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Acoustical-optical assessment of Pacific herring and their predator assemblage in Prince William Sound, Alaska

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Abstract

The Pacific herring *Clupea pallasi* population in Prince William Sound (PWS), Alaska, is both a valuable commercial resource and an important forage species for marine fish and wildlife. Historically, the herring were managed by a combination of age-structured models and egg deposition estimates. When these methods predicted a large return for spring 1993 that failed to materialize, we began surveying with echointegration–purse seine methods. After a decade of acoustic surveys, we show the new approach yields highly precise biomass estimates, which are consistent with historical measures of the miles of beach spawning. When compared, we show the traditional methods overestimated stock biomass, which resulted in harvest rates approaching 40%. In contrast, the acoustic methods are most likely to underestimate biomass. Since the acoustic estimates can be quickly obtained, we recommend their use to set harvest quotas for the fishery in the spring just prior to harvest. The shift from the traditional preseason to inseason management practices for herring in PWS is consistent with the Precautionary Principle by the fact that protection of the spawning population does not rely on the ability of science to predict how the population is changing. Furthermore, synoptic infrared measurements on our night-time acoustic surveys revealed herring to be the most important winter forage to marine birds and wildlife in PWS, including the endangered Steller sea lion *Eumetopias jubatus*. Given the importance of forage to marine birds and wildlife in the North Pacific during the extended winter conditions (October–March), the implementation of inseason management for herring using echointegration–purse seine techniques may be the most effective method to restore depressed populations of marine birds and mammals in the North Pacific.

Keywords: Acoustic surveys; Pacific herring; Inseason management; Steller sea lions

1. Introduction

The Pacific herring (*Clupea pallasi*) population in Prince William Sound (PWS) has supported an intermittent commercial fishery over the last century due to large fluctuations in biomass (Roundsefell, 1929; Thomas et al., 1991). There has been considerable speculation on how oil spills, disease and climate influence stock biomass fluctuation, but overfishing as a factor in population declines was not well documented (Bailey et al., 1995; Brown et al., 1996; Marty et al., 1998). However, new evidence suggests that overfishing may have played a role in the recent declines of the PWS stock.

The importance of accurate stock assessment procedures for herring management is increased by the fact that Pacific herring in PWS are one of the most important forage fish available to marine wildlife in the winter (Thomas et al., 1991; Thomas and Thorne, 2001). Furthermore, many piscivorous species in the Gulf of Alaska, including the endangered Steller sea lion (*Eumetopias jubatus*), have experienced major declines that are attributed to food limitation (DeMaster and Atkinson, 2002).

Historically, the herring in PWS were managed by a combination of age-structured models, egg deposition estimates and test fishing. In 1993, these traditional, preseason methods predicted a large spring return that failed to materialize. As a consequence, the local fishers union, Cordova District Fishermen United, secured funding for a fall 1993 acoustic survey to ascertain the status of the herring stock.

Although this was the first acoustic survey of the PWS herring biomass, Pacific herring stocks from Alaska to California have been assessed with acoustic techniques for management purposes since the early 1970s (Thorne, 1977a, b; Trumble et al., 1982; Thorne et al., 1983; Thorne and Tho-

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mas, 1990; Thomas and Thorne, 2001). In most cases, these acoustic estimates of biomass were part of a preseason prediction for establishing harvest quotas for the following spring. The requirements for the acoustic surveys were well established: (1) comprehensive coverage of the population, (2) biological information on species and size composition, and (3) correct target strength scaling (Thorne, 1983a). Thomas et al. (2002) document our research into the target strength scaling. This paper focuses on improvements to comprehensive coverage of the population and the collection of biological information.

The initial acoustic survey in PWS confirmed that a population collapse had occurred (DeCino et al., 1995; Thomas et al., 1997). Subsequently, acoustic surveys of the adult herring were conducted during fall in 1994 and 1995, and during early spring since 1995. The objectives of this paper are to: (1) describe the survey techniques that were developed to assess this herring stock, (2) compare the acoustic estimates with traditional herring assessment techniques, and (3) discuss the value of acoustic monitoring of herring to research, management, the economy and the ecosystem.

2. Methods

Effective survey design begins with a consideration of the objectives, which in turn leads to requirements for precision (Thorne, 1983a). Our initial objective was to assess the abundance of Pacific herring in PWS as input to fishery management decisions. For precision, we looked at historic data on the stock fluctuation and concluded that we wanted to be able to detect an annual change in the population level of about ±20% with 95% probability.

The next step was a consideration of the sampling tools available for assessment. We had at our disposal various net sampling techniques, scientific (down-looking) acoustics, commercial sonars, and aerial surveys. The paramount consideration was the sampling power relative to the requirements for precision. Based on previous measurements, we estimated that we needed about 5% coverage to achieve 20% precision (Scheaffer et al., 1986). Since our scientific acoustic system sampled the depth ranges occupied by herring at a rate equivalent to 6 m^2 s^{-1}, 5% coverage would require 2.4 ship-years of effort to representatively sample the 9000 km^2 of PWS. As that level was not feasible, it was clear that we needed either sampling tools with even higher power, a more effective survey design, or both.

We knew from previous investigations that the bulk of the adult Pacific herring population in PWS characteristically exhibits four seasonal distributions: (1) a post-spawning, feeding migration to the ocean that usually starts in May, (2) a post-feeding migration to protected regions of PWS for over-wintering in October, (3) an over-wintering aggregation behavior in protected shoreline regions from November through March, and (4) a migration to spawning beaches in April.

Acoustic techniques are impractical on feeding and post-feeding migrations of herring because: (1) the population is moving along physical and biological gradients that vary annually, (2) the vertical distribution of the feeding fish can vary by the diversity of available prey organisms, (3) the herring are mixed into a complex assemblage of plankton and nekton making separation of targets difficult, and (4) the population is undergoing rapid change in growth and survival so its biological parameters are quite unstable. Vilhjálmsson and Carscadden (2002) came to the same conclusion for Icelandic capelin (*Mallotus villosus*) after 20 years of acoustically surveying. In addition, the spawning migrations to the beaches represent their own complexity because the fish are moving rapidly and occupying shallow rocky and kelp infested habitats that are not conducive to sampling. By elimination, we are left with the fall-winter period. In contrast to spring-summer periods, the herring population at this time is the most contagious and temporally, geographically and biologically stable. Initial survey data suggested that the bulk of the over-wintering herring occupy less than 1% of the surface area of PWS. The scientific acoustic system could cover that area in less than 8 days. However, those areas need to be located.

We ultimately developed a four-stage sampling approach (Cochran, 1977): (1) aerial and sonar reconnaissance, (2) verification and mapping, (3) repeated echointegrations and (4) subsampling school groups for biological information. The goal of the first step, aerial and sonar reconnaissance was to locate areas suspected of holding school-groups. Both aerial survey and sonar techniques have extremely high sampling power. This stage was assisted by historical information and local fishers' knowledge of the site fidelity of over-wintering herring. From the fishers we learned that predator assemblages (primarily Steller sea lions, humpback whales, glaucus and glaucus-winged gulls, common murres and pelagic cormorants) aggregated in herring over-winter areas, which facilitated locating school groups by aerial surveys. From fisheries and subsistence hunters operating in the Sound during the winter, we developed a network of sentinel observers to alert us about predator or subsurface fish aggregations that were observed on their acoustics. In general, we discovered that herring began to aggregate in the Sound in the late October, and as winter approached the distribution shifted to more protected areas that were usually close to major spring spawning locations.

The second stage of the survey was conducted at night with a dark-vessel to minimize boat avoidance and take advantage of a more favorable vertical distribution of the herring (Thomas et al., 1997). Its goal was to verify the presence of herring in suspect areas and develop a map of the area occupied by the school-groups using a searchlight sonar, echosounder and GPS plotter. Again, the high sampling power of the sonar allowed us to rapidly delineate the boundaries of herring concentrations.

The third stage of the survey was echointegration. Once the boundaries of the herring distribution were established, an echointegration survey using scientific echosounders (Thorne, 1983a, b, MacLennan and Simmonds, 1992) was conducted to estimate the fish density. Echointegration estimates of density were made with one to three frequencies (38, 70 and 120 kHz) following a zigzag survey track. We separated the zigs from the zags to create two series of parallel transects. The searchlight sonar remained in continuous operation during the echointegration measurement phase of the survey (1) to verify absence of school avoidance to the vessel, (2) to monitor the school group to end of the transect, and (3) to avoid collision with submerged rocks and the shoreline.

All echointegration systems were fully calibrated using procedures documented in Foote et al. (1987). Two replicate estimates of biomass per unit surface area were obtained from the two sets of parallel transects in each survey, in addition to estimates from multiple frequencies. The zig-zag survey was then repeated multiple times to develop a sufficient number of independent estimates to achieve the desired precision. A weighted mean estimate was calculated for each parallel-transect survey, with weighting by transect duration. The mean biomass per unit surface area was extrapolated over the area covered by the survey, which was determined from the GPS data. The repeated survey estimates were used to determine the precision of the biomass estimates (Scheaffer et al., 1986).

The fourth and final stage of the herring surveys was to sample the previously echointegrated, herring school-groups for biological information using a commercial purse seine (McClatchy et al., 2000). This step was implemented by providing a second vessel with the coordinates of a herring school for sampling. The purse seines used ranged in depth from 18 to 31 m (10–17 fathoms) and had range of 1–2 cm stretched mesh in the bunt. We used a random sample of only one to three seine catches to collect the biological information due to the large size of the commercial seine used. The species and size composition of the net catches were used to estimate target strengths for converting backscatter to biomass. The density of the herring school-groups was too high even at night to collect reliable in situ target strengths.

Initial estimates of Pacific herring biomass from these surveys were based on a target strength to length relationship for Pacific herring of $TS = 26.5 \log L - 76.4$, where L is length in cm. This equation had evolved from many different sources including in situ measurements of individual herring, comparisons with catches and comparisons with independent measures of abundance (Thorne, 1977a; Trumble et al., 1982). Subsequently, we conducted ex situ experiments to better understand the target strength characteristics (Thomas et al., 2002). These experiments indicated that the target strength assumption was reasonable, and corrections for the historical survey results were not necessary. However, subsequent surveys have incorporated the changes associated with depth that are recommended by Thomas et al. (2002).

Visual observations of predators (sea lions, other marine mammals and birds) were integrated into the acoustic surveys beginning in 2000 (Thomas and Thorne, 2001). Visual observations during hours of darkness used a Texas Instruments Model M100 “NightSight” (27 × 18° field of view) or a Raytheon Model 200 “NightSight” (12 × 6° field of view). Steller sea lions and whales were enumerated along the acoustic transects, while major bird concentrations and activities were logged.

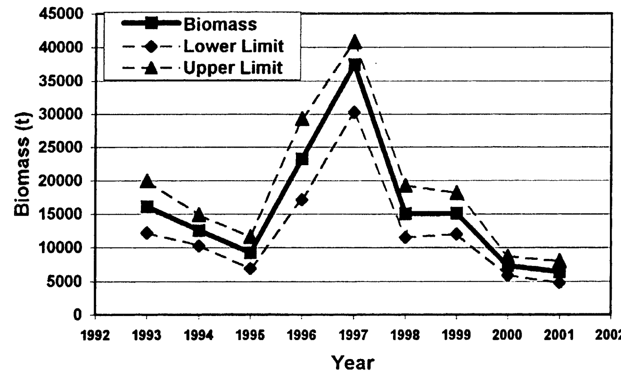

Fig. 1. Results of acoustic biomass herring estimates in PWS (dashed lines are 95% confidence limits).

3. Results

3.1. Annual biomass assessments

The initial two acoustic surveys estimated an abundance of 16 082 metric tons (t) in the fall of 1993 and 12 555 t in fall 1994 (Fig. 1). With a moratorium on fishing, the population rebuilt to 23 203 and 37 498 t in the spring of 1995 and 1996, respectively. However, after reopening the commercial fishery, the acoustic surveys in the springs of 1998 and 1999 showed a decline to about 17 000 t. After test fishing in the spring of 1999, management cancelled the fishery. The spring survey of 2000 and 2001 showed the population to have fallen to a new, all-time lows of 7281 and 6384 t, respectively.

3.2. Comparison with historical techniques

Historical information on the abundance of Pacific herring in PWS consists of commercial catch records, aerial estimates of the length (mile-days) of spawn (milt) patches along beaches and herring spawn (egg) deposition surveys (Biggs et al., 1992; Donaldson et al., 1992; Funk, 1994). The commercial catch records date back to 1969, whereas the mile-days of spawn date to the early 1970s. Egg deposition surveys were conducted in 1981–1982, 1988–1992, and 1994–1997. In addition, the Alaska Department of Fish and Game (management) has used various sources of information to make forecasts of run biomass using an age-structured assessment model since 1980 (Baker et al., 1991; Sharp et al., 1996; Quinn et al., 2001).

The Alaska Department of Fish and Game continues to measure mile-days of spawn, as it has since 1974. As this was

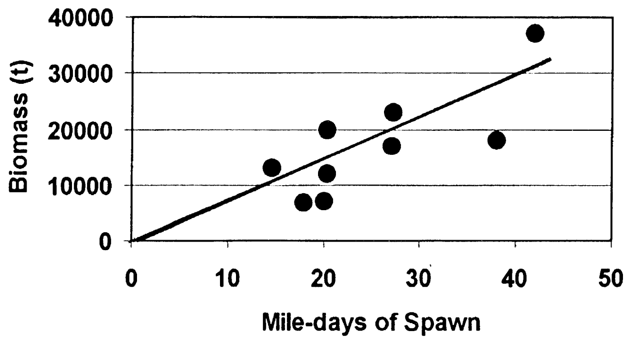

Fig. 2. The relationship between acoustic biomass estimates and the miles-of-spawn indice ($Y = 697X$, $r^2 = 0.75$) for herring in PWS, 1993–2002.

the most complete data record, we compared the estimates of the mile-days of spawn and acoustic estimates of biomass between 1993 and 2002 and found a positive correlation with a coefficient of 0.75 (Fig. 2).

The mile-days of spawn index was used as a relative abundance indicator. However, since it correlated well with the acoustic estimates, we used the correlation to convert mile-days of spawn to an absolute estimate of biomass, and hind-cast herring abundance back to 1973. The hind-cast indicates that the population showed a general increase to a peak in 1988 of about 100 000 t, followed by a rapid decline after the *Exxon Valdez* oil spill in 1989 (Fig. 3).

The egg deposition estimates were in general agreement with this hind-cast except for 1990–1992. During this time, the hind-cast estimates indicated a population in decline, while the egg deposition estimates indicated a major increase in population abundance. Similarly, the age-structured analysis produced estimates that increased from 108 671 t in 1988 to 120 658 t in 1992, at a time when the mile-days of spawn were decreasing (Sharp et al., 1996).

It is apparent that the harvest quotas were driven by the estimates from the egg deposition surveys and age-structured analysis. During the 1990–1992 interval when the hind-cast estimates indicate that the biomass was decreasing, the harvests were increasing. In fact, in 1991 and 1992, the exploitation rates were 0.35 and 0.39, respectively, based on the hind-cast estimates. Between 1990 and 1992, 40 000 t were removed from a population that the hind-cast estimated at 61 000 t in 1989.

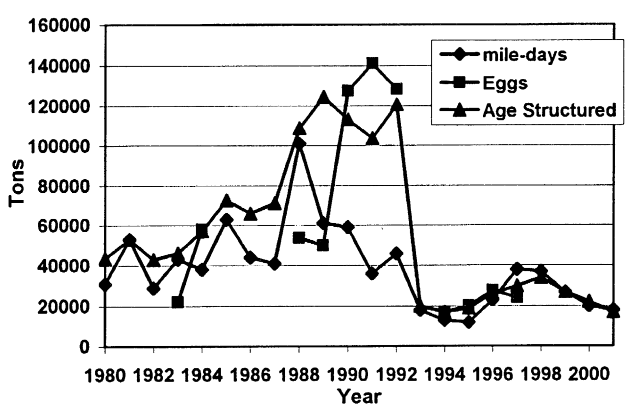

Fig. 3. Comparison of estimates from the age-structured model, egg deposition and mile-days of milt converted to absolute values.

With the collapse of herring, management placed a moratorium on fishing from 1994 to 1996. The population experienced favorable recruitment in 1994 and 1996 to reach a biomass of between 30 000 and 40 000 t (Kirsch and Thomas, 1997). Since this biomass exceeding the management threshold for spawning biomass (22 000 t) commercial fishing was resumed in spring 1997. The harvest quota was placed at 5000 t. Unfortunately, the next spring after this fishery the acoustic survey estimated that the population dropped to 15 029 ± 4150 t, which was below the management threshold. However, the age-structure model did not reflect this decline (Fig. 3). Consequently, management opened another fishery for spring 1998 with a quota of 5000 t. Subsequently, the acoustic estimates of the population declined to only 7281 t by 2000 (Thorne, 2000). The mile-days of spawn reflected the increase between 1995 and 1997 as well as a decrease between 1997 and 1998, and subsequent decreases between 1998 and 2001. By 1999, it was obvious to all estimators that the population had fallen below threshold, and a fishing moratorium was again imposed that remains in effect to this date. However, post-mortem indicates that the exploitation rate on the declining population in 1998 was about 33%.

3.3. Predator aggregations

Our initial objective was to develop an effective assessment tool for herring management. In pursuit of that goal, we observed that herring were the target of many predators. Our observations of the coincidence of herring and Steller sea lions led to our discovery of night-time foraging by Steller sea lions on herring (Thomas and Thorne, 2001). Over a 3-year period, we found strong correlations ($r^2 = 0.88$–0.98) between our acoustic estimates of biomass and synoptic counts of Steller sea lions at various locations of overwintering herring (Thorne and Thomas, 2002). Subsequent comparisons between our annual estimates of herring in PWS and the long-term census data on Steller sea lion abundance in PWS taken at The Needle, which is the major haul-out within PWS (Kruse et al., 2000; Sease et al., 2001) also show a very strong correlation. The herring population declined by 88% between 1989 and 2000, while the Steller sea lion count declined 86% (Fig. 4). Further, the Steller count in 1973 was 25% of the peak count in 1990, while the herring miles of spawn the first year it was measured, 1974 was 22% of its peak value measured in 1988. Steller sea lion counts also declined after 1989 at sites adjacent to PWS. The average decline between 1989 and 2000 for the three major adjacent sites, Wooded Island, Seal Rocks and Point Elhrington, was 72%. This substantial decline contrasts with the overall trend in the Eastern Gulf of Alaska, which was a minor decline.

The combination of acoustics and infrared sensors also showed close associations between herring and marine bird foraging activity at night. The sea bird assemblage was domi-

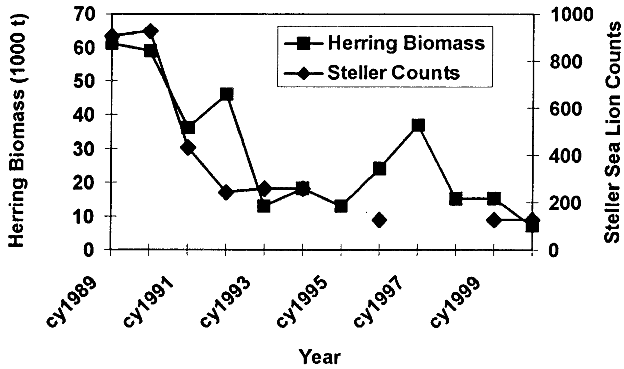

Fig. 4. Comparison of Steller sea lion counts and herring abundance in PWS, 1989–2000. Steller sea lion counts are from NMFS/ADF&G census at The Needle.

nated by two species, glaucous gulls and pelagic cormorants, but murres were also common. While all three species were highly correlated with the herring abundance, the glaucous gulls were also closely associated with the Steller sea lions. The foraging behavior of the Steller sea lions in most cases consisted of stunning the herring, then feeding on the stunned fish at the surface. That behavior apparently facilitated feeding by the gulls.

4. Discussion

The estimates of the PWS herring population from the acoustic techniques correlated well with the mile-days of spawn index. That result alone is not a strong verification. All techniques are subject to sources of variability and bias. However, when the relationship is used to hind-cast the population trends, the result reveals a very logical and rational basis for the historical population changes. It appears that the herring population from 1973 to 1988 was relatively stable and slightly increasing. However, the hind-cast estimates clearly show a sharp decline subsequent to the *Exxon Valdez* oil spill in 1989 that included impacts of recruitment failure and disease. Unfortunately, that decline was not detected because the egg deposition and age-structured models were suggesting a substantial increase from 1989 to 1993 (Sharp et al., 1996) when our evidence indicates the population was actually declining. As a result, harvest rates approached 40% during 1991 and 1992. These relatively high harvest rates on a declining population clearly accelerated the decline. The subsequent collapse argues against the accuracy of the estimates from the egg deposition surveys and age-structured analysis. An increasing mortality following the oil spill could be at least a partial explanation for failure of the age-structured analysis, since an assumption of constant natural mortality is implicit in the approach. The failure of the egg deposition method may reflect the problem of large extrapolations.

We used the regression model that forced the relationship between the acoustic biomass estimates and the mile-days of spawn index through the origin because of the theoretical relationship between the two parameters. The slope of the relationship would be about 10% higher using the general regression equation. However, the same conclusion would be reached with both regression models.

In contrast to the overestimation problem that appears to have resulted from both the egg deposition and age-structured methods during the 1989–1992 period, the acoustic surveys of herring only overestimate if non-herring targets are counted, incorrect TS is used to convert backscatter to biomass, or calibration is erroneous. We have isolated surveys to times when the herring are in single species aggregations of adults. We verify species and age composition. We have verified the TS function for use with herring. Our calibration procedures are meticulous and consistent. Consequently, we do not see overestimation as a problem. Underestimation by truncating fish schools or missing concentrations can still occur and not be detected, but considerable evidence from various survey experiments suggests such errors are minor (Thomas et al., 1997). In addition, minor underestimation is acceptable since it adheres to the Precautionary Principle (O'Riordan, 1992; Dovers and Handmer, 1995). An additional consideration is that the variance of our acoustic estimates is based on variability among complete surveys, rather than a measure of internal variability as is the case with egg deposition surveys. It is interesting that the best fit occurs between the acoustics and the miles of spawn. Both are based on techniques with very high sampling power.

The strong correlation between our estimates of herring biomass and the NMFS/ADF&G census counts of Steller sea lions provides additional support for the accuracy of the herring biomass estimates. We have established that Steller sea lions extensively and almost exclusively target herring during the extended Alaskan winter period (Thomas and Thorne, 2001; Thorne and Thomas, 2002). Consequently, it is not surprising to see similar trends in abundance. Conversely, the correlation with herring demonstrates that it is important to accurately assess major forage stocks in order to understand population fluctuations of important, and often endangered, predators.

While the acoustic estimates correlated well with the mile-days of spawn, it is important to note that the mile-days of spawn measurement occurs too late to impact the fishery for that year. In contrast, the spring acoustic surveys can be conducted immediately prior to a fishery opening. If acoustic surveys had been in place as the primary management tool, the overfishing that took place in 1991, 1992 and 1998 most likely would not have occurred. The economic and ecological consequences of incorrect management are substantial. The fishery remains closed to this date, and many piscivorous species suffered substantial declines.

5. Conclusion

This study points out two major advantages of acoustic techniques (1) direct assessments can be made immediately prior to a harvest, (2) the most likely direction of error is toward underestimation. In contrast, both the egg deposition surveys and the age-structured analysis are indirect and both depend on assumptions of constant natural mortality over the subsequent year. It is clear in this case that erroneous deterministic and indirect measures of herring biomass were harmful to herring stocks and the fisheries and wildlife that depended upon them.

While error toward underestimation is preferable to overestimation, the error can be minimized by a well-considered survey design. Our experience shows that a thorough understanding of the distributional characteristics of the target population is a critical factor for accurate assessment.

An important additional benefit of accurate and consistent long-term monitoring of a major forage species such as herring is an improved understanding of the auxiliary populations that depend upon the abundance of that forage. Such information is critical to improved understanding of ecosystem health and function.

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