Journal of Great Lakes Research 51 (2025) 102456

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

# Reducing bias in *Coregonus artedi* abundance estimates using stationary up-looking acoustics

Ryan C. Grow [a,*], Eric Berglund [b], Friedrich Fischer [b], Michael D. Rennie [a,c,1]

[a] Lakehead University, Ontario, Canada
[b] Ontario Ministry of Natural Resources, Ontario, Canada
[c] IISD Experimental Lakes Area, Manitoba, Canada

ARTICLE INFO

Communicated by Anna Baker

*Keywords:*
Coregonidae
Vessel avoidance
Spawning migration
Commercial fishing quota
Fish management

ABSTRACT

Mobile hydroacoustic surveys using ship-based down-looking transducers are widely used to estimate densities for ecologically and economically important pelagic fishes. However, this method likely underestimates densities of some surface-oriented species due to biases associated with the acoustic surface exclusion zone and ship avoidance behaviours. We compared cisco (*Coregonus artedi*) density estimates from a stationary up-looking platform survey to a standard down-looking acoustic survey. Both systems were deployed during the fall cisco spawn in Thunder Bay, Lake Superior 2020–2022. Cisco density estimates from the stationary up-looking platform were on average 6.7 times higher in the upper water column (~1–10 m) and 2 times higher over the entire water column (~1–45 m) than those from standard mobile surveys. Ship avoidance behaviour associated with mobile surveys was apparent in the upper water column; median cisco densities observed by the platform fell from ~36 to ~9 fish/ha when the ship passed near the platform. Abundance estimates from the platform when not influenced by ship avoidance provided higher quota estimates than the standard survey in 2020 and 2022, but were similar in 2021. A multi-day deployment of the platform tracked a progressive daily increase in fish densities, highlighting the sensitivity of mobile survey results to the day they are conducted, often dictated by environmental conditions. Our results show promise in applying stationary acoustic deployments in fisheries surveys, with improved accuracy and reduced effort compared to mobile acoustic surveys in the management and monitoring of pelagic fishes in the Great Lakes.

## 1. Introduction

Hydroacoustic fisheries surveys are an important tool for fisheries researchers and managers to quantify and monitor the status and trends of populations (Kubečka et al., 2009; Simmonds and MacLennan, 2005). Acoustic surveys are used to estimate fish densities over broad, spatially diverse areas and allow for sampling in areas where traditional netting methods are impractical due to the size of the ecosystem or concerns over lethal sampling methods applied to sensitive species (Qiao et al., 2006; Warner et al., 2012; Yule et al., 2007). The use of acoustics for fisheries surveys relies on the emission of high frequency sound pulses from a transducer and the measurement of the returning echoes from targets, such as fish or lakebeds (Haslett, 1969). Acoustic surveys also allow the depth of the fish to be measured (by knowing the time until the echo returns) and the fish's length estimated because the strength of the echo is proportional to the volume of the swim bladder (which is the primary source of returning sound from fish; Foote, 1980; Love, 1971).

Mobile acoustic surveys can sample large spatial scales much faster than standard net-based surveys (Boswell et al., 2010; Guillard and Vergès, 2007; Yule et al., 2009a,b). In the Laurentian Great Lakes, mobile down-looking surveys have been used to monitor the status and trends in pelagic fish populations, estimate their densities and assist in setting quotas for commercially significant species (Parker-Stetter et al., 2009; Yule et al., 2012). Due to large scale management and sustainability challenges, acoustic methods are frequently used in the Great Lakes to monitor fish population status and trends region-wide, as these methods minimize biases related to gear efficiency and fish availability (Davison et al., 2015; Hoffman et al., 2009) and are non-destructive

* Corresponding author.
*E-mail address:* rgrow@lakehead.ca (R.C. Grow).

[1] Given his role as Editor, Michael Rennie had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Anna Baker.

https://doi.org/10.1016/j.jglr.2024.102456
Received 24 February 2024; Accepted 26 September 2024
Available online 18 October 2024

(Guillard and Vergès, 2007). Where gear efficiency describes bias related to the percentage of fish that encounter a given sampling method resulting in successful capture (Davison et al., 2015), fish availability describes bias from species-specific vulnerability to different sampling methods (Sampson, 2014). Acoustic surveys reduce bias from both of these sources, as sound waves do not discriminate among different sizes or speeds of fish and in most cases cannot be visually or physically detected/avoided by fish. As a result, acoustic methods are thought to provide less biased estimates of abundance and biomass compared to traditional net-based collection methods (Stockwell et al., 2007; Yurista et al., 2014). Although acoustic surveys can be subject to efficiency bias when fish density is so high that fish obscure the echoes of others directly behind them resulting in density underestimation, it is rare in ecosystems like the Great Lakes (Stockwell et al., 2007) and is considered negligible in comparison to net-based efficiency biases (Barange et al., 1996).

Despite the benefits of acoustic surveys, limitations exist based on deployment methods and technology. While density and size are easily estimated in acoustic surveys using equations developed from ensonifying many different species and sizes of fish in situ (Love, 1971), determination of species composition is generally only achievable if paired with traditional trawl or gillnet sampling to assign species composition to size distributions. Additionally, two regions of absent data known as acoustic dead zones or exclusion zones exist in traditional down-looking acoustic surveys (i.e., regions that are difficult to measure reliably), and occur in waters above or within a few meters (m) of the transducer and near the bottom (Fig. 1). The bottom exclusion zone is the area near the bottom of a given acoustic survey where the spherical shape of the sound pulse interacts with the strong signal of the bottom, overwhelming and obscuring fish in the radius; slope and roughness can also increase the height of this zone. This zone has been well studied (Mello and Rose, 2009; Totland et al., 2009), and can be addressed with correction factors, either by extending nearby estimates into the exclusion zone or by assuming there are no fish in the exclusion zone (Kotwicki et al., 2013). The surface exclusion zone consists of the portion of the water column closest to the transducer and is present due to a combination of near-field exclusion zones, deployment vessel draft interference, transducer deployment depth, and surface bubble interference (Parker-Stetter et al., 2009; Totland et al., 2009). Although correction factors can also address this exclusion zone, it is often a more complex task as the surface waters often have higher or more variable fish densities and are usually larger in physical extent by a few meters. Additionally, some fish species may be disturbed by the presence of a large ship and exhibit avoidance behaviours such as diving or herding, leading to a density underestimation of surface fish that tend to occupy this upper portion of the water column (DuFour et al., 2018; Guillard et al., 2010). Partially due to these complications and the lack of tools able to assess it, the surface exclusion zone has received considerably less attention than the bottom exclusion zone.

By contrast, up-looking acoustic survey methods (i.e., De Robertis et al., 2018; Elliott et al., 2021; Grow et al., 2020) eliminate many of the uncertainties associated with the surface exclusion zone. Up-looking surveys can be done actively using tow bodies (Grow et al., 2020) or passively from moored stationary platforms equipped with upward facing acoustics (De Robertis et al., 2018; Elliott et al., 2021; Grow et al., 2020). These survey methods can generate fish density estimates across bathymetrically and spatially diverse regions especially in complex substrates or areas over or near underwater features like reefs, where traditional down looking acoustics or net based surveys may have difficulty sampling. Stationary up-looking acoustics also offer the advantage of more extensive temporal sampling, which, while trading off some spatial breadth (relative to mobile surveys), enables the detection of detailed fish movement patterns (not possible with mobile surveys). Differences compared to traditional methods can be striking. For example, a recent study utilizing a multi-directional acoustic tow body pulled at mid-water depths found density estimates for pelagic fish species 2.5 times higher compared to traditional down-looking surveys (Grow et al., 2020). Similarly, an up-looking acoustic platform reported densities of alewife (*Alosa pseudoharengus*) double those of traditional down-looking acoustic methods, in addition to previously undocumented diel vertical migration (DVM) patterns (Elliott et al., 2021; Riha et al., 2017). These findings highlight the potential advantages of up-looking approaches to provide both improved accuracy for acoustic survey methods applied to surface-oriented fishes, and unique insights into fish movement patterns.

One such surface-oriented fish that would benefit from the application of this technology are cisco (*Coregonus artedi*) in Lake Superior. Cisco management and research relies heavily on estimates from mobile down-looking surveys and is unique in that these surveys often directly inform cisco quota setting as cisco are both an important forage fish and a commercially targeted species; whereas, acoustic surveys often focus on forage fish for the sake of informing predator quotas (Fisch et al., 2019a; Pratt et al., 2016; Warner et al., 2008; Yule et al., 2012). Additionally, managing these fish is challenging due to their sporadic recruitment and decades-long decline (Vinson et al., 2016). Cisco are also mainly targeted commercially for their roe, with annual yields of over 1,000 metric tons of fish biomass across many state/provincial management jurisdictions and various tribal organizations (Pratt et al.,

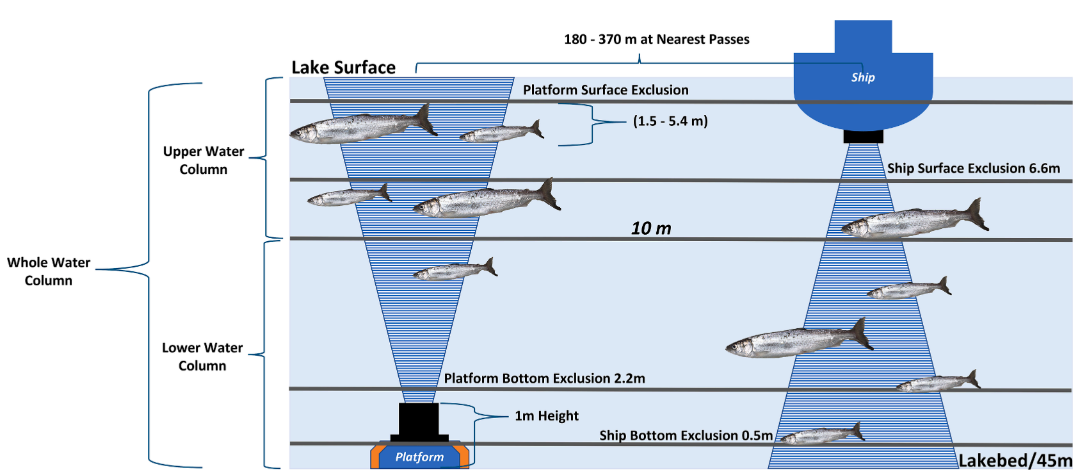


**Fig. 1.** Diagram of acoustic survey methods. The typical ship-based down-looking survey method is shown on the right and the up-looking platform based acoustic survey method is on the left. The platform was deployed at 34 m of depth on average. The two water column analysis sections (upper and lower water column) are displayed with their approximate depths. The fish pictured are cisco (*Coregonus artedi*).

2016). With these factors in mind obtaining unbiased population estimates is crucial for cisco management and conservation.

In this study, we build on this growing body of knowledge to assess the viability of a stationary up-looking platform as a novel fish survey tool in freshwater ecosystems. Based on previous studies, we predicted higher fish density estimates from the up-looking surveys compared to down-looking surveys, especially in the upper section of the water column, due to better characterization of this region by up-looking deployments and eliminating the potential for ship avoidance behaviour. Additionally, we evaluate insights possible from multi-day deployments of the up-looking platform to reveal temporal patterns in cisco spawning migrations and provide an analysis of the effect of varying sampling schedules on density estimation. Finally, we calculated cisco quota estimates using data from both mobile and stationary acoustic deployments to evaluate the potential of this novel system to contribute to adaptive management approaches to cisco harvest.

## 2. Methods

### 2.1. Survey design

#### 2.1.1. Description of acoustic surveys

Acoustic systems were deployed from the research vessel (R/V) Superior Explorer, operated by the Ontario Ministry of Natural Resources (MNR) between October 29 and November 23 for three years from 2020 to 2022. The stationary up-looking platform ('acoustic platform' hereafter), manufactured by The Oceanscience Group Ltd. (Poway, CA, USA), was equipped with an upward-aimed 121 kHz 8° circular split-beam transducer operated with a BioSonics, Inc. (Seattle, WA, USA) DT-X Sub, powered by 2 to 4 DEEPSEA (San Diego, CA, USA) 12 V batteries (Fig. S1). The ship acoustic system consisted of a single downward facing 70 kHz 5° circular split-beam transducer deployed off the starboard side of the ship via a pole mount to a depth of 1 m below the lakes surface, connected to a separate BioSonics DT-X system and laptop. These two frequencies have been shown to provide similar results (see review in Yule et al., 2009a,b), and are recommended by the Standard Operating Procedures for Fisheries Surveys in the Great Lakes (Parker-Stetter et al., 2009). Acoustic data on both systems were collected with acquisition thresholds set at −100 dB (dB), pulse durations set at 0.4 ms and realized ping rates of 2 pings per second for the ship and 5 pings per second for the acoustic platform. Acoustic platform deployment locations were determined similarly to methods in De Robertis et al. (2018), using previous (2018) down-looking mobile fall cisco surveys to identify areas of representative fish density in Thunder Bay as well as their proximity to current survey transects for the given year (Electronic Supplementary Material (ESM) Fig. S2). For both survey methods, each night of sampling began after twilight and ended before sunrise, lasting approximately seven hours and twenty minutes of sampling per night. The acoustic platform was deployed from one to three nights at each location in each year sampling continuously (Table 1). For the ship, each transect was approximately 80 km long and ship speed was approximately 11 km/h. A water temperature profile was collected with a HOBO mini logger (ITM Instruments INC., Toronto, ON, CAN) at each acoustic platform deployment location to provide an accurate sound speed and absorption coefficient for acoustic data processing (Parker-Stetter et al., 2009). For each night of the ship survey, we recorded when the ship passed closest to the acoustic platform along its transect (ranging between 180 m and 370 m of the platform) in order to directly examine any ship avoidance behaviour exhibited by the fish, as recorded by the acoustic platform.

#### 2.1.2. Pelagic gillnet survey

Concurrent to acoustic sampling, 28 pelagic gillnet sites were sampled between October 29 and November 23 during 2020–22 along acoustic transects (Fig. 2). These nets are part of the MNR standard fall cisco survey. Gillnets were suspended 10 m below the water's surface regardless of bathymetric depth and consisted of ten 3 m by 30 m panels of 38 mm (mm)–152 mm clear monofilament graded stretch mesh (total net length of 300 m). All nets fished for 8–10 h (overnight sets).

### 2.2. Data analyses

#### 2.2.1. Data processing and preparation

All acoustic data were processed with Echoview Software, Version 11 (Echoview Software Pty. Ltd., Hobart, TAS, Australia). Field calibrations of the ship and acoustic platform echosounders were carried out using a 38 mm tungsten carbide sphere and applied following Foote (1987). We created near-field and bottom exclusion lines (or surface exclusion in the case of the acoustic platform) and removed regions of bad data in the ship and acoustic platform echograms via manual visual inspection (Parker-Stetter et al., 2009). For the acoustic platform, the surface exclusion line was adjusted by hand to eliminate obvious noise from wave action and entrained air bubbles, which is equivalent to adjusting the bottom exclusion zone in down-looking surveys. The ship-based down-looking transducer's surface exclusion line was set at 6.6 m, while the acoustic platform's surface exclusion line varied across deployments and with surface conditions, ranging between 1.5 m and 5.4 m on average (Table 1). The fish density estimates obtained from this layer (10 m – surface exclusion line) were not extrapolated into the exclusion zone, but the nature of the fish density calculation takes into account the total volume of water sampled, minimizing the impact of varying exclusion depths. The bottom exclusion line was set to 0.5 m off the bottom (using Echoview's bottom picking algorithm and manually inspected by hand for any errors) or at a maximum of 45 m (Minnesota Department of Natural Resources acoustic cisco survey SOP) for the down-looking survey, and for the acoustic platform was equal to the deployment depth minus the sum of the 1.2 m nearfield exclusion and the 1 m transducer mount depth for the stationary up-looking survey (Table 1). To focus the analyses on cisco, we used a minimum of −41.2 dB and maximum of −31.5 dB for target strength (TS) and applied the corresponding volume backscattering strength (Sv) within Echoview. The limits were based on the minimum sexually mature adult size of 300 mm and the largest cisco (496 mm) sampled by MNR in gill net surveys. Additionally, this survey takes place during the season that cisco are known to congregate in Thunder Bay to spawn, and the concurrent MNR gill nets caught nearly exclusively cisco (see Results). Therefore, all fish density estimates we derived from the acoustic data were assumed to be cisco density estimates. Each mobile transect or stationary deployment

**Table 1**
Year, latitude, longitude, mean surface exclusion depth, bottom exclusion depth (Bottom depth – 1.2 m nearfield exclusion plus 1 m from platform height) and nights deployed each year for all fall acoustic platform deployments in Thunder Bay, Lake Superior.

| Location | Year | Latitude | Longitude | Mean Surface Exclusion Depth (m) | Bottom Exclusion Depth (m) | Nights Deployed |
|---|---|---|---|---|---|---|
| TB1 | 2020 | 48.47091 | −88.96392 | 3.5 | 29.8 | 2 |
| TB2 | 2020 | 48.43092 | −89.09435 | 1.5 | 38.1 | 2 |
| TB3 | 2020 | 48.34828 | −89.11034 | 3.4 | 34.2 | 3 |
| TB2 | 2021 | 48.43966 | −89.07544 | 2.5 | 38.8 | 1 |
| TB3 | 2021 | 48.30215 | −89.08254 | 5.4 | 23.6 | 2 |
| TB1 | 2022 | 48.4706 | −88.96368 | 2.2 | 30.4 | 2 |
| TB3 | 2022 | 48.34992 | −89.11034 | 4.3 | 33.4 | 1 |

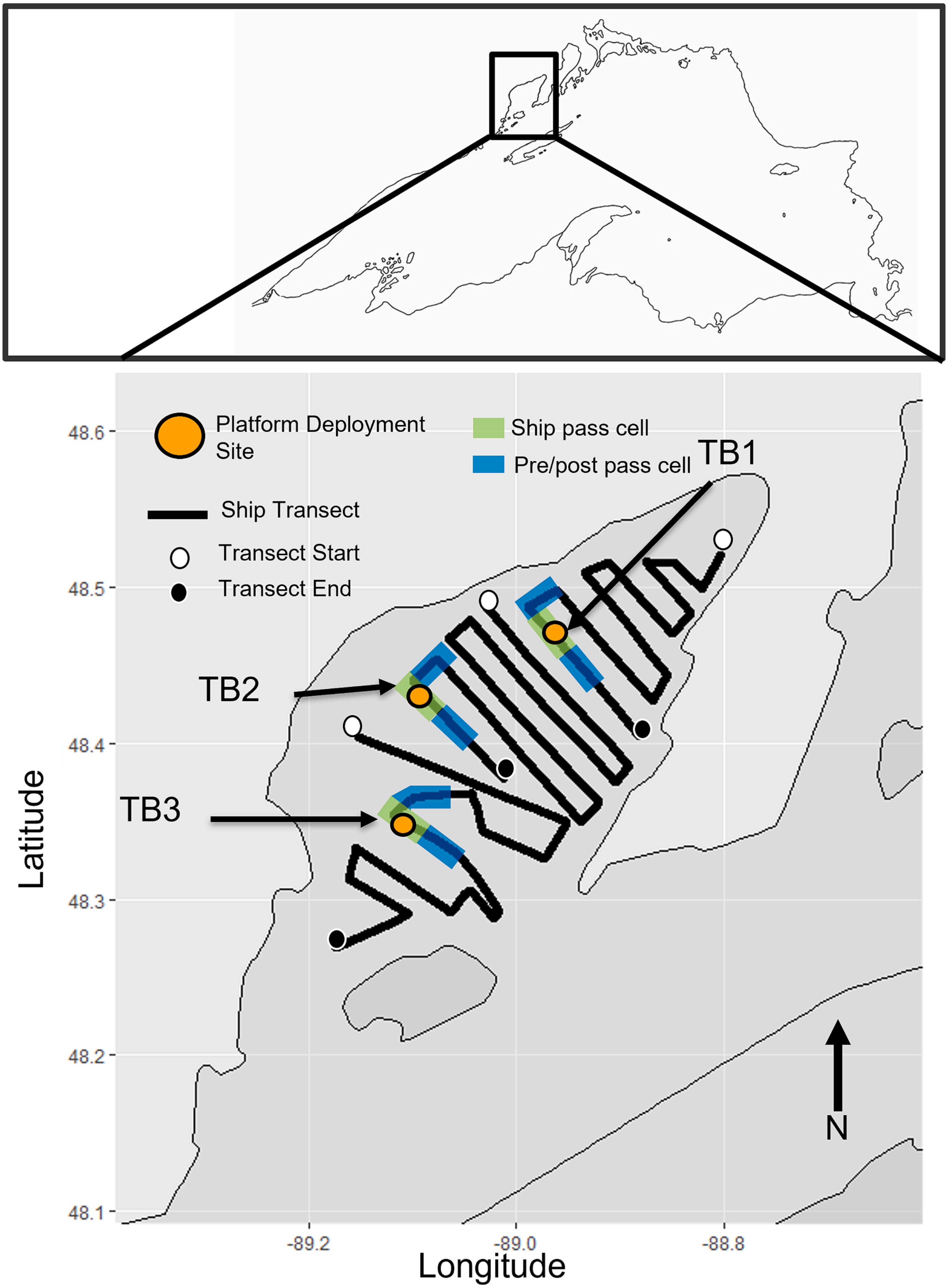


**Fig. 2.** Map of acoustic platform deployment locations and concurrent Thunder Bay Ontario Ministry of Natural Resources fall cisco survey transects. Each transect (shown in black lines) was approximately 80 km in length. All transects were sampled between October 29 and November 23 in 2020–22. Circles indicate approximate locations of cocurrent acoustic platform deployment locations sampled. The three locations/transects are Thunder Bay 1 (TB1), Thunder Bay 2 (TB2), and Thunder Bay 3 (TB3) and are abbreviated in subsequent figures. The 28 gillnets were deployed following a random sample design along each ship acoustic transect.

was divided into 20-min intervals (for the mobile survey, 20 min at ~11 km/h is ~3700 m cells) to ensure that each cell was an independent sample (Hrabik et al., 2006) while targeting a reasonable number of single echo detections (SEDs).

#### 2.2.2. Whole water column and depth-specific comparisons

To prepare the stationary up-looking and ship-based data for statistical analyses and comparisons between methods, the data for the whole water column (~1 m–45 m) were initially examined as a single unit to reflect current standard practice of obtaining cisco density estimates for management purposes. Subsequently, to evaluate depth-dependence of results between the two methods, the data from both mobile and stationary surveys were split into two depth layers and reanalyzed. The upper water column layer was defined as ~1–10 m based on the recommendation of Yule et al. (2012) to improve cisco density estimates in this layer during spawning periods, 10 m being a typical measurement increment in the Lake Superior acoustic surveys (Rudstam et al., 2009) and similar to the lower threshold (~4–9 m) applied in other recent up-looking acoustic work (Grow et al., 2020). The lower water column layer was defined as 10 m to the lakebed (or to a maximum of 45 m for the mobile surveys) to examine how the stationary up-looking unit performed within the portion of the water column that is adequately sampled by standard down-looking acoustics.

For each analysis of up-looking and down-looking data (i.e., whole water column as well as separate water layers), cisco density ($D_{i,t,k,m,y}$) for each individual 20-min cell $i$, each paired stationary acoustic deployment and down-looking transect location $t$, water column layer $k$, survey method $m$, and survey year $y$ were calculated with the echo integration method by:

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

where $ABC$ is the area backscattering coefficient for each combination of $i$, $t$, $k$, $m$, and $y$ that provided greater than 20 SEDs available within each cell (Parker-Stetter et al., 2009). The $ABC$ (in m$^2$) was calculated by multiplying the mean thickness of the beam (in m) being integrated by the mean volume backscattering coefficient of the domain ($s_v$ in m). Beam thickness took into account any sections of the water column that were excluded (surface or bottom exclusion zones) to avoid extrapolating fish density over a larger volume/depth than sampled. By convention, $S_v$ is equal to $10^{sv/10}$, where $S_v$ is the mean linearized volume backscattering strength then converted to decibels (dB/m). The respective $ABC$s were scaled by $\sigma$ (in m$^2$); their respective mean backscattering cross sections ($\sigma_{i,t,k,m,y}$), which was calculated by $10^{\mathrm{TS}/10}$, where TS is the mean linearized target strength of the SEDs then converted to the domain in dB relative to 1 m$^2$. Finally, we applied a conversion factor of 10,000 to convert fish/m$^2$ to fish/ha. When fewer than 20 SEDs (but greater than 0) were available in a cell, we altered Eq. (1) so that the mean TS for each layer used for scaling was the average for the entire transect/deployment. When fewer than 20 SEDs were available in any layer/transect combination, we used a global estimate of TS based on averaging TS in that layer over all seven deployments/transects. If there were no SEDs in a cell or if any cells had Sv backscatter but no SEDs we assumed that we were detecting echoes from fish smaller than spawning cisco, and those cells were assigned a density of 0 fish/ha.

#### 2.2.3. Ship avoidance comparisons

In order to assess any possible boat avoidance effects, we also examined the upper water column cisco density detected by the acoustic platform in the 20 min cell in which the ship passed closest to it and compared that density to those of the adjacent 20 min cells before and after the pass. Additionally, to ensure that the area near the acoustic platform was not simply an area of significantly lower cisco density, we examined the cisco density detected by the ship in the upper water column to the cells before and after the pass.

#### 2.2.4. Temporal comparisons

In order to better understand the impacts of temporal variation on assessing spawner abundance (as a given area is only sampled one night in typical mobile down-looking acoustic surveys during the cisco spawning period), we examined the average cisco density estimates obtained by the acoustic platform for three consecutive nights $n$ at station TB3 in 2020 and also compared them to the single average density estimate obtained by the ship survey during the first night of the stationary units 3-night deployment using Eq. (1) to calculate fish density/ha each night.

#### 2.2.5. Sample schedule comparisons

Finally, we sub-sampled the stationary up looking dataset to mimic varying sampling schedules to provide direction to future studies utilizing stationary acoustics over varying deployment times. We compared fish density estimates produced from selecting data from 20 min blocks of recordings once every one, two, three, four, or five hours, 40 min every hour, and 20 and 60 min at solar midnight, to the estimates obtained by running the stationary unit non-stop for the first day of deployment at the sampled locations in a given year. Sampling for smaller windows of time may permit much longer deployments, so long as density estimates are not biased by less frequent sampling schedules.

#### 2.2.6. Spawner biomass estimates

In order to relate the data obtained from both survey methods more directly to adaptive-management applications, cisco density estimates for the whole water column were converted to spawner biomass $B_{i,t,k,m,y,w,s}$ for each method across survey years, $y$, by multiplying cisco density ($D_{i,t,k,m,y}$) by the mean cisco weight $w$ in kg from the gillnet survey and the ratio of females from the gillnet survey $s$:

$$B_{i,t,k,m,y,w,s}(kg) = D_{i,t,k,m,y}{*}w_y{*}s_y \quad (2)$$

We then estimated quota for the Thunder Bay region (in kg/ha) by multiplying mean spawner biomass ($B_{i,t,k,m,y,w,s}$) by the surface area of Thunder Bay (~66,600 ha) and a value of 0.1, which follows the current published management suggestion of setting the quota to 10–15 % of spawner biomass (Fisch et al., 2019b; Stockwell et al., 2009; Yule et al., 2006).

### 2.3. Statistical analyses

#### 2.3.1. Whole water column and depth-specific comparisons

Three separate three-way ANOVAs were then used to compare cisco densities derived from ship-based down-looking survey to those from the acoustic platform for all three water layers (total water column, lower water column, upper water column). Specifically, the effects of survey method $m$, each paired stationary acoustic deployment and down-looking transect location $t$, and survey year $y$ on cisco densities ($D_{i,t,k,m,y}$) for each individual 20-min cell $i$ was applied to the whole water column comparison by:

$$D_{i,t,m,y}\ m_i{*}t_i{*}y_i \quad (3)$$

Due to the non-normal distribution of residuals, all cisco density data were square root transformed to better meet the assumptions of normality and homogeneity of variance. For all three-way ANOVA's (n = 3) an α = 0.017 was used to assess significance to account for the family-wise error rate of 0.05. A Tukey's HSD test was applied post hoc (also using α = 0.017) to examine pairwise differences among means.

#### 2.3.2. Ship avoidance comparisons

Due to the relatively low occurrence of events where the ship passed within 370 m to the acoustic platform (N = 7), we used permutation tests to evaluate comparisons of median cisco densities during ship passage and assess ship avoidance behaviour. The tests evaluated the difference between median cisco densities in the 20 min cell where the ship passed nearest to the platform and densities in the 20 min cells before and after the pass for both the stationary up-looking platform and the mobile down-looking ship acoustics (Permutation Tests, iterations = 100,000, α = 0.05). Briefly, the original difference between when the ship passed nearest to the platform with adjacent 20 min cells was compared to the permuted difference of randomly shuffled data (e.g., sampled without replacement). The p-value for this test is expressed as the proportion of observations that equal or exceed the original observed difference between the 20 min cell of ship passage vs. those immediately before or after ship passage (i.e., the probability that a difference of equal or greater effect would be observed based on random comparisons only).

#### 2.3.3. Temporal comparisons

To examine the effect of sample night on the mean cisco density estimates obtained by the acoustic platform across three days with the typical single night estimate obtained by the ship survey at TB3 in 2020 conducted the first night, we also used a one-way ANOVA test (α = 0.05) to compare mean cisco densities detected each night.

#### 2.3.4. Sample schedule comparisons

To examine the effect of sample scheduling as well as any potential interaction with schedule and year of sampling on whole bay cisco density estimates obtained by the acoustic platform, we also used a two-way ANOVA test (α = 0.05) by each schedule each sample year (to be on the conservative side we only used the first night of sampling at each location each year, because for some samples we only had one night of data).

#### 2.3.5. Spawner biomass estimates

Finally, differences in cisco quota estimates derived from the acoustic platform and those from mobile surveys were examined using a two-way ANOVA (α = 0.05) comparing the two survey methods within each survey year. These quota estimates were calculated for each 20 min cell to obtain a robust average density estimation. All statistical tests were conducted in the R Program version 3.4.0 (R Core Team, 2020).

## 3. Results

### 3.1. Gillnet catch

Over all years, 518 fish were caught in 28 gillnet samples. The catch was almost exclusively adult cisco (N = 517) that were all between 217 mm and 496 mm (total length; Table 2), with the only other species caught being a single lake trout (711 mm) in 2020.

### 3.2. Whole water column comparisons

A three-way interaction between acoustic method, location, and year was not significant for cisco densities across the whole water column (three-way ANOVA, $F_{2,\,615} = 2.02$, $p = 0.134$, ESM Table S1). However, all three two-way interactions were significant for whole-water column cisco densities: the interaction of survey method and location ($F_{2,\,615} = 29.06$, $p < 0.001$), survey method and year ($F_{2,\,615} = 15.50$, $p < 0.001$), and location and year ($F_{2,\,615} = 56.47$, $p < 0.001$). Based on a Tukey's HSD test, mean cisco densities obtained from the acoustic platform were significantly higher ($p < 0.017$) than the traditional down-looking acoustic survey at TB1 in 2020 and 2021, and at TB3 in 2020 and 2022, but at TB2 in 2021 the ship obtained significantly higher cisco densities than the acoustic platform (Fig. 3A). Cisco densities were not statistically different among methods across the rest of the locations and years included in the study ($p > 0.017$; Fig. 3A).

### 3.3. Depth-specific comparisons

When we divided the water column into an upper and lower section, we found that in the upper water column, a three-way interaction between method, location, and year was also not significant (three-way ANOVA, $F_{2,\,627} = 3.54$, $p = 0.030$, α = 0.017, ESM Table S1). However, all three two-way interactions were significant for differences in cisco densities for the upper water column; the interaction of survey methods and location ($F_{2,\,627} = 6.50$, $p = 0.002$), survey method and year ($F_{2,\,627} = 11.69$, $p < 0.001$), and location and year ($F_{2,\,627} = 41.25$, $p < 0.001$). Cisco density in the ~1–10 m layer was significantly higher in the acoustic platform-based survey compared to the ship-based survey for every transect ($F_{1,\,627} = 224.48$, $p < 0.001$), although it varied in magnitude across location and sample year (Fig. 3B).

For the deeper 10–45 m layer, the three-way interaction between method, location, and year was also not significant ($F_{2,\,627} = 0.43$, $p = 0.652$, ESM Table S1). However, all three two-way interactions were significant for differences in cisco densities for the lower water column; the interaction of survey methods and location ($F_{2,\,627} = 13.45$, $p < 0.001$), survey method and year ($F_{2,\,627} = 14.73$, $p < 0.001$), and location and year ($F_{2,\,627} = 46.96$, $p < 0.001$). Based on a Tukey HSD test, mean cisco densities obtained from the traditional down-looking acoustic survey were significantly higher ($p < 0.017$) than the acoustic platform at TB2 in 2020 and 2021 but not significantly different at any other deployment location ($p > 0.017$; Fig. 3C).

### 3.4. Ship avoidance comparisons

We observed a significant decrease in the median cisco density estimates for the acoustic platform within the upper water column in the 20 min cell closest to the ship's passage compared to the two adjacent 20 min cells before and after the ship passed the platform compared to what would be expected from random (permutation test, iterations = 100,000; $T = 48.70$; $p = 0.034$; Fig. 4). In the nearby 20-min cells, fish density estimates were ~36 fish/ha in upper water column, but when the ship passed nearest to the platform, they fell to ~9 fish/ha. In contrast, the ship detected significantly higher median cisco density

**Table 2**
Summary of cisco gillnet data across years (total number of cisco caught, percentage of catch female, mean cisco weight and harvest) and mean cisco quota estimate (kg) by acoustic survey method in Thunder Bay, Lake Superior. Harvest provided by the Ontario Ministry of Natural Resources for years where data were available (Ministry of Natural Resources and Forestry Upper Great Lakes Management Unit Lake Superior, 2023).

| Year | # Cisco | Percent Female | Mean Weight (kg) | Method | Harvest (Thousands of kg) | Mean Quota Estimate (Thousands of kg) | Mean Quota Estimate No TB2 2021 (Thousands of kg) |
|---|---|---|---|---|---|---|---|
| 2020 | 240 | 45 % | 0.373 | Ship | 122.1 | 42.5 | 42.5 |
| | | | | Platform | | 123.0 | 123.0 |
| 2021 | 165 | 61 % | 0.484 | Ship | 123.1 | 151.7 | 80.7 |
| | | | | Platform | | 134.8 | 143.2 |
| 2022 | 112 | 44 % | 0.376 | Ship | 120.0 | 30.4 | 30.4 |
| | | | | Platform | | 58.7 | 58.7 |

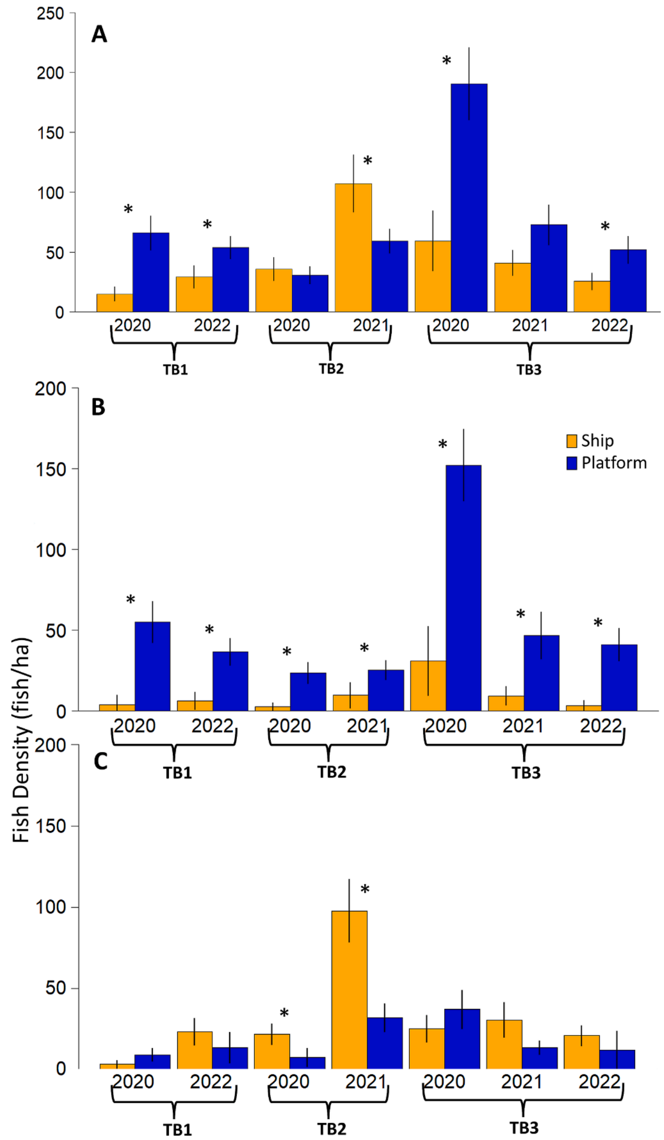


**Fig. 3.** Acoustic platform vs ship whole (~1–45 m/lakebed) water column (A), upper (~1–10 m) water column (B) and lower (~10–45 m/lakebed) water column (C) cisco density across location and year. Bars show mean cisco density from ~20 different 20-min-long sections of the water column on the seven Thunder Bay sampling locations/transects from each night of sampling. All ship transects include one night of sampling (refer to Table 1 for number of nights sampled for each acoustic platform deployment). The three locations/transects are defined in Fig. 2. Asterisks represent significant differences (whole: $p < 0.05$, upper and lower: $p < 0.017$) between the two survey methods within a given year and transect for individual deployments/transects as determined by a Tukey HSD test. Error bars indicate 95 % confidence intervals around each mean.

estimates (~24 fish/ha) in the upper water column in the 20 min cell closest to the ships passage past the acoustic platform compared to adjacent 20 min cells (~0 fish/ha; iterations = 100,000; $T = 23.61$; $p = 0.032$; Fig. 4). This suggests that the decrease in upper water column cisco density detected by the acoustic platform when the ship was passing closest to it was not simply an artifact of lower fish densities at the location where the platform was deployed.

### 3.5. Temporal comparisons

There was a significant effect of sample night on the mean cisco density estimates at TB3 in 2020 (One-way ANOVA; $F_{2,\ 105} = 3.80$, $p = 0.026$). A post hoc Tukey test found that the platform recorded significantly higher mean density estimates on night three compared to night one ($p = 0.02$) and the platform recorded significantly higher densities on night one, two, and three compared to the ship densities recorded on night one (which was the only night that the boat surveyed; $p < 0.001$; Fig. 5).

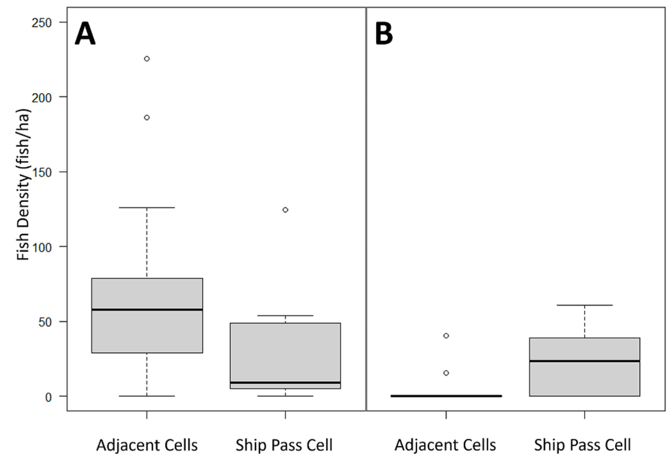


**Fig. 4.** Median upper water column (~1–10 m) cisco density in the 20 min cell during and cells adjacent to the ship passing the acoustic platform. Bars show median cisco density in the upper water column detected by the acoustic platform (A) and the ship (B) from all years and locations/transects sampled in Thunder Bay.

### 3.6. Sample schedule comparisons

There was a significant effect of sample year on the mean cisco density estimates (Two-way ANOVA; $F_{2,\ 354} = 13.28$, $p < 0.001$), but there was no significant effect of sampling schedule on cisco density estimates and no interaction between sample schedule and year ($p > 0.76$; Fig. 6).

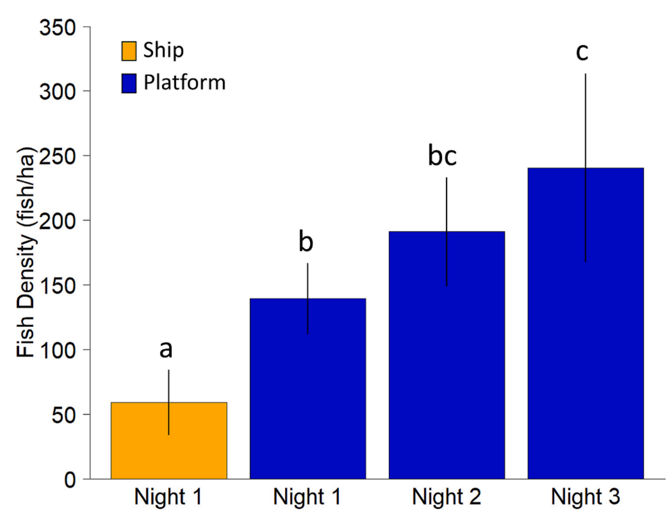


**Fig. 5.** Acoustic platform and ship whole water column (~1–45 m/lakebed) cisco density across sample nights at TB3 in 2020. Bars show mean cisco density from ~20 different 20-min-long sections of the water column on the seven Thunder Bay sampling locations/transects from each night of sampling. Lowercase letters represent significant differences ($p < 0.05$) between the mean density estimates as determined by a Tukey HSD test. Error bars indicate 95 % confidence intervals around each mean.

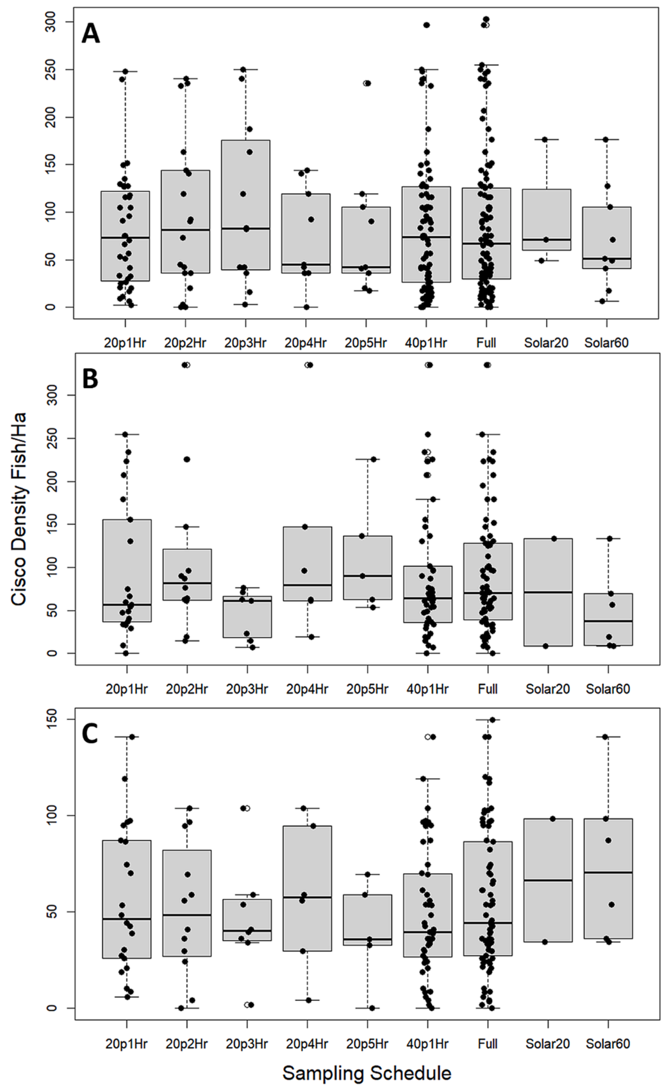


**Fig. 6.** Boxplot comparison of different sampling schedules by the stationary platform for a maximum of one night of sampling for each sampled location (see Table 1 for more detail) for 2020 (A), 2021 (B), and 2022 (C). Categories are in the format of number of minutes sampled per a given number of hours (ex. 20p1hr means it is as if the unit was collecting data for 20 min every 1 h) except for when the data were collected non-stop (Full) and only for 20 or 60 min at solar midnight. Black bars indicate the median cisco density (cisco/Ha) values for a given sampling schedule.

### 3.7. *Spawner biomass estimates*

Using whole water column estimates, there was a significant interaction between survey method and year for cisco spawner biomass estimates (Two-way ANOVA, $F_{2,\ 623} = 9.79$, $p < 0.001$). The post hoc Tukey test found that cisco spawner biomass estimates were significantly higher from the acoustic platform survey compared to those from the ship in 2020 ($p < 0.001$), but there was no significant difference between estimates in 2021 ($p = 0.76$) or 2022 ($p = 0.21$; Fig. 7). Upon closer inspection, there was one clear outlier observed in 2021 at TB2. Unlike all other deployments, this data point was taken the day after a major weather event. To prevent extreme weather events from affecting our data, we excluded this data point from the whole water column spawning biomass estimates as similarly done in Aglen et al. (1999). With the outlier excluded, there was no significant interaction (Two-way ANOVA, $F_{2,\ 564} = 1.63$, $p = 0.197$), but the main effect of method ($F_{1,\ 564} = 38.59$, $p < 0.001$) and year ($F_{2,\ 564} = 14.35$, $p < 0.001$) were both significant, with the platform consistently estimating higher whole water column spawner biomass across all three years (Fig. 7).

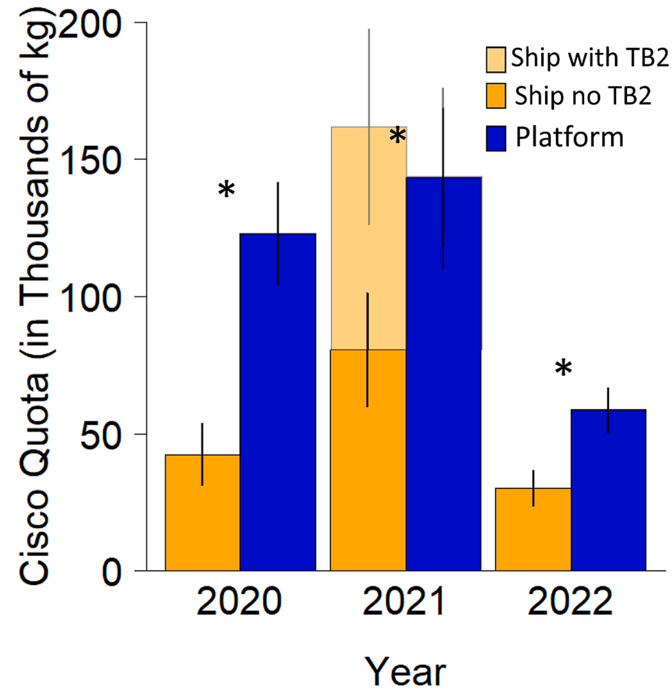


**Fig. 7.** Acoustic platform vs ship whole water column (~1–45 m/lakebed) cisco quota biomass estimate (in thousands of kg) each year in Thunder Bay, based on whole water column estimates of cisco density excluding TB2 2021 due to weather impact concerns (biomass also shown with TB2 2021 included faded behind the other bar). Bars show the mean estimated cisco quota based on applying an exploitation rate of 10 % spawner biomass across years. Cisco quota from 2021 is depicted with and without data from TB2 due to the weather related outlier in the TB2 data set. Asterisks represent significant difference ($p < 0.001$) associated with the main effect of survey method. Error bars indicate 95 % confidence intervals around each mean.

## 4. Discussion

The stationary acoustic platform provided significantly (6.7 times) higher estimates of cisco density compared to the traditional ship-based down-looking survey in the upper water column across all survey sites, and 2 times greater (41 more fish/ha on average) across the entire water column, significantly so in two of the three sites surveyed, consistent with other up-looking acoustic surveys in the Great Lakes (Grow et al., 2020; Riha et al., 2017). In the most extreme case, TB1 in 2020, the acoustic platform detected 4.3 times more fish per hectare over the entire water column compared to the ship-based system. However, there was a lack of difference and even a potential reversal in trends observed at the TB2 site. Notably, the TB2 acoustic platform deployment location had the least number of nights sampled across all three years (3 nights) compared to other sites (4 nights at TB1 and 6 nights at TB3). Though there is likely some temporal autocorrelation present in our data, it is similar to that in standard single-vessel downward-looking surveys which are typically conducted over multiple nights, as the area each survey can cover in a single evening is limited by duration of darkness and vessel speed.

One potential explanation for the consistent and significant differences in fish densities observed in the upper water column could be attributed to ship avoidance behaviour by cisco in the upper (<10 m) water column. This idea is supported by other recent work in the Great Lakes that have suggested that boat avoidance behaviours of pelagic fishes are especially notable in surface waters under large vessels (DuFour et al., 2018). The R/V Superior Explorer is ~17 m in length, but similar results were observed on board larger vessels (DuFour et al., 2018; Grow et al., 2020). Recent work comparing uncrewed surface vessels to larger manned acoustic vessels (USV's) found little detectable impact of vessel avoidance for fishes in waters >5 m of Lake Michigan and Huron (Evans et al., 2023). However, these USV's down-looking nearfield exclusions are of similar magnitude as traditional ship based surveys, and have surface expression that could influence fish behaviors similar to that of vessels. Also, our study was focused on a spawning aggregation of cisco which may behave differently than epilimnetic fish communities made up predominantly of alewife, as was the case in Lakes Michigan and Huron (Evans et al., 2023). If fish are avoiding surveys as they are typically conducted (e.g., from mobile ships under steam) as our results and those of others suggest (Elliott et al., 2021, Grow et al., 2020), then quota estimates could be significantly underestimated. This indicates that the use of multiple acoustic strategies, especially stationary up-looking platforms that can obtain unimpacted observation of fish with 5 m of the surface, may be necessary to thoroughly assess the impacts of vessel avoidance and account for possible differences in fish communities across systems. This may have major implications for typical acoustic surveys and management of pelagic fishes in the Great Lakes as fisheries managers rely on accurate acoustic estimates to help inform quotas and monitor the overall population trends of Great Lakes fishes.

In support of this, our study found that the up-looking acoustic platform either provided higher quota estimates or matched those from the traditional down-looking survey. However, the up-looking platform did so more efficiently in terms of use of available resources (ship and crew time) and total time required at sail. While it is important to acknowledge the platform deployments in the current study require a trade-off of reduced spatial coverage, other studies have shown that the simultaneous deployment of multiple up-looking units can provide comparable data as mobile surveys with significantly reduced demands on available resources (De Robertis et al., 2018). In the context of the current study (estimation of spawning cisco aggregation densities), mobile down-looking surveys are conducted over a ~6-h period at night, navigating in darkness, and require multiple nights of ship time during typically adverse November weather conditions. By contrast, the deployment and retrieval of an acoustic platform (or even an array of several acoustic platforms) can be done at any time of day, allowing for the work to be done in the safest conditions possible, with comparably much shorter ship time and staffing requirements. Deploying/retrieving the acoustic platform takes less than 20 min; thus, an array of three to four units could easily be deployed or retrieved over the course of a single field day in good conditions after collecting data spanning days to weeks (or even longer time periods, based on programming schedules; e.g. De Robertis et al., 2018).

The continuous sampling approach applied in our intensive sampling schedule on the stationary platform deployment indicated that the loss of accuracy associated with lower sampling frequency and less power-intensive schedules was minimal. Comparable cisco density estimates for Thunder Bay were obtained for all sampling schedules evaluated. While some variation was present among recording schedules, differences among schedules were non-significant, and much smaller than differences in fish density observed across sites and years or across the three consecutive nights of deployment at TB3 in 2020. As such, less intensive sampling schedules for stationary acoustic deployments appear to be sufficient to capture among-year differences in the timing of peak spawning migrations, allowing for longer-term deployments and offer greater opportunities for deployment in logistically challenging locations (such as the Lake Superior Shoals) or seasons (such as sampling under ice).

Another drawback of current ship-based acoustic methods is that they trade temporal detail for increased spatial coverage, and in the case of the current study, confound time with space (as different regions are surveyed on different nights). As mobile surveys are conducted over a relatively short time window (e.g., just two to three nights in November), they could easily miss spawning aggregations that take several nights to accumulate (Yule et al., 2009a,b), potentially underestimating the true spawning stock available for safe harvest and generating unreliable quota estimates. An array of multiple (3–4) stationary platforms programmed to record data over several weeks allows for both spatial and temporal coverage with reduced survey effort, providing better estimates of both the timing of peak spawn and a more representative estimate of spawner densities in a particular area generally. In the present study, this was evident in our three-night deployment at TB3 in 2020, where each night the stationary acoustic platform recorded progressively higher cisco densities as the spawn likely began to reach its peak while the ship only sampled the first night, resulting in a much lower ship-based estimate of spawner density than the platform.

While more research is necessary before prescribing lake wide correction factors to traditional mobile down-looking acoustic survey fish density estimates, for the present location, study species, and vessel, we would recommend applying a 6.7 multiplier to cisco density estimates obtained in the upper 10 m of the water column from ship-based acoustics to better account for standard survey biases. In other Great Lakes, up-looking surveys have also provided some promise in producing improved estimates of pelagic populations, specifically in the case of pelagic alewife populations in Lake Ontario (Elliott et al., 2021; Riha et al., 2017). Additionally, recent mobile up-looking surveys over a large region in Lake Superior saw similar magnitude of differences in detected fish densities in the upper water column between standard down-looking and up-looking surveys as those reported here (Grow et al., 2020). Aside from the need to test this survey method in other locations and for different species before making large scale corrections, there is also a need to further explore transducer orientation as a source of differences in backscatter readings. In a recent study on caged European whitefish (*Coregonus lavaretus* L.) of known size classes, their up-looking unit obtained consistently greater TS values than paired down-looking transducers (Wanzenböck et al., 2020). However, when the authors calculated the estimated total lengths of single targets via linear regression, they found that the up-looking TS values produced predicted lengths much closer to the actual fish lengths of fish used in the experiment. This observation provides additional support for up-looking acoustics to be utilized for obtaining accurate fish density estimates, especially when precision of the size structure of the fish community is required.

One drawback of the up-looking acoustic survey is that the exclusion zone with the largest vertical extent is expected to shift to the bottom of the water column; however, this impact is already present to some degree in down-looking acoustic estimates. Within the 10–45 m/lakebed layer, estimates of fish density between the platform and down-looking surveys were similar. The ship estimates were 1.8 times higher on average than the acoustic platform estimates, but this relationship was only significant for one location (TB2) in two years (2020 and 2021) out of seven total deployments. This higher density in the lower water column in down-looking vs. up-looking surveys could be due to the biases introduced by the transducers near-field exclusion zone being transferred to the bottom of the water column with this acoustic arrangement. However, in Lake Superior, cisco inhabit waters of 20 m on average at night (Rosinski et al., 2020) and are targeted by commercial nets in waters <10 m during their November spawning period (Yule et al., 2012). As such, this bias would be expected to be less influential than the biases introduced by the upper water column exclusion zone in traditional down-looking surveys, especially when considering pelagic species like cisco, but should be considered further for surveys of more benthic-oriented species like lake whitefish (*Coregonus clueaformis*). The evidence from this study suggests that the benefits provided by stationary up-looking surveys have the potential to overcome the uncertainties associated with the method. With further study and modifications around platform-based survey design, stationary up-looking surveys could provide low-cost and low-effort acoustic surveys of pelagic fishes in freshwater ecosystems compared to current mobile acoustic methods. Up-looking platforms appear to better characterize the upper water column than current mobile acoustic methods, with very little loss of information at greater depths (with the exception of benthic fishes).

## CRediT authorship contribution statement

**Ryan C. Grow:** Writing – original draft preparation, Conceptualization, Methodology, Software, Validation, Formal analysis, Visualization, Investigation, Funding acquisition, Data curation, Project administration. **Eric Berglund:** Data curation, Resources, Writing – review & editing. **Friedrich Fischer:** Project administration, Resources, Writing – review & editing. **Michael D. Rennie:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing.

## 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.

## Acknowledgements

Captain David Montgomery and the crew of the R/V Superior Explorer for timely and expert advice on deployment strategies and equipment. Technical assistance from Dr. Haley Viehman and Briony Hutton (Echoview), and Brian Moore and Asa Packer (Biosonics). Generous financial support from Lakehead University by way of scholarships and teaching assistantships from the Dean of Science and Environmental Studies, Department of Biotechnology, and Graduate Studies as well as a President's Award and Ontario Graduate Scholarship to Dr. Grow. This work was also supported financially through an Ontario Early Researcher Award, Natural Sciences and Engineering Research Council of Canada Discovery grant awarded to Dr. Rennie, as well as infrastructure support from the Ontario Research Fund, the Canadian Foundation of Innovation from a John Evans Leadership Fund, the Real-time Aquatic Ecosystem Observation Network to Dr. Rennie, and from the Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health. We would also like to thank Dr. Lars Rudstam, Dr. Brian Shuter, and Dr. Rob Mackereth for their insights and reviews of the earlier versions of the manuscript. We also thank the Guest Editor and two anonymous reviewers for their thoughtful and detailed editorial contributions to the manuscript.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2024.102456.

## References

Aglen, A., Engås, A., Huse, I., Michalsen, K., Stensholt, B.K., 1999. How vertical fish distribution may affect survey results. ICES J. Mar. Sci. 56, 345–360. https://doi.org/10.1006/jmsc.1999.0449.

Barange, M., Hampton, I., Soule, M., 1996. Empirical determination of in situ target strengths of three loosely aggregated pelagic fish species. ICES J. Mar. Sci. 53, 225–232. https://doi.org/10.1006/jmsc.1996.0026.

Boswell, K.M., Wilson, M.P., MacRae, P.S., Wilson, C.A., Cowan Jr, J.H., 2010. Seasonal estimates of fish biomass and length distributions using acoustics and traditional nets to identify estuarine habitat preferences in Barataria Bay, Louisiana. Mar. Costal Fish. 2, 83–97. https://doi.org/10.1577/C09-022.1.

Davison, P., Lara-Lopez, A., Anthony Koslow, J., 2015. Mesopelagic fish biomass in the southern California current ecosystem. Deep Sea Res. 2 Top Stud. Oceanogr. 112, 129–142. https://doi.org/10.1016/j.dsr2.2014.10.007.

De Robertis, A., Levine, R., Wilson, C.D., 2018. Can a bottom-moored echo sounder array provide a survey-comparable index of abundance? Can. J. Fish. Aquat. Sci. 75, 629–640. https://doi.org/10.1139/cjfas-2017-0013.

DuFour, M.R., Mayer, C.M., Qian, S.S., Vandergoot, C.S., Kraus, R.T., Kocovsky, P.M., Warner, D.M., 2018. Inferred fish behavior its implications for hydroacoustic surveys in nearshore habitats. Fish. Res. 199, 63–75. https://doi.org/10.1016/j.fishres.2017.11.018.

Elliott, C.W., Holden, J., Connerton, M.J., Weidel, B.C., Tufts, B.L., 2021. Stationary hydroacoustics demonstrates vessel avoidance biases during mobile hydroacoustic surveys of alewife in Lake Ontario. J. Great Lakes Res. 47, 514–521. https://doi.org/10.1016/j.jglr.2021.01.013.

Evans, T.M., Rudstam, L.G., Sethi, S.A., Warner, D.M., Hanson, S.D., Turschak, B., Farha, S.A., Barnard, A.R., Yule, D.L., DuFour, M.R., O'Brien, T.P., McDonnell, K.N., Watkins, J.M., Koproski, S.R., Wells, S.E., Dieter, P.M., Kocher, E., Roberts, J.J., Senczyszyn, S.A., Esselman, P.C., 2023. Fish avoidance of ships during acoustic surveys tested with quiet uncrewed surface vessels. Fish. Res. 267, 106817. https://doi.org/10.1016/j.fishres.2023.106817.

Fisch, N.C., Bence, J.R., Myers, J.T., Berglund, E.K., Yule, D.L., 2019a. A comparison of age- and size-structured assessment models applied to a stock of cisco in Thunder Bay, Ontario. Fish. Res. 209, 86–100.

Fisch, N.C., Bence, J.R., Myers, J.T., Berglund, E.K., Yule, D.L., 2019b. Evaluating the sustainability of a cisco fishery in Thunder Bay, Ontario, under alternative harvest policies. N. Am. J. Fish Manag. 39, 543–559. https://doi.org/10.1002/nafm.10290.

Foote, K.G., 1980. Importance of the swimbladder in acoustic scattering by fish: a comparison of gadoid and mackerel target strengths. J. Acoust. Soc. Am. 67, 2084–2089. https://doi.org/10.1121/1.384452.

Foote, K.G., 1987. Fish target strengths for use in echo integrator surveys. J. Acoust. Soc. Am. 82, 981–987. https://doi.org/10.1121/1.395298.

Grow, R.C., Hrabik, T.R., Yule, D.L., Matthias, B.G., Myers, J.T., Abel, C., 2020. Spatial and vertical bias in down-looking ship-based acoustic estimates of fish density in Lake Superior: lessons learned from multi-directional acoustics. J. Great Lakes Res. 46, 1639–1649. https://doi.org/10.1016/j.jglr.2020.08.010.

Guillard, J., Balay, P., Colon, M., Brehmer, P., 2010. Survey boat effect on YOY fish schools in a pre-alpine lake: evidence from multibeam sonar and split-beam echosounder data. Ecol. Freshw. Fish 19, 373–380. https://doi.org/10.1111/j.1600-0633.2010.00419.x.

Guillard, J., Vergès, C., 2007. The repeatability of fish biomass and size distribution estimates obtained by hydroacoustic surveys using various sampling strategies and statistical analyses. Int. Rev. Hydrobiol. 92, 605–617. https://doi.org/10.1002/iroh.200710948.

Haslett, R.W.G., 1969. The target strengths of fish. J. Sound Vib. 9, 181–191. https://doi.org/10.1016/0022-460X(69)90026-1.

Hoffman, J.C., Bonzek, C.F., Latour, R.J., 2009. Estimation of bottom trawl catch efficiency for two demersal fishes, the Atlantic croaker and white perch, in Chesapeake Bay. Mar. Coast. Fish. 1, 255–269. https://doi.org/10.1577/c08-048.1.

Hrabik, T., Schreiner, D., Balge, M., Geving, S., 2006. Development of a hydroacoustic survey design to quantify prey fish abundance in the minnesota waters of lake superior. Min. Dept. Nat. Res., Invest. Rep 530. https://www.leg.mn.gov/docs/2006/other/060320.pdf.

Kotwicki, S., Ianelli, J., Punt, A.E., Horne, J.K., De Robertis, A., Ianelli, J.N., 2013. Combining bottom trawl and acoustic data to model acoustic dead zone correction and bottom trawl efficiency parameters for semipelagic species. Can. J. Fish. Aquat. Sci. 70, 208–219. https://doi.org/10.1139/cjfas-2012-0321.

Kubečka, J., Hohausová, E., Matěna, J., Peterka, J., Amarasinghe, U.S., Bonar, S.A., Hateley, J., Hickley, P., Suuronen, P., Tereschenko, V., Welcomme, R., Winfield, I.J., 2009. The true picture of a lake or reservoir fish stock: a review of needs and progress. Fish. Res. https://doi.org/10.1016/j.fishres.2008.09.021.

Love, R.H., 1971. Measurements of fish target strength: a review. Fish. Bull. 69, 703–715.

Mello, L.G.S., Rose, G.A., 2009. The acoustic dead zone: theoretical vs. empirical estimates, and its effect on density measurements of semi-demersal fish. ICES J. Mar. Sci. 66, 1364–1369. https://doi.org/10.1093/icesjms/fsp099.

Ministry of Natural Resources and Forestry Upper Great Lakes Management Unit Lake Superior, 2023. Lake Superior Commercial Fishing Summary for 2022. Queen's Printer for Ontario, Ontario, Canada.

Parker-Stetter, S.L., Rudstam, L.G., Sullivan, P.J., Warner, D.M., 2009. Standard operating procedures for fisheries acoustic surveys in the Great Lakes. Great Lakes Fish. Comm. Spec Pub.

Pratt, T.C., Gorman, O.T., Mattes, W.P., Myers, J.T., Quinlan, H.R., Schreiner, D.R., Seider, M.J., Sitar, S.P., Yule, D.L., Yurista, P.M., 2016. The state of Lake Superior in 2011. Great Lakes fishery commission. Spec. Publ. 16. https://doi.org/10.13140/RG.2.1.1715.8005.

Qiao, Y., Tang, X., Brosse, S., Chang, J., 2006. Chinese sturgeon (*Acipenser sinensis*) in the Yangtze River: a hydroacoustic assessment of fish location and abundance on the last spawning ground. J. Appl. Ichthyol. 22, 140–144.

R Core Team, 2020. R: a language and environment for statistical computing.

Riha, M., Walsh, M.G., Connerton, M.J., Holden, J., Weidel, B.C., Sullivan, P.J., Holda, T. J., Rudstam, L.G., 2017. Vertical distribution of alewife in the Lake Ontario offshore: implications for resource use. J. Great Lakes Res. 43, 823–837. https://doi.org/10.1016/j.jglr.2017.07.007.

Rosinski, C.L., Vinson, M.R., Yule, D.L., 2020. Niche partitioning among native ciscoes and nonnative rainbow smelt in Lake superior. Trans. Am. Fish. Soc. 149, 184–203. https://doi.org/10.1002/tafs.10219.

Rudstam, L.G., Parker-Stetter, S.L., Sullivan, P.J., Warner, D.M., 2009. Towards a standard operating procedure for fishery acoustic surveys in the Laurentian Great Lakes, North America. ICES J. Mar. Sci. 1391–1397. https://doi.org/10.1093/icesjms/fsp014.

Sampson, D.B., 2014. Fishery selection and its relevance to stock assessment and fishery management. Fish. Res. 158, 5–14. https://doi.org/10.1016/j.fishres.2013.10.004.

Simmonds, J., MacLennan, D., 2005. Fisheries Acoustics: Theory and Practice. John Wiley & Sons.

Stockwell, J.D., Yule, D.L., Hrabik, T.R., Adams, J.V., Gorman, O.T., Holbrook, B.V., 2007. Vertical distribution of fish biomass in Lake Superior: implications for day bottom trawl surveys. N. Am. J. Fish Manag. 27, 735–749. https://doi.org/10.1577/m06-116.1.

Stockwell, J.D., Ebener, M.P., Black, J.A., Gorman, O.T., Hrabik, T.R., Kinnunen, R.E., Mattes, W.P., Oyadomari, J.K., Schram, S.T., Schreiner, D.R., Seider, M.J., Sitar, S.P., Yule, D.L., 2009. A synthesis of cisco recovery in lake superior: implications for native fish rehabilitation in the Laurentian Great Lakes. N. Am. J. Fish Manag. 29, 626–652. https://doi.org/10.1577/m08-002.1.

Totland, A., Johansen, G.O., Godø, O.R., Ona, E., Torkelsen, T., 2009. Quantifying and reducing the surface blind zone and the seabed dead zone using new technology. ICES J. Mar. Sci. 66, 1370–1376. https://doi.org/10.1093/icesjms/fsp037.

Vinson, M.R., Evrard, L.M., Gorman, O.T., Yule, D.L., 2016. Status and trends in the Lake Superior fish community, 2015. glfc.int 10–20. https://www.usgs.gov/publications/status-and-trends-lake-superior-fish-community-2015.

Wanzenböck, J., Kubecka, J., Sajdlova, Z., Frouzova, J., 2020. Hydroacoustic target strength vs. fish length revisited: Data of caged, free-swimming European whitefish (*Coregonus lavaretus L.*) suggest a bi-phasic linear relationship under a limited range of tilt angles. Fish. Res. 229. doi:10.1016/j.fishres.2020.105620.

Warner, D.M., Kiley, C.S., Claramunt, R.M., Clapp, D.F., 2008. The influence of alewife year-class strength on prey selection and abundance of age-1 Chinook salmon in Lake Michigan. Trans. Am. Fish. Soc. 137, 1683–1700. https://doi.org/10.1577/T07-130.1.

Warner, D.M., Claramunt, R.M., Schaeffer, J.S., Yule, D.L., Hrabik, T.R., Pientka, B., Rudstam, L.G., Holuszko, J.D., O'Brien, T.P., 2012. Relationship between mid-water trawling effort and catch composition uncertainty in two large lakes (Huron and Michigan) dominated by alosines, osmerids, and coregonines. Fish. Res. 123–124, 62–69. https://doi.org/10.1016/j.fishres.2011.11.021.

Yule, D.L., Adams, J.V., Stockwell, J.D., Gorman, O.T., 2007. Using multiple gears to assess acoustic detectability and biomass of fish species in Lake Superior. N. Am. J. Fish Manag. 27, 106–126. https://doi.org/10.1577/m06-090.1.

Yule, D.L., Addison, P.A., Evrard, L.M., Cullis, K.I. and Cholwek, G.A., 2009. 2008 spawning cisco investigations in the Canadian waters of Lake Superior. In: US Geological Survey Technical Report 4-08. https://www.researchgate.net/publication/264890503.

Yule, D.L., Schreiner, D.R., Addison, P.A., Seider, M.J., Evrard, L.M., Geving, S.A., Quinlan, H.R., 2012. Repeat surveys of spawning cisco (*Coregonus artedi*) in western Lake Superior: timing, distribution and composition of spawning stocks. Adv. Limnol. 63, 65–87. https://doi.org/10.1127/advlim/63/2012/65.

Yule, D., Stockwell, J., Evrard, L., Cholwek, G., 2006. Comparison of commercial landings of cisco to acoustic estimates of abundance in Thunder Bay and Black Bay, Ontario. U.S. Geol. Survey 1–60. https://www.researchgate.net/publication/265984530.

Yule, D.L., Stockwell, J.D., Schreiner, D.R., Evrard, L.M., Balge, M., Hrabik, T.R., 2009b. Can pelagic forage fish and spawning cisco (*Coregonus artedi*) biomass in the western arm of Lake Superior be assessed with a single summer survey? Fish. Res. 96, 39–50. https://doi.org/10.1016/j.fishres.2008.09.012.

Yurista, P.M., Yule, D.L., Balge, M., VanAlstine, J.D., Thompson, J.A., Gamble, A.E., Hrabik, T.R., Kelly, J.R., Stockwell, J.D., Vinson, M.R., 2014. A new look at the Lake Superior biomass size spectrum. Can. J. Fish. Aquat. Sci. 71, 1324–1333. https://doi.org/10.1139/cjfas-2013-0596.