fish of the Great Lakes. In Great Lakes fisheries and policy management: a binational perspective. Edited by W. W. Taylor and C. P. Ferreri. Michigan State University Press, East Lansing, MI. pp. 259-306.

Brandt, S. B. 1980. Spatial segregation of adult and young-of-the-year alewives across a thermocline in Lake Michigan. Transactions of the American Fisheries Society 109:469-478.

Brandt, S. B., J. J. Magnuson, and L. B. Crowder. 1980. Thermal habitat partitioning by fishes in Lake Michigan. Canadian Journal of Fisheries and Aquatic Sciences37:1557-1564.

Brandt, S. B., D. M. Mason, D. B. MacNeill, T. Coates, and J. E. Gannon. 1987. Predation by alewives on larvae of yellow perch in Lake Ontario. Transactions of the American Fisheries Society 116:641-645.

Brooking, T. E., L. G. Rudstam, M. H. Olsen, and A. J. VanDeValk. 1998. Sizedependant alewife predation on larval walleyes in laboratory experiments. North American Journal of Fisheries Management 18:960-965.

Brooks, J. L. 1968. The effects of prey size selection by lake planktivores. Systematic Zoology 17:272-291.

Brown, E. H., Jr. 1972. Population biology of alewives, Alosa pseudoharengus, in Lake Michigan, 1949-1970. Journal of the Fisheries Research Board of Canada 29:477-500.

Clady, M. D. 1976. The influence of temperature and wind on the survival of early stages of yellow perch, Perca flavescens. Journal of the Fisheries Research Board of Canada 33:133-138.

Crowder, L. B. 1980. Alewife, rainbow smelt and native fishes in Lake Michigan: competition of predation. Environmental Biology of Fishes 5:225-233.

Crowder, L. B., and J. J. Magnuson. 1982. Thermal habitat shifts by fishes at the thermocline in Lake Michigan. Canadian Journal of Fisheries and Aquatic Sciences 39:1046-1050.

Crowder, L. B., J. J. Magnuson, and S. B. Brandt. 1981. Complimentarity in the use of food and thermal habitat by Lake Michigan fishes. Canadian Journal of Fisheries and Aquatic Sciences 38:662-668.

Eck, G. W., and L. Wells. 1987. Recent changes in Lake Michigan's fish community and their probable causes, with emphasis on the role of the alewife (Alosa pseudoharengus). Canadian Journal of Fisheries and Aquatic Sciences 44(Supplement 2):53-60

Eshenroder, R. L. 1977. Effects of intensified fishing, species change, and spring water temperature on yellow perch, Perca flavescens, in Saginaw Bay. Journal of the Fisheries Research Board of Canada 34:1830-1838.

Eshenroder, R. L., M. E. Holey, T. K. Gorenflo, and R. D. Clark, Jr. 1995. Fishcommunity objectives for Lake Michigan. Great Lakes Fishery Commission, Special Publication 95-3. Ann Arbor, MI.

Evans, M. S. 1986. Recent major declines in zooplankton populations in the inshore region of Lake Michigan: probably causes and implications. Canadian Journal of Fisheries and Aquatic Sciences 43:154-159.

Fleischer, G. W., R. L. Argyle, and G. L. Curtis. 1997. In situ relations of target strength to fish size for Great Lakes pelagic planktivores. Transactions of the American Fisheries Society 126:786-794

Foote, K. G. 1980. Effects of fish behavior on echo energy: the need for measurements of orientation distribution. Journal du Conseil International pour l'Exploration de la Mer 39:193-201

Foote, K. G. 1985. Rather-high-frequency sound scattering by swimbladdered fish. The Journal of the Acoustical Society of America 78:688-700

Forney, J. L. 1971. Development of a dominant year class in a yellow perch population. Transactions of the American Fisheries Society 100:739-749.

Francis, J. T., S. R. Robillard, and J. E. Marsden. 1996. Yellow perch management in Lake Michigan: a multi-jurisdictional challenge. Fisheries 21(2):18-20.

Gannon, J. E. 1976. The effects of differential digestion rates of zooplankton by alewife, Alosa pseudoharengus, on determinations of selective feeding. Transactions of the American Fisheries Society 105:89-95.

GLFC (Great Lakes Fishery Commission). 1995. Lake Michigan committee 1995 annual meeting. Great Lakes Fishery Commission, Ann Arbor, MI.

GLFC (Great Lakes Fishery Commission). 2000. Lake Michigan committee 2000 annual meeting. Great Lakes Fishery Commission, Ann Arbor, MI.

Heyer, C. J., T. J. Miller, F. P. Binkowski, E. M. Caldarone, and J. A. Rice. 2001. Maternal effects as a recruitment mechanism in Lake Michigan yellow perch (Perca flavescens). Canadian Journal of Fisheries and Aquatic Sciences 58:1477-1487.

Hile, R. and F. W. Jobes. 1940. Age, growth and production of the yellow perch, Perca flavescens (Mitchill) of Saginaw Bay. Transactions of the American Fisheries Society 70:102-122.

Hirethota, P. 2002. Young-of-the-year yellow perch assessment in Wisconsin waters of Lake Michigan - 2002. Prepared for the Yellow Perch Task Group. Yellow Perch Task Group Meeting, December 2002. 4 pp.

Hokanson, K. E. F. 1977. Temperature requirements of some percids and adaptations to the seasonal temperature cycle. Journal of the Fisheries Research Board of Canada 34:1524-1550.

Horne, J. K. 2000. Acoustic approaches to remote species identification: a review. Fisheries Oceanography 9:356-371.

Horne, J. K., and C. S. Clay. 1998. Sonar systems and aquatic organisms: matching equipment and model parameters. Canadian Journal of Fisheries and Aquatic Sciences 55:1296-1306.

Hrabik, T. R., J. J. Magnuson, and A. S. McLain. 1998. Predicting the effects of rainbow smelt on native fishes in small lakes: evidence from laong term research on two lakes. Canadian Journal of Fisheries and Aquatic Sciences 55:1364-1371.

Janssen, J., and S. B. Brandt. 1980. Feeding ecology and vertical migration of adult alewives (Alosa pseudoharengus) in Lake Michigan. Canadian Journal of Fisheries and Aquatic Sciences 37:177-184.

Jude, D. J., and F. J. Tesar. 1985. recent changes in the inshore forage fish of Lake Michigan. Canadian Journal of Fisheries and Aquatic Sciences 42:1154-1157.

Kelso, J. R. M., and F. J. Ward. 1977. Unexploited percid populations of West Blue Lake, Manitoba, and their interactions. Journal of the Fisheries Research Board of Canada 34:1655-1669.

Kohler, C. C., and J. J. Ney. 1980. Piscivory in a land-locked alewife (Alosa pseudoharengus) population. Canadian Journal of Fisheries and Aquatic Sciences 37:1314-1317.

Krueger, C. C., D. L. Perkins, E. L. Mills, and J. E. Marsden. 1995. Predation by alewives on lake trout fry in Lake Ontario: role of an exotic species in preventing restoration of a native species. Journal of Great Lakes Research 21(Supplement 1):458-469.

Loftus, D. H., and P. F. Hulsman. 1986. Predation on larval lake whitefish (Coregonis clupeaformis) and lake herring (Coregonis artedii) by rain bow smelt (Osmerus mordax). Canadian Journal of Fisheries and Aquatic Sciences 43:812-818.

Love, R. H. 1969. Maximum side-aspect target strength of an individual fish. Journal of the Acoustical Society of America 46:746-752.

Love, R. H. 1971. Dorsal-aspect target strength of an individual fish. Journal of the Acoustical Society of America 49(3):816-23.

Love, R. H. 1977. Target strength of a fish at any aspect. Journal of the Acoustical Society of America 62(6):1397-1403.

Makauskas, D. 2002. Yellow Perch Update. Prepared for the Yellow Perch Task Group. Yellow Perch Task Group Meeting, December 2002. 9 pp.

Makauskas, D. and D. Clapp. 2000. Status of yellow perch in Lake Michigan and Yellow Perch Task Group progress report. Annual report to the Lake Michigan Technical Committee. Great Lakes Fishery Commission Meeting, March 2000, Ann Arbor, MI. 33 pp.

Makauskas, D. and D. Clapp. 2001. Status of yellow perch in Lake Michigan and Yellow Perch Task Group progress report. Annual report to the Lake Michigan Technical Committee. Great Lakes Fishery Commission Meeting, March 2001, Sault Ste. Marie, Ontario. 33 pp.

Mason, D. M., and S. B. Brandt. 1996. Effect of alewife predation on survival of larval yellow perch in an embayment of Lake Ontario. Canadian Journal of Fisheries and Aquatic Sciences 53:1609-1617.

Mittlebach, G. G. 1986. Predator-mediated habitat use: some consequences for species interactions. Environmental Biology of Fishes 8:61-65

Neter, J., M. H. Kutner, C. J. Nachtsheim, and W. Wasserman. 1996. Applied linear statistical models. McGraw-Hill, New York.

Noble, R. L. 1970. Evaluation of the Miller high-speed sampler for sampling yellow perch and walleye fry. Journal of the Fisheries Research Board of Canada 27:1022-1044.

O'Gorman, R., E. L. Mills, and J. S. DeGisi. 1991. Use of Zooplankton to assess the movement and distribution of alewife (Alosa pseudoharengus) in south-central Lake Ontario in spring. Canadian Journal of Fisheries and Aquatic Sciences 48:2250-2257.

Ona, E. 1990. Physiological factors causing natural variation in acoustic target strengths of fish. Journal of the Marine Biological Association of the United Kingdom 70:107-127.

Pientka, B., J. M. Dettmers, and B. Graeb. 2001. Yellow perch population assessment in southwestern Lake Michigan, including the identification of factors that determine year class strength. Annual performance report to the Illinois Department of Natural Resources. Aquatic Ecology Technical Report 01/04. 38 pp .

Post, J. R., and D. J. McQueen. 1988. Ontogenetic changes in the distribution of larval and juvenile yellow perch (Perca flavescens): a response to predators or prey? Canadian Journal of Fisheries and Aquatic Sciences 45:1820-1826

Rudstam, L. G., A. J. VanDeValk, and M. D. Scheuerell. 2002. Comparison of acoustic and Miller high-speed sampler estimates of larval fish abundance in Oneida Lake, New York. Fisheries Research 57:145-154.

Sanderson, B. L., T. R. Hrabik, J. J. Magnuson, and D. M. Post. 1999. Cyclic dynamics of a yellow perch (Perca flavescens) population in and oligotrophic lake: evidence for the role of intraspecific interactions. Canadian Journal of Fisheries and Aquatic Sciences 56:1534-1542.

Shroyer, S. M., and T. S. McComish. 2000. Relationship between alewife abundance and yellow perch recruitment in southern Lake Michigan. North American Journal of Fisheries Management 20:220-225.

Smith, S. H. 1970. Species interactions of alewives in the Great Lakes. Transactions of the American Fisheries Society 99:754-765.

Thorne, R. E. 1983. Assessment of population abundance by hydroacoustics. Biological Oceanography 2:253-262.

Wamer, D. M., L. G. Rudstam, and R. A. Klumb. 2002. In situ target strength of alewives in freshwater. Transaction of the American Fisheries Society 131:212-223.

Wells, L. 1968. Seasonal depth distribution of fish in southeastern Lake Michigan. United States Fisheries and Wildlife Service, Fishery Bulletin 67:1-15.

Wells, L. 1977. Changes in yellow perch (Perca flavescens) populations of Lake Michigan, 1954-1975. Journal of the Fisheries Research Board of Canada 34:1821-1829.

Wells, L. 1980. Food of alewives, yellow perch, spottail shiners, trout-perch and slimy and fourhorn sculpins in Southeastern Lake Michigan. United States Fisheries and Wildlife Service Technical Papers 98.

