Exxon Valdez Oil Spill
Long-Term Herring Research and Monitoring Program Final Report

Intensive Surveys of Juvenile Herring

Exxon Valdez Oil Spill Trustee Council Project 15120111-G
Final Report

Peter S. Rand
Prince William Sound Science Center
P.O. Box 705
Cordova, AK 99574

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Study History: This project emerged from concern about the precision of acoustic surveys for juvenile herring supported through another project (15120111-F). Prior to this project, a single survey was conducted to characterize densities and abundance of juvenile herring in Prince William Sound. This project was focused on quantifying variability of results from surveys that were repeated over contiguous nights.

Abstract:
Pacific herring (*Clupea pallasii*) have not recovered in abundance since their decline in the early 1990s in Prince William Sound, Alaska. Annual monitoring of the adult population has been on-going for decades, but less attention has been focused on the juvenile stages. No information currently exists on the precision of hydroacoustic surveys targeting juvenile herring in Prince William Sound. We tracked seasonal and spatial patterns in densities of juvenile Pacific herring (ages 0 and 1, individuals km^{-2}, occupying the top 30 m of the water column) using hydroacoustics during an overwinter period during 2013-2014 in Simpson Bay in eastern Prince William Sound. We relied on trawl catches to apportion total backscatter to juvenile herring. We observed a discontinuous pattern through the fall-spring period, punctuated with a late October peak of 753,885 herring km^{-2}. Juvenile herring density dropped by 96% over the winter, but then increased again during the spring. Precision of the survey determined by replicate transect sampling (coefficient of variation of density) ranged from 2-106%, with a mean across the surveys of 52%. A number of challenges exist for monitoring juvenile herring, particularly surveying in shallower habitat and limited access to their habitat by vessels in the early spring due to the presence of shelf ice.

Key words: *Clupea pallasii*, hydroacoustic survey, juvenile Pacific herring, mid-water trawl capture, Prince William Sound, Simpson Bay, survey precision

Project Data:
*Description of dat*a – Acoustic data is in the form of *.DT4 files that contain the GPS cruise track and measures of acoustic backscatter collected on each research cruise. Data were analyzed using Echoview 7.1, and echointegration results are exported in the form of *.CSV files. Trawl data used to ground-truth estimates are archived under a separate *Exxon Valdez* Oil Spill Trustee Council project (16120111-A, Bishop & Lewandoski 2018).

Data archive and custodians –
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https://portal.aoos.org/gulf-of-alaska.php#metadata/694e5c71-ccd9-448f-b3ae-1730807bcd01/project

There are no limitations on the use of the data, however, it is requested that the authors be cited for any subsequent publications that reference this dataset. It is strongly recommended that careful attention be paid to the contents of the metadata file associated with these data to evaluate data set limitations or intended use.

<u>Citation:</u>

Rand, P.S. 2018. PWS Herring Program - Intensive surveys of juvenile herring, *Exxon Valdez* Oil Spill Long-Term Herring Research and Monitoring Program Final Report (*Exxon Valdez* Oil Spill Trustee Council Project 15120111-G), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

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EXECUTIVE SUMMARY

Pacific herring (*Clupea pallasii*) have not recovered in abundance since their decline in the early 1990s in Prince William Sound (PWS), Alaska. Annual monitoring of the adult population has been on-going for decades, but less attention has been focused on the juvenile stages. No information currently exists on the precision of hydroacoustic surveys targeting juvenile herring in PWS. We tracked seasonal and spatial patterns in densities of juvenile Pacific herring (ages 0 and 1, individuals km^{-2}, occupying the top 30 m of the water column) using hydroacoustics during an overwinter period during 2013-2014 in Simpson Bay in eastern PWS. We relied on trawl catches to apportion total backscatter to juvenile herring.

Based on the results of 22 separate nights of trawl surveys, Pacific herring represented the majority of catches in this survey (median proportion by number = 0.86). Walleye pollock (*Gadus chalcogrammus*) was encountered less frequently in the survey (median proportion of 0.03). Other fish, including capelin (*Mallotus villosus*) and sand lance (*Ammodytes hexapterus*), made up the remainder of trawl catches (0.08 %). Based on length frequency, nearly all the collections in the fall surveys (October-December, Cruises #1-4) were composed of age-0 and age-1 herring, whereas a combination of juveniles and adults were captured in the survey area in the spring.

A total of 8 cruise were conducted, each with three replicate surveys conducted over contiguous nights during a fall period in 2013 and a spring period in 2014. On two cruises, only two replicates were performed, resulting in data from a total of 22 acoustic surveys. The survey area ranged from a high of 12.6 km^2 to a low of 4.7 km^2. The spatial extent of the surveys conducted during the spring of 2014 was limited due the presence of shelf ice throughout the head of the bay.

We found a significant effect of cruise on juvenile herring densities ($p<0.01$). Density of juvenile herring was significantly greater in late October 2013. Densities dropped to their lowest level in early December. Density of juvenile herring remained relatively low during the spring period, but increased significantly by April. The precision of the survey varied considerably over the study period. The coefficient of variation of densities ranged from 2-106%, with a median of 53.2%. We found significantly higher densities of juvenile herring in the inner vs. the outer bay, reflected in a positive regression relationship along the main bay axis (from the outer bay to the inner bay). Out of the 16 surveys with significant regressions, the pattern of higher densities in the inner bay held in all but three surveys.

INTRODUCTION

The Pacific herring (*Clupea pallasii*) population of Prince William Sound (PWS) has not recovered since a population decline occurred in 1993 following the *Exxon Valdez* oil spill. A number of hypotheses have been evaluated to understand the causes of the decline and the lack of recovery in this species (e.g. Deriso et al. 2008; Pearson et al. 2012). Survival of overwintering juvenile herring is considered a limiting factor in recruitment to the spawning population, and has been the focus of past and ongoing research (Norcross et al. 2001).

Early life history of PWS herring has been described. Juvenile Pacific herring in PWS are known to metamorphose from the larval phase in June and July, and ultimately recruit into bays by August (Norcross et al. 2001; Stokesbury et al. 2002). During this time a variety of predators, including fishes, marine mammals and birds, rely on herring as an important nutritional resource (e.g. Suryan et al. 2000). Juvenile herring may succumb to starvation or losses from disease during the subsequent, overwintering period (Paul and Paul 1998; Kocan et al. 1999; Elston and Meyers 2009). Oceanographic conditions in the region clearly modulate these biological processes (Cooney et al. 2001; Eslinger et al. 2001; Norcross et al. 2001). Understanding the distribution of juvenile herring within and describing temporal trends are critical steps in understanding how these factors may be limiting recovery in this species.

Spatial patterns of juvenile herring in coastal bays in this region have been described. Stokesbury et al. (2000) identified surface waters of 0-30 m as important habitat for juvenile herring and described patterns of greater density of fish in the heads of bays. Schools of juvenile herring are tightly aggregated during July, but become more uniformly distributed in surface waters by October. Centers of abundance in PWS have been noted to occur in the northeastern and southwestern portion of PWS (Stokesbury et al. 2000; Norcross et al. 2001).

While there have been some reports on seasonal patterns of herring density based on 2-3 separate surveys separated by months, there have been no studies to date that have investigated more resolved temporal patterns (sub-monthly) of herring abundance during the critical overwintering period.

There has been some concern about the repeatability of hydroacoustic surveys in estimating fish abundance (e.g. Gangl and Whaley 2004). Prior to this project, only a single survey for juvenile herring was conducted in each sampling location. For this project, we set out to evaluate the precision of juvenile hydroacoustic surveys by repeating survey efforts over contiguous nights.

We report on results of field work conducted during October 2013 to April 2014 in Simpson Bay in eastern PWS. The main objective of this project was to evaluate variability in acoustic estimates of juvenile herring abundance and evaluate temporal trends in abundance during the overwintering period.

OBJECTIVE

This project objective is to conduct intensive acoustic surveys for juvenile herring before and after winter to ascertain immigration/emigration and mortality rates during their overwintering period.

METHODS

Surveys

We conducted coupled acoustic and trawl surveys over eight cruises from October 2013 to April 2014 in Simpson Bay in eastern PWS (Table 1).

During the 2013-2014 survey, we conducted eight cruises with each cruise consisting of up to 3 replicate surveys over a period of 3 days. The survey period consisted of a fall and spring period, with cruises in each period spaced about two weeks. Individual cruises are referred to by number, as described in Table 1. The traditional zig-zag, mobile transect design (Thorne 1983; Stokesbury et al. 2002) was used in the study (Figs. 2 & 3).

Table 1. Intensive survey cruise dates, total survey area and estimates of abundance and biomass for juvenile herring in Simpson Bay, Prince William Sound, Alaska. Coefficient of variation (CV) estimates are included, determined by three replicate surveys on each cruise date. Estimates during Cruises #1 and 7 are a mean of only two replicates. Mean CV: 53.2.

Cruise	Dates	Survey Area (km^2)	Density Estimate (fish km^{-2})	Coefficient of Variation
#1	2-4 October 2013	11.3	189,026	
#2	16-19 October 2013	13.3	212,630	1.8
#3	28-31 October 2013	12.6	753,885	23.2
#4	3-6 December 2013	11.4	31,040	91.5
#5	21-24 February 2014	6.2	17,901	105.8
#6	5-8 March 2014	5.6	33,654	77.2
#7	15-18 March 2014	5.5	310,024	
#8	2-6 April 2014	7.4	252,379	19.6

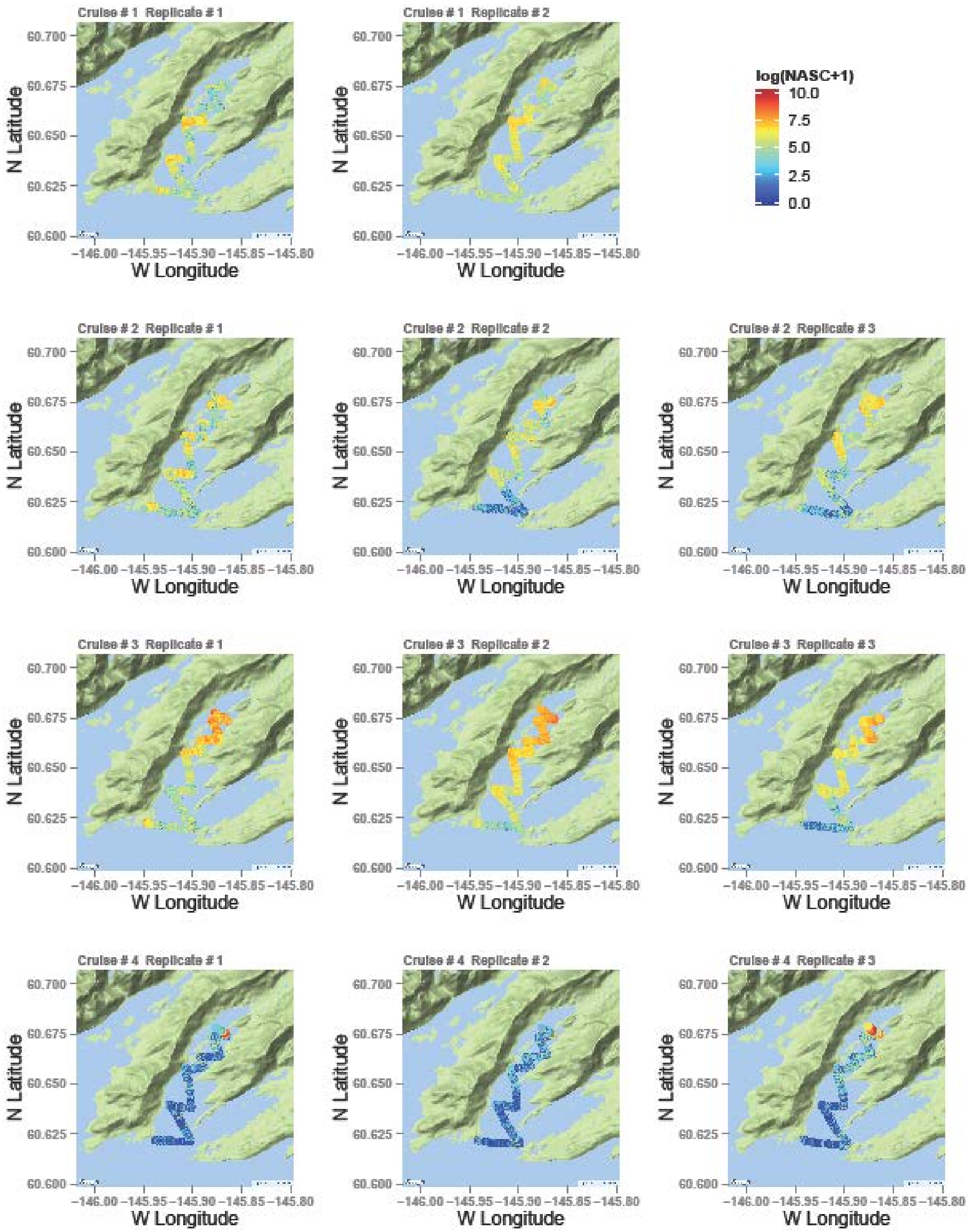

Figure 1. Tracks of each cruise in Simpson Bay during 2013. Cruise dates appear in Table 1. Colors indicate total acoustic backscatter (NASC, m^2 nm^{-2}) along the cruise track.

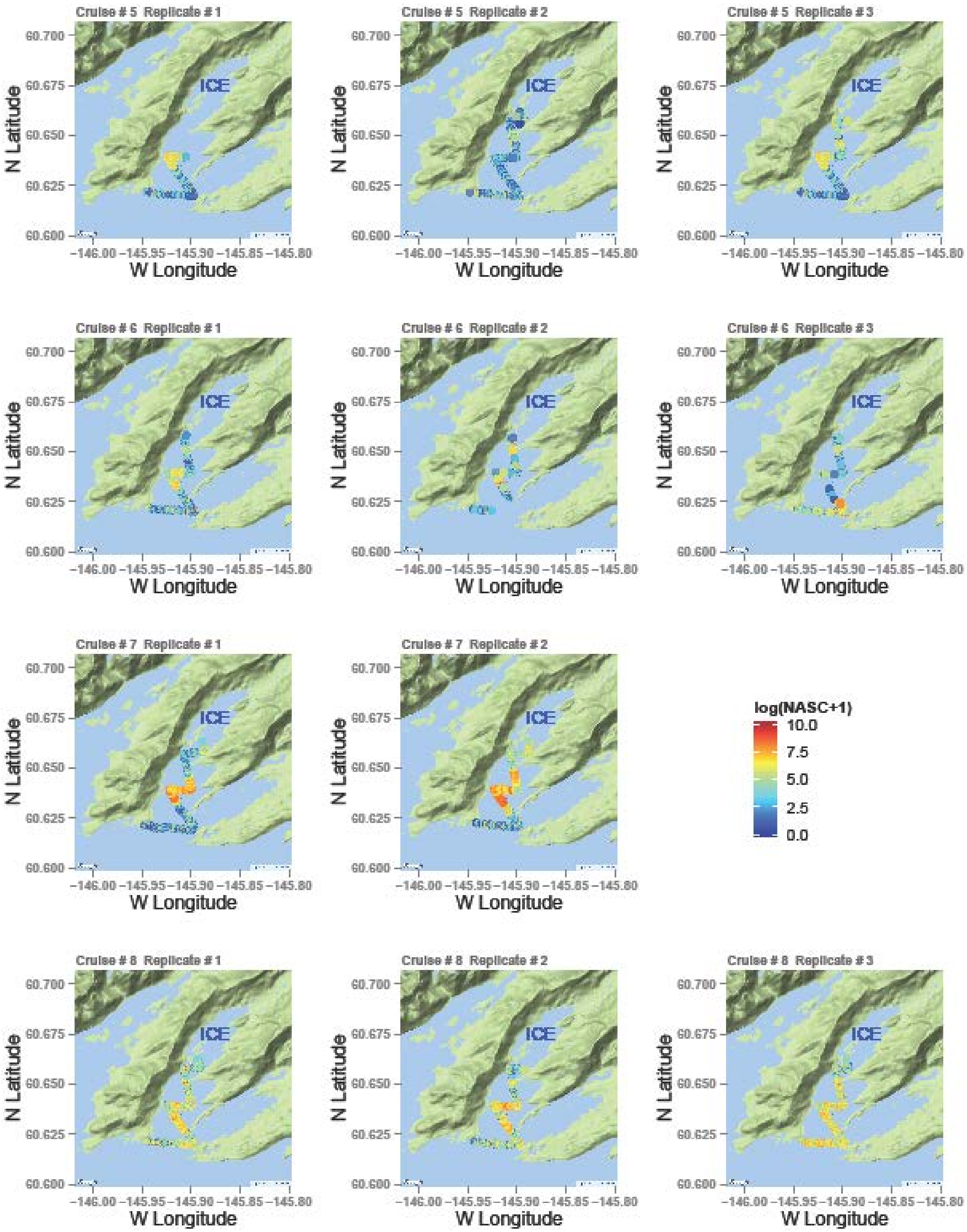

Figure 2. Tracks of each cruise in Simpson Bay during 2014. Cruise dates appear in Table 1. Colors indicate total acoustic backscatter (NASC, m^2 nm^{-2}) along the cruise track.

Coupled Acoustic and Trawl Data Collection

To collect acoustic data, a BioSonics 124 kHz digital split-beam transducer (7.6^{o} beam) was mounted down-looking on a 1.2 m long aluminum towfin and deployed off an 18 m vessel (*F/V Montague*). The echosounder was configured to transmit 3 pings s^{-1}, the source level was 221.2 dB (re 1 µPa at 1 m) with a pulse duration of 0.4 ms. Transects were conducted after sunset, and the deck lights were extinguished to avoid responses of herring to light. Tow speeds were maintained at approximately 2-3 knots and the transducer was positioned approximately 1-2 m below the surface. The transducer was calibrated by the standard sphere method (Foote et al. 1987), and calibration results were determined to vary <1.5% during this study. Position of the vessel along the transect was recorded with a Garmin 17x NMEA 0183 high-sensitivity GPS (accuracy rating under typical conditions < 10 m) connected via a power/data cable to the BioSonics DT-X top box so GPS coordinates were integrated as a cruise track into the *.DT4 data files.

During each night survey, 1 to 4 separate trawls were conducted to characterize the species and size distribution of acoustic targets. Juvenile herring were captured using a midwater trawl (14 m × 11 m × 22 m; Innovative Net Systems, Inc., Milton, LA) with a 38 mm mesh size reducing down to 12 mm mesh at the codend. Trawl tows were carried out onboard the same vessel conducting the hydroacoustic surveys, and the same trawl was used for all cruises. Tows were generally limited to 20 min duration. Tows were conducted immediately following completion of hydroacoustic surveys in areas where high acoustic backscatter had been detected.

We pooled trawl data over all trawls conducted during each night of the survey. Fishes were identified to species and were measured (standard, fork and total lengths to the nearest millimeter) onboard the research vessel. We measured lengths from a subsample of catches up to a total of 200 individuals per night. We considered juvenile herring (ages 0 and 1) to be <= 150 mm total length (TL). We averaged lengths from this pooled sample for use in estimating target strength separately for each night's acoustic survey (see below). We estimated juvenile herring catch per unit effort (CPUE) for each trawl during the survey by estimating total juvenile catches (# of all herring <= 150 mm TL) divided by the duration of the trawl (in minutes). Catch rates for each trawl event were averaged across all trawls conducted during each cruise. We tested for differences in CPUE between cruises by applying analysis of variance (ANOVA) with cruise number as the main effect. Tukeys post-hoc tests (TukeyHSD implemented in R) were conducted and differences were determined to be significant at $p<0.05$.

Acoustic data were manually inspected and post-processed in Echoview 7.1 (Sonar Data Pty., Ltd.). A -60.0 dB threshold was applied to the mean volume backscattering strength echograms (S_V, MacLennan et al. 2002) prior to echo integration. A bottom detection algorithm was applied to the data, and results were then manually edited to remove echoes from the substrate and associated sources of acoustic backscatter. Additional manual inspections removed any remaining undesired data (i.e., reverberation, bubble noise, etc.) and the echograms were binned into 10 m horizontal by 10 m depth analysis cells. Backscatter below 30 m was excluded from further analysis (although see Sensitivity Analysis section below), as the trawl was not capable of capturing fish deeper than 30 m in the water column. Further, these deeper depths are not preferred habitat for juvenile Pacific herring (Stokesbury et al. 2000). Acoustic data were echo integrated in Echoview, and were output in the form of the area backscatter coefficient (s_a, m^2 m^-

^{2}) for echo-integration or the nautical area scattering coefficient (NASC, m^2 nm^{-2}, as in MacLennan et al. 2002) for purposes of plotting and evaluating spatial patterns.

We partitioned the acoustic backscatter into three categories: Pacific herring, walleye pollock (*Gadus chalcogrammus*), and other fishes. To estimate echo amplitudes for each category, we applied the general equation:

$$TS = 20 \log10 L - 2.3 \log10(1 + Z/10) - b_{20}$$

Where L is mean fork length (cm), Z is mean water depth (m) and b_{20} is the species-specific intercept value. Lengths for each category were derived from fish collected in either trawls or, during 2012, in cast or gill nets. Depths, Z, for each analysis bin (10, 20 and 30 m) were applied in the equation. We applied values from the literature for b_{20}: Pacific herring (-65.4, Thomas et al. 2002), walleye pollock (-66, Traynor 1996) and a generalized physoclist fish for the other fish category (-67.4, Foote 1987).

The mean target strength (dB) for each fish category was calculated as described above and converted to linear echo amplitude (σ_{bs}, m^2 where $\sigma_{bs} = 10^{(TS/10)}$, as in MacLennan et al. 2002). Linear echo amplitudes were summed for each trawl (i.e. sum of σ_{bs} for all fish, total echo amplitude) and for each target category (herring, pollock or other fishes) within the trawls in a given night. The trawl-derived acoustic species proportion for each night of trawls was then calculated by dividing the species echo amplitude by the total echo amplitude for the trawl (Parker-Stetter et al. 2013).

We report on numbers of herring derived from the herring proportion of s_a for each sampling distance unit (EDU, MacLennan et al. 2002):

$$\text{Fish density (no. of herring} \cdot km^{-2}) = s_a / 10^{(TS/10)} \cdot 10^6$$

Based on the catch data, we estimated the proportion of the total herring captured that were juveniles and multiplied this by fish density to arrive at a juvenile herring density. The survey area (in km^2) was estimated as the convex hull containing the set of coordinates of the ship's track during each acoustic survey.

We determined precision of our estimates (coefficient of variation) for densities of juvenile herring by considering each night-time survey during a cruise as a transect replicate. Differences in juvenile herring density by cruise date were determined by applying ANOVA with cruise as the main factor and each night-time survey as a replicate. Values for density were log-transformed prior to analysis to normalize the data.

We evaluated spatial patterns in the acoustic data by applying a generalized linear regression model. The response variable was NASC (log transformed, and summed over depth interval 0 – 30 m). The latitude and longitude coordinates at each 10 m EDU across the entire survey transect were included as explanatory variables. To align the main bay axis to compass North, we rotated the transect latitude and longitude coordinates around a point at the head of each bay. We considered positive regressions along latitude as support for the hypothesis of higher densities of fish in the inner vs. the outer bay. This allowed us to interpret significant regression coefficients describing patterns over northing directions as changes across the main bay axis. We considered regression coefficients with p values < 0.05 to be significant, and expressed the resulting slope parameters as changes in densities across distance in kilometers assuming 1 degree latitude = 111 km.

Evaluating effect of changes in survey area

Given the smaller survey area during the spring based on the presence of shelf ice, we carried out a separate analysis of the data by restricting the analysis to the outer bay for all cruises. We extracted a subset of the data from the full survey by including only survey points below latitude 60.659096^{o} that served as the dividing line between inner and outer Simpson Bay. We applied ANOVA to the resulting data set and carried out post-hoc comparisons (as described above) to determine differences in herring density between cruises and related it to the results we found in the analysis of the entire data set.

Evaluating sensitivity to the depth threshold

We evaluated whether our conclusions were robust to changes in the depth strata that delineates the habitat for juvenile herring in our study. While Stokesbury et al. (2000) defines surface waters of 0-30 m as preferred habitat for juvenile herring, we acknowledge this could be a source of uncertainty in our analysis. We adjusted this nominal value of 30 m up and down by 10 m (i.e. applied thresholds of 20 and 40 m) and quantified divergence (proportional change) from the baseline estimate of juvenile herring density in our survey. By repeating some of the key statistical analyses, we determined if some our key results are robust over this threshold range.

All statistical analyses were carried out using R version 3.2.0 (2015-04-16).

RESULTS

Based on the results of 22 separate nights of trawl surveys, Pacific herring represented the majority of catches in this survey (median proportion by number = 0.86, Fig. 3). Walleye pollock was encountered less frequently in the survey (median proportion of 0.03). Other fish, including capelin (*Mallotus villosus*) and sand lance (*Ammodytes hexapterus*), made up the remainder of trawl catches (0.08 %). Based on length frequency, nearly all the collections in the fall surveys (October-December, Cruises #1-4) were composed of age-0 and age-1 herring, whereas a combination of juveniles and adults were captured in the survey area in the spring (Fig. 4).

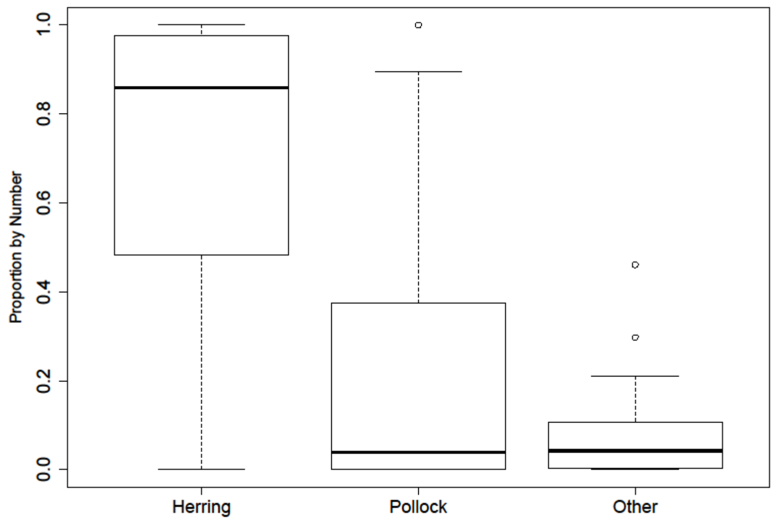

Figure 3. Proportion of herring, pollock and other fishes captured in midwater trawls in Simpson Bay during the study period. The dark lines represent the median over the study period, the box represents the 25th and 75th percentile of the distribution, and the whiskers represent 1.5 times the inter-quartile range.

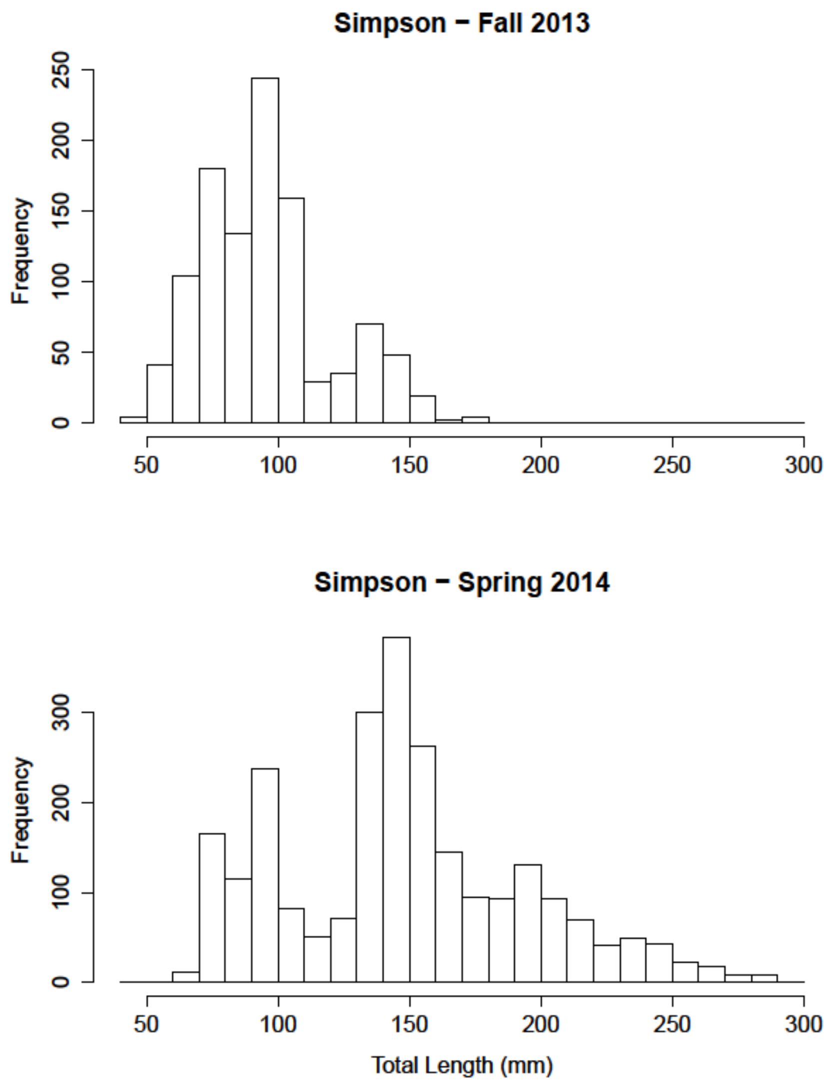

Figure 4. Total lengths (mm) in of herring collecting in the midwater trawls during 2013 and 2014 surveys in Simpson Bay, Prince William Sound.

A total of 22 acoustic surveys were completed, with 3 replicate transects completed in all but two cruises (Cruises #1 and #7 included 2 replicates as a result of adverse weather conditions, Figs. 1 & 2, Table 1). The survey area ranged from a high of 12.6 km^2 to a low of 4.7 km^2 (Table 1). The spatial extent of the surveys conducted during the spring of 2014 was limited due the presence of shelf ice throughout the head of the bay (Fig.2).

We found a significant effect of cruise on juvenile herring densities ($p<0.01$, Figure 5). Density of juvenile herring increased during October 2013, and densities during Cruise #3 was significantly higher than densities measured during Cruises #4, 5 and 6. Depending on which cruises one compares it to (#2 or #1), juvenile herring density increased by a factor of 9 to 12 times over a period of less than one month, then dropped to its lowest level in early December

(Table 1, Fig. 5). The juvenile herring CPUE of the trawl survey during Cruise #3 was significantly higher (p<0.01) than the CPUE estimated during the other fall cruises, thus providing additional evidence of elevated herring abundance in the survey area during this cruise.

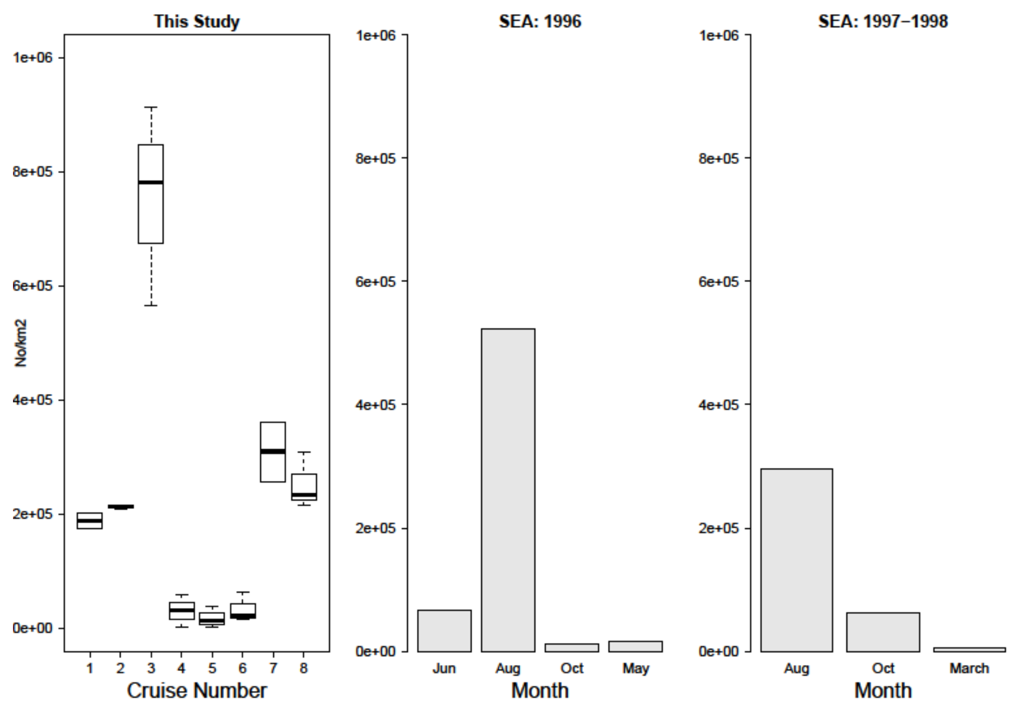

Figure 5. Densities (no km^{-2}) of juvenile herring determined through hydroacoustic surveys during the 2013-2014 cruises compared to results from earlier Sound Ecosystem Assessment (SEA) surveys (1996 and 1997-1998) in Simpson Bay, Prince William Sound. Dates for cruise numbers appear in Table 1.

Density of juvenile herring remained relatively low during the spring period (Cruises # 5-6, Figure 5), but increased significantly by Cruise #8. Densities observed during this period may be biased due to a reduction in the survey area, with no acoustic sampling effort taking place in the inner bay due to the presence of shelf ice. Densities during Cruise #8 were significantly higher than that measured during Cruise #5 (p=0.03). The highest densities during the spring were observed during Cruises #7 and #8. The patterns of CPUE during the spring reflected these patterns. The juvenile herring CPUE was observed to be significantly higher during Cruise #8 compared to Cruises #2, #4 and #5 (p<0.02), but was not found to be significantly different than the peak observed during Cruise #3.

The precision of the survey varied considerably over the study period. The CV of densities were lowest during Cruise #2, 3 and 8 (2-23%), moderate during Cruises #4, 6 (77-92%), and the least precise during Cruise #5 (106%, Table 1).

We found a significant trend of NASC in the inner vs. the outer bay, reflected in a positive regression relationship along the main bay axis (from the outer bay to the inner bay). Out of a total of 16 significant regressions, the pattern of higher densities in the inner bay held in all but three surveys (the exceptions were replicate #1 of Cruise #1 and replicates #1 and 3 during Cruise #8). The effect was most dramatic during Cruise #3, with regression coefficient exceeding 10.9 in all three survey replicates, representing a 2% increase in density per km from the outer to the inner bay, or a 20% higher density from the inner to the outer bay.

Evaluating effect of changes in survey area

By restricting the analysis of acoustic data to the outer bay, the greatest changes were observed for Cruises #3 and 4 (Fig. 5). Densities for these cruises were reduced by 50 and 88%, respectively, owing to the disproportionate amount of herring in the inner bay during those cruises. We still found significant differences between cruise dates, but the difference between Cruise #3 and Cruise #6 became non-significant, owing to the reduction in the mean herring density during Cruise #3. However, as a result of the reduction in density during Cruise #4, we found the herring density during this cruise to be significantly lower than densities observed during Cruises #1, 2 and 8, a difference not determined to be significant in the analysis of the entire data set.

Sensitivity Analysis of Depth Threshold

We determined that altering the depth threshold had variable effects on densities depending on the timing of the cruise. Densities were lowered by 60% for Cruises #5 and 6 by decreasing the depth threshold from 30 to 20 m. Our estimates of densities increased by a slightly smaller amount (30-50%) by increasing the depth threshold to 40 m for Cruises #2, 3 and 5 (Fig. 7). These results indicate a disproportionate amount of fish occupying the 20-30 m depth strata.

Our ANOVA results that explored the temporal patterns in densities across survey dates were robust to changes in these threshold values. The effect of cruise timing on densities was significant ($p<0.01$) for all depth thresholds examined.

DISCUSSION

Our approach for estimating juvenile herring biomass produced relatively precise estimates of abundance judging by variation across replicate transect sampling in Simpson Bay during 2013-2014. While some of the surveys yielded densities with relatively low precision, our sampling was able to detect significant changes in abundance over the study period, and provides some insight into dynamics of the herring population in recent years. Combining acoustic surveys and mid-water trawling was an effective method of quantifying juvenile herring biomass in PWS judging by the relatively high precision of estimates generated in this study. ca Precision of acoustic surveys of adult herring just prior to the spring spawning period in PWS has been determined to be ~ 30% (R. Thorne, Prince William Sound Science Center, unpubl. data). We were able to reach this level of precision on three surveys (Cruise #2, 3 & 8), periods where densities were generally higher.

The high densities of juvenile herring observed during our late October 2013 survey in Simpson Bay appears to be without precedence in the recent era of hydroacoustic surveying in this ecosystem. We note that Cruise #3 was initiated following an intense storm on 28 October 2013 that drove record high temperatures, rainfall and localized flooding in the Southcentral region of Alaska (see http://akclimate.org/Summary/Statewide/2013/Oct). Norcross et al. (2001) reported densities of 524,123 herring km^{-2} of age-0 herring in Simpson Bay during August 1996 (the highest reported in that study). Our estimate for late October 2013 was 753,885 herring km^{-2} (a mean of three replicate night surveys during 28-31 October 2013), a value 44% greater than the earlier survey. Juvenile herring densities within aggregations in October 1995 were reported by Stokesbury et al. (2002) to be 3.01 fish m^{-3} (average of 263 schools in 4 separate bays in PWS, including age-0, age-1 and age-2 herring). We computed the maximum densities observed over the transects conducted during late October 2013 in Simpson Bay (0.09-0.2 fish m^{-3} over the three replicates) and noted they were an order of magnitude lower than that reported by Stokesbury et al. (2002) in 1995. It is important to note, however, that our sampling unit was 10 m by 10 m, so densities measured at finer spatial scales may result in higher volumetric densities. Regardless, this suggests 1995 may have been a stronger year class for juvenile herring in PWS compared to 2013, or, conversely, the year 1995 was characterized by the presence of dense schools. The highest density of juvenile herring reported in Norcross et al. (2001, August 1996) is equivalent to a volumetric density of 0.02 fish m^{-3} (assuming herring occupy 0-30 m depth strata) which is lower than our mean volumetric density of 0.03 fish m^{-3} during late October 2013.

Based on results of acoustic surveys, Norcross et al. (2001) suggested juvenile herring mortality occurred between August and October and Stokesbury et al. (2002) estimated mortality between several survey periods separated by months. The current study described a discontinuous temporal pattern in herring densities resolved over finer time scales that raises questions on whether an acoustic survey of this type can provide insights into the processes of immigration, emigration and mortality of juvenile herring occurring simultaneously in PWS. The strong peak in abundance in late October and relatively high densities during the late spring were conspicuous features of our results, and were robust to our assumptions of depth thresholds and changes in the survey area over the period of study. This spike in density in late October may represent a wave of juvenile herring advecting into the system, possibly as a result of the strong storm that occurred just prior to our Cruise #3. While the variability across replicate surveys that were separated in time by 24 hours appeared to be constrained, it does appear that extending this time period between surveys to weeks can result is substantially higher variability. More work is clearly needed to understand these temporal dynamics of herring within bays.

Another way to interpret this seasonal pattern is that herring may be shifting between habitats within the bay and our survey may not provide a reliable index of their abundance. Some recent hydroacoustic observations in PWS bays during November 2015 using an Autonomous Surface Vehicle indicated that fish schools of high density exist in shallow habitat (< 5 m) along the shorelines throughout the inner bays (Zenone and Boswell, Florida International University, unpubl. data). Juvenile herring are commonly captured in shallow habitat in Prince William Sound using beach seines (Johnson et al. 2010) and this habitat may be particularly important for them. Future efforts to describe seasonal patterns in juvenile herring in this ecosystem should adopt a more integrated survey approach that includes sampling shallow as well as deep water habitat.

If we interpret the decline in density of juvenile herring following our late October 2013 survey as a mortality event, our mortality rates are markedly higher than those reported by Stokesbury et al. (2002). Our estimates of daily mortality rate between the late October peak biomass and the times of the subsequent surveys (including the November 6, 2013 survey in Simpson Bay reported in the final report of *Exxon Valdez* Oil Spill Trustee Council project 16120111-F (Rand et al. 2018) yielded a wide range of mortality rates (2.7% to 25.7% d^{-1}) representing a much higher and broader range than that reported in the earlier study (1 – 2% d^{-1}). It appears unlikely that a mortality event occurring during the late October Intensive Survey and the early November survey in Simpson Bay (an elapsed period of only 7 days) could have resulted in a drop in the population by 88%. We suspect fish may have emigrated out of the bay or into habitat not effectively sampled by our acoustic gear, as described above.

While densities during December-March in Simpson Bay were low, we observed higher densities during late March and early April (Cruises # 7 and 8, Figure 5). During this latter cruise, trawls near the shelf ice edge in the upper bay indicated very high densities of juvenile herring, and suggests that these fish occupied habitat associated with ice edges and may represent an important refuge from predation. We were not able to effectively sample this habitat, so we acknowledge that surveys in the bay during periods characterized by shelf ice may provide biased estimates of juvenile herring abundance.

Our sensitivity analysis indicated that our conclusions are robust to the decision over which depths are considered preferred habitat for juvenile herring. However, we emphasize that the application of this threshold is a source of uncertainty, considering our estimates changed up to 60% based on a 10 m change in the applied depth threshold in our analysis. Further, results of the sensitivity analysis were complex, which is likely a result of seasonal changes in occupied depths of herring in Simpson Bay. Advances in acoustic methods to distinguish species (in our case, primarily herring and pollock) may help resolve this issue. Alternatively, a more focused trawl survey that targets different depth strata in PWS could help provide a better means of defining preferred habitat for these species, and ultimately reduce uncertainty in acoustic estimates of density (e.g. Stokesbury et al. 2000).

Recognizing that the traditional acoustic survey design is not likely surveying all the available habitat, and our current lack of understanding of how juvenile herring move between these habitats, it is difficult to draw any firm conclusions at this point concerning overall population and survival trends. It is important to keep in mind that these are open systems that likely exhibit a high degree of physical and biological flux. It is going to take advances in technology and survey approaches to better understand these dynamics.

CONCLUSIONS

We tracked seasonal and spatial patterns in densities of juvenile Pacific herring (ages 0 and 1, individuals km^{-2}, occupying the top 30 m of the water column) using hydroacoustics during an overwinter period during 2013-2014 in Simpson Bay in eastern PWS. We observed a discontinuous pattern through the fall-spring period, punctuated with a late October peak of 753,885 herring km^{-2}. Juvenile herring density dropped by 96% over the winter, but then increased again during the spring. Precision of the survey determined by replicate transect sampling over a three day period (coefficient of variation of density) ranged from 2-106%, with a mean across the surveys of 52%. A number of challenges exist for monitoring juvenile herring, particularly surveying in shallower habitat and limited access to their habitat by vessels in the early spring due to the presence of shelf ice.

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