



# Spatial and vertical bias in down-looking ship-based acoustic estimates of fish density in Lake Superior: Lessons learned from multi-directional acoustics



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## ABSTRACT

Hydroacoustic surveys using hull-mounted down-looking transducers are useful for estimating pelagic fish densities; however, this method may miss shallow fish owing to the acoustic surface dead zone and vessel avoidance. Our objective was to compare pelagic fish density estimates acquired by a traditional down-looking acoustic survey to estimates obtained by a new multi-directional-towed sled capable of sampling the entire water column using upward-, sideways-, and downward-aimed transducers simultaneously. We deployed both systems concurrently in the western arm of Lake Superior during a period of stable stratification. We found the two survey approaches provided significantly different estimates of fish density in the upper water column layer (~4–9 m below the lake surface) with the sled up-looking transducer providing 56 times higher densities compared to the traditional ship down-looking method. Densities also varied significantly in the 9–14 m layer where densities were 6.2 times higher in the sled survey. Midwater trawl sampling indicated that cisco (*Coregonus artedii*) and rainbow smelt (*Osmerus mordax*) were the predominant species occupying the uppermost 14 m of the water column. The two acoustic approaches provided similar results at water column depths >14 m where rainbow smelt and kiyi (*Coregonus kiyi*) were predominant. Overall, the sled-based method estimates were, on average, 2.5 times higher for the whole water column. Our findings show that the new sled can reduce bias by better sampling the surface dead zone leading to more accurate estimation of pelagic fish densities for both management and research.

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## Introduction

Accurately estimating fish abundance is key to the management and sustainability of fisheries across the globe. Mobile acoustic survey methods are commonly used to obtain density estimates of pelagic fish species (Kubečka et al., 2009; Warner et al., 2012; Yule et al., 2007, 2013a). In the Laurentian Great Lakes, mobile acoustic surveys, using hull-mounted transducers (hereafter “down-looking surveys”), have been used to provide estimates of abundance for commercially-harvested species, like cisco

(*Coregonus artedii*) in Lake Superior (Fisch et al., 2019; Hrabik et al., 2006a; Pratt et al., 2016; Yule et al., 2012), and estimates of prey availability to inform stocking rates for salmonids in Lake Michigan (Tsehaye et al., 2014). Despite the widespread use of acoustic surveys, there are still limitations to the method that need to be recognized. For example, estimates of fish size structure and density are acquired with acoustics, but net sampling is needed for ground-truthing species composition and size distribution (McClatchie et al., 2000). Also, the near surface acoustic dead zone in traditional down-looking surveys can lead to bias in fish density estimates of the upper water column. The depth of the transducer, the nearfield exclusion zone, and surface noise all contribute to the near surface dead zone that can extend to 5 or more meters (Rudstam et al., 2009; Totland et al., 2009; Yule, 2000). Furthermore, some fish species in the upper water column may be disturbed by the presence of a large ship and exhibit avoidance,

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diving, or herding behavior (Draštík and Kubečka, 2005; Guillard et al., 2010; Thorne, 1983; Trumpickas et al., 2020). Estimates of pelagic fish biomass in Lake Superior (using data from down-looking acoustic surveys) are known to be lower than predicted by ecological models (Yurista et al., 2014) and prey-supply versus predator-demand bioenergetic studies (Negus, 1995; Negus et al., 2008). These observations suggest that the surface dead zone and vessel avoidance may impact pelagic fish estimations. Unfortunately, little is known about how these issues may affect the estimation of fish densities of different species in the upper water column of large freshwater systems like Lake Superior.

Up-looking hydroacoustic surveys overcome some of the pitfalls related to bias in fish density estimates in the near surface dead zone. Researchers have explored stationary deployments by placing transducers at the lake bottom and aiming them towards the surface (De Robertis et al., 2018), and by using mobile deployments with transducers mounted on tow bodies (Connerton and Holden, 2016), autonomous vehicles (Scalabrin et al., 2009), or frames extended from the bow of a ship aiming upwards (Baran et al., 2017). The use of bottom-moored transducers has advanced our understanding of fish distributions near the surface (Jarolim et al., 2010), but this approach shifts the problem of the near field to the bottom of the water column or near to the mounted device (De Robertis et al., 2018; Thorne et al., 1989). A recent study utilizing a mobile up-looking approach found that an average of 50% of the alewife (*Alosa pseudoharengus*) in Lake Ontario were being missed by the traditional down-looking method (Connerton and Holden, 2016). Riha et al., (2017) also used both up-looking and down-looking acoustic data to detail the diel distribution of alewife during summer months in Lake Ontario. Together, these studies highlight the potential bias in strictly using down-looking transducers, as large numbers of alewife resided in the surface dead zone of Lake Ontario. Some towed and autonomous systems have been equipped with up-, side-, or down-looking capabilities (Riha et al., 2017; Scalabrin et al., 2009), but, to our knowledge, no studies have attempted to estimate fish densities over the entire water column using all three aiming directions in concert.

Given the knowledge gaps in our understanding of fish density within the upper water column of Lake Superior, a new acoustic

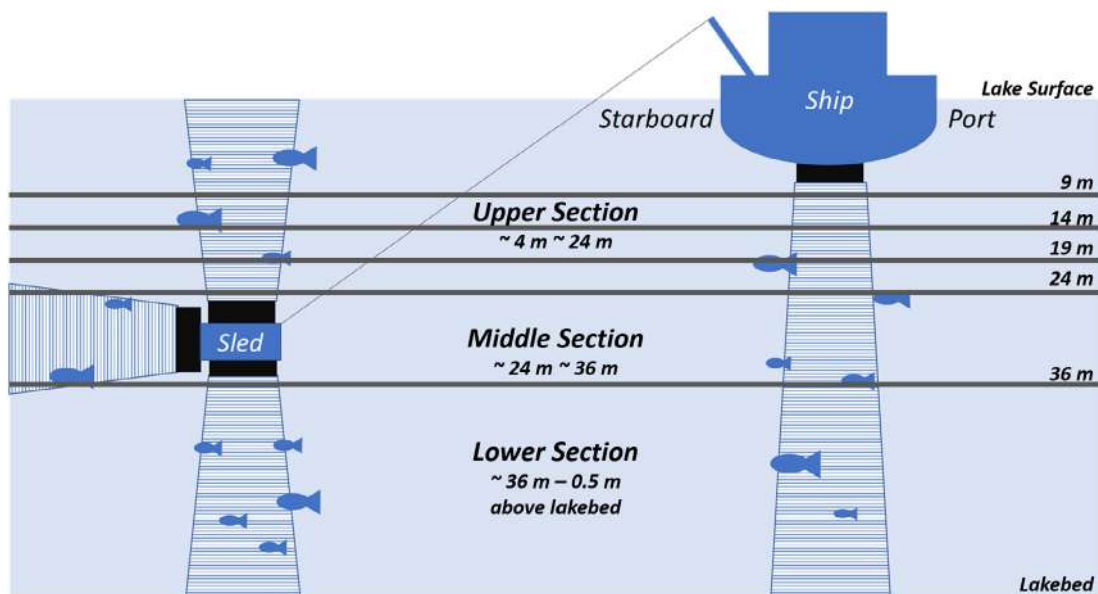
survey method utilizing a multi-directional tow body (hereafter referred to as the “sled”) equipped with upward-, sideways-, and downward-aimed transducers deployed in concert was a logical next step. The multi-directional sampling capabilities of this sled allowed sampling of the whole water column; therefore, not sacrificing information from some layer of the water column for a different layer. We conducted a comparative study between this sled and a traditional down-looking survey in western Lake Superior during stable stratification when lake-wide down-looking surveys are normally conducted (Yule et al., 2013a). Our objectives were to: 1) determine if there were significant differences between total pelagic fish densities obtained by the multi-directional sled and a traditional ship-based down-looking survey; 2) if differences were observed, we sought to determine what layer of the water column was contributing most to the differences; and 3) determine the species composition in the layers where significant differences were measured. Understanding whether important prey species such as cisco, bloater (*Coregonus hoyi*), kiyi (*Coregonus kiyi*), and rainbow smelt (*Osmerus mordax*) were being systematically underestimated owing to their position in the water column could provide key information for better assessment of the status and trends of these fish populations. To accomplish our third objective, we collected mid-water trawl samples to understand how species composition varied by water column depth in our study area.

## Methods

### Survey design

#### Description of new multi-directional acoustic sled

Both acoustic systems were deployed simultaneously from the U.S. Geological Survey (USGS), Great Lakes Research Center, research vessel (R/V) Kiyi. The sled, manufactured by Bellamare LLC (San Diego, CA, USA), was equipped with an upward-aimed 70 kHz split-beam transducer, a starboard side-aimed 120 kHz split-beam transducer, and a downward-aimed 70 kHz split-beam transducer all operated with a Biosonics, Inc. (Seattle, WA, USA) DT-X Sub (Fig. 1). These two frequencies have been shown



**Fig. 1.** The typical ship-based down-looking survey method is shown on the right and the multi-directional sled-mounted acoustic survey method is on the left. The sled was typically deployed ~58 m behind the ship, ~8.5 m off the starboard side, and at ~30 m deep at 8 km/h. The water column analysis sections (upper, middle, lower) are displayed with their approximate depths.

**Table 1**

Acoustic transducers used in this study. All transducers were split-beam, circular beam configuration and were manufactured by BioSonics, Inc. The ship used a BioSonics portable DT-X echosounder and the sled used a BioSonics submersible DT-X echosounder. Ping rates were set at 2 pings per second but approximately 1 ping per second was realized. The height of the nearfield exclusion zone was calculated as  $2 \times$  the transducer nearfield plus the mount depth (2.3 m) for the ship transducer.

Frequency (kHz)	Orientation	Survey Method	Beam Angle	Height of Nearfield Exclusion Zone (m)
70	Up-looking	Sled	5.0°	5.6
70	Down-looking	Sled	5.0°	5.6
120	Side-looking	Sled	8.0°	1.7
123	Down-looking	Ship	7.5°	3.7

to provide similar results (see review in Yule et al., 2009), and are recommended by the Standard Operating Procedures for Fisheries Surveys in the Great Lakes (GLSOP; Parker-Stetter et al., 2009). The frequency selection was chosen to reduce dead zones on the sled because the side looking 120 kHz has a shorter near field yet covers the larger near fields on the upward and downward aimed 70 kHz transducers dead zones. Additionally, the sled was equipped with an actuator fin to allow for real-time remote pitch and roll adjustments. The R/V Kiyi was equipped with a dedicated winch to tow, power, and communicate with the sled. The communications system consisted of a guarded fiber optic cable connecting the DT-X Sub and the actuator fin to onboard laptops running Visual Acquisition (VisAcq) 6 provided by BioSonics and STINGRAY software developed by Greensea Systems, Inc. (Richmond, VT, USA). The VisAcq software allowed us to program the DT-X Sub for operation and observe the acoustic data in real-time to ensure proper functioning of the transducers. The STINGRAY software allowed us to observe the sled's pitch, roll, and depth in real time and allowed for remote adjustments to the actuator fin to promote optimal towing. The ship acoustic system consisted of a single downward facing 123 kHz split-beam transducer deployed through a sonar tube to a depth of 2.3 m below the lakes surface, connected to a separate BioSonics DT-X system and laptop. All transducers were split-beam, circular, and had narrow ( $<8^\circ$ ) beams (Table 1). Acoustic data were collected with acquisition thresholds set at  $-100$  dB (dB), pulse durations set at 0.4 ms and a realized ping rate of 1 ping per second. The normal towing position of the sled was 8.5 m to the starboard side of the ship, 58 m back, and 30 m deep (Fig. 1). Data from the sled echosounder were time synchronized to the ship's acoustic system (which had a global positioning system) for comparison of survey estimates.

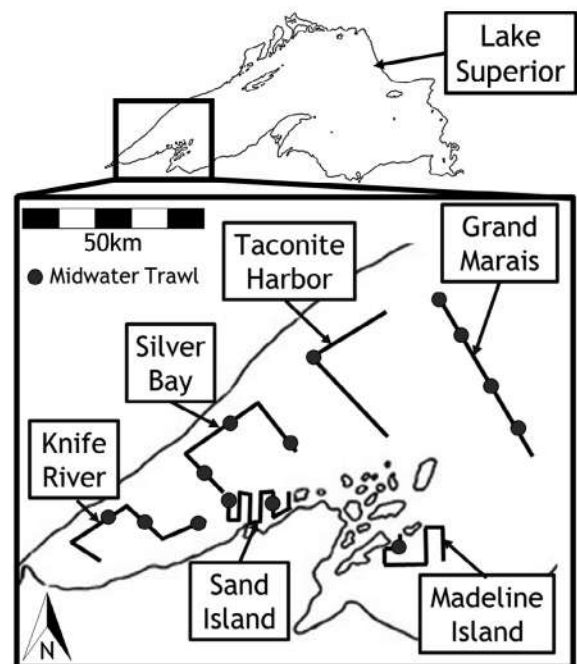
#### Acoustic surveys

Six transects were sampled in the western arm of Lake Superior (Fig. 2) between August 21–27, 2018 with both the sled and the ship-based down-looking survey method. Each night of sampling began 30 min after nautical twilight and ended 30 min before nautical sunrise, approximately six hours and forty minutes of sampling per night. Each transect was approximately 50 km long and ship speed was approximately 8 km/h. The sled was occasionally raised from its normal towing depth along the Madeline Island and Sand Island transects to prevent it from hitting the lakebed. A water temperature profile was collected with an electronic bathythermograph (SBE19plus profiler, SeaBird, Bellevue, WA, USA) at the start and end of each transect. We ensured sampling during normal conditions by avoiding sampling with wave heights exceeding approximately 1 m.

#### Mid-water trawl survey

Following the acoustic sampling, 14 mid-water trawl sites were sampled between August 28 and 31, 2018, along the acoustic transects (Fig. 2). Trawl sampling could not be done simultaneously because the sled and the mid-water trawl could not be deployed

safely at the same time. Additionally, recent work has shown that trawling can have significant effects on simultaneous hydroacoustic fish density estimates (Trumpickas et al., 2020). The mid-water trawl had 15.2 m headrope and footrope lines and 13.7 m breast lines. The mesh graduated from a stretch measure of 152 mm at the mouth to 13 mm at the cod end (further description of the trawl can be found in Yule et al., 2013b). We used NETMIND trawl mensuration sensors (NorthStar Technical, Inc., St. John's, NL, Canada) to record the headrope depth and trawl wingspread at approximately 10 s intervals during deployment. Additional depth information was measured at 2 s intervals by placing miniature depth/temperature loggers (Star Oddi hf., Garðabær, Iceland) on the headrope and footrope lines. Headrope depths ranged from 1.4 m to 60.1 m with speeds around 4.4 km/h. All trawls with headrope depths  $>25$  m ( $N = 4$ ) were fished for 40 min (i.e., approximately 3 km). Trawls with headrope depths  $<25$  m ( $N = 10$ ) were fished for 20 min (i.e., approximately 1.5 km). These trawl samples were later aggregated based on average headrope depth into six layers ( $<9$  m, 9–14 m, 14–19 m, 19–24 m, 24–36 m, and  $>36$  m) and observed species compositions in each layer were compared to the acoustic data (details to follow). The electronic bathythermograph was deployed at the end of every trawl station to measure temperature conditions.



**Fig. 2.** Map of transects in the western arm of Lake Superior. Each transect (shown in black lines) was approximately 50 km in length. All transects were sampled between August 21–26, 2018. Circles indicate approximate locations of mid-water trawls sampled between August 28–31, 2018. The six transects are Grand Marais (GM), Knife River (KR), Madeline Island (MA), Silver Bay (SB), Sand Island (SI), and Taconite Harbor (TH) are abbreviated in subsequent figures.

## Data analyses

### Data processing and preparation

The data from the two acoustic survey methods were processed with Echoview Software Ver. 8 (Echoview Software Pty. Ltd., Hobart, TAS, Australia) in accordance with the GLSOP (Parker-Stetter et al., 2009; Rudstam et al., 2009). Field calibrations of the ship and sled echosounders were carried out using a 33 mm tungsten carbide sphere for the 120 kHz transducers and a 36 mm sphere for the 70 kHz transducers. Calibration results were applied following Foote et al. (1987).

We followed the GLSOP recommendations for creating near-field exclusion lines and eliminating bad data in the ship and sled acoustic echograms. The bottom lines were scrutinized and adjusted to prevent integrating bottom echoes. The surface line was adjusted to eliminate obvious noise from air bubbles. The open water portions of echograms containing ship noise, acoustic cross talk, and shadow bottoms were excluded by drawing bad data regions in Echoview. The ship-based down-looking transducer's surface exclusion depth was set at 3.7 m, while the sled's surface exclusion zone varied across transects with surface conditions (average surface exclusion lines by transect were: Grand Marais = 6.3 m, Madeline Island = 4.3 m, Silver Bay = 4.2 m, Sand Island = 4.1 m, Taconite Harbor = 3.8 m, and Knife River = 3.2 m). We used a minimum target strength (TS) detection threshold of  $-55$  dB (within single target detection method 2 in Echoview) to identify single targets. This was based on first developing TS frequency distributions with a threshold of  $-75$  dB and choosing a threshold that fell in a "valley" (Parker-Stetter et al., 2009). It follows that the applied  $-55$  dB threshold eliminated most macroinvertebrates and young-of-year smelt (YOY), but not the larger YOY coregonines (Rudstam et al., 2003; Mehner, 2006). A minimum range-dependent threshold of  $-61$  dB was applied to the volume backscattering strength ( $S_v$ ) echogram per the GLSOP. The  $S_v$  is defined as the ratio of intensity of sound scattered back in the direction of the transducer by a unit volume to the intensity of the incident plane wave (Iida et al., 1996). Each transect was divided into 20-minute intervals (20 min at  $\sim 8$  km/h is  $\sim 2700$  m cells) to ensure that each cell was an independent sample while targeting a reasonable number of single echo detections (SED's; Hrabik et al., 2006b).

The sled side-looking echograms were processed by excluding data within 1.7 m of the transducer and beyond 60 m. This 1.7–60 m range was chosen because the acoustic data were generally of high quality, requiring the creation of few bad data regions. At 60 m range the height of the beam is 8.4 m which is close to the width of the layer missed by excluding the near field zones of the up-looking and down-looking sled transducers (11.7 m = 0.5 m of vertical separation on the sled plus 5.6 m each for the up- and down-looking transducer nearfields). Additionally, we split the side-looking data roughly in half ( $\sim 2$ –28 m and 28–60 m) to examine the relationship between fish density and distance from the sled. This was done to explore if there was evidence that densities were greater further away from the sled which might occur if the vessel (or sled) were acting to herd fish laterally.

In order to prepare the sled-based and ship-based data for statistical analyses, the data for the whole water column ( $\sim 4$  m to 0.5 m off the lakebed) were initially examined and then split into six subsections or depth layers. Four layers were defined in the upper water column ( $\sim 4$ –9 m, 9–14 m, 14–19 m, and 19–24 m) that were sampled with the sled up-looking transducer. We also defined a middle section (sled's side-looking beam  $\sim 24$  m–36 m vertical depth), and lower section (sled's down-looking transducer;  $> 36$  m). For the two deepest layers, fish density ( $D_{i,t,k,m}$ ) for

individual cell  $i$ , transect  $t$ , water column layer  $k$ , and survey method  $m$  were calculated with the echo integration method per Parker-Stetter et al. (2009) by:

$$D_{i,t,k,m}(\text{number/ha}) = 10,000 * ABC_{i,t,k,m} \sigma_{i,t,k,m}^{-1} \quad (1)$$

where  $ABC$  is the area backscattering coefficient for each combination of  $i$ ,  $t$ ,  $k$ , and  $m$ . The  $ABC$  was calculated by multiplying the mean thickness of the beam being integrated by the mean volume backscattering strength coefficient of the domain ( $S_v$ ). By convention,  $S_v$  is equal to  $10^{S_v/10}$ , where  $S_v$  is the mean volume backscattering strength in decibels (dB). The respective  $ABC$ s were scaled by their respective mean backscattering cross sections ( $\sigma_{i,t,k,m}$ ), which was calculated by  $10^{TS/10}$ , where  $TS$  is the mean target strength of the SEDs in the domain in dB. The uppermost four subsections had to be treated differently because some cells had fewer than the recommended 20 SEDs. When fewer than 20 SEDs were available in a cell, we used Eq. (1) but the mean  $TS$  for each layer used for scaling was the average for the entire transect. When fewer than 20 SEDs were available in a layer/transect combination, we used a global estimate of  $TS$  based on averaging  $TS$  in that layer over all 6 transects (see Table 2 for details).

### Statistical analyses

The layers of the water column sampled by the sled were compared to the ship-based down-looking survey to determine whether there were significant differences in density estimates across acoustic survey methods. Due to the non-normal distribution of residuals, all fish density data were natural log transformed prior to the statistical tests in order to better meet the assumptions of normality and homogeneity of variance. A constant of 0.1 was added to all data prior to transformation because zeros occurred in the dataset. First, a two-way ANOVA was applied to the whole water column comparison, and, when it resulted in significant differences between survey methods, a separate two-way ANOVA was performed on each water column layer. Fish density ( $D_{i,t,k,m}$ ) was the dependent variable and the model tested the effects of  $t$  (six transects),  $m$  (two survey methods), and the interaction between  $t$  and  $m$ :

$$\ln(D_{i,t,k,m} + 0.1) = m_{i,k} * t_{i,k} \quad (2)$$

A Tukey HSD test was applied post hoc to examine which transects contained significant differences between the ship and sled survey. All statistical tests were conducted in the R Program version 3.4.0 (R Foundation for Statistical Computing, Vienna, Austria). For the initial whole water column ANOVA we used an  $\alpha = 0.05$ , and for all following tests ( $n = 6$ ) we used an  $\alpha = 0.0073$  (after Bonferroni correction) for significance testing among factor levels. The log transformed fish density estimates were then averaged and back-transformed (with removal of the constant) for data display after statistical analysis, making all reported fish densities geometric means.

For the side-looking comparison a similar method to the one described above was carried out. However, the model tested the effects of  $t$  (six transects), horizontal distance ( $h$ , two horizontal water column sections), and an interaction between  $t$  and  $h$ :

$$\ln(D_{i,t,h} + 0.1) = h_i * t_i \quad (3)$$

Similar to the vertical water column analysis, a Tukey HSD test was applied post hoc to examine which transects contained significant differences between the  $\sim 2$ –28 m and 28–60 m horizontal ranges. For the ANOVA we used an  $\alpha = 0.05$  for significance testing among factor levels.

**Table 2**

Mean target strength (TS), mean volume backscattering strength ( $S_v$ ), number of single target detections, and geometric mean fish density in the four layers of the upper water column (~4–9 m, 9–14 m, 14–19 m, and 19–24 m) by transect and acoustic survey method. The transect codes are as follows: Sand Island (SI), Knife River (KR), Silver Bay (SB), Taconite Harbor (TH), Grand Marais (GM), and Madeline Island (MA). When <20 single target detections were available for the ship in the ~4–9 m layer and the sled in the 19–24 m layer, we used a global estimate of TS based on averaging TS in that layer over all 6 transects. Fish density represents the geometric mean of ~20 different cells within each transect and water column layer.

Layer	Transect	Method	Single Targets	Mean TS (dB)	Mean $S_v$ (dB)	Single Targets/ha m	Fish Density (fish/hectare)
4–9 m	GM	Ship	6	-51.95*	-97.41	1.47	0.05
4–9 m	GM	Sled	115	-51.16	-79.86	6.51	3.80
4–9 m	KR	Ship	1	-49.43*	-99.72	0.44	0.03
4–9 m	KR	Sled	34	-41.08	-74.51	0.76	5.86
4–9 m	MA	Ship	19	-51.16*	-94.39	3.93	0.34
4–9 m	MA	Sled	219	-50.94	-79.58	9.20	20.76
4–9 m	SB	Ship	13	-50.79*	-89.74	5.29	0.26
4–9 m	SB	Sled	60	-34.21	-60.61	1.61	42.53
4–9 m	SI	Ship	16	-49.46*	-83.72	5.88	1.14
4–9 m	SI	Sled	286	-36.12	-64.81	6.35	30.05
4–9 m	TH	Ship	6	-52.51*	-93.21	2.58	0.13
4–9 m	TH	Sled	258	-41.05	-68.99	7.86	16.89
9–14 m	GM	Ship	63	-39.29	-76.87	3.53	1.33
9–14 m	GM	Sled	199	-39.74	-67.61	8.48	21.73
9–14 m	KR	Ship	32	-39.86	-77.18	3.25	3.36
9–14 m	KR	Sled	147	-34.19	-66.12	5.87	14.47
9–14 m	MA	Ship	192	-41.99	-75.45	9.10	16.95
9–14 m	MA	Sled	205	-41.30	-68.56	13.89	68.77
9–14 m	SB	Ship	119	-39.55	-72.59	11.14	9.34
9–14 m	SB	Sled	181	-36.47	-65.77	6.84	35.82
9–14 m	SI	Ship	98	-40.51	-72.65	8.25	17.74
9–14 m	SI	Sled	141	-38.28	-70.90	4.60	16.20
9–14 m	TH	Ship	75	-39.95	-75.16	7.40	5.44
9–14 m	TH	Sled	286	-37.76	-65.66	13.51	50.82
14–19 m	GM	Ship	206	-37.54	-71.79	4.92	4.12
14–19 m	GM	Sled	114	-35.27	-65.60	8.12	6.74
14–19 m	KR	Ship	184	-41.72	-73.94	7.95	14.53
14–19 m	KR	Sled	143	-43.31	-71.81	9.41	31.60
14–19 m	MA	Ship	229	-42.16	-76.77	4.62	7.30
14–19 m	MA	Sled	49	-41.66	-73.26	7.12	6.70
14–19 m	SB	Ship	97	-39.92	-76.18	3.89	4.48
14–19 m	SB	Sled	50	-39.19	-72.49	3.04	5.59
14–19 m	SI	Ship	112	-41.63	-77.48	4.09	4.90
14–19 m	SI	Sled	38	-44.52	-79.23	2.02	2.41
14–19 m	TH	Ship	102	-38.81	-73.73	4.28	8.41
14–19 m	TH	Sled	63	-38.39	-70.10	4.92	18.02
19–24 m	GM	Ship	185	-36.63	-77.96	1.21	1.74
19–24 m	GM	Sled	16	-40.88**	-75.92	1.73	1.95
19–24 m	KR	Ship	231	-41.33	-76.58	2.34	10.81
19–24 m	KR	Sled	35	-37.70	-73.06	3.21	5.20
19–24 m	MA	Ship	42	-41.70	-84.25	1.05	0.50
19–24 m	MA	Sled	2	-42.60**	-83.51	1.14	0.08
19–24 m	SB	Ship	118	-39.77	-81.67	0.95	4.16
19–24 m	SB	Sled	18	-36.98**	-77.06	1.44	1.90
19–24 m	SI	Ship	126	-41.41	-82.54	1.01	2.89
19–24 m	SI	Sled	22	-45.00	-82.74	1.53	2.26
19–24 m	TH	Ship	300	-35.82	-74.01	3.01	6.07
19–24 m	TH	Sled	21	-35.23	-72.65	2.39	3.78

\* ship global TS for 4–9 m used = -50.65.

\*\* sled global TS for 19–24 m used = -38.03.

## Results

### Whole water column comparisons

There were significant differences in fish densities for the whole water column (Table 3) between survey methods [ $F(1, 239) = 95.37, p < 0.001$ ], among transects [ $F(5, 239) = 2.69, p = 0.022$ ], and the interaction of survey methods and transects [ $F(5, 239) = 2.80, p = 0.018$ ]. Based on the Tukey HSD test, fish densities obtained from the sled were significantly higher ( $p < 0.05$ ) than the traditional down-looking acoustic survey in the Grand Marais, Silver Bay, and Taconite Harbor transects (Fig. 3). Fish densities were not statistically different among methods in the Knife River ( $p = 0.65$ ), Madeline Island ( $p = 0.13$ ), and Sand Island transects ( $p = 0.45$ ; Fig. 3).

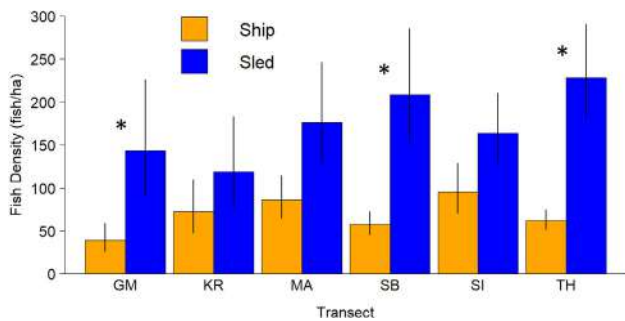
### Depth-specific comparisons

We observed significant variability in differences between methods depending on depth strata. The greatest difference observed was the influence of survey method on estimates of density in the ~4–9 m layer [ $F(1, 224) = 179.53, p < 0.0001$ , Fig. 4A]. The interaction between transect and survey method was not significant for this layer [ $F(5, 224) = 0.75, p = 0.59$ ], despite a significant difference in fish density between transects [ $F(5, 224) = 5.95, p < 0.0001$ ]. The Tukey HSD indicated that the fish density in the ~4–9 m layer was significantly higher in the sled-based survey compared to the ship-based survey for every transect ( $p < 0.001$ ; Fig. 4A). For the 9–14 m layer, there was a significant survey method effect [ $F(1, 238) = 57.53, p < 0.0001$ ; Fig. 4B]. The interaction between transect and survey method was also significant for

**Table 3**

Two-way ANOVA results for acoustic fish density estimates for the whole water column and the six water column layers. The effects of ship or sled survey method, transect, and an interaction between method and transect were tested in the models. For the whole water column ANOVA, an  $\alpha$  value of 0.05 was used to assess significance. For the other layer-based ANOVA's a Bonferroni  $\alpha$  value of 0.0073 was used to assess significance.

Water Column Layer (m)	Model Factor	df	Mean Squares	F-Ratio	P-value
~4–Lakebed	Method	1	55.77	95.37	<0.0001
	Transect	5	1.57	2.69	0.022
	Method*Transect	5	1.64	2.80	0.018
	Residuals	239	0.59	–	–
~4–9	Method	1	827.03	179.53	<0.0001
	Transect	5	27.39	5.95	<0.0001
	Method*Transect	5	3.44	0.75	0.59
	Residuals	224	4.61	–	–
9–14	Method	1	140.60	57.53	<0.0001
	Transect	5	18.62	7.62	<0.0001
	Method*Transect	5	9.68	3.96	0.0018
	Residuals	238	2.44	–	–
14–19	Method	1	3.37	0.90	0.34
	Transect	5	17.80	4.72	0.00039
	Method*Transect	5	3.34	0.89	0.49
	Residuals	239	3.77	–	–
19–24	Method	1	15.71	4.46	0.036
	Transect	5	44.19	12.54	<0.0001
	Method*Transect	5	2.13	0.60	0.70
	Residuals	239	3.52	–	–
~24–36	Method	1	0.00	0.00	1.00
	Transect	5	12.99	7.89	<0.0001
	Method*Transect	5	1.94	0.39	0.24
	Residuals	239	1.65	–	–
~36–Lakebed	Method	1	0.86	0.39	0.53
	Transect	5	17.07	7.78	<0.0001
	Method*Transect	5	1.35	0.62	0.69
	Residuals	239	2.19	–	–



**Fig. 3.** Comparison of geometric mean fish density (fish/hectare) measured for the whole water column (~4 to 0.5 m above lakebed) by the multi-directional sled-mounted acoustic survey method (Sled) and the ship-based down-looking survey method (Ship). Bars show geometric mean fish density from ~20 different ~2,700 m long sections of the water column on the six western arm sampling transects. The six transects are defined in Fig. 2. The error bars represent the 95% confidence intervals around each mean. Asterisks indicate significant differences ( $p < 0.05$ ) between survey methods for transects based on a Tukey HSD.

this layer [ $F(5, 238) = 3.96, p = 0.0018$ ], and there was a significant difference in fish density between transects [ $F(5, 238) = 7.62, p < 0.0001$ ]. The Tukey HSD indicated that fish densities in the 9–14 m layer were significantly higher in the sled survey compared to the ship survey for the Grand Marais and Taconite Harbor transects (Fig. 4B). For the layers below 14 m depth to the lakebed (Fig. 4C–4E), none of the fish density estimates varied significantly between survey methods for any transect [all  $F(1, 238) \leq 4.46$ , all  $p$  values  $\geq 0.036$ ; Table 3]. The interaction between transect and survey method was also not significant for the layers below 14 m [all  $F(5, 238) \leq 0.89$ , all  $p$  values  $\geq 0.49$ ], but there was a significant difference in fish density between transects [all  $F(5, 238) \geq 4.72$ , all  $p$  values  $\leq 0.0004$ ] for all these layers (Table 3). Furthermore, the volume corrected density of SEDs were higher for the sled-based upward aimed transducer than for the ship-based down-looking

survey in 5 of 6 cases for the 4–9 m layer, 4 of 6 cases for the 9–14 m layer, and 4 of 6 cases for the 14–19 m layer (Table 2). However, the SED density for the 19–24 m layer were equivocal.

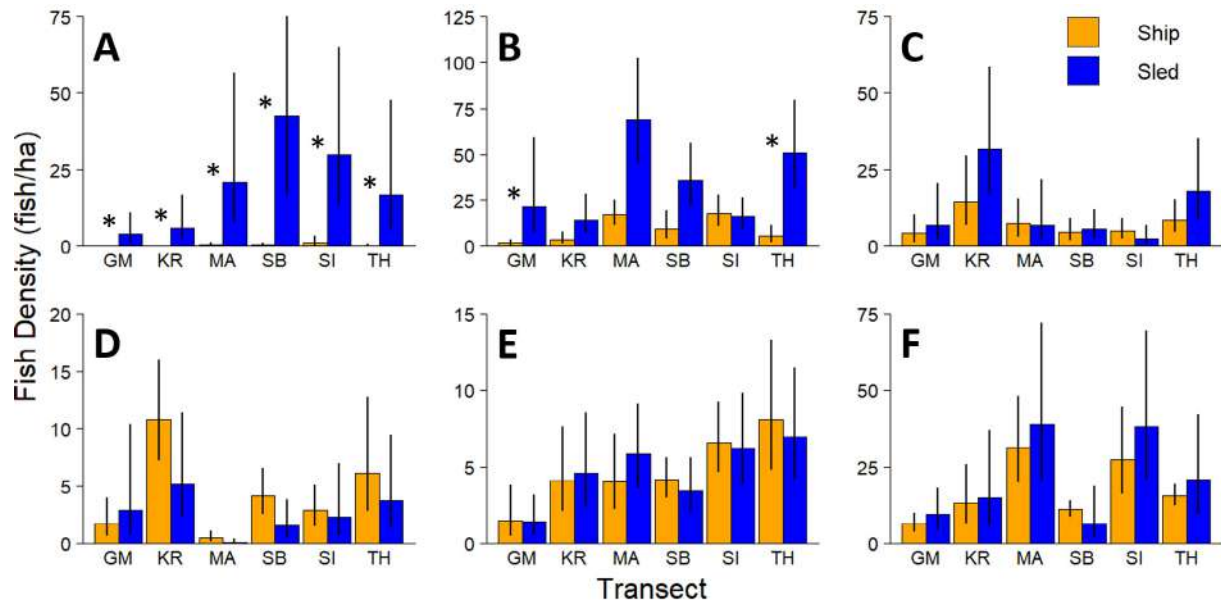
#### Sled Side-looking comparison

To test for the possibility of fish avoidance or aggregation behavior in response to the sled, we compared the density estimates measured near the sled (~2–28 m) and further from the sled (28–60 m) with the side-looking transducer using a two-way ANOVA. There was a significant transect effect [ $F(5, 252) = 5.53, p < 0.001$ ], but fish densities did not vary between the 2–28 m and 28–60 m distances [ $F(1, 252) = 1.38, p = 0.24$ ; Fig. 5], nor was the interaction term significant [ $F(5, 252) = 0.51, p = 0.77$ ] indicating a lack of avoidance of the sled.

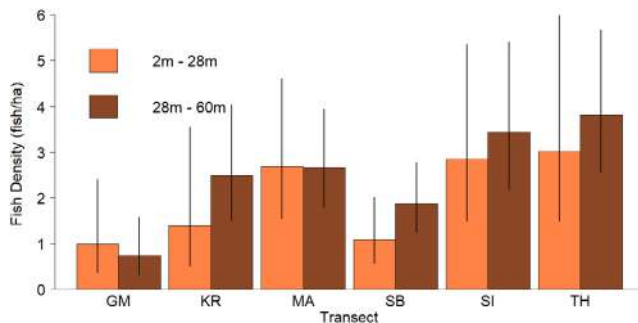
#### Mid-water trawl catch comparison to acoustic data

A total of 864 fish were caught in the 14 mid-water trawl samples. The catch was dominated by YOY rainbow smelt ( $N = 601$ ) that were all smaller than 53 mm. When selecting a minimum target strength of –55 dB, we made the decision that our acoustic survey would enumerate densities of yearling-and-older (YAO) fish. Thus, when calculating species percentages by depth layer, we did so with and without the 601 YOY rainbow smelt included (Table 4). The catch included 28 YOY coregonines, nine of which were too small or damaged to be identify to species. These YOY coregonines (mean length = 53 mm  $\pm$  15 mm SD) were generally larger than the YOY smelt and were likely of a size to be detected with the applied acoustic threshold (Mehner, 2006).

When the YOY rainbow smelt were excluded, the catch above 9 m of water column depth was dominated by cisco (71.4%), while YAO rainbow smelt (46.9%) and cisco (31.5%) were predominant in the 9–14 m layer. Below 14 m the catch was a mix of rainbow smelt, cisco, bloater and kiyi. We developed length frequency



**Fig. 4.** Comparison of geometric mean fish density (fish/hectare) measured for the upper water column (A: ~4–9 m, B: 9–14 m, C: 14–19 m, D: 19–24 m), middle portion of the water column (E: ~24–36 m), and lower portion of the water column (F: ~36 to 0.5 m above lakebed) by the multi-directional sled-mounted acoustic survey method (Sled) and the ship-based down-looking survey method (Ship). Bars show geometric mean fish density from ~20 different ~2,700 m long sections of the water column on the six western arm sampling transects. The six transects are defined in Fig. 2. The error bars represent the 95% confidence intervals around each mean. Asterisks indicate significant differences ( $p < 0.05$ ) between survey methods for transects based on a Tukey HSD.



**Fig. 5.** Comparison of geometric mean fish density (fish/hectare) measured for two horizontal subsections of the side-looking beam of the sled (2–28 m and 28–60 m.) Bars show geometric mean fish density from ~20 different ~2,700 m long sections of the water column on the six western arm sampling transects. The six transects are defined in Fig. 2. The error bars represent the 95% confidence intervals for each mean. There were no significant differences ( $p < 0.05$ ) in density between distances from the sled for any transects based on a Tukey HSD.

distributions of fish caught in each depth layer to compare to TS distributions measured by the different sled transducers and the ship down-looking transducer. In general, the target strength distributions measured by the sled up-looking transducer matched the distributions obtained by the ship down-looking transducer in the four uppermost layers (~4–9 m, 9–14 m, 14–19 m and 19–24 m; Fig. 6). One exception was the sled up-looking transducer detected fewer small (<–50 dB) targets, and a greater number of large (>–40 dB) targets than the ship down-looking transducer in the ~4–9 m layer (Fig. 6A). In fact, the ship detected no targets >–40 dB in the ~4–9 m layer. The size distributions of YAO fish caught in the uppermost 4 layers were generally consistent with the target strength distributions of fish that were detected with both acoustic survey methods (Fig. 6).

The target strength distribution of fish measured by the sled side-looking transducer differed from the distribution of targets detected by the ship down-looking transducer in the ~24–36 m

layer (Fig. 7A). This was expected because fish detected by the side-looking transducer were sampled in side-aspect relative to the axis of the horizontally aimed beam, while fish detected with the ship transducer were likely positioned dorsal–ventral to the vertically aimed beam. The target distributions measured at depths >36 m were similar, with the targets detected with the sled slightly larger, on average, than targets detected by the ship transducer (Fig. 7B).

## Discussion

The multi-directional acoustic sled provided significantly different estimates of fish density compared to the traditional ship-based down-looking survey. Estimated fish densities obtained by the sled were significantly higher than those obtained by the traditional ship-based survey for all six transects within the upper ~4–9 m of the water column. The sled-based estimates were on average 56 times higher in this layer when compared to estimates obtained by traditional ship-based methods. Within the 9–14 m layer, the trend of the sled detecting higher fish density estimates continued but was only significant for the Grand Marais and Taconite Harbor transects. This was not the case for the middle and lower sections of the water column (14 to 0.5 m above lakebed), where no significant differences existed between survey methods for all transects. These results for the middle and lower sections of the water column are consistent with past research because traditional down-looking surveys are thought to have adequate sample volumes at these depths (Rudstam et al., 2009; Yule et al., 2007), and apparently vessel avoidance is minimal. When the fish density estimates obtained from the whole water column were compared, the sled detected significantly more fish than the traditional ship-based down-looking survey method in the Grand Marais, Silver Bay, and Taconite Harbor transects. Notably, these three transects had the deepest average bathymetric depths (Grand Marais = 120 m, Silver Bay = 210 m, and Taconite Harbor = 165 m). Differences in whole water column densities obtained along the shallower transects (average bathymetric depths: Knife

**Table 4**  
Trawl catch composition in water column layers used in the analysis of acoustic data. Trawls were binned to a depth layer where most of the fishing occurred based on the trawl average headrope depth. Total numbers of each species were divided by the total catch for each water column layer. Percentages were calculated for all captured fish (top) and after removal of young-of-year (YOY) rainbow smelt (Smelt)  $\leq 53$  mm (bottom) because the applied acoustic threshold of  $-55$  dB used in this study was chosen to exclude YOY rainbow smelt.

All captured fish								
Layer (m)	Trawls	Headrope Depth (m)	Catch	Smelt %	Cisco %	Bloater %	Kiyi %	Unid. Cor. %
< 9	3	1.4, 3.3, 4.0	35	62.9	28.6	2.9	0.0	5.7
9–14	4	6.7, 8.2, 8.9, 9.4	303	74.9	14.9	2.0	6.3	2.0
14–19	2	12.5, 15.1	82	74.4	9.8	0.0	15.9	0.0
19–24	1	17.9	30	13.3	36.7	6.7	43.3	0.0
24–36	2	29.2, 29.9	403	95.0	0.2	3.2	1.5	0.0
> 36	2	43.9, 60.1	11	18.2	0.0	9.1	63.6	9.1
Totals	14		864					
YOY Smelt ( $\leq 53$ mm) removed								
Layer (m)	Trawls	Headrope Depth (m)	Catch	Smelt %	Cisco %	Bloater %	Kiyi %	Unid. Cor. %
<9	3	1.4, 3.3, 4.0	14	7.1	71.4	7.1	0.0	14.3
9–14	4	6.7, 8.2, 8.9, 9.4	143	46.9	31.5	4.2	13.3	4.2
14–19	2	12.5, 15.1	24	12.5	33.3	0.0	54.2	0
19–24	1	17.9	26	0.0	42.3	7.7	50.0	0
24–36	2	29.2, 29.9	47	57.4	2.1	27.7	12.8	0
>36	2	43.9, 60.1	9	0.0	0.0	11.1	77.8	11.1
Totals	14		263					

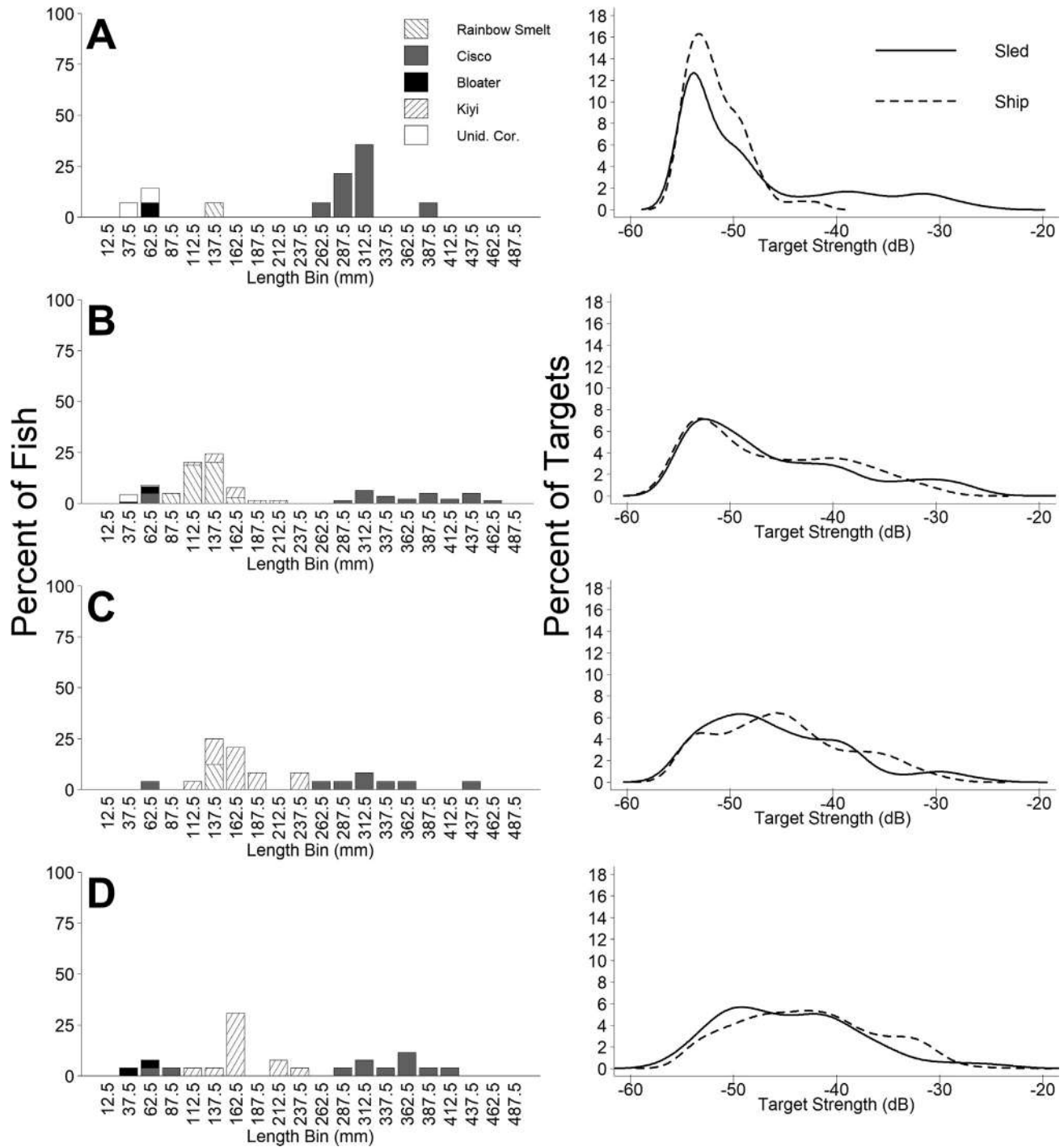
River = 106 m, Sand Island = 100 m, and Madeline Island = 64 m) did not vary significantly. This suggests that there may be a benefit to utilizing the sled when sampling deeper areas of Lake Superior. Overall, our findings were consistent with recent work using up-looking surveys in the Great Lakes (Connerton and Holden, 2016; Riha et al., 2017) in that we found average fish density estimates for the whole water column were greater, approximately 2.5-fold, when using the sled compared to the traditional ship-based down-looking survey method. In the most extreme case, Taconite Harbor, the sled detected 3.7 times higher fish densities than the ship-based system. Our depth-specific analyses indicated that traditional down-looking acoustic surveys underestimate fish densities in the upper water column. Careful consideration needs to be given to any ship-based acoustic density estimates that do not account for the potential for additional fish residing near the surface.

Patterns in fish density measured in specific depth layers shows that fish were being missed within the upper water column by traditional down-looking surveys due to a combination of the surface dead zone and/or vessel avoidance behavior. This pattern is more related to vessel avoidance because the surface exclusion zone for the up-looking transducer on the sled was often larger than that of the ship. The sled appears to have better sampled undisturbed fish that were unavailable to the traditional ship-based acoustic survey method. We do not believe that fish were attracted to, or actively avoiding, the sled as there was no significant relationship between fish densities detected near and far from the sled by the side-looking transducer. Additionally, given that the sled measured significantly higher fish densities within the top 9 m of the water column in all six transects, and no significant differences were observed past 14 m depths, we must conclude that vessel avoidance in the upper water column was the main reason for underestimation of densities with the ship-based survey. These findings are consistent with DuFour et al., (2018) who showed that fish avoidance, evoked by even small vessels, can be detected at depth. In future research, the sled could be deployed at progressively greater depths and distances away from the ship to more explicitly determine whether there is measurable evidence of vessel avoidance.

The underestimation of fish in the upper water column also has major implications for understanding the Lake Superior food web. The results from our surveys indicate that there is likely greater

biomass of pelagic fish in Lake Superior than traditional ship-based surveys have estimated in the past. The higher fish densities detected by the sled in the upper layer has implications on previous work describing diel vertical migration (DVM) of fishes in Lake Superior (Ahrenstorff et al., 2011; Hrabik et al., 2006a; Stockwell et al., 2010). It is possible that the upper extent of DVM migrations at night, measured during these studies with down-looking transducers, might have been biased deeper because fish in upper surface waters went undetected. Our findings also suggest that there may be more feeding opportunities for piscivorous fishes in the upper water column than previously estimated. More targeted studies of interactions between fish, zooplankton, and primary producers in the upper water column of Lake Superior will be beneficial for explaining the ecological significance of the uppermost 14 m to the whole lake. Furthermore, better understanding the role and function of the upper water column in Lake Superior will be important for determining how species dynamics might change in response to anthropogenic stressors like invasive species or climate change because this is the portion of the water column where these stressors will occur.

Past studies have identified lower than expected estimates of pelagic fish biomass in Lake Superior (Negus, 1995; Negus et al., 2008; Yurista et al., 2014). Yurista et al., (2014) created a predictive biomass size spectra (BSS) model for Lake Superior which performed well when compared to actual BSS measurements for most trophic levels, except for prey fish. The model overestimated prey fish BSS, and Yurista et al. (2014) mentioned the surface dead zone issue as a possible factor for the observed discrepancy. Negus (1995) developed a bioenergetics model for piscivores in western Lake Superior and found that prey consumption greatly exceeded estimates of biomass and production of prey fish species. She speculated that underestimation of prey fish biomass most likely accounted for this phenomenon (Negus, 1995). An updated bioenergetic analysis in 2008 suggested piscivores in Lake Superior were at or near carrying capacity (Negus et al., 2008), yet more accurate estimates of total prey fish abundance may have led these authors to reach a different conclusion. Our work provides a possible underestimation of 2.5-fold, which is bracketed by suggested potential underestimates identified by these studies. It is possible that continuing to improve estimates of prey fish in the upper water column with the sled could help reconcile the perceived bio-

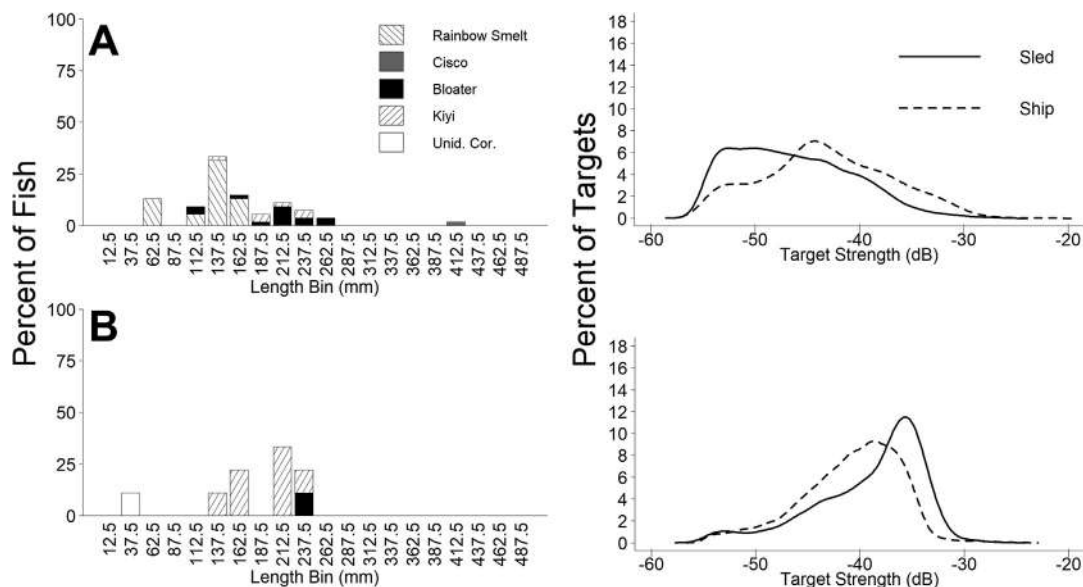


**Fig. 6.** Distribution of fish species caught (left) and single targets detected (right) in the four sections of the upper water column (A: ~4–9 m, B: 9–14 m, C: 14–19 m, D: 19–24 m). Fish species size distributions were obtained by midwater trawling. Single targets were obtained by the multi-directional sled-mounted acoustic survey method (Sled) and the ship-based down-looking survey method (Ship). Total single targets detected varied by water column layer and survey method; A: Ship 61 targets, Sled 972 targets; B: Ship 579 targets, Sled 1,159 targets; C: Ship 930 targets, Sled 457 targets; and D: Ship 1,002 targets, Sled 114 targets.

mass shortage and improve our understanding of the fisheries in Lake Superior and the other Great Lakes.

One of the limitations of our study was the influence of surface conditions on the sled-based up-looking data. Based on the GLSOP (Parker-Stetter et al., 2009) all data below ~3.7 m were included in the ship-based down-looking fish density estimates. However, on average, due to surface noise related to wave action and bubbles, we had to exclude data deeper than 3.7 m in five of the six transects for the sled-based acoustic survey. YOY rainbow smelt and

coregonines tend to occupy the top 10 m of the water column during stable stratification (Parker-Stetter et al., 2009; Myers et al., 2014). The -55 dB threshold we applied likely precluded the detection of YOY rainbow smelt (Rudstam et al., 2003). Despite excluding the smallest of fish targets, we still observed significantly more fish in the upper layer with the sled than the ship. This trend held even in our most extreme case, the Grand Marias transect, where the ship sampled 2.6 m more of the upper water column but still estimated lower fish density than the sled. This



**Fig. 7.** Distribution of fish species caught (left) and single targets detected (right) in the middle (A: ~24–36 m), and lower portion of the water column (B: ~36 to 0.5 m above lakebed). Fish distributions were obtained by midwater trawling. Single targets were obtained by the multi-directional sled-mounted acoustic survey method (Sled) and the ship-based down-looking survey method (Ship). Total single targets detected varied by water column layer and survey method; A: Ship 2,086 targets, Sled 2,897 targets; B: Ship 28,053 targets, Sled 2,735 targets.

further supports vessel avoidance as a primary factor contributing to the underestimation of fish density by our downlooking ship-based survey.

We demonstrate that a mobile multi-directional acoustic survey is tenable for fish density estimations in large freshwater systems. The fish density estimations from the acoustic sled could be applied to address ongoing fish management issues on Lake Superior, e.g. the sustainability of commercial cisco harvest. Cisco populations in Lake Superior support commercial roe fisheries having a lake-wide yield of 1200 metric tons in 2011 (Pratt et al., 2016). Commercial fishers target cisco during November by suspending gill nets in the upper water column (Yule et al., 2012). Unfortunately, a general decline in recruitment of cisco since 1990 has raised concerns about the sustainability of these roe fisheries (Pratt et al., 2016). Management agencies generally set quotas that aim to limit harvest to 10–15% of spawning female biomass (Stockwell et al., 2009). In the present study, cisco were most common in trawls fished in the upper-most 24 m of the water column (Table 4), and although catches of YAO fish in the uppermost 9 m were low ( $N = 14$  fish), cisco represented 71% of this total. Given that estimates derived from the sled exceed down-looking estimates at the surface, use of the sled to estimate spawning cisco densities could affect future cisco stock assessments.

## Conclusions

Our findings in Lake Superior are consistent with work on Lake Ontario (Connerton and Holden, 2016, Riha et al., 2017) showing traditional down-looking acoustic surveys underestimate pelagic fish densities in the upper portions of the water column. Our design did not allow us to completely disentangle the relative roles of vessel avoidance from other potential factors that contribute to observed differences. Future studies that systematically examine the effects of distance between multi-directional tow bodies and ships, or long-range and low-noise autonomous underwater vehicles (Moline et al., 2015) outfitted with multiple transducers aimed in varying directions, may be able to isolate vessel effects on fish behavior. In the meantime, the acoustic sled we describe has potential to collect less biased mobile up-looking data as efficiently

as traditional acoustic surveys. Fisheries researchers have a long history of working to overcome limitations to provide more accurate fisheries data. While our findings provide a context that identifies bias in down-looking large vessel surveys, additional work is needed to illuminate the potential magnitude vessel avoidance plays in near surface fish density estimation in large ecosystems.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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