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Sparse targets in hydroacoustic surveys: Balancing quantity and quality of *in situ* target strength data

Mark R. DuFour[a,*], Christine M. Mayer[a], Patrick M. Kocovsky[b], Song S. Qian[a], Dave M. Warner[c], Richard T. Kraus[b], Christopher S. Vandergoot[b]

[a] *University of Toledo, Department of Environmental Sciences, Lake Erie Center, 6200, Bayshore Rd., Oregon, OH 43616, USA*
[b] *U.S. Geological Survey, Great Lakes Science Center, Lake Erie Biological Station, 6100 Columbus Ave., Sandusky, OH 44870, USA*
[c] *U.S. Geological Survey, Great Lakes Science Center, 1451 Green Rd., Ann Arbor, MI 48105, USA*

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ABSTRACT

Hydroacoustic sampling of low-density fish in shallow water can lead to low sample sizes of naturally variable target strength (TS) estimates, resulting in both sparse and variable data. Increasing maximum beam compensation (BC) beyond conventional values (i.e., 3 dB beam width) can recover more targets during data analysis; however, data quality decreases near the acoustic beam edges. We identified the optimal balance between data quantity and quality with increasing BC using a standard sphere calibration, and we quantified the effect of BC on fish track variability, size structure, and density estimates of Lake Erie walleye (*Sander vitreus*). Standard sphere mean TS estimates were consistent with theoretical values (−39.6 dB) up to 18-dB BC, while estimates decreased at greater BC values. Natural sources (i.e., residual and mean TS) dominated total fish track variation, while contributions from measurement related error (i.e., number of single echo detections (SEDs) and BC) were proportionally low. Increasing BC led to more fish encounters and SEDs per fish, while stability in size structure and density were observed at intermediate values (e.g., 18 dB). Detection of medium to large fish (i.e., age-2+ walleye) benefited most from increasing BC, as proportional changes in size structure and density were greatest in these size categories. Therefore, when TS data are sparse and variable, increasing BC to an optimal value (here 18 dB) will maximize the TS data quantity while limiting lower-quality data near the beam edges.

1. Introduction

Fisheries researchers often rely on hydroacoustic estimates of fish size and abundance (MacLennan, 1990; MacLennan and Holiday, 1996; Rose, 2003; Simmonds and MacLennan, 2005); however, this technique's effectiveness can be limited when sampling low-density fish in shallow-water, resulting in a small sample size (Kubecka and Wittingerova, 1998; Knudsen and Saegrov, 2002). In addition, TS estimates are highly variable (McClatchie et al., 1996), therefore, at times estimates may be based on both sparse and variable data. Conventional data analysis methods (Rudstam et al., 2009; Parker-Stetter et al., 2009; Kocovsky et al., 2013) restrict data to a subset of high quality (i.e., accurate and precise) TS estimates collected near the acoustic beam axis, within the 3 dB beam width (i.e., 6 dB two-way beam width; Simmonds, 1984; Simmonds and MacLennan, 2005). While the practice of limiting data quantity is intended to ensure quality, the net effect may reduce accuracy and precision of population level estimates due to small sample size, especially when fish are sparsely distributed. Therefore, when TS data are already limited, it may be beneficial to use more permissive data analysis procedures to balance quantity and quality of TS data.

Increasing maximum beam compensation (e.g., greater than 3 dB beam width) can increase quantity of TS data (Rudstam et al., 2009); however, this may result in reduced data quality (Ehrenberg and Torkelson, 1996). Maximum beam compensation (BC) controls the maximum allowable adjustment applied to single echo detections (SEDs) measured off the acoustic beam axis. SEDs measured off-axis have lower TS measurements than similar SEDs measured on-axis due to phase differences in the received sound pulse (i.e., directivity loss). Off-axis SED TS-measurements are adjusted (i.e., compensated) to theoretical on-axis values using a beam compen-

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[*] Corresponding author.
E-mail addresses: mark.dufour@rockets.utoledo.edu, mrdufour4265@gmail.com (M.R. DuFour), christine.mayer@utoledo.edu (C.M. Mayer), pkocovsky@usgs.gov (P.M. Kocovsky), song.qian@utoledo.edu (S.S. Qian), dmwarner@usgs.gov (D.M. Warner), rkraus@usgs.gov (R.T. Kraus), cvandergoot@usgs.gov (C.S. Vandergoot).

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sation function which describes the acoustic beam pattern and theoretical directivity loss (Reynisson, 1999). Increasing BC uses a larger portion of the acoustic beam, resulting in a larger sampled volume and the inclusion of additional SEDs. However, inconsistencies between theoretical and realized acoustic beam patterns (Simmonds, 1984), as well as small-angle approximation errors caused by transducer motion (Furusawa and Sawada, 1991) and low signal-to-noise ratios (Kieser et al., 2000) can cause measurement errors in compensated TS estimates. These measurement errors can result in incorrect compensation of off-axis targets, the degree of which may increase with distance from the acoustic beam axis.

TS data are critical to estimating size and abundance of low-density fish using echo-counting; however, TS data are naturally variable, affecting accuracy and precision of these estimates. Natural TS variability is caused by changes in orientation and physiological characteristics affecting the swim bladder (Ona, 1990; McClatchie et al., 1996; Hazen and Horne, 2004; Frouzova et al., 2005), which reflects 90% of the sound energy contributing to TS estimates (Foote, 1980). Echo-counting relies on SEDs, where the acoustic characteristics of individual fish are described by multiple grouped SEDs (i.e., a fish track; Kieser and Mulligan, 1984; Ehrenberg and Torkelson, 1996). Increasing TS data quantity using more permissive BC can increase the number of SEDs per fish track and the number of fish tracks, thereby providing more information to estimate individual fish size, population size structure, and density. Although increasing TS data quantity may introduce additional compensation related variability (i.e., measurement error), it is not clear if this extra variation contributes substantially to total variability in fish size estimates. Therefore, identifying the effect of BC on variability of fish size estimates, and estimates of population size structure and density will help determine the optimal balance between TS data quantity and quality.

Lake Erie walleye (*Sander vitreus*) is an economically and ecologically important species (Locke et al., 2005) that presents a challenging scenario for hydroacoustic quantification. Walleye migrate throughout Lake Erie and into Lakes St. Clair and Huron during the spring and summer and return to Ohio waters of western Lake Erie during autumn (Wang et al., 2007). To date, the population has been monitored primarily through an inter-agency gill net survey; however, researchers are exploring the integration of hydroacoustic sampling. During the primary fall sampling period, the population occupies a large expanse of relatively shallow water habitats (<15 m; Pandit et al., 2013), resulting in sparse TS data for estimating size structure and density.

Our goal was to identify the optimal BC to estimate walleye size structure and density using echo-counting, balancing the benefits of data quantity against the costs to quality. First, to identify the contribution of measurement error, we quantified the BC effect on quantity and quality of TS estimates using a standard sphere. Next, we determined the effect of BC on in-lake survey data by (1) quantifying the relative contribution of BC to TS variability in fish tracks, and (2) identifying the BC effect on population size structure and density estimates. These steps optimized the use of collected hydroacoustic data to determine walleye size structure and density.

2. Methods

2.1. Beam compensation effect on TS measurement error

We performed a transducer calibration to measure the change in quantity and quality of TS estimates with increasing BC (Foote et al., 1987). We collected data with a BioSonics DTX split-beam hydroacoustic system and a 210 kHz transducer (3 dB beam width = 6.5°) using a 0.2 ms pulse duration and 15 pings per second (pps) from a 36.4 mm diameter tungsten carbide sphere, with theoretical TS = −39.6 dB at 1460 m/s speed of sound through ~15 °C water throughout the acoustic beam. The sphere was positioned approximately 5 m below the face of the transducer. We held the calibration sphere near the acoustic beam axis to assess on axis sensitivity, and moved it throughout the beam to asses beam pattern consistency and beam compensation accuracy. Raw data were imported and analyzed in Echoview version 5 software (Echoview Software Pty. Ltd., Hobart, Australia). SED filter criteria were set to match those recommended in the Great Lakes Standard Operating Procedures (Parker-Stetter et al., 2009), except BC, which was increased to the maximum (35 dB) allowed for BioSonics data. The distribution of SEDs among transducer beam quadrants was not even; therefore, we took a random subset (N = 500) from each quadrant (1–4; Fig. 1A). This reduced the total number of SEDs included in the calibration from 5942 to 2000, with 500 randomly sampled from each quadrant. From the subset of SED, we obtained SED TS estimates within 7 BC intervals (0.00–6.49 dB, 6.50–9.49 dB, 9.50–12.49 dB, 12.50–15.49 dB, 15.50–18.49 dB, 18.50–25.49 dB, and 25.50–35.00 dB). We transformed SED TS estimates into backscattering cross-section (σ_{bs}) values to calculate mean and standard deviation within BC intervals. Standard deviation of σ_{bs} was converted to standard deviation in dB using the delta method described in Crockett et al. (2006). We counted the number of SEDs within each BC interval, and summed these to show cumulative increase with BC.

We estimated sample beam angle (i.e., wedge angle) associated with the maximum BC in each BC interval. For each BC interval, we subset the calibration SEDs by the maximum amount of correction applied (i.e., 6, 9, 12, 15, 18, 25, and 35 dB), corresponding with the maximum BC from each interval. Next, we took the absolute value of estimated major and minor axis angles and summed the maximum values. This produced a maximum estimated sample wedge angle for each BC interval, used to estimate water volume sampled. Estimated sample wedge angles matched those displayed on beam pattern polar plots provided by BioSonics factory calibrations. For the following survey data, we calculated wedge volume sampled in Echoview using wedge angles estimated from calibration data.

2.2. Hydroacoustic and gill net survey description

We compared sample data from paired gill net and hydroacoustic surveys to understand the effect of BC on TS variability and density estimates. We performed 21 paired sampling events at 19 locations in Lake Erie's western basin and Sandusky sub-basin during the fall of 2012 (Fig. 2A and B). At each site we sampled fish with overnight multi-filament gill net sets of approximately 396.5 m by 1.8 m with stretch meshes ranging from 51 to 127 mm. Overnight gill nets were set during late afternoon prior to sunset and lifted in the early morning after sunrise to encompass crepuscular foraging periods. Gill nets were suspended 2 m below the surface to target walleye and reduce bycatch following previously established survey protocols for walleye assessment (Pandit et al., 2013). Catches were identified to species, and total length (TL) was measured to the nearest mm. Hydroacoustic data were collected during the daytime; on days adjacent to overnight gill net sets. Three sites were collected while the gill nets were soaking, and sixteen sites were collected either prior to setting or after gill nets were lifted, with average length of time between gill net soak and hydroacoustic sampling ~3.5 h (min 0 and max 7 h). Hydroacoustic sampling at two sites was delayed to the day after, ~29 h after the gill nets were lifted. We sampled 3–8 1000-m transects at each sample site (Fig. 2C). We used a down-facing transducer deployed from a BioSonics towed body at a depth of 1 m alongside the vessel, and sampled transects at ~8 km/h. We used the same data collection settings described above including 15 pps. Sampling speed and pulse rate produced ~7 pings per meter of transect, while sampling

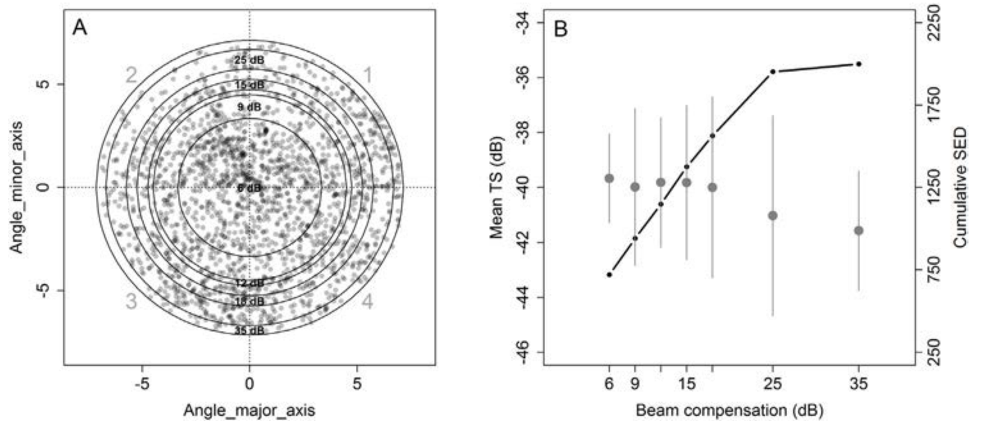

Fig. 1. Results from calibration including A) subset of single echo detection (gray dots) locations within the acoustic beam cross-section, associated beam compensation (BC) interval (black circles), and beam quadrants (1–4), and B) summary of single echo detection target strength (TS) estimate quantity and quality within BC intervals. Large dots represent mean TS estimate, while vertical lines correspond to 1 standard deviation from the mean. The ascending dot interrupted black line represents the cumulative increase in single echo detections with increasing BC.

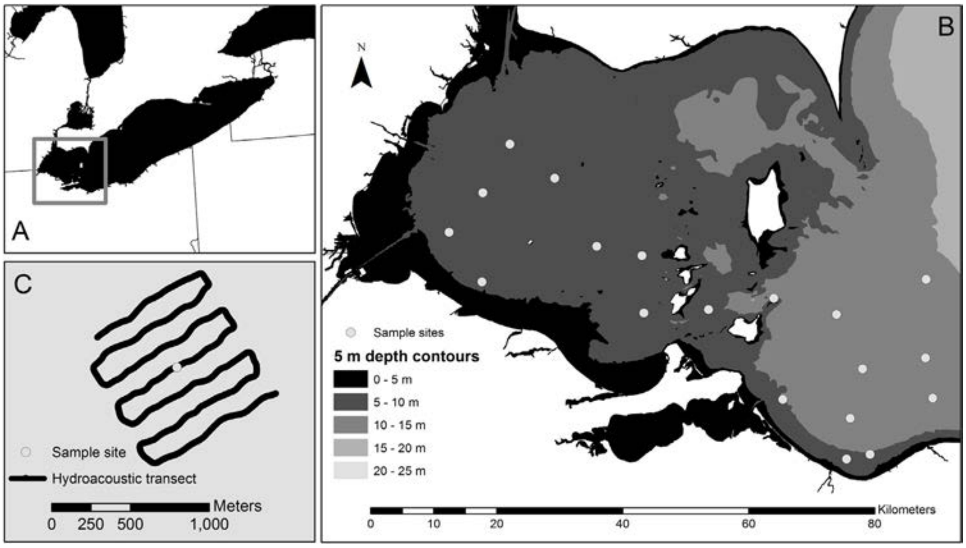

Fig. 2. Survey location in A) western Lake Erie, including B) 19 sampling sites in Ohio waters, and C) multiple hydroacoustic transects per sampling event.

time at each site ranged from ~30 min to 1 h. Transducer position and acoustic nearfield excluded the first 1.5 m of water from analysis, while the acoustic bottom dead zone excluded an additional 0.3 m near the lake floor.

2.3. Beam compensation contribution to TS variability in fish tracks

We analyzed hydroacoustic survey data with Echoview software over a range of BC to quantify its relative contribution to TS variability in fish tracks. We were interested primarily in large targets; therefore, restricted compensated SEDs to greater than −55 dB. This excluded smaller fish, invertebrates, and other reverberation sources from the fish track analyses. In addition, this setting was well above the uncompensated TS noise at 1 m depth (mean = −127 dB); therefore, signal-to-noise ratio was consistently high and not a concern in detecting SEDs near the acoustic beam edge. Noise estimates were collected over the same survey area and season during the following year, 2013. We analyzed the 21 sample sites 7 separate times using Great Lakes Standard Operating Procedure (Parker-Stetter et al., 2009) SED filter settings while increasing BC each time (i.e., 6, 9, 12, 15, 18, 25 and 35 dB). Individual fish were identified using fish tracking algorithms, which group SEDs based on user-defined settings that restrict or permit search and inclusion criteria (Myriax, 2010). We used permissive settings to define a fish track, including 1 minimum number of SEDs and 1 minimum number of pings per track, and a 2 ping maximum gap between SEDs. However, we used restrictive search and inclusion settings for SEDs within a fish track, including 4D track detection algorithms where Alpha was set at 0.6-major axis, 0.6-minor axis, and 0.5-range (m), and Beta was set at 0.4-major axis, 0.4-minor axis, and 0.5-range (m). Target gates were restricted to 2 m for major and minor axis directions, with a range of 0.2 m and 0%-missed ping expansion. We also adjusted the weighting factors to 50%-range, 20%-major axis, and 10%- each for minor axis, TS, and ping gap. We estimated fish tracks under these settings for each BC scenario, which provided consistent visual agreement between echograms and automated fish tracks. Summaries of fish tracks from each BC analysis included standard deviation of σ_{bs}, mean TS (dB), and number of SEDs. We included only fish tracks from a size range encompassing age-1+ walleye (i.e., $300 < \mathrm{TL} < 910$ mm, Pandit et al., 2013) corresponding to $-36 < \text{mean TS} < -26.6$ dB. We describe fish size determination from TS below (see Section 2.4).

We used a Bayesian hierarchical ANCOVA model (Eq. (1); Qian and Shen 2007) to partition sources of variation in fish tracks between BC, mean TS (dB), number of SEDs per fish track, and residual variation. Using traditional fixed-effect ANCOVA, designed for hypothesis testing, would be inappropriate for our data set (i.e., unbalance data with assumed correlation among observations) and objective, leading to biased mean squared errors and F-statistics (McCulloch, 2005). However, by assuming correlation among observations and "batching" coefficients together under prior distributions, Bayesian hierarchical methods allow us to summarize the data and identify contributions to total variation without bias (Gelman, 2005).

$$\begin{aligned} & y_{ij} \sim lognormal\left(\mu_{ij}, \tau\right) \\ & \mu_{ij} = \beta 1_j + \beta 2_j * TS_{mean} + \beta 3_j * N_{\mathrm{SED}} \\ & \beta 1_j \sim normal\left(\mu.\beta 1, \tau.\beta 1\right) \\ & \beta 2_j \sim normal\left(\mu.\beta 2, \tau.\beta 2\right) \\ & \beta 3_j \sim normal\left(\mu.\beta 3, \tau.\beta 3\right) \end{aligned} \quad (1)$$

where y_{ij} represent log-normally distributed standard deviations of individual fish tracks (measured in σ_{bs}) from all acoustic analyses and index value j represents the seven separate BC analyses. The $\beta 1_j$ represents the BC specific effects (i.e., intercepts) on standard deviation of σ_{bs}, and $\beta 2_j$ and $\beta 3_j$ are the BC specific effects (i.e., slopes) between mean TS and number of SEDs per fish track and standard deviation of σ_{bs}, respectively. BC specific parameters ($\beta 1_j$, $\beta 2_j$, and $\beta 3_j$) were characterized by normal distributions with low-information hyper-priors for mean ($\mu.\beta; normal(0, 0.125)$) and standard deviation ($\tau.\beta$; uniform$(0, 0.125)$). Similarly, we described residual variation in the standard deviation of fish tracks as τ over the 0–0.125 range of a uniform distribution. We reported variance components and trends for each factor of interest.

2.4. Beam compensation effect on size structure

To compare length distribution of fish from gill nets with hydroacoustic results, we pooled length data collected from all gill net samples and converted TL to TS (dB) using Love's (1971) dorsal-aspect multi-species equation (Eq. (2)). We used Love's (1971) equation as an approximation of the TL and TS relationship as there were no empirical relationships developed for Lake Erie's large-target fish community.

$$TS = 19.2 * \log_{10}(TL) + 0.9 * \log_{10}(\lambda) - 62.3 \quad (2)$$

where *TS* is target strength in dB, *TL* is total length in cm, and λ is frequency specific wavelength in m. Fish were grouped into 20-mm total length and 0.5-dB TS bins and histograms were plotted for comparison. We grouped fish tracks under each BC analysis into 0.5-dB TS bins using mean TS. We selected gill net and hydroacoustic data from a range over which both gears sampled the fish community with minimal selectivity and catchability biases (Warner et al., 2002; Vandergoot et al., 2011; i.e., $300 < \mathrm{TL} < 600$ mm; $-36 <$ mean TS < -30 dB). TS histograms from gill net and each BC analysis (i.e., 6, 9, 12, 15, 18, 25, and 35) were plotted for visual comparison.

We tested the difference between histograms with the *clus.lf* function in the R package *fishmethods* (Nelson, 2014). This is a variation on the Kolmogorov-Smirnov test based on pairwise comparisons between histograms from sample groups, or in our case different sample methods. The test statistic (D_s; Eq. (3)) is based on the cumulative length frequency distributions ($S_1(X)$ and $S_2(X)$). A permutation test is used to generate a distribution of test statistics for comparison with the observed D_s, and to determine the probability of similarity between groups. Sample sites were treated as the experimental unit, and we tested for differences between sampling methods (i.e., Gill nets, 6, 9, 12, 15, 18, 25, and 35) with 12 0.5-dB size classes ranging from −36 to −30 dB (defined in Section 2.5). We generated 1000 permuted test statistics for comparison with $\mathrm{D_s}$. An explicit description of *clust.lf* methods and terminology can be found in Nelson (2014).

$$D_s = max|S_1(X) - S_2(X)| \quad (3)$$

2.5. Beam compensation effect on density

We compared fish density estimates to identify the effect of BC on small, medium, and large size groups across the survey. We estimated densities using echo-counting methods (Kieser and Mulligan, 1984; Ehrenberg and Torkelson, 1996), where fish track counts were divided by the acoustically sampled water volume (i.e., wedge volume). Fish track data were categorized as small, medium, and large targets based on mean TS estimates. Small targets reflected the smallest range of fish available to gill nets (i.e., $300 < \mathrm{TL} < 400$ mm; $-36 <$ mean TS < -33.5 dB), while medium targets represented the larger range of fish available to gill nets (i.e., $400 < \mathrm{TL} < 600$ mm; $-33.5 <$ mean TS < -30 dB). Large targets represent those fish primarily unavailable to gill nets (i.e., $\mathrm{TL} > 600$ mm; mean TS > -30 dB) due to lower size selectivity of the largest fish in the population (Vandergoot et al., 2011). Site-specific counts of small, medium, and large targets were divided by wedge volume sampled (scaled to 10,000 m^3) within each site to generate site-specific density estimates. Site-specific estimates were averaged to produce an overall volumetric density estimate (fish/10,000 m^3). We repeated this for each BC analysis resulting in seven volumetric density estimates for each size group. We then visually compared the change in density with increasing BC.

2.6. Encounter rates and sample effort

We estimated the change in encounter rates with increased sampling effort (i.e., number of sampled transects) for each size group using the 6 dB BC analysis data and a Monte Carlo simulation. We separated site-specific sample data into 1000 m intervals, and coded each interval as 1 or 0, dependent on whether a fish (i.e., mean TS > -36 dB) was encountered or not. To estimate encounter rate for sampling only one transect at a site, we randomly selected a site and from that site randomly selected one interval (coded 1 or 0), representing a single sample. To estimate encounter rate for sampling two or more transects at a site, we randomly selected a site and from that site randomly selected two or more transects (up to 8). If the group of transects encountered a fish we coded this as 1, if not then 0, representing a single sample. We repeated this process 100 times generating 100 samples for each sampling scenario (1–8 transects). We estimated encounter rate for each sampling scenario by dividing the number of samples encountering fish by the total number of samples (100). We repeated this process 1000 times for each scenario (1–8 transects), and performed the entire simulation for each size group of fish. We report the mean encounter rates from 1000 simulated values.

3. Results

3.1. Beam compensation effect on TS measurement error

As measured from a tungsten calibration sphere, target strength quantity and quality showed an inverse relationship over a range of BC (6–35 dB) (Table 1; Fig. 1B). The cumulative quantity of TS data increased from 721 SEDs at 6 BC to 2000 SEDs at 35 BC. The rate at which SEDs were added (SEDs/dB BC) gradually decreased between 6 and 25 BC, dropping substantially between 25 and 35 BC. The quality (accuracy and precision) of TS estimates declined slightly with increasing BC. Mean TS estimates were accurate at 6

Table 1
Summary statistics of single echo detection target strength estimates within seven beam compensation intervals. TS mean comparable to theoretical value of standard sphere under calibration conditions described in methods, −39.6 dB.

BC range	BC bin	σ_{bs} mean	σ_{bs} sd	TS mean	TS sd	SEDs	Cumulative SEDs	SED rate
0–6	6	1.08E−04	1.74E−05	−39.67	1.61	721	721	120.17
6–9	9	1.01E−04	2.88E−05	−39.98	2.86	220	941	104.56
9–12	12	1.04E−04	2.47E−05	−39.81	2.37	208	1149	95.75
12–15	15	1.04E−04	2.93E−05	−39.82	2.81	227	1376	91.73
15–18	18	1.00E−04	3.30E−05	−39.99	3.30	188	1564	86.89
18–25	25	7.89E−05	2.87E−05	−41.03	3.64	389	1953	78.12
25–35	35	6.97E−05	1.52E−05	−41.57	2.18	47	2000	57.14

Table 2
Survey-scale results of sampling characteristics, single echo detections per fish, number of fish tracks, and density (fish/10,000 m^3) estimates for three size groups over a range of beam compensations.

BC (dB)	Sample Wedge Angle (°)	Sample Volume[a]	Mean SED/Fish Track	Fish Track Counts	Mean Density	% Change
			Small (−36 to −33.5 dB)			
6	6.5	54.0	2.1	87	1.8	0%
9	8.1	67.1	2.5	134	2.2	22%
12	9.5	78.6	2.8	158	2.1	17%
15	10.5	86.9	3.0	180	2.1	18%
18	11.5	95.3	3.2	191	2.0	12%
25	13.4	110.8	3.7	244	2.1	18%
35	14.3	118.2	4.0	284	2.4	32%
			Medium (−33.5 to −30 dB)			
6	6.5	54.0	2.1	44	0.9	0%
9	8.1	67.1	2.3	67	1.0	13%
12	9.5	78.6	2.5	84	1.1	30%
15	10.5	86.9	2.7	97	1.1	29%
18	11.5	95.3	2.9	113	1.2	33%
25	13.4	110.8	3.4	148	1.4	57%
35	14.3	118.2	3.7	165	1.4	63%
			Large (−30 to −24 dB)			
6	6.5	54.0	2.1	14	0.3	0%
9	8.1	67.1	2.3	29	0.5	69%
12	9.5	78.6	2.8	35	0.4	54%
15	10.5	86.9	3.0	44	0.5	87%
18	11.5	95.3	3.7	46	0.5	97%
25	13.4	110.8	4.1	58	0.6	103%
35	14.3	118.2	4.3	77	0.7	147%

[a] 10,000's of m^3.

Table 3
Comparison of target strength (TS) histograms generated from gill net and seven hydroacoustic beam compensation analyses using *clust.lf* function in the R based *fishmethods* package. The number above the diagonal are the D_s statistic calculated for comparison with D_s distribution generated through a randomization procedure. Numbers below the diagonal are the proportion of D_s distribution greater than the D_s statistic, signifying probability that histograms were generated from the same population.

	clust.lf TS histogram comparison results							
	Gill net	BC 6	BC 9	BC 12	BC 15	BC 18	BC 25	BC 35
Gill net		0.056	0.045	0.065	0.067	0.078	0.077	0.067
BC 6	66%		0.045	0.03	0.036	0.054	0.042	0.037
BC 9	77%	66%		0.056	0.053	0.077	0.068	0.058
BC 12	51%	97%	60%		0.037	0.043	0.032	0.040
BC 15	54%	96%	73%	91%		0.029	0.027	0.045
BC 18	40%	75%	41%	85%	97%		0.039	0.064
BC 25	37%	81%	35%	91%	96%	80%		0.029
BC 35	50%	85%	46%	78%	72%	42%	88%	

BC (−39.67 dB) but were nearly 2 dB lower at 35 BC (−41.57 dB). Accuracy of mean TS estimates varied within 0.5 dB of standard values over the range of 6–18 BC, and began to decrease at larger BC (25 and 35). Precision of mean TS estimates decreased slightly with BC, with the largest standard deviation (3.64 dB) coming from 25 BC.

3.2. Beam compensation contribution to TS variability in fish tracks

Biological sources of variability had a proportionally greater effect on fish tracks than measurement sources. Fish movement, orientation, and physiological condition quantified as residual variation dominated total variation, while fish size (mean TS) was the second largest source of variation (Fig. 3A). Variation increased similarly with fish size for all BC settings ($\mu.\beta2 = 0.246$; 95% credible interval = 0.230–0.260), (Fig. 3B). The number of SEDs within a fish track contributed the third most variation to fish tracks (Fig. 3A), but was proportionally small and showed similar slightly increasing relationships for all BC settings (Fig. 3C; $\mu.\beta3 = 0.101$; 95% credible interval = 0.066–0.149). In addition, as BC increased the variation within fish tracks attributed to SEDs stabilized as the BC specific slopes began to decrease. Finally, the BC analysis setting was variable but contributed the least variation to surveyed fish tracks on average (Fig. 3A). The impact of BC on variation increased slightly but was stable across intermediate BC settings (Fig. 3D; BC 9–18).

3.3. Beam compensation effect on size structure

Gill net length frequencies generated from 20-mm length bins indicated three distinct size groups that included walleye. A small size group from 300 to 400 mm (−36 to −33.5 dB) was comprised of 18% age-1+ walleye, as well as high proportions of gizzard shad (*Dorosoma cepedianum*) and white bass (*Morone chrysops*). A medium size group from 400 to 600 mm (−33.5 to −30 dB) was comprised of 74% age-2+ walleye, with small proportions of gizzard shad, lake whitefish (*Coregonus clupeaformis*), and channel catfish (*Ictalurus punctatus*). A large size group 600–910 mm (−30 to −26 dB) included 94% walleye, with a few lake whitefish, channel catfish, and common carp (*Cyprinus carpio*). After converting TL (mm) to TS (dB) and grouping by 0.5-dB TS bins, the size structure remained similar with three dominant size groups (Fig. 4B). Increased BC produced greater fish counts and SEDs per fish (Table 2) for all size groups. Count frequencies from all observed sample groups (i.e., gill nets, and BC 6–35) between −36 and −30 dB generally decreased with size (Fig. 5; black bars), while most showed distinct decreases in count frequencies at −33.5 dB. None of the observed TS frequency histograms was statistically different (i.e., probability of similarity <5%) from one another, however the range in probability of similarity was great (Table 3; 35–97%). All BC TS-histograms matched with gill nets ranging from 37 to 77% probability of similarity. Additionally, probabilities were generally highest between adjacent BC indicating incremental changes in measured size structure consistent with the estimated BC effects from the ANCOVA analysis (Fig. 3B).

3.4. Beam compensation effect on density

Increased BC produced greater fish counts and density estimates (Fig. 6A) as well as proportional increases in density (Table 2) for all

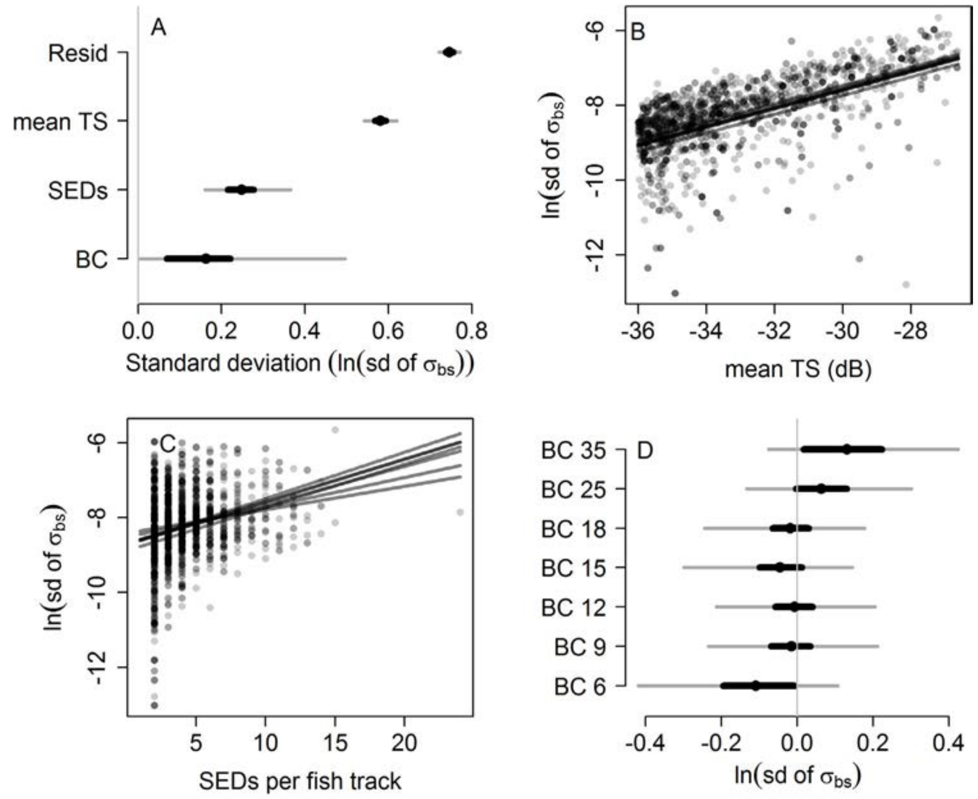

Fig. 3. Summary plots of ANCOVA model including A) proportional contributions of variation, B) beam compensation (BC) specific relationship between $ln(sd\ of\ \sigma_{bs})$ and mean TS, C) BC specific relationship between $ln(sd\ of\ \sigma_{bs})$ and number of single echo detections (SEDs) per fish track, and D) BC specific influence on $ln(sd\ of\ \sigma_{bs})$. Black dots in A and D represent mean values, while black and gray lines represent 50 and 95 percent credible intervals, respectively. Gray circles in B and C represent raw data values, and black lines are BC specific regression estimates.

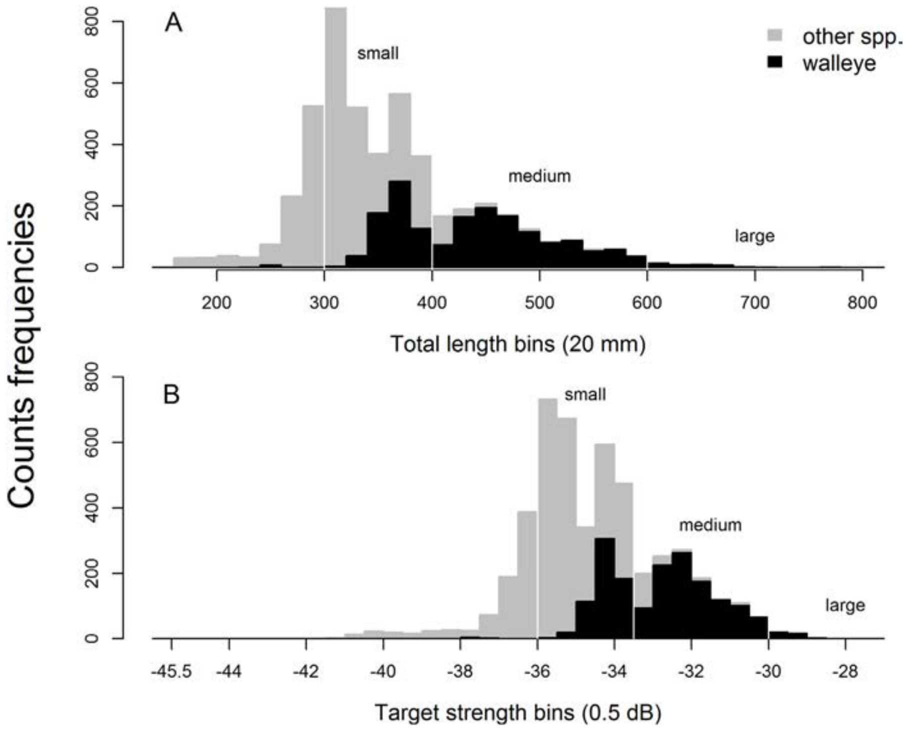

Fig. 4. A) Total length frequency and B) converted target strength frequency histograms from gill net data. The black portion of histograms corresponds with walleye targets, while the light gray portion corresponds to other species. The vertical white lines partition fish into three distinct size groups (small, medium, and large).

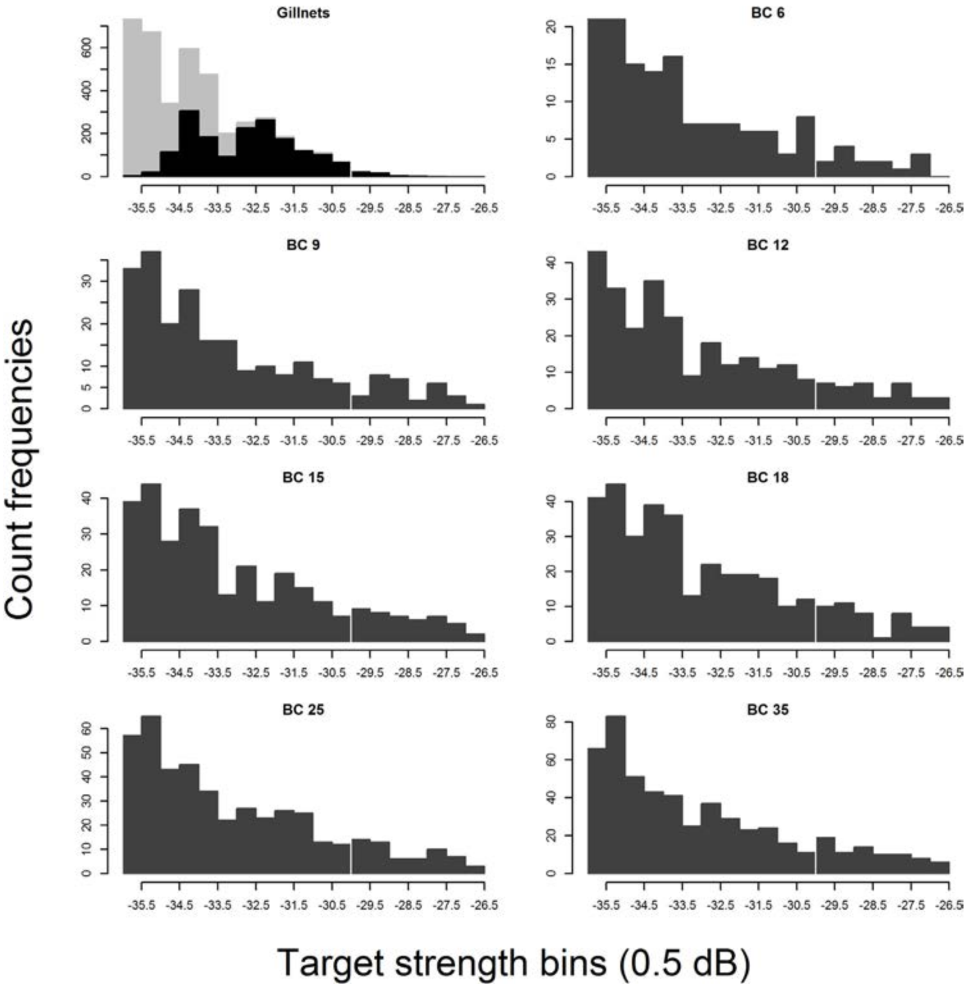

Fig. 5. Comparison of target-strength frequency histograms from gill nets and each beam compensation (BC) analysis. Black portion of the gill net histograms corresponds with walleye, while the light gray portion corresponds with other species. BC specific histograms from hydroacoustic data with unknown species composition are displayed in dark gray. Comparable size ranges across sampling scenarios include small and medium size groups between −36 and −30 dB, while the large size group (TS > −30 dB; affected by selectivity and catchability biases) is distinguished by a vertical white line.

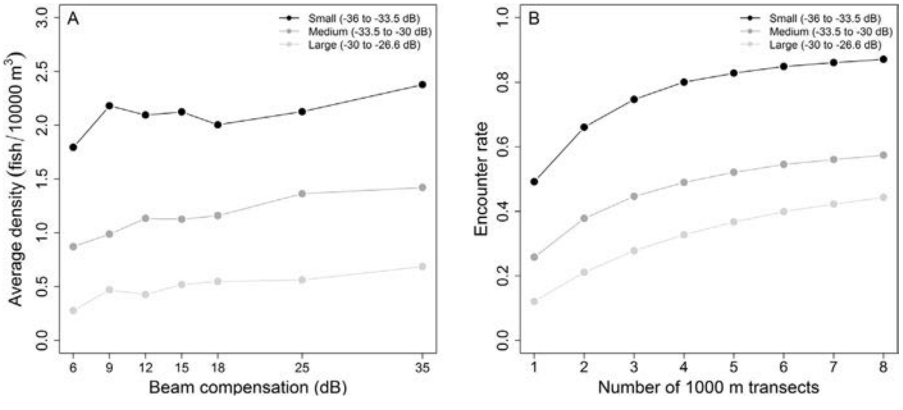

Fig. 6. A) Density estimates for three size groups over a range of beam compensations. B) Encounter rates for three size groups over a range of sample efforts, ranging from 1 to 8 sampled transects per site. Black dots and lines represent the small size group, dark gray dots and lines represent the medium size group, and light gray dots and lines represent the large size group.

size groups. These patterns were related to sample volumes, which increased with additional compensation of off-axis targets and a greater wedge volume sample. All size range densities proportionally increased with an initial 3-dB BC increase, corresponding with an approximately 1.5 ° increase in the sample wedge angle. Small fishes maintained similar densities across BC 12 through 25 with minimal change up to 35 dB compensation. Densities of medium sized targets stabilized around 30% increase between BC 12 through 18, and large sized fish stabilized around a 95% increase between 15 and 25-dB compensation. Medium and large size groups (i.e., TL > 400 mm; mean TS > −33.5 dB) are primarily comprised of age-

2+ walleye representing the bulk of the fishery, and are of particular interest to fishery managers.

3.5. Encounter rates and sample effort

Encounter rates increased across size groups when sampling more transects at a site under the 6 dB BC analysis (Fig. 6B). Encounter rates were highest for the smallest size group (−36 to −33.5 dB) across sampling scenarios, ranging from ~48 to 87% probability. Encounter rates were more similar for medium (−33.5 to −30 dB) and large size groups (−30 to −26.6 dB), ranging from ~25 to 57% and ~12 to 44% probability, respectively. Encounter rates for the small size group neared an asymptote more quickly, while medium and large size groups increased more gradually.

4. Discussion

Sparse TS data can reduce the quality of hydroacoustic-based size and abundance estimates, particularly for low-density fish in shallow water. Additionally, restrictive data analysis procedures can further limit TS data. However, in some situations, a more permissive use of BC can improve size and density estimates in support of fishery management decisions. We have shown that hydroacoustic surveys can produce representative and informative size and density estimates of Lake Erie walleye in relatively shallow habitats (i.e., < 15 m). A combination of hydroacoustic system capabilities and survey conditions allowed for an optimal balance between quantity and quality of TS data with intermediate BC settings (i.e., 18 dB). Our results suggest that the contribution of BC to fish track variability is minimal compared to other sources. In addition, in cases where fish targets are sparse, increasing BC can improve size structure and density estimates of medium to large acoustic targets (i.e., > −33.5 dB or ~400 mm). Finally, we have provided a framework for future studies to optimize TS data use when limited by survey conditions and conventional data analysis.

Stability in TS estimate accuracy up to 18 dB compensation demonstrated that the theoretical beam pattern expressed by the first-order Bessel function in Echoview software closely matched the realized beam pattern (Simmonds, 1984) of the BioSonics DTX split-beam system and 210 kHz transducer used in this study. However, at BC above 18 dB there appeared to be a breakdown, as estimated mean TS was lower than expected while variation around mean TS increased. Reduced accuracy and precision near the beam margins is likely due to a deviation between theoretical and realized beam patterns (Simmonds, 1984), errors in the small angle approximations of the major (θ_x) and minor (θ_y) axes (Furusawa and Sawada, 1991; Kieser et al., 2000), or possibly side lobe interference (Simmonds and MacLennon, 2005). Compensation errors are exacerbated near the acoustic beam edges because the beam pattern is hyperbolic, therefore, angle approximation errors near the beam edge will result in an estimate further from the true value than similar errors near the beam axis (Furusawa and Sawada, 1991). Here, given the decreasing trend in TS estimates with increasing BC, it appears that underestimated small angle approximations led to reduced compensation and lower than expected TS estimates near the beam edges. Nevertheless, these results indicate that BC settings used during data processing could be increased to 18 dB, increasing data quantity without a decrease in data quality.

The importance of measurement error to mean TS estimates is dependent on its relative contribution to total variation in surveyed TS data. We found that variation in fish track mean TS estimates, defined as standard deviation of backscattering cross-section (σ_{bs}), increased with successive BC settings. However, the proportional contribution of measurement-derived sources (i.e., BC and number of SEDs) was smaller than natural sources (i.e., mean TS and residual variation). Residual variation was a substantial component of total variation in TS estimates from fish tracks, most likely generated from uncontrollable biological sources such as fish movements, changes in orientation, and physiological characteristics (Ona, 1990; Kloser and Horne, 2003). TS estimates of larger fish (i.e., greater mean TS) can vary proportionally more under similar movements and orientations compared to smaller fish, due to increased directional scattering with size (McCartney and Stubbs, 1971; Foote and Nakken, 1978; Olsen, 1990) supported by the positive relationship we found between ln(sd of σ_{bs}) and mean TS and large contribution to total variation. Additionally, mean TS is considered a random variable due to the inherent uncertainty associated with its estimation (Simmonds and MacLennan, 2005); therefore, including more SEDs from individual fish may increase TS variability within fish tracks. However, the increased quantity of data per fish track will improve mean TS estimates and reduce variability in the estimated size structure of the population (Ehrenberg and Torkelson, 1996). Here, we identified a weakly positive relationship between ln(sd of σ_{bs}) and number of SEDs, but this did not contribute substantially to total variation and decreased with increasing BC. As discussed above, increased BC can also lead to increased variation in TS estimates (Simmonds, 1984; Furusawa and Sawada, 1991; Kieser et al., 2000). BC variation may also be related to directional scattering fish, as the incident angle of fish perpendicular to the beam axis will increase slightly near the beam edge at higher BC (+2.5° from 6 dB to 18 dB BC), but we could not directly quantify this potential source. Nonetheless, here we observed a relatively low contribution from BC when compared to natural sources. Additionally, the BC specific effect on fish track variability was smallest at 6 dB and relatively stable between 9 and 18 dB, increasing beyond 18 dB. Therefore, a more permissive use of BC, up to 18 dB, is possible for improving individual fish size estimates.

Increasing BC increased number of SEDs per fish and likely improved encounter rates with large fish targets, which ultimately improved mean TS estimates and population size structure estimates. Small to medium walleye population size-structures were comparable between gill nets and hydroacoustic data analyzed over all BC analyses, as well as among BC analyses, ranging from 35 to 97% similarity. A visual comparison lends support for BC between 12 and 18 dB, as each includes characteristics associated with the gill net histogram; two frequency peaks between −36 and −33.5 dB, a distinct decrease in frequency at −33.5 dB, and peak mass around −32 dB. This threshold (−33.5 dB or 400 mm) is an important characteristic in Lake Erie as the fish above are predominantly age-2+ walleye. However, we cannot assume that the gill net sample represents the true size structure of the population. Every sampling method has biases, and therefore a match between methods does not necessarily equate to a match with the true population. Previous studies have shown that the gill net configuration used in this study has greater selectivity for fish in the 300–600 mm size range, while reduced selectivity for fishes greater than 600 mm (Vandergoot et al., 2011). In addition, suspended gill nets sample only a portion of the water column leaving mostly benthic fish unavailable to the gear. Biases from hydroacoustic data include low data quantity (i.e., sparse data) with small BC and low data quality near the beam edges with large BC, the effects compounded by variable survey conditions (Furusawa and Sawad, 1991; Saavedra et al., 2012). In addition, hydroacoustics under sample surface and near bottom waters. Given these known biases, we may conclude that neither method perfectly samples and may differentially sample that target population. Although methods may differentially sample the population, reducing statistical fit between gill nets and BC histograms, similarities in observed data lend strength to our evaluation of hydroacoustic data processing methods by providing a secondary reference based on physical samples.

Fish densities increased with increasing BC indicating that all fishes were under-sampled with low BC; however, the changes were not proportional among size groups. Under-sampling of low-density patchily distributed fish can be intensified by low sample volumes and spatial coverage (Aglen, 1989), and further exacerbated given hydroacoustic blind spots in the nearfield and bottom dead zones. We showed under a fixed BC (6 dB) that increasing the number of sampled transects (i.e., sample volume) at a site would increase encounter rates with small, medium, and large targets. However, given that transect length cannot be extended and blind zones have already been minimized, increasing BC and subsequently water volume sampled can help reduce this bias. Interestingly, fish size groups responded differently to increasing BC, as stability in density estimates occurred over a large range (e.g., 12–25 dB) for the small size group, over intermediate compensation for the medium size group (e.g., 12–18 dB), and over higher compensation for the large size group (e.g., 15–25 dB). Encounter rates likely influenced density estimates, as stability (i.e., nearing an asymptote) in encounter rates corresponded with density estimates. We saw that stability in encounter rates and densities occurred under lower sample efforts for smaller fish, while medium and large sizes required greater sample efforts to reach stability. Size-related avoidance behavior (Olsen, 1990; Soria et al., 1996; Misund, 1997) may contribute to differential density responses across size groups, particularly in shallow water hydroacoustic surveys (Kubecka and Wittingerova, 1998; Knudsen and Saegrov, 2002); however, we did not directly study this potential effect. Consequently, there appears to be stability reached in densities between 15 and 18 dB for all size groups. Therefore, these patterns across size groups suggest intermediate BC provided more complete density estimates, with the greatest proportional increases occurring in medium and large sized fish (i.e., age 2+ walleye).

5. Conclusions

This study occurred in a relatively shallow, low-noise environment, which aided the effectiveness of increased BC during analysis. Large fish targets (i.e., > −36 dB mean TS) in western Lake Erie, in general, had a high signal-to-noise ratio, therefore a “swamping” effect (Kieser et al., 2000) near the beam margins was not a concern. Measurement errors related to transducer motion were limited by the shallow water environment (Furusawa and Sawada, 1991), and can be further managed by adjusting pulse duration and ping rates to minimize the time between source and return echoes. Additionally, our BioSonics DTX split-beam hydroacoustic system and 210 kHz transducer performed well across a range of BC. However, situation-specific outcomes should never be applied as a blanket recommendation. For instance, we caution increasing BC in low signal-to-noise ratio settings that might occur with smaller targets in deeper water. Rather, we suggest that users consider increasing BC settings specifically when experiencing limited TS data, while sampling sparse large-targets in shallow water. This study suggests that natural sources of variability (i.e., movement, orientation, physiology, and size) contributed the most uncertainty to mean TS estimates, and that BC did not substantially increase mean TS estimate uncertainty. Further, increasing BC to 18 dB provided an optimal balance between TS data quantity and quality, which improved medium and large size group (i.e., primarily age-2+ Lake Erie walleye) acoustic size-structure, encounter rates, and density estimates. Finally, these results broadly demonstrate that balancing the benefits of data quantity with the costs of data quality can improve TS data use for population-scale surveys.

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