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Accuracy and precision of hydroacoustic estimates of Gizzard Shad abundance using horizontal beaming

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ABSTRACT

Prey-density data are often used when making management decisions for piscivorous fish species (i.e. stocking rates). Gizzard Shad (*Dorosoma cepedianum*) are an important prey species in lakes and reservoirs throughout much of the United States. Currently, gill nets are the most common gear used to collect Gizzard Shad data used for deriving population characteristics, but this gear can be time and labor intensive, lacks precision, and may lack accuracy. Horizontally-oriented echosounders may be a better alternative, but accuracy and precision must be measured to determine if this sampling technique produces reliable data. We released Gizzard Shad into a net pen (15-m long × 15-m wide × 4.5-m deep with 6.35-mm square mesh) to produce several different densities of fish. Mean densities were estimated using five passes with a Simrad® EK60 120 kHz split-beam echosounder. Density estimates were acquired by echo-counting and echo-integration. Mean density estimates were then compared to known densities using a linear mixed-effects model and relative standard error (RSE) was calculated for each trial from the five sampling passes. Both echo-counting and echo-integration had slopes not significantly different from one (t = 0.82, d.f. = 13, P = 0.33; t = 3.58, d.f. = 13, P = 0.55) but intercepts that were significantly greater than zero (t = 2.89, d.f. = 88, P < 0.01; t = 3.53, d.f. = 88, P < 0.01) indicating horizontally-oriented echosounders can accurately detect changes in Gizzard Shad density, but may overestimate actual density, particularly when small. Horizontally-oriented echosounders accurately estimated relative Gizzard Shad density with good sampling precision (i.e., when imaging the same aggregation of fish), indicating data collected with this method would be reliable when making management decisions.

1. Introduction

Prey-density data are used when making management decisions for piscivorous fish species because prey fish abundance can affect the growth and survival of piscivorous sport-fishes (Evans et al., 2014; Persson et al., 2007; Yodzis, 1994). Low prey densities can negatively affect the growth (Garvey and Stein, 1998; Hartman and Margraf, 1992; Kolar et al., 2003) and survival (Fox, 1989; Kolar et al., 2003; Szendrey and Wahl, 1996) of piscivorous sport-fishes. However, high prey abundances can also negatively affect juvenile sport-fish species through competition for similar prey items (Byström et al., 1998; Olson et al., 1995). In many aquatic systems, piscivore populations are supplemented or maintained through stocking efforts to improve recreational fishing (Boxrucker, 1986; Terre et al., 1993), providing an opportunity to use information about prey density to determine appropriate stocking numbers for sportfishes (Donovan et al., 1997; Hoxmeier and Wahl, 2002; Skov et al., 2003), but only if prey density can be accurately measured. Therefore, prey density data are useful when making management decisions for piscivorous fishes.

Gizzard Shad (*Dorosoma cepedianum*) are an important prey species in lakes and reservoirs throughout southern and mid-latitudes of the United States, and routinely have the highest density and largest biomass of all prey types within these systems (Carline et al., 1984; Johnson et al., 1988; Miranda, 1983). Because Gizzard Shad have high densities, they are a common prey source for piscivorous predators (Graham, 1999; Stahl et al., 1996; Storck, 1986). Additionally, Gizzard Shad have high caloric value making them and energetically efficient prey species (Eggleton and Schramm, 2002; Strange and Pelton, 1987). Therefore, Gizzard Shad can have a large impact on predator communities making accurate abundance estimates critical to effective and sustainable piscivore management. Currently, gill nets are the most common gear used to collect data on Gizzard Shad population

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characteristics, but hydroacoustics have the potential to produce improved abundance data with less effort at the same level of precision (i.e., low enough variance to detect small changes in abundance; Van Den Avyle et al., 1995b). Gillnet-derived estimates of Gizzard Shad abundance can be time and labor intensive, lack precision, and may lack accuracy (i.e., may not actually reflect true abundance and size structure; Van Den Avyle et al., 1995a,b). Hydroacoustic sampling has potential to provide precise estimates of pelagic prey fish abundance with less time and effort (Taylor and Maxwell, 2007; Taylor et al., 2005; Van Den Avyle et al., 1995a). For example, surface-set gill nets take seven times more person-hours than hydroacoustics to collect sufficient samples to detect a 25% difference in mean catch rates of Gizzard Shad (includes data processing time for hydroacoustic sampling; Van Den Avyle et al., 1995a). It takes 30–40 net nights to detect a 25% difference in Gizzard Shad abundance using gill nets (Wilde, 1995), but only 14–25 5-min hydroacoustic transects (14–25 total person-hours for sampling and processing; Van Den Avyle et al., 1995a). Therefore, sampling Gizzard Shad populations with hydroacoustics would result in reduced time and effort to acquire Gizzard Shad population characteristics with similar precision (Dennerline et al., 2012; Van Den Avyle et al., 1995a).

Traditional hydroacoustic sampling procedures utilize a transducer oriented vertically, beaming straight down or at a slight angle (Parker-Stetter et al., 2009; Simmonds and MacLennan, 2008; Vondracek and Degan, 1995), which can be ineffective in shallow water due to reduced sample volume (especially after nearfield exclusion and the bottom-associated dead-zone are considered) and fish behavior (boat avoidance or avoidance of hypoxic conditions in the hypolimnion; Godlewska et al., 2009; Roberts et al., 2009; Simmonds and MacLennan, 2008; Yule, 2000). As a result, only a small proportion of the water column is sampled when using a vertically oriented echosounder in shallow systems. Further, reduced sample volume combined with a non-homogenous distribution of fish (i.e., patchy distributions) can result in highly variable estimates (Balk, 2001; Bodine et al., 2011; Stockwell et al., 2007). Gizzard Shad are typically found near the lake surface and would not be sampled effectively using vertical beaming, but may be sampled effectively with horizontally-oriented echosounders (Miller, 1960).

The relatively large body of literature measuring accuracy and precision of vertical beaming suggests that hydroacoustics is more precise than other fish sampling methods. In comparative studies, vertical beaming had higher precision than seining, trawling, rotenone, surface and bottom-set gill nets, electrofishing, (Achleitner et al., 2012; Van Den Avyle et al., 1995a) drop traps (Nellbring, 1985), and experimental gill nets (Hansson, 1984, 1993). Horizontal beaming may have similar precision to vertical beaming, but because horizontal beaming samples near-surface fish, surface disturbances may have an increased effect on precision (Gangl and Whaley, 2004; Totland et al., 2009). Uncertainty associated with fish aspect may also affect estimated densities (Balk, 2001; Balk et al., 2017). Further, spatial heterogeneity in fish abundance may differ for near-surface fish and fish inhabiting deeper locations, resulting in variation in precision estimated between horizontal and vertical approaches. Only a limited number of studies have evaluated the precision of horizontal beaming (Balk, 2001; Draštík et al., 2009; Duncan and Kubecka, 1996; Kubecka et al., 2000; Yule, 2000), but they all indicate hydroacoustic estimates have better precision than other sampling methods. However, these studies have only considered precision of a few fish species and none have evaluated Gizzard Shad. As such, further research is needed to quantify precision for Gizzard Shad data collected with horizontal echosounders. Comparisons between horizontally-oriented echosounder estimates and gillnets (Boswell et al., 2007; Kubecka et al., 1994; Tátrai et al., 2008), purse seining (Yule, 2000), and push trawls (Boswell et al., 2007) identified differences in relative abundance estimates among gears, but these studies could not confirm which, if any, gear had greater accuracy because the true population characteristics of the target species were unknown; a common problem when trying to establish gear accuracy. Knowledge of the experimental accuracy and precision of horizontally-oriented echosounders would determine if Gizzard Shad population data collected with this gear provides better data for management decision making.

Gizzard Shad abundance and size structure are often considered when making sportfish management decisions, but current sampling techniques are inefficient and may be unreliable. Horizontal beaming has real promise as a method to collect precise and accurate data with less effort than current sampling methods, but research is needed to confirm this (Van Den Avyle et al., 1995a). In this study, we tested the precision and accuracy of hydroacoustic estimates by sampling known abundances of Gizzard Shad.

2. Material and methods

Gizzard Shad ranging from 60 to 300 mm total length (TL) (stocked at densities from 0.04 to 0.52 fish/m^3) were collected from Lake Carl Blackwell near Stillwater, OK, daily July 11–September 18 2017. Fish were captured using vessel-based electrofishing methods; all captured fish were counted and released into a nylon net pen (15-m long × 15-m wide × 4.5-m deep with 6.35-mm square mesh) located within the lake. Fish were given $\geq$ 30 min to acclimate based on observations that fish behavior inside the pen was similar to unconstrained fish within the lake after this period of time (observations made with an ARIS® Explorer 1800 imaging SONAR operating at 1.8 MHz). The pen remained in the water for no more than four consecutive days (net set) and fish were added to increase total density between trials. Each trial consisted of five repeated passes along the confined population. The pen was then removed, fish released and the net reset the beginning of the following week. The number of fish added was not predetermined, but we ensured that a wide range of fish abundances were sampled, (fish were counted as placed in net) typically with low- and high-density trials occurring within each net set (37–526 individuals; Table 1). For analyses, known abundance was divided by the volume of the net (1012.5 m^3) to determine density. A total of 22 trials (8 total net sets) with different fish densities was conducted.

To estimate handling mortality, dead fish (typically 5–25 individuals per net set) were collected from the net daily and counted. At the end of each 3- or 4-day net set, the net was retrieved and remaining

Table 1
Trial number, net set, abundance and density for each net pen (15-m long × 15-m wide × 4.5-m deep) trial to evaluate Gizzard Shad (*Dorosoma cepedianum*) density estimation with a horizontally-oriented echosounder.

Trial	Net Set	Abundance	Density (fish/m^3)
1	1	308	0.30
2	1	352	0.35
3	2	43	0.04
4	2	104	0.10
5	2	154	0.15
6	2	204	0.20
7	2	335	0.33
8	2	385	0.38
9	3	72	0.07
10	3	387	0.38
11	3	461	0.46
12	3	468	0.46
13	3	526	0.52
14	4	37	0.04
15	4	333	0.33
16	5	299	0.30
17	5	384	0.38
18	6	66	0.07
19	6	174	0.17
20	6	229	0.23
21	7	139	0.14
22	8	90	0.09

Table 2
Echosounder, transducer and analysis parameters used during data collection and analyses for net pen trials with Gizzard Shad.

	Value
System parameters	
SIMRAD EK60 split-beam echosounder	
Operating Frequency	120 kHz
Pulse Duration	0.256 ms
Pulse rate	10 Hz
Transducer parameters	
Two-way beam angle	−20.7
Collection Threshold	−70 dB
Beam width	7°
Nearfield range	2 m
Analysis Threshold	
Target strength	−65 dB
Single target detector	
Pulse length determination level	6 dB
Minimum normalized pulse length	0.5
maximum normalized pulse length	1.8
Maximum beam compensation	6 dB
Maximum standard deviation of	
Minor axis angle	1.0°
major-axis angles	1.0°

dead fish (i.e., fish that did not float) were also counted. All live fish removed were enumerated and measured (mm TL). Known fish density for each trial was adjusted assuming a constant initial mortality rate for all fish introduced through the week (i.e., total mortalities quantified when the net pen was removed were attributed proportionally based on number of fish added between recordings with a constant proportion assumed to die after each addition).

Acoustic backscatter data were collected with a calibrated Simrad® EK60 120 kHz echosounder and split beam transducer (ES120-7C). Echosounder data were collected at 10 Hz with a threshold of −70 dB. Transducer properties can be found in Table 2. An imaging sonar (ARIS® Explorer 1800) was deployed simultaneously with the echosounder and was equipped with an 8° concentrator lens. The imaging sonar (operating at 1.8 MHz) data were used to ensure fish had natural behaviors. The 120 kHz transducer and ARIS® were mounted to the same bracket and lowered to a depth of 1 m along the inside edge of the net pen, and aimed across the pen (Fig. 1). Use of a common bracket on which both acoustic transducers were mounted allowed us to use the tilt and roll sensor of the ARIS® to ensure the 120 kHz split-beam transducer was aimed at 3.5° downward from horizontal (angle chosen to reduce surface noise and maximize sample volume). Recordings were collected by pulling the boat along one side of the net five times consecutively with a

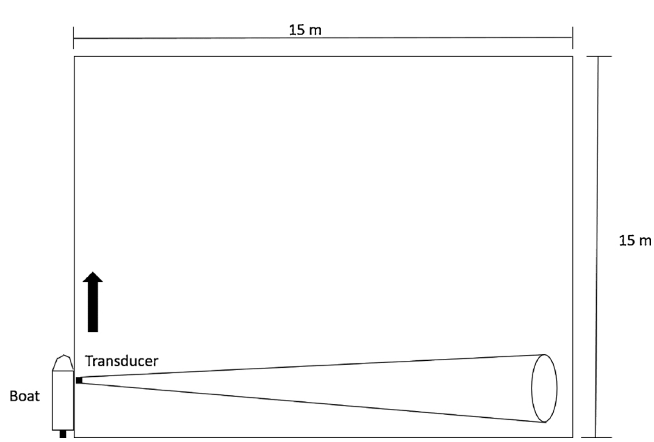

Fig. 1. Diagram depicting the net pen used to test the accuracy and precision of Gizzard Shad abundance using hydroacoustic sampling. Arrow indicates the direction that the vessel-mounted transducer moved to sample a known number of fish within the net pen.

mean speed of 0.1 m/s (each pass was considered one trial). Trials occurred at night because shad were less aggregated and further from the net walls, making echo-counting possible (Schael et al., 1995). Daytime observations using the imaging SONAR indicated shad were attracted to periphyton growing on the net, making separation of fish targets from pen edges difficult. Trials were conducted in late summer when water temperatures were 23°–30 °C (mean = 26.8 °C; SD = 1.96).

Raw acoustic backscatter data were visualized and processed using Echoview® 8.1. A target-detection algorithm (detection parameters are in Table 2) was used to detect fish targets that were then manually converted to fish tracks (consisting of at least five targets). Because samples were taken at night when Gizzard Shad tend to disperse from their aggregations (Miller, 1960), most fish were observed as individual targets. When aggregations of fish occurred (only 2 observed during the study), an echo-integration technique was used to estimate the number of fish within the aggregation (volume backscattering strength of each aggregation [the sum of reflected energy over a given volume] was scaled by mean target strength [the amount of sound energy reflected by an individual] using individual fish tracks from the same sampling pass to calculate mean target strength assuming random orientation), and the estimated number of fish from the aggregation were then added to the total abundance (Boswell et al., 2007; Busch and Mehner, 2009). Total number of fish counted in each transect (both from single-target counting and estimates from echo integration) was divided by the volume of water ensonified during the trial to produce an estimated density (fish/m^3). The net pen returned a strong, consistent echo approximately 15 m from the transducer and at closer distances when approaching perpendicular sides. Any potential targets that were not clearly differentiable from the net pen echo were excluded from analysis. Acoustically derived fish densities (fish • m^{-3}) were compared to known densities (based on number of fish in the pen) and a relative standard error (RSE; SE/Mean) was calculated from the five replicates of each trial. We also estimated fish density (fish/m^2) using echo-integrating for each pass using the mean TS from each respective pass to determine which method better estimates density.

A linear mixed-effects model was used to compare estimated fish densities to known densities with net set and trial as random effects using the software package R ((lme; Pinheiro et al., 2017)). *T*-tests were used to test for differences between observed slope and a hypothesized slope of 1.0 and the observed y-intercept and a hypothesized y-intercept of zero. An ANOVA was used to test for differences in density between the five replicate recordings to detect any influence of previous recordings on subsequent recordings (e.g., boat avoidance) with trial as a random effect (ANOVA; R Core Team, 2018). Significance within each test was evaluated with $\alpha \leq 0.05$. Relative standard error (calculated from each set of five replicate measurements at each fish density) were tested to determine if RSE was consistent across known fish densities with simple linear regression (lm; R Core Team, 2018).

3. Results

We used 5181 Gizzard shad ranging in size from 60 to 300 mm TL, which produced target strengths from −23 to −62 dB (Fig. 2). Estimated density was directly proportional to actual density with a slope of 0.89 and intercept of 0.13 when counting target tracks (Fig. 3). The slope was not significantly different from one (t = 0.82, d.f. = 13, P = 0.33), but the intercept was significantly greater than zero (t = 2.89, d.f. = 88, P < 0.01). There were no significant differences in fish density between the five measurements in each trial ($F_{4,105}$ = 0.38, P = 0.82). Echo-counting had a mean RSE of 6.8% and ranged from 2 to 14% across all densities. There was no apparent trend for RSE as density changed ($F_{1,20}$ = 0.02, P = 0.88, Fig. 4).

When echo-integrating, estimated density was also directly proportional to actual density with a slope of 0.79 and intercept of 0.86 (Fig. 3). The slope was not significantly different from one (t = 3.58, d.f. = 13, P = 0.55, but the intercept was significantly greater than

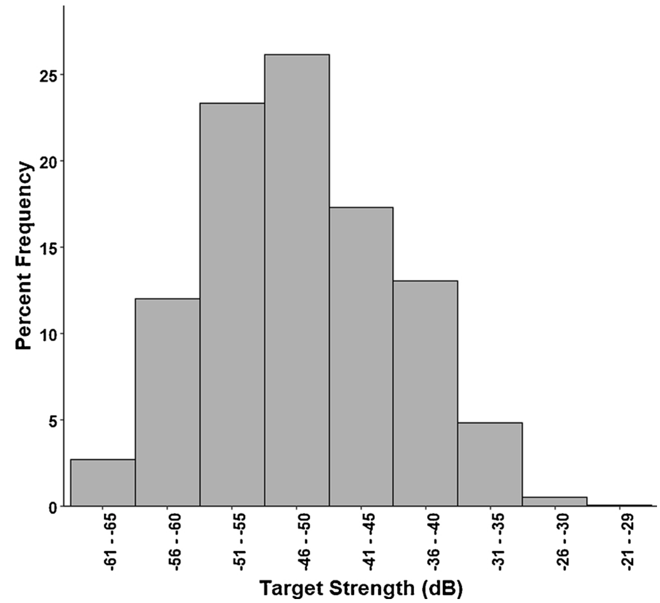

Fig. 2. Frequency of measured target strengths from Gizzard Shad within a 15-m long × 15-m wide × 4.5-m deep net pen in Lake Carl Blackwell, Stillwater, OK imaged by a horizontally-oriented 120 kHz split-beam transducer (transducer and analysis parameters given in Table 2).

zero (t = 3.53, d.f. = 88, $P < 0.01$). Echo-integration had a mean RSE of 11% and ranged from 3 to 25% across all densities. There was no trend for RSE as density changed ($F_{1,20} = 0.05$, $P = 0.81$, Fig. 4).

4. Discussion

Our results suggest hydroacoustic sampling can accurately detect differences in Gizzard Shad density by counting fish tracks or echo-integrating (i.e., slope of known abundance and estimated abundance was not significantly different from one), but may slightly overestimate

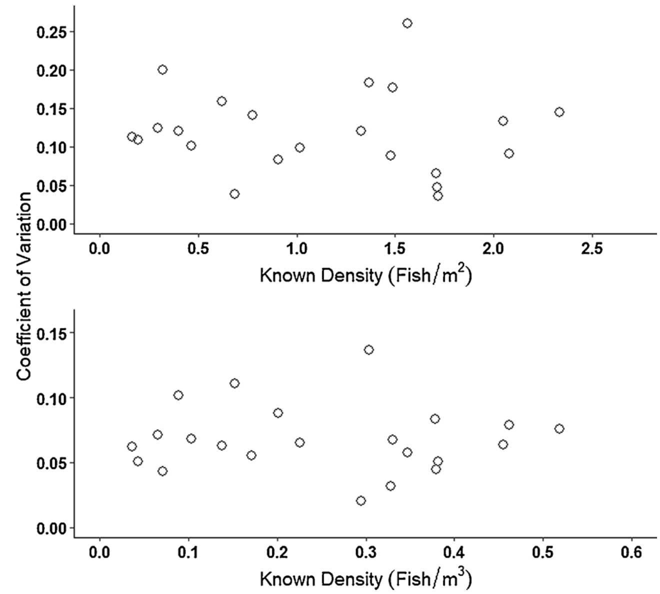

Fig. 4. Relative standard error (SE/mean) for hydroacoustic density estimates measured at different known Gizzard Shad densities in net pen trials using echo-integration (top) and target counting (bottom). Relative standard errors are based on 5 replicate passes of the net with the same fish assemblage.

at all densities for both approaches (intercept was significantly greater than zero), becoming less pronounced as density increases. Although not statistically different than one, the estimated slopes were less than one. This was likely caused by an overestimation of fish abundance at low densities. Over-estimation is expected at low densities because Gizzard Shad often aggregate near the surface (Becker, 1983; Bodola, 1966; Miller, 1960), suggesting there was a greater density (fish/m^3) of fish in the portion of the net pen that was sampled by the acoustic beam (approximately 20%). This phenomenon should be minimized in shallow water and when sampling distance is not artificially restricted because a larger portion of the water column will be sampled, including

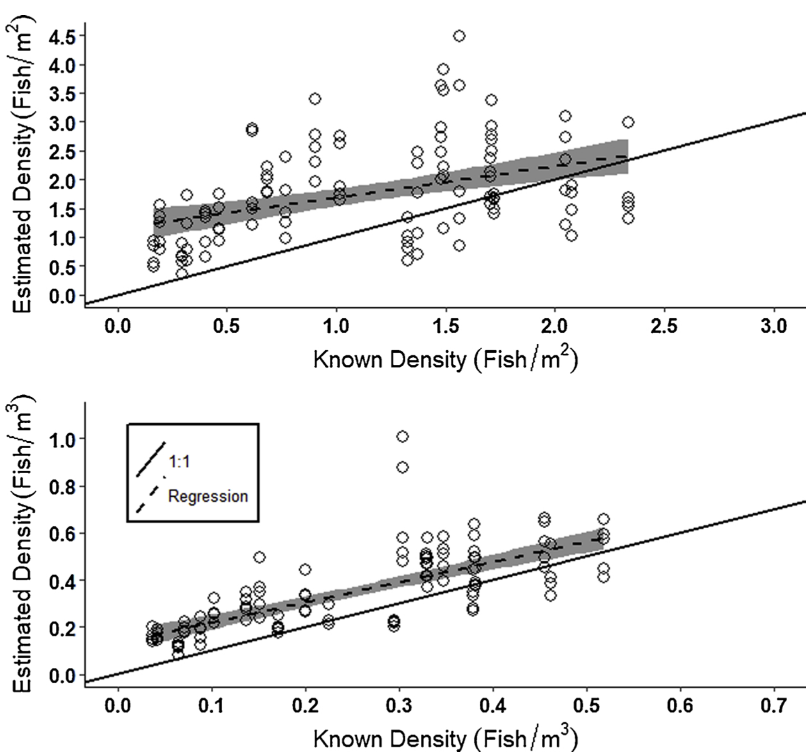

Fig. 3. Regression line (dashed line) depicting the change in estimated density (fish/m^3) at different known fish densities measured within a net pen (15-m long × 15-m wide × 4.5-m deep) with a horizontally-oriented echosounder using echo-integration (top) and target counting (bottom). Shaded area represents the 95% confidence interval of the slope; solid line is the 1:1 slope line that would indicate complete accuracy.

deeper areas with lower abundances of fish. Over-estimation could also result from boat avoidance (Draštík and Kubečka, 2005), increasing the number of fish in the far-field of the acoustic beam (which is larger and extends deeper in the water column than the portion of the beam nearer the transducer). However, boat avoidance seems unlikely because similar densities of fish tracks were detected both near and far from the transducer and no difference in density was detected among the five repeated measurements for each trial (i.e., if boat avoidance occurred, an increase in abundance at the opposite end would have been observed for later passes).

Gear accuracy in lakes and reservoirs has been difficult to estimate because we often do not know true abundance; therefore, limited literature is available investigating accuracy with known populations (Fujimori et al., 1996; Santucci et al., 1999). However, research without known fish densities has determined that accuracy of hydroacoustic estimates can be affected by uncertainty in standard sphere calibration, TS estimates, species delineation, and fish behavior (Demer, 1994; Simmonds and MacLennan, 2008), spatial sampling error (Simmonds and MacLennan, 2008), and analysis techniques and parameters used (O'Driscoll, 2003; Rose et al., 2000; Simmonds and MacLennan, 2008), among other factors. Without knowing the true density of fish in the sample area, a true accuracy cannot be determined. Controlling the number of individuals can be difficult to accomplish on a large scale, but can be addressed on a smaller scale, as we did with a large net pen.

We found horizontally-oriented echosounder density estimates also have a high degree of precision compared to other gears used to sample Gizzard Shad. In a multiple-gear evaluation, the precision (RSE) of various gears when sampling shad species (*Dorosoma* spp.) ranged from 11 to 61% (Van Den Avyle et al., 1995a). These values are all higher than our mean RSE when target-track counting (6%) and all but vertical hydroacoustics are higher than our mean RSE when echo-integrating. No prior studies have compared precision of Gizzard Shad abundance estimates from horizontally-oriented echosounders with other gears, but horizontally-oriented echosounder abundance estimates have less variation than purse seining for salmonids (Yule, 2000) and combining data from split beam echosounders with DIDSON data increased precision of anadromous fish abundance estimates (Hughes, 2012; Warren, 2006). Our results are, therefore, consistent with other literature, suggesting that hydroacoustics may produce more precise data than other gears that measure fish abundance.

Some aspects of study design affect precision, so it is possible that precision will differ between different sampling applications with the same gear (Clarke and Green, 1988; Hansson, 1993; Kowalewski et al., 2015; Kritzer et al., 2001; Snijders, 2005). For hydroacoustic sampling, samples from small spatial scales (as done in our study) leads to greater precision, but short transect lengths and limited replication (also characteristic of our study) can lead to reduced precision (Hansson, 1993; Kowalewski et al., 2015; Kritzer et al., 2001). Because our results suggest that horizontal beaming has a high precision despite low replication and small transect length, there is potential to further improve precision with increased sample size (Kritzer et al., 2001) and duration (Kowalewski et al., 2015; Vondracek and Degan, 1995). However, reduced spatial heterogeneity in our study, caused by confining fish in a net pen, may have reduced measured variance and consequently artificially increased our precision estimate (Baroudy and Elliott, 1993). Additional research should be conducted to evaluate the precision of horizontal echosounders when sampling Gizzard Shad at larger spatial scales (i.e., whole-lake sampling), but our study provides an estimate of precision at smaller scales (i.e. within a transect or single fish aggregation).

When echo-counting, there is a possibility of counting individual fish multiple times (double counting; Hanchet and Ingerson, 1996; Larson, 2013; Troyer, 1993). Based on observations from the imaging SONAR, we believe that double counting was minimal. Fish were moving slowly and did not often enter the beam from the trailing edge (part of the beam towards rear of vessel) or leave the beam from the leading edge (part of beam towards front of vessel). Therefore, double counting likely did not have an impact on our density estimates.

When sampling with horizontal beaming, echo-integration should be used with caution. Because fish are ensonified laterally, fish orientation will have a large impact on measured TS that is used when echo-integrating (Boswell and Wilson, 2008; Frouzova et al., 2005; Kubečka, 1994). TS values used for echo-integration can have a large impact on biomass estimations (Boswell et al., 2009) when beaming horizontally. Our results suggest echo-integration can be used when sampling Gizzard Shad with horizontal beaming, but with less precision, likely caused by fluctuations in mean TS due to changes in fish aspect between passes.

Our results suggest horizontal echosounders should be considered for sampling Gizzard Shad in shallow reservoirs because they produce accurate relative abundance data, have a high degree of precision at the scale tested, and efficiently sample near-surface fish that vertically-oriented echosounders would not. Hydroacoustic sampling (including data processing time) typically requires less person-hours than other common Gizzard Shad sampling methods at a given level of precision (Van Den Avyle et al., 1995a). The use of hydroacoustic sampling techniques to collect Gizzard Shad population data could therefore increase the accuracy and precision of biomass estimates in shallow reservoirs, which would improve overall fisheries management.

Declaration of interest

None.

Acknowledgements

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