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Estimating Abundance of Adult Striped Bass in Reservoirs Using Mobile Hydroacoustics

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Abstract.— Hydroacoustic surveys have proven valuable for estimating reservoir forage fish abundance but are more challenging for adult predators such as striped bass *Morone saxatilis*. Difficulties in assessing striped bass in reservoirs include their low density and the inability to distinguish species with hydroacoustic data alone. Despite these difficulties, mobile hydroacoustic surveys have potential to provide useful data for management because of the large sample volume compared to traditional methods such as gill netting and the ability to target specific areas where striped bass are aggregated. Hydroacoustic estimates of reservoir striped bass have been made using mobile surveys, with data analysis using a threshold for target strength in order to focus on striped bass-sized targets, and auxiliary sampling with nets to obtain species composition. We provide recommendations regarding survey design, based in part on simulations that provide insight on the level of effort that would be required to achieve reasonable estimates of abundance. Future surveys may be able to incorporate telemetry or other sonar techniques such as side-scan or multibeam in order to focus survey efforts on productive habitats (within lake and vertically). However, species apportionment will likely remain the main source of error, and we see no hydroacoustic system on the horizon that will identify fish by species at the spatial and temporal scale required for most reservoir surveys. In situations where species composition can be reliably assessed using traditional gears, abundance estimates from hydroacoustic methods should be useful to fishery managers interested in developing harvest regulations, assessing survival of stocked juveniles, identifying seasonal aggregations, and examining predator–prey balance.

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Introduction

Hydroacoustic methods have proven effective for estimating reservoir forage fish abundance. These mobile surveys are cost-effective to carry out (after the initial purchase cost of equipment) and provide fine-scale information on spatial distribution (e.g., Degan and Wilson 1995; Schael et al. 1995; Taylor et al. 2005). The ability to sample a large volume, compared to other methods such as gill netting, is important for forage species such as threadfin shad *Dorosoma petenense* that often occur at high but patchy densities. Estimating forage fish abundance by species is often straightforward because the pelagic zone typically contains only a few prey species.

Applying hydroacoustic methods to adult predators such as striped bass *Morone saxatilis* has been more challenging, but prior attempts at assessments of land-locked salmonids suggest that the application may hold promise for large predators in other systems (Yule 2000; Gangl and Whaley 2004; and reviewed in Taylor and Maxwell 2007). Practical difficulties include the relatively low density of adult predators and the inability to distinguish species with hydroacoustic data alone. Effective hydroacoustic methods for adult striped bass would be welcome, however, because other assessment techniques such as capture–recapture methods are laborious (Hightower and Pollock 2013, this volume) or provide only relative indices of abundance (e.g., annual gill-net surveys).

The purposes of this chapter are to review prior hydroacoustic surveys of striped bass and discuss design considerations in planning future surveys. We also consider recent developments in hydroacoustic equipment and whether technological advances will enhance our ability to survey reservoir populations of striped bass.

Prior Hydroacoustic Studies

We found three published studies that used hydroacoustic methods to estimate abundance of adult striped bass. Two were conducted in lakes and the third was carried out in the lower Hudson River estuary. All three studies (summarized below) used scientific fishery hydroacoustic systems. This type of system consists of an echo sounder that produces the digital signal that is transmitted underwater by the transducer. Returning echoes from a fish or other object are received by the transducer and amplified by the echo sounder. The timing of the returning echo determines the range of the object from the transducer while the intensity of the returning echo (target strength) is proportional to the size of the fish target (Love 1977) and can be used to separate individuals according to expected sizes (e.g., of predators versus smaller prey). A laptop computer controls the data acquisition parameters and also stores data from the echo sounder for later analysis. Older studies used either single- or dual-beam transducers, which had limited ability to resolve positions of fishes within the acoustic beam (Ehrenberg and Torkelson 1996). More recent studies have adopted split-beam transducers, which increase the precision of positioning within the beam and also decrease the variation in the estimate of target strength of the returning echo (Ehrenberg and Torkelson 1996). Transducer beam widths are chosen to optimize the detection of fish targets while limiting acoustic noise not attributed to fish. Typically, acoustic beams are cones between 6° and 15° wide. The volume of water sampled increases with distance from the transducer (apex), with the volume near the apex poorly sampled. Two of the three studies reviewed below use a single vertically oriented transducer to sample from 2 m below the surface to near bottom. If the fishes are expected to occupy near-surface waters, an additional transducer is oriented horizontally to sample the upper water column (Figure 1). Two of the three studies used split-beam target tracking to identify individuals and estimate abundance. In target tracking, echoes showing a consistent trajectory through the acoustic beam are grouped together and counted as a single fish track (Taylor and Maxwell 2007). One study used echo integration to estimate density. This analytical approach is

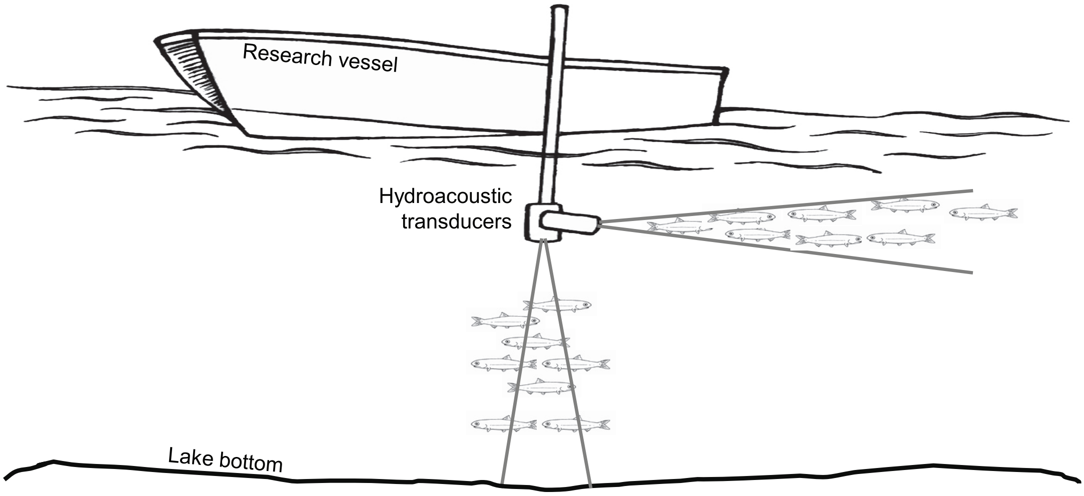

FIGURE 1. Two transducers deployed from the research vessel for simultaneous down-looking and side-looking deployments to sample fish targets throughout the water column.

appropriate when fish density is high and it is not feasible to track individual fish. It is based on the principle that the total acoustic energy returned from a sampled water volume is proportional to the number of fish in that volume (Taylor and Maxwell 2007). Information about the acoustic size (target strength) of an average individual fish is required to translate the total acoustic energy returned into an estimate of fish density. We focus below on the unique aspects of each study. Detailed information on fishery hydroacoustic theory and principles are provided elsewhere (Brandt 1996; Simmonds and MacLennan 2005).

Mueller and Horn (1999) carried out mobile hydroacoustic surveys of Lakes Mead and Powell and estimated striped bass abundance from areas of the lake greater than 20 m deep. The surveys were conducted in August of 1996 and 1997. Densities of striped-bass sized targets were relatively low, allowing individual targets to be counted to produce fish abundance estimates. They used a minimum threshold target strength of –40 dB to limit the analysis to fish estimated to be larger than 16 cm, based on studies relating target strength to fish size (Love 1977; MacLennan and Simmonds 1992). Catches from vertical gill netting (surface to depths >30 m) were used to partition the hydroacoustic estimates among species, with striped bass comprising an estimated 74–89% of the fish larger than 16 cm. The abundance estimates varied substantially between the 2 years (1.9 and 3.0 million in Lake Powell, 0.8 and 1.3 million in Lake Mead) and 90% confidence intervals were close to or included 0, so there was clearly much uncertainty associated with the estimates. The striped bass estimates along with similar estimates for prey species were used to examine predator:prey relationships and to explain the poor condition and die-offs observed for striped bass (Gustaveson and Blommer 2013, this volume).

Hartman and Nagy (2006) used mobile hydroacoustic surveys to estimate the abundance of striped bass, white perch *Morone americana* and bay anchovy *Anchoa mitchilli* in the lower Hudson River estuary. Their analysis was done from a depth of 2 to 0.5 m above bottom (with depths ranging up to 18 m), and the estimates were extrapolated to account for the entire water column. They estimated fish densities using echo integration and partitioned the density estimates into size-classes using an equation from Hartman and Nagy (2005) relating target strength to fish length. Midwater trawl catches were used to partition the size-specific density estimates among species. They also made a limited number of gill-net sets to determine whether their target species occurred within 0.5 m of the bottom. No striped bass were collected within this acoustically inaccessible zone. Their estimates of total abundance for striped bass (90 mm and larger) were 0.76 million in December 1995 and 1.47 million in December 1997. A high percentage of the estimated total in 1997 was in the size range classified as age 0.

Stewart et al. (2007) conducted mobile surveys during February using side- and down-looking transducers to estimate striped bass abundance in Lake Pleasant, Arizona. The focus of their study was to evaluate the impact of invading striped bass on an important and historically strong largemouth bass *Micropterus salmoides* fishery. Their analysis was based on individual fish tracks. Fish estimated to be larger than 125 mm (2005) or 150 mm (2006), based on Love's equation (Love 1977), were assumed to be potential predators. Striped bass comprised 25–38% of the fish in this size range, assuming that horizontal gill-nets set at the surface and on bottom obtained a representative sample of the population of interest.

Design Considerations

A primary advantage of mobile hydroacoustic surveys is the ability to sample a greater proportion of the reservoir in a sampling day compared to fixed-gear (e.g., gill net) or other direct sampling (e.g., trawls). Also, the volume sampled can be reliably estimated, whereas fixed-gear methods sample an unknown volume and catch rates depend partly on fish movement. Despite these advantages, a mobile hydroacoustic survey may still only represent a small fraction of the entire volume of the lake because of the narrow beam width of the hydroacoustic transducers. An effective survey design will consider time and resources available and sample a sufficiently representative geographic area and portion of the total volume, based on available information about density and seasonal distribution of striped bass. As an example, we calculated the number of fish that might be observed along a 1,000-m transect of a mobile hydroacoustic survey, assuming homogeneous distribution throughout a reservoir and using a striped bass population estimate of 136,227 fish age 1 and older from Smith Mountain Lake (Moore et al. 1991). The storage volume for Smith Mountain Lake (1,082,480 acre-feet) was obtained from a Federal Energy Regulatory Commission environmental impact statement document. Converting to cubic meters (and assuming a completely random striped bass distribution) generates a density estimate of 0.0001020 age-1+ striped bass per cubic meter. Unless the survey transects are predominately done at depths greater than 10 m, it is not likely that more than a single striped bass would be observed along any 1,000-m transect if using a 6° downward-oriented transducer (Table 1). Using a wider 15° transducer slightly more than doubles the expected number of fish encountered, but it also reduces the resolution, so there is less ability to separate individual fish targets, particularly near the bottom.

We then simulated a variety of spatial distributions of striped bass in a reservoir and simulated sampling of the population using a mobile acoustic survey and a range of sampling efforts. The population distribution and mobile survey were simulated using Wildlife Simulation Package (WiSP; Zucchini et al. 2007) in the statistical programming language R (R Development Core Team 2009). The simulated striped bass population was based on the assessment used above from Smith Mountain Lake, Virginia (Moore et al. 1991). The simulated reservoir had a total area of about 10,000 ha and a population of 137,000 individuals. To simplify the simulation, we assumed that all fish were located at the 10-m depth stratum and that the survey was done using a 15° conical downward-oriented transducer. This results in a higher encounter rate than depicted in Table 1 and would be similar to seasonal periods in which striped bass are concentrated in a vertical band

TABLE 1. Calculated beam width and sampling volume for a 1,000-m-long transect. Beam width calculated for two common transducer beam widths, 6° and 15°. Beam volume is calculated for 5-m depth interval centered on each stratum. Fish counted per 1,000 m assumes a system-wide density of 0.000102 fish/m^3, as derived from Moore et al. (1991).

	6° beam			15° beam		
Depth stratum (m)	Beam width (m)	Beam volume (m^3)	Fish per 1,000 m	Beam width (m)	Beam volume (m^3)	Fish per 1,000 m
5	0.52	2,620	0.27	1.32	6,583	0.67
10	1.05	5,241	0.53	2.63	13,165	1.34
15	1.57	7,861	0.80	3.95	19,748	2.01
20	2.10	10,482	1.07	5.27	26,330	2.69
25	2.62	13,102	1.34	6.58	32,913	3.36
30	3.14	15,722	1.60	7.90	39,496	4.03
35	3.67	18,343	1.87	9.22	46,078	4.70
40	4.19	20,963	2.14	10.53	52,661	5.37
45	4.72	23,584	2.41	11.85	59,244	6.04
50	5.24	26,204	2.67	13.17	65,826	6.71

of suitable or preferred habitat (Coutant 2013; Rice et al. 2013; Thompson and Rice 2013; all this volume). The assumed vertical distribution determined the beam width and detection of individuals along a survey transect. We chose four types of distribution for this exercise: (1) a homogeneous and random (Poisson) distribution of individuals throughout the reservoir, (2) a distribution gradient with higher densities in one region of the reservoir as may be found during seasons of restricted thermal habitats or spawning season, (3) a patchy distribution that may be driven by the distribution of forage species or habitat preferences, and (4) a patchy distribution within a gradient (Figure 2). The effort for each survey varied from five parallel transects (approximately 40 km total survey length) to 50 transects (400 km total survey length). The first transect was randomly located and remaining transects were evenly spaced across the hypothetical reservoir. If an individual was within the detection width of the transducer beam, it was counted and the sampled area was estimated. A distance method was used to estimate the total abundance (Borchers et al. 2002). We simulated each level of effort 30 times and calculated the mean abundance and coefficient of variation for each level. The results are also presented in terms of the total distance traveled to provide guidance for designing a survey or monitoring program. Mobile surveys are usually conducted from small vessels at speeds between 1.5 and 2 m/s (5–7 km/h), which would equate to a maximum of 40–50 km survey distance per 8-h sample day.

This exercise highlighted two important considerations when designing a mobile hydroacoustic survey for fishes like striped bass in reservoirs. First, using a minimal effort level of 40 km of transects, and assuming a random and homogeneous distribution of fish in the system, coefficient of variation approached 20% (Figure 2). Second, as the population distribution departs from homogeneous, uncertainty in abundance estimates increases. In the extreme case of two large patches, coefficient of variation approached 60% for the lowest effort level. The coefficient of variation did not fall below 20% until effort was increased by 60% or another half-day of effort (Figure 2). For this 10,000-ha reservoir and the types of spatial distribution and patchiness simulated

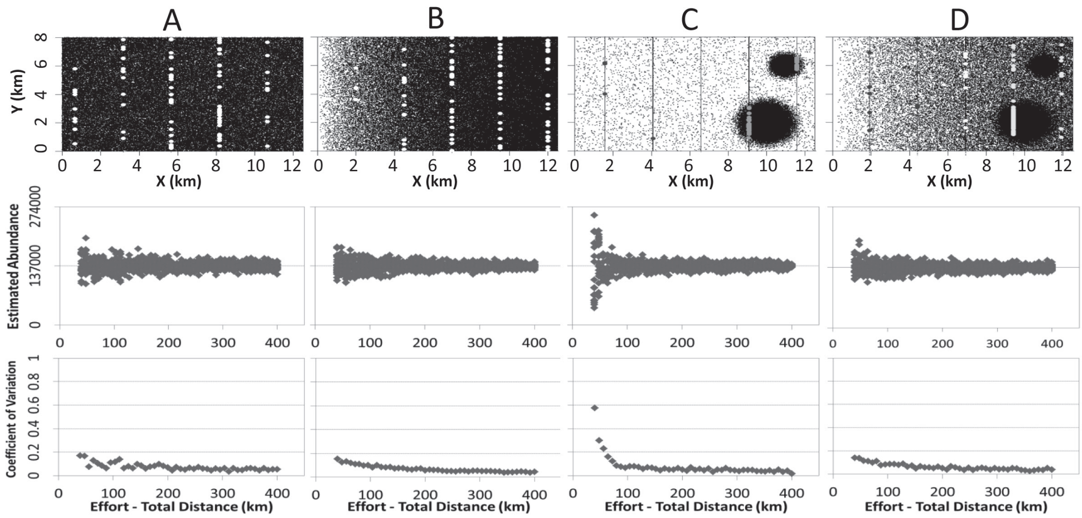

FIGURE 2. Results from a simulation survey of four types of spatial distribution of striped bass and varying level of survey effort. See text for description of system, population and survey. Top row shows the simulated 8,000 × 12,500 m rectangular reservoir with four types of striped bass distribution: (A) a homogeneous random distribution, (B) a gradient distribution varying 10-fold along the *x*-axis, (C) a patchy distribution with densities 100-fold higher in patches compared to surrounding system, and (D) two patches within a gradient distribution with densities 30- to 100-fold higher in patches compared to surrounding system. Vertical lines are shown as an example of the level of effort equivalent to 40 km and individuals that were detected along each transect (highlighted dots). Second row shows estimated abundances from 30 simulations at each level of survey effort (40 to 400 km). Bottom row shows coefficient of variation at each level of survey effort (SD/mean).

here, a survey effort level of 100 km of transects (2 d) would produce reasonable population estimates for large pelagic fishes such as striped bass. However, this exercise included some simplifying population and survey conditions: (1) single species, (2) fixed depth of all individuals, and (3) simple systematic (parallel) survey design. We encourage biologists and managers to consider this simulation approach when designing their survey for striped bass, paying particular attention to any prior knowledge about the spatial arrangement (e.g., patchiness) of the striped bass population and possible logistical constraints that may dictate a different survey design (e.g., zigzag pattern). As we discuss below, considerations must also be given to mixed-species communities and the need to apportion the hydroacoustic density estimates based on directed sampling for species identification.

Another potential design issue is that striped bass may occupy habitats that are not readily surveyed using hydroacoustics. For example, striped bass that are in shallow nearshore areas, within about 0.5 m of the bottom, within submerged standing timber, or in highly localized summer refuges such as springs or tributaries (Coutant 1985) would be difficult or impossible to survey. The best strategy here would be to determine times of the day or year when striped bass are separated from structure, bottom, and other species. For example, Mueller and Horn (1999) reported that during winter, striped bass were often closely associated with the bottom but, at night, would rise and disperse throughout the water column.

A hydroacoustic survey using a split-beam sonar provides some information about fish size based on the strength of returning echoes. If the survey is done using target tracking (which we recommend), then the average target strength for the series of echoes from an individual fish can be used to estimate fish size, using a regression equation such as that developed by Hartman and Nagy (2005). Using this approach to track individual fish, it should be possible to separate small forage fishes from larger fish such as striped bass (Figure 3). This does not eliminate the need for traditional sampling to get species composition (e.g., gill netting), but it does mean that species composition can be estimated for a specific size range of interest (e.g., the range containing adult striped bass).

Vertical gill netting can be a useful method for estimating species composition in open water (Mueller and Horn 1999). The main limiting factor for this method is that catches tend to be small, resulting in poor estimates of species composition over the larger zone of the hydroacoustic transect. Horizontal gill nets fished at the surface or bottom may be effective if large targets believed to be striped bass are distributed throughout the water column. Fishing a suspended gill net at a particular depth could be very effective in certain seasons (e.g., when striped bass are concentrated due to summer habitat squeeze), although setting the nets can be difficult and catches are often low (Stewart et al. 2007; Bergthold and Bettoli 2009).

One strategy for improving the precision of hydroacoustic surveys for striped bass would be to narrow the spatial scope of the survey. A data-driven approach for defining the spatial scope would be to implant transmitters in a subset of fish. Locations of radio- or sonic-tagged fish within the reservoir would make it possible to stratify by zone or habitat type, with proportionally more hydroacoustic sam-

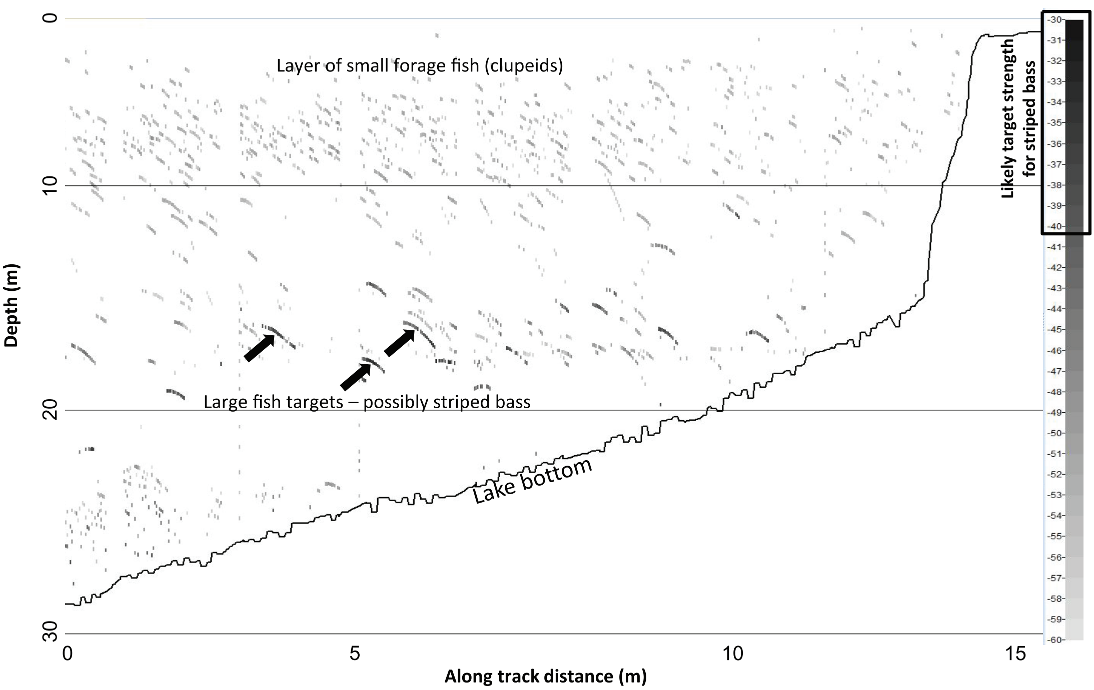

FIGURE 3. Example echogram from Badin Lake, North Carolina showing a layer of small forage fish (clupeids) within the first 10 m with larger fish targets (possibly including striped bass) between 10 and 20 m deep. The dashed box on the right side of the echogram indicates the range of target strengths (TS; –40 to –27 dB) that would be expected for striped bass larger than 150 mm, based on the relationship provided by Hartman and Nagy (2005). For clarity, only three large fish targets are identified.

pling in strata containing more striped bass. If depth- or temperature-sensing transmitters were used, the reservoir could be stratified in three dimensions. Information about the vertical distribution of striped bass should increase the efficiency of the hydroacoustic survey, simplify the analysis of hydroacoustic data, and reduce uncertainty about species composition of hydroacoustic targets. For example, Thompson (2006) used depth- and temperature-sensing tags to show that striped bass in Badin Lake, North Carolina were concentrated into a limited volume of (marginally) suitable habitat during summer due to temperature and dissolved oxygen requirements. Because of this "habitat squeeze" (Coutant 1985, 2013), summer would be a very efficient time to conduct a hydroacoustic survey for striped bass. However, one practical concern about a summer survey is that fish sampling for species composition could result in considerable mortality of striped bass.

If a data-driven approach is not feasible, initial weights for proportional sampling by stratum could be equal or based on information from anglers or area biologists. Preliminary weights could be updated as hydroacoustic data become available. For the hydroacoustic survey of Lakes Powell and Mead, Mueller and Horn (1999) limited their analysis of hydroacoustic data to areas of the lake greater than 20 m deep, based on the experience of area biologists.

A hydroacoustic survey during summer could also be useful for monitoring the decline in suitable habitat (habitat squeeze). The survey would provide three-dimensional information about where striped bass-sized targets are concentrated. Coupled with water quality data and predictions from reservoir water quality models (Ruane et al. 2013, this volume), it should lead to a greater understanding of how habitat squeeze impacts reservoir striped bass. It could also be used to assess the effectiveness of potential engineering methods intended to create better temperature-dissolved oxygen habitat (Mobley et al. 2013, this volume).

Field Trial of Simulated Survey Methodology

The mobile survey methodology described above was field tested on 2 September 2010 at Jordan Lake near Raleigh, North Carolina. The pilot survey was conducted in the Haw River arm, where summer die-offs of striped bass had been observed in prior years (N. C. Oakley, North Carolina Wildlife Resources Commission, personal communication). Four transects with a total distance of 10.1 km were done using a down-looking BioSonics DT-X split-beam system with a frequency of 430 kHz and a 7° transducer beam. Fish tracking was done using Echoview software, and tracks with an average target strength less than –35 dB were excluded. This target strength should correspond to an average size of about 35 cm, based on Love's (1971) dorsal aspect equation.

We detected six fish tracks with mean target strength greater than –35 dB. These fish were located at a depth of about 3 m, where water temperature was 29°C and dissolved oxygen concentration was about 2 mg/L. The dissolved oxygen level was less than 1 mg/L at a depth of 4 m, so we assumed the effective search volume was between our starting range of 0.5 m and the bottom or 4 m, whichever was less. This produced an estimated sampling volume for our transects of 16,204 m^3 or a fish density of 0.0004/m^3. This density is slightly higher than the estimate assumed in Table 1, but striped bass in Jordan Lake were concentrated into a limited depth range, and the six fish we detected may have included multiple species. The low number of detected targets also makes clear the difficulty of conventional sampling to get species composition. Fish sampling might be aided here by the apparently clumped spatial distribution for striped bass in this arm of the lake. All six targets we detected were less than 1 km apart and three of the six were at the same location.

Conclusions and Future Directions

Hydroacoustic surveys have several advantages over traditional methods such as gill netting.

Gear selectivity (relative vulnerability to capture across size-classes) is not an issue, whereas both gill nets and electrofishing are known to be size selective. Hydroacoustic surveys can cover large areas at fine resolution compared to the coarse resolution of traditional gears. It is also straightforward to expand hydroacoustic survey results to a whole-system abundance estimate if sufficient sampling is performed in each stratum, whereas traditional methods provide only an index of relative abundance.

Generating a lake-wide abundance estimate for striped bass-sized targets would typically require less than a week of transect effort in order to achieve reasonable precision. Relatively more effort would be needed if the distribution of striped bass is patchy, although information about the patchiness from telemetry, preliminary hydroacoustic surveys, or other data sources could result in a much more efficient and cost-effective survey.

Additional field effort would be required to partition the lake-wide abundance estimate among species. The sampling locations (areas and depths) and gears (e.g., gill-net orientation and mesh sizes) would be based on the hydroacoustic results. This should make the fish sampling more effective, as there may be relatively few species within the habitats occupied by adult striped bass. For example, striped bass comprised 74–89% of the vertical gill-net catch of fish 16 cm and larger within Lakes Powell and Mead (Mueller and Horn 1999). Similarly, mid-water trawl sampling in the lower Hudson River indicated that 100% of the fish between 30 and 100 cm were striped bass (Hartman and Nagy 2006).

A future direction for mobile hydroacoustic surveys may be to increase the sampling volume through the use of other sonar technologies. As we show in Table 1, striped bass may be rare along any given transect owing to the narrow transducer beam used. Other sonar technologies may provide information on the distribution of large fishes in reservoirs that could help guide the survey design. Multibeam echo sounders can increase the sampling swath by 10-fold, and many side-scan sonar systems are capable of sampling at least 100-m-wide swaths. Neither of these systems can currently provide quantitative information that could produce abundance estimates, but presence of large targets or groups or schools of large fishes could be used to focus effort using the split-beam echo sounder. Another approach is to orient a split-beam transducer at an oblique angle at the depth where striped bass are expected to occupy. Sample volume could be increased threefold compared to a vertically oriented transducer; however, this approach would only work if striped bass are well above the bottom. Alternatively, a horizontally aimed transducer towed at the expected depth of striped bass vertical distribution would increase the sample volume compared to surface-mounted transducers by more than sevenfold.

Abundance estimates from a hydroacoustic survey should be valuable to the fishery manager. These estimates would provide a context for interpreting creel survey results, that is, in assessing the extent to which fishing impacts the adult population. Hydroacoustic estimates can also be used to examine the effectiveness of a stocking program, not only survival from stocking to recruitment into the fishery, but also the adult population produced at different stocking rates. Estimates of population size can also be valuable for examining the predator:prey ratio. Hydroacoustic surveys often produce abundance estimates for forage fish as well as predators and would be valuable for examining whether current (or proposed) stocking levels might overwhelm the prey base. Tagging methods can also be used to estimate absolute abundance of striped bass, but it is difficult to generate the sample sizes needed to obtain precise estimates (see Hightower and Pollock 2013). Our view is that hydroacoustic surveys have the greatest potential of the available sampling gears for producing whole-lake abundance estimates that would allow for more advanced management approaches.

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References

Bergthold, C. L., and P. W. Bettoli. 2009. Growth, diet, and sampling of rainbow trout in three Tennessee reservoirs. Tennessee Wildlife Resources Agency, Fisheries Report 09-04, Nashville.

Borchers, D. L., S. T. Buckland, and W. Zucchini. 2002. Estimating animal abundance: closed populations. Springer-Verlag, London.

Brandt, S. B. 1996. Acoustic assessment of fish abundance and distribution. Pages 385–432 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Coutant, C. C. 1985. Striped bass, temperature, and dissolved oxygen: a speculative hypothesis for environmental risk. Transactions of the American Fisheries Society 114:31–61.

Coutant, C. C. 2013. When is habitat limiting for striped bass? Three decades of testing the temperature–oxygen squeeze hypothesis. Pages 65–91 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and hybrid striped bass. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Cyterski, M., J. Ney, and M. Duval. 2003. Estimation of surplus biomass of clupeids in Smith Mountain Lake, Virginia. Transactions of the American Fisheries Society 132:361–370.

Degan, D. J., and W. Wilson. 1995. Comparison of four hydroacoustic frequencies for sampling pelagic fish populations in Lake Texoma. North American Journal of Fisheries Management 15:924–932.

Ehrenberg, J. E., and T. C. Torkelson. 1996. Application of dual-beam and split-beam target tracking in fisheries acoustics. ICES Journal of Marine Science 53:329–334.

Gangl, R. S., and R. A. Whaley. 2004. Comparison of fish density estimates from repeated hydroacoustic surveys on two Wyoming waters. North American Journal of Fisheries Management 24:1279–1287.

Gustaveson, W., and G. Blommer. 2013. History of striped bass management in the Colorado River. Pages 15–23 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and hybrid striped bass. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Hartman, K. J., and B. W. Nagy. 2005. A target strength and length relationship for striped bass and white perch. Transactions of the American Fisheries Society 134:375–380.

Hartman, K. J., and B .W. Nagy. 2006. Winter distribution and abundance of Hudson River fishes using hydroacoustics. Pages 175–196 *in* J. R. Waldman, K. E. Limburg, and D. L. Strayer, editors. Hudson River fishes and their environment. American Fisheries Society, Symposium 51, Bethesda, Maryland.

Hightower, J. E., and K. H. Pollock. 2013. Tagging methods for estimating population size and mortality rates of inland striped bass populations. Pages 249–262 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and hybrid striped bass. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Love, R. H. 1971. Dorsal-aspect target strength of an individual fish. Journal of the Acoustical Society of America 49:816–823.

Love, R. 1977. Target strength of an individual fish at any aspect. Journal of the Acoustical Society of America 62:1397–1403.

MacLennan, D. N., and E. J. Simmonds. 1992. Fisheries acoustics. Chapman and Hall, New York.

Mobley, M., E. Shallenberger, M. W. Beutel, P. Gantzer, and B. Sak. 2013. Oxygen diffusers to create and maintain summer fish habitat. Pages 197–208 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and hybrid striped bass. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Moore, C. M., R. J. Neves, and J. J. Ney. 1991. Survival and abundance of stocked striped bass in Smith Mountain Lake, Virginia. North American Journal of Fisheries Management 11:393–399.

Mueller, G., and M. J. Horn. 1999. Description of the pelagic zooplankton and fish communities of Lakes Powell and Mead. U.S. Geological Survey, Bureau of Reclamation, Open

File Report 99-109. Available: http://pubs.usgs.gov/of/1999/0109/report.pdf (January 2012).

R Development Core Team. 2009. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Available: www.r-project.org. (January 2012)

Rice, J. A., J. S. Thompson, J. A., Sykes, and C. T. Waters. 2013. The role of metalimnetic hyposia in striped bass summer kills: consequences and management implications. Pages 121–145 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and hybrid striped bass. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Ruane, R. J., G. E. Hauser, and A. F. Sawyer. 2013. Water qualtiy modeling as a management tool for striped bass and hybrid striped bass. Pages 161–179 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and hybrid striped bass. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Schael, D. M., J. A. Rice, and D. J. Degan. 1995. Spatial and temporal distribution of threadfin shad in a southeastern reservoir. Transactions of the American Fisheries Society 124:804–812.

Simmonds, J., and D. MacLennan. 2005. Fishery acoustic theory and practice. Blackwell Scientific Publications, Oxford, UK.

Stewart, W. T., M. M. Meding, and D. R. Rogers. 2007. Lake Pleasant striped bass. Arizona Game and Fish Department, Research Branch, Technical Guidance Bulletin No. 11, Phoenix.

Taylor, J. C., and S. W. Maxwell. 2007. Hydroacoustics: lakes and reservoirs. Pages 153–172 *in* D. H. Johnson, B. M. Shrier, J. S. O'Neal, J. A. Knutzen, X. Augerot, T. A. O'Neill, and T. N. Pearsons. Salmonid field protocols handbook: techniques for assessing status and trends in salmon and trout populations. American Fisheries Society, Bethesda, Maryland.

Taylor, J. C., J. S. Thompson, P. S. Rand, and M. Fuentes. 2005. Sampling and statistical considerations for hydroacoustic surveys used in estimating abundance of forage fishes in reservoirs. North American Journal of Fisheries Management 25:73–85.

Thompson, J. S. 2006. The influence of temperature and forage availability on growth and habitat selection of a pelagic piscivore. Doctoral dissertation. North Carolina State University, Raleigh.

Thompson, J. S., and J. A. Rice. 2013. The relative influence of thermal experience and forage availability on growth of age 1–5 striped bass in two southeastern reservoirs. Pages 93–120 *in* J. S. Bulak, C. C. Coutant, and J. A. Rice, editors. Biology and management of inland striped bass and hybrid striped bass. American Fisheries Society, Symposium 80, Bethesda, Maryland.

Yule, D. 2000. Comparison of horizontal acoustic and purse-seine estimates of salmonid densities and sizes in eleven Wyoming waters. North American Journal of Fisheries Management 20:759–775.

Zucchini, W., D. L. Borchers, M. Erdelmeier, E. Rexstad, and J. Bishop. 2007. A Wildlife Simulation Package, WiSP 1.2.4. Institut fur Statistik und Okonometrie, Geror-August-Universitat Gottingen, Platz der Gottinger Seiben 5, Gottingen, Germany.