The Role of Pacific Herring as Critical Winter Forage for Steller Sea Lions

Final Report

by

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Introduction

The objectives of this study were to document the winter-period herring prey field available to Steller sea lions in Prince William Sound (PWS) and around the Kodiak Archipelago and to investigate the factors that determine Steller sea lion foraging intensity on herring. The study duration was slightly more than four years, from October 1, 2004 to December 31, 2008. During this time 32 cruises were conducted in PWS and off the Kodiak Archipelago. The cruises focused on direct quantitative measurements of co-occurring patches of herring and their marine wildlife predators. Other efforts in this project included an extensive examination of historic data bases, some modeling of Steller sea lion foraging behavior, experiments on herring location and behavior using passive acoustic systems and studies of herring energetics. This final report summarizes the project, including a description of the cruises, publications and other presentations and a brief description of the project results and findings.

Summary of Cruises, Publications and Presentations

Nineteen major cruises and 13 supplemental cruises were conducted under the project (Table 1). Many of these cruises included multiple vessels and aerial surveys. A major cruise is defined as a five day or longer duration, a supplemental cruise less than 5 days. Fifteen of the major cruises and 9 of the supplemental cruises were conducted in PWS, the remainder off Kodiak. A summary of the cruise observations in both locations is given in Table 2a,b.

The primary objective of the cruises was to measure herring abundance and distribution while synoptically counting Steller sea lions and whales. In addition, seabirds were counted during several cruises. Night-time investigations of marine mammal predation were also conducted using an infrared scanner. Details of the methodology are provided in various publications from the project.

Three peer-reviewed publications have resulted from this project to date. The project contributed to a fourth peer-reviewed publication. Seven additional papers were published in conference proceedings. Six additional oral presentations and three poster presentations were given at conferences that did not publish proceedings. Several community (public) presentations were also given. A list of the publications and presentations is given in Table 3. As is often the case, peer-reviewed publications lag the duration of the project. It is estimated that four to six additional peer-reviewed publications will result from this project over the next two years.

Summary of Results

Annual Variation in PWS Herring Abundance

Since 1993, the biomass of adult herring in PWS has been measured with three different techniques: hydroacoustics, an aerial survey index of the accumulated miles of milt along beaches, and by simulations with an age-structured assessment (ASA) model (Hulson et al. 2008). For the past several years, the hydroacoustic surveys have been a cooperative effort between the Alaska Department of Fish and Game (ADF&G), Cordova and the Prince William Sound Science Center (PWSSC), including this study. The aerial survey is an historical method used since 1973. It is a robust (nonextrapolated) index of the amount of spawning by adult herring, and is highly correlated with the hydroacoustic estimates of adult herring biomass. The aerial survey index has been converted to an absolute estimate of herring biomass through its correlation with acoustic estimates since 1993 (Thomas and Thorne 2003; Thorne and Thomas 2008). The ASA model produces non-robust (extrapolated) and subjectively-weighted, deterministic predictions.

The estimates from the three approaches are shown in Figure 1. The herring population in 1993 was in a collapsed state following the Exxon Valdez Oil Spill (Thorne and Thomas 2008). It recovered slightly to 1997, then declined rapidly following a reopened commercial fishery. During the time period of this study, 2004-2008, the herring biomass has remained low and fairly consistent. The hydroacoustic estimates ranged from 12,700 to 20,400 mt, but confidence intervals have been broad, typically ±40%. The converted mile-days of spawn index (hindcast) has been the most consistent, ranging from 12,449 to 16,568 mt. Both the hydroacoustic and mile-days estimators show a low in 2006, followed by a rebound the past two years. The ASA model appears to have badly underestimated the last two years. In any case, the herring population was clearly at historically low values during this study period.

Further details are provided by Thorne and Thomas (2008) referenced in Table 3.

Observed Co-occurrence of Herring and Steller Sea Lions in PWS

Steller sea lions were visually enumerated during all PWS cruises. In addition, aerial surveys counts were made during fall 2004 and spring 2005, 2006 and 2007. Overall, the numbers of Steller sea lions counted during cruises were significantly correlated with the synoptic hydroacoustic surveys of herring biomass ($r = 0.79$, $p < 0.01$) (Fig. 2). However, there was a seasonal component to this relationship. Steller sea lions showed a consistent, but relatively low co-occurrence with herring throughout most of the winter,

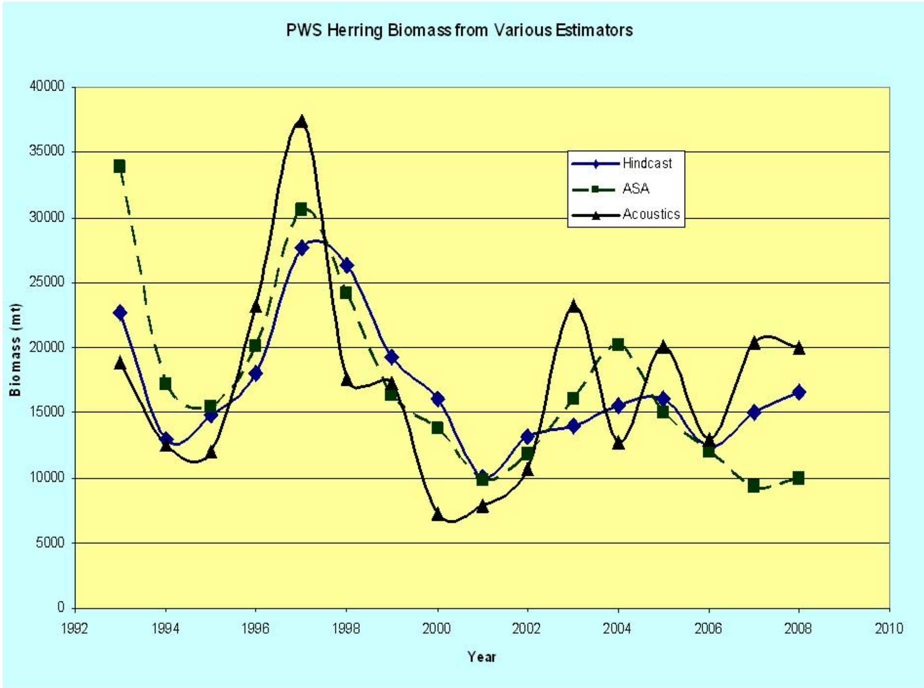

Figure 1. Recent history of PWS adult herring biomass estimates

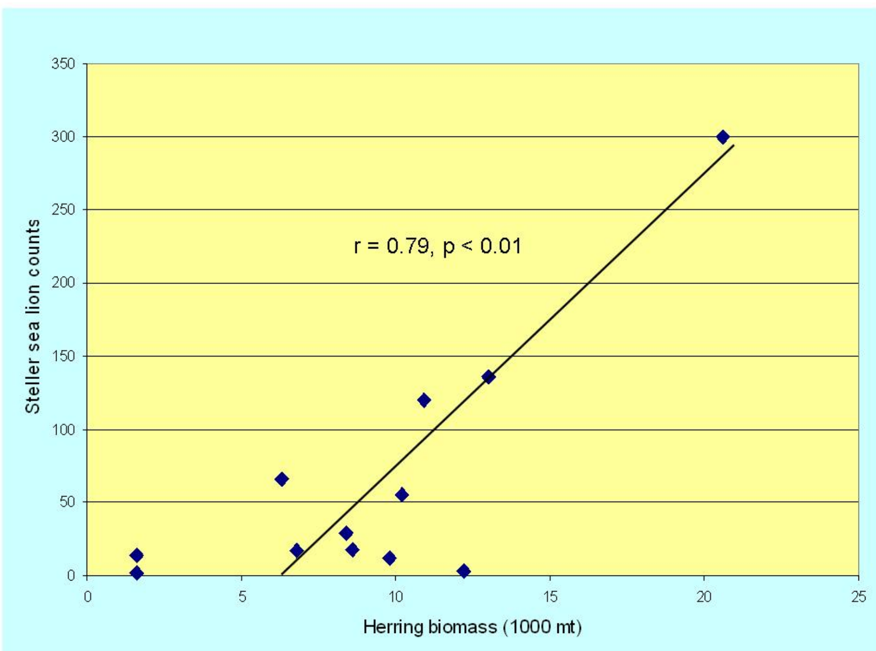

Figure 2. Scatter diagram of Steller sea lion counts and herring biomass. Values from Table 2a.

but the co-occurrence increased sharply as herring began to stage for spawning in late March (Fig. 3). In contrast, humpback whales appeared to forage heavily on herring during early winter and again around spawning, but disappeared in late February/early March. It is likely that the low numbers of whales during this time period is associated with whale migrations to and from Hawaii. The correlation between Steller sea lion counts and herring biomass improves when the seasonal component is removed and the limited sampling capability of the surface vessel is replaced with synoptic aerial survey counts ($r = 0.88$, $p < 0.01$) (Fig. 4).

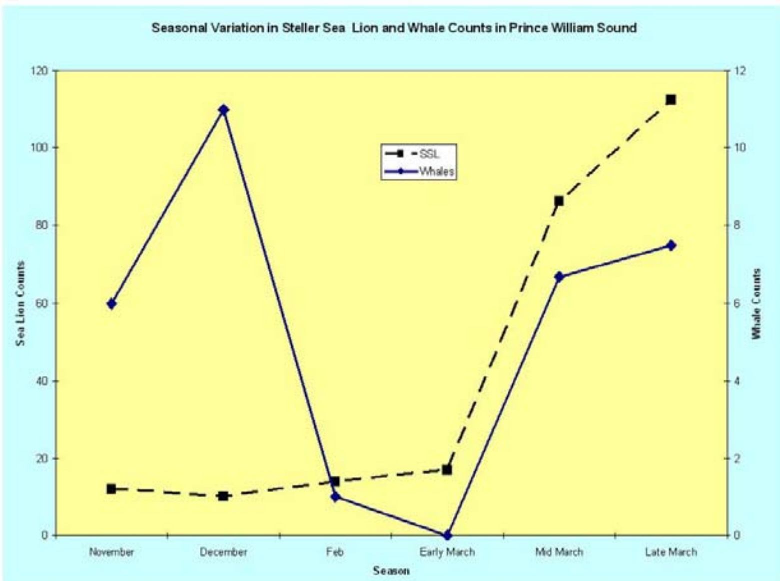

Figure 3. Seasonal variation in vessel counts of Steller sea lions and whales.

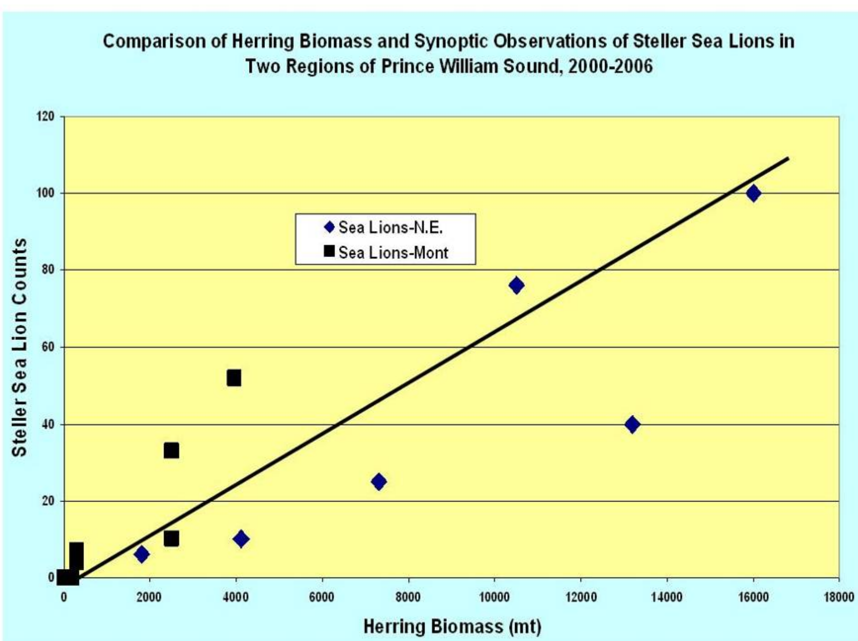

Figure 4. Comparison of herring biomass and synoptic aerial survey estimates of Steller sea lions in PWS, 2000-2006, from Thorne and Thomas 2008.

It is most likely that these correlations between Steller sea lions and herring represent predator/prey interactions rather than population level responses because of the mobility of the Steller sea lion population. There are no rookeries in PWS. However, it is apparent that Steller sea lions make foraging trips into PWS during winter specifically for herring. These foraging trips may include use of PWS haulouts, especially the Glacier Island haulout nearest to the major herring spawning locations in Port Fidalgo and Port Gravina. However, Steller sea lions in PWS during winter are primarily rafting near shore and near adult herring aggregations. Often the herring are located in sheltered bays and inlets, in which case the sea lions and herring essentially occupy the same area day and night. When herring are offshore, the Steller sea lions raft near shore during day, typically in sheltered locations, then rapidly reacquire the herring school locations after dusk. Steller sea lions in PWS during winter are virtually never found more than 100 m offshore during day, perhaps an adaptation to potential predation by transient Orcas. On one occasion an Orca was observed approaching an area occupied by over 100 Steller sea lions. All the sea lions immediately vacated the area at high speed.

In addition to the main focus of this research, adult herring during winter, there were four major cruises that focused on juvenile herring abundance and six minor cruises that took place during spring after herring spawning. With one exception, foraging activity by Steller sea lions on juveniles was minor. The lone exception occurred in Sawmill Bay during March. Adult herring are frequently found in this area in early March. The Steller sea lions observed in Sawmill Bay may have been a legacy of a previous adult presence. No sea lions were directly observed foraging near or on age 0 herring concentrations. Whales were also observed foraging on juvenile concentrations on one occasion only. In this case, the foraging whales were a mother and calf, and several other whales were just offshore working on adult herring schools. There were no direct observations of Steller sea lions foraging on herring during the spring cruises. Steller sea lions were typically observed near salmon terminal areas at this time.

Further details are given in Thorne and Thomas (2008) referenced in Table 3.

Indications of Impacts of the Exxon Valdez Oil Spill on Steller Sea Lions

While the correlations between Steller sea lions and herring in PWS observed during this study were clearly predator/prey interactions, we found a long-term relationship between historical numbers of Steller sea lions from agency aerial surveys in PWS and the herring biomass as measured by the accumulated miles of herring spawn (milt), as shown in Fig. 5. Both herring and SSL numbers in PWS declined in a similar fashion following the 1989 oil spill. Since this is a longer-term data set, it undoubtedly contains some actual Steller sea lion population trend as well as the predator/prey behavior documented in our cruise data. In fact, there was a corresponding overall decline in the Gulf of Alaska Steller sea lion population in the decade following EVOS. A detailed examination of this decline shows the magnitude was a function of proximity to PWS, so events in PWS, namely the decline in the herring population following the oil spill, likely contributed to the overall Steller sea lion population decline in the Gulf of Alaska (Fig. 6).

Further details are given in Thorne and Thomas (2006) and Thorne (2007) referenced in Table 3.

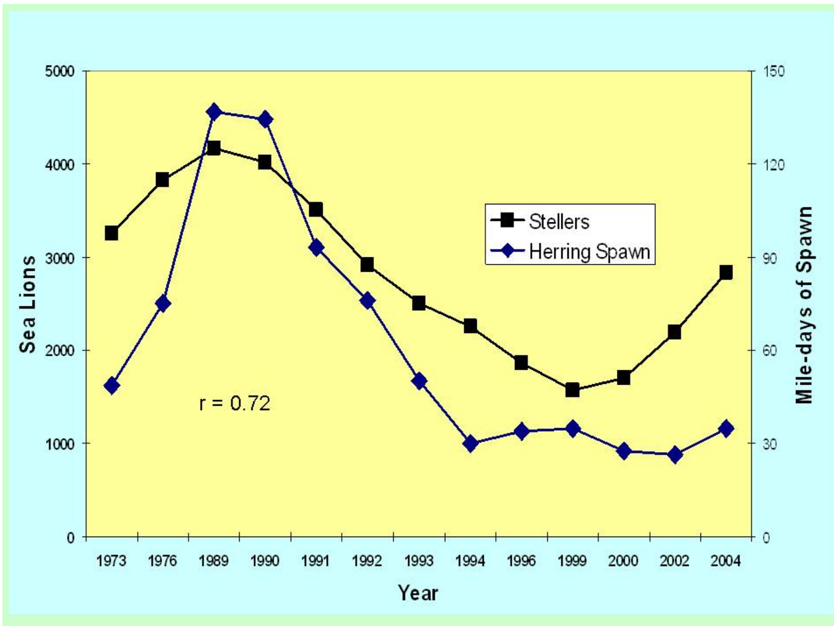

Figure 5. Correlation between aerial survey index of herring in PWS and corresponding agency aerial survey counts of Steller sea lions in PWS, 1973-2004

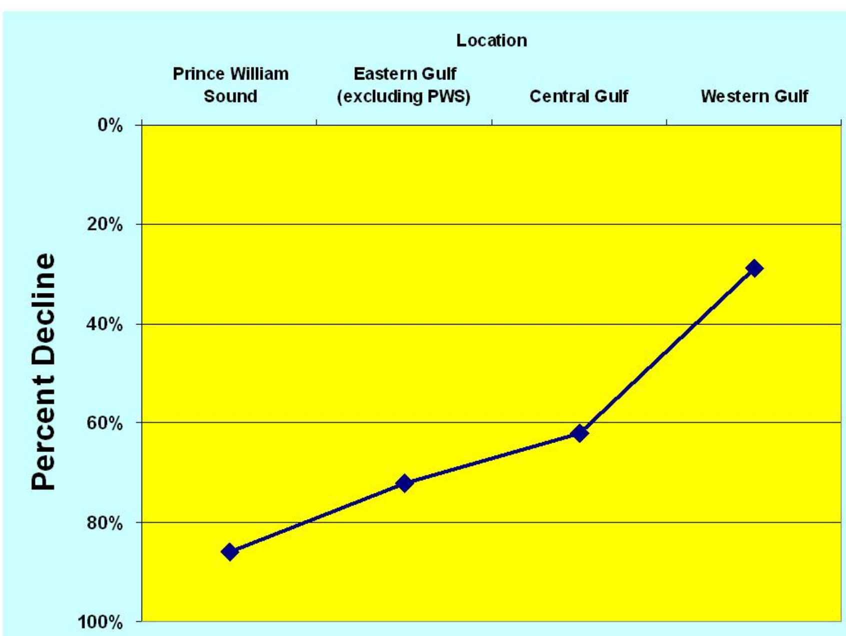

Figure 6. Geographic variation in GOA Steller sea lion declines over the decade following the Exxon Valdez Oil Spill

Overall correlations between SSL and pollock within PWS

There was a surprisingly vitriolic reaction from some quarters to the report by Thomas and Thorne (2001-**Nature**) that Steller sea lions in PWS were focusing on herring during winter rather than walleye pollock. While the role of herring as forage for Steller sea lions is now much better understood and widely recognized, we continued during this study to examine the possibility that pollock were a Steller sea lion foraging target during winter in PWS. No comprehensive pollock surveys were undertaken during this study, but Steller sea lions counts were made both from vessel and airplane over historic pollock locations in PWS. As reported in Thorne (2008), "only one Steller sea lion was ever detected above pollock concentrations in PWS throughout 5 years of extensive, winter-period aerial and vessel surveys". This individual was likely in transit. The observation does not exclude incidental take of pollock by Steller sea lions. Juvenile pollock are found in inshore waters, although no direct foraging activity of sea lions on juvenile pollock was observed during this study. In addition, evidence suggests that a small percentage of adult pollock move inshore during winter to forage on juvenile herring. However, there is clearly little or no foraging by Steller sea lions on the spawning concentrations of pollock during winter in PWS. This contrast with observations in the Gulf of Alaska and Bering Sea may result from the different depth regimes. Adult pollock during winter in PWS are primarily distributed between 175 and 300 m depths. In contrast, much of the pollock habitat in the GOA and Bering Sea is on the continental shelf and less than 100 m depth. Predation by Steller sea lions on pollock in the GOA and Bering Sea may result from the inability of pollock to achieve the depths needed to discourage sea lion predation.

Further details on this subject are given in Thorne (2008) referenced in Table 3.

Summary of Observations from Kodiak

During the study duration 2005 to 2008, four major and four supplemental surveys were conducted within the Kodiak Archipelago including the Alaska Mainland. The major focus of the surveys was the Uganik Bay area. However other areas were opportunistically surveyed. An attempt was made to assess the distribution and abundance of herring within Uganik Bay and the associations with Steller sea lion (Table 2b). During the timeframe the general distribution and abundance of herring within Uganik Bay was highly variable ranging from 500 metric tons to 6,400 metric tons. Depth of herring schools ranged from the bottom (50m-90m) to the surface depending on light, tides, and predation levels. Normally herring depth was shallower at night than during the day. In general the herring tended to aggregate in either South Arm or the Northeast Arm or both but would quickly vacate an area as well.

Without exception, aggregation of herring biomass in either area resulted in simultaneous observations of sea lions. When density was high and the biomass above 2,000 metric tons, large rafts and abundance (>100 animals) of sea lions were observed; when density was lower and biomass less than 2,000 metric tons sea lions were still observed, but in smaller foraging groups of one to nine animals. Similar to PWS, these correlations between Steller sea lions and herring likely represent predator/prey interactions. The association was evident not only during winter, but during the spring herring spawning period as well. In the Uganik Bay area the Steller sea lions were primarily rafting near shore and near the densest herring aggregations, but little was observed of their nighttime behavior. Aerial and vessel-based observations resulted in the discovery of two previously undocumented sea lion transitional haulout locations in both South Arm and Northeast Arm. While they undoubtedly exist, we were unable to document any major offshore herring aggregations due to inclement ocean conditions off Kodiak in the winter.

This co-occurrence of herring and sea lions was not unique to Uganik Bay within the Kodiak Archipelago; any considerable concentration of herring was always accompanied by a sea lion aggregation, but not always quantified. This was observed in Amook, Deadman, Three Saints, Kiliuda, Danger, Paramanof, Kukak, Ugak, and McCords bays. While herring aggregations were always associated with sea lions, sea lions were not restricted to association with herring biomass; over 75 sea lions were documented in Kizhuyak Bay in March 2006 foraging on a large biomass of juvenile capelin.

Of the 11 humpback whales identified in Uganik Bay during December 2005, eight had been previously sighted. Sightings of six of these eight were recorded by Denny Zwieflhofer (U.S. Fish and Wildlife Service) in Uganik Bay in January 2005. Thus, nearly 55% of humpback whales sighted in December 2005 were seen in the same location 11 months prior. Additional sightings of many these same whales were documented in February 2007. These data on humpback whales suggest some interesting mechanisms in the fidelity to winter forage areas. Similar to PWS, humpback whales tend to entirely leave the Uganik area by late February and March. During the early winter in Uganik Bay, humpback whales tend to be the most abundant whale species and appear to be targeting herring and other smaller prey (such as layers of chaetagnaths, euphasiids, amphipods, juvenile pollock or capelin). Juvenile pollock were often coincidentally caught with herring in Northeast Arm. In April, occurrence of humpback whales is sporadic while abundance of fin whales in Uganik Bay during the herring sac roe fishery has been 7-12 animals in April 2006 through 2008 and appears to be targeting adult herring as a prey source.

Future publication of these results in a peer-reviewed journal is anticipated.

Comparisons Between PWS and Kodiak

The correlations between herring and Steller sea lions were similar in both PWS ($r = 0.79$) and Kodiak ($r = 0.83$). Both were significant at the 99% level. However, the parameters of the regression equations were very different (Fig. 7). The intensity of Steller sea lion foraging on herring is much higher off Kodiak relative to the biomass values. While these relationships are somewhat confounded by seasonal differences (see Fig 3), the differing slopes may represent the much higher overall numbers of Steller sea lions around the Kodiak Archipelago. In contrast to PWS, where there are no rookeries, there are major rookeries in the vicinity of the herring over-wintering and spawning areas off Kodiak. Consequently, the length of foraging trips is considerably greater for PWS. The same consideration probably exists for the humpback whales, which would need to travel farther to forage in PWS. The more remote location may also explain the lack of fin whales foraging on herring in PWS (fin whales are more oceanic in distribution as is Kodiak). Finally, the studies off Kodiak located transitional Steller sea lion haulouts near the major herring over-wintering locations. No similar haulouts are found in PWS. This difference may reflect the greater threat from transient Orca whales in the Kodiak Archipelago.

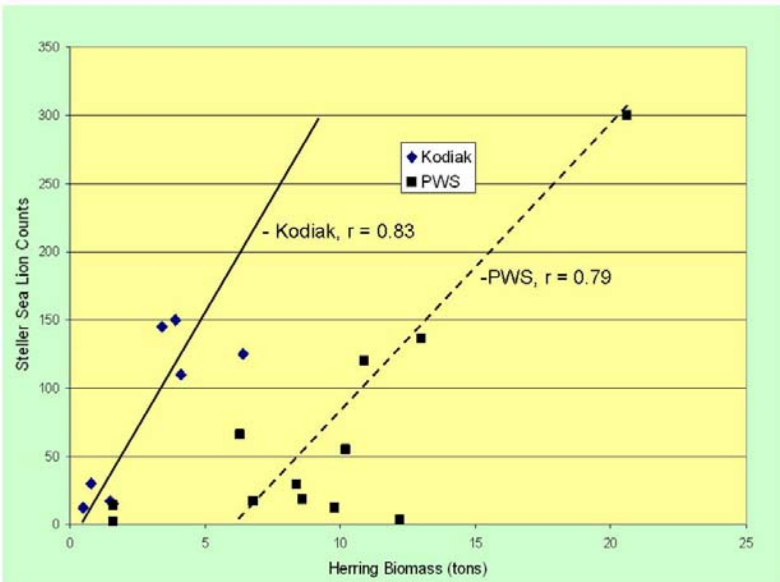

Figure 7. Comparison of herring and Steller sea lion associations between PWS and Kodiak.

Compilation of Herring and Pollock Distributional Characteristics

The objective of this specific study was to review the literature and databases from surveys of Pacific herring and walleye pollock in Prince William Sound, Alaska, to characterize distributions. The motivation was to provide information to help explain distributions and dive patterns of marine mammals, especially Steller sea lions. Three parameters in particular seemed relevant to marine mammal foraging behavior: vertical distributions, school densities and horizontal distributions. The following is a brief summary of findings. The analysis of surveys on adult herring during the month of March showed a mean depth that ranged from 17.0 to 25.1 m. The surveys included one daytime example with a mean depth of 18.2 m. Mean night-time depth of herring from the November-December period ranged from 12.3 to 23.4 m. Depth distributions were unimodal in virtually all cases (Fig. 8). Only one survey was available for juvenile pollock, but it included both day and night observations. Mean night-time depth was

20.5 m and mean daytime depth was 44.4 m. The mean depth from all surveys of adult pollock throughout PWS in 2001 was substantially deeper at 205 m.

Peak transect densities of herring at night were very consistent regardless of season, varying only from 0.105 to 0.410 kg/m^3. Peak densities for juvenile pollock were considerably lower than that of herring at night (0.011 kg/m^3), but were higher during day (0.066 kg/m^3) than during night. Adult pollock densities were considerably lower at 0.001 kg/m^3.

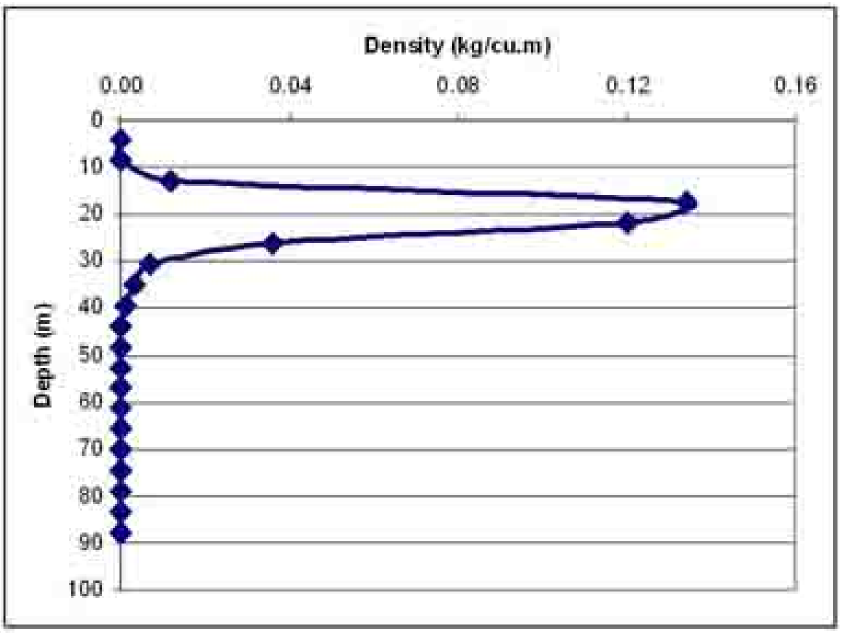

Figure 8. Typical night-time vertical distribution of adult herring in PWS.

Descriptions of herring and juvenile pollock distributions prior to 1999 are presented in Stokesbury et al. (2000) and Norcross et al. (2001). The distributional information in both publications is from the October 1995 and March 1996 surveys, both emphasize juvenile distributions, but the latter is restricted to herring. Stokesbury et al (2000) states that juvenile herring were primarily distributed at the heads of bays. Walleye pollock distribution (presumably juveniles) was also within bays, but not heads of bays. Adult herring were more likely distributed in passages or near shore in open waters. Norcross et al. (2001) reiterates these distributions, but also shows maps of age 0 and age 1-2 herring distributions in October and March. Those maps indicate widespread distribution within most of the bays throughout Prince William Sound, with highest concentrations in the northeast and southwest. Stokesbury et al. (2000) states that the walleye pollock (presumably juvenile) distribution was roughly similar to that of juvenile herring, concentrated in northeast and southwest regions. Adult winter period distributions are more limited. Adult pollock are primarily restricted to two deep basins regions: (1) from

Hinchinbrook Entrance north into the main basin and (2) the deep basin east and south of Knight Island. The major concentrations of adult herring during October/November are found in two regions: (1) on both sides of the north end of Montague Island and (2) in northeast PWS off Knowles Head and extending both directions into Port Gravina and Port Fidalgo. Later in the winter, the distribution becomes more concentrated within bays and harbors in those same regions.

Details of this study were provided as Appendix 1 of the Second Semi-Annual Report of this project. Note after the completion of this specific review, we documented large, migrating adult herring schools at depths over 100 m during day in PWS. These schools vertically migrated at night to typical near-surface depths. Whales, but no Steller sea lions were foraging on these schools during day. Both whales and Steller sea lions foraged on these schools at night. Note also, that herring in Southeast Alaska are distributed considerably deeper during day than typical for PWS (Thorne 1977a, b). However, there has been a trend toward deeper daytime distributions of herring in PWS over the past 3 years. It is speculated that the change may be in response to increased marine mammal and seabird predation. There has also been a shift in overwintering distribution from around Montague Island to Port Fidalgo and Port Gravina. This shift clearly appears to be a response to increasing humpback whale predation.

An update of this compilation is anticipated for future publication.

Impacts of Steller Sea Lions on herring mortality

The daily food requirement of Steller sea lions is well documented and varies with size, sex, condition and season (Winship and Trites 2003). The foraging correlation calculated by Thorne and Thomas (2006) was one sea lion per 150 mt of herring biomass. Assuming a daily ration of 40 kg, Steller sea lions under these circumstances would be removing 0.027% of the herring per day or 0.8% per month. As these were prespawning aggregations, it is unlikely that the foraging period would be more than 2-3 weeks. However, lesser foraging rates would be likely over about 6 mos of the overwintering period, as seen in Fig. 3. Further, at the peak of the herring biomass in 1988 there were over 4,000 sea lions in the Prince William Sound vicinity. This number would be capable of removing about 1% of the current herring biomass each day. Currently, whales appear to be the greater threat to herring. It is estimated that whales in PWS may be able to remove 15-20% of the biomass on an annual basis, an exploitation level higher than the historic commercial fishery on the stock.

Further details are given in Thorne (2007) referenced in Table 3.

Experiments with Passive Acoustics

One part of our research involved the use of passive acoustics to detect the presence-or-absence of spawning herring aggregations at specific times and locations in PWS.

Herring are known to release gas from their swim bladders and this release makes noise. If the local acoustic environment and the individual-, school-, and predator-related aspects of gas release and sound production were well understood, the sound intensities, phase correlations and range information may be useful for determining the presence/absence and for coarsely estimating size and abundance of fish. In addition, where large schools of fish reside, there often are associated predator assemblages, which also could be large sound sources that would help to detect the presence of fish. If a specific noise spectrum can be identified with the spawning aggregations and their predators, it could be used to optimize the effort allocation on active acoustic stock assessment surveys. In addition, such acoustic information could serve as a unique means to quantitatively monitor predator prey interactions and fish mortality over time and space.

During spring 2007, we conducted extensive measurements of the noises produced by herring under predation from Steller sea lions and humpback whales. We demonstrated that gas release of herring and the activity of their predators produce sound of unique pre-determined spectral signatures that can be used to identify their presence at the site over a range of several kilometers.

Details of the study are given in Thomas et al. (2007) referenced in Table 3.

<u>Seabird predators on Steller Sea Lions</u>

Winter surveys in March 2005 estimated the number of seabirds in Prince William Sound to be approximately 200,000 (McKnight et al. 2006) and Pacific herring are a key dietary component for many of them. The objective of the seabird work was to characterize the relationship between the winter distribution of seabird species and different age classes of herring in Prince William Sound. For this component, an observer recorded birds during 5 adult (Dec 04, Mar 05, Feb, Mar and Oct 06) and 4 juvenile (Mar and Nov 07, 08) herring cruises. For each seabird survey, the observer followed US Fish and Wildlife Service survey protocols. The observation range was 100 m off port, 100 m off starboard and 100 m directly ahead of and above the boat. Beginning in Nov 07, this range was increased to 150 m on each side and ahead.

Common Murre, loons (primarily Pacific Loon) and Gulls (primarily Glaucous-winged Gull), were the most common species or species group observed during the 2004-2006 adult herring surveys. Beginning in March 2007 with the addition of survey areas with juvenile herring, Common Murre and Marbled Murrelet (both diving seabirds), and large Gulls (primarily Glaucous-winged Gull) were the most numerous seabirds on transects. We found that each of these three seabirds had a distinct distribution pattern: Common Murre and Marbled Murrelet appeared at times to have very little overlap in distribution (Fig. 9). Large gulls (primarily Glaucous-winged Gulls) were found in very large aggregations but often with few murres or murrelets present.

The distributions of the most numerous seabirds appeared to reflect preferences for different herring age and size classes. Marbled Murrelet closely followed the seasonal movements of juvenile herring (age 0-2). Murrelet densities were higher in early winter in bays with juvenile herring schools but became scarce as numbers of juvenile herring decreased in late winter. Common Murre were most often encountered in deeper waters with aggregations of adult herring (age-3 or older Fig. 9). During November cruises, murres were relatively scarce in bays dominated by juvenile herring. High numbers of murres were regularly recorded in deeper waters near the mouth of Port Gravina and Port Fidalgo where adult herring also occurred. However, in March when more adult herring were entering these two bays, murres were present in large numbers compared to November. The distribution pattern for Black-legged Kittiwakes was less pronounced than for murres and murrelets, with kittiwake densities marginally higher around juvenile herring schools. The two large gulls, Glaucous-winged Gull and the less numerous Herring Gull were opportunistic and fed in areas with large fish concentrations, regardless of location and herring age class (juvenile or adult) of the fish present (Fig 10). Because both these species feed at or very close to the surface, they may rely on diving ducks, loons and cormorants to drive fish to the surface. Among the other relatively abundant seabirds, Cormorants were concentrated in southwest Prince William Sound, feeding around both juvenile and adult herring schools. Loons (primarily Pacific Loon) were associated with areas where adult herring were present.

Future publication of these results in a peer-reviewed journal is anticipated.

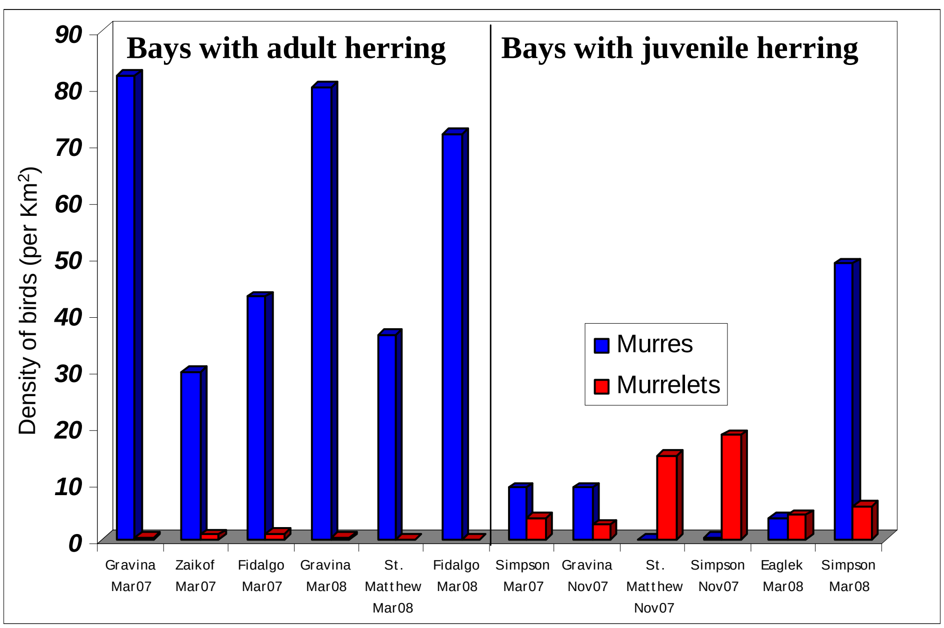

Figure 9. Densities of Common Murre and Marbled Murrelet relative to herring age class

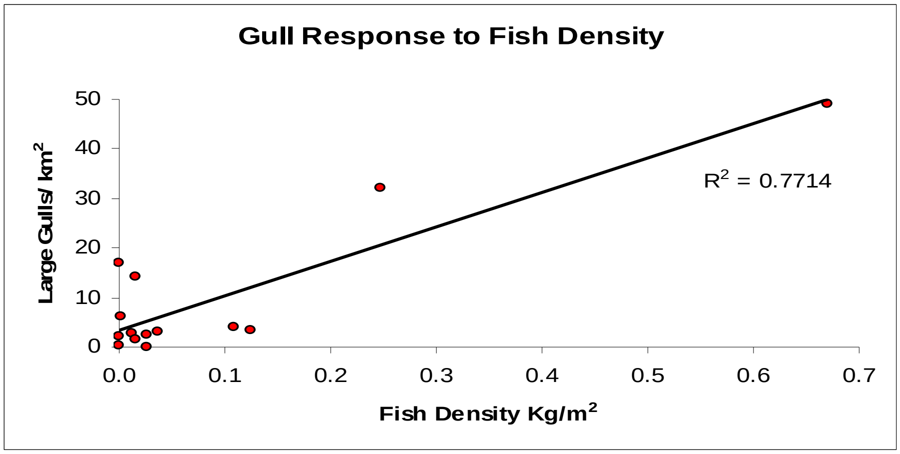

Figure 10. Relationship between densities of large gulls (Glaucous-winged and Herring) and fish observed during hydroacoustic surveys in March and November 2007. Gull densities were positively related to fish densities (R^2=0.77, P<0.001)

Herring Energetic Considerations

Herring are important as Steller sea lion forage because of their relatively high energy content and their availability in coastal areas such as Prince William Sound. Historically, strong cohorts of about one billion age-3 herring have recruited in PWS (Funk 2007). The magnitude of this number virtually trivializes the significance of the biomass represented by the half billion or so pink salmon fry released by PWS hatcheries. Furthermore herring reside in coastal waters year round whereas salmon are only present in coastal waters only early and late in their life. Herring thus play a highly significant role in the PWS pelagic ecosystem.

Although herring are considered to be a fatty fish, there is concern that their energy content may not be sufficient for over-winter survival (Paul and Paul 1998). Thus Steller seal lions have available in PWS a food source that potentially may be plentiful but is subject to variability in terms of food quality. Accordingly we investigated the role of energy content of juvenile herring before and after the winter period at several key sites with PWS in conjunction with our herring population surveys. Whole-body energy content of the whole herring was found to increase exponentially with length (Fig. 11). However, regardless of size, all herring were found to decrease in food value (energy content) over the winter (Fig. 11). Larger juvenile herring caught earlier in the winter period would be a more desirable Steller sea lion prey. Spatial variability in herring energy appears to depend on herring size. Therefore Steller sea lions should seek locations with larger herring as prey. If Steller sea lions were not able to find larger herring and become satiated as early as possible, they would have to consume an increasingly larger number of the lower quality herring to compensate. Thus Steller sea lions would find it necessary to consumer greater numbers of herring in the late winter to obtain the same caloric intake compared to the fall.

This study continues with funding from EVOS TC. Future publication of these results in a peer-reviewed journal is anticipated.

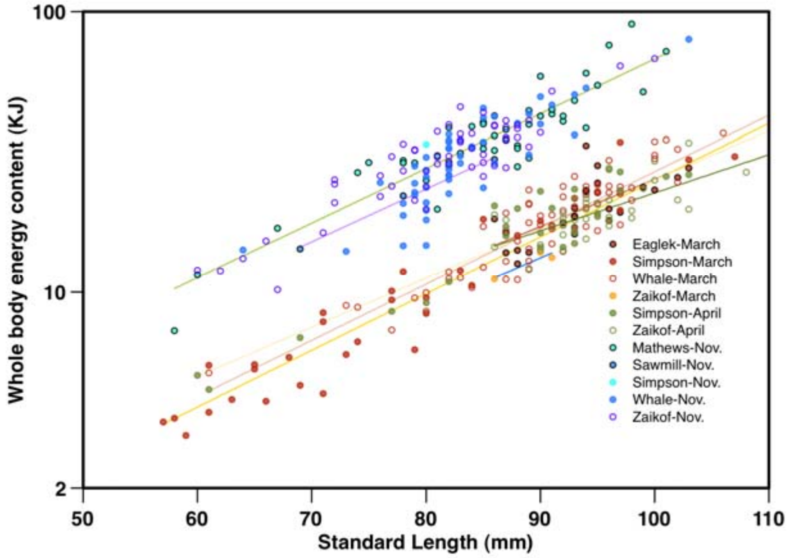

Figure 11. Whole body energy content (KJ) of PWS age-0 herring in relation to standard length (mm) in March and November 2007 by sampling site. Each symbol represents a separate fish sample.

<u>Modeling Steller Sea Lion Foraging Behavior</u>

Many theoretical and experimental studies suggest that synergistic interactions between resources and predators influence foraging decisions and their fitness consequences. This framework, however, has been ignored almost completely by hypotheses on causes of the population decline of Steller sea lions (SSLs) (Eumetopias jubatus)in western Alaska. By comparing predictions from a dynamic state variable model to empirical data on the behaviour of individuals instrumented with satellite-linked time-at-depth recorders, we develop and find preliminary support for the hypothesis that, during winter in Prince William Sound, juvenile SSLs (a) underutilise walleye pollock, a predictable resource in deep strata, due to predation risk from Pacific sleeper sharks, and (b) underutilise the potential energy bonanza of inshore aggregations of Pacific herring due to risk from either killer whales, larger conspecifics, or both. Further, under conditions of resource scarcity—induced by overfishing, long-term oceanographic cycles, or their combination—trade-offs between mortality risk and energy gain may influence demographic parameters. Accordingly, computer simulations illustrated the theoretical plausibility that a decline of Pacific herring in shallow strata would greatly increase the number of deep foraging dives, thereby increasing exposure to sleeper sharks and mortality rates. These results suggest that hypotheses on the decline of SSLs should consider synergistic effects of predators and resources on behaviour and mortality rates. Empirical support for our model, however, is limited and we outline tasks for empirical research that emerge from these limitations. More generally, in the context of today's conservation crises, our work illustrates that the greater the dearth of systemspecific data, the greater the need to apply principles of behavioural ecology toward the understanding and management of large-scale marine systems.

Details of this study are published in Frid et al. (2008) referenced in Table 3.

Future Directions

The genesis of this study can be found in concerns about the endangered status of the western stock of Steller sea lions, especially in relation to the valuable commercial fishery on walleye pollock. The focus on herring results from the documentation of Steller sea lion foraging on herring during winter (Thomas and Thorne 2001), and the subsequent controversy over the relative importance of herring versus pollock as a critical food source for Steller sea lions. Historically, interest in the status of the PWS herring population has resulted from its commercial value and importance to a healthy ecosystem. Herring in PWS were recognized to be in a collapsed state following the Exxon Valdez Oil Spill (EVOS), but there was little evidence of a linkage between the collapse and the EVOS. During the four plus years of this study, and largely as a result of this study, this linkage has become much more obvious. Consequently, the Exxon Valdez Oil Spill Trustee Council has increasing focused attention on the plight of the PWS herring stock, now listed as one of only two species that have not recovered from the EVOS. In FY 2007, The Trustee Council funded three studies at PWSSC that complemented the research conducted under this study. The Trustee Council focus is on juvenile herring nursery habitat and its relation to the lack of herring population recovery. Under Trustee Council direction a first draft of an Integrated Herring Restoration Program was recently completed. The main goal of the program is to determine what, if anything, can be done to successfully recover the Pacific herring in PWS from the effects of EVOS. In order to determine what steps can be taken, the program examines the factors limiting recovery of herring in PWS, identifies and evaluates potential recovery options, and recommends a course of action for achieving restoration. In February 2009, the Trustee Council issued an RFP for future work in relation to herring recovery. It is likely that several aspects of the research initiated in this study will be carried on under the Trustee Council program. There is no question based on the results of this research that a recovered PWS herring population would contribute considerably to the health of Steller sea lions, as well as several other marine mammals and seabirds that depend on herring as critical winter forage.

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Table 1-Summary of cruises conducted during this study

	Major		Supplemental	
Year (Fiscal)	PWS	Kodiak	PWS	Kodiak
2005	2	1	4	1
2006	5	1	4	1
2007	4	1	1	1
2008	3	1		1
2009	1			
Total	15	4	9	4

Table 2a. Details of PWS Cruises

Date	Category	Adult Herring Biomass (1000mt)	Steller Sea Lion Counts
November 13-18, 2004	Major	9.8	12
December 12-15, 2004	Supplemental	1.6	2
March 19-24, 2005	Major	12.2	3
March 26-30, 2005	Major	8.4	29
Spring 2005 (3)	Supplemental	n.d.	43
December 3-5, 2005	Supplemental	ins	2
January 31-Feb 9, 2006	Major	1.6	14
March 6-12, 2006	Major	ins	1
March 16-22, 2006	Major	13	136
March 26-April 1, 2006	Major	6.3	66
Spring 2006 (3)	Supplemental	n.d.	10
October 21-27, 2006	Major	Juvenile	4
December 1-5, 2006	Supplemental	8.6	18
March 8-14, 2007	Major	6.8	17
March 18-26, 2007	Major	10.9	120
March 29-April 2, 2007	Major	20.6	300
November 5-13, 2007	Major	Juvenile	5
March 16-23, 2008	Major	Juvenile	35
March 26-30, 2008	Major	10.2	55
November 5-13, 2008	Major	Juvenile	3

Table 2a Continued

Date	Whale Counts	Bird Counts	Comment
November 13-18, 2004	6		
December 12-15, 2004	0	Yes	
March 19-24, 2005	2		
March 26-30, 2005	1	Yes	
Spring 2005 (3)	0		Most on salmon
December 3-5, 2005	0		
January 31-Feb 9, 2006	1	Yes	
March 6-12, 2006	0		
March 16-22, 2006	15		
March 26-April 1, 2006	3	Yes	
Spring 2006 (3)	7		Most on salmon
October 21-27, 2006	1	Yes	
December 1-5, 2006	22		Most in Sawmill Bay
March 8-14, 2007	0	Yes	Most SSL working on juveniles in Sawmill Bay
March 18-26, 2007	3		
March 29-April 2, 2007	15		Most in Port Gravina
November 5-13, 2007	5	Yes	MMs not working juveniles
March 16-23, 2008	5	Yes	MMs not working juveniles except in Sawmill
March 26-30, 2008	11		
November 5-13, 2008	23	Yes	MMs working adults, SSL with whales

Table 2b. Details of Kodiak Uganik Bay Cruises

Date	Category	Adult Herring Biomass (1000mt)	Steller Sea Lion Counts
February 14-24, 2005	Major	3.4	145
April 11-15, 2005	Supplemental	0.8	30
December 10-17, 2005	Major	1.6	15
April 14-16, 2006	Supplemental	0.5	12
February 17-March 2, 2007	Major	4.1	110
April 12-14, 2007	Supplemental	6.4	125
Dec 07-Jan 08	Supplemental	1.5	17
April 6-10, 2008	Major	3.9	150

Table 3-List of Publications and Presentations

Peer-reviewed Publications

Thorne, R.E. 2008. Walleye pollock as predator and prey in the Prince William Sound ecosystem. Pp: 289-304, In: G.H. Kruse, K. Drinkwater, J.N. Ianelli, J.S. Link, D.L. Stram, V. Wespestad and D. Woodby (eds), Resiliency of gadid stocks to fishing and climate change. Alaska Sea Grant, University of Alaska, Fairbanks

Thorne, R.E. and G.L. Thomas 2008. Herring and the "Exxon Valdez" oil spill: an investigation into historical data conflicts. ICES Journal of Marine Science 65(1):44-50.

Frid, A., J. Burns, G.G. Baker and R.E. Thorne 2008. Predicting synergistic effects of resources and predators on foraging decisions by juvenile Steller sea lions. Oecologia 10.1007/s00442-008-1189-5, 12 p.

Frid, A., Dill, L.M., Thorne, R. E., Blundell, G. M. 2007. Inferring prey perception of relative danger in large-scale marine systems. Evolutionary Ecology Research, Vol. 4.

Conference Proceedings (published, non-peer review)

Thorne, R.E. and G.L. Thomas 2008. Acoustic assessment of trophic dominance in a marine ecosystem, Proceedings of Acoustics 08, Paris, 155th meeting of the Acoustical Society of America. 5 p.

Thomas, G.L. T. Hahn and R.E. Thorne 2007. Integrating passive and active acoustics for assessment of fish stocks. Proc. Oceans 2007, Vancouver, B.C., Canada, Oct 1-4, 2007. IEEE Publications. 10.1109/OCEANS.2007.4449243.

Thorne, R.E. 2007. When endangered species collide: Ecosystem restoration in Prince William Sound, Alaska. Proc. Oceans07, Aberdeen, Scotland, June 18-21, 2007. IEEE Publications.

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Thomas, Gary L., Thomas R. Hahn, and R.E. Thorne. 2006. Combining passive and active underwater acoustics with video and laser optics to assess fish stocks. Proceedings of the Oceans 2006 IEEE/MTS Meeting in Boston, MA. 10.1109/OCEANS.2006.307069.

Thorne, R.E. 2005. Monitoring Pacific herring abundance with combined acoustic and optical technologies. Proc. Oceans05, Washington D.C. Sept 20-23, 2005

Thorne, R.E. 2005. Effectively addressing ecosystem understanding: solutions to the limitations of current fisheries and oceans policy. Proc. Oceans05, Washington D.C. Sept 20-23, 2005

Table 3-continuted

Oral Presentations at Conferences, not published-
Alaska Marine Science Symposium 2009
What has 16 years of acoustic surveys taught us about herring, EVOS and the Prince William Sound ecosystem? by Richard E. Thorne, PWSSC

Alaska Marine Science Symposium 2008
Trends in Prince William Sound Herring Abundance and Distribution: Predator Impacts by Richard E. Thorne, Mary Ann Bishop, Thomas Kline, Kathy Kuletz and Richard Crawford

International Symposium on Herring-Linking Herring Galway 08
Interactions Between Herring and Predators in Prince William Sound, Alaska by Thorne, R.E., Bishop, M.A. Dawson, N., Kuletz, K. and Crawford, R.

Acoustic Surveys of Herring in Prince William Sound, Alaska: A Long and Successful Series by Thorne, R.E. and Thomas, G.L.

American Fisheries Society-Lake Placid, New York 2006
Did the Exxon Valdez Oil Spill change the natural mortality of herring and invalidate the age-structured model? by Richard E. Thorne and Gary L. Thomas

American Fisheries Society Anchorage 2005
Acoustic Surveys and the Wasp-Waist Concept: An Approach to Ecosystem Understanding by Richard E. Thorne and Gary L. Thomas

Posters (no publication)
American Fisheries Society, Anchorage 2005
Implications of the Prince William Sound Herring Population Crash-Did it Impact Steller Sea Lions? by Gary L. Thomas and Richard E. Thorne

Effectively Addressing Ecosystem Understanding: Solutions to the Limitations of Current Fisheries and Oceans Policy by Gary L. Thomas and Richard E. Thorne

Ocean Sciences, Hawaii, 2005
A Comparison of Direct and Indirect Estimates of Herring Abundance in Prince William Sound, Alaska, 1980-2005 by Richard E. Thorne and Gary L. Thomas

Table 3-continuted

Public Presentations

Speaker	Date	Location	Title
R. Thorne	March 05	Simon Frazer U	Pacific herring, Steller sea lions and the wasp-waist concept: Illustrating an effective approach to ecosystem understanding
R. Thorne	April 05	Cordova	Ecosystem-based Fisheries Management
R. Thorne	May 06	Cordova	PWSSC Herring Research
R. Thorne	Nov 06	Cordova	Investigations into the Role of Walleye Pollock as Predator and Prey in the Prince William Sound Ecosystem