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DEVELOPMENT OF A HYDROACOUSTIC SURVEY DESIGN TO QUANTIFY PREY FISH ABUNDANCE IN THE MINNESOTA WATERS OF LAKE SUPERIOR

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Abstract.--We designed and implemented a hydroacoustic and mid-water trawl assessment program in Minnesota waters of Lake Superior during 2003 and 2004 to estimate the density, biomass and composition of pelagic prey fish. Hydroacoustic data were collected in August and October 2003, and August and early September 2004. Hydroacoustic data collection in October 2003 and August and September 2004 occurred in conjunction with mid-water trawl sampling to identify species composition. Approximately 225 km of transects were sampled in 2003, and 300 km were sampled in 2004. Small coregonids (<150mm) comprised 80% of the trawl catch by number in 2003 and larger (>150mm) coregonids comprised 54% of the trawl catch in 2004. Spawning-size lake herring (>305mm) represented 7% and 17% of the trawl catch by numbers in 2003 and 2004, respectively. The density, biomass and composition of prey fishes were estimated for areas with bottom depths <80m and >80m for each of the three Minnesota management units for both years. Fish density estimates in 2003 ranged from 80 fish per hectare in MN1 waters >80m, to 447 fish per hectare in waters <80m of MN1. In 2004, fish density ranged from 93 fish per hectare in MN2 waters >80m to 234 fish per hectare in MN3 waters >80m. Estimates of total fish biomass in 2003 were 375 metric tons in MN1, 1066 metric tons in MN2, and 1821 metric tons in MN3. In 2004, the estimated total fish biomass was 1391 metric tons for MN1, 1004 metric tons for MN2, and 8220 metric tons for MN3. For all Minnesota management units combined, spawning-size lake herring dominated total fish biomass in both 2003, (86%, 2800 metric tons, 4.3 kg/ha) and 2004 (68%, 7240 metric tons, 11.0 kg/ha). Lake herring <300mm and all other coregonids represented 12% (407 metric tons) of the total biomass in 2003, and 29% (3041 metric tons) in 2004. The remaining biomass for both years was comprised mainly of rainbow smelt and siscowet.

Introduction

Within the last century, the Lake Superior food web has changed as a result of over fishing, the introduction of exotics, and habitat degradation. The control of sea lamprey, decreases in commercial fishing and the stocking of lake trout in the 1950s initiated restoration efforts on the Great Lakes (Hansen et al. 1995). These management policies facilitated the recovery of naturally reproducing populations and have led to a substantial increase in the abundance of wild lean lake trout (*Salvelinus namaycush namaycush*), which are now thought to comprise over 90% of the lake trout population (Bronte et al. 2003). The "lean" lake trout, which generally inhabits areas of the lake <80 m in depth and the "siscowet" lake trout (*Salvelinus namaycush siscowet)*, which inhabits deeper areas, are increasing in abundance and placing a greater demands on prey fish resources (Negus 1995; Harvey et al. 2003). The increased demand on forage fish has initiated the need to comprehensively estimate the amount of forage fish available in the lake (Schreiner 1995). One facet of this effort is the collaboration between the Minnesota Department of Natural Resources (MNDNR) and the University of Minnesota Duluth (UMD) focused on estimating the biomass of pelagic fishes within the Minnesota waters of Lake Superior.

The objective of this project was to develop an acoustic program to quantify the abundance of pelagic prey fishes that are important to predatory lake trout and pacific salmon (rainbow smelt and various species of coregonines) in Minnesota waters of Lake Superior. That goal was to be achieved in a series of steps. The first step was to identify the appropriate resolution for analyses of fish density and assess the amount of sampling effort needed to estimate biomass for spatial units. Secondly, to determine the cost of implementing a design that incorporates the identified sample density. Third, and most importantly, was to implement a sampling scheme that estimated the density, total abundance and biomass of prey fish populations in Minnesota waters of Lake Superior. We provide estimates of transect distance:survey area, which is needed to estimate fish density and biomass for prey fish for each of the three Minnesota management units. These findings are derived from sampling conducted in August and October of 2003, and were applied to the survey design in 2004.

Materials and Methods

Survey Design

Hydroacoustic data were collected aboard the MNDNR research vessel using a 120 kHz split beam acoustics system during August 21-27, 2003. The research vessel (R/V) Blue Heron was not set up for midwater trawling during this portion of sampling, so no fish samples were collected. Delays occurred during manufacturing of the midwater trawl and the R/V Blue Heron was not outfitted for trawling until fall 2003. Hydroacoustic transects were planned to cover broad spatial areas in both nearshore and offshore regions in each of the three Minnesota management units (Figure 1). In August 2003 sampling was attempted in MN3 using the MNDNR research vessel, but due to inclement weather, equipment malfunction, and scheduling conflicts, no useful acoustic data was collected. In 2004, all three management units were sampled using both hydroacoustics (70kHz split beam system) and midwater trawls.

During the October 2003 and August and September 2004 cruises, the R/V Blue Heron was equipped for midwater trawling. From October 14-17, 2003, hydroacoustic and midwater trawl data were collected simultaneously in areas similar to those covered in August in addition to three transects in MN3. In 2004, midwater trawl sampling occurred simultaneously with hydroacoustic data collection in all management units in August and September. All transect locations, acoustic information and trawl locations were georeferenced using a Differential GPS (DGPS) system. Raw acoustic data and trawl information were saved on computer hard drives and later copied to compact discs for data processing and archiving. Calibrations of the echosounder were performed using a tungsten carbide reference sphere (Foote et al. 1987, Foote 1990).

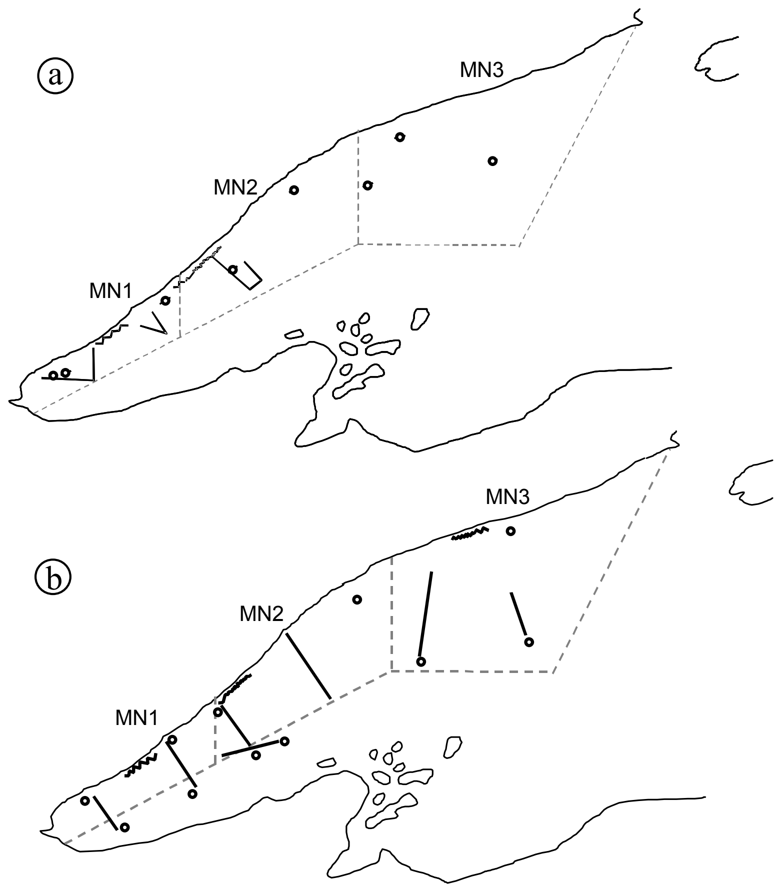

Figure 1. Locations of hydroacoustic data collection (lines) and midwater trawl sampling (circles) in a) August and October 2003 and b) August and September 2004.

The midwater trawls were aimed at depths of fish aggregations observed from the acoustic system, and fish data from those tows were used for species identification and to refine target strength relationships by incorporating additional species length data. Using the hydroacoustic information along with the species composition from the trawls, estimates of density and biomass for lake herring, rainbow smelt, and deepwater ciscoes were calculated.

Trawl Species Identification

Individual fish collected from midwater trawls in 2003 and 2004 were identified to species, and total length was recorded for comparison to hydroacoustic target strength measurements. Coregonids were identified using the taxonomic key in Becker (1983).

Data Analysis

Acoustic data was collected using Biosonics Visual Acquisition software, and data was analyzed using Echoview analysis software (v. 3.25.55, Sonardata Pty. Ltd 1995-2004). Data from each transect were processed identically, using the following procedures.

Data Quality

Prior to analysis, it was necessary to manually edit each echogram to ensure that only true fish echoes were included in analysis. Each echogram was examined for acoustic "noise" not likely attributable to fish backscatter (e.g. ship depth sounder/electrical interference, surface wave disturbance), and such regions were excluded from analysis to remove potential for biased density estimates. Additionally, the Echoview bottom detection function was used to exclude sound returned from the lake floor from echo integration.

Echo Integration

Echo integration was used to calculate the total amount of sound backscattered within an echogram. For all data, echo integration was performed for the entire length and depth of each transect and the minimum raw echo-strength threshold was –65dB. These analyses provided the Nautical Area Scattering Coefficient (NASC - a measure of the average amount of sound reflected by fish per aerial square nautical mile) for each transect.

Single Target Detection

Scaling NASC using the expected size of an acoustic fish is necessary to calculate fish density. The single target detection algorithm of Echoview uses a suite of parameters to define raw echoes as likely fish-targets. The settings used for single target detection along all transects are shown in Figure 2. Echo strength for each target identified is then corrected for sound attenuation due to depth and angle off axis, providing a true measure of the sound reflected. From this, the average target strength (TSmean) for each transect was calculated. All "noise" regions identified in quality control of raw echo echograms (described above) were also excluded from single target analysis.

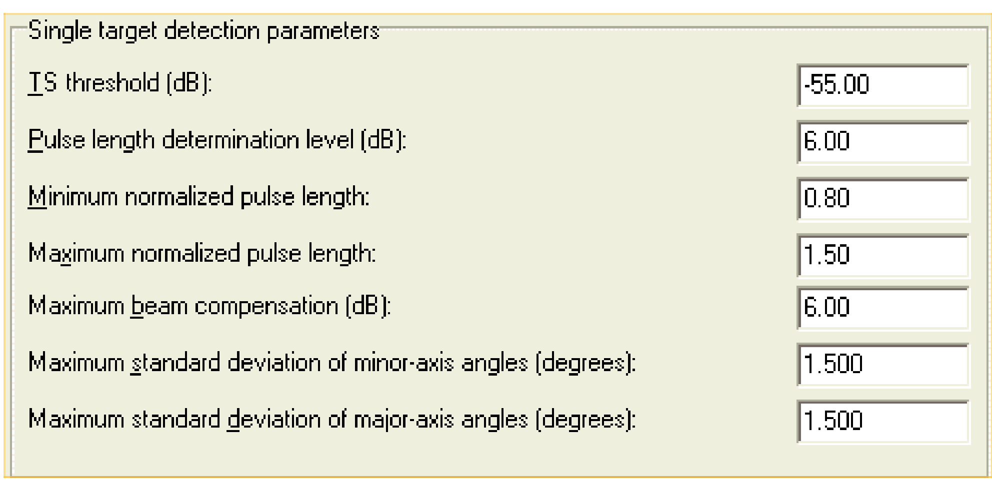

Figure 2. Echoview single target detection parameter settings used for all hydroacoustic data collected in Minnesota waters in August and October 2003 and 2004.

Fish Density Calculations

Results from echo integration and single target detection were used to calculate fish density for each transect using:

$$\text{Density} \left({}^{\text{fish}}/_{\text{ha}}\right) = \frac{\text{NASC}}{4\,\pi * 10^{(\text{TSmean}/10)} * 342.9904} \tag{1}$$

where NASC is the nautical area scattering coefficient ($m^2 * n.mi^{-2}$), $4\,\pi * 10^{(\text{TSmean}/10)}$ is the average backscattering cross-section of an acoustic target (m^2), and 342.9904 is the number of hectares per square nautical mile. For Minnesota waters, fish density was calculated for two bottom depth zones (<80 m and >80 m) within each pre-established management unit (MN1, MN2 and MN3). All acoustic transects within a management unit or depth zone of interest were used to determine average fish density (fish/ha) for that area. The resulting density estimate (fish/ha) for each area was then multiplied by the number of hectares in that area to determine the total number of fish in that region. For both years, trawl data proportions were used to proportion the total number of acoustic fish into species-specific number and biomass estimates. All fish captured in trawls were used for species-specific proportioning of acoustic densities.

Sample Density and Variability

We assessed the importance of sample size on estimates of fish density from data collected in MN1, which contained the highest ratio of transect km:total survey area. To do so, we divided survey transects into smaller segments that would allow randomization tests to be performed. The first step in these analyses was to identify the most appropriate length of segments to use in the remainder of the analyses. The fish density calculation requires estimation of mean target strength (mean acoustic size or sigma) within a segment. We examined variability in mean target strength as it related to segment size by analyzing transects divided into segments of varying length. Segments 400 m in length were considered the finest resolution possible because shorter segments contained too few single targets to obtain reasonable estimates of mean target strength. Often, segments smaller than 400 m contained less than 10 single fish echoes (in some cases none) and provided highly variable estimates of mean backscatter (mean acoustic fish size). We then used autocorrelation functions (S-plus, v. 6.2, Insightful inc.) to examine spatial correlation between segments ranging in size from 400 m to 1200 m. When the appropriate spatial resolution was identified, we then selected 250 random combinations of 5, 10, 15, 20, 25 and 30 segments, respectively. We then estimated mean fish density and 95% confidence intervals for each sample density and examined the associated relationships.

Biomass of fish species

When possible, fish collected in midwater trawls were individually weighed for use in biomass estimation. If individual weights were not taken, species-specific length-weight relationships from other regions of Lake Superior were used. Biomass of fish along each transect was determined using the species proportions and average weight of fish caught in trawl samples collected simultaneously with hydroacoustic data. For each transect, fish species proportions were multiplied by the total number of acoustic fish to determine the total number of each species. The total number of each species was then multiplied by the average weight of an individual of that species to calculate biomass.

Fish Density and Biomass Error Estimation

Each transect was divided into 800 m segments, and each segment was used to estimate density along the transect. Autocorrelation analysis was used to ensure adjacent segments along transects could be considered independent samples. If a transect did not meet this criteria, it was reanalyzed at decreased resolution until autocorrelation analysis showed independence between segments.

All independent acoustic density estimates from within an area of interest were used to calculate the 95% confidence interval about that density estimate. Error about biomass estimates was then found using:

$$\frac{|95\%CI|}{density} = proportion95\%CI \qquad 2$$

$$\pm\, proportion\ (95\%CI)*biomass = biomass95\%CI \qquad 3$$

Results

Trawl Catch

Species Composition

Species were grouped into size classes for analysis of trawl catches (Table 1). Small coregonids dominated midwater trawl catches in 2003 in all MN management units (Figure 3). Small herring had the highest catch per effort of all species in MN1 waters<80m, and was also high in MN1>80 m. In 2003, the highest CPE of small bloater catches was in MN1 and MN2 waters>80 m, while small kiyi catch was highest in MN3 waters>80m. Catches of spawning-size lake herring varied slightly across all units and depths in 2003, ranging from a low of 10 fish per hour in MN3>80 m to a high of 32 fish per hour in MN2<80 m. Smelt CPE was highest in MN1 waters, and CPE for all other species was low in all MN management units. Actual numbers of fish collected are shown in Table 2.

Overall fish CPE was lower in 2004 than in 2003 due to the large decrease in the amount of small coregonids caught (Figure 3). In 2004, large herring CPE increased in MN1<80 m (where high CPE of small herring was recorded in 2003). Spawning-size herring decreased in both depth zones of MN1 and MN2 when compared to 2003. In MN3, however, spawning-size herring CPE increased for both depth zones. An increase in the CPE of both large and small kiyi was also found in MN2 waters>80 m. Smelt and other species CPE was low for all MN management units in 2004. For all areas combined, CPE of small coregonids decreased 87% from 2003 to 2004, while CPE of large coregonids increased 554% from 2003 to 2004 (Table 3).

Table 1. Species size classes and codes used for midwater trawl and hydroacoustic data analysis.

Species	Genus and species name	code	Length (mm)
Cisco	*Coregonus artedi*	lh-sp	≥305 (12 inches)
		lh-lg	150-304
		lh-sm	<150
Bloater	*Coregonus hoyi*	bl-lg	≥150
		bl-sm	<150
Kiyi	*Coregonus kiyi*	ki-lg	≥150
		ki-sm	<150
Shortjaw Cisco	*Coregonus zenithicus*	sj-lg	≥150
Rainbow Smelt	*Osmerus mordax*	sm-lg	≥100
		sm-sm	<100
Siscowet	*Salvelinus namycush siscowet*	sw	any
Deepwater Sculpin	*Moxocephalus thompsoni*	dws	any
Other			any

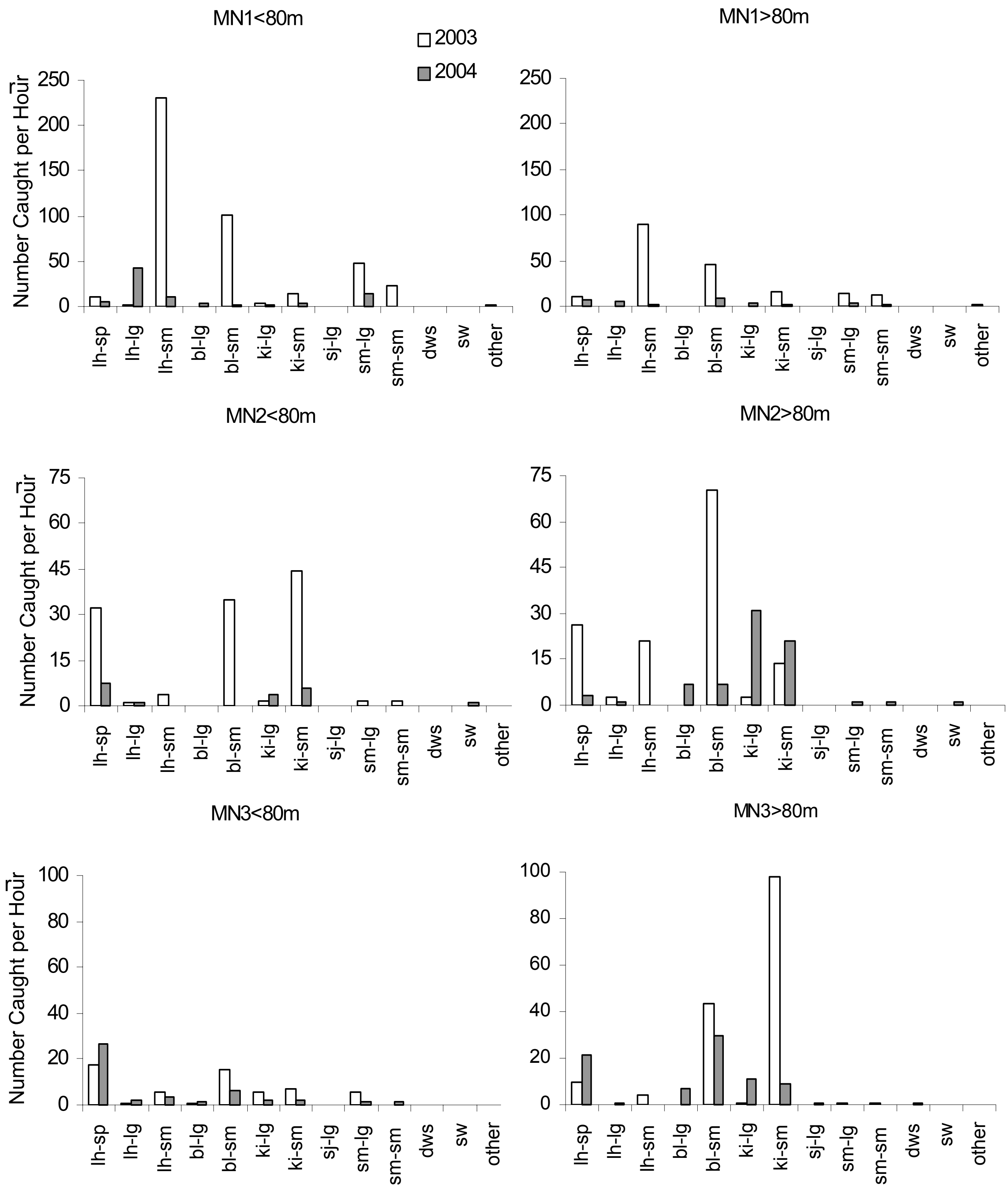

Figure 3. Species and size catch per effort for midwater trawl samples collected in Minnesota waters of Lake Superior in 2003 and 2004.

Table 2. Actual numbers of fish collected in midwater trawl samples in 2003 and 2004.

			Trawl	Number Caught												
Year	Unit	Depth	Duration (min)	lh-sp	lh-lg	lh-sm	bl-lg	bl-sm	ki-lg	ki-sm	sj-lg	sm-lg	sm-sm	dws	sw	other
2003	MN1	<80m	157	30	5	603		266	7	39		123	59	1	1	4
	MN1	>80m	62	11		93		48		16		15	12			1
	MN2	<80m	65	35	1	4		38	2	48		2	2			
	MN2	>80m	71	31	3	25		83	3	16						
	MN3	<80m	90	26	1	8	1	23	8	11		8				
	MN3	>80m	128	20		9		93	1	209		2	2			
2004	MN1	<80m	60	6	42	11	4	1	1	3	0	14				
	MN1	>80m	50	6	5	2	0	8	3	1		3	1			
	MN2	<80m	50	6	1	0	0		3	5					1	
	MN2	>80m	60	3	1		7	7	31	21		1	1		1	
	MN3	<80m	50	22	2	3	1	5	2	2	0	1	1			
	MN3	>80m	116	41	2	0	14	57	21	17	1	0	0	1		

Table 3. Relative changes in CPE, average fish weight, fish density and fish biomass between 2003 and 2004 in Minnesota waters of Lake Superior.

Unit	Depth	Small Coregonid CPUE	Large Coregonid CPUE	Spawning Herring CPUE	Average Fish Weight	Total Fish Density	Total Biomass
MN1	<80m	-96%	925%	-48%	520%	-70%	87%
	>80m	-91%	+infinite%	-32%	400%	68%	741%
MN2	<80m	-93%	73%	-78%	131%	-18%	91%
	>80m	-73%	669%	-89%	-22%	7%	-17%
MN3	<80m	-57%	-10%	52%	77%	124%	296%
	>80m	-74%	3983%	126%	397%	-8%	356%
ALL MN		-87%	554%	-19%	261%	-12%	226%

Length frequencies for trawl catches in 2003 and 2004 are shown in Figures 4 and 5. In 2003, the size ranges of all species were very similar for all management units and depth zones, although the number caught varied. In 2004, size distributions were much more variable between depth zones and management units. In MN1<80 m, adult lake herring were slightly smaller than in all other areas, and did not include many individuals over 12 inches.

For all management units and depth zones combined, small lake herring catches decreased in 2004, although the average size was larger than in 2003 (Figure 6). Additionally, the adult lake herring size distribution in 2003 contained mainly fish of spawning size, while in 2004, there were adults smaller than spawning size present. Mean small kiyi and small bloater sizes increased in 2004 compared to 2003, and both species showed an increase in maximum length in 2004. Small smelt were not captured in 2004, and the mean size of large smelt was similar for both years.

Comparison of fish size from trawls and hydroacoustics

Portions of echograms coinciding with depths sampled by midwater trawls were analyzed to estimate fish size distributions. The target strength of individual fish detected within the path of the trawl was converted to length (Love 1971). This allowed for a comparison of the acoustic length frequency distribution with the size distribution of fish collected in the trawls (Figure 7). The mean size estimated using acoustics did not differ significantly from that observed in the trawls. These data will be used to create a Lake Superior-specific models for estimation target strength and length relationships.

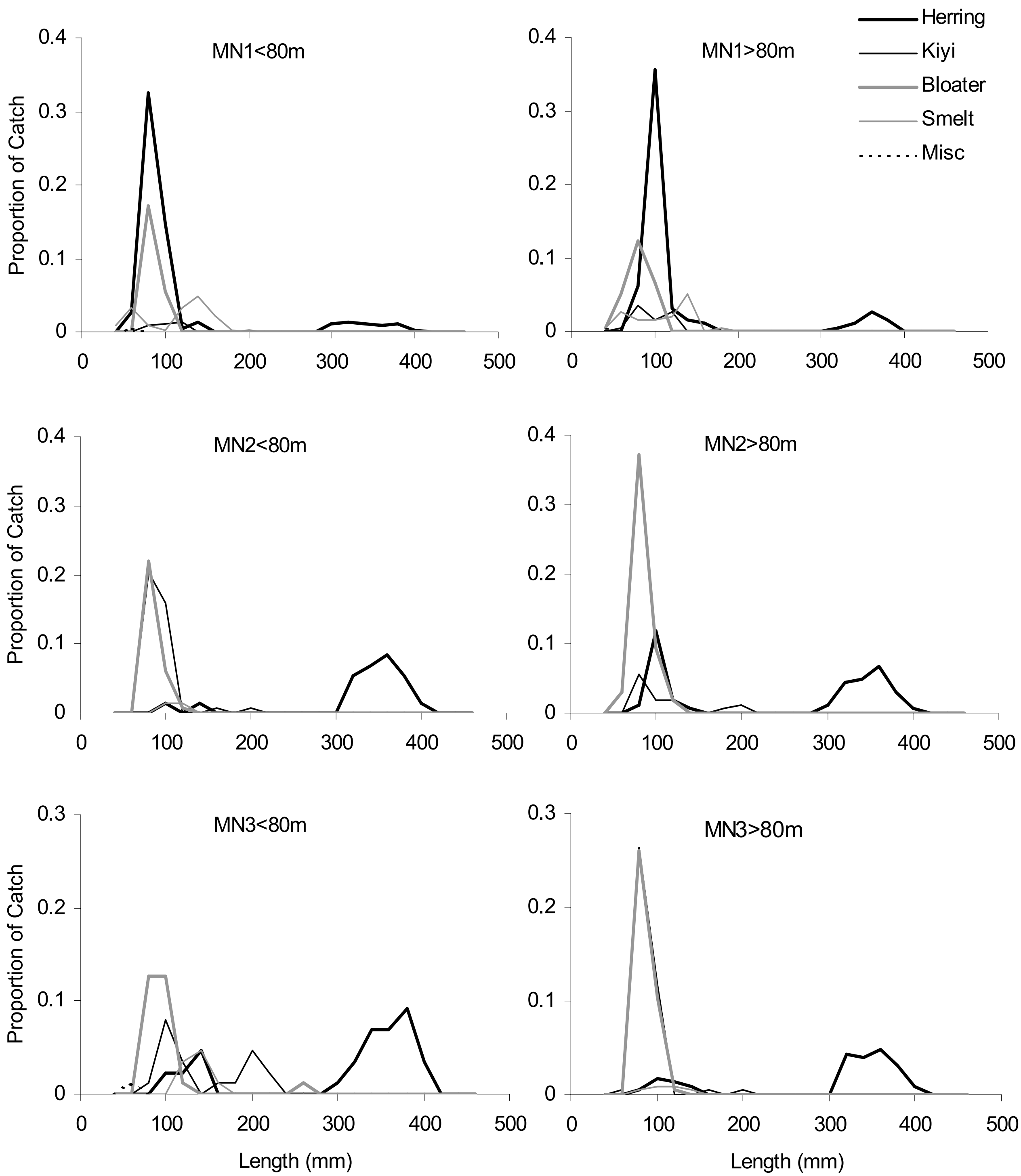

Figure 4. Length frequencies of fish collected in Minnesota waters of Lake Superior using a midwater trawl in 2003.

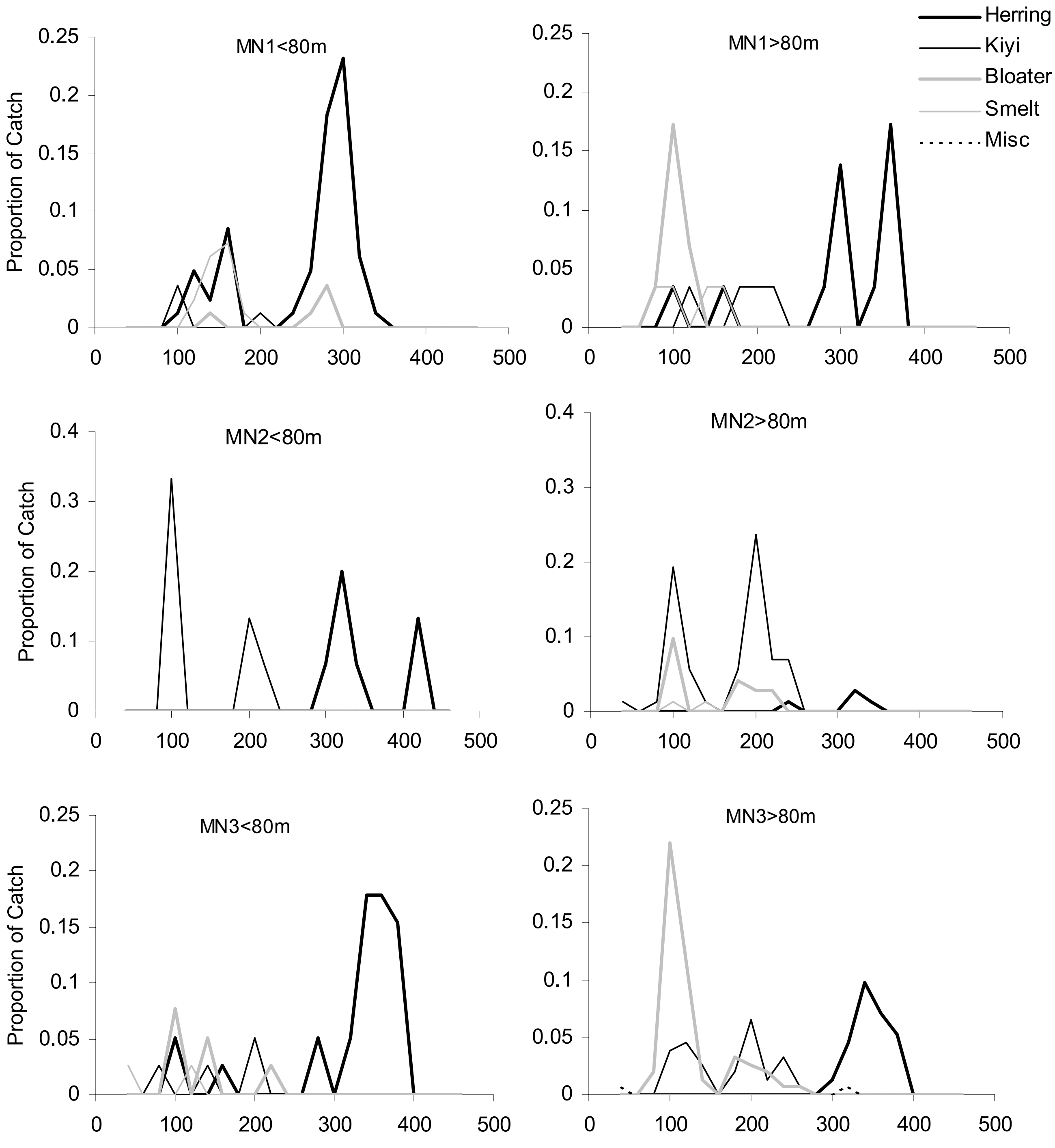

Figure 5. Length frequencies of fish collected in Minnesota waters of Lake Superior using a midwater trawl in 2004.

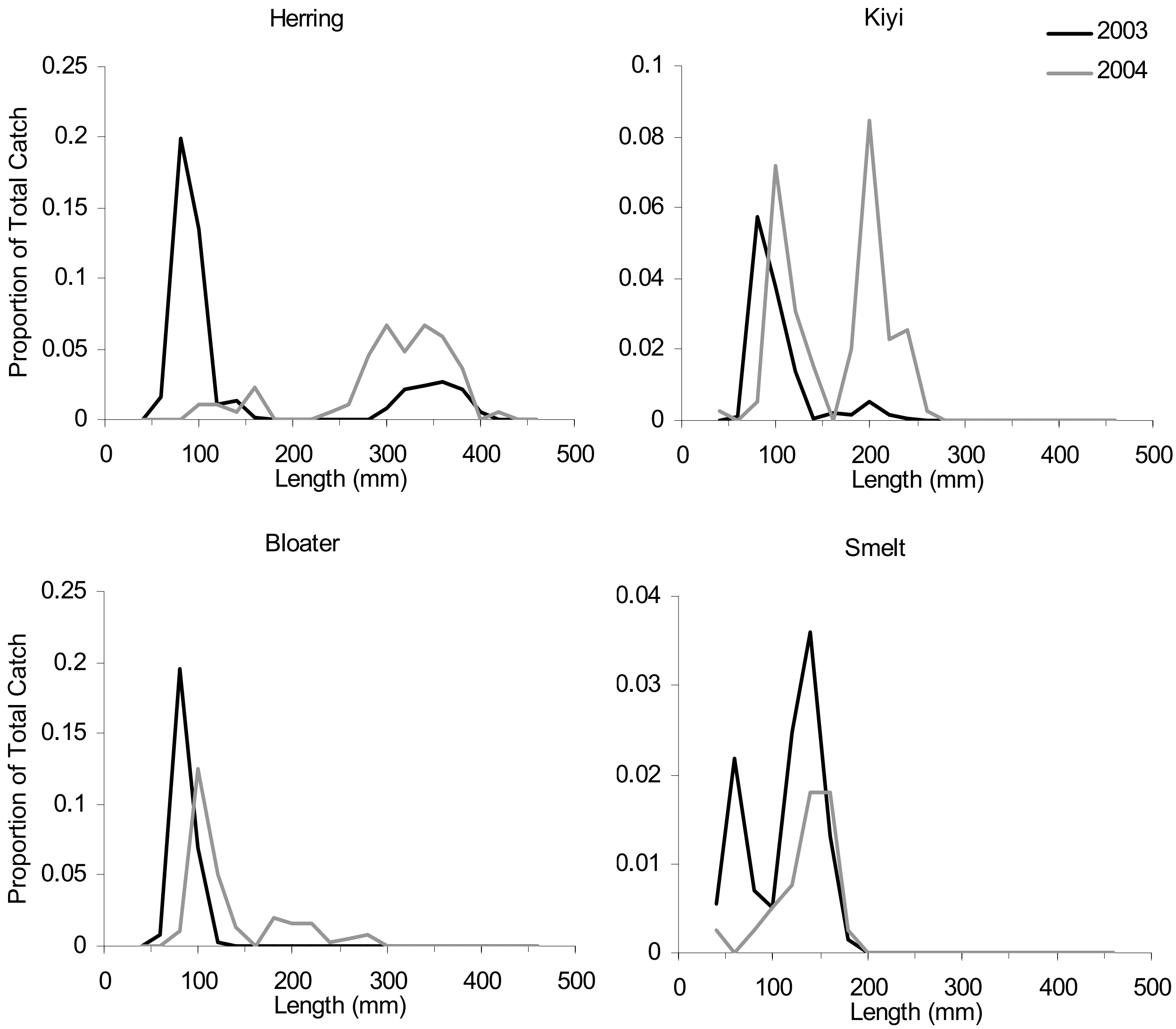

Figure 6. Length frequency for all midwater trawl samples collected in all Minnesota waters of Lake Superior in 2003 and 2004.

Hydroacoustic Data

Sample Density and Variability

In 2003, we assessed the influence of sampling effort on the variability about our estimates of fish density. We used information collected in MN1, which contained the highest sampling effort per unit area. We began by separating transects into smaller segments to identify the most appropriate resolution for analysis based on the number of single targets detected (which is used to calculate the mean fish size and fish density over a defined area). Results from segments ranging in size from 100 m to 1500 m indicated that fewer than 50 single fish targets were detected in segments shorter than 800 m (Figure 8).

Furthermore, the mean size of acoustic targets varied as segment size was changed. Mean acoustic size or "sigma" is very influential in estimating fish density and is an extremely important variable. The estimated mean acoustic size of fish targets and the associated variability became more consistent as segment size approached 800 m in length (Figure 9) and the standard deviation was approximately 1.3 db for segments 800 m or longer in length.

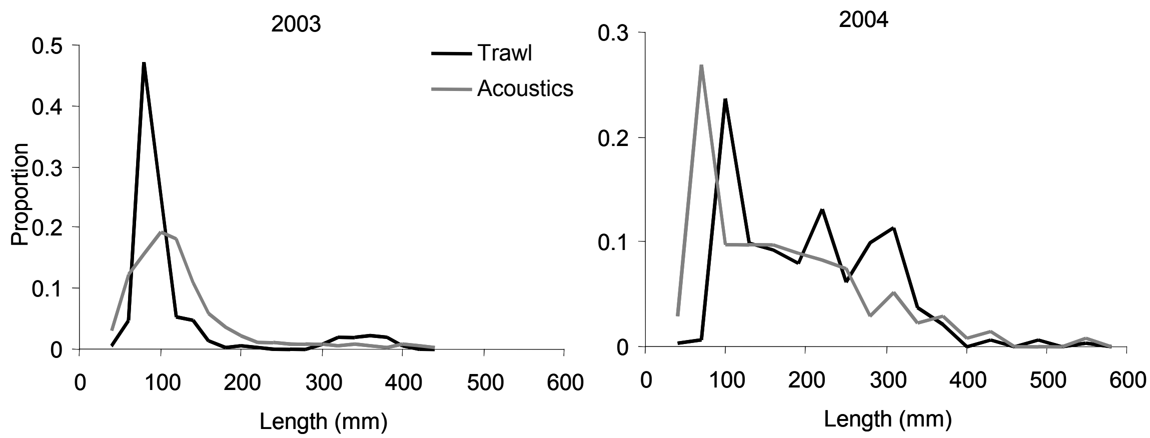

Figure 7. Comparison of the trawl fish lengths with acoustic size of targets identified within the trawl path for 2003 and 2004.

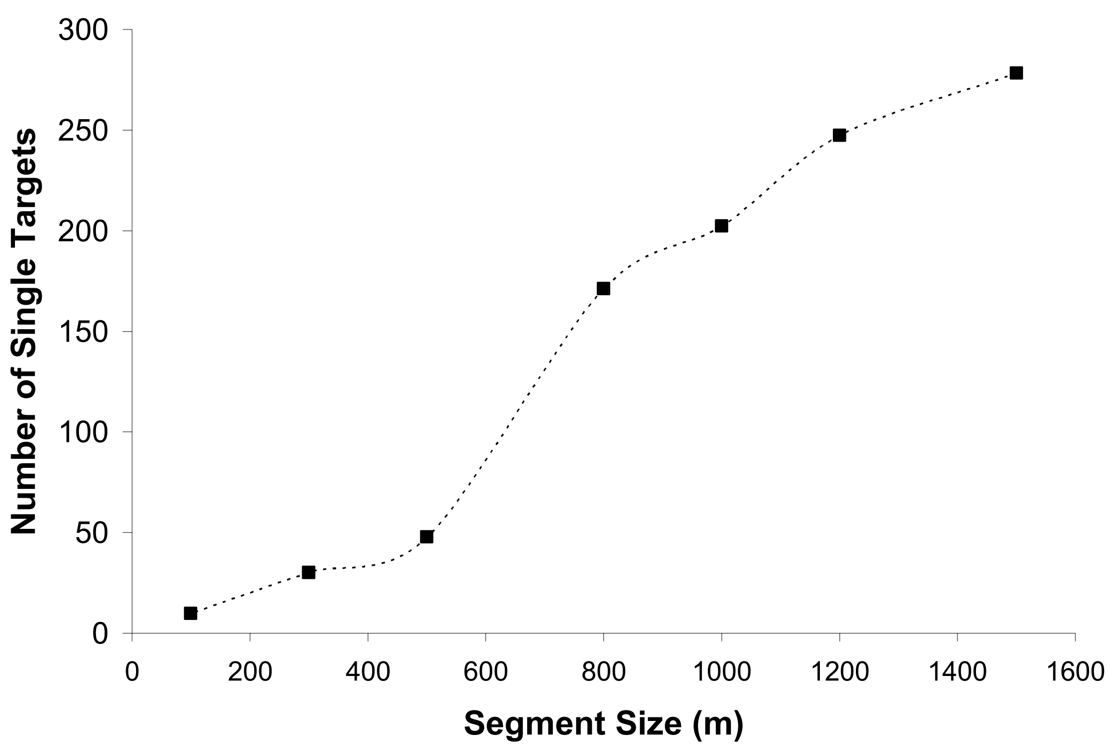

Figure 8. The average number of single fish targets detected in transect segments of varying length in MN1.

In addition, autocorrelation analyses of fish density indicated that segments 800 m in length were not correlated with the nearest (neighbor) segments in Minnesota waters (Figure 10). Thus, we used 800 m segments as samples in the estimation of variance and confidence intervals of fish density.

Once the segment size of 800 m was identified, we then drew 250 random combinations of 5, 10, 15, 20, 25 and 30 segments to estimate mean density and identify the relationship between sample density and variability about the estimated fish density in MN1. The mean estimated density of fish within MN1 was similar for each scenario (Figure 11). However, the variability among the estimates indicated that there was higher uncertainty when less than 16000 m of acoustic transect (20-800 m segments) was included in MN1 (Figure 11).

The amount of variability associated with acoustic estimates of fish density was negatively related to the number of 800 m samples (Figure 12). The ratio of 95% confidence intervals to mean densities was approximately 50% when 4km of transect were performed in MN1. This ratio declined and appeared to stabilize at approximately 20 km of transect distance or a sample density of approximately 0.018 km of transect:square km of the survey area. This trend indicates that the number of kilometers of transect should be scaled to the area to be surveyed. Based on this estimate of needed sample density and the assumption that the lowest variability in the estimates is desired, we would need to sample approximately 20 km of transects in MN1, 34 km of transects in MN2 and 65 km of transects in MN3. Our results indicate that we probably adequately sampled all zones in 2003 and 2004, except in 2003 when we greatly under-sampled MN-3.

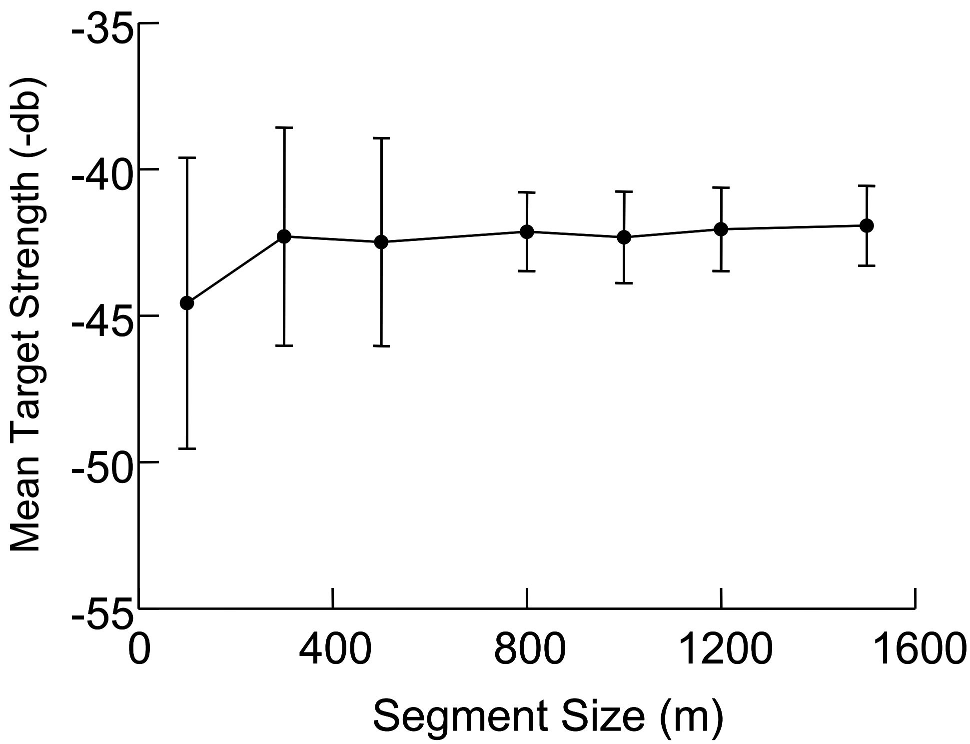

Figure 9. Mean target strength (mean backscatter or sigma) found in segments of varying length in MN1 in 2003. Error bars indicate standard deviations about the mean.

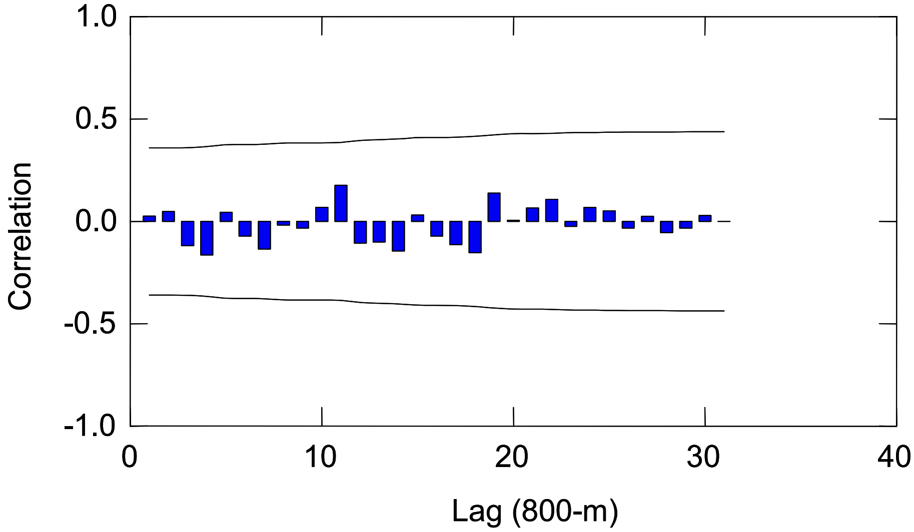

Figure 10. Plot showing correlation between 800 m segments varying distances from one another. A lag of one indicates the level of correlation between the nearest neighbor segments.

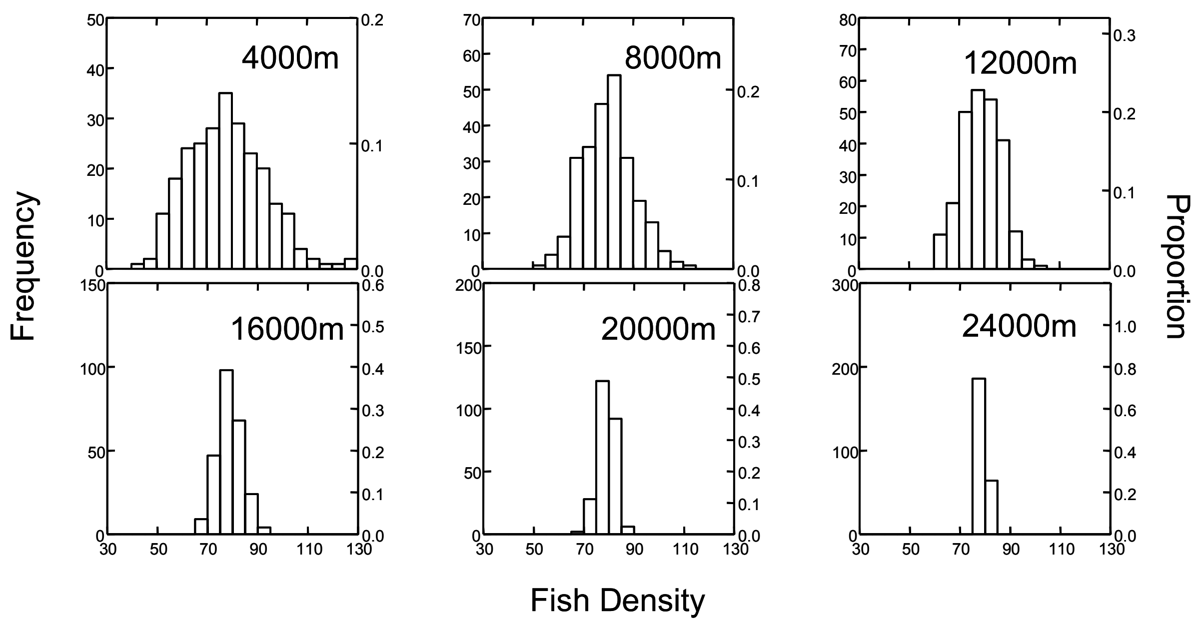

Figure 11. Frequency distributions of mean fish density derived from 250 random combinations of densities obtained from various numbers of 800m transect segments.

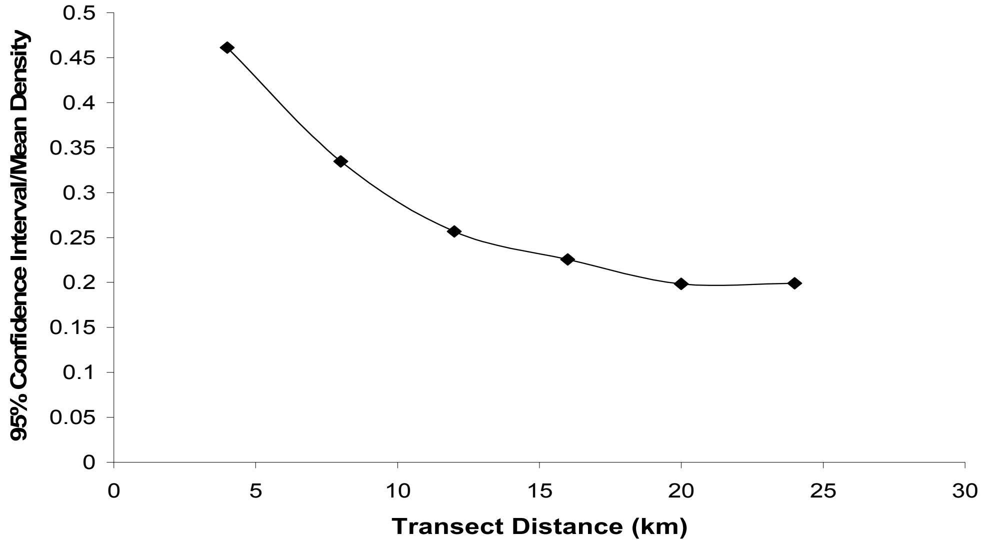

Figure 12. The ratio of the estimated 95% confidence interval divided by the mean estimate of fish density in MN1 vs. transect distance covered.

Fish Density Estimates

The estimated fish density in Minnesota management units in 2003 ranged from approximately 80 fish per hectare in areas >80 m in MN1 to 447 fish per hectare in shallow waters of MN1 (Table 4). For all management units combined, fish density was 334 per hectare for water <80m deep, and 185 per hectare for water >80 m. MN1 and MN3 supported similar fish densities (232 and 249 fish per hectare respectively), while the average fish density in MN2 was lower at 91 per hectare.

In 2004, fish density was highest in water >80 m deep in MN3, with 235 fish per hectare. Fish density in 2004 was lowest in MN2 waters <80m (94 per hectare). For all MN units, fish density in both depth zones was similar, with 151 per hectare in water <80 m, and 181 per hectare in water >80 m. As in 2003, fish density was lowest in MN2 (96 per hectare). MN1 fish density (135 per hectare) was lower than MN3 (233 per hectare) in 2004. From 2003 to 2004, the fish density in MN1<80 m decreased from 447 per hectare to 135 per hectare, and can likely be attributed to the large decrease in the number of small coregonids captured in this area between 2003 and 2004 (Figure 13). Additionally, fish density in MN3<80 m increased from 93 per hectare in 2003 to 208 per hectare in 2004 (Figure 13). For all MN waters combined, fish density decreased by 12% from 2003 to 2004 (Table 3).

Fish density estimates were scaled to absolute abundance using the areas of each managements units to determine the total number of fish in each management unit and depth zone (Table 5). The largest change in fish numbers between 2003 and 2004 occurred in MN1<80 m, again due to the decline in small coregonids. For all other areas, the total number of fish was similar between years, although the species composition of fish within areas changed. In MN3>80 m The number of spawning-size herring increased from 5.2 million in 2003 to 21.5 million in 2004.

Table 4. Estimates of fish density and total number of fish in each management unit and depth zone for 2003 and 2004.

Management Unit	Bottom Depth	Area (ha)	2003 Density (fish/ha)	2003 Number of Fish (millions)	2004 Density (fish/ha)	2004 Number of Fish (millions)
MN1	<80m	44,959	447.0	20.1	134.9	6.1
	>80m	63,794	80.3	5.1	135.1	8.6
MN2	<80m	8,533	160.6	1.4	132.3	1.1
	>80m	180,507	88.1	15.9	93.8	16.9
MN3	<80m	14,879	93.1	1.4	208.5	3.1
	>80m	343,473	255.8	87.9	234.7	80.6
MN1	all	108,753	231.9	25.2	135.0	14.7
MN2	all	189,040	91.4	17.3	95.6	18.1
MN3	all	358,352	249.1	89.3	233.6	83.7
All	<80m	68,371	334.2	22.9	150.6	10.3
All	>80m	587,774	185.3	108.9	180.6	106.2
All MN	all	656,145	200.8	131.7	177.5	116.5

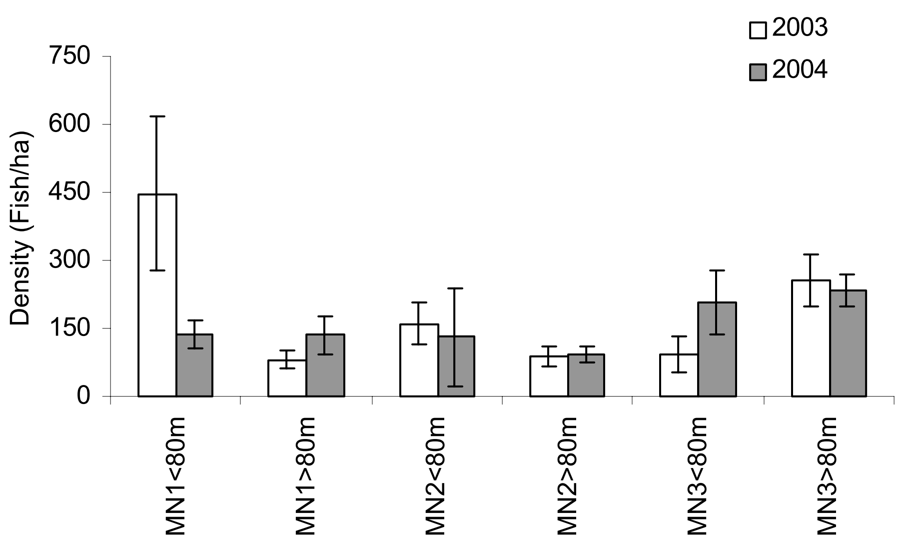

Figure 13. Fish density estimates (number/ha) with 95%CI for Minnesota waters of Lake Superior for 2003 and 2004.

Table 5. Total number by species in October 2003 for each depth zone of the Minnesota management units of Lake Superior using acoustic and midwater trawl data.

		Bottom Depth	Total Fish	Number by species and size (millions)												
Year	Unit	(m)	(millions)	lh-sp	lh-lg	lh-sm	bl-lg	bl-sm	ki-lg	ki-sm	sj-lg	sm-lg	sm-sm	dws	sw	other
2003	MN1	<80m	20.1	0.5	0.1	10.6	0.0	4.7	0.1	0.7	0.0	2.2	1.0	0.0	0.0	0.1
2003	MN1	>80m	5.1	0.3	0.0	2.4	0.0	1.3	0.0	0.4	0.0	0.4	0.3	0.0	0.0	0.0
2003	MN2	<80m	1.4	0.4	0.0	0.0	0.0	0.4	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
2003	MN2	>80m	15.9	3.1	0.3	2.5	0.0	8.2	0.3	1.6	0.0	0.0	0.0	0.0	0.0	0.0
2003	MN3	<80m	1.4	0.4	0.0	0.1	0.0	0.4	0.1	0.2	0.0	0.1	0.0	0.0	0.0	0.0
2003	MN3	>80m	87.9	5.2	0.0	2.4	0.0	24.3	0.3	54.7	0.0	0.5	0.5	0.0	0.0	0.0
2004	MN1	<80m	6.1	0.4	3.1	0.8	0.3	0.1	0.1	0.2	0.0	1.0	0.0	0.0	0.0	0.0
2004	MN1	>80m	8.6	1.8	1.5	0.6	0.0	2.4	0.9	0.3	0.0	0.9	0.3	0.0	0.0	0.0
2004	MN2	<80m	1.1	0.4	0.1	0.0	0.0	0.0	0.2	0.4	0.0	0.0	0.0	0.0	0.1	0.0
2004	MN2	>80m	16.9	0.7	0.2	0.0	1.6	1.6	7.2	4.9	0.0	0.2	0.2	0.0	0.2	0.0
2004	MN3	<80m	3.1	1.7	0.2	0.2	0.1	0.4	0.2	0.2	0.0	0.1	0.1	0.0	0.0	0.0
2004	MN3	>80m	80.6	21.5	1.0	0.0	7.3	29.8	11.0	8.9	0.5	0.0	0.0	0.5	0.0	0.0

Fish Biomass Estimates

The biomass of each species in metric tons (Table 6) and kilograms per hectare (Table 7) was found using the average weight for each species and the total number of each species. In 2003, spawning-size lake herring dominated the biomass in all management units and depth zones, ranging from 58% of the biomass in MN1<80 m to 95% in MN2<80 m. For all areas and depth zones combined, spawning-size lake herring biomass (2,800 metric tons) comprised 86% of the total biomass (Figure 14). All coregonids together represent 98% of the total biomass of fish found in Minnesota waters of Lake Superior. The total fish biomass of Minnesota waters was 3,263 metric tons in 2003. Area-corrected biomass calculations show a range of spawning-size lake herring from 1.3 kg/ha in MN1<80 m to 12.1 kg/ha in MN2<80 m (Table 6, Figure 14). For all Minnesota waters, spawning-size lake herring averaged 4.3 kg/ha, and all coregonids combined averaged 4.9 kg/ha.

In 2004, the total biomass of fish in Minnesota waters increased to 10,630 metric tons. Although spawning-size lake herring again dominated the biomass with 7,240 metric tons (Figure 14), this only represented 68% of the total biomass - a decrease of 18% compared to 2003. Large herring, large bloater, large kiyi and siscowet all increased in biomass in 2004, and combined contributed 27% of the total biomass. A single specimen of shortjaw cisco captured in the midwater trawls yielded a shortjaw biomass estimate of 113 metric tons in MN3>80 m. Area-corrected biomass estimates for spawning-sized lake herring in 2004 showed an increase from 2003, ranging from 2 kg/ha in MN1<80m to 34 kg/ha in MN3<80 m and averaging 11 kg/ha for all MN waters (Figure 14). The coregonid biomass increased greatly when compared to 2003, with 15.5 kg/ha for all management units and depths combined.

Changes from 2003 to 2004

Small coregonid CPE decreased in every management unit between 2003 and 2004. During this same time period, large coregonid (not including spawning herring) CPE increased dramatically (>500%) in nearly all MN units (Table 2). Additionally, the proportion of large coregonids and spawning-size herring in trawl catches greatly increased in 2004 (Figure 6). This change in fish proportions led to a 261% increase in average fish weight. When these larger weights and higher proportions of larger fish were applied to acoustic density estimates, the result was an overall increase in fish biomass of 226% between 2003 and 2004 (Table 2).

Table 6. Biomass in metric tons (±95% CI, in parentheses) for fish species and size classes (Table 1) for Minnesota management units of Lake Superior in 2003 and 2004 determined using hydroacoustics and midwater trawl samples.

		Bottom	Metric Tons												
Year	Unit	Depth(m)	lh-sp	lh-lg	lh-sm	bl-lg	bl-sm	ki-lg	ki-sm	sj-lg	sm-lg	sm-sm	dws	sw	other
2003	MN1	<80m	154.8	15.5	33.2	0.0	14.1	4.0	2.4	0.0	23.6	2.5	0.0	17.2	0.1
			(58.5)	(5.9)	(12.6)	-	(5.3)	(1.5)	(0.9)	-	(8.9)	(1.0)	-	(6.5)	(0.0)
		>80m	85.9	0.0	13.1	0.0	3.2	0.0	1.2	0.0	3.9	0.4	0.0	0.0	0.0
			(20.9)	-	(3.2)	-	(0.8)	-	(0.3)	-	(1.0)	(0.1)	-	-	-
	MN2	<80m	103.5	1.9	0.4	0.0	1.3	0.5	0.8	0.0	0.2	0.1	0.0	0.0	0.0
			(29.3)	(0.6)	(0.1)	-	(0.4)	(0.1)	(0.2)	-	(0.0)	(0.0)	-	-	-
		>80m	854.1	52.0	14.1	0.0	26.3	7.7	3.8	0.0	0.0	0.0	0.0	0.0	0.0
			(221.3)	(13.5)	(3.7)	-	(6.8)	(2.0)	(1.0)	-	-	-	-	-	-
	MN3	<80m	125.4	2.5	1.4	1.6	1.4	3.9	0.5	0.0	1.3	0.0	0.0	0.0	0.0
			(51.9)	(1.0)	(0.6)	(0.7)	(0.6)	(1.6)	(0.2)	-	(0.5)	-	-	-	-
		>80m	1476.6	0.0	17.7	0.0	72.4	6.8	103.5	0.0	5.9	0.7	0.0	0.0	0.0
			(335.8)	-	(4.0)	-	(16.5)	(1.6)	(23.5)	-	(1.3)	(0.2)	-	-	-
	MN1	all	240.7	15.5	46.3	0.0	17.4	4.0	3.5	0.0	27.5	3.0	0.0	17.2	0.1
			(86.8)	(5.6)	(16.7)	-	(6.3)	(1.4)	(1.3)	-	(9.9)	(1.1)	(0.0)	(6.2)	(0.0)
	MN2	all	957.6	53.9	14.6	0.0	27.6	8.2	4.7	0.0	0.2	0.1	0.0	0.0	0.0
			(189.0)	(10.6)	(2.9)	-	(5.5)	(1.6)	(0.9)	-	(0.0)	(0.0)	-	-	-
	MN3	all	1601.9	2.5	19.1	1.6	73.7	10.7	104.0	0.0	7.1	0.7	0.0	0.0	0.0
			(424.0)	(0.7)	(5.0)	(0.4)	(19.5)	(2.8)	(27.5)	-	(1.9)	(0.2)	-	-	-
	All	<80m	383.7	20.0	35.0	1.6	16.8	8.4	3.7	0.0	25.0	2.6	0.0	17.2	0.1
			(110.0)	(5.7)	(10.0)	(0.5)	(4.8)	(2.4)	(1.1)	-	(7.2)	(0.7)	(0.0)	(4.9)	(0.0)
	All	>80m	2416.6	52.0	45.0	0.0	102.0	14.5	108.5	0.0	9.8	1.1	0.0	0.0	0.0
			(432.7)	(9.3)	(8.0)	-	(18.3)	(2.6)	(19.4)	-	(1.7)	(0.2)	-	-	(0.0)
	All MN		2800.3	72.0	79.9	1.6	118.7	22.9	112.2	0.0	34.8	3.7	0.0	17.2	0.1
			(580.1)	(14.9)	(16.6)	(0.3)	(24.6)	(4.7)	(23.2)	-	(7.2)	(0.8)	(0.0)	(3.6)	(0.0)
2004	MN1	<80m	89.3	348.2	11.7	32.8	1.0	2.3	0.5	0.0	14.2	0.0	0.0	0.0	0.0
			(20.5)	(79.8)	(2.7)	(7.5)	(0.2)	(0.5)	(0.1)	-	(3.3)	-	-	-	-
		>80m	494.6	246.0	115.2	0.0	13.5	25.9	1.2	0.0	8.9	0.7	0.0	0.0	0.0
			(151.7)	(75.5)	(35.3)	-	(4.1)	(7.9)	(0.4)	-	(2.7)	(0.2)	-	-	-
	MN2	<80m	128.8	11.9	0.0	0.0	0.0	7.4	1.0	0.0	0.0	0.0	0.0	58.2	0.0
			(105.2)	(9.7)	-	-	-	(6.0)	(0.8)	-	-	-	-	(47.6)	-
		>80m	161.5	20.2	0.0	74.4	9.2	251.9	14.6	0.0	2.0	0.8	0.0	262.7	0.0
			(30.2)	(3.8)	-	(13.9)	(1.7)	(47.2)	(2.7)	-	(0.4)	(0.2)	-	(49.2)	-
	MN3	<80m	506.4	21.9	2.7	5.4	3.7	4.7	1.0	0.0	0.4	0.0	0.0	0.0	0.0
			(169.1)	(7.3)	(0.9)	(1.8)	(1.2)	(1.6)	(0.3)	-	(0.1)	(0.0)	-	-	-
		>80m	5859.8	171.0	0.0	374.3	186.9	922.9	42.7	115.6	0.0	0.0	0.5	0.0	0.0
			(900.6)	(26.3)	-	(57.5)	(28.7)	(141.8)	(6.6)	(17.8)	-	-	(0.1)	-	-
	MN1	all	583.9	594.2	126.9	32.8	14.4	28.2	1.7	0.0	23.1	0.7	0.0	0.0	0.0
			(106.5)	(108.4)	(23.2)	(6.0)	(2.6)	(5.1)	(0.3)	0.0	(4.2)	(0.1)	0.0	0.0	0.0
	MN2	all	290.3	32.0	0.0	74.4	9.2	259.2	15.5	0.0	2.0	0.8	0.0	320.9	0.0
			(91.3)	(10.1)	0.0	(23.4)	(2.9)	(81.6)	(4.9)	0.0	(0.6)	(0.3)	0.0	(101.0)	0.0
	MN3	all	6366.2	192.9	2.7	379.7	190.6	927.6	43.7	115.6	0.4	0.0	0.5	0.0	0.0
			(980.5)	(29.7)	(0.4)	(58.5)	(29.4)	(142.9)	(6.7)	(17.8)	(0.1)	(0.0)	(0.1)	0.0	0.0
	All	<80m	724.6	381.9	14.5	38.2	4.7	14.3	2.5	0.0	14.7	0.0	0.0	58.2	0.0
			(192.8)	(101.6)	(3.9)	(10.2)	(1.2)	(3.8)	(0.7)	0.0	(3.9)	(0.0)	0.0	(15.5)	0.0
	All	>80m	6515.9	437.2	115.2	448.7	209.5	1200.7	58.5	115.6	10.9	1.5	0.5	262.7	0.0
			(852.8)	(57.2)	(15.1)	(58.7)	(27.4)	(157.2)	(7.7)	(15.1)	(1.4)	(0.2)	(0.1)	(34.4)	0.0
	All MN		7240.4	819.1	129.7	486.9	214.2	1215.0	60.9	115.6	25.5	1.5	0.5	320.9	0.0
			(995.8)	(112.7)	(17.8)	(67.0)	(29.5)	(167.1)	(8.4)	(15.9)	(3.5)	(0.2)	(0.1)	(44.1)	0.0

Table 7. Biomass in kg/ha (+95% CI, in parentheses) for fish species and size classes (Table 1) for Minnesota management units of Lake Superior in 2003 and 2004 determined using hydroacoustics and midwater trawl samples.

		Bottom	kg/ha												
Year	Unit	Depth(m)	lh-sp	lh-lg	lh-sm	bl-lg	bl-sm	ki-lg	ki-sm	sj-lg	sm-lg	sm-sm	dws	sw	other
2003	MN1	<80m	3.4	0.3	0.7	0.0	0.3	0.1	0.1	0.0	0.5	0.1	0.0	0.4	0.0
			(1.3)	(0.1)	(0.3)	-	(0.1)	(0.0)	(0.0)	-	(0.2)	(0.0)	(0.0)	(0.1)	(0.0)
		>80m	1.3	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
			(0.3)	-	(0.1)	-	(0.0)	-	(0.0)	-	(0.0)	(0.0)	-	-	(0.0)
	MN2	<80m	12.1	0.2	0.0	0.0	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
			(3.4)	(0.1)	(0.0)	-	(0.0)	(0.0)	(0.0)	-	(0.0)	(0.0)	-	-	-
		>80m	4.7	0.3	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			(1.2)	(0.1)	(0.0)	-	(0.0)	(0.0)	(0.0)	-	-	-	-	-	-
	MN3	<80m	8.4	0.2	0.1	0.1	0.1	0.3	0.0	0.0	0.1	0.0	0.0	0.0	0.0
			(3.5)	(0.1)	(0.0)	(0.0)	(0.0)	(0.1)	(0.0)	-	(0.0)	-	-	-	-
		>80m	4.3	0.0	0.1	0.0	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
			(1.0)	-	(0.0)	-	(0.0)	(0.0)	(0.1)	-	(0.0)	(0.0)	-	-	-
	MN1	all	2.2	0.1	0.4	0.0	0.2	0.0	0.0	0.0	0.3	0.0	0.0	0.2	0.0
			(0.8)	(0.1)	(0.2)	-	(0.1)	(0.0)	(0.0)	-	(0.1)	(0.0)	(0.0)	(0.1)	(0.0)
	MN2	all	5.1	0.3	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			(1.0)	(0.1)	(0.0)	-	(0.0)	(0.0)	(0.0)	-	(0.0)	(0.0)	-	-	-
	MN3	all	4.5	0.0	0.1	0.0	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
			(1.2)	(0.0)	(0.0)	(0.0)	(0.1)	(0.0)	(0.1)	-	(0.0)	(0.0)	-	-	-
	All	<80m	5.6	0.3	0.5	0.0	0.2	0.1	0.1	0.0	0.4	0.0	0.0	0.3	0.0
			(1.6)	(0.1)	(0.1)	(0.0)	(0.1)	(0.0)	(0.0)	-	(0.1)	(0.0)	(0.0)	(0.1)	(0.0)
	All	>80m	4.1	0.1	0.1	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
			(0.7)	(0.0)	(0.0)	-	(0.0)	(0.0)	(0.0)	-	(0.0)	(0.0)	-	-	(0.0)
	All MN		4.3	0.1	0.1	0.0	0.2	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0
			(0.9)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	-	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
2004	MN1	<80m	2.0	7.7	0.3	0.7	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0
			(0.5)	(1.8)	(0.1)	(0.2)	(0.0)	(0.0)	(0.0)	-	(0.1)	-	-	-	-
		>80m	7.8	3.9	1.8	0.0	0.2	0.4	0.0	0.0	0.1	0.0	0.0	0.0	0.0
			(2.4)	(1.2)	(0.6)	-	(0.1)	(0.1)	(0.0)	-	(0.0)	(0.0)	-	-	-
	MN2	<80m	15.1	1.4	0.0	0.0	0.0	0.9	0.1	0.0	0.0	0.0	0.0	6.8	0.0
			(12.3)	(1.1)	-	-	-	(0.7)	(0.1)	-	-	-	-	(5.6)	-
		>80m	0.9	0.1	0.0	0.4	0.1	1.4	0.1	0.0	0.0	0.0	0.0	1.5	0.0
			(0.2)	(0.0)	-	(0.1)	(0.0)	(0.3)	(0.0)	-	(0.0)	(0.0)	-	(0.3)	-
	MN3	<80m	34.0	1.5	0.2	0.4	0.2	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0
			(11.4)	(0.5)	(0.1)	(0.1)	(0.1)	(0.1)	(0.0)	-	(0.0)	(0.0)	-	-	-
		>80m	17.1	0.5	0.0	1.1	0.5	2.7	0.1	0.3	0.0	0.0	0.0	0.0	0.0
			(2.6)	(0.1)	-	(0.2)	(0.1)	(0.4)	(0.0)	(0.1)	-	-	(0.0)	-	-
	MN1	all	5.4	5.5	1.2	0.3	0.1	0.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0
			(1.0)	(1.0)	(0.2)	(0.1)	(0.0)	(0.0)	(0.0)	-	(0.0)	(0.0)	-	-	-
	MN2	all	1.5	0.2	0.0	0.4	0.0	1.4	0.1	0.0	0.0	0.0	0.0	1.7	0.0
			(0.5)	(0.1)	-	(0.1)	(0.0)	(0.4)	(0.0)	-	(0.0)	(0.0)	-	(0.5)	-
	MN3	all	17.8	0.5	0.0	1.1	0.5	2.6	0.1	0.3	0.0	0.0	0.0	0.0	0.0
			(2.7)	(0.1)	(0.0)	(0.2)	(0.1)	(0.4)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	-	-
	All	<80m	10.6	5.6	0.2	0.6	0.1	0.2	0.0	0.0	0.2	0.0	0.0	0.9	0.0
			(2.8)	(1.5)	(0.1)	(0.1)	(0.0)	(0.1)	(0.0)	0.0	(0.1)	(0.0)	0.0	(0.2)	0.0
	All	>80m	11.1	0.7	0.2	0.8	0.4	2.0	0.1	0.2	0.0	0.0	0.0	0.4	0.0
			(1.5)	(0.1)	(0.0)	(0.1)	(0.0)	(0.3)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.1)	0.0
	All MN		11.0	1.2	0.2	0.7	0.3	1.9	0.1	0.2	0.0	0.0	0.0	0.5	0.0
			(1.5)	(0.2)	(0.0)	(0.1)	(0.0)	(0.3)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.1)	-

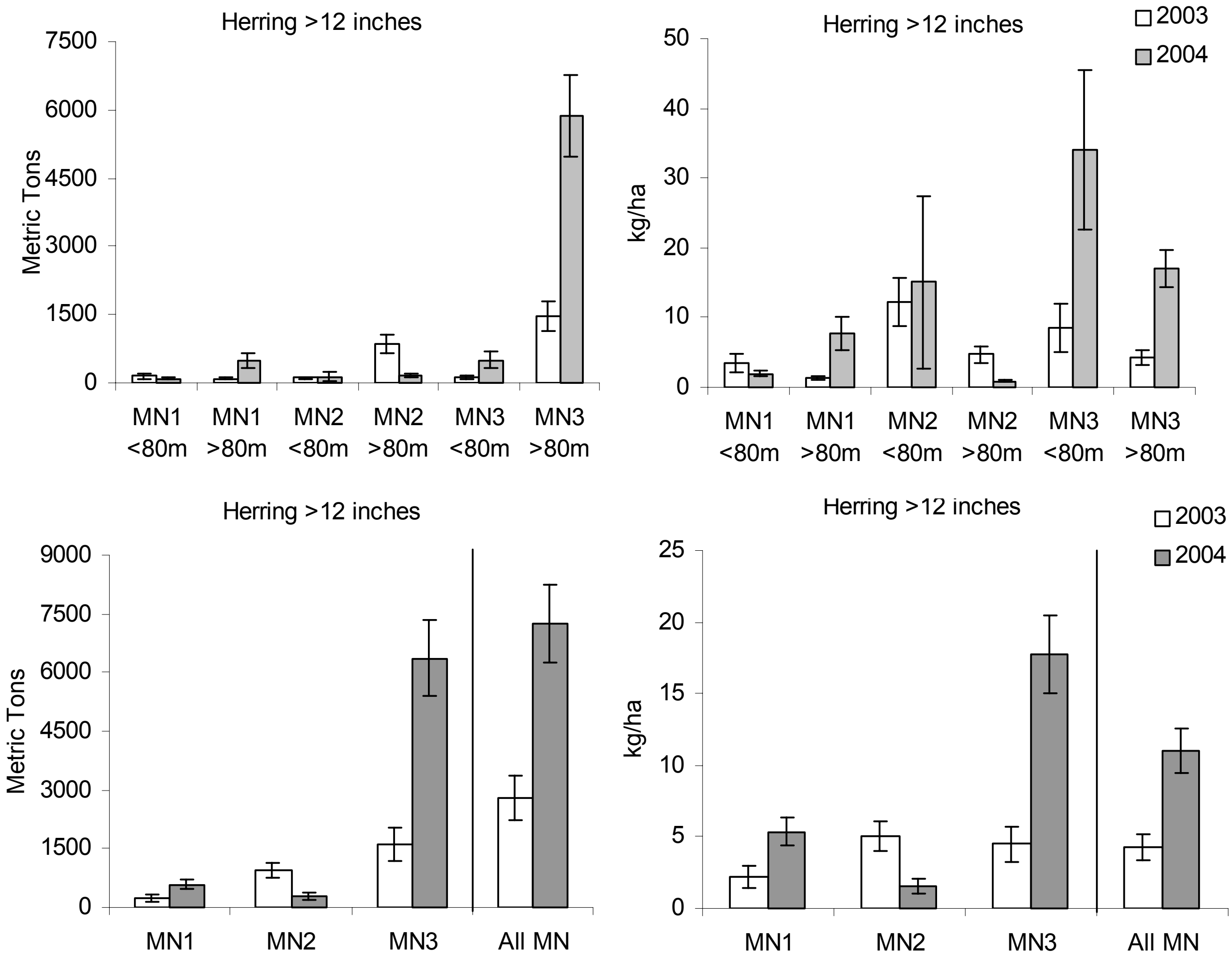

Figure 14. Biomass of a spawning-size lake herring ($\geq$ 12 inches) in metric tons and kg/ha with 95% CI by a) depth and management unit, and b) management unit in Minnesota waters of Lake Superior.

Design Summary

We gained valuable insight from our initial sampling schemes. We feel confident that the nearshore areas, <80 m can be effectively sampled using the MNDNR vessel at a much lower cost than using a larger (>50ft) vessel. We also learned that the larger vessel is safer, more effective and critical to sampling the offshore areas. The larger vessel is also essential to identify species composition of the acoustic signals by capturing fish with the mid-water trawl. The combination of using small and large vessels in Minnesota appears to be the most cost effective method to secure valid acoustic estimates of pelagic prey. Based on completed surveys, efficient surveys would include approximately 20 km of off shore transects in MN1, 34 km of transects in MN2 and 65 km of transects in MN3.

In 2003 our prototype survey design appeared to sample an adequate area in MN1 and MN2. However, MN3 is much larger than the other units and proved more difficult to sample owing to the greater area and the need to extend transects further into open water. Weather presented a constraint when using the smaller MNDNR research vessel and we experienced equipment failure from the large waves encountered when sampling MN3. Thus, it is likely that large vessels will be needed to adequately sample this unit in the future. We estimate that approximately 65 km of transects are needed to obtain accurate estimates of fish density and biomass. We estimate that approximately two nights of mid-water trawling are needed in MN3, which would allow approximately 20 km of hydroacoustic data to be collected in conjunction with the trawling effort. When collecting hydroacoustic data, a speed of approximately 10 km/hr. is required to maintain the proper transducer tow body performance. Using this approximation, we estimate that one additional ship day on the R/V Blue Heron would be needed to achieve 65 km of transects if the MNDNR vessel is used to sample the near shore areas.

We recommend that the MNDNR vessel sample an 18 k transect in the nearshore, <80 m, portion of each zone. In MN-1, a logical transect would run from Knife River to Two Harbors. In MN-2, possible transect would run from Twin Points to Silver Bay. In MN-3, the transect could run approximately 9 k on each side of Grand Marais. An additional transect 9k on each side of Taconite Harbor could be considered if time allows. All transects should run on a zigzag course with approximately 45 degree turns between 5 m – 80 m of depth. We realize that working along Minnesota's steep shoreline at night is dangerous and the shallow depth will ultimately be determined by the captain, considering crew and vessel safety.

It is critical that the large vessel used for the survey have mid-water trawling capability. We recommend that trawls be conducted in both nearshore and offshore zones in each management unit if possible. We recommend one trawl near shore and one trawl off shore in MN-1; in MN-2—one trawl near shore and two trawls off shore; and in MN-3—one trawl near shore and three trawls off shore. All trawls should be done as close as possible (in time) to the acoustics sampling in each location. This level of effort would require approximately 6 days of ship time on the large vessel, with the survey design approximating that conducted in 2004 (Figure 15).

We realize that any sampling design will require flexibility as the conditions and questions change. This is our attempt to provide a template that can be used for the current objective of estimating forage fish biomass in Minnesota waters. We expect the design to evolve as experience is gained and the biological questions change. Several logical foci for future studies include:

1. Five-year time series to determine annual variation and trends in forage fish biomass.
2. Comparison of fall spawning assessment vs. summer mixed stock assessment.
3. Tracking mortality of year classes based on changes in length frequency.
4. Build acoustic-based estimates of age frequencies to be used in catch-at-age models.

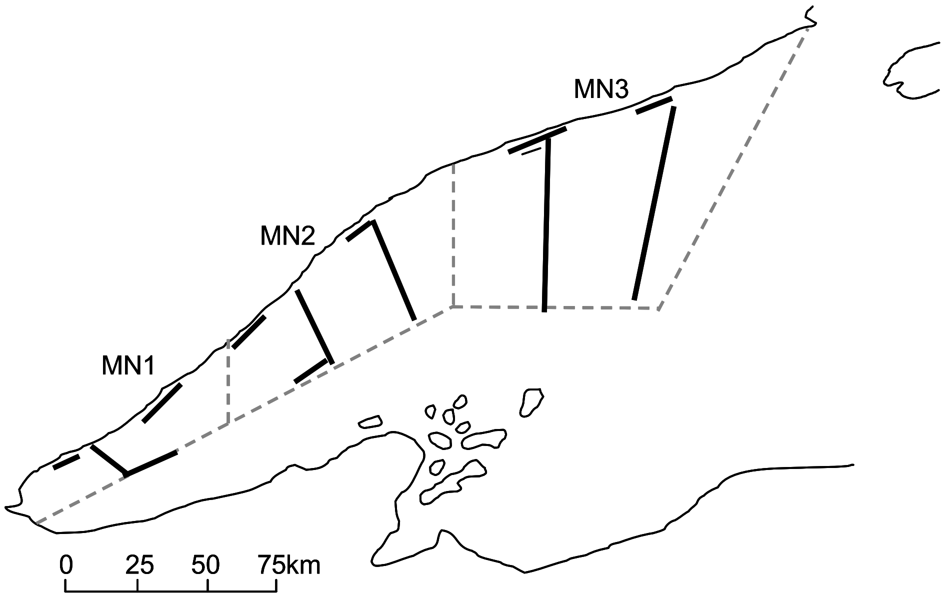

Figure 15. Possible transects for future forage fish surveys in Minnesota waters that adhere to the effort levels identified in surveys conducted in 2003 and 2004.

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