PILOT STUDY TO ESTIMATE LAKE HERRING SPAWNER ABUNDANCE AND NUMBER OF EGGS DEPOSITED IN A LAKE SUPERIOR STATISTICAL GRID.

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July 1, 2005

Introduction

Over the last century humans have harvested tens of thousands of metric tons of lake herring *Coregonus artedi* from Lake Superior. The commercial harvest of lake herring in Wisconsin waters of Lake Superior peaked in the 1940s at 2,450 metric tons annually and harvest remained high through the early 1960's when operators targeted herring flesh (Selgeby 1982) mostly during the spawning season (MacCallum and Selgeby 1987). Through the 1960s, annual harvest dropped markedly as stocks began to plummet. Lawrie and Rahrer (1972) suggested the lake herring decline likely resulted from successive overfishing whereby effort was first directed to spawning grounds near ports and successively to more remote grounds. By the early 1960s many stocks had likely collapsed, but the decline in readily-accessible stocks was not apparent from harvest statistics that remained relatively stable as more remote stocks were fished. Selgeby (1982) later analyzed commercial catch data from Wisconsin waters and concurred with the Lawrie and Rahrer's (1972) sequential overfishing hypothesis. Following the collapse, annual harvest of lake herring in Wisconsin waters generally remained low (roughly 100 metric tons), showed a modest increase in the early 1990's (roughly 230 metric tons), but has since steadily declined back to a level of 100 metric tons.

Recently commercial operators have shifted from targeting herring flesh to targeting roe. Most females are caught in suspended gill nets, fished no shallower than 2 fathoms (3.7 m) below the surface during the reproductive period from October through early December. As spawning continues into December the market value of roe diminishes and commercial fishing for lake herring ceases.

The Wisconsin Department of Natural Resources (WI DNR) surveys commercial fishermen to estimate the biomass of lake herring harvested by statistical grid (Figure 1). From 2001-2003 an average of 93 metric tons of lake herring were harvested annually from Wisconsin waters. The greatest harvest has been from grids 1307 (55% of the total), 1305 (13%), 1409 (9%), 1306 (6%) and 1310 (6%). Several grids around the Apostle Islands currently sustain little or no harvest (e.g., 1208 (<0.1% of the total) and 1309 (1%)). Because there are no surveys to estimate spawning female numbers, estimates of the proportions of harvested adult females and eggs are lacking. The goal of this study was to develop methods for estimating mature female lake herring densities and the number of eggs deposited in a statistical grid. If successful, survey methods could be applied to more statistical grids to better understand the impact of commercial fishing on Lake Superior lake herring.

Several studies have demonstrated that lake herring populations can be enumerated by acoustic techniques during non-spawning periods (Rudstam et al. 1987; Hrabik et al. 2004; Yule et al. *In Review*). To our knowledge, our study will be the first application of acoustic techniques to enumerate spawning lake herring. The tendency for female lake herring to be pelagic during the spawning season should allow for successful acoustic assessment. By combining information on density estimates of mature females, their size-structure, and fecundity-size relationships it should also be possible to estimate the number of eggs deposited. All three estimates (mature female densities, size structure, and fecundity) will have inherent sampling variability. We hypothesize that uncertainty in the estimate of number of eggs deposited will stem foremost from estimating spawning female densities. Because we are likely to estimate female lake herring size-structure and fecundity with better precision, we predict our estimate of deposited eggs will be less sensitive to these data inputs.

The objectives of this study were to 1) determine feasibility of using acoustic techniques in combination with midwater trawling to estimate female numbers on spawning grounds in statistical grid 1409 (Figure 1), 2) if feasible, combine population estimates with size-structure and fecundity information to estimate the numbers of eggs deposited in that grid, 3) conduct a sensitivity analysis to determine which data input contributed the greatest uncertainty to our estimate of deposited eggs, and 4) compare female population estimates and egg deposition estimates to commercial catches of females and roe to directly estimate fishing mortality on lake herring and their eggs. The sensitivity analysis will help identify how best to utilize available resources to improve the overall survey design. Direct estimates of fishing mortality of lake herring (and their eggs) will help facilitate understanding of harvest sustainability, identified by the Lake Superior Technical Committee as a high research priority (Ebener, *In review*).

Methods

Acoustic data for this study were collected at night on 30 November and 1 December, 2004, aboard the USGS research vessel *Kiyi*. Sampling commenced 30 min after nautical twilight and ended by 0100 hours each night. We sampled in a systematic fashion conducting a series of parallel transects spaced at roughly 2.5 km intervals (Figure 2). Acoustic sampling occurred while traveling at speeds of 4-5 knots. The depth distribution, size, and abundance of fish were estimated using a BioSonics (Seattle, WA, USA) DT-X digital echosounder equipped with a 120 kHz split-beam transducer with a half-power beam width of 6.7°. The transducer was mounted on a BioSonics Inc. 1.2-m-long towbody and was deployed at a depth of 1 m below the surface. We sampled at a pulse frequency of 3 ping/s with the pulse duration set at 0.4 msec. Raw echo integration data were collected using a -75 dB threshold. A standard target calibration was performed on 30 November using a 33 mm tungsten carbide sphere (theoretical TS of –41.2 dB). *In situ* mean targets strength (TS) of the sphere equaled –40.8 dB, within the measurement capabilities of the system ($\pm$ 0.4 dB) and the confidence limits around the theoretical TS value. Vessel position was measured with an Ashtech BRG2 differentially corrected GPS unit (accurate to 1 m) and positional information was embedded in the acoustic data files. We also collected bathythermograph profiles at four sites using a SEACAT Model 19 Profiler (Sea-Bird Electronics, Inc., Bellevue, WA, USA).

Trawling

We conducted a total of six midwater trawls and one bottom trawl to assess fish community composition (Figure 2). The midwater trawl (Gourock Trawls, Ferndale, WA, USA) had 15.2 m head rope, foot rope, and breast lines. The mesh tapered from 150 mm square measure at the mouth to 6 mm square measure at the cod end. The bottom trawl head rope and foot rope were both 11.9 m and breast lines were 3.0 m. The bottom trawl also had 6 mm square measure at the cod end. We used NETMIND™ trawl mensuration sensors (Northstar Technical Inc., Saint John's, NF, Canada) to monitor and record the midwater trawl head rope depth, head rope temperature, trawl mouth height, and trawl wingspread at roughly 10-s intervals during deployment. Only the wingspread sensors were deployed on the bottom trawl.

Fish processing

Captured fish were iced in the field and transported to the Lake Superior Biological Station at Ashland, WI, for processing the following morning. Each trawl catch was sorted to species, counted and weighed to the nearest 0.01 kg. All fish from small catches

(< ~200 individuals per species) were measured to the nearest millimeter. A random sub-sample of 50 fish was measured when catches of a single species were larger. In these cases, the length frequency by species was apportioned to the entire catch based on the distribution of measured individuals. Size structure of the lake herring, rainbow smelt *Osmerus mordax*, bloater *Coregonus hoyi*, and lake whitefish *Coregonus clupeaformis* were characterized by constructing length-frequency distributions using 25 mm length bins.

We used an ovary sub-sampling technique and linear regression to quantify the relationship between fecundity and weight of mature female lake herring. A sub-sample of captured lake herring were sexed and their reproductive state was assessed (i.e., unknown; males = immature, mature; and females = immature, ripe and spent). Ovaries of ripe females were removed, placed in individually numbered Ziploc™ bags, and frozen. Ovaries were later thawed, blotted for 1 min to remove excess water and weighed to nearest 0.1 g. Ovaries were then pickled in 100% glacial acetic acid for 30 min, rinsed with water, blotted for 1 min and reweighed to the nearest 0.1 g. Five sections were sub-sampled from a single ovary per female (one near each end and three from the middle) and 100 eggs from each sub-sample were placed on a plastic weighing dish and weighed to the nearest 0.1 mg. The estimated number of eggs per female was calculated by multiplying the total weight of the pickled ovaries by 100 and dividing this product by the average weight of 100 eggs. We used linear regression to quantify the relationship between fecundity and weight of mature females.

Acoustic data post processing

Acoustic data files were processed with Echoview acoustic post-processing software (version 3.10.132.06, SonarData Pty LTD, Tasmania, Australia). Water temperature profiles showed isothermic conditions with an average temperature of 5°C, therefore, we used an algorithm in Echoview to set the speed of sound at 1,422 m/s and the absorption coefficient at 0.005802 dB/m. A line 0.2 m above the lake bottom was defined on echograms using an Echoview algorithm. Bottom tracking anomalies were eliminated by visually inspecting echograms and manually redefining the bottom. We defined cells on echograms measuring 10 m high and 1,000 m in length and fish densities were estimated for each cell. Echoview software measures fish backscattering on an area basis by calculating a nautical area backscattering coefficient (*NASC*):

$$NASC\ (\text{m}^2/\text{nautical mile}^2) = 4\pi \times 1852^2 \times 10^{(Sv/10)} \times T,$$

where *Sv* is the mean volume backscattering strength of the domain being integrated, 4π is the number of steradians in a sphere converting backscattering cross section to scattering cross section, 1,852 is the number of meters per nautical mile, and *T* is the mean thickness of the domain being integrated in meters.

Fish density estimates were obtained by scaling cell *NASC* values by the mean backscattering cross section of individual fish (i.e., σ) in each cell, calculated from the mean TS. By convention, TS = 10 log (σ). We used the following algorithm to estimate fish density on a per area basis (FD_A) from NASC:

$$FD_A\ (\text{number/ha}) = ((NASC / (4\pi * \sigma))*342.9904,$$

where 342.9904 is the number of hectares in a square nautical mile.

When estimating total fish densities per cell we applied a -60 dB backscattering volume strength (Sv) threshold. To estimate σ we used the single target detection criteria (split beam method 1) available in Echoview. The single target detection parameters we used are presented in Appendix A. Only echoes exceeding –55 dB were used to calculate σ.

Acoustic densities versus trawl densities

To estimate the densities of mature lake herring from acoustic data we first conducted an analysis to determine the appropriate TS cutoff to separate large lake herring (> 250 mm TL) from smaller pelagic fish like rainbow smelt and juvenile lake herring. We compiled midwater trawl catches from a total of 17 stations collected from the eastern end of Lake Superior during the 2004 field season where large lake herring represented 100% of the catch of fish exceeding 250 mm. We estimated total fish densities and densities of lake herring exceeding 250 mm (fish/m^3) in each trawl by dividing the numbers caught by the volume of water swept by the trawl, calculated by multiplying the tow distance by the trawl mouth opening. Although the trawl mouth opening geometry is subject to variation owing to variables like vessel speed and warp line out, we assumed a 10 m by 10 m opening for all tows based on experience with the trawl mensuration system. The paths of midwater trawls were overlayed on echograms using trawl mensuration data and an Echoview parallelogram drawing tool (both the echogram and trawl mensuration data were time tagged). Acoustic density estimates in the trawl path were calculated on a per volume basis (FD_V, fish/m^3) so that acoustic density estimates could be compared to trawl density estimates using the same units. The following formula was used:

$$FD_V \text{ (fish/m}^3) = 10^{Sv/10}/\sigma.$$

Using Echoview we developed frequency distributions of echoes meeting the single target detection criteria within each trawl path using 1 dB wide bins from -55 to -20 dB. We then calculated what proportion of the total targets in each trawl path exceeded -42 dB, -41 dB, -40 dB, etc., up to -32 dB. We multiplied the total FD_V in each trawl by each proportion. Linear regression was used to measure the correlation coefficient (r) between the trawl density of large herring and the density derived from the eleven 1-dB cutoffs using each trawl tow as a sample unit. We developed a bivariate plot with correlation coefficient (r) values on the y-axis and target strength cutoffs on the x-axis. We fitted a 3rd order polynomial line to the plot, and used this polynomial model to predict at what TS value the correlation coefficient was maximized. To estimate densities of lake herring female exceeding 250 mm we multiplied the total fish density in each cell by the proportion of fish exceeding the TS cutoff with the maximum correlation coefficient. After defining the TS cutoff to calculate densities of lake herring exceeding 250 mm, we compared our cutoff value to an equation predicting lake herring lengths from TS developed by Rudstam et al. (1987).

Estimating mean densities and mapping fish distributions

Because fish aggregate to spawn, acoustic density data will be typically autocorrelated, meaning data points in close proximity will usually be more correlated than those that are separated by greater distances. Acoustic data are typically collected by sampling continuously using a regular grid; thus samples lack true independence which violates the assumption of classical variance estimators and random sampling theory. Maravelias et al. (1996) showed that geostatistical techniques can be used to map acoustic survey data containing few observations of very high values and many observations of low values. In a geostatistical analysis the spatial dependency of a variable is quantified and partitioned across distance classes (i.e., lags). This spatial function is normally presented in a variogram. A statistical model (e.g., linear, exponential, Gaussian, etc.) is then fit to the variogram data. Once the spatial structure has been modeled, the model can be used to map distributions using a linear spatial prediction method such as ordinary kriging. Geostatistical algorithms to calculate estimation variance are also available (Petitgas and Lafont 1997).

Total fish densities per 1,000 m bin were calculated by summing all 10-m high cells in each bin down to within 2 m of the bottom. Large lake whitefish were predominant in our lone bottom trawl sample. By excluding fish echoes within 2 m of the bottom we minimized inclusion of lake whitefish in our density estimates of lake herring exceeding 250 mm. We calculated the arithmetic means of total fish densities and densities of lake herring exceeding 250 mm in statistical grid 1409 using the 1,000 m bins as sample units. Estimation variance of fish densities (σ_E^2) was calculated using EVA2 software (Petitgas and Lafont 1997). EVA2 requires fitting a model to the global variogram. The variogram was constructed using six lags in 2,000 m increments for a maximum variogram modeling distance of 12,000 m. Using a 2,000 m lag distance, 59 data pairs were obtained in the first lag satisfying the recommended minimum number of 30 pairs needed for constructing the variogram. Best-fit exponential models were developed by examining Akaike's Information Criterion using VESPER Version 1.6 software (Minasny et al. 2005). EVA2 uses a formula for calculating estimation variance when the mean from samples inside a polygon is calculated by the arithmetic mean (Matheron 1971). The statistical grid 1409 polygon was then divided into smaller finite elements (i.e., discretized) by defining a grid size of 1 km^2. Using grids of finer scale (i.e., $< 1{,}000$ m^2) is unjustified given the acoustic density estimates were summarized using 1,000 m bins.

To map fish densities we used ordinary kriging available in VESPER. The kriging algorithm uses the observed point data and the variogram model to predict fish densities at unsampled locations based on their separation distances. VESPER kriging outputs were converted to ARC GIS Raster grid files using an ASCII-to-grid tool in ArcToolbox. Maps showing fish densities were prepared using ArcGIS version 9.1 (ESRI, Redlands, CA).

Estimating eggs deposited in and harvested from statistical grid 1409

We estimated the total number of eggs deposited by females in statistical grid 1409 using the following approach. The acoustic estimate of lake herring exceeding 250 mm in grid 1409 was apportioned to 25 mm length bins based on the frequency distribution of female lake herring caught by midwater trawling. The mean weight of a female lake herring at each bin midpoint was calculated using a length-weight equation derived from lake herring captured during this survey. We estimated the average fecundity of females at each bin midpoint using the fecundity versus weight equation we developed. Numbers of females in each length bin were multiplied by the average fecundity for that length bin to estimate the numbers of eggs per bin, and then summed across all bins to estimate total eggs deposited in grid 1409.

To estimate what proportion of eggs carried by spawning lake herring that were harvested, we combined information on the biomass of lake herring harvested, size-structure of harvested fish and the relationship of fecundity to female size we developed. The biomass of harvested lake herring was estimated by combining WI DNR and Red Cliff Band of Lake Superior Chippewas annual catch statistics. The majority of harvest (96%) was from commercial operators targeting females in suspended gill nets so we assumed that females represented 100% of the total catch. We developed a length frequency distribution using 25 mm bins of harvested females based on 72 individual length measurements of green females caught by commercial operators during late

October to mid November around the Apostle Islands (WI DNR file data). We estimated the average weight at each bin midpoint using our lake herring length-weight equation. We multiplied the count of fish in each 25 mm bin by their predicted mean weight and summed all the bins to estimate the weight of the 72 green females. We then determined what proportion of the total weight of the 72 fish was in each bin and used these values to apportion the total biomass of harvested lake herring to length bins. We converted harvested biomass to harvested numbers in each length bin using our lake herring length-weight relationship. Finally, numbers of females in each length bin were multiplied by the average fecundity for that length bin to estimate the numbers of eggs per bin, and then summed across all bins to estimate the total number of eggs harvested in grid 1409.

To generate confidence intervals for the number of eggs deposited in statistical grid 1409, we used a bootstrap approach that incorporated uncertainty in each of the three estimates used to calculate numbers of egg deposited: density of lake herring exceeding 250 mm, size-structure of spawning females, and the mass-fecundity relationship. We believed the length-weight relationship would contribute very little to uncertainty in our egg deposition estimates, so we held this relationship constant. First, we randomly selected 75 density estimates with replacement and calculated a mean density. Next, we randomly selected 5 midwater trawls with replacement and calculated the mean percent contribution to the total catch of spawning-size female lake herring for each length bin class (midpoints 263, 288, 313, 338, 363, 388, and 413 mm). One of the six midwater trawls did not capture lake herring, thus we used only five midwater trawls to measure uncertainty in size-structure. We then apportioned the mean bootstrap density estimate to length bins based on the bootstrapped mean percent of total catch for each length bin. Third, we assumed the weight-length relationship was constant, and assigned a mean mass for all fish assigned to each length bin. Fourth, for the mass-fecundity relationship, we randomly selected 22 pairs of observations (mass, number of eggs) with replacement, calculated the slope and intercept from this regression, and applied this regression to the average weight for each length bin to calculate average number of eggs per female in each length bin. We then multiplied the number of females in each length bin by their corresponding estimated number of eggs per female in that length bin to generate number of eggs/ha. Finally, we summed across length bins and multiplied by the surface area of grid 1409 (17,133 ha) to estimate number of eggs deposited in the statistical grid. This process was repeated 1,000 times to generate a distribution of number of eggs deposited. We used the bias-corrected percentile method to calculate 95% confidence intervals (Manly 1997).

To examine how sensitive our estimates were to each component, we held two of the three (density of lake herring exceeding 250 mm, size-structure, and fecundity) constant (observed values) and varied the other component to estimate numbers of eggs deposited. This was done for each of the three components. Comparing the variability around the mean estimates for each of the 1,000 simulations for each of these scenarios would illustrate where our greatest uncertainty was and indicate where future sampling effort should be concentrated.

Results

A total of 3,027 fish were caught in the 6 midwater trawls. Rainbow smelt were predominant (79.8%), followed in decreasing order by lake herring (18.8%), bloater (0.9%), spoonhead sculpin *Cottus ricei* (0.4%) and ninespine stickleback *Pungitius pungitius* (< 0.1%). Three distinct size modes were observed (Figure 3A): one mode at 63 mm comprised of rainbow smelt, and two larger modes (188- and 338-mm) comprised largely of lake herring. We identified the sex of 209 lake herring caught by midwater trawl (Figure 3B). Females and males represented 47% and 53% of the fish less than 250 mm, respectively, while females accounted for 94.5% of the 55 lake herring greater than 250 mm. Of the 94 lake herring identified as females, all (N = 42) smaller than 250 mm were immature (Figure 3C), and all greater than 250 mm (N = 52) were mature (22 were ripe and 30 were spent).

We measured fecundity of the 22 ripe females and found a significant relationship with weight (Figure 4). The model predicting fecundity from weight was:

$$\text{Fecundity (no. eggs)} = -86.5 + 46.5 \text{ x weight (grams)},$$

with $R^2 = 0.880$, $N = 22$, $P < 0.0001$, and range = 126.6 – 567.5 g.

Not all fish were weighed so we developed a weight versus length equation (Figure 5) from 138 lake herring (both sexes):

$$\ln(\text{weight(g)}) = -12.7 + 3.16 \text{ x } \ln(\text{length(mm)}),$$

with $R^2 = 0.99$, $N = 138$, $P < 0.0001$, and range = 141 – 422 mm.

A total of 779 fish from 10 species were caught in the lone bottom trawl sample. Rainbow smelt and other small demersal species like trout-perch *Percopsis omiscomaycus*, spoonhead sculpin, slimy sculpin *Cottus cognatus*, deepwater sculpin *Myoxocephalus thompsoni* and ninespine sticklebacks dominated the catch of fish (Figure 6), and rarely did these species exceed 175 mm. Of the 82 fish greater than 175 mm, 65 (79.3%) were lake whitefish, 10 (12.2%) were lake herring and 7 (8.5%) were other species. We sexed the ten lake herring caught in the bottom trawl and found seven males and three females. Trawling results indicate that female lake herring were largely pelagic during the nighttime hours of late November.

Estimating mean densities and mapping fish distributions

Using an *Sv* threshold of -60 dB and a TS threshold of -55 dB, fish densities measured by midwater trawling were correlated (R^2 =0.645) with acoustic density estimates of fish within the trawl path (Figure 7). The slope of the best fit line (1.11) did not vary significantly (P = 0.82) from one, suggesting the two estimates approached a 1:1 relationship.

The correlation coefficients derived from regressing midwater trawl densities of lake herring exceeding 250 mm against acoustic density estimates derived using the eleven 1-dB cutoffs ranged from 0.24 to 0.58 (Figure 8). Based on the 3rd order polynomial line fit we determined that the correlation coefficient was maximized at a TS cutoff of -35.6 dB. It follows that when estimating densities of mature females we multiplied the total fish density in each cell by the proportion of fish with TS exceeding -35.6 dB. This cutoff value is consistent, albeit 1 dB larger than the predicted mean TS of a 250 mm lake herring using the Rudstam et al. (1987) equation (-36.6 dB).

The arithmetic mean fish density of all fish > -55 dB in grid 1409 equaled 1,237 fish/ha (N = 75 cells), while the mean density of lake herring exceeding 250 mm in grid 1409 equaled 19.5 fish/ha. The estimation variance (σ_E^2) of the total fish density estimate predicted by the EVA2 software equaled 18,600 and the estimation variance of the density of lake herring exceeding 250 mm equaled 3.6. The relative estimation errors for the total fish density and lake herring exceeding 250 mm density (i.e., σ_E/arithmetic mean) equaled 11.0% and 9.7%, respectively. Assuming errors were distributed normally, the 95% confidence interval (95% CI) can be calculated by the mean $\pm$ 1.96 σ_E. The 95% CI surrounding the density of all fish equaled 970 – 1504 fish/ha while the 95% CI surrounding the density estimate of lake herring exceeding 250 mm equaled 15.8 - 23.2 fish/ha. Using a surface area of 17,113 hectares, we estimate the total pelagic fish numbers in statistical grid 1409 at 21.2 million (95% CI = 16.6 – 25.8 million). The total number of lake herring exceeding 250 mm equaled 334,000 (95% CI = 270,000 – 398,000).

Variograms were used to estimate variance for total fish densities and densities of fish greater than 250 mm (Figures 9A and 9B). By convention, one minus the ratio of the variogram model nugget to the model sill is a measure of the total variation explained by spatial structuring (Maravelias et al. 1996). It follows that roughly 67% of the variation in total fish densities is explained by spatial structuring and roughly 33% of the variation is due to a combination of random variation and micro-scale variation (Maravelias et al. 1996). Roughly 58% of the total variation in densities of lake herring exceeding 250 mm is explained by spatial structuring. Because more than half of the total variation is explained by spatial structuring it is appropriate to use ordinary kriging to map distributions of fish densities (Personal communication, Dr. David Mulla, Department of Soil, Water and Climate, University of Minnesota, St. Paul, MN).

Variogram models were used to perform ordinary kriging to map densities of total fish (Figure 10) and densities of lake herring exceeding 250 mm (Figure 11). Both high and low fish density areas are evident on both maps. Locations with high total fish densities (Figure 10) generally had bathymetric depths exceeding 20 m while shallower areas tended to have lower total fish densities. Total fish densities were highest within a few km southeast of Madeline Island, in West Channel west of Basswood Island, and near the City of Bayfield, WI. Total fish densities were low southeast of Basswood Island, on the shallow flat east of the Sioux River mouth, and tended to decrease with increasing distance southeast of Madeline Island.

Densities of lake herring exceeding 250 mm (Figure 11) were highest southwest of Madeline Island, with moderate densities present east of Basswood Island and southeast of Madeline Island. The highest observed density of large fish targets approached 75 fish/ha. The concentration of large fish southwest of Madeline Island was suspended between 10 and 20 m depth over a generally soft bottom where bottom depths ranged from 20 to 30 m. Densities of large fish in all other locations were generally lower. The standard deviation of kriging estimates of densities of lake herring exceeding 250 mm per 1 km^2 grid cell increase with increasing distances from observed data (Figure 12).

Frequency distributions of targets meeting the single-target classification criteria grouped by 10-m-high depth strata (Figure 13) suggest that spawning lake herring distributions were also structured vertically. The proportion of large targets consistent with lake herring exceeding 250 mm was highest in the upper 20 m of the water column. At greater depths, smaller fish targets made up a larger portion of the total TS distributions.

Estimating eggs cast in a statistical grid and sensitivity analysis

We estimate the number of eggs cast by female lake herring in statistical grid 1409 at 4.439 billion eggs. Based on our bootstrapping approach, the estimates for the number of eggs cast ranged from 3.157 billion to 6.602 billion eggs (Figure 14) and the lower and upper 95% confidence intervals were 3.446 and 5.370 billion eggs, respectively. Incorporating uncertainty in the acoustic estimate of spawning female density, size-structure, and fecundity one at a time revealed that density of spawning females led to the greatest variability in estimating numbers of eggs cast (Figure 15), followed by uncertainties in size-structure. Uncertainty in the mass-fecundity relationship contributed very little to the overall variability when isolated from the other two factors (Figure 15). These results suggest that focusing efforts to improve precision of mature female density estimates will result in better precision of estimates of the numbers of eggs deposited.

The biomass of lake herring caught by commercial operators (WI DNR data) and tribal gill net fishers (Red Cliff Band of Lake Superior Chippewas data) equaled 3,291 kilograms. The length-frequency distribution of a sample of 72 harvested females (Figure 16) showed that fish smaller than 325 mm were too small to be caught by gill nets. We estimate that 6,900 female lake herring carrying 152 million eggs were harvested from statistical grid 1409 during the 2004 spawning season. We estimate fishing mortality of mature female herring and their eggs in statistical grid at 2.1% and 3.4%, respectively. Given the uncertainty in estimating mature female densities and the number of eggs deposited, exploitation rates of adult females and eggs could be as high as 2.6% (6,900 harvested / 270,000 females in grid 1409) and 4.4% (152 million eggs harvested / 3.446 billion cast), respectively. These high-end estimates do not account for uncertainty in the harvest estimates. Because gill nets are size-selective, fishing mortality rates of females greater than 400 mm was likely greater than for smaller females. By multiplying the total estimate of lake herring exceeding 250 mm by the proportion of lake herring exceeding 400 mm caught in midwater trawls, we estimate that 8,400 females exceeding 400 mm occupied statistical grid 1409. The harvest of fish greater than 400 mm was estimated at 2,500 fish for an exploitation rate of 29.5%. When calculating these estimates of exploitation we assumed that mature lake herring densities in statistical grid 1409 measured over the two nights of sampling were representative of the entire fishing season. If female lake herring move rapidly away from spawning grounds after they spawn, or if "waves" of spawning herring come and go over the fishing season, then mortality estimates would be lower.

Discussion

This pilot study demonstrates that numbers of spawning females and the numbers of eggs they deposit in a statistical grid can be estimated with reasonable precision. Our sensitivity analysis showed that variability in the estimate of spawning female herring densities contributed the most uncertainty to the estimate of lake herring eggs deposited in statistical grid 1409. However, the relative estimation error (i.e., σ_E/arithmetic mean) of the mature female lake herring density estimate in grid 1409 was low (9.7%). Precision of acoustic estimates could be improved by increasing the number of transects, but at the expense of less coverage. Given our acoustic survey design using parallel transects spaced at roughly 2.5 km provided density estimates having reasonable precision, suitable for management decisions, we recommend no changes to the overall design.

The time required to complete this pilot study of grid 1409 can be used to forecast the time required to complete a larger study to sample six Wisconsin statistical grids (1210, 1307, 1308, 1309, 1310, and 1409). To sample one statistical grid took a crew of five people two days. It took an additional two-person crew three days to process the catch. Biological technicians spent three weeks entering data, measuring fecundity and preparing GIS products. Acoustic data processing, geostatistical modeling, catch data analysis and report writing took one scientist six weeks. It follows that an expanded study of six Wisconsin statistical grids would require 10-12 vessel days, 10-15 weeks of biological technician time and 3-4 months for a scientist to prepare findings. Given that estimates of fishing mortality rates of lake herring are presently lacking, continued study of this important resource seems justified.

Finding generally poor agreement between acoustic densities and midwater trawl catches of large fish has been reported elsewhere in the fisheries literature. In the present study, the slope of the regression between trawl catches of lake herring exceeding 250 mm and acoustic density estimates using the -35.6 dB cutoff equaled 1.11 with an R^2 of 0.34. This result is consistent with the findings of Parkinson et al. (1994) in a study of kokanee salmon in Couer d'Alene Lake, Idaho, where total fish densities ranged from 0 to 3,700 fish/ha. Parkinson et al. (1994) compared acoustic densities and midwater trawl densities of age 1-3 kokanee (105 – 245 mm) and reported a slope of 0.70 and a correlation coefficient of 0.5 (R^2 = 0.25), similar to the results in the present study.

Efforts to characterize mature female lake herring size structure, and the analysis we conducted to determine the appropriate TS threshold cutoff to enumerate mature female lake herring acoustically, could have benefited from additional midwater trawling data. As we expand sampling to more statistical grids, the additional trawling data will allow us to better define the size structure of spawning females. A total of 30 or more midwater trawl tows around the Apostle Islands could also be used to compare trawl density estimates of mature females to acoustic density estimates to determine if the two gears provide similar results.

Total exploitation of mature female lake herring from grid 1409 is likely low compared to historic peak levels, but because commercial gill nets capture the largest females, exploitation of lake herring exceeding 400 mm likely remains high. By comparing acoustic density estimates of lake herring exceeding 250 mm to commercial catch statistics we estimate the conditional fishing mortality rate of female herring, or *m*

(Ricker 1975), in grid 1409 during 2004 at 0.021. Selgeby (1982) presents the location of six major spawning areas used historically by lake herring including a site southwest of Madeline Island (Bayfield fishing grounds) that we also identified in the present study (Figure 11). Selgeby (1982) reported that instantaneous rates of fishing mortality (F) of lake herring from the Bayfield fishing grounds between 1936 and 1950, when annual exploitation was the highest on record, ranged from 0.18 to 0.67. By convention $m = 1 - e^{-F}$, thus conditional fishing mortality rates between 1936 and 1950 ranged from 0.17 to 0.49 annually. Because larger female lake herring are more vulnerable to commercial gill nets (Figure 16), our estimate of m for female lake herring exceeding 400 mm was higher (0.295) than for all mature females, and within the range reported by Selgeby (1982). We conclude that current exploitation levels of all mature lake herring at the Bayfield fishing grounds is low compared to historic levels, but fishing mortality of females exceeding 400 mm likely remains at a high level.

This study shows that acoustic techniques in concert with ordinary kriging can be used to identify lake herring spawning areas. We propose expanding our effort to sample other statistical grids around the Apostle Islands in upcoming years. If successive years of sampling show that the same areas tend to have high lake herring densities, this would suggest that lake herring have the ability to selectively choose spawning "habitat" and the possible existence of unique stocks. Genetic techniques could possibly be used to test for unique genetic profiles. Another way to test if these areas with high densities of large fish represent spawning grounds is to revisit these sites with larval sampling gear during spring. A proposal describing a study to assess larval lake herring densities in statistical grids 1309 and 1409 was recently submitted to the Great Lakes Science Center for consideration.

Acknowledgements

We thank the Captain and crew of the R/V Kiyi for their assistance in the field. We would like to also thank Ed Roseman, Jean Adams, David Warner and Patrick Sullivan and Jaci Savino for the excellent reviews they provided on an earlier version of this report.

Literature cited

Ebener, M.P., Editor. *In review*. The state of Lake Superior in 2000. Great Lakes Fishery Commission Special Publication.

Hrabik, T.R., and O.T. Gorman. 2004. Development of a lake-wide acoustic monitoring program for Lake Superior pelagic fishes, 2003 Completion report. Great Lakes Fishery Commission. 19 pp.

Lawrie, A.H., and J.F. Rahrer. 1972. Lake Superior: Effects of Exploitation and Introductions on the Salmonid Community. Journal of the Fisheries Research Board of Canada 29:765-776.

MacCallum, W.R., and J.H. Selgeby. 1987. Lake Superior revisited 1984. Canadian Journal of Fisheries and Aquatic Sciences 44:23-36.

MacDonald, P.D.M. 1987. Analysis of length frequency distributions. Pages 371-384 *in* R.C. Summerfelt and G.E. Hall, editors. Age and growth of fish. Iowa State University Press, Ames.

Manly, B.F.J. 1997. Randomization, bootstrap and monte carlo methods in biology. 2nd Edition. Chapman & Hall, London.

Maravelias, C.D., D.G. Reid, E.J. Simmonds and J. Haralabous. 1996. Spatial analysis and mapping of acoustic survey data in the presence of high local variability:

geostatistical application to the North Sea herring (*Clupea harengus*). Canadian Journal of Fisheries and Aquatic Sciences 53: 1497-1505.

Matheron, G. 1971. The theory of regionalized variables and their applications, Les cashiers du Centre de Morphologie Mathematique, fasc. 5, Centre de Geostatistique, Fontainebleau, 212 p.

Minasny, B., McBratney, A.B., and Whelan, B.M., 2005. VESPER version 1.62. Australian Centre for Precision Agriculture, McMillan Building A05, The University of Sydney, NSW 2006.

Parkinson, E.A., B.E. Rieman and L.G. Rudstam. 1994. Comparison of acoustic and trawl methods for estimating density and age composition of kokanee. Transactions of the American Fisheries Society 123: 841-854.

Petitgas, P., and Lafont, T. 1997. EVA2: Estimation Variance. Version 2. A geostatistical software on Windows 95 for the precision of fish stock assessment surveys. ICES CM, Y:22 22.

Ricker, W.E. 1975. Computation and interpretation of biological statistics in fish populations. Bulletin 191 of the Fisheries Research Board of Canada. Ottawa, Canada.

Rudstam, L.G., C.S. Clay, and J.J. Magnuson. 1987. Density and size estimates of cisco (*Coregonus artedi*) using analysis of echo peak PDF from a single-transducer sonar. Canadian Journal of Fisheries and Aquatic Sciences 44:811-821.

Selgeby, J.H. 1982. Decline of the lake herring (*Coregonus artedii*) in Lake Superior: an analysis of the Wisconsin herring fishery, 1936-78. Canadian Journal of Fisheries and Aquatic Sciences 39:554-563.

Stockwell, J.D., L.M. Evrard, D.L. Yule, O.T. Gorman, and G.A. Cholwek. 2005. Status and trends of prey fish populations in Lake Superior, 2004. Report to the Great Lakes Fishery Commission, Ann Arbor, Michigan.

Yule, D.L., C. Anderson, and G.D. Siesennop. In Review. Acoustic assessment of forage fish and lake trout in Minnesota lakes: application of a Bayesian mixture modeling approach to apportion acoustic targets to predator and prey. Transactions of the American Fisheries Society.

Figures

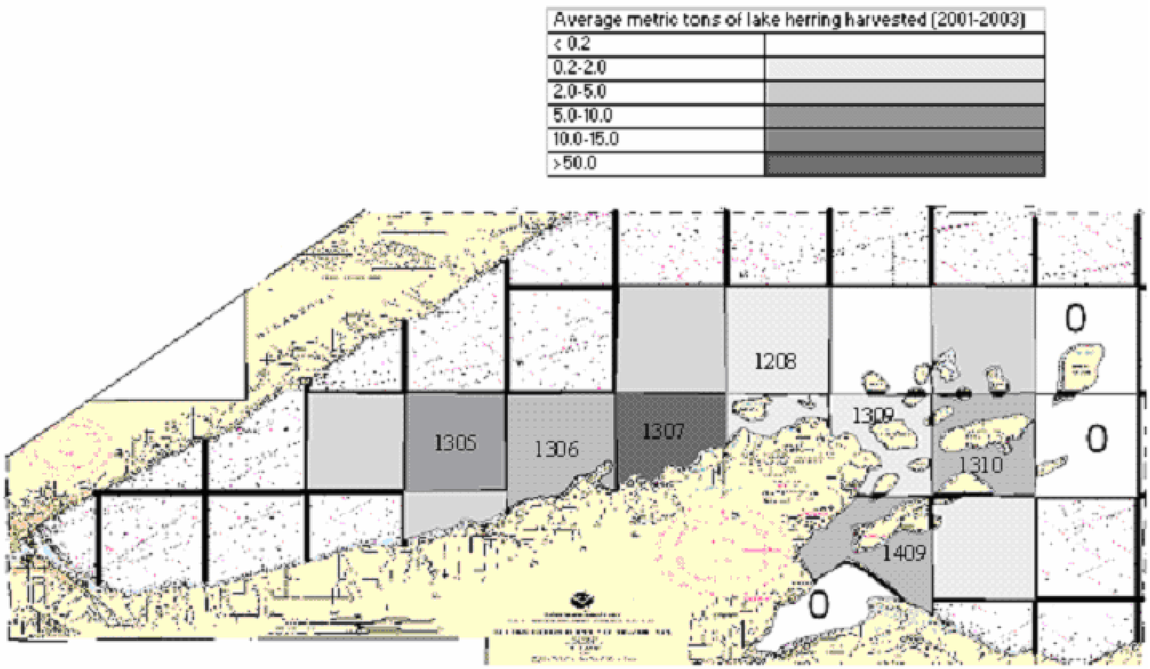


Figure 1. Map showing the average biomass (metric tons) of lake herring harvested annually by commercial operators by statistical grid in Wisconsin waters of Lake Superior averaged over the period 2001 to 2003. Data provided by the WI DNR.

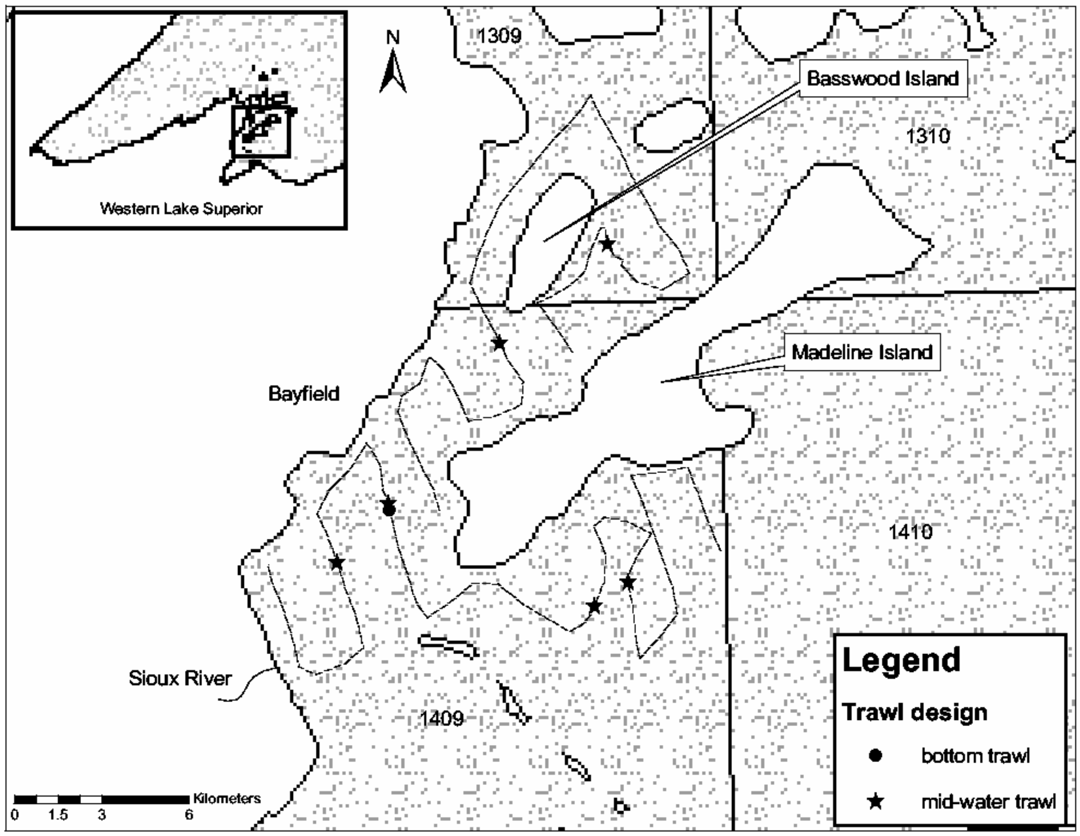
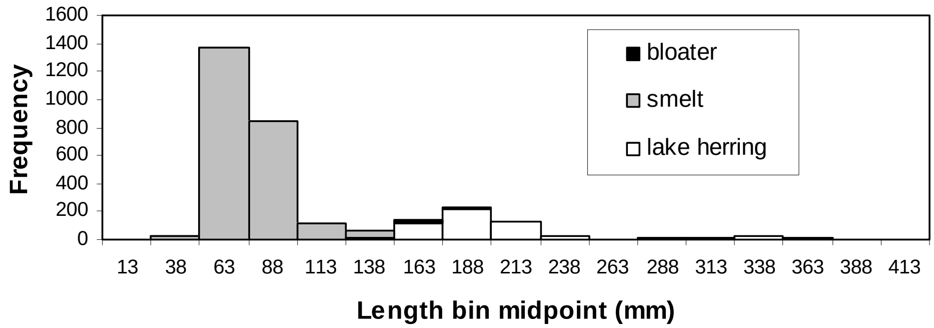
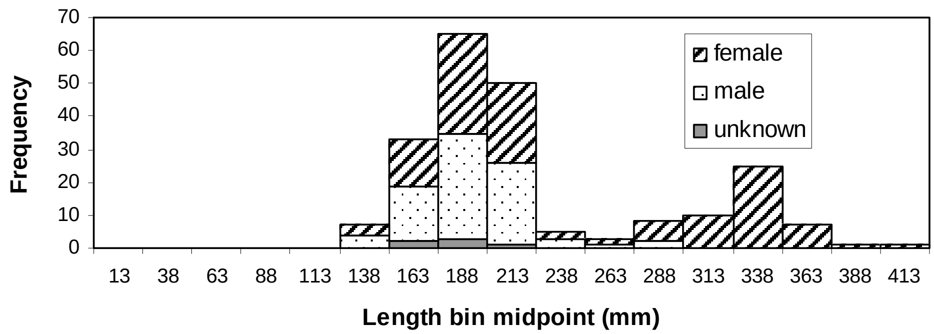


Figure 2. Map of transects (dashed lines), midwater trawl and bottom trawl stations sampled during the nights of 30 November and 1 December 2004.

A)



B)



C)

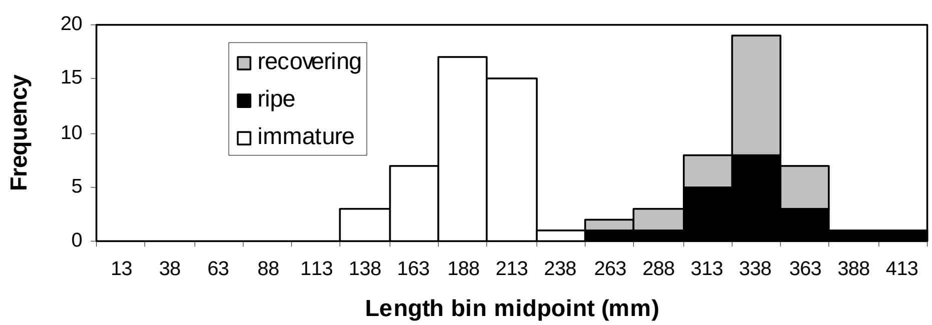


Figure 3. A) Length-frequency distribution of bloater, rainbow smelt, and lake herring caught in six night midwater trawls between 30 November and 1 December 2004. B) Length-frequency distribution of female and male lake herring captured in midwater trawls. C) Reproductive state of females captured in midwater trawls.

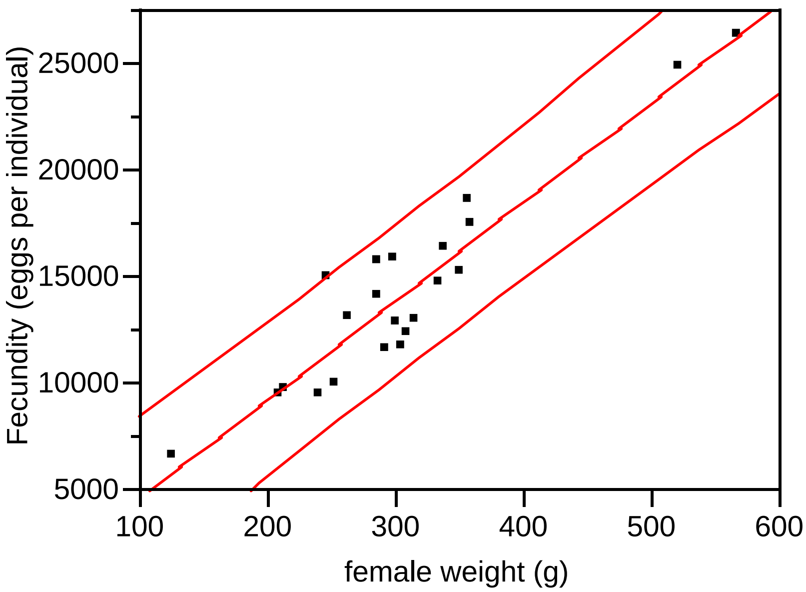


Figure 4. Fecundity versus weight of female lake herring. Fecundity (eggs per individual) equals -86.5 + 46.5 x weight (g), with $R^2 = 0.880$, N = 22, $P < 0.0001$, and range = 126.6 – 567.5 g. The outer lines are the 95% prediction intervals.

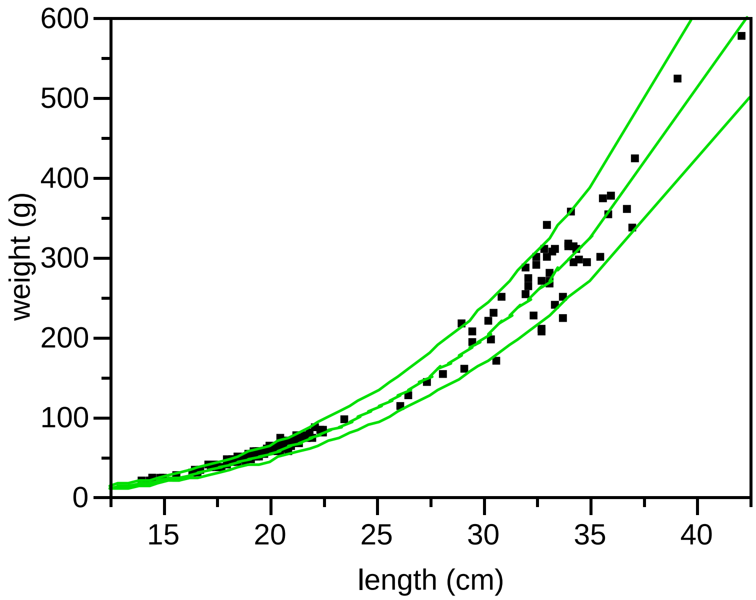


Figure 5. Plot of weight versus length of lake herring captured on 30 November and 1 December 2004. ln (weight(g)) = -12.7 + 3.16 x ln (length(mm)), with R^2 = 0.99, N = 138, P < 0.0001, and range = 141 – 422 mm. The outer lines are the 95% prediction intervals.

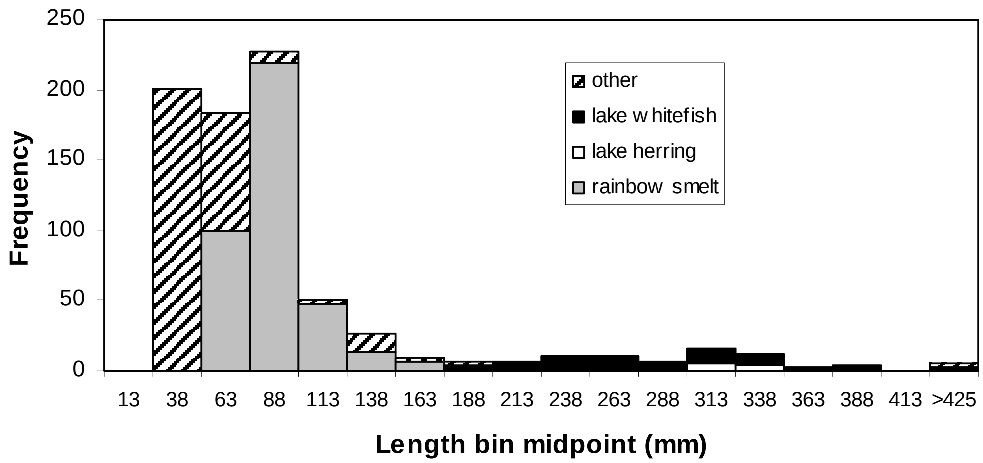


Figure 6. Length frequency distribution of rainbow smelt, lake whitefish, lake herring and other species caught in one night bottom trawl (1 December 2004). Other species equals the pooled catch of bloater, deepwater sculpin, lake trout *Salvelinus namaycush*, ninespine stickleback, slimy sculpin, spoonhead sculpin and trout perch.

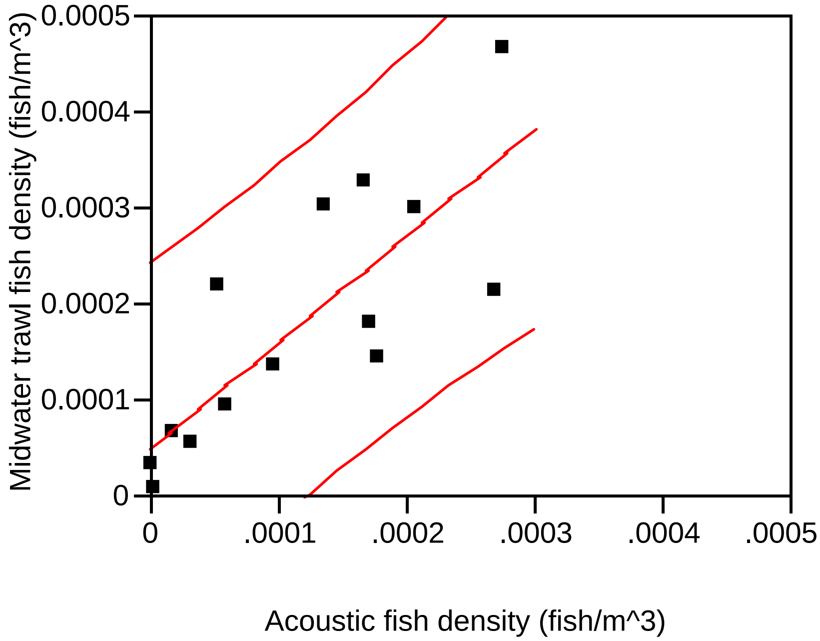


Figure 7. Density estimates of all fish caught in midwater trawl tows versus acoustic density estimates within the trawl path using an *Sv* threshold of -60 decibels and a TS threshold of -55 decibels (see Methods section for details).

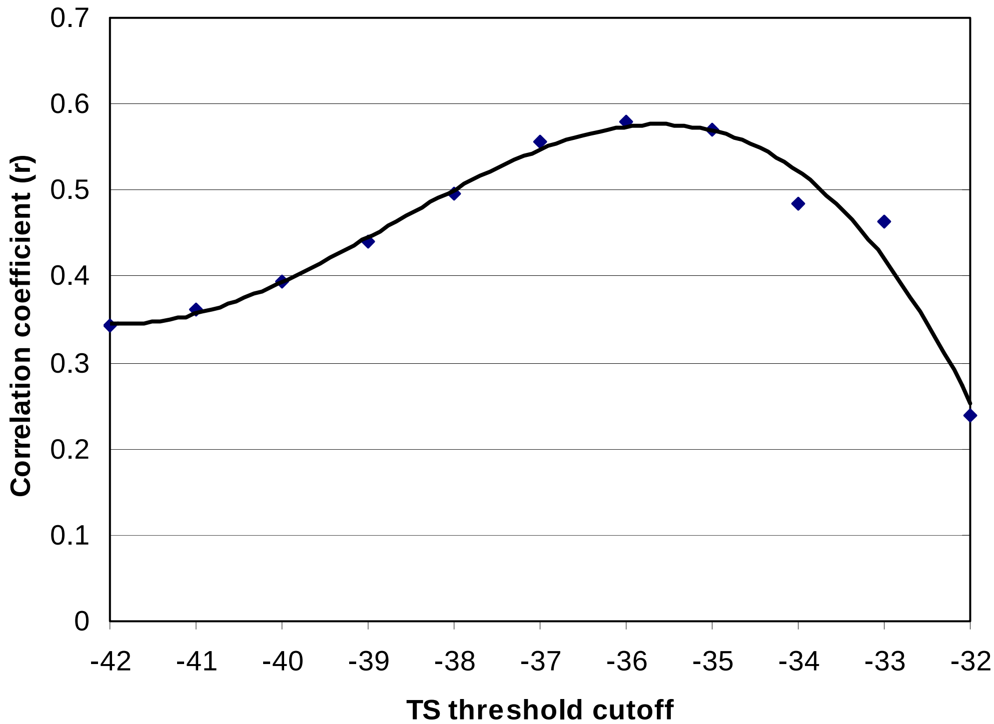
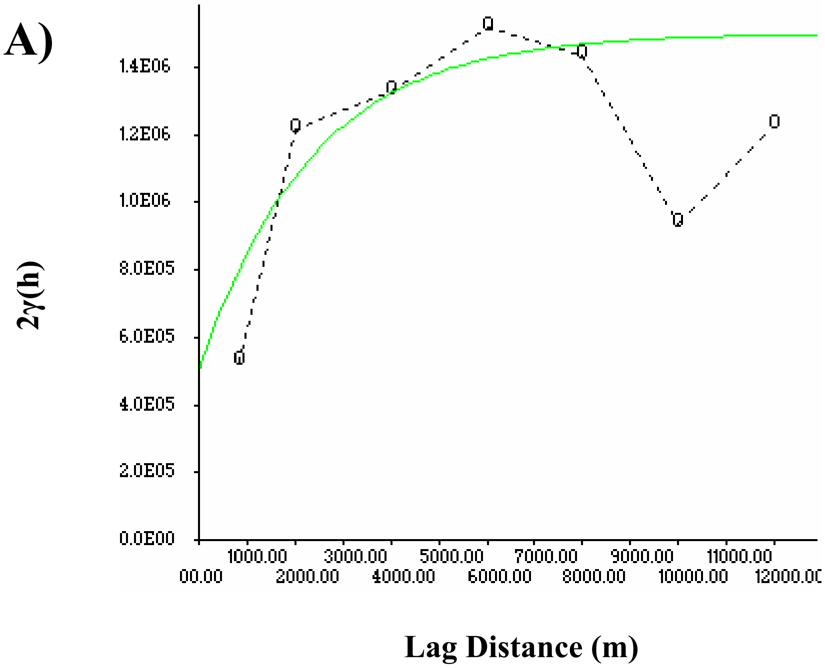


Figure 8. Results of the analysis to determine the target strength (TS) cutoff that maximized the correlation coefficient derived when midwater trawl densities of lake herring exceeding 250 mm were regressed against acoustic density estimates developed using each TS cutoff (see Methods section for details). A 3rd order polynomial line was fit to the data. The correlation coefficient was maximized at a TS cutoff of -35.6 dB.

A)



B)

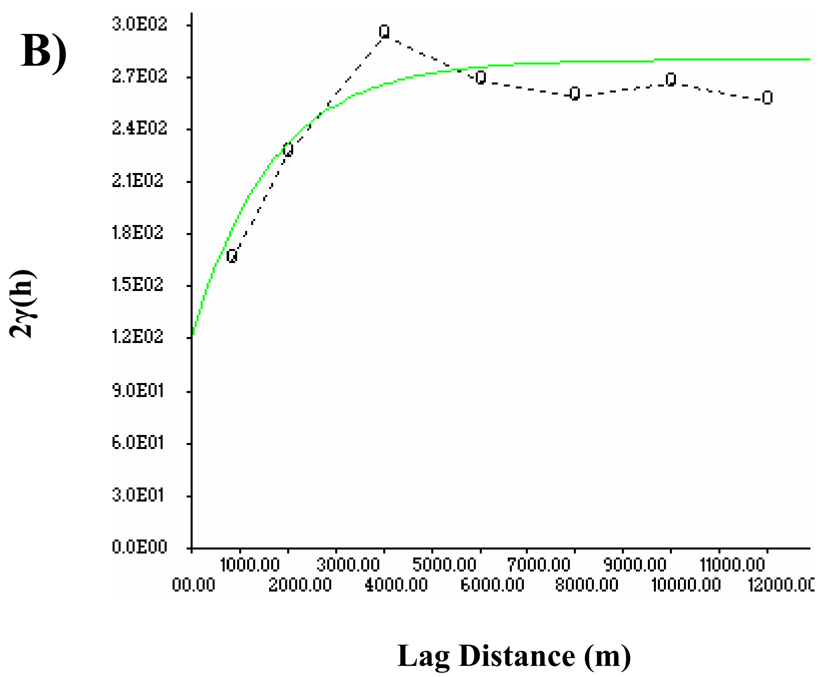


Figure 9. Variograms and exponential models of A) total fish densities and B) densities of fish greater than 250 mm (TS > -35.6 dB).

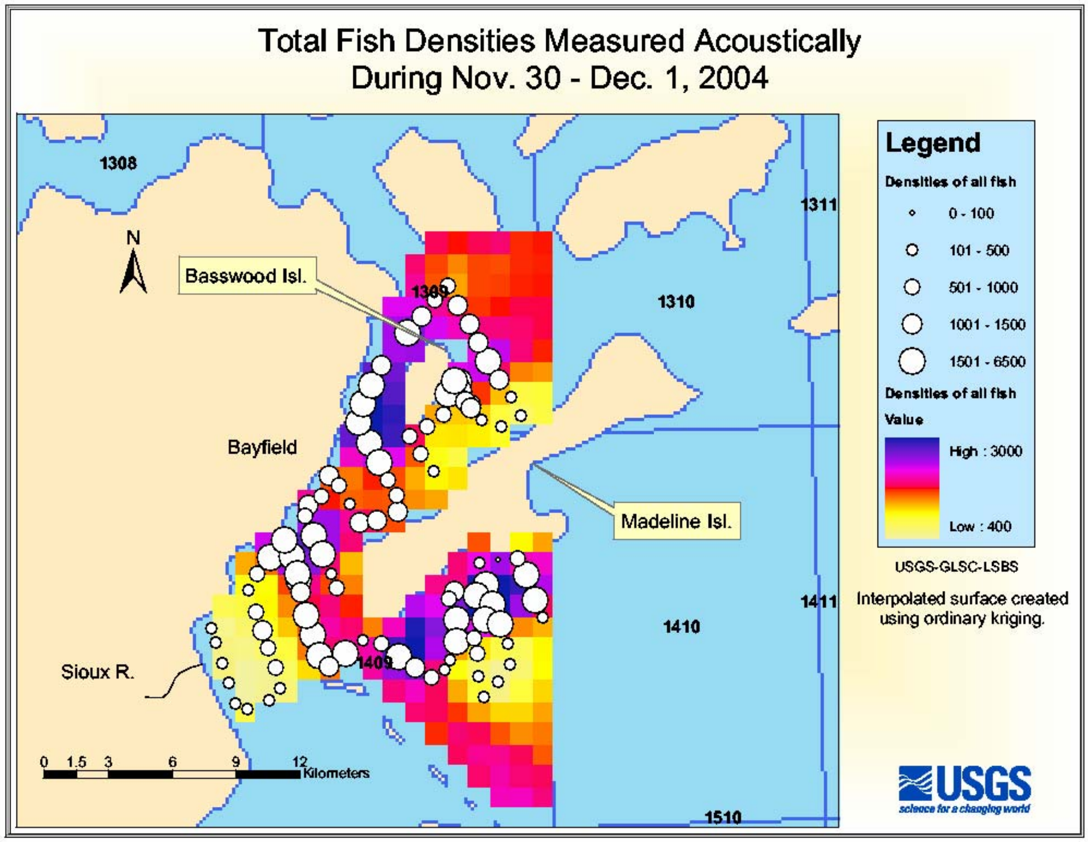


Figure 10. Map of total fish densities in the area surveyed. The interpolated surface was created by ordinary kriging using VESPER software version 1.6. The point data (N = 103) used to develop the variogram are shown using graduated symbols. Grid size in the interpolated surface equals 1 km^2.

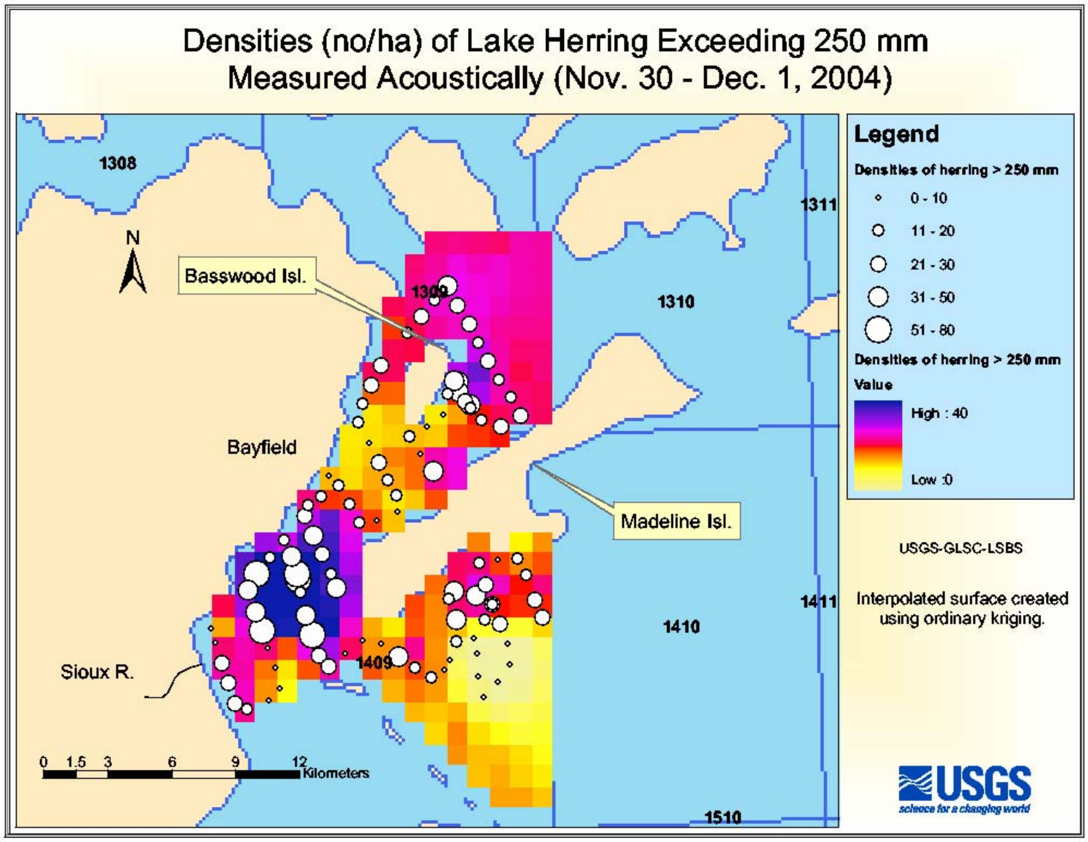


Figure 11. Map of densities of fish exceeding 250 mm in the area surveyed. The interpolated surface was created using ordinary kriging using VESPER software version 1.6. The point data (N = 103) used to develop the variogram are shown using graduated symbols. Grid size in the interpolated surface equals 1 km^2.

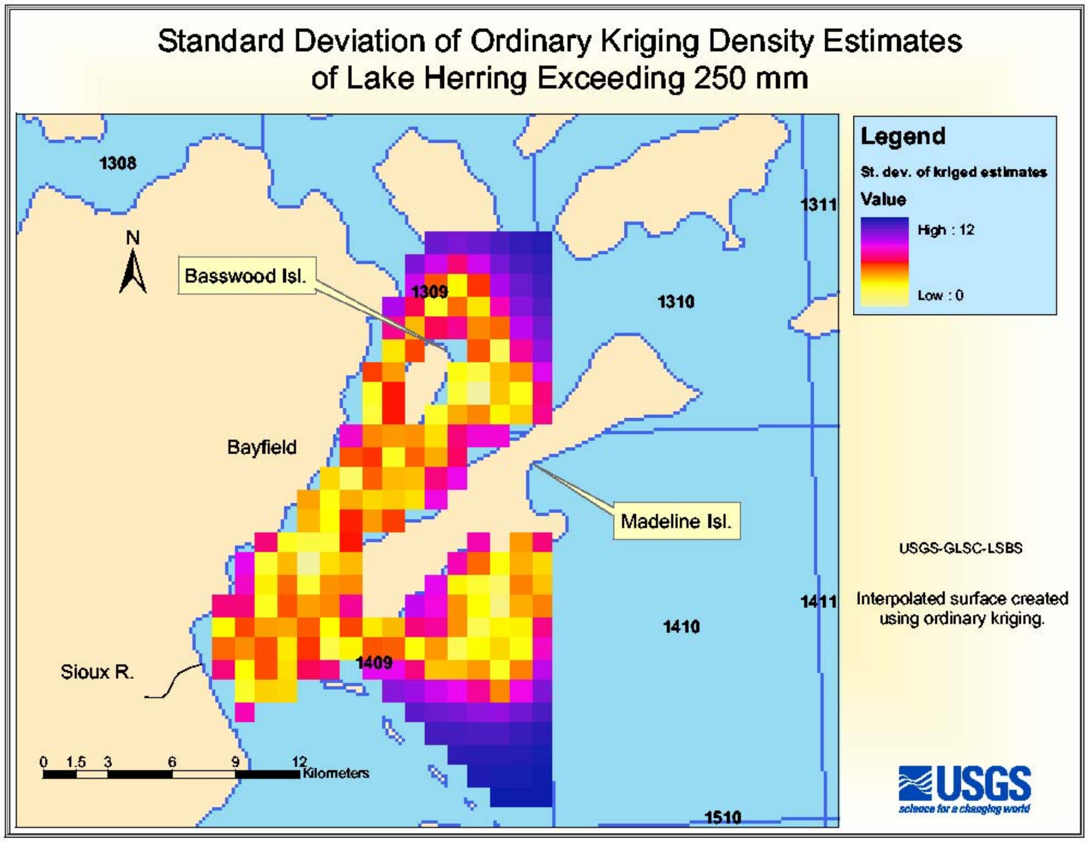


Figure 12. Map showing the standard deviation of ordinary kriging predictions of lake herring densities exceeding 250 mm estimated by VESPER software version 1.6. Grid size in the interpolated surface equals 1 km^2.

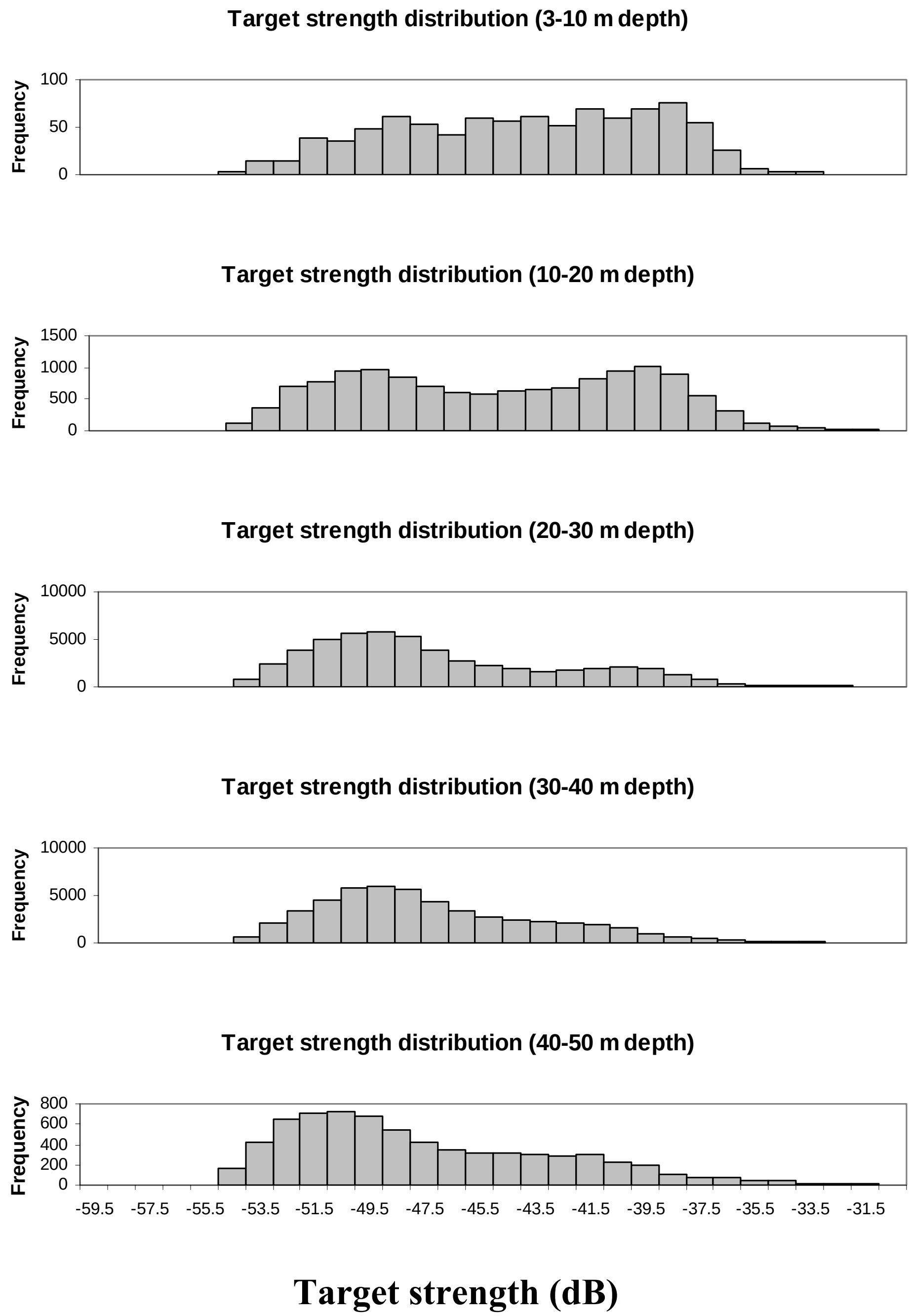


Figure 13. Target strength frequency distributions of all targets meeting the single-fish classification criteria grouped by 10-m-high depth strata.

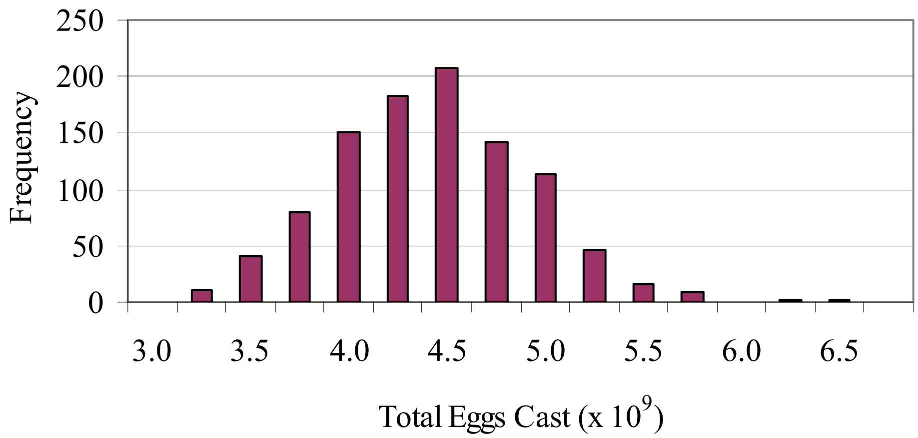


Figure 14. Frequency distribution of number of eggs cast by lake herring in statistical grid 1409 from 1,000 bootstrap simulations concurrently incorporating uncertainty in estimates of spawning female densities, size-structure of trawl catches, and the relationship between fecundity and mass. The relationship converting length to mass of fish was held constant. The upper and lower 95% confidence intervals were 3.446 and 5.370 billion eggs, respectively (see Methods section for details).

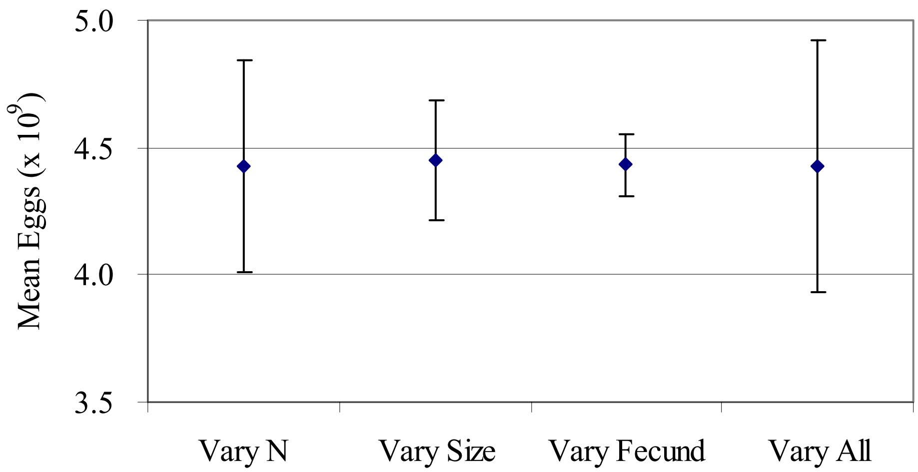


Figure 15. Mean number of eggs cast (± one standard deviation) for 1,000 simulations of varying female density ("Vary N"), size-structure ("Vary Size"), or fecundity ("Vary Fecund") one at a time, or all at once ("Vary All").

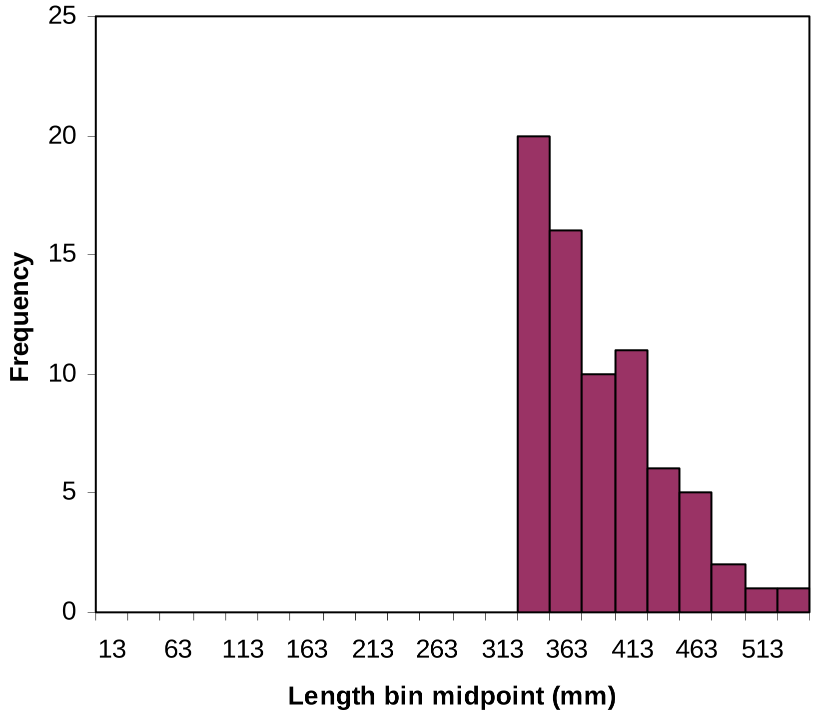


Figure 16. Length-frequency of green females harvested by commercial operators from the Apostle Islands Region of Wisconsin (31 October - 17 November 2004). A total of 72 fish were measured.

Appendix A. Echoview single target detection parameters used during this study.

Single target detection parameters	Parameter value
TS threshold (dB)	-55.00
Pulse length determination level (dB)	6.0
Minimum normalized pulse length	0.8
Maximum normalized pulse length	1.5
Beam compensation model	BioSonics
Maximum beam compensation (dB)	6.0
Maximum standard deviation of minor-axis angles (degrees)	1.5
Maximum standard deviation of major-axis angles (degrees)	1.5