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Hydroacoustic Assessment of Inland Salmonid Populations

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Abstract – Hydroacoustics is potentially a valuable assessment tool for coldwater pelagic fish species such as salmonids that are typically underrepresented using traditional sampling methods such as standard gill nets. We conducted hydroacoustic surveys on five lakes to evaluate the use of hydroacoustics for assessing Rainbow Trout (*Oncorhynchus mykiss*), Brook Trout (*Salvelinus fontinalis*), and Cisco (*Coregonus artedi*) populations in Minnesota lakes. We determined that mean hydroacoustic population estimates for Rainbow Trout and Brook Trout yielded results similar to mark-recapture studies, but that error estimates were large as a result of low densities. We evaluated temporal and diurnal trends in Cisco densities and found that nighttime surveys were preferable to daytime surveys for estimating abundances. Finally, we evaluated different sampling strategies and determined that differences between transects could be eliminated through the application of autoregressive and moving average models. Using guidelines outlined in this report, we recommend that hydroacoustics continue to be developed as an assessment tool for managers interested in monitoring salmonid populations.

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INTRODUCTION

Hydroacoustics (i.e. using transmitted sound in water), has been used extensively in marine and freshwaters during the past 40 years to assess abundance, spatial distributions, and the behavior of fish populations (Brandt 1996, Simmonds and MacLennan 2005, Winfield et al. 2012). Because sound travels efficiently through water (~1475 m/s), large areas can be sampled relatively quickly and information on fish distributions can be collected in vertical and horizontal dimensions (Brandt 1996). Sound is reflected primarily from the swim bladders of fish and secondarily from muscle tissue, so that sound is reflected in relation to length (Love 1971). Although species cannot be directly identified by their acoustic signal, size information can be obtained that can be used to scale overall backscatter and estimate densities (Simmonds and MacLennan 2005).

There are several limitations to using hydroacoustics to survey fish populations in small inland lakes. First, scientific-grade echosounders tend to have narrow beam widths (typically 5-8°) and therefore sample less volume in shallow systems when using a vertical beam orientation. Secondly, backscatter cannot be analyzed in the nearfield where wave fronts are not parallel (Simmonds and MacLennan 2005). The nearfield depth is primarily dependent on the transducer frequency and beam angle (Parker-Stetter et al. 2009) and ranges from 2 - 6 m for frequencies typically used in freshwaters. Thirdly, hydroacoustics cannot be used to effectively sample fish within 0.5 m of the bottom (Brandt et al. 1996) or in vegetation where sound is quickly attenuated. Because of these limitations, hydroacoustics in inland lakes is most likely suitable for sampling cold-water pelagic species, such as salmonids, that may suspend midwater and are typically located below the thermocline where they are most susceptible to hydroacoustic sampling.

In Minnesota, native coldwater salmonids such as Cisco (*Coregonus artedi*) and Brook Trout (*Salvelinus fontinalis*) are likely to be negatively impacted by climate change as water temperatures warm and hypolimnetic oxygen declines during periods of stratification (Kling et al. 2003, Jacobson et al. 2008, Fang and Stefan 2009, Jacobson et al. 2010). For example, models of Minnesota lakes using future climate scenarios predict that only 1/3 of the lakes currently containing Cisco will retain suitable coldwater habitat for this species during the next 50 years (Fang et al. 2012). As climate changes occur, effective sampling strategies are imperative for monitoring these populations and providing information that can be used to inform management decisions.

Currently, native salmonids in Minnesota are under-sampled using traditional standard gill net assessments that do not effectively target pelagic species; therefore, developing improved sampling techniques to more accurately assess these populations is an important goal. Hydroacoustics have been used previously to successfully estimate *Coregonus* spp. densities, biomass, distribution, and behavior in lakes (Rudstam et al. 1987, Aku et al. 1997, Busch and Mehner 2009, Ahrenstorff et al. 2013). Similarly, hydroacoustics have been used to assess the abundance of pelagic salmonid piscivores such as *Oncorhynchus* spp. (Beauchamp et al. 1997, Ruzycki et al. 2003). However, there is limited research regarding the application of hydroacoustics in small lakes, particularly in regards to the accuracy of hydroacoustic estimates, the influence of survey design, and the effects of temporal and spatial variability on density estimates. The objective of this study, therefore, was to evaluate the use of hydroacoustics for estimating within-lake salmonid abundance, distribution, and behavior in small Minnesota lakes, and to determine guidelines for optimizing survey design and data analysis.

METHODS

Hydroacoustic data collection and analysis

Hydroacoustic surveys were conducted with a Biosonics (Biosonics Inc., Seattle, Washington) DTX echosounder and split-beam 123-kHz transducer with a circular 6° half-power beam angle. The unit was connected to a global positioning system to collect positional data. Data were collected at a pulse duration of 0.4 msec and a ping rate between 5 – 15 pings/sec, depending on the maximum depth at which data were collected (Parker-Stetter et al. 2009). Prior to each survey, the unit was calibrated with a tungsten-carbide reference sphere (Parker-Stetter et al. 2009).

Mobile surveys were conducted with the transducer deployed on a vertical pole mount 0.65 m below the water surface and the sampling speed of the boat maintained at 8 km/h. The beam was oriented downward at 90° below the surface for vertical down-looking surveys and 5° below the surface for horizontal side-looking surveys.

Hydroacoustic data were analyzed using Echoview 5.3 (Myriax Software Pty., Hobart, Tasmania). Upper water column depths corresponding to temperatures greater than 20°C were excluded from the analysis, given that these temperatures are actively avoided by salmonids such as Brook Trout, Rainbow Trout (*Oncorhynchus mykiss*), and Cisco (Frey 1955, Cherry et al. 1977, Coutant 1977). Data were divided into horizontal cells either 10 m or 20 m in size (Table 1). Volumetric density (ρ_{vS}, individuals/m^3) was calculated for horizontal cells by using the standard hydroacoustic equation:

$$\rho_{vS} = \frac{p_S}{\bar{\sigma}_{bs}} * s_v \tag{1}$$

where p_S is the expected proportion of the total number of fish which belong to species S, $\bar{\sigma}_{bs}$ is the weighted mean backscattering cross-section of all species, and s_v is the linear mean volume backscatter of the data being analyzed (S_v):

$$s_v = 10^{\frac{S_v}{10}} \tag{2}$$

The weighted mean backscattering cross-section ($\bar{\sigma}_{bs}$) was calculated using the equation:

$$\bar{\sigma}_{bs} = \sum_{S=0}^{N_S-1}\left(p_S 10^{\frac{TS_S}{10}}\right) \tag{3}$$

where N_S is the total number of species and TS_S is the expected target strength returned from an individual fish of species S.

A minimum threshold was applied to single target data based on the minimum lengths of the species of interest using single target and/or net data and converting lengths to target strength using equations published in the literature (e.g. Love 1971, Rudstam et al. 1987). Single target detection parameters were set according to the Standard Operating Procedures for Fisheries Acoustic Surveys in the Great Lakes (Parker-Stetter et al. 2009). A minimum TS threshold was applied to S_v data that was 6 dB lower than the ST threshold (Rudstam et al. 2009).

Densities (individuals/m^3) of horizontal cells (Table 1) were imported into R (2.15.1, R Core Team 2012) and plotted to determine the minimum bottom depth where salmonids were absent. Observations at depths shallower than this minimum bottom depth were excluded from the analysis. To account for temporal correlations in the data, fish densities were modeled using an autoregressive-moving average process (Venables & Ripley 2002), denoted as an ARMA(p, q) where p denotes the autoregressive order and q denotes the moving average order. The full autoregressive-moving average model was a regression of fish density on depth with ARMA(2, 2) residual errors; this model and all subsets down to an intercept-only model with independent errors were fit to the data, and the best fit model was determined using Bayesian information criteria (BIC) (Schwarz 1978). Bathymetric data were generated for each lake and were used to estimate lake volume by depth. Shallow depths where salmonids were absent and depths where temperatures exceeded 20°C were removed from volume estimates. The best fit model was then applied to the volume by depth data to generate a lake-wide population estimate constrained to the deeper and cooler locations where salmonids were expected to be present. Confidence intervals for the abundance estimates were constructed using parametric bootstraps in which the best fit model was used to generate 5000 new data sets with the same error structure; these simulated data sets were then used to estimate total abundance, and the middle 95 percentile of the boot-strapped abundance estimates represents the 95% confidence interval.

TABLE 1. Analysis parameters for down-looking hydroacoustic surveys used on the six different lakes evaluated in this study.

Lake name	Horizontal cell size (m)	ST threshold (-dB)	S_v threshold (-dB)	Min length (mm)
Little Andrus	10	-37	-43	200[a]
Allen	20	-43	-49	100[a]
Pillager	10	-45	-51	100[b]
Carlos	10	-47	-53	80 [b]
Flour	10	-43	-49	125[b]

[a]Based on target-strength equation from Love (1971)
[b]Based on Cisco target-strength length equation from Rustam et al. (1987)

Biomass estimates for Cisco were generated by developing a lake-specific length-weight regression for Cisco based on net catches. TS_S from each cell (if >30 targets) or from each transect was converted to a mean length using a published regression (Rudstam et al. 1987). The lake-specific length-weight regression for Cisco was then applied to the mean length estimates to calculate volumetric biomass (kg/m^3) in each horizontal cell. Overall biomass (kg) was modeled using the same procedure as for population estimates (see above).

Assessment of stream trout in lakes

Little Andrus (Snowshoe, DOW: 11005400) in Cass County was reclaimed with Rotenone on 7 Oct 2009 and was stocked with Brook Trout on 15 Apr 2010. Daytime down-looking hydroacoustic surveys were conducted on Little Andrus pre-reclamation on 30 Jul 2009 and on 5 Oct 2009, and daytime down-looking and side-looking surveys were conducted post-reclamation on 28 Apr 2010. Monofilament gill nets (15.24 x 1.82 m panels of 19, 25, 32, 38, 51 mm bar mesh) were set on 30 Jul 2009 and 5 Oct 2009 concurrent with hydroacoustic sampling. Trap nets were also set on 6 Oct 2009. Fish retrieved from gill nets and trap nets set in October were marked and released as part of a mark-recapture study that was done in conjunction with reclamation. Little Andrus hydroacoustic data were analyzed using the parameters listed in Table 1. Greater than 95% of Brook Trout captured in gill nets and trap nets were larger than the 200 mm minimum size that was used. Densities of Brook Trout greater than 200 mm were calculated by scaling estimates with species proportions from net data.

Allen Lake (DOW: 18020800) in Crow Wing County was reclaimed in autumn 2007 and was stocked with Brook Trout and Rainbow Trout in October 2008. Additional Brook Trout were stocked on 2 Jun 2009. A daytime down-looking hydroacoustic survey was conducted on Allen Lake on 29 Jul 2009. Allen Lake hydroacoustic data were analyzed using the parameters listed in Table 1. The minimum size of Rainbow Trout and Brook Trout captured in trap nets in September was 185 mm, so the minimum length threshold for the July data was set at 100 mm to account for growth.

Assessment of Cisco in small lakes

Temporal inter-month and inter-annual variability in population estimates were explored using mobile daytime down-looking hydroacoustic surveys conducted on Pillager Lake (DOW: 11032000) during the following dates: 30 Jun 2009, 6 Aug 2009, 8 Sept 2009, 9 Oct 2009, 14 Jun 2010, 19 Aug 2010, 16 Sept 2010, 5 Nov

2010, 24 Jun 2011, 19 Aug 2011, 15 Sep 2011, 3 Nov 2011, 22 Jun 2012, 15 Aug 2012, 12 Sep 2012, and 16 Oct 2012. Standardized transects were conducted on each date that corresponded to a coverage of 7.1 km of transect per 0.83 km^2 of lake area. Pillager Lake hydroacoustic data were analyzed using the parameters listed in Table 1. The horizontal distributions of Cisco were mapped by modeling spatial correlation with geostatistics and using ordinary kriging in the Geostatistical Analyst of ArcGIS. Vertical densities of Cisco were calculated by exporting all S_v data in 1 m depth intervals and scaling data using a depth-specific mean target strength estimate.

The effects of sampling design were investigated using back-to-back whole lake transects on Lake Carlos (DOW: 21005700) during a mobile night down-looking survey on 6 Sep 2012. One transect ("straight") disproportionately sampled the deepest waters while the other transect ("zigzag") bisected the deepest depths and sampled a greater variety of depths. Vertical gill nets (10-m panels of 9.5, 13, 19, 32, 38, 45, 51 mm bar mesh) were set overnight at the deepest hole in the north basin during the night of 5 Sep 2012 and in the deepest hole in the south basin during the night of 6 Sep 2012. Fish captured in vertical gill nets were identified, measured, a subsample were weighed, and the depth of capture was recorded. Hydroacoustic data were analyzed using the parameters listed in Table 1. Vertical densities of Cisco were calculated by exporting all S_v data in 1 m depth intervals and scaling with a depth-specific TS_S.

The effects of sampling design, diel variability, and inter-day variability was explored using down-looking mobile surveys on Flour Lake (DOW: 16014700) on 16-18 Jul 2012. Whole lake transects were conducted back-to-back during daylight (at least 2 h after sunrise) and at night (at least 1 h after sunset) on subsequent dates. Transects included a "straight" transect that disproportionately sampled the deepest waters and a "zigzag" transect that bisected the deepest depths and sampled a greater variety of depths. Vertical gill nets (10-m panels of 9.5, 13, 19, 32, 38, 45, 51 mm bar mesh) were set overnight in the each of the three deepest holes of different basins during the nights of 16-18 Jul 2012. Fish captured in vertical gill nets were identified, measured, a subsample were weighed, and the depth of capture was recorded. Hydroacoustic data were analyzed using the parameters listed in Table 1.

RESULTS

Assessment of stream trout in lakes

Gill net data from Little Andrus on 30 Jul 2009 and gill net and trap net data on 5-6 Oct 2009 indicated that percentages of fish greater than 200 mm were 90% and 75%, respectively. Hydroacoustic density estimates were scaled proportionately. Estimates of the number of Brook Trout in Little Andrus pre-reclamation were 1,175 ± 730 on 30 Jul 2009 and 565 ± 365 on 5 Oct 2009. These hydroacoustic estimates were not significantly different than the mark-recapture estimate of 960 ± 420. Little Andrus was stocked post-reclamation with 367 adult Brook Trout on 15 Apr 2010 (total weight 403.7 lbs). On 28 Apr 2010, no backscatter were detected during the downward-looking hydroacoustic survey, but results from a side-looking hydroacoustic survey indicated the presence of several Brook Trout-sized targets in the top 3.0 m of the water column. Using side-looking hydroacoustics, estimates of adult Brook Trout during the April survey were 215 ± 100.

Allen Lake was stocked post-reclamation in Oct 2008 with Brook Trout (4,308 fingerlings/total weight 215 lbs; 1,015 yearling/total weight 203 lbs; and 155 adult Brook Trout/total weight 160 lbs) and Rainbow Trout (3,330 fingerlings/total weight 222 lbs; 1,550 yearlings/total weight 1,115 lbs). An additional Brook Trout stocking (83 yearlings/ total weight 59 lbs) occurred on 2 Jun 2009.

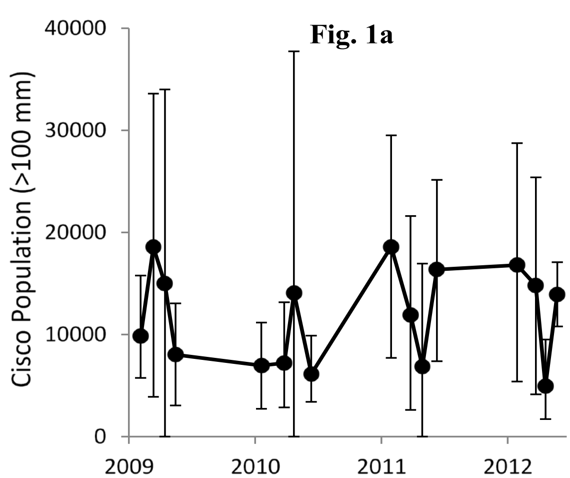
Rainbow and Brook Trout-sized hydroacoustic targets were located in Allen Lake between 4.8 and 5.6 m depth, corresponding to an average temperature of 17.5°C and dissolved oxygen concentration of 4.0 mg/L. The hydroacoustic estimate of trout abundance was 1070 ± 465. In Oct 2009, Brook Trout (3,914 fingerlings/total weight 106 lbs) and Rainbow Trout (3,330 fingerlings/total weight 313 lbs) were restocked. A mark-recapture study conducted in Sept 2010 estimated a population of 515 ± 290 age-1 Brook Trout and 400 ± 180 age-2 Brook Trout.

Assessment of Cisco in small lakes

Monthly population estimates of Cisco >100 mm in Pillager Lake were variable (Figure 1a). There were no significant effects of month (ANOVA, $F(3,12)=0.33$, $p>0.05$) or year (ANOVA, $F(3,12)=0.14$, $p>0.05$) on Cisco population estimates. Monthly estimates were averaged to attain an annual population estimate of 8,500-13,500 individuals per year, although the error around these estimates was considerable (Figure 1b). Spatially, Cisco were aggregated during daytime surveys, and the location of these aggregates varied by survey (Figure 2). Vertically, Cisco were located throughout the water column in June and after autumn turnover, but were concentrated during the months of August and September in depth strata where temperatures were less than 20°C and oxygen concentrations were greater than lethal limits (Figure 3).

In the north and south basins of Lake Carlos, >99% of Cisco captured in vertical gill nets were distributed below the thermocline between 15–40 m depths, which corresponded to peak vertical hydroacoustic density estimates on the "straight" and "zigzag" transects (Figure 4). Horizontal density estimates (individual/m^3) using 10-m analysis cells were highly correlated with bottom depths, with the highest densities occurring over the deepest depths. An ARMA(1,1) autoregressive-moving average model was applied to the density data and generated Cisco (>85 mm) population estimates that were nearly identical between the two transects. The "straight" population estimate was 605,000 ± 230,000 (95% CI) and the "zigzag" population estimate was 593,000 ± 176,000 (95% CI). Combining transects, representing an approximate doubling of sampling effort, generated a population estimate with a slightly tighter confidence interval of 606,000 ± 146,000 (95% CI). Mean biomass estimates were also nearly identical between transects, but the error estimates were larger. The "straight" biomass estimate was 36,500 ± 22,500 (95% CI) kg, the "zigzag" biomass estimate was 34,300 ± 11,800 (95% CI) kg, and the combined estimate was 35,600 ± 10,100 (95% CI) kg.

Nearly all (>98%) Cisco captured in vertical gill nets on Flour Lake were located below the thermocline between 7 and 21 m depths. Population estimates on Flour Lake were significantly lower during the day than at night (Figure 5). Generally, the "zigzag" transects provided lower error estimates than the "straight" transects, but the zigzag transects also represented a 60% increase in sampling effort. Combining transects represented an additional 30% increase in sampling effort that resulted in tighter confidence intervals. Cisco population estimates were not significantly different in subsequent nights, but there was a significant difference between subsequent daytime estimates once transects were combined (Figure 5). Biomass estimates followed patterns similar to population estimates, except that the TS_S estimates were lower during Day 1 transects so that biomass estimates were higher and more similar to those estimated from night surveys.



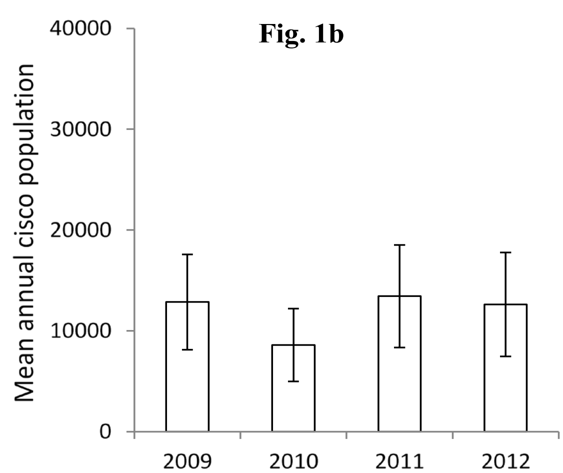


FIGURE 1. Population estimates of Cisco in Pillager Lake estimated using hydroacoustics by month (Figure 1a) and by year (Figure 1b). Error bars are ± 95% CI.

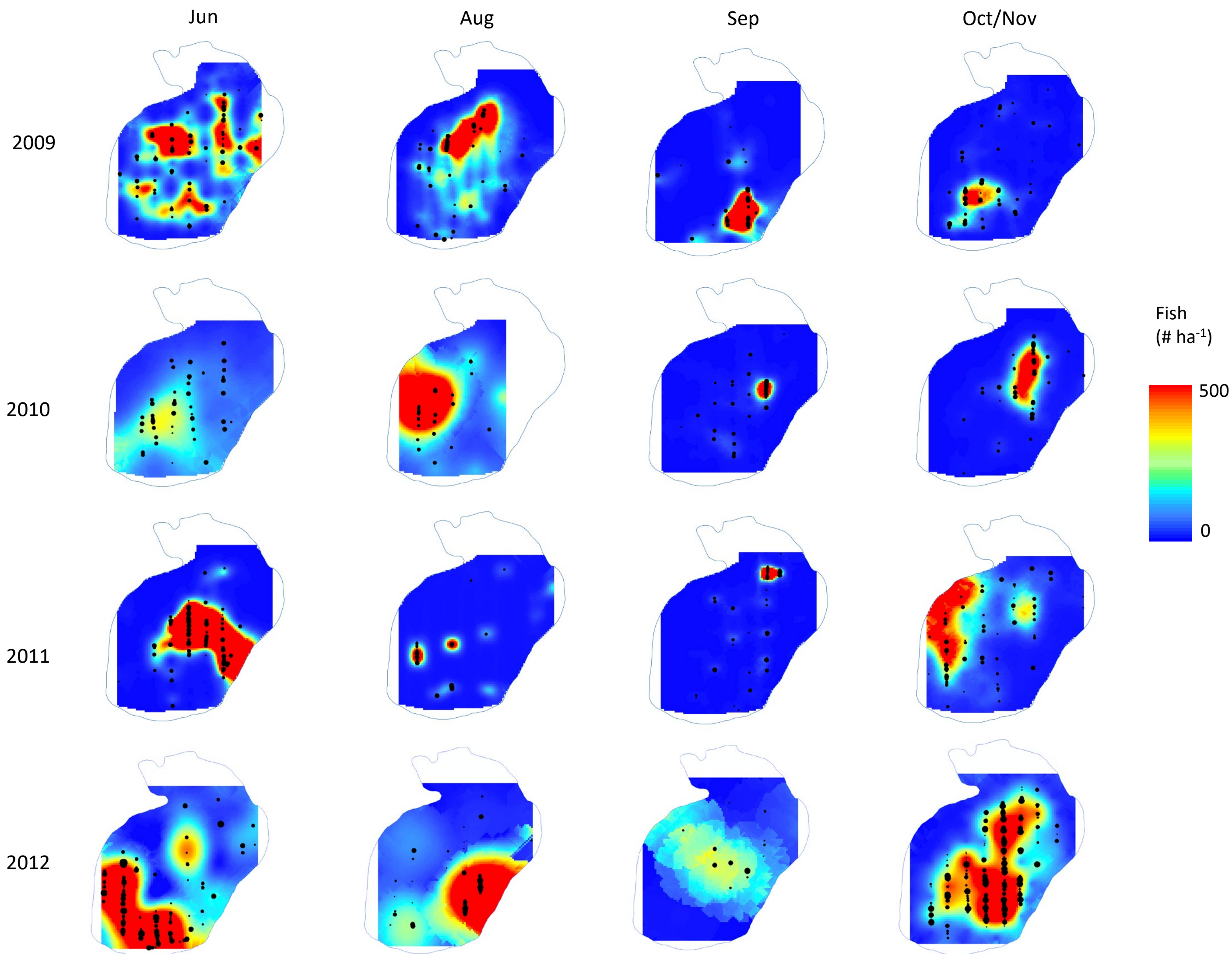


FIGURE 2. Kriged maps of Cisco spatial distribution by year and month. Colors shades represent fish density (individuals/ha) and black circles represent single fish targets identified using hydroacoustics.

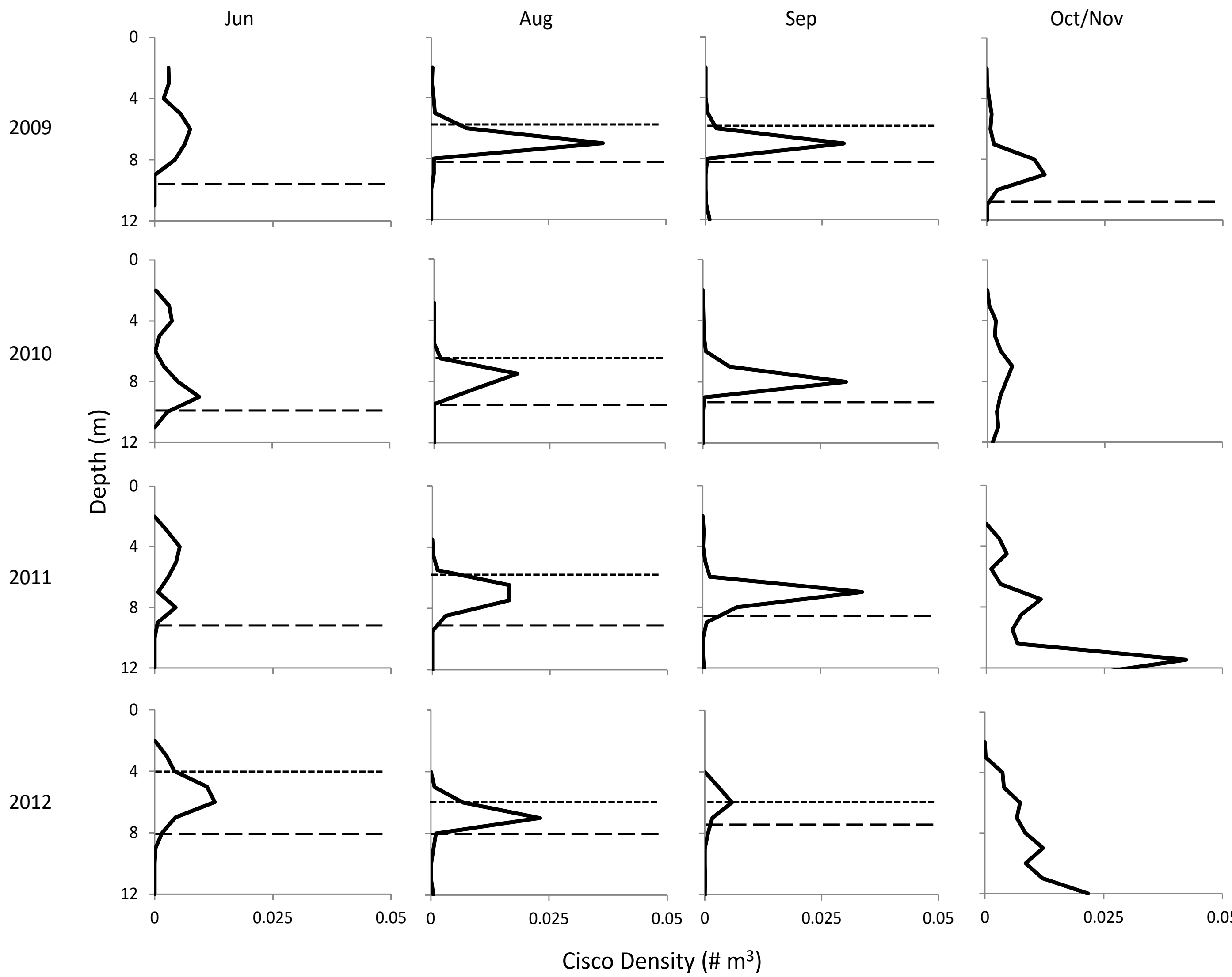


FIGURE 3. The vertical distribution of Cisco (individuals/m^3) in Pillager Lake by month and year. The short dashed lines represent the depth of 20°C temperatures and the long dashed lines represent the depth of lethal oxygen concentration (Jacobson et al. 2008).

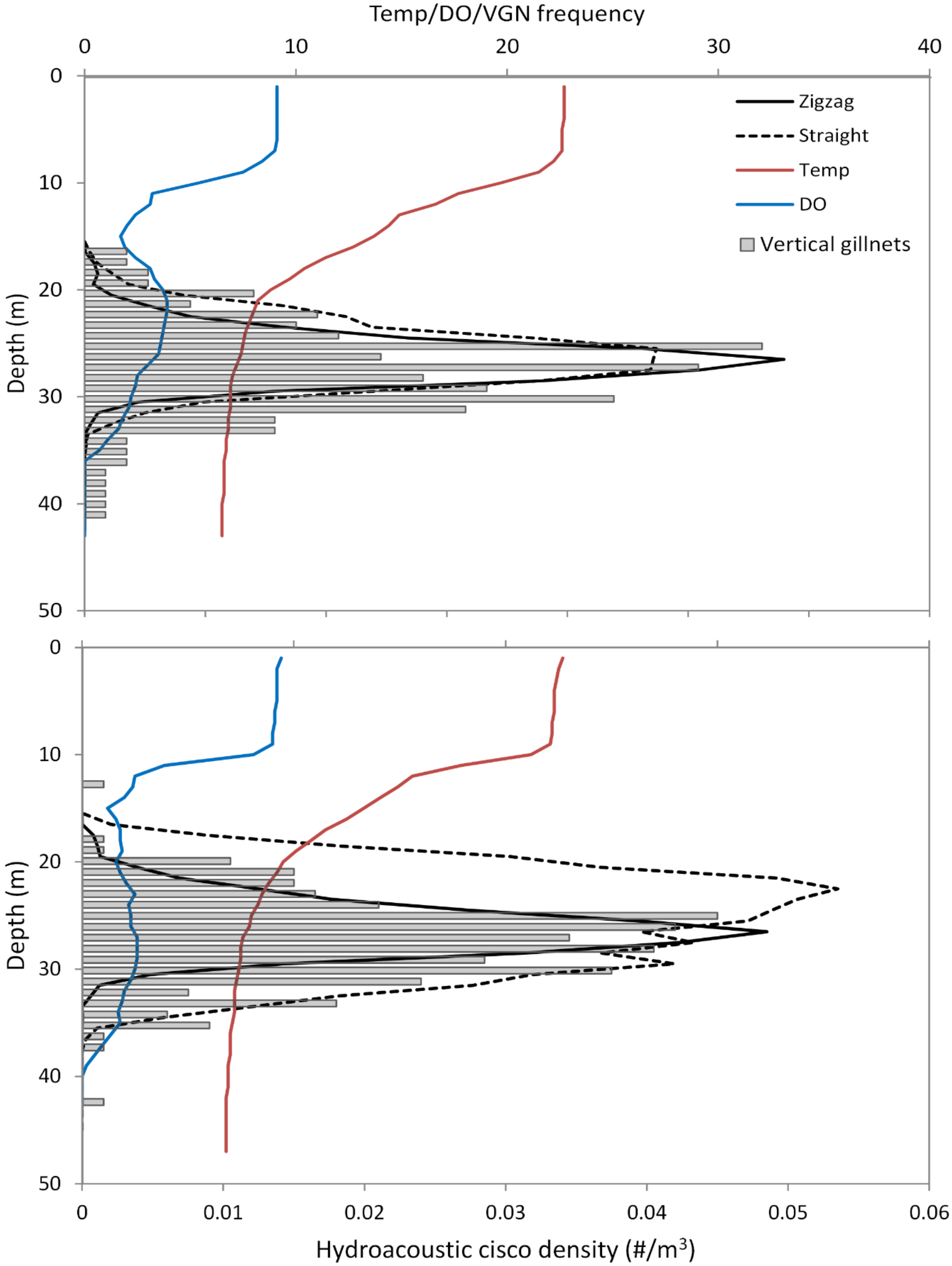


FIGURE 4. The distribution of Cisco captured in vertical gill nets in the north basin (top panel) and in the south basin (bottom panel) compared to hydroacoustic vertical density estimates (individuals/ha) from the “straight” and “zigzag” transects. Temperature (°C) and dissolved oxygen (mg/L) profiles are also plotted.

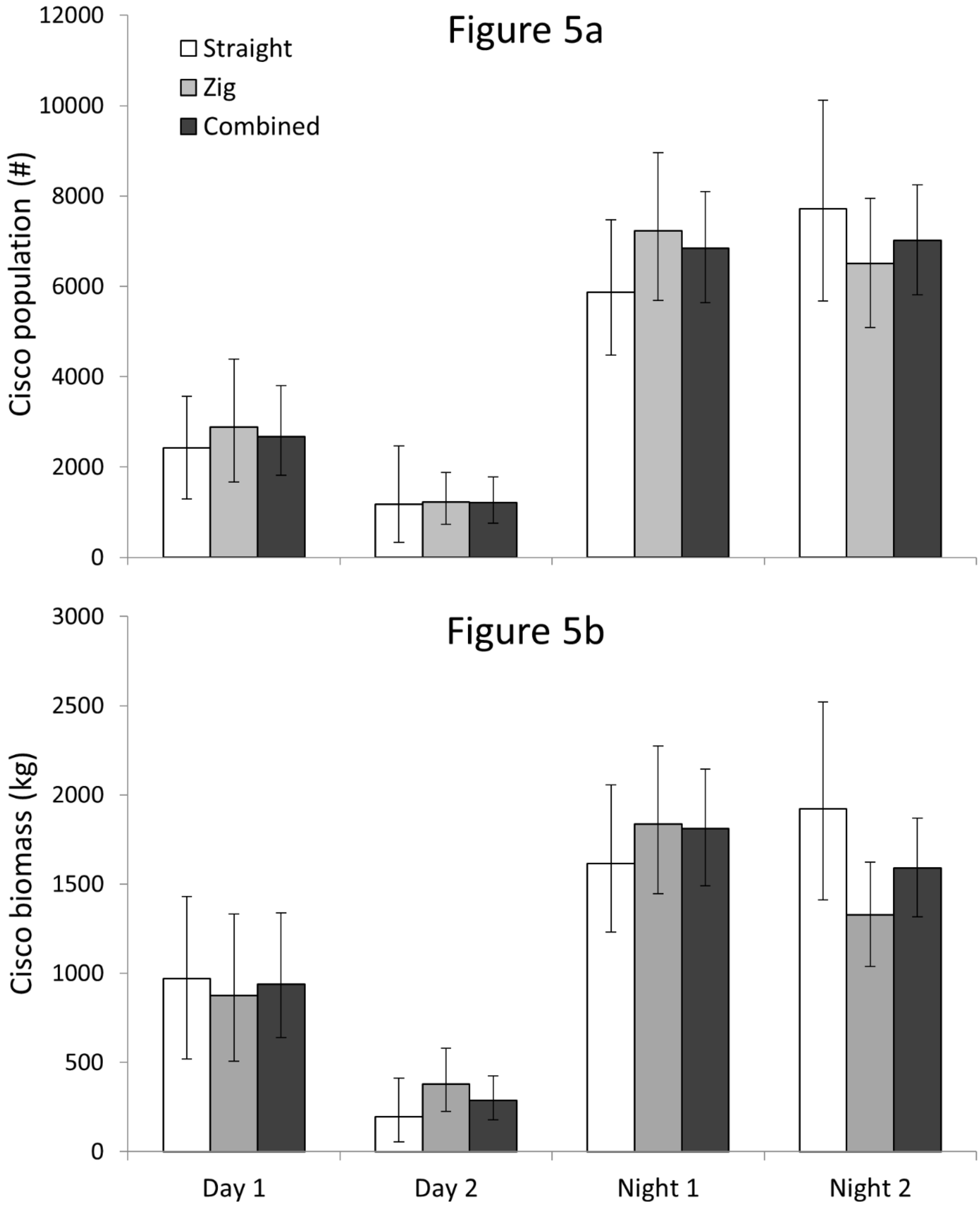


FIGURE 5. Flour Lake population (Figure 5a) and biomass (Figure 5b) estimates for the "straight", "zigzag", and combined transects for subsequent survey days and nights.

DISCUSSION

Assessment of stream trout in lake

Little Andrus and Allen Lakes are managed as put, grow, and take trout fisheries, and are therefore periodically reclaimed with Rotenone when other species become abundant. These lakes represented a unique scenario in which population estimates generated by hydroacoustics could be compared to either mark-recapture estimates or to a known number of stocked fish. In both lakes, hydroacoustic population estimates were statistically similar to mark-recapture population estimates or to the known number of stocked fish, suggesting that hydroacoustics may provide a reliable mean estimate of pelagic salmonid abundance. However, the error estimates for all sampling dates in both lakes were considerable. Density estimates in both lakes were best fit with a simple mean, suggesting that fish were not clustered and that the large confidence intervals were likely a result of low densities.

The mean hydroacoustic estimate of Brook Trout in Little Andrus was approximately half the mark-recapture estimate in October 2009, although the confidence intervals overlapped (Figure 1). A visual inspection of the echogram from October 2009 indicated that many Brook Trout-sized targets were located within the bottom 0.75 m of the water column. These targets could not be easily resolved from the substrate and were mostly excluded. Additionally, targets within the bottom 0.5 m were located in the acoustic dead zone where backscatter is only partially integrated due to the shape of the beam (Simmonds and MacLennan 2005). Therefore, the October hydroacoustic estimate of Brook Trout in Little Andrus was likely an underestimate. The mean estimate from the July 2009 survey may have been more representative given that hypoxia likely excluded fish from the bottom and epilimnetic temperatures greater than 20°C likely excluded Brook Trout from the top 4 m and from nearshore areas where they would be less susceptible to hydroacoustic sampling. Similarly, the July 2009 survey for trout on Allen was conducted when warm (>20°C) epilimnetic temperatures and low dissolved oxygen levels concentrated trout in 4.5 – 5.5 m depths. The disadvantage of conducting hydroacoustic surveys for pelagic salmonids during periods when they were concentrated into narrow strata near the thermocline was that the volume of water sampled at these depths was only a fraction of that sampled when fish were located deeper. For example, the area sampled by the beam at 5 m depth was only 25% the area sampled by the beam at 10 m depth.

Hydroacoustic surveys for stream trout in Little Andrus and Allen Lakes were conducted during daylight hours. Currently, there is conflicting evidence regarding the most appropriate time of day for conducting hydroacoustic surveys of salmonids such as *Oncorhynchus* spp. In lakes where salmonids schooled during the day, nighttime surveys were preferable, while in lakes where fish migrated nearshore or to the surface at night, daytime surveys were preferable (e.g. Beauchamp et al. 1997, Yule et al. 2000). However, most hydroacoustic surveys of salmonids have been conducted in lakes and reservoirs in western states where there may be extensive habitat <20°C available nearshore and near-surface even in mid-summer. Further investigation should be conducted on Minnesota lakes to determine the most appropriate time of day for conducting hydroacoustic surveys of Rainbow Trout and Brook Trout.

Assessment of Cisco in small lakes

Daytime hydroacoustic surveys were not an effective method for assessing Cisco populations in Pillager Lake due to large variability in the estimates. Confidence intervals were greater than 40% of the mean for all surveys dates, except one. The sole exception was the survey conducted on 16 Oct 2012 when a relatively homogenous distribution of Cisco allowed for error estimates of approximately 20% of the mean. The best fit statistical model for the densities in Pillager Lake were generally either an autoregressive model, a moving average model, or a combination of both, indicating that populations were aggregated. Spatial mapping of Cisco densities in Pillager Lake supported this hypothesis and further indicated that there was no consistency in the location of these aggregates.

There was no evidence that sampling during a particular time period (e.g. early stratification, late stratification, post stratification) increased the accuracy of population estimates in Pillager. It is important to note, however, that all surveys on Pillager were conducted during the day and that typically night hydroacoustic surveys yield higher density estimates and a more homogenous distribution for schooling pelagic fish (Eckmann 1991, Appenzeller and Leggett 1992, Degan and Wilson 1995). Two night hydroacoustic surveys were conducted during this time series; unfortunately, large densities of *Chaoborus* spp. prevented the data from being analyzed using the same thresholds as the daytime data. Visual inspection of the echograms did indicate approximately twice as many fish tracks, fewer aggregates, and a more homogenous spatial distribution than data collected during the day. In the future, nighttime hydroacoustic surveys would be preferable for assessing Cisco populations in Pillager, although a lower frequency than the 120-kHz used in this study may be necessary to eliminate backscatter from *Chaoborus* (Knudsen et al. 2006).

Temporal changes in the vertical distributions of Cisco in Pillager were also examined monthly from 2009-2012. During early- and post-stratification, Cisco were distributed across a variety of depths, but during the months of late-stratification, Cisco were squeezed in narrow strata where temperatures were less than 20°C and dissolved oxygen concentrations were above lethal limits. These hydroacoustic results were consistent with depth data collected from acoustically tagged fish in the same lake (A. Carlson, personal communication). The monthly patterns in vertical distribution were consistent during all years of the study.

Nighttime hydroacoustic surveys on Lake Carlos for Cisco > 80 mm generated population estimates with a relatively small confidence interval, particularly when the two transects were combined. Cisco density estimates in Carlos were highly correlated with bottom depth, so that using an overall mean to estimate densities resulted in higher population estimates from the "straight" transect that disproportionately sampled a greater amount of deep water than with the "zigzag" transect. Applying an autoregressive-moving average model generated population estimates that were nearly identical, effectively eliminating differences due to sampling design. The combined transect whole lake population estimate of ~600,000 is remarkable given that a total of nine Ciscoes were captured in 13 standard lake survey assessments in Carlos since the 1950s. However, standard gill net sites sampled depths less than 14 m, whereas Cisco were predominantly located at depths greater than 20 m in Carlos (Figure 4).

In Flour Lake, night surveys yielded higher hydroacoustic density estimates of Cisco >125 mm than day surveys. These results were consistent with previous studies of *Coregonus* spp. that found significantly higher densities at night (Eckmann 1991, Guillard and Verges 2007). Both day and night density estimates were best fit with either a simple mean or a linear regression with depth, suggesting that Cisco were either: a) homogenously distributed or b) aggregated but not effectively sampled. At night, the first explanation seems more probable given that Cisco targets were abundant and evenly distributed, but during the day, the second explanation seems more probable given that Cisco targets were scarce and more likely to be located near the bottom. In Flour Lake, density estimates were more variable in subsequent days than subsequent nights, which was partially attributable to differences in TS_S estimates. These results are also consistent with previous work that found greater bias in TS_S measurements during the day when fish were aggregated (Appenzeller and Leggett 1992, Fréon et al. 1993, Fréon et al. 1996).

In summary, the results of this study indicate that night hydroacoustic surveys should be used to assess Cisco populations and should be evaluated for Rainbow Trout and Brook Trout. Additional research should be conducted to determine the most appropriate time period (i.e. pre-stratification, early-stratification, late-stratification, post-stratification) for using hydroacoustic surveys. However, preliminary data from this study suggests that early-stratification surveys are advantageous because they allow for the separation of warm- and cool-water species above the thermocline (e.g. yellow perch) and cold-water species below the thermocline (e.g. Cisco and stream trout). Late-stratification surveys have similar advantages, but they may yield more variable results if salmonids are squeezed into narrow strata where single target resolution becomes difficult and sampling volume is reduced. We have determined that sampling design should encompass a representative distribution of depths and that by doing so, variability in sampling design can be addressed through the application of auto-regressive and moving average models. The application of these models is a promising method for addressing the issues of non-independence among observations that has typically been one of the main challenges associated with analyzing hydroacoustic data.

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