

# Herring and the “Exxon Valdez” oil spill: an investigation into historical data conflicts

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It was generally believed that the 1989 “Exxon Valdez” oil spill did not cause the collapse of the Prince William Sound Pacific herring (*Clupea pallasii*) population because of a 4-year gap between the spill and the collapse. However, we noted in a previous paper that some data suggested an earlier timing for the herring decline. We examine historical patterns of herring spawn, anomalies in historical fisheries model predictions, changes in predation behaviour of Steller sea lions (*Eumetopias jubatus*), and a decadal database of acoustic measurements of herring biomass. Behaviour of adult herring makes them especially vulnerable to damage from oil spills, something that was either unknown or misunderstood at the time of the spill. We therefore argue that the start of the herring decline was coincident with the oil spill, and that the decline took place over a 5-year period, rather than the single-year collapse previously reported. Although a comprehensive management approach is now in use for herring, the tools were not in place at the time of the oil spill or the subsequent collapse.

**Keywords:** acoustic survey, age-structured assessment, environmental impact assessment, “Exxon Valdez” oil spill, Pacific herring, Prince William Sound, stock assessment.

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## Introduction

The impacts of oil spills on marine mammals and seabirds are well documented (Peterson *et al.*, 2003). Direct mortality results from contact with the floating oil and long-term exposure to oil toxins residing in the spill-affected areas. In contrast, evidence for direct mortality to fish exposed to oil is limited. It is well known that the fishery for Pacific herring (*Clupea pallasii*) in Prince William Sound (PWS) collapsed in 1993, when commercial fishers could not locate fishable concentrations despite a pre-season estimate of 133 852 t from the age-structured assessment (ASA) model used by the management agency, the Alaska Department of Fish and Game (Pearson *et al.*, 1999; Carls *et al.*, 2002; www.evosc.state.ak.us). Links between the collapse and the March 1989 “Exxon Valdez” oil spill (EVOS) appeared unlikely because of the 4-year gap between the oil spill and the collapse (Quinn *et al.*, 2001; Marty *et al.*, 2003). Further, harm to herring from the oil spill was considered unlikely because average water column concentrations of petroleum hydrocarbons were significantly below the levels considered toxic for adult fish (Bienert and Pearson, 1995).

We began annual acoustic surveys of the herring stock in 1993 after the collapse was detected. The methodology of the surveys is detailed in Thomas and Thorne (2003). The acoustic biomass estimates from 1993 to 2002 compared favourably with a traditionally measured index known as the mile-days of spawn, hereafter referred to for clarity as mile-days of milt. The value of this index declined precipitously between 1988 and 1993, unlike the estimates from a revised ASA model that showed a dramatic

single-year collapse of the herring stock between 1992 and 1993 (Quinn *et al.* 2001). The discrepancy suggested to us that the herring population decline may have begun immediately after the EVOS, rather than 4 years later.

Hulson *et al.* (2008) re-examine historical data using several versions of the ASA model, including some of the acoustic data. They generally supported the hypothesis that the main decline started in 1992 when disease affected a large population that was in weakened condition. However, despite their sophisticated and comprehensive analysis, they concluded that alternative views were also consistent with the existing data.

Here, we argue for an alternative view that the herring decline began earlier and was associated with the EVOS. Our approach is threefold. First, we update and expand the original analysis of Thomas and Thorne (2003). Second, we examine changes in the predation behaviour of Steller sea lions (*Eumetopias jubatus*) for evidence of the timing of the collapse of herring. Finally, we describe a mechanism of damage to adult herring by the oil spill that we believe would have increased the mortality of herring after the EVOS.

## Methods

Pacific herring stocks from Alaska to California have been assessed acoustically for management purposes since the early 1970s (Thorne, 1977a,b, 1983; Trumble *et al.*, 1983). The surveys are based on echo integration techniques (Thorne, 1971, 1983a,b; MacLennan and Simmonds, 1992). The acoustic surveys in PWS

adhere to a multistage sampling design (Cochran, 1977). Initial focus is on location of adult herring aggregations within PWS, then echo integration surveys are conducted over the areas occupied by herring schools. The surveys are repeated several times to develop multiple, independent estimates of the biomass of specific fish aggregations. The repeat estimates are used to determine the precision of the biomass estimates (Scheaffer *et al.*, 1986), and after the echo integration surveys, the herring schools are subsampled for biological information with a commercial purse-seine (McClatchie *et al.*, 2000). The size composition of the herring in the net catches is used to estimate the target strength in order to convert backscatter to biomass (Thomas *et al.*, 2002).

For the analyses herein, we use the results of annual acoustic surveys from 1993 to 2005 (Table 1). The annual estimates are from spring surveys except for the first 2 years, which were made in autumn. However, several seasonal surveys were made during the period 1995–1997, and there was no significant difference between the results of autumn and spring surveys, so it is

concluded that the annual index of abundance is similar irrespective of the season when the survey was carried out. This finding has subsequently been corroborated by extensive seasonal surveys of herring migration and behaviour since 2000.

Historical information on the abundance of Pacific herring in PWS includes aerial estimates of the length of milt patches along beaches and an ASA model (Quinn *et al.*, 2001; Hulson *et al.*, 2008). Additionally, estimates of total egg deposition from diver surveys were made on ten occasions between 1984 and 1997. The Alaska Department of Fish and Game (ADF&G) has conducted the annual aerial surveys of milt since 1973, but here we use the historical values recently compiled by Steve Moffitt of ADF&G, Cordova (Table 1). Historical photos from the aerial surveys of milt are currently being digitized and reanalysed, so these values may change in the future. However, early indications are that the changes will be minor (S. Moffitt, pers. comm.). Egg-deposition values are taken from ADF&G data, reported in Quinn *et al.* (2001).

**Table 1.** Databases for PWS herring and related measurements, 1973–2005.

Year	Mile-days of milt	Average ASA estimate (t)	Egg-deposition estimate (t)	Acoustic estimate (t)	Sea lion counts in PWS and vicinity	Sea lion counts in PWS
1973	48.6	–	–	–	3260	–
1974	75.2	–	–	–	–	–
1975	42.4	–	–	–	–	–
1976	33.7	–	–	–	3849	–
1977	73.5	–	–	–	–	–
1978	36.3	–	–	–	–	–
1979	73.2	–	–	–	–	–
1980	69.9	53 521	–	–	–	–
1981	139.1	63 386	–	–	–	–
1982	65.1	52 750	–	–	–	–
1983	99.9	58 799	–	–	–	–
1984	86.8	72 135	58 089	–	–	–
1985	149.4	90 969	–	–	–	–
1986	152.2	80 260	–	–	–	–
1987	156	83 960	–	–	–	–
1988	232.9	118 861	53 785	–	–	–
1989	184.7	120 577	49 914	–	4351	907
1990	143.7	104 891	127 478	–	4124	926
1991	64.9	93 279	140 964	–	3480	430
1992	99.2	105 800	128 263	–	2951	242
1993	40.7	27 722	–	18 812	2292	258
1994	20	18 665	17 069	12 555	2492	260
1995	32.4	19 339	20 022	12 070	–	–
1996	39.1	25 282	27 669	23 203	1731	–
1997	56	32 777	24 000	37 400	–	–
1998	48.6	34 233	–	17 655	–	–
1999	37.8	29 304	–	17 301	1505	–
2000	24.6	18 978	–	7 280	1565	–
2001	16.8	13 196	–	6 330	–	–
2002	23.1	16 487	–	10 700	2193	–
2003	28.6	23 099	–	23 200	–	–
2004	34.8	24 750	–	12 700	2831	–
2005	33.4	19 242	–	20 100	–	–

Age data on herring in PWS have been collected by ADF&G since 1980. The ASA model has been run to forecast the PWS adult herring biomass most years since 1993, and has included several versions. All versions reconstruct the population history of the herring since 1980, and all show similar herring abundance trends from 1980 to 1993 except the original 1993 version. In our earlier analysis (Thomas and Thorne, 2003), we used the 1997 run of the model, but in this analysis, to avoid reliance on a single version, we use the average of all official ADF&G runs of model versions between 1993 and 2006 (Table 1).

Our original analysis used simple linear regression to compare the acoustic data with other measures of abundance. The best correlation was with the index mile-days of milt. As both ASA and egg-deposition estimates are made in terms of herring biomass, we used the results of the regression analysis with the acoustic estimates to convert the mile-days of milt index to a comparable scale. This is referred to as a “hindcast” or a “hydroacoustic index” by Hulson *et al.* (2008), but in reality it is the index mile-days of milt expressed in terms of biomass.

In addition to updated analysis of the various historical estimates of herring abundance, we hypothesize that a major collapse of herring, a wasp-waist or keystone species (Rice, 1995; Cury *et al.*, 2003) in PWS, should have had detectable impacts on other species. The literature on the recovery of piscivorous birds and mammals after the EVOS is replete with suggestions that the herring collapse was a factor that delayed any recovery. Here, we use historical data on the number of Steller sea lions that overwinter in PWS as an ecological indicator of this possible change, for several reasons. First, there is considerable evidence of a strong correlation between Steller sea lions and herring aggregations overwintering in PWS (Thomas and Thorne, 2003). Second, although population trends between predator and prey are likely to be lagged and perhaps, therefore, not useful for our purpose, a herring population change should cause immediate and detectable changes in the foraging behaviour of a highly mobile predator such as a Steller sea lion. Third, evidence indicates that direct mortalities of Steller sea lions from EVOS were minor (Calkins *et al.*, 1994) and would not confound the analysis. Finally, there is a considerable database on Steller sea lions because of their endangered status, and the possible implications of the highly valued walleye pollock (*Theragra chalcogramma*) fishery in their decline (Ferrero and Fritz, 2002). The National Marine Fisheries Service (NMFS) has conducted periodic aerial surveys of Steller sea

lions on various haulouts and rookeries for several decades (Kruse *et al.*, 2000; Sease *et al.*, 2001). There are 13 years with NMFS counts of Steller sea lions in PWS and vicinity between 1973 and 2004, including five made during the critical post-EVOS years 1989–1993 (Table 1). In addition, we conducted 18 synoptic aerial surveys of foraging Steller sea lions in conjunction with acoustic herring surveys between 2000 and 2006. Daytime visual and night-time infrared observations along the acoustic transects were used to ground-truth the aerial surveys (Thomas and Thorne, 2001). These surveys were used to confirm the strength of the predator–prey relationship and the co-occurrence of Steller sea lions and herring in PWS.

## Results

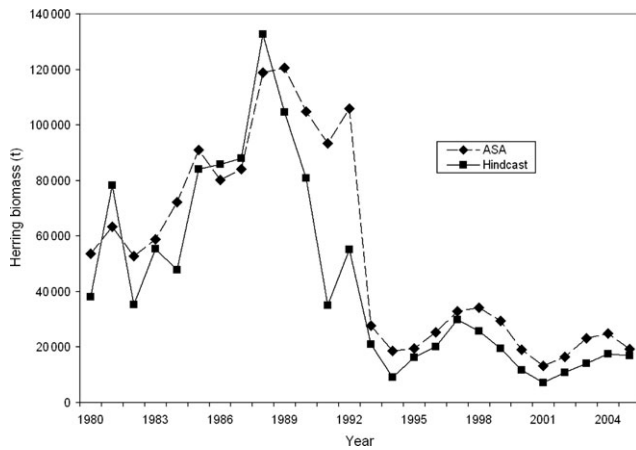
### Herring database comparison

The acoustic survey estimates of herring biomass from 1993 to 2005 and the corresponding mile-days of milt are positively correlated at a 99% level of significance (Table 2). The resulting estimates of herring biomass from the converted mile-days of milt index generally compare well with those from the ASA model in both trend and value (Figure 1). However, the hindcast using mile-days of milt shows a moderately steep decline that began in 1989 and continued to 1994, except for a small deviation in 1992. In contrast, the estimates from the ASA model remained high until a catastrophic single-year decline of ~80 000 t between 1992 and 1993 (Figure 1).

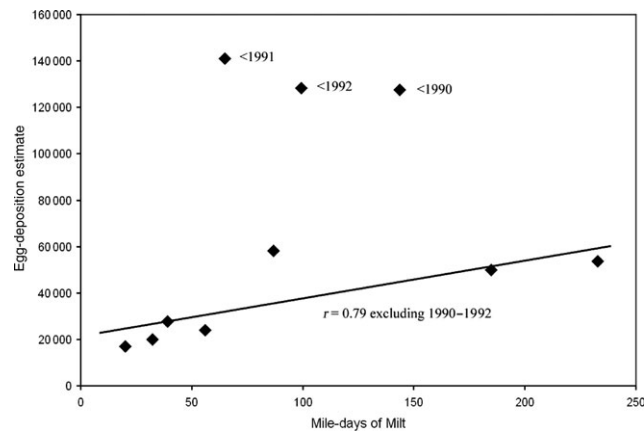
Comparison of the acoustic values with other observations shows too that the acoustic estimates are positively correlated (99%) with the ASA estimates, but not with the egg-deposition estimates (Table 2). Further, the mile-days of milt values from 1980 to 2005 are positively correlated (99%) with the ASA estimates, but not with the egg-deposition estimates. However, if the 1990–1992 values are excluded, the mile-days of milt and egg-deposition values are positively correlated (95%), and the correlation coefficient with the ASA estimates increases from 0.90 to 0.97 (Table 2). Only the ASA model estimates, which include egg deposition as a variable, are positively correlated with the entire egg-deposition dataset (95%). We conclude, therefore, that the 1990–1992 egg-deposition values, which are central to the data conflict described in Hulson *et al.* (2008), may be anomalous (Figure 2).

**Table 2.** Results of simple linear regression analyses.

Variable 1	Variable 2	Period	<i>r</i>	<i>n</i>	<i>t</i> -value	Significance
Herring acoustics	Mile-days of milt	1993–2005	0.79	13	4.27	99%
Herring acoustics	Herring ASA	1993–2005	0.69	13	3.16	99%
Herring acoustics	Herring eggs	1993–2005	0.63	4	1.15	Not significant
Mile-days of milt	Herring ASA	1980–2005	0.90	26	10.12	99%
Mile-days of milt	Herring ASA	Excluding 1990–1992	0.97	23	18.28	99%
Mile-days of milt	Herring eggs	1984–1997	0.27	10	0.79	Not significant
Mile-days of milt	Herring eggs	Excluding 1990–1992	0.79	7	2.88	95%
Herring ASA	Herring eggs	1984–1997	0.68	10	2.62	95%
Steller sea lions	Herring acoustics	2000–2006	0.88	18	7.41	99%
Greater PWS sea lions	Herring hindcast	1973–2004	0.78	13	4.13	99%
PWS sea lions	Herring hindcast	1989–1993	0.86	5	2.93	90%
PWS sea lions	Herring ASA	1989–1993	0.59	5	1.28	Not significant



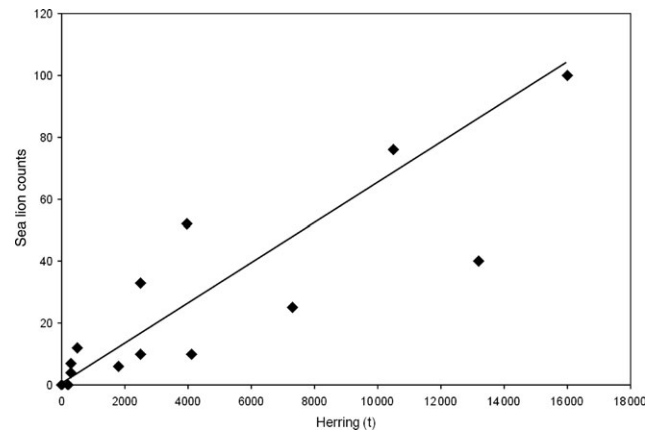
**Figure 1.** Comparison of historical estimates of herring biomass based on mile-days of milt (hindcast) and the averaged ASA model for PWS, 1980–2005.



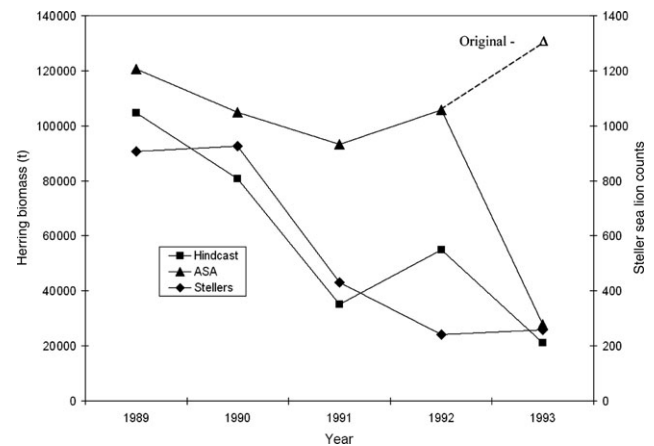
**Figure 2.** Scattergram of egg-deposition estimates and mile-days of milt values for PWS, 1984–1997.

### Independent trends

The analysis of Steller sea lion population trends was a three-step process. The first step was to verify short-term correlations between herring and Steller sea lions. Synoptic counts of Steller sea lions from the aerial surveys were positively correlated (99%) with prespawning herring abundance as estimated from the acoustic surveys (Table 2; Figure 3). Second, there is a positive correlation (99%) between agency counts of Steller sea lions in the greater PWS region (including adjacent rockeries) between 1973 and 2004 and the corresponding hindcast of herring abundance based on mile-days of milt (Tables 1 and 2). The final step was to look at Steller sea lion trends within PWS during the critical time period. There was no agency count of Steller sea lions in PWS in 1988, but Steller sea lion numbers did decrease steadily between 1989 and 1993. Both the pattern and the magnitude of the Steller sea lion decline compare well with the pattern and magnitude of the herring decline estimated from mile-days of milt (Figure 4). Further, the annual agency counts are positively correlated (90%) with the annual estimates from the mile-days of milt (Table 2). In contrast, Steller sea lion numbers do not correlate with the ASA model estimates, despite the comparable endpoint.



**Figure 3.** Comparison of herring biomass estimates from acoustic surveys and synoptic aerial counts of foraging Steller sea lions in various regions of PWS, 2000–2006.



**Figure 4.** Comparison of Steller sea lion abundance trends from agency aerial surveys in PWS with herring estimates from the mile-days of milt index and the ASA model for the critical post-EVOS years.

### A new mechanism for damage

Acoustic observations made 17 years ago suggest that Pacific herring make routine migrations to the surface at night to gulp air (Thorne and Thomas, 1990). Subsequently, this behaviour has been comprehensively documented using infrared and visual technologies (Thomas and Thorne, 2001). Recent research shows that herring also release gas bubbles and break the water surface in response to predation (Thomas *et al.*, 2007). These behaviours make herring highly vulnerable to contact with a surface toxicant such as an oil spill. Adult herring are also highly aggregated during late winter, although juveniles are more cosmopolitan (Stokesbury *et al.*, 2000; Thomas and Thorne, 2003). The 13 years of survey data reveal occasions where >90% of the adult herring population was in a few large aggregations distributed within a total area of 10 km<sup>2</sup>. Such behaviour places the adult herring in a situation where even a small oil spill could affect most of the spawning stock. The EVOS overlapped the areas where adult herring typically aggregated in PWS during March (Peterson *et al.*, 2003), so

such a huge oil spill probably overlapped most of the PWS adult herring stock. The surfacing behaviour of herring would ensure that they were exposed to oil via ingestion and gill-filament emersion. As a consequence, arguments that herring were not impacted by the EVOS because water column hydrocarbon levels were low (Bienert and Pearson, 1995) are, in our opinion, not relevant to the debate. Despite the absence of direct observation, herring would have been exposed to toxic levels of oil at the surface. In addition, the coating of their gills with crude oil raises the possibility of mechanical suffocation, which in its effect could swamp the extent of the mortality from oil toxicity. Both oil toxicity through gill-filament absorption and suffocation were determined to play a major role in the Sakhalin Island herring die-off after an earthquake-induced oil spill (Sakhalin Environmental Watch, 2000). However, toxicologists need to examine this mechanism of exposure to surface toxins in more detail, because many fish species have open gas bladders similar to herring, also undergo diel vertical migration, and may gulp air at the surface.

## Discussion

The results of our analysis concur with the statement of Hulson *et al.* (2008) that the historical estimates show generally good agreement, except 1989–1992. However, our opinion is that the evidence supports an earlier herring decline, for several reasons: (i) the better agreement of the acoustic data with the mile-days of milt index, (ii) the corresponding decline in abundance of foraging Steller sea lions, (iii) the expectation of damage to adult herring from oil, and (iv) the problem with accounting for a die-off of ~80 000 t of adult herring.

We acknowledge that this analysis of the various estimators is very basic and intended only to identify areas of agreement and disagreement. We explore neither normality nor non-linearity. However, even the simple analysis confirms that the mile-days of milt index is a viable measure of population abundance, a fact not appreciated in previous studies (Quinn *et al.*, 2001). Hulson *et al.* (2008) state that the major conflict is between male and female products from 1988 and 1992. We would limit that conflict to the period 1990–1992 (Figure 2). They also state that there is a conflict between the spawning age composition and the hydroacoustic dataset, but the real secondary conflict, in our opinion, is between the spawning age composition and the mile-days of milt, because acoustic information was not collected before 1993. We would argue that this secondary conflict is to be expected. An undetected increase in mortality of adult herring would cause the ASA model to overestimate, because it incorporates the relative number of older fish to estimate recruitment. Therefore, the spawning age composition is not definitive without knowledge of the real mortality rate, which is lacking. However, we agree that these statistics alone are inconclusive, which is why we explored other arguments.

The ability of Steller sea lions to locate and forage on prespawning herring populations has long been recognized, and the direct associations measured in this study were highly significant. Steller sea lions are efficient and highly mobile predators. The correlation between the abundances of Steller sea lions and herring in PWS between 1989 and 1993 is clearly a predator–prey cooccurrence rather than a population response. Overall, the western stock of Steller sea lions showed little change over the 4-year period (Calkins *et al.*, 1994), but the decline in abundance in PWS was substantial and closely matched the herring decline. Although there is variability in the estimates of both sea lions

and herring, there is a notable similarity between the pattern of sea lion decline and the herring decline estimated from the mile-days of milt index over the 5-year period 1989–1994 (Table 1).

It is virtually certain that adult herring came into direct contact with surface oil. There are also several indications that both the early and adult life history stages were damaged by the oil spill. Premature hatching, low larval weights, reduced growth, and elevated morphological and genetic abnormalities were observed in the early life history stages of the 1989 year class of PWS herring (Brown *et al.*, 1996). Adult herring sampled after the spill had liver lesions (Moles *et al.*, 1993). Oil exposure has been shown in laboratory tests to depress immune functions and to allow the expression of viral disease (Carls *et al.*, 1998). As herring are subject to intense predation, even a minor decrease in herring performance would have increased their natural mortality.

The argument for a disease-related decline after 1992 also requires a die-off of ~80 000 t of adult herring (>1.5 billion adult fish) in a single year, nearly 75% of a historically large herring population. Heavy layers of dead and dying herring have been found at the sea surface in cases of only moderate die-offs attributable to toxicity or disease (Meyers *et al.*, 1999). The herring die-off in the Sakhalin Islands region in 1999 was estimated at 905–11 167 t and covered more than 12 km of beach, 1–6 m wide and up to 0.5 m deep (Sakhalin Environmental Watch, 2000). Further, in the previously reported cases of herring die-offs attributable to VHS, the dead herring at the surface were accompanied by large numbers of dead predators, including walleye pollock (Meyers *et al.*, 1999). PWS is a busy waterway. After EVOS, it was one of the most intensely observed marine ecosystems on earth, with an estimated \$2 billion spent in clean-up, damage assessment, and restoration. Despite this intensity of observations, no major die-off of herring in PWS has been documented. Further, no major die-off of walleye pollock or of other dominant herring predators has been documented. Instead, pollock abundance was documented to be at historical highs (Thomas *et al.*, 1997). In contrast, our analysis based on the miles-days of milt index requires a relatively minor increase in natural mortality beginning in 1989, which we attribute to oil exposure. This argument not only spreads the increased natural mortality over 5 years, but changes the balance between natural and fishing mortality, because the fishery harvest is from a smaller population. In all, 40 000 t of fish were removed by the commercial fishery between 1990 and 1992. We believe that a moderately steep 5-year decline, the result of a greater natural mortality attributable to oil damage and an intensive commercial fishery, offers a more reasonable explanation for the collapse of Pacific herring than a cataclysmic collapse without any documentation of fish corpses.

Both our analysis and that of Hulson *et al.* (2008) suffer from a lack of data before 1993. Despite the use of the term “hydroacoustic index” by Hulson *et al.* (2008), there were no acoustic data before autumn 1993, and the main contribution of our subsequent acoustic data to this argument is to provide validity to the historical mile-days of milt index. Similarly, the thesis of Hulson *et al.* (2008) may suffer from the paucity of disease information on PWS herring before 1993. Systematic sampling of disease prevalence did not begin until 1994 (Quinn *et al.*, 2001). Finally, although sophisticated models can back-calculate to 1980, the ASA model was not actually used for herring management until 1993, and there is universal belief that the first estimate may have been erroneous.



A lesson to be learned from this evaluation, however, is that no level of sophisticated post-disaster analysis can replace the routine collection of well-considered environmental and fisheries management data. We support the ultimate conclusion of Hulson *et al.* (2008) that management would benefit from a comprehensive management framework, as provided by the ASA, and a methodology to provide a timely check on potential changes in mortality rates and biomass, as provided by acoustics. However, there was no comprehensive management approach in PWS before the herring collapse, and currently there are many applications of ASA-based management approaches that do not have associated direct assessment output such as from acoustics to guard against unanticipated changes in natural mortality. On the basis of the PWS herring experience, we conclude that it is risky to rely for management solely on an ASA-based management approach that cannot respond in timely manner to changes in natural mortality, whether from an oil spill or climate change.

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