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Exxon Valdez Oil Spill Trustee Council

PRINCE WILLIAM SOUND HERRING RESTORATION PLAN

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Exxon Valdez Oil Spill Trustee Council

441 W. 5th Ave., Suite 500 • Anchorage, AK 99501-2340 • 907 278 8012 • fax 907 276 7178

PLEASE COMMENT

You can help the Trustee Council by reviewing this draft restoration plan and providing your comments. Please provide comments by the close of business on April 8, 2008. You can comment by:

Mail: Exxon Valdez Oil Spill Trustee Council
441 W. 5th Avenue, Suite 500
Anchorage, AK 99501
Attn: PWS Herring Restoration Plan

Telephone: 1-800-478-7745 (within Alaska)
1-800-283-7745 (outside of Alaska)
Collect calls will be accepted from fishers and boaters who call through the marine operator.

Fax: 907-276-7178

E-mail: michael_baffrey@alaska.gov

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Michael Baffrey, Executive Director

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EXECUTIVE SUMMARY

PLAN GOALS

The Exxon Valdez Oil Spill (EVOS) Trustee Council has classified the Prince William Sound (PWS) population of Pacific herring (*Clupea pallasi*) as a resource that has not recovered from the effects of the 1989 oil spill. The PWS herring population was increasing prior to 1989 with record harvests reported just before the spill. The 1989 year class was one of the smallest cohorts of spawning adults recorded, and by 1993, the fishery had collapsed with only 25% of the expected adults returning to spawn. The PWS fishery was closed from 1993 – 1996 but reopened in 1997 and 1998 based on an increasing population. Numbers again declined and the fishery was closed from 1999 through 2006. Reasons for the population collapse and failure to recovery remain largely unknown.

The main goal of this plan is to determine what, if anything can be done to successfully recover Pacific herring in Prince William Sound from the effects of the *Exxon Valdez* Oil Spill. In order to determine what steps can be taken, this plan will examine the reasons for the continued decline of herring in the Sound, identify and evaluate potential recovery alternatives, and establish a course of action for achieving restoration.

BACKGROUND

The Pacific herring is one of 180 species of fish classified within the family Clupeidae and the order Clupeiformes. They occur in waters of the continental shelf from northern Baja California to arctic Alaska, westward to Russia and south to Japan and the west coasts of Korea. They also occur along the Arctic Ocean from the White Sea eastward to Ob Inlet (Hay 1985) (Fig. 1).

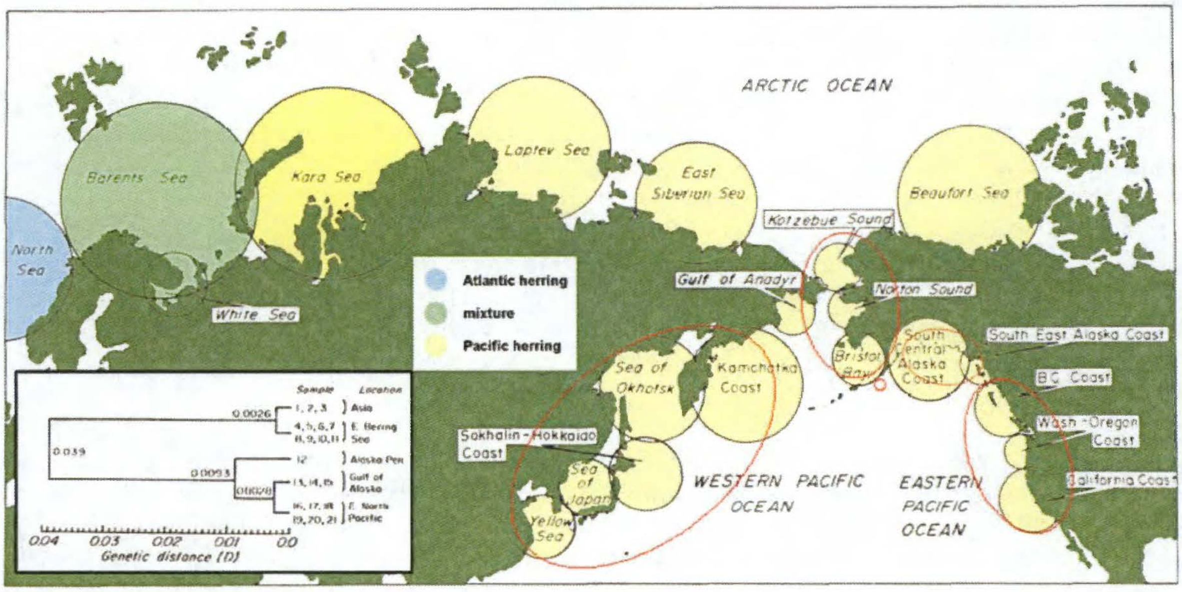


Fig. 1. Global distribution of Pacific herring (adapted from Hay 1985)

The four Pacific herring life stages, eggs, larvae, juveniles and adults, are all found in PWS in various seasons and locations (Brown and Carls 1998). Spawning in PWS typically takes place in April and the spawning season varies from five days to three weeks. Pacific herring typically spawn along the same beaches each year, although the volume of eggs and shoreline distances varies (Brown and Carls 1998; Carls et al. 2002). For example, from 1994 to 1997, the annual spawning beach length ranged from 23.3 to 68.5 km (Willette et al. 1998). Figure 2 shows Pacific herring spawning beds located throughout PWS based upon 1973 - 2006 data from the Alaska Department of Fish and Game (Moffitt 2006, pers. comm.)

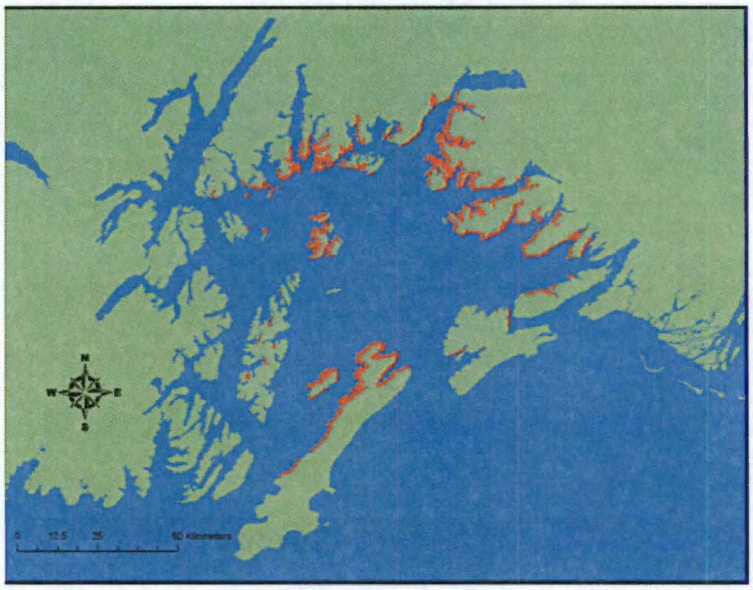


Fig.2. Pacific herring spawning beds located throughout PWS based upon 1973 - 2006 data from the Alaska Department of Fish and Game (Moffitt 2006, pers. comm.)

During spawning, the eggs attach to eelgrass, rockweed (*Fucus* sp) and kelp in shallow subtidal and intertidal areas. The eggs hatch in May, about 24 days after spawning depending on temperature (Hart 1973; Brown and Carls 1998). After hatching the larval herring migrate to the surface, congregate nearshore and continue to grow. Initially, the larvae have yolks that will last a few days, are poor swimmers and currents significantly affect their distribution. The larvae become juveniles in July, about 10 weeks after hatching. In the fall, the juveniles move into deeper water but nearshore habitat remains important for at least the first year, and they may spend up to two years in nearshore areas or bays before joining the adult population residing in deeper waters (Brown and Carls 1998).

In PWS, adult Pacific Herring rarely spawn before their third year and may live up to 15 years. The average life span of a PWS herring is 9 years. After spawning in the spring, adult Pacific herring disperse from the spawning aggregations to multiple schools in deeper waters, presumably close to the entrance of PWS (Brown and Carls 1998). In the fall, adult and two year old fish return from summer feeding areas and over-winter in central and eastern PWS.

Newly hatched larvae carry a yolk sac that is typically depleted in the first week. The earliest larval stages begin feeding on invertebrate eggs and small zooplankton such as copepods. While the larval Pacific herring grow and congregate nearshore through their first summer, they continue to live mainly on copepods but may also eat other crustaceans, barnacle larvae, mollusk larvae or young fishes (Brown and Carls 1998). As they move into deeper waters, copepods remain an important food for both juvenile and adult pacific herring, but adults also feed on larger crustaceans and small fish. During winter, as temperature and light decrease, food supply becomes limited and both young and adult year classes stop feeding functionally. Survival of young herring through the winter depends on the amount of food that was available in the preceding summer and their ability to store sufficient lipid reserves to sustain them over the winter. For the older age classes, winter is less limiting on direct survival, but may affect their reproductive condition and spawning capacity in the spring (Carls et al. 2001).

The Exxon Valdez Oil Spill

The PWS herring population was increasing prior to 1989 with record harvests reported just before the oil spill (Fig. 3).

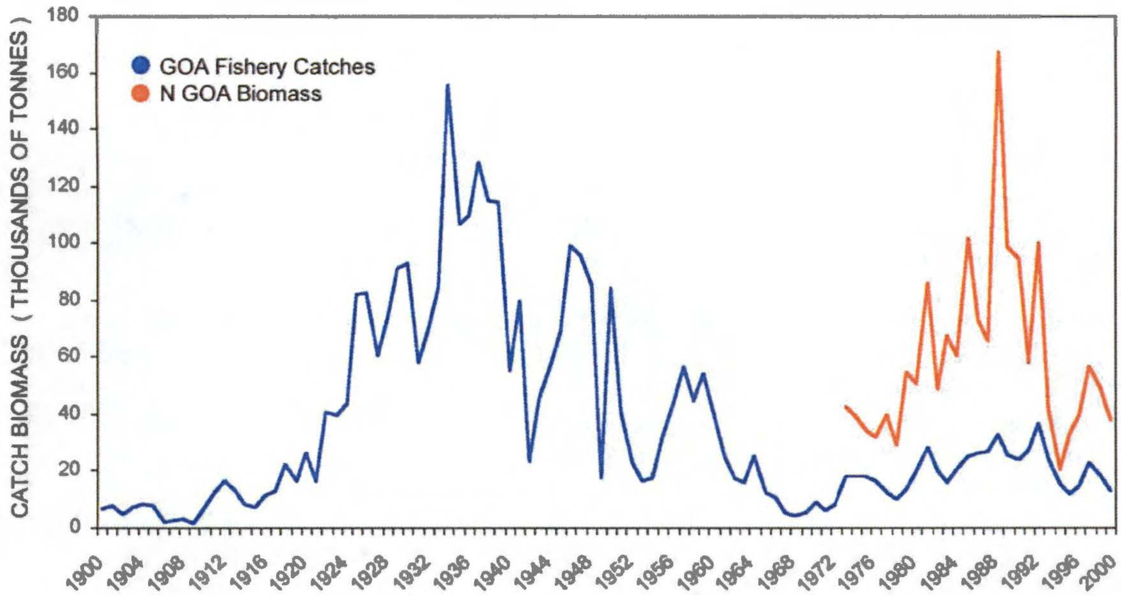


Fig. 3. Pacific herring fishery catches in the Gulf of Alaska (blue line) and estimated annual biomass of herring in PWS (red line) (Brown, 2007).

After the oil spill, the 1989 year class of herring was one of the smallest cohorts of spawning adults recorded, and by 1993, the fishery had collapsed with only 25% of the expected adults returning to spawn.

The population collapse stopped the commercial fishery, and ignited debate about the cause. Some are convinced that the spill was the cause; others believe it was caused by natural systems (Rice and Carls 2007). Unfortunately, we will never know with certainty what the cause was or when it started, as the there is a conflict between data interpretations (Hulson et al. 2008, Thorne and Thomas 2008). Unhealthy fish were detected at the same time as the crash, but disease surveillances were not underway in the previous years. Hydro-acoustic estimates of over wintering populations were initiated in 1993, after the decline in population was detected, and hence are not available during or prior to the decline or crash. The spill certainly affected the 1989 year class, as eggs and as larvae, resulting in one of the poorest recruitments ever observed. While oil continues to linger on some beaches in PWS, lingering exposures to new year classes is not suspected because there is little or no overlap of present day spawning sites with lingering oil. There is no known mechanism for continued oil exposures to this species. Direct oil effects were no longer detectable after 1990 in herring (Pearson, Elston et al. 1999; Carls, Marty et al. 2002) and strong recruitment of the 1988 year-class (in 1991) suggested that oil effects were restricted to the 1989 year class. No plausible oil-related mechanisms have been developed to explain a delayed response after intervening years of no response. Understanding the cause of the population decline or crash, and when it started, is no longer possible with certainty.

FACTORS POTENTIALLY LIMITING RECOVERY

Many herring populations ebb and flow, but only a few remain depressed for long time periods. Many factors likely contribute, so this is a complex issue. Natural factors, including climate changes, inter-species competition, sub-optimal recruitment, disease, and predation may be reasons for the continued population depression.

Disease

A significant factor in the inability of the Pacific herring population in PWS to recover is age-dependent mortality from three pathogens: mesomycetozoan Ichthyophonus hoferi, viral hemorrhagic septicemia virus (VHSV), and filamentous bacteria (associated with cutaneous ulcers). Beginning in 1993 with a severe outbreak of VHSV and ulcers, epidemics have cycled through the Pacific herring population in PWS about every 4 years. Epidemics of VHSV-ulcers in 1993 and 1998 were followed by epidemics of I. hoferi that peaked in 2001 and 2005. Unfortunately there are no long-term disease data sets for other herring populations, or other species with which to make comparisons.

Prince William Sound Pacific herring had a major VHSV-ulcer disease outbreak in 1993, moderate disease in 1997–1998, and mild disease in 2002. However, as the VHSV-ulcer outbreaks have decreased in severity, the significance of I. hoferi has increased. An original hypothesis was that disease was a sporadic event associated with exceeding carrying capacity (Marty et al. 1998), but the 1998, 2001, 2002, and 2005 disease events occurred when the population was relatively low.

The causes for sustained disease problems are not apparent. Immune suppression can be caused after acute exposure to oil, but no herring living today in PWS were alive and exposed in 1989, and no continuing exposure to lingering oil is suspected. At present, the relationship among disease and other factors, such as the lack of food, is not apparent. The PWS Pacific herring population remains too low to allow commercial fishing and there is no hypothesis to explain the continuing disease or adequate information to predict when disease problems will abate.

Predation

Previous research has not eliminated predators as a potential factor in limiting Pacific herring recovery in PWS. Herring are of great importance in the PWS ecosystem; as roughly second- or third-order consumers, they transfer energy from zooplankton to a wide variety of consumers including humpback whales, harbor seals, birds, and other fish. Herring may also significantly influence or control the grazing pressure exerted on lower trophic levels (Cole & McGlade 1998). The relationships between herring and multiple predators is complex, with ample opportunity for large or increasing predator populations to significantly influence the herring population.

Oceanographic changes

Pacific herring stocks have been shown to respond to climatic changes, with increases in populations during warm conditions when plankton production is generally better than during cold years. The Gulf of Alaska populations have increased during the positive phase of the Pacific Decadal Oscillation, when the Gulf of Alaska is stormy, warm and the water is well-mixed (Brown 2006). The favorable conditions for these populations appear to be related to higher plankton production, as there are larger fish at equivalent ages when zooplankton are more abundant. However, anomalously cold conditions have been detected in PWS beginning in 2006 which may have a negative impact on herring populations (Weingartner 2007).

Contaminants in habitat

The waters and majority of the PWS shoreline are among the cleanest habitats in the world. Polynuclear aromatic hydrocarbon loads in the water are very low (Carls et al. 2002). Less than 0.2% of the shoreline has evidence of oil contamination, the current and historical human habitation sites and areas where *Exxon Valdez* oil remains (Boehm et al. 2004; Short et al. 2002 report). Only trace concentrations of persistent organic pollutants (e.g., pesticides and polychlorinated biphenols) are detectable in intertidal areas (Short et al. 2006 report).

Lingering oil toxicity does not appear to be limiting Pacific herring recovery in PWS. For oil exposure to be a cause of the current population depression, 1) lingering oil must have continued to exert new effects, or 2) the oil exposures of 1989 must have caused a persistent biological effects.

1. *Lingering oil effects are not suspected.* There is no evidence of significant herring exposure to oil in PWS after 1990. Unlike the habitat of certain other species (pink salmon, sea otters, and harlequin ducks), oil did not persist in herring habitat (open water and intertidal shorelines), thus the herring population is not affected by a chronic source of lingering oil. Northeastern spawning areas were not affected by the *Exxon Valdez* oil spill, nor were north-central spawning grounds (which are not currently utilized by the herring). There was little overlap between shoreline oiling and herring spawning on Montague Island and in the Naked Island group (another area not currently utilized by herring).

2. *Persistent effects from the initial oil spill in 1989 are speculative.* For oil exposures in 1989 to have a continuing effect in PWS herring, either of two criteria would have to be met: a) long-term oil impacts in exposed individuals, or b) a possible cascade effect. Potential long-term impacts include morphological defects, genetic changes, poorer growth, and immune suppression. Fish with morphological defects, such as reduced cardiac function, were probably eliminated by natural selection rather quickly. Reduction in genetic diversity as a result of exposure to oil is unlikely; the population had little time to adapt to oil because exposure was not chronic for the PWS herring population. There is no evidence of reduced genetic diversity in PWS herring. Long term growth reductions were not evident; mass at age increased for several years after 1992. The remaining hypothesis, long-term immune suppression is also unlikely. While disease continues to cycle in PWS herring and is probably limiting herring recovery, there are no studies (in PWS or elsewhere) linking a long-term immune suppression in fish to contaminant exposure. The plausibility of immune-compromised individuals surviving for long periods is small. Disease challenge would likely remove impaired individuals from the population, particularly after annual winter starvation events when fish are least resistant. Each fall VHSV drops to undetectably low levels only to rebuild in the spring. This natural cycling does not require individuals damaged as a result of oil exposure to introduce disease into the population.

Possible cascade effects are highly speculative. We are unaware of any reports of oil-related cascade effects in pelagic fish species or their prey. The primary support for a cascade effect is the persistent population depression, coupled with the persistent association with disease. The causes for the persistent disease are not understood, suggesting an unknown cascade effect. Also supporting a cascade effect is the simultaneous collapse in the pink salmon population in PWS in 1992 - 1993. Populations of two species with very different life histories and survival strategies collapsed in the same localized region (PWS) but did not collapse elsewhere in Alaska. Thus, these collapses appear to be a PWS phenomenon. This fuels speculation of a cascade effect linked to the oil spill with no known mechanism.

Lack of recruitment

Following a population crash in 1993, Prince William Sound herring experienced very low recruitment from the 1995 through 1998 year classes. The current history of low herring recruitment in PWS is not without precedent in other west coast herring populations, though these consecutive low recruitment events are relatively rare. Simultaneous poor recruitment was not observed in other North American herring populations during the late 1990s. However, four-year to six-year runs of low recruitment have occurred at other times in other herring populations, including Togiak (2000-2003), Sitka (1971-1973) and Craig (1971-1975) in Alaska, Prince Rupert (1963-1966), Queen Charlottes (1990s), Vancouver (1960s), Strait of Georgia (1960s) in British Columbia, and Cherry Point (1970s) in Washington. The timing of low recruitment events appears to vary randomly among the sampled North American herring populations.

The low recruitment events in PWS in the 1990s broke down a strong correlation between PWS and Sitka recruitments. Prince William Sound has experienced 3 modest recruitment events since the 1993 population collapse (the 1993, 1994, and 1999 year classes), but biomass has yet to increase above low levels. Strong recruitment from the lowest biomass levels has not been observed at PWS or Prince Rupert, but five of the ten examined herring populations (Togiak, Sitka, Craig, Queen Charlotte Islands, and West Coast of Vancouver Island) have generated extremely strong recruitment events from the lowest biomass levels. While the low recruitments from the 1995 to 1998 year classes are within the range of natural variability, recovery of PWS herring will require further recruitment events, combined with increased adult survival from disease and other sources.

The continued existence of herring populations is threatened when the number of consecutive low recruitments approaches the reproductive lifespan. Herring in PWS came dangerously close to the reproductive lifespan threshold with 4 successive years of near-zero recruitment in the late 1990s, following previous low recruitment in the early and mid-1990s. Moderate recruitment in 1999 may sustain the population provided adult mortality is not excessive, at least for the short term. Recovery of PWS herring will require further above-average or strong recruitment events, combined with increased adult survival from disease and other sources. Because we do not know the cause of the current series of low recruitment events, it is not possible to predict if recruitment will get better or worse.

CURRENTLY FUNDED HERRING RESEARCH

Predators

Predation is likely contributing to the suppression of herring populations in Prince William Sound and marine mammals and seabirds are major predators on these fish. Any restoration effort must understand whether or not increased herring production will merely result in more predators rather than more herring. Fisheries management models currently use broad and highly uncertain estimates of natural mortality. Predation is the major source of mortality, even if underlying causes are disease or starvation.

Juvenile herring are heavily predated by multiple species of seabirds including five species injured by the EVOS (Bishop 2007). Research will focus on the spatial and temporal abundance of seabird predators in and around juvenile herring schools, as well as the physical and biological characteristics of the schools used for feeding. The estimates of juvenile herring consumption produced by this work will aid in planning future restoration efforts as well as in assessing the role of seabird predation on herring recruitment by providing data to both herring and ecosystem modeling.

Ongoing studies of killer whales and their effect on Pacific herring will be broadened to include a satellite tagging program to examine habitat preference and to aid in a more extensive examination of feeding habits using observational and chemical techniques (Matkin 2007). Killer whale research will more clearly delineate the role of killer whales in the nearshore ecosystem and possible effects on the restoration recovery of herring.

Long-term systematic disease monitoring and research since 1994 has suggested a relationship between disease and the continuing population decline of herring in the Sound. A comprehensive three-year Herring Disease Program will begin in 2007 to examine the epizootic mortality resulting from infectious and parasitic diseases (Hershberger 2007). This program will provide predictive metrics that can forecast future disease epidemics and offer empirical relationships useful in developing adaptive management policies to mitigate the effects of epizootic and chronic diseases.

Ecological Factors
Any effort to restore or enhance herring production will require understanding of the ecological factors that may be affecting recruitment success including oceanographic changes, food scarcity, chemical pollution/changes, and habitat loss or compromise.

Food may be a limiting factor for juvenile herring. An understanding of the variability in abundance and distribution of herring prey may lead to a greater understanding of why certain nursery bays are more productive than others (Batten 2007). Recent Continuous Plankton Recorder data has shown large differences in mesozooplankton biomass on the Alaskan shelf from 2004 and 2005 (Batten 2006). Understanding changes in herring food supply from year to year, whether a shift in distribution, or timing, of zooplankton abundance could help understand the fluctuations in the population and, in turn, support management of this resource. Recruitment may also be contingent on young of the year herring attaining, from zooplankton, sufficient whole body energy content (WBEC) to survive their first winter (Kline 2007). The high rate of disease, as well as predation pressures, may also require young herring to have an increased energy demand in the winter that is not currently being met. A detailed study of the energy consumption rates of overwintering herring in the Prince William Sound in comparison to herring in other parts of Alaska may provide information on the high level of recruitment failures that will provide valuable information to managers for a recovery strategy (Vollenweider 2007).

Oceanographic factors also play a large role in the success or failure of a herring year class. Recruitment is highly influenced by conditions within nursery sites which affect survival within the first year. Studies of the physical oceanography of nursery fjords has indicated that each site has a unique set of hydrographic conditions that are influenced by both local processes and water exchange between the Gulf of Alaska and Prince William Sound (Gay and Vaughan 2001). A hydrographic time series within nursery fjords will collect high resolution data on currents and hydrography to determine the dominant mechanisms of water exchange and circulation within two experimental fjords; one located in a highly productive sub-region and one located in less productive sub-region influenced by tidewater glacial outflow (Gay 2007). This will provide critical information on where the most productive potential nursery bays would be located if a direct intervention approach is suggested by the Herring Recovery Plan.

The Alaska Coastal Current (ACC) is also an important focus habitat for herring as it links Prince William Sound and continental shelf marine habitats. Terrestrial runoff from around the Gulf of Alaska affects ACC dynamics and its nutrient and sediment load although oceanic processes substantially modify these influxes. The GAK 1 line has been monitoring the ACC continually for 36-years and data collected from provides the long-term temporal context of the natural variability of the ACC and Prince William Sound (Weingartner 2007). The data will also be essential in understanding how herring are affected by variations in temperature, salinity, and density and how this variability could affect recovery.

In addition to the oceanographic data collected, *ShoreZone* mapping will be conducted in the Sound to provide a single mapping protocol that includes geomorphology, substrate type, and biological substrate on all beaches. *ShoreZone* mapping, in addition to the data from research on other ecological factors, will fill data gaps by providing a contiguous data set from across the entire spill area using a standard protocol (Lindeberg 2007). The data set will be useful to the recovery process, as it combines photographs of the entire beach area and provides information that can be sorted by location, substrate type, and other factors.

Global Influence
Information on abundance, distribution and condition of key herring life stages is a critical part of a successful herring recovery plan. There is, however, a general lack of scientific information on the life

history of Pacific herring in Prince William Sound. More information is required for the success of future enhancement efforts designed to improve the survival rate of juveniles into adulthood.

Barometers of the PWS herring population are the adult abundance and condition, as monitored in March, and the juvenile abundance and condition going into and coming out of the long winter period (Thorne 2007). A direct capture effort in March 2007 and March 2008 will not only fill data gaps for herring at this important time, but will provide biological samples that can be utilized for disease, marking, and stable isotope research projects that are currently underway.

Chemical analysis of trace element concentrations in herring otoliths will provide key geographic signatures of natal habitats that, in combination with *ShoreZone* mapping and ongoing oceanographic projects, will clearly define where the productive herring habitats are located. This will allow for the protection of the most important populations and identify those environmental variables needed to enhance other populations (Bickford/Norcross 2007). As a comparison to the PWS herring stock, Sitka Sound's herring stocks remain healthy and relatively intact. Otolith chemistry collected from this population will be used as a control group, providing baseline data to compare to the depleted herring stocks in PWS (Meuret-Woody 2007). This comparison will be essential in crafting the herring recovery program as it provides a clear picture of threats effecting the depressed PWS herring population that could potentially be limited or removed.

In addition to otolith chemistry, fatty acid analysis (FAA) of herring cardiac tissue will be help in determining herring stock structure at fine spatial scales and will establish if otolith chemistry methods can be used to corroborate FAA techniques (Otis/Bickford 2007). Results should allow researchers to better define ecologically significant stock boundaries likely affecting how commercially exploited herring populations are assessed and managed.

Databases and Modeling

The ability to process and make historical and current herring data available to researchers will play a large role in the success of a herring recovery plan. The development of a life-stage specific, ecosystem based model of the PWS herring that will aid in the integration of ecological data that has been gathered on herring over the last two decades and will be able to simulate the processes that cause the chronic decrease in herring stocks (Kiefer 2007). More specifically, it can be used to test the unresolved hypotheses of why the herring have not recovered to pre-spill densities. The model will be housed in a geographic information system developed specifically for marine applications and will be available for interactive viewing and downloading of files over the Internet.

A web portal will provide assess to modeling data and GIS visualizations for the researchers and the pubic (Moffitt 2007). Researchers will utilize the web portal as a resource to assist in consolidating, accessing, and synthesizing herring data. Currently, herring related data sets are not widely available and are not shared among herring researchers. The new web portal will facilitate the sharing of spatial and temporal herring data that will be important during the development and implementation of the herring recovery plan.

POTENTIAL RESTORATION ACTIONS

It may be possible to restore herring populations in Prince William Sound through the use of direct restoration or intervention methods such as the moving of fertilized eggs to habitats more favorable for survival or the release of juveniles reared in hatcheries. However, the efficacy of these or other direct restoration methods need to be proven and may be technically infeasible or too costly. Furthermore, the use of direct restoration activities may cause unintended adverse environmental outcomes such as the increase in incidence of disease to herring or other fishes.

Regardless of whether active restoration methods are used, monitoring will play an important role in the restoration process. Monitoring will be required as part of any active restoration program to evaluate the efficacy of various active restoration methods, the status of recovery, and the potential occurrence of unintended adverse impacts.

No action – allow natural recovery

If direct restoration activities are found to be impractical, too costly, or too risky, then monitoring may be the only viable means of helping to restore herring populations. Monitoring in itself can be an effective restoration tool that enables the natural recovery of populations by detecting and ameliorating impediments to the natural recovery. For example, monitoring might lead to a better understanding of the role of disease, predictability of disease outbreaks, and disease management practices that reduce disease impacts. Monitoring of herring populations and critical life-history attributes might also allow for the development of better predictive models of herring stocks, more protective fisheries management practices, and longer-term sustainability of the stock. Furthermore, monitoring might reveal unknown sources of human-induced impacts on herring that, if identified, could be ameliorated and removed as an impediment to natural recovery.

Active enhancement program

Enhancement is the release of cultured herring to supplement natural recruitment so as to assist recovery or restoration of the population to historical levels. Therefore, the purpose of enhancement is to increase numbers and biomass of herring to levels exceeding natural carrying capacity. That is, something is done so that combined effects of disease, food supply and predation are overcome. This usually means adding young herring raised in captivity, where survival rates can exceed those in the wild, back to the environment.

The issue of enhancement of marine fish populations is controversial. There is an influential part of the fisheries science community, mainly from the ecological side, that is steadfastly opposed to the concept of marine finfish enhancement. There is another component, mainly the practitioners, who are comfortable with the concept and worry little about biological implications. However, even the detractors of the concept suggest that the activity may be warranted when all other conventional management procedures fail. Even then there are reservations about the efficacy of the approach if density-dependent factors regulating recruitment occur after the release of cultured fish. This is a focal point for this issue in Prince William Sound.

A decision to investigate the feasibility of enhancement does not necessarily mean that the EVOS Trustee Council is committed to the concept or determined to engage in enhancement activity. Instead, the intention is to examine the implications of the concept, as it applies to herring in Prince William Sound. Full scale enhancement activity would require several years of preparation, mainly to develop and determine some technological issues, such as mass marking of young fish prior to release. Mass marking and other technological activities are fundamental pre-requisites of enhancement activity. Therefore, because the development of these technological issues will take time, it is important that some investigations begin immediately. It also is important to understand that these investigations also could result in a definitive conclusion the enhancement of herring is impractical or far too expensive.

We suggest a sequential three-phase plan that could lead to full scale enhancement within five years. Each phase consists of several concurrent steps of complementary activities. Phase I will consist of three activities, each of which could resulting a conclusion that enhancement of herring is not warranted,

because of technological or biological issues. Therefore we reiterate: the first components of a restoration plan are to determine the technological and logistical feasibility of the plan. These steps will not necessarily lead to enhancement activity.
Herring restoration in PWS could proceed in three distinct consecutive phases, each of which has several distinct but concurrent activities or 'steps'. The three phases and suggested durations are:

Year 1 - Justification, decision rules and feasibility
Year 2-5 - Pilot scale enhancement and methodology tests
Year 5-9 - Full scale enhancement

Each phase would have several steps or activities that could be conducted concurrently within the duration of each phase. Please see Appendix B – Enhancement Review for more detail on each phase.

1. Develop decision rules and reference points
Write and define a contract to prepare a report that: (i) presents data on the past and present state of Prince William Sound herring, with comments on the strengths and weaknesses of the information; (ii) defines criteria, such as abundance levels, that would be a basis for initiating enhancement activity and suspending or stopping such activity following favorable responses of the population; (iii) defines criteria where possible extinction is a concern and that would warrant implementation of 'conservation hatcheries.

2. Assessment and development of mass marking technology
Write and define a contract to prepare a report that will provide definitive approaches and/or methodology to mass marking. This report would include detailed review and analysis of the Japanese work and experience with mass marking of herring. The report(s) should comment on the success rates for establishing marks and the costs related to different marking scenarios, at both ends of the process (marking and reading the marks at later stages).

3. Recapture and mark-detection methodology – a pre-application statistical guide concerned with issues of scale.
There is a need for a dedicated report that comments on the feasibility of marking and different mark-recapture rates. Some relatively simple modeling and statistical analyses should investigate the options and financial costs of several release-recapture scenarios and relate this to the cost of rearing herring, prior to release.

RESEARCH NEEDS

Research is in progress on many of the issues addressed above affecting Pacific herring in PWS. These efforts have only begun to address the complex interactions that are affecting herring populations and more questions have come to light as the research progresses. The questions that still need to be answered in order to move herring toward restoration include:

1. Are there credible ways, other than cumulative distance (spawn miles and mile-days) that herring spawn may be quantified, or made into an index, that would be biologically realistic?

2. Can retrospective analysis of growth during the first and second years of life, estimated from analyses of archival collections of herring scales, be used to comment on inter- and intra-annual variation in growth and survival of herring in PWS? Could such retrospective analyses be used to explain more about the biological events that occurred during the last two decades?

3. What are the key competitor species of herring and how do they affect each life stage?

4. What effects are oceanographic changes in PWS having on each life stage of herring?

5. What is the distribution of larvae and juveniles and the factors that are quantitatively important to determining year class strength?

6. What are the parameters that are significant to herring recruitment?

7. Is disease causal and impacting the population, or is it symptomatic and reflecting poor body condition?

8. Could their potentially be a relationship between larval release and disease effects in the general population?

9. Are there any suitable mass marking techniques for Pacific herring eggs, larvae or juveniles in PWS that are feasible, practical and affordable?

10. What ranges of marked animals must be released in order to have sufficient recaptures to evaluate success?

11. Can criteria or reference points be established that can be used to govern potential enhancement activity of herring in Prince William Sound? Specifically, biological or assessment what criteria would be used to initiate, suspend or stop enhancement activities?

12. How much would it cost to implement a pilot-scale enhancement facility in the spill area?

13. How much would it cost to implement a full-scale enhancement facility in the spill area?

14. What would be the annual costs of maintaining an enhancement program and would the EVOSTC remain the sole funding source for the program?

15. What permitting would be required for an enhancement program?

16. Is egg translocation a viable alternative to a hatchery program?

A STRATEGY AND DECISION MAKING FRAMEWORK

The restoration program for PWS herring can be managed adaptively as portrayed in Fig. 4, where the problem evaluation, policy decisions, research, monitoring and outcomes are all related in way that leads to logical decision making and provides order and context for the various program activities.

The strategy begins with definition of the problem and establishing objectives for restoration. Next the conceptual model is specified then the options are evaluated along with their uncertainties. If the there are many uncertainties, as there are with herring, then targeted research needs to be carried out, the first step in the restoration ladder. That research then tells us more about the survival of herring in the PWS ecosystem and we can evaluate the conceptual model and possibly change it to complete the loop. At some level of certainty we will perhaps undertake a pilot release of juvenile herring to test predictions of survival from a quantitative version of the conceptual model. The outcome is monitored, results are evaluated, and we complete the adaptive loop again with model revision, take further action, or stop the program depending on the outcome. Finally we may reach a stage that either the system is on its way to restoration (known from monitoring) or large-scale intervention is implemented based on what has been learned adaptively and the predicted chances of success. The suggested annual cycle of program activities is shown in Fig. 5.

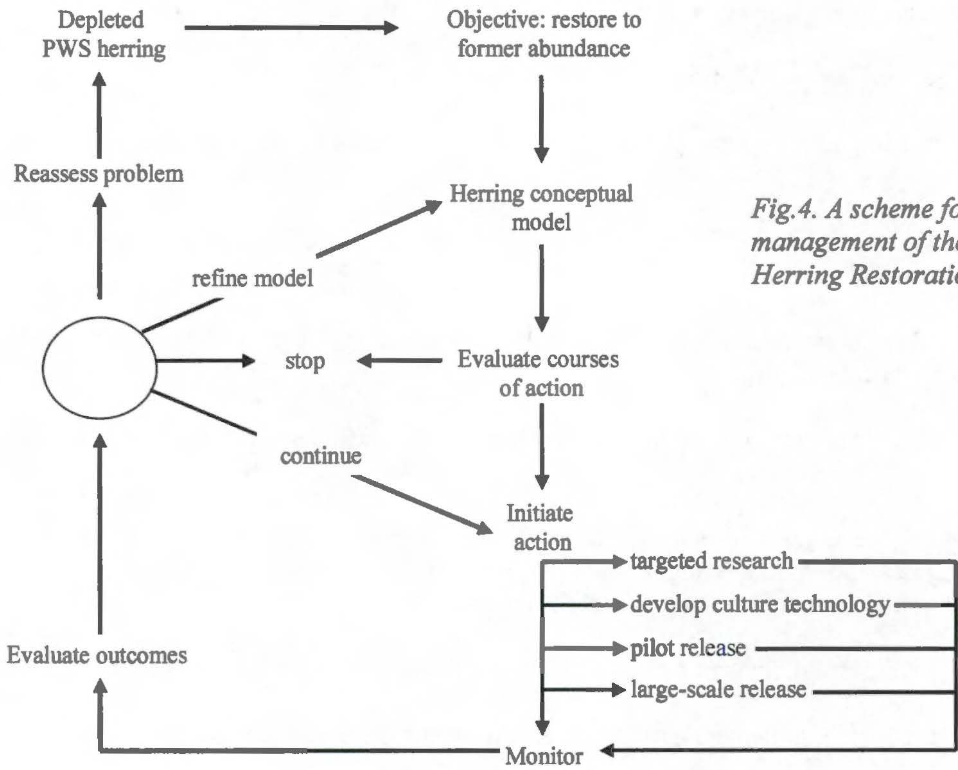


Fig.4. A scheme for adaptive management of the PWS Herring Restoration Program.

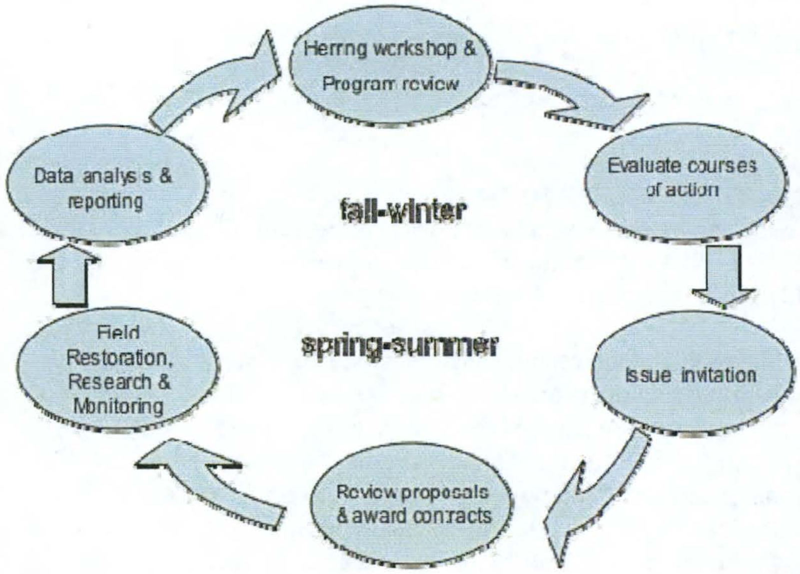


Fig. 5. The annual cycle of program activities for the Pacific herring program.

The annual cycle starts in the fall-winter period with an evaluation of the ongoing program activities for Pacific herring being carried out in Prince William Sound that includes peer reviewers. The reviewers recommend courses of action along with the Herring Committee and the Executive Director. If new activities are warranted they are requested in the annual invitation issued in late winter. If ongoing programs need to be modified they are also adjusted through the Executive Director using the peer review guidance. New and modified work is proposed to the Trustee Council for their consideration during the summer.

NEXT STEPS

The Herring Restoration Plan will need to be implemented in several steps that coincide with data gathered from ongoing research and monitoring efforts.

1. The FY09 Invitation for Proposals should specifically request projects that seek to answer the questions included in this document under "Research Needs".

2. The Herring Steering Committee should be reduced in size, but include a representative from each of the stakeholders. This will allow for more efficient and cost effective operation of the Committee while ensuring that each interested group has a seat at the table.

3. The third annual Herring Roundtable should be focused on results from FY08's research and its incorporation into an updated Herring Restoration Plan.

4. After meeting with Japanese researchers, who have been successfully raising Pacific herring for commercial uses, and analyzing data gathered by funded PI's, the Herring Steering Committee should make a recommendation to the Executive Director and the Trustee Council regarding a full-scale enhancement program.

5. A pilot-scale enhancement program would be beneficial in determining the feasibility of a larger scale program, identifying potential issues before significant funds are spent, and establish a relationship for permitting with the Alaska Department of Fish and Game.

REFERENCES

Batten, S.D. 2007. Acquisition of Continuous Plankton Recorder Data. Restoration Project 070624. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 22 pp.

Bickford, N.A., B.L. Norcross. 2007. Herring Restoration in PWS: Identifying Natal and Nursery Habitats. Restoration Project 070782. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 34 pp.

Bishop, M.A., K.J. Kuletz. 2007. Seabird Predation on Juvenile Herring in Prince William Sound. Restoration Project 070814. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 48 pp.

Boehm PD, Page DS, Brown JS, Neff JM, Burns WA. 2004. Polycyclic aromatic hydrocarbon levels in mussels from Prince William Sound, Alaska, USA, document the return to baseline conditions. Environmental Toxicology and Chemistry 23:2916-2929.

Brown, E.D. and M.G. Carls. 1998. Restoration notebook: Pacific herring (*Clupea pallasi*). Exxon Valdez Oil Spill Trustee Council, Anchorage, AK. 8 pp.

Carls, M.G., G.D. Marty, and J.E. Hose. 2001. Synthesis of the toxicological and epidemiological impacts of the Exxon Valdez oil spill on Pacific herring in Prince William Sound, Alaska. Restoration Project 99328. *Exxon Valdez Oil Spill Trustee Council Final Report*, Anchorage, AK. 86 pp.

Carls, M. G.; Marty, G. D.; Hose, J. E. 2002. Synthesis of the toxicological impacts of the *Exxon Valdez* oil spill on Pacific herring (*Clupea pallasi*) in Prince William Sound, Alaska, USA. *Canadian Journal of Fisheries and Aquatic Sciences*, 59, (1), 153-172.

Cole, J., McGlade, J. 1998. Clupeoid Population Variability, the Environment and Satellite Imagery in Coastal Upwelling Systems. Reviews in Fish Biology and Fisheries 8:445-471

Gay, S.M. 2007. Project 070817. Physical oceanographic factors affecting productivity in juvenile Pacific herring nursery habitats. Restoration Project 070817. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 20 pp.

Gay, S. M., Vaughan, S.L. 2001. Seasonal hydrography and tidal currents of bays and fjords in Prince William Sound, Alaska. Fisheries Oceanography 10: 159-193

Hart, J.L. 1973. Pacific fishes of Canada. Bulletin 180. Fisheries Research Board of Canada, Ottawa, Canada. 740 pp.

Hay DE. 1985. Reproductive biology of Pacific herring (Clupea harengus pallasi). Can J Fish Aquat Sci 42(Suppl 1):111-126.

Herschberger, P., J. Hansen, D. Elliott, E. Emmenger, R. Kocan, G. Kurath, S. LaPatra, J. Winton. 2007. Restoration Project 070819. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 77 pp.

Hulson, J.F., Miller, S.E., Quinn, T.J., Marty, G. D., Moffitt, S. D., Funk, F. 2008. Data conflicts in fishery models: incorporating hydroacoustic data into the Prince William Sound Pacific herring assessment model. ICES Journal of Marine Science, January 1, 2008; 65(1): 25 - 43.

Kiefer, D.A., E. Brown, V.M. Tsontos. 2007. An Ecosystem Model of Prince William Sound Herring. Restoration Project 070810. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 50 pp.

Lindeberg, M.R. 2007. *ShoreZone* mapping for Prince William Sound. Restoration Project 070805. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 32 pp.

Matkin, C. 2007. Monitoring, Tagging, Feeding Studies, and Restoration of Killer Whales in Prince William Sound/Kenai Fjords in 2007. Restoration Project 070742. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 25 pp.

Meuret-Woody, H. 2007. Identification of Essential Habitat for Pacific Herring (Clupea Pallasi) in Sitka Sound for Comparison to Prince William Sound i.e. Source vs. Sink Habitat. Restoration Project 070834. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 32pp.

Moffitt, S.D., R. Bochenek. 2007. Herring Data and Information Portal. Project 070822. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 24 pp.

Otis T, Heinz R, Bickford N. 2007. Using otolith chemistry to discriminate Pacific herring stocks in Alaska. Restoration Project 070769. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 18 pp.

Pearson, W. H., R. A. Elston, et al. 1999. Why did the Prince William Sound, Alaska, Pacific herring (Clupea pallasi) fisheries collapse in 1993 and 1994? Review of hypotheses. Cananadian Journal of Fisheries and Aquatic Sciences 56: 711-737.

Rice, S., Heintz, R., Moran, J., Quinn, T., Straley, J. 2007. Significance of Whale Predation On Natural Mortality Rate of Pacific Herring in Prince William Sound. Restoration Project 070804. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 51 pp.

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

Vollenweider, J.J., Heintz, R.A. 2007. Are Herring Energetics in PWS a Limiting Factor in Successful Recruitment of Juveniles and Reproduction Investment of Adults? Restoration Project 070806. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 27 pp.

Willette, T.S., Carpenter, G.S., Hyer, K. and J.A. Wilcock. 1998. Herring natal habitats. Restoration Project 97166. *Exxon Valdez Oil Spill Trustee Council Final Report*, Anchorage, AK. 257 pp.

Weingartner, T. 2007. Long-Term Oceanographic Monitoring of the Alaska Coastal Current. Restoration Project 070340. *Exxon Valdez Oil Spill Trustee Council Project Proposal*, Anchorage, AK. 32 pp.

APPENDIX A – SCIENCE REVIEW

Herring populations ebb and flow over time, in the best of conditions. Prince William Sound herring, once a robust stock supporting the ecosystem and commercial fisheries, has been depressed since 1993, with little fishing after that date. The cause of the depleted stock is controversial, and the lack of recovery is unknown. We have a large list of factors that impact herring, and we often know the direction of impact of these factors, but we seldom now which is more dominant in certain years. Herring have a complex life history, foraged on by many predators on all life stages. Future management decisions, including the possible engagement of enhancement interventions, will need and desire a stronger information base on herring and the factors that influence their survival and recovery.

The purpose of this appendix is review the status of natural recovery science and identify the most pressing information gaps. Specifically, this section will 1) briefly review the possible causes for the population decline of Pacific herring (*Clupea pallasi*) in Prince William Sound (PWS), 2) review factors affecting survival, 3) identify the information necessary to understand the current situation, 4) review research efforts currently underway (FY 2007, 2008), and 5) provide potential guidance for intervention activities should they be accepted as necessary.

Possible causes for the population decline; How important is the cause?

The population collapse, detected in spring 1993 (4 years after the *Exxon Valdez* spill) stopped the predicted fishery, and ignited debate about the cause. Some are convinced that the spill was causal, others posit natural causes (Rice and Carls 2007). Unfortunately, we will never know with certainty what the cause was or when it started, as the there is a conflict between data interpretations (Hulson et al. 2008, Thorne and Thomas 2008). Unhealthy fish were detected at the same time as the crash, but disease surveillances were not underway in the previous years. Hydro-acoustic estimates of over wintering populations were initiated in 1993, after the decline in population was detected, and hence are not available during or prior to the decline or crash. The spill certainly affected the 1989 year class, as eggs and as larvae, resulting in one of the poorest recruitments ever observed. While oil continues to linger on some beaches in PWS, lingering exposures to new year classes is not suspected because there is little or no overlap of present day spawning sites with lingering oil. There is no known mechanism for continued oil exposures to this species. Direct oil effects were no longer detectable after 1990 in herring (Pearson, Elston et al. 1999; Carls, Marty et al. 2002) and strong recruitment of the 1988 year-class (in 1991) suggested that oil effects were restricted to the 1989 year class. No plausible oil-related mechanisms have been developed to explain a delayed response after intervening years of no response. Understanding the cause of the population decline or crash, and when it started, is no longer possible with certainty.

More important is understanding the lack of recovery since the decline, as our goal is to attain recovery.

Many herring populations ebb and flow, but only a few remain depressed for long time periods. Many factors likely contribute, so this is a complex issue. However, the factors leading to the lack of recovery are in operation in this time period, and available to study if we are collectively clever enough.

Natural factors, including climate changes, inter-species competition, sub-optimal recruitment, disease, and predation may be reasons for the continued population depression. Simultaneous reductions in fish size at age in PWS and Sitka (about 750 km to the south) and decreases in their food supply suggest that large-scale climate or oceanographic factors drive the bottom up energetic base at a regional level. Sufficient food is necessary for survival through winter starvation; failure to acquire adequate energy stores is the primary cause of overwinter mortality (particularly in juveniles) (Blaxter and Holiday 1963; Hay, Brett et al. 1988; Paul, Paul et al. 1998). In spring, fish with marginal energy reserves may be weak and more susceptible to disease and predation. Lethargic survivors with viral hemorrhagic septicemia virus (VHSV) were observed in spring 1993, consistent with relatively low zooplankton production in 1991 and 1992 and a relatively large herring population. Disease measurements from 1993 through 2002 continued to suggest the population was restricted by chronic disease; recruitment was negatively affected by VHSV and life spans were shortened by *Ichthyophonus* (Marty, Miller et al. Submitted). The hypothesis that a genetic bottleneck (caused by the depressed population numbers) restricts current recovery is not supported; genetic diversity within the population and exchange with surrounding populations is substantial (Hose submitted).

Factors affecting survival

The world is a dangerous place for Pacific herring. They are relatively small, schooling, abundant, mobile planktivores (forage fish) that provide a key link between lower trophic levels (typically crustaceans and small fish) and higher tropic levels [whales, sea lions, birds, and other fish; (Hart 1973; Hourston and Haegele 1980; Bakun 2006)]. Their position between first- or second-order consumers and larger predators essentially guarantees that the herring population is responsive to seasonal, oceanographic, and climate-driven changes in producer (phytoplankton) and predator populations and distributions. Intra- and interspecific competition are also important factors with an important nuance; herring may prey on early life stages of their predators, leading to trophic instability and possible abrupt regime shifts (Bakun 2006). Thus, the balancing act between trophic worlds explains in part why this relatively short-lived fish (about 15 y maximum) generally survives no more than 9 y (Ware 1985) and why population abundance is highly variable. However, survival during earlier life stages may be an even more important influence on population size; strongly recruiting year classes typically influence population size and age structure until senescence. Early life stages are particularly vulnerable to physical variability, resulting in high inter-annual variability and reproductive success (Bakun 2006).

Numerous age-dependent factors affect herring survival, including fishing. The latter will not be discussed because commercial herring fishing has generally been closed in PWS since 1993 except for 1997 and 1998. Predation and disease are "life cycle events" occurring at all life stages throughout the herring life time. Some predation and disease events are highly visible, such as epizootics resulting in massive fish kills and the presence of mixed predator assemblages surrounding feeding on densely aggregated spawning adult herring (Wilson and Womble 2006). At least 25 vertebrate predators may prey on spawning herring, including gulls, ducks, geese, cormorants, grebes, loons, murres and other birds, Steller sea lions, gray whales, killer whales, and humpback whales (Wilson and Womble 2006), plus numberous fish species including cod, salmon, and sharks. While the epizootics and visible spawning event may only last a few days, significant predation often preceeds during the staging of the spawning event, and predation and chronic mortality from disease are on-going events that continue throughout the year. The chronic mortailites through predation and disease are much less visible and more difficult to quantify, but probably add up to very significant levels of predation. Specific predators and pathogens target the entire herring life history, encompassing herring eggs, eggs, larvae, juveniles, and adults. The spring spawning herring represent a rich source of food for predators just emerging from winter; the large aggregations of predators at herring runs suggests spawning events are an important food resource for predators (Wilson and Womble 2006).

Herring eggs must be sufficiently stocked in energy from bottom up forces, and survive 'top down' disease and predation forces. Once deposited, environmental forces (temperature, wave forces, salinity, UV) come into play. Egg mortality is high (about 75%, ranging from 67 to 100%) and tends to be greatest in upper intertidal areas and lowest at intermediate depths (Palsson 1984; Rooper, Haldorson et al. 1999). The amount of time eggs are exposed to air may be related to susceptibility to wave action and predation by birds and hypoxia, desiccation, air-water temperature differentials, and exposure to ultraviolet light may also increase risk factors for eggs in the upper intertidal (Alderdice and Velsen 1971; Hunter, Taylor et al. 1979; Alderdice and Hourston 1985; Rooper, Haldorson et al. 1999). Crabs, sea anemones, sea cucumbers, and snails consume significant amount of herring eggs (Haegele 1993). Perhaps lower survival at the lowest spawn depths can be explained by greater access time by water-oriented predators because immersion time is longer and possibly because lower incubation temperatures prolong that access. In addition, low oxygen and microorganism invasions may kill large numbers of eggs; eggs in the middle of multiple layers have reduced survival (Alderdice and Hourston 1985; Hay 1985). In general, the strategy operating here is to swamp the predators with a massive spawning event.

Larval mortality is caused by advection, disease, predation, and limited food availability, and other factors (McGurk 1993; McGurk, Paul et al. 1993; Norcross and Frandsen 1996). Loss of planktonic stages caused by diffusive and advective processes may explain large variations in population abundance; geographic patterns may be partially maintained in areas the limit egg and larval advection (Sanvicente-Anorve, Soto et al. 2006). A broad range of invertebrates and fish prey upon larvae by filtration , entrapment (e.g., ctenophores and jellyfish), or targeted feeding (Hart 1973; Alderdice and Hourston 1985). Suitable food must be located before irreversible starvation occurs if larvae are to survive. This observation forms the basis of the critical period hypothesis (Hjort 1914), that larval survival is the prime determinant of year-class strength, dependent on larval transition from endogenous to exogenous food. Low growth rates result in a longer exposure time for mortality through predation or transport out of favorable oceanographic regions (Cushing, 1990; Leggett and Deblois, 1994). A longer larval period could result in poor condition for juvenile herring that must prepare for winter (Paul et al., 1998; Foy and Paul, 1999; Norcross, et al. 2001). Transport offshore can lead to increased mortality from lack of food, salinity intolerance or increased predation pressure (Stevenson, 1962; Alderdice and Hourston, 1985; Stocker et al, 1985; McGurk, 1989; Wespestad and Moksness, 1990). The larval stage may be the determinant of year class strength (Norcross, Kelly et al. submitted), but is a very difficult life stage to assess in a quantitative manner.

To survive, juveniles must escape predation and accumulate sufficient energy for winter starvation. Predation is the greatest source of loss for age 0 juvenile herring from the time of metamorphosis through fall (Stokesbury, Kirsch et al. 2000; Stokesbury, Kirsch et al. 2002). Sufficient energy storage to maintain age 0 and age 1 juveniles over winter is critical to juvenile herring survival in PWS (Critical Period Hypothesis). Food availability declines in winter months (the highest percentage of empty stomachs is in December; (Norcross, Brown et al. 2001) and fish in cold regions often fast or reduce feeding (Blaxter and Holiday 1963; Hay, Brett et al. 1988; Paul, Paul et al. 1998). Consequently, whole body energy content drops over winter; YOY juveniles either consumed relatively less energy than adults during this period or only those with the highest energy content in the fall survived (Paul, Paul et al. 1998). Lab-based studies are required to measure the minimum energy levels that allow for winter survival under differing conditions (different temperatures, different activity levels, different disease histories). Indexing juvenile survival before and after winter may be the easiest life stage prior to adult recruitment to assess the net result from all factors impact the early life stages.

Apparent natural mortality is lower at the onset of adulthood than in juvenile and senescent adults, thus the overall mortality function is U-shaped (Vetter 1988; Hampton 2000; Tanasichuk 2000). The relationship between size and predation may in part explain declining natural mortality rates as herring approach adulthood. Increased body size may be a survival strategy to avoid predation (Houde 1997; Pedersen 1997) and larger-bodied juvenile herring are more likely to have sufficient energy reserves to survive winter starvation periods (Foy and Paul 1999; Stokesbury, Foy et al. 1999; Metcalfe and Monaghan 2003). Schooling is another survival strategy, common both to juveniles and adults; it is apparently an anti-predator tactic that increases survival odds for individual fish and schooling may have a sentry effect by increasing awareness of predators (Blaxter 1985). Schooling may increase feeding effectiveness and have hydrodynamic, migration, reproduction, and learning advantages (Freon, Cury et al. 2005). Survival of adult herring is dependent on both intrinsic and extrinsic factors; these are related because populations adapt to extrinsic pressures (Reznick, Ghalambor et al. 2002; Reznick, Bryant et al. 2006).

Intrinsic factors that may influence adult fish survival include growth rate, body size, genetics, reproductive effort, and senescence. Growth rate and longevity are influenced by water temperature (Terzibasi, Valenzano et al. 2007). Pacific herring are relatively small [about 70 g at maturation ($\geq$3 y) and 200 g maximum in the oldest age classes]; growth becomes asymptotic at roughly 10 y (Tanasichuk 2000). The total herring lifespan in PWS is fairly short (15 y), consistent with the typical relationship between life span and body size among all species (Roff 1992; Metcalfe and Monaghan 2003). Genetic heritage determines how fast fish grow, how they utilize and store energy, innate behavior, reproduction, and lifespan, thus is arguably *the* central intrinsic factor. Reproductive stress and age-related reduction in metabolic efficiency might destabilize homeostasis and predispose adult herring to death (Woodhead 1979; Tanasichuk 2000). In particular, Tanasichuk (Tanasichuk 2000) demonstrates that increasing proportions of surplus energy in Pacific herring are allocated to gonads and argues that this demonstrates progressively greater reproductive strain in aging fish. However, because the rate of somatic growth becomes asymptotic, allocation of proportionally more energy to reproduction might simply mean that proportionately less energy is required for growth, leaving relatively more for reproduction without necessarily causing life-threatening physiological stress. Senescence, representing a combination of genetic heritage, accumulating physiological defects, and possibly growth history, ultimately limits individual lifespans. In fish species with gradual senescence (such as herring), age-dependent organ and cellular degeneration occur, including loss of muscle fiber and endocrine abnormalities (Patnaik, Mahapatro et al. 1994; Terzibasi, Valenzano et al.

2007), probably a result of the progressive failure of physiological repair mechanisms to repair damage and maintain homeostatis (Valdesalicil and Cellerino 2003). The incidence of cancer also increases with age. These factors explain increased mortality rates as mature fish age.

Extrinsic (habitat) factors responsible for adult herring mortality include predation, starvation, disease, inter-specific competition, and contaminants. These in turn are influenced by ocean conditions, climate change, and intricate ecological relationships involving predators, prey, intra- and inter-specific competition. Regional oceanic conditions appeared to be a dominant factor prior to the spill, as shown by 4-year pattern of synchronic in recruitment between Sitka and PWS. Post spill, different factors would appear to be dominant between the two regions as the synchrony disappeared.

Which factors are more important? This is a complex question; can the relative importance of each source of natural mortality be determined? The solution is not easy and may be impossible; natural mortality is one of the most difficult parameters to assess in fish populations (Vetter 1988; Tanasichuk 2000; Hewitt and Hoenig 2005). Most dead fish disappear without a trace. Adequate information on juveniles is not easily gathered prior to adult recruitment. Dominant factors may be different in different regions; dominant factors may change from year to year. Science has a handle on various factors, positive and negative, but does not have quantitative data on the relative importance for each factor. Instead of biologically based estimates of natural mortality, stock assessment models depend on modeled parameters or other estimates (Tanasichuk 2000; Cotter, Burt et al. 2004).

Research necessary to understand herring populations

Goal
Develop a higher level of understanding of how the mechanisms and processes in the ecosystem influence Pacific herring in PWS; This information is needed to predict trends in the population, and to make management and enhancement decision regarding the population, and evaluate the population response to those decisions.

Population Monitoring, bottom up forcing, top down forcing
Population monitoring is needed to evaluate the bottom up and top down forces regulating herring populations, as well as providing a baseline framework for evaluating any possible enhancement activities. Many of these activities will be challenging and expensive. The trick is that we need as many of these research themes covered simultaneously as each year is a new and different challenge to each of the life stages. For this reason, we will never be able to gather data on all of the co-variants each year; priorities will need to gather the most valuable information.

Research theme areas
1.a Adult population monitoring: Continued, detailed monitoring of adult population status is needed; As we study bottom up and top down factors, the status of the population (the net result of all factors) needs to be monitored so that we can correlate population changes with other factors. Monitoring needs have to continuity over time. This would include hydro-acoustic assessments in the winter, fish collections for age composition (and other indices measures such

as size at age, energy content, disease status), as well as monitoring the status through models using age/length and mile days of spawn for input. Some of these activities may be normal agency responsibility, but some supplementation is probably needed to maintain a long term data set.

1.b. Juvenile population indexing; numbers, quality, recruitment: Year class strength is determined prior to year 3 (probably the first year), but standard assessments only monitor fish after year 3 when they recruit into adults schools. We know too little about distribution of larvae and juveniles and factors that are quantitatively important to determining year class strength. We need assessments of juvenile numbers and quality (energy content) of age-zero and age -one juveniles before and after winter. Studies are needed to develop juvenile distribution and a procedure to have a cost effective way to index juvenile numbers. These studies could provide samples to assess quality. Studies on larval drift and success are desireable, but are probably too expensive to be a long term monitoring tool. Measurements of age zero production and quality at the end of summer integrate the various factors regulating larval success potentially obviating the need for larval studies. However, larval studies may be very important if enhancement strategies propose depositing large quantities in a viable habitat..

1.c. Indexing bottom up productivity measurements: While measurement of age-0 abundance and quality integrates bottom-up productivity, it is still necessary to monitor changes in energy available to larvae and juveniles. A combination of physical and biological oceanography measurements are needed; some could comprise a monitoring program that would complement the adult monitoring and also be generally useful to managers. In addition process studies should be developed to specifically identify parameters significant to herring recruitment. The goal would be to have a suite of measurements that can explain good and bad larval recruitment years, good and bad survival through age-zero and age-one winters, and provide a baseline of measurements for future indexing. Scale for process studies and monitoring is a significant issue. Process studies should contrast locations while monitoring should be sufficiently detailed to resolve variability within the Sound., and hopefully between regions. .

2. Top-down factors limiting recruitmemt: Disease and predation are suspected as dominant limiting factors, and come into play for all life stages, before and after recruitment. Disease and predation may not be independent factors (do fish die of disease, or are weakened animals preyed upon before they die?). While we recognize the direction of impact, we do not have adequate quantitative estimates. Generally predation is considered an important determinant of herring survival , and disease epizootics periodically cause major declines to clupeid populations around the world (Sindermann 1990; Rahimian and Thulin 1996; Meyers et al. 1986; McVicar 1999; Ward et al. 2001) . Recent studies suggest disease may be a much larger issue than is currently acknowledged.

2.a. Predation assessments are needed, ranging from marine mammal, bird, fish predation on adults and juveniles, to fish and invertebrate predation on larvae, as well as the predation impact on eggs. All life stages are affected. The problem is the quantitative assessment of various life stages by the competing predators. Modeling will yield clues, but some hard input data is needed to support the modeling. Quantifying predation on larvae is problematic, and assessing survival at the juvenile life stage at the end of the first summer is probably the first practical point for assessing the net effect of disease and predation up to that life stage.

2.b. Long-term pathogen and disease surveillances are required to monitor the natural dynamics of the major herring pathogens in PWS and also to test adaptive disease management strategies intended to mitigate the negative impacts of these diseases. For example, following a major epizootic of ichthyophoniasis that killed more than 300 million herring in the marine waters around Sweeden (Rahimian and Thulin 1996), an ICES (2003) recommended: "member countries are encouraged to continue monitoring the prevalence of *Ichthyophonus hoferi*, if appropriate in conjunction with herring stick assessments, so as to be aware of changes in status that may forecast an epizootic disease outbreak.". This approach of pathogen surveillance represents an appropriate forecasting tool for chronic diseases, like ichthyophoniasis; however, kinetics of other herring diseases in PWS (including VHS and VEN) are much more rapid and novel predictive tools must be developed and implemented to forecast their annual impacts. Assessments in the past have focused on spawning adults; future assessments need to evaluate incidence levels in age-zero and age-one fish, before and after the winter.

2.c. Empirical studies on the significance of disease at different life stages is needed. Disease assessments of wild fish populations have an interpretation problem: does infection necessarily lead to terminal disease-related mortality, or can the infection reside at low intensities in the host for extended periods and only result in disease-related mortality after interactions with adverse environmental conditions? Empirical studies, focused on disease mechanisms and their significance, are needed to define the significance of pathogen and disease surveillances. These empirical studies, investigating pathogen virulence, disease kinetics, energetic costs, and immunological mechanisms of defense must be performed on all life stages of Pacific herring under controlled conditions, using specific pathogen-free (SPF) and immunologically naïve herring hosts with a known disease-free history. Additionally, a ready supply of SPF herring will undoubtedly be required as positive controls for development and implementation of predictive tools that will compare their metrics of disease susceptibility to those of wild PWS herring.

3. Modeling, to sort out the relative importance of these factors: The life-stage specific, ecosystem-based modeling is an obvious way to explore these multivariate relationships, yet models need realistic data with reasonably complete inputs. Sensitivity analyses must be performed to determine how mortality interacts with year class to determine stock size. Further models are needed to determine how disease intensity influences mortality through acute effects and vulnerability to predation. Models are also needed to determine if environmental features can be identified that drive production of younger year classes. An open approach is recommended, whereby a broad range of investigators and modelers have direct data access. The goal of modeling should be to provide mechanistic rather than correlative understanding of this complex natural system (Cooney, Allen et al. 2001).

4. Enhancement infra-structure studies: If enhancement activities are to be considered as an option at some point, several supporting studies will be needed. Mass marking methods, such as otolith marking, need to be developed so that enhancement success can be evaluated. Enhancement strategies and techniques need further refinement. Natural larval mortalities are high, so studies on factors enhancing larval success (prey availability, quality), identifying quality larval habitat for success, predicting larval release sites and drift to those habitat sites may be useful studies. If juveniles are release, the same sort of studies are needed relative to this life stage. Studies are also needed to identify the down side to enhancement, such as the relationship between larval release and disease effects in the general population.

Review of current research (2007, 2008)

Research is in progress on many of the needs discussed above (Table 1). These efforts will only begin to address the complex relationships needed to understand the system; few questions will be adequately resolved in the next year or two as these specific projects are completed. As is typical for a complex system, we can expect that new questions will arise as the work proceeds. Some investigators have suggested that complex marine ecosystems can never be fully explained (Walters and Collie 1988). We are less pessimistic and agree with Cooney et al. (Cooney, Allen et al. 2001) that understanding mechanisms and functional relationships will adequately address at least some of the questions asked.

Databases and Modeling

Two projects are underway with the goal of assembling coherent, comprehensive data sets for the purposes of modeling, GIS visualization, and access for researchers (Kiefer In progress; Moffit In progress). In the past, herring-related data were not widely available and were not shared among herring researchers. A new web portal will facilitate the sharing of spatial and temporal herring data that will be important during the development and implementation of the herring recovery plan for PWS (Moffit In progress). A life-stage specific, ecosystem-based model of PWS herring is being devised that will aid in the integration of ecological data gathered on herring over the last two decades and will simulate processes that cause chronic decrease in herring stocks (Kiefer In progress). It can be used to examine why the PWS herring population has not recovered to pre-spill levels. The model will be housed in a geographic information system developed specifically for marine applications and will be available for interactive viewing and downloading of files over the Internet.

Abiotic factors

Two physical oceanographic studies are underway, one designed for large-scale long-term monitoring (Weingartner In progress) and one specific to juvenile herring in PWS (Gay In progress.). Chemistry is currently missing from these studies; nutrient cycling is a key player at primary trophic levels. Because Pacific herring are dependent of plankton for food and primary productivity is heavily influenced by physical factors, the physical condition of the environment and its changes are important to the species. The Alaska Coastal Current (ACC) is important habitat for herring because it links Prince William Sound and continental shelf marine habitats. Terrestrial runoff from around the Gulf of Alaska affects ACC dynamics and its nutrient and sediment load although oceanic processes substantially modify these influxes. The GAK 1 line has been monitoring the ACC continually for 36-years and data collected from provides the long-term temporal context of the natural variability of the ACC and Prince William Sound (Weingartner In progress). Long-term monitoring data are essential to understand how herring are affected by variations in temperature, salinity, and density and how this variability could affect recovery.

Herring recruitment is highly influenced by conditions within nursery sites, affecting survival in the first year of life. Studies of the physical oceanography of nursery fjords has indicated that each site has a unique set of hydrographic conditions that are influenced by both local processes and water exchange between the Gulf of Alaska and Prince William Sound (Gay and Vaughan 2001). A hydrographic time series within nursery fjords will collect high resolution data on currents and hydrography to determine the dominant mechanisms of water exchange and circulation within two experimental fjords; one located in a highly productive sub-region and one located in less productive sub-region influenced by tidewater glacial outflow (Gay In progress.). This will provide critical information on where the most productive potential nursery bays would be located if a direct intervention approach is suggested by the herring recovery plan.

Biological factors
Studies focused on the food and energy requirements of Pacific herring and predators are underway. Conspicuously absent from study is primary productivity, the food resource on which zooplankton depend and which is heavily influenced by physical and chemical factors (daylight, nutrients, temperature, water column stability, etc.). Predator studies are also limited; predation by birds and whales is being studied but studies of other predators and competitors are missing, particularly fish.

Food may be a limiting factor for juvenile herring. An understanding of the variability in abundance and distribution of herring prey may lead to a greater understanding of why certain nursery bays are more productive than others (Batten In progress). Recent continuous plankton recorder data have shown large differences in mesozooplankton biomass on the Alaskan shelf from 2004 and 2005 (Batten, Hyrenbach et al. 2006). Understanding changes in herring food supply from year to year, whether a shift in distribution, or timing, of zooplankton abundance could help understand the fluctuations in the population and, in turn, support management of this resource. Recruitment may also be contingent on young of the year herring attaining, from zooplankton, sufficient whole body energy content (WBEC) to survive their first winter (Kline In progress). The high rate of disease, as well as predation pressures, may also require young herring to have an increased energy demand in the winter that is not currently being met. A detailed study of the energy consumption rates of overwintering herring in the Prince William Sound in comparison to herring in other parts of Alaska may provide information on the high level of recruitment failures that will provide valuable information to managers for a recovery strategy (Vollenweider In progress).

The "critical period hypothesis" is currently being investigated as a potential mechanism for reduced recruitment. Pre- and Post- winter juvenile nutritional content are currently be assessed in PWS from field-caught samples. Pre-winter condition is an index which integrates summer production, while post-winter condition reflects the severity of energetic costs throughout the winter. Together they may index seasonal bioenergetics that have been shown to play a large role in juvenile survival. These analyses are fairly inexpensive with the exception of obtaining samples. However, continued monitoring of juvenile energetics can be facilitated by sample collection from other projects such as the juvenile abundance surveys currently underway by Thorne et al.. Nutritional sampling should be continued into the future to establish trends that can be correlated with other variables (prey availability, oceanographic conditions). This may be the best way to index the net effects from all factors (bottom up and top down) through the egg-larvae-juvenile stages of the first year which is very difficult to study in a quantitative way.

Predation is likely contributing to the suppression of herring populations in Prince William Sound and marine mammals and seabirds are major predators on these fish. How predator and herring populations are related must be understood and quantifiable before any restoration effort takes place and in particular, whether increased herring production will yield a larger herring population or merely result in more predators. Fisheries management models currently use broad and highly uncertain estimates of natural mortality. Schools of herring represent a rich, aggregated resource for predators such as birds and whales (Wilson and Womble 2006). Research underway is focused on the spatial and temporal abundance of seabird predators in and around juvenile herring schools, as well as the physical and biological characteristics of the schools used for feeding (Bishop and Kuletz In progress). Estimates of juvenile herring consumption produced by this work will aid in planning future restoration efforts as well as in assessing the role of seabird predation on herring recruitment by providing data to both herring and ecosystem modeling. Ongoing studies of killer whales and their effect on Pacific herring will be broadened to include a satellite tagging program to examine habitat preference and to aid in a more extensive examination of feeding habits using observational and chemical techniques (Matkin 2007). Killer whale research will more clearly delineate the role of killer whales in the nearshore ecosystem and possible effects on the restoration recovery of herring. Studies are also underway to quantify humpback whale predation on herring in PWS compared to those Sitka, a location with healthy herring stock (Rice In progress).

Essential herring habitat
Several projects focus on essential herring habitat. Mapping of the intertidal shoreline (ShoreZone) is being conducted in PWS and other parts of Alaska, including Sitka, to provide a single mapping protocol that includes geomorphology, substrate type, and biological substrate on all beaches (Lindeberg In progress). Combined with data from research on other ecological factors and the previously described database (historic spawning maps) (Moffit In progress), shoreline mapping will provide a common reference point for many projects In combination with *ShoreZone* mapping and ongoing oceanographic projects, chemical analysis of trace element concentrations in herring otoliths may provide key geographic signatures of natal habitats that should clearly define where productive herring habitat is located (Bickford and Norcross In progress). This may allow for the protection of the most important herring populations in PWS and identify those environmental variables needed to enhance other populations. Otolith chemistry collected from herring in Sitka Sound, a healthy reference stock, will provide baseline data to compare to the depleted herring stock in PWS (Meuret-Woody In progress). This comparison may yield an understanding of the factors causing depression of the PWS herring population and how they could potentially be limited or removed. These relationships should also provide insight into the wisdom and feasibility of designing a herring recovery program for PWS.

Herring population monitoring
Detailed monitoring of the PWS herring population is necessary to understand its size, fluctuations, and relationship to the other abiotic and biotic components of the ecosystem. Considerable routine monitoring and modeling of all these factors will be necessary to

adequately understand functional relationships and mechanisms. Without these data there is little chance that a recovery effort could be adequately assessed. More population monitoring is recommended than is currently taking place, not only for herring but for other fish, crustaceans (e.g., copepods and euphausiids), and predators (as discussed previously). One highly informative approach may be to use passive sonar techniques to locate schools on multi-kilometer scales (Makris, Ratilal et al. 2006). In addition, efforts to discriminate stock structure and substructure may prove crucial to understanding detail within PWS. One such study in progress is designed to examine herring stock structure at fine spatial scales and determine if otolith chemistry and fatty acid analysis of cardiac tissue are useful discriminators of this structure (Otis, Heintz et al. In progress). Results should allow researchers to better define ecologically significant stock boundaries, likely affecting how commercially exploited herring populations are assessed and managed and providing further insight into the possibility of restoration in PWS.

Barometers of the PWS herring population are the adult abundance and condition, as monitored in March, and the juvenile abundance and condition going into and coming out of the long winter period (Thorne In progress). A direct capture effort in March 2007 and March 2008 is filling data gaps for herring at this important time, and providing biological samples that can be utilized for current disease, marking, and stable isotope research projects.

Long-term trends of the relative abundance indices of juveniles are needed. Since year class strength is determined prior to age 3, juvenile abundance is a more sensitive indicator of cohort success and factors contributing to their success than estimates made from adult fish. Additionally, monitoring programs limited to adult fish are unable to detect poor year cohorts until fish have recruited to the fishery, which is particularly deleterious for harvested stocks. In BC, the predictive relationship between juvenile abundance (age-0 & age-1) and subsequent recruitment (age-3+) is used as a course indicator of year class strength nearly 2 years prior to recruitment (*27c*). A current project underway (Thorne et al.) provides the platform for juvenile fish collection that can be shared with other groups currently working to assess juvenile nutritional content and other analyses which require samples.

Disease
Long-term systematic disease monitoring and research since 1994 has suggested a relationship between disease and the continuing population decline of herring in the Sound (Marty, Quinn II et al. 2003). A comprehensive three-year herring disease program began in 2007 to examine the epizootic mortality resulting from infectious and parasitic diseases (Hershberger, Kocan et al. In progress). Stocks outside of PWS (Sitka Sound and Puget Sound) serve as references and comparisons to PWS stock. This program will provide predictive metrics that can forecast future disease epidemics and offer empirical relationships useful in developing adaptive management policies to mitigate the effects of epizootic and chronic diseases.

Hatchery culture
Herring hatchery techniques may prove useful if remediation is needed for the PWS herring population and this avenue is being explored by one EVOSTC study (Linley In progress). To the best of our knowledge, hatchery production of forage fish does not take place anywhere in the United States. However, some Pacific herring are cultured in Japan and several groups have

done so for research in North America (Carls 1987; Johnson, Carls et al. 1997; Vines, Robbins et al. 2000; Hershberger, Kocan et al. In progress). Multiple year classes have been concurrently raised by Hershberger et al. (Hershberger, Kocan et al. In progress) and are part of the aforementioned disease study.

Summary

To fully understand the Pacific herring population in PWS and predict future change, major study will be required to determine the functional processes and mechanisms in the ecosystem. Because herring occupy the niche between lower and upper trophic levels, they are highly sensitive to environmental change, both non-biological and biological at every life stage. In other words, "bottom up" and "top down" factors strongly influence the herring population; this influence is likely nonlinear and is clearly difficult to predict. In the short period for which biomass estimates are available (1970 to present), PWS herring conform to typical Clupeid 'boom and bust' cycles. A highly organized, coordinated set of studies is required to understand why, and to provide a scientific foundation to management and enhancement decisions in the future.. This understanding and the tools needed to discern change in the ecosystem are needed before remediation is contemplated. Many studies are now in progress, yet several more will likely be necessary and we have pointed out some of the deficiencies, such as lack of primary productivity and nutrient cycling studies to address bottom up pressures and expanded study of top down factors such as increased predator and competitor surveillance. Disease cycling in the population clearly adds to the complexity and will clearly take several years to understand. Any effort to restore or enhance herring production will require understanding of the ecological factors that may be affecting recruitment success including food scarcity (dependent on oceanographic factors), chemical pollution/changes, changes in niche utilization among species, and habitat loss or compromise. We will likely always be seeking more information, expecially since the environment is in a continuous evolution of change. However, we will be more comfortable with these changes as we gain a high level of understanding and begin to have a better handle on predicting the changes before they happen. To this end, enhancement experiments may offer some tests of the modeling capability.

References

Alderdice, D. F. and A. S. Hourston (1985). "Factors influencing development and larval survival of Pacific herring (Clupea harengus pallasi) eggs and larve to beginning of exogenous feeding." Canadian Journal of Fisheries and Aquatic Sciences 42(Supplement 1): 56-68.

Alderdice, D. F. and F. P. J. Velsen (1971). "Some effects of salinity and temperature on early development of Pacific herring (*Clupea pallasi*)." Journal of the Fisheries Research Board Canada 28: 1545-1562.

Bakun, A. (2006). "Wasp-Waist populations and marine ecosystem dynamics: navigating the "predator pit" topographies." Progress in Oceanography 68: 271-288.

Batten, S. (In progress). "Acquisition and application of continuous plankton recorder data." EVOSTC Project 070624.

Batten, S. D., K. D. Hyrenbach, et al. (2006). "Characterising meso-marine ecosystems of the North Pacific." Deep-Sea Research Part II-Topical Studies in Oceanography 53: 270-290.

Bickford, N. and B. Norcross (In progress). "Herring restoration in PWS: identifying natal and nursery habitats." EVOSTC Project ????

Bishop, M. A. and K. Kuletz (In progress). "Seabird predation on juvenile herring in Prince William Sound." EVOSTC Project 070814.

Blaxter, J. H. S. (1985). "The herring: a successful species?" Canadian Journal of Fisheries and Aquatic Sciences 42, Supplement No. 1: 21-30.

Blaxter, J. H. S. and F. G. Holiday (1963). "The behavior and physiology of herring and other clupeids." Adv Mar Biol 1: 261-393.

Carls, M. G. (1987). "Effects of Dietary and Water-Borne Oil Exposure on Larval Pacific Herring (*Clupea harengus pallasi*)." Marine Environmental Research 22(4): 253-270.

Carls, M. G., G. D. Marty, et al. (2002). "Synthesis of the toxicological impacts of the *Exxon Valdez* oil spill on Pacific herring (*Clupea pallasi*) in Prince William Sound, Alaska, USA." Canadian Journal of Fisheries and Aquatic Sciences 59(1): 153-172.

Cooney, R. T., J. R. Allen, et al. (2001). "Ecosystem Control of Pink Salmon (Oncorhynchus Gorbuscha) and Pacific Herring (Clupea Pallasi) Populations in Prince William Sound, Alaska." Fisheries Oceanography 10 (Suppliment 1): 1-13.

Cotter, A. J. R., L. Burt, et al. (2004). "Are Stock Assessment Methods Too Complicated?" Fish and Fisheries 5(3): 235-254.

Foy, R. J. and A. J. Paul (1999). "Winter Feeding and Changes in Somatic Energy Content of Age-0 Pacific Herring in Prince William Sound, Alaska." Transactions of the American Fisheries Society 128(6): 1193-1200.

Freon, P., P. Cury, et al. (2005). "Sustainable Exploitation of Small Pelagic Fish Stocks Challenged by Environmental and Ecosystem Changes: a Review." Bulletin of Marine Science 76(2): 385-462.

Gay, S. M. (In progress.). "Physical oceanographic factors affecting productivity in juvenile Pacific herring nursery habitats." EVOSTC Project 070817.

Gay, S. M. and S. L. Vaughan (2001). "Seasonal hydrography and tidal currents of bays and fjords in Prince William Sound, Alaska." Fisheries Oceanography 10: 159-193.

Haegele, C. W. (1993). "Epibenthic Invertebrate Predation of Pacific Herring, Clupea-Pallasi, Spawn in British-Columbia." Canadian Field-Naturalist 107(1): 83-91.

Hampton, J. (2000). "Natural Mortality Rates in Tropical Tunas: Size Really Does Matter." Canadian Journal of Fisheries and Aquatic Sciences 57(5): 1002-1010.

Hart, J. L. (1973). Pacific fishes of Canada, Fisheries Research Board of Canada.

Hart, J. L. (1973). Pacific fishes of Canada. Bulletin 180. Ottawa, ON, Fisheries Research Board of Canada.

Hay, D. E. (1985). "Reproductive-Biology of Pacific Herring (Clupea-Harengus-Pallasi)." Canadian Journal of Fisheries and Aquatic Sciences 42: 111-126.

Hay, D. E., J. R. Brett, et al. (1988). "Experimental Impoundments of Prespawning Pacific Herring (Clupea-Harengus-Pallasi) - Effects of Feeding and Density on Maturation, Growth, and Proximate Analysis." Canadian Journal of Fisheries and Aquatic Sciences 45(3): 388-398.

Hay, D. E., Schweigert, J., Thompson, M., Haegele, C. W. Analyses of juvenile herring surveys for recruitment prediction in the Strait of Georgia. P2002-03. Proceedings of the PSARC Pelagic Subcommittee Meeting, Fisheries and Oceans Canada, September 4-6, 2002.

Hershberger, P., R. Kocan, et al. (In progress). "Prince William Sound herring disease program." EVOSTC Project 070819.

Hewitt, D. A. and J. M. Hoenig (2005). "Comparison of Two Approaches for Estimating Natural Mortality Based on Longevity." Fishery Bulletin 103(2): 433-437.

Hjort, J. (1914). "Fluctuations in the great fisheries of northern Europe." Rapp P-V Reun Cons Int Explor Mer 20: 1-228.

Hose, J. E. (submitted). "Genetic diversity in Pacific herring (*Clupea pallasi*) from Prince William Sound, Alaska." Journal of Fish Biology.

Houde, E. D. (1997). "Patterns and Trends in Larval-Stage Growth and Mortality of Teleost Fish." Journal of Fish Biology **51**: 52-83.

Hourston, A. S. and C. W. Haegele (1980). "Herring on Canada's Pacific coast." Canadian Special Publication of Fisheries and Aquatic Sciences **48**: 23.

Hunter, J. R., J. H. Taylor, et al. (1979). "Effect of ultraviolet irradiation on eggs and larvae of the northern anchovy, *Engraulis mordax*, and the Pacific mackerel, *Scomber japonicus*, during the embryonic stage." Photochemistry and Photobiology **29**: 325-338.

ICES. 2003. Report of the Working Group on Pathology and Diseases of Marine organisms. Aberdeen, UK 11-15 March 2003.

Johnson, S. W., M. G. Carls, et al. (1997). "Reproductive success of Pacific herring, Clupea pallasi, in Prince William Sound, Alaska, six years after the Exxon Valdez oil spill." Fishery Bulletin **95**(4): 748-761.

Kiefer, D. A. (In progress). " An ecosystem model of Prince William Sound herring: a management and restoration tool." EVOSTC **Project 070810**.

Kline, T. C. (In progress). "Prince William Sound herring forage contingency." EVOSTC **Project 070811**.

Lindeberg, M. (In progress). "Shorezone mapping for Prince William Sound." EVOSTC **Project 070805**.

Linley, T. (In progress). "Development of culture technology to support restoration of herring in Prince William Sound: use of in vitro studies to validate and optimize restoration actions." EVOSTC **Project 070821**.

Makris, N. C., P. Ratilal, et al. (2006). "Fish population and behavior revealed by instantaneous continental shelf-scale imaging." Science **311**(5761): 660-663.

Marty, G. D., S. E. Miller, et al. (Submitted). "Role of *Ichthyophonus hoferi*, viral hemorrhagic septicemia virus, and cutaneous ulcers in preventing recovery of a Pacific herring (*Clupea pallasi*) population."

Marty, G. D., T. J. Quinn II, et al. (2003). "Role of disease in abundance of a Pacific herring (*Clupea pallasi*) population." Canadian Journal of Fisheries and Aquatic Sciences **60**: 1258-1265.

Matkin, C. (2007). "Monitoring, tagging, feeding studies, and restoration of killer whales in Prince William Sound / Kenai Fjords in 2007." EVOSTC **Project 070742**.

McGurk, M. D. (1993). "Allometry of Herring Mortality." Transactions of the American Fisheries Society 122(6): 1035-1042.

McGurk, M. D., A. J. Paul, et al. (1993). "Relationships between Prey Concentration and Growth, Condition, and Mortality of Pacific Herring, Clupea-Pallasi, Larvae in an Alaskan Sub-Arctic Embayment." Canadian Journal of Fisheries and Aquatic Sciences 50(1): 163-180.

McVicar AH. 1999. *Ichthyophonus* and related organisms. Pp 661-687 *In*: Fish Diseases and Disorders, Volume 3 Viral, Bacterial, and fungal infections. Woo PTK, Bruno DW (eds). CAB International Publishing, New York

Metcalfe, N. B. and P. Monaghan (2003). "Growth versus lifespan: perspectives from evolutionary ecology." Experimental Gerontology 38: 935-940.

Meuret-Woody, H. (In progress). "Identification of essential habitat for Pacific herring in Sitka Sound for comparison to Prince William Sound." EVOSTC Project 070834.

Meyers TR, AK Hauck, WD Blackenbeckler, T Minicucci. 1986. First report of viral erythrocytic necrosis in Alaska, USA, associated with epizootic mortality in Pacific herring, *Clupea harengus pallasi* (Valenciennes). Journal of Fish Diseases 9: 479-491.

Moffit, S. (In progress). "Herring data and information portal." EVOSTC Project ????

Norcross, B. L., E. D. Brown, et al. (2001). "A synthesis of the life history and ecology of juvenile Pacific herring in Prince William Sound, Alaska." Fisheries Oceanography 10: 42-57.

Norcross, B. L. and M. Frandsen (1996). "Distribution and abundance of larval fishes in Prince William Sound, Alaska, during 1989 after the *Exxon Valdez* oil spill." American Fisheries Society Symposium 18: 463-486.

Norcross, B. L., S.-B. Kelly, et al. (submitted). "An early life history model for Pacific herring in Prince William Sound, Alaska."??

O'Farrel, M. R., Larson, R. J. Year-class formation in Pacific herring estimated from spawning-date distributions of juveniles in San Francisco Bay, California. *Fishery Bulletin* 2005, 103, 130-141.

Otis, T., R. Heintz, et al. (In progress). "Using otolith chemistry to discriminate Pacific herring stocks in Alaska." EVOSTC Project 070769.

Palsson, W. A. (1984). Egg mortality upon natural and artificial substrata within Washington State spawning grounds of Pacific herring (*Clupea harengus*). Seattle, University of Washington. Masters: 191.

Patnaik, B. K., N. Mahapatro, et al. (1994). "Aging in Fishes." Gerontology 40(2-4): 113-132.

Paul, A. J., J. M. Paul, et al. (1998). "Fall and spring somatic energy content for Alaskan Pacific herring (*Clupea pallasi* Valenciennes 1847) relative to age, size and sex." Journal of Experimental Marine Biology and Ecology 223(1): 133-142.

Pearson, W. H., R. A. Elston, et al. (1999). " Why did the Prince William Sound, Alaska, Pacific herring (Clupea pallasi) fisheries collapse in 1993 and 1994? Review of hypotheses." Cananadian Journal of Fisheries and Aquatic Sciences 56: 711-737.

Pedersen, B. H. (1997). "The Cost of Growth in Young Fish Larvae, a Review of New Hypotheses." Aquaculture 155(1-4): 259-269.

Rahimian H, J Thulin. 1996. Epizootiology of *Ichthyophonus hoferi* in herring populations off the Swedish west coast. Diseases of Aquatic Organisms 27:187-195.

Reznick, D., M. Bryant, et al. (2006). "The evolution of senescence and post-reproductive lifespan in guppies (*Poecilia reticulata*)." Plos Biology 4(1): 136-143.

Reznick, D., C. Ghalambor, et al. (2002). "The evolution of senescence in fish." Mechanisms of Ageing and Development 123(7): 773-789.

Rice, S. D. (In progress). "Significance of whale predation on the natural mortality rate of Pacific herring in PWS." EVOSTC Project 070804.

Rice, S. D. and M. G. Carls (2007). Prince William Sound herring: an updated synthesis of population declines and lack of recovery. Juneau, Alaska, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Auke Bay Laboratories.

Roff, D. A. (1992). The evolution of life histories. New York, Chapman and Hall.

Rooper, C. N., L. J. Haldorson, et al. (1999). "Habitat factors controlling Pacific herring (Clupea pallasi) egg loss in Prince William Sound, Alaska." Canadian Journal of Fisheries and Aquatic Sciences 56: 1133-1142.

Sanvicente-Anorve, L., L. A. Soto, et al. (2006). "Relationship patterns between ichthyoplankton and zooplankton: A conceptual model." Hydrobiologia 559: 11-22.

Sindermann C. 1990. Fungi. Pp 57-78 *In*· Principal diseases of marine fish and shellfish, Second Edition, Volume 1: Diseases of Marine Fish. Academic Press, New York

Stokesbury, K. D. E., R. J. Foy, et al. (1999). "Spatial and Temporal Variability in Juvenile Pacific Herring, Clupea Pallasi, Growth in Prince William Sound Alaska." Environmental Biology of Fishes 56(4): 409-418.

Stokesbury, K. D. E., J. Kirsch, et al. (2000). "Spatial Distributions of Pacific Herring, Clupea Pallasi, and Walleye Pollock, Theragra Chalcogramma, in Prince William Sound, Alaska." Fishery Bulletin 98(2): 400-409.

Stokesbury, K. D. E., J. Kirsch, et al. (2002). "Natural mortality estimates of juvenile Pacific herring (*Clupea pallasi*) in Prince William Sound, Alaska." Canadian Journal of Fisheries and Aquatic Sciences **59**(3): 416-423.

Tanasichuk, R. W. (2000). "Age-Specific Natural Mortality Rates of Adult Pacific Herring (Clupea Pallasi) From Southern British Columbia." Canadian Journal of Fisheries and Aquatic Sciences **57**(11): 2258-2266.

Terzibasi, E., D. R. Valenzano, et al. (2007). "The Short-Lived Fish Nothobranchius Furzeri as a New Model System for Aging Studies." Experimental Gerontology **42**(1-2): 81-89.

Terzibasi, E., D. R. Valenzano, et al. (2007). "The short-lived fish *Nothobranchius furzeri* as a new model system for aging studies." Experimental Gerontology **42**: 81-89.

Thorne, R. (In progress). "Trends in adult and juvenile herring distribution and abundance in PWS." EVOSTC **Project 070830**.

Valdesalicil, S. and A. Cellerino (2003). "Extremely Short Lifespan in the Annual Fish Nothobranchius Furzeri." Proceedings of the Royal Society of London Series B-Biological Sciences **270**: S189-S191.

Vetter, E. F. (1988). "Estimation of natural mortality in fish stocks: a review." Fishery Bulletin **88**(1): 25-42.

Vines, C. A., T. Robbins, et al. (2000). "The effects of diffusible creosote-derived compounds on development in Pacific herring (*Clupea pallasi*)." Aquatic Toxicology **51**(2): 225-239.

Vollenweider, J. J. (In progress). "Are herring energetics in PWS a limiting factor?" EVOSTC **Project 070806**.

Walters, C. J. and J. S. Collie (1988). "Is research on environmental-factors useful to fisheries management?" Canadian Journal of Fisheries and Aquatic Sciences **45**: 1848-1854.

Ward, TM, F Hoedt, L McLeay, WF Dimmlich, M Kinloch, G Jackson, R McGarvy, PJ Rogers, K Lones. 2001. Effects of the 1995 and 1998 mass mortality events on the spawning biomass of sardine, *Sardinops sagax*, in South Australian waters. ICES Journal of Marine Dcience 58: 865-875.

Ware, D. M. (1985). "Life history characteristics, reproductive value, and resilience of Pacific herring (*Clupea harengus pallasi*)." Canadian Journal of Fisheries and Aquatic Science **42 Supplement No. 1**: 127-137.

Weingartner, T. (In progress). "Long-term oceanographic monitoring of the Gulf of Alaska ecosystem." EVOSTC **Project 070340**.

Wilson, M. F. and J. N. Womble (2006). "Vertebrate exploitation of pulsed marine prey: a review and the example of spawning herring." Rev Fish Biol Fisheries 16: 183-200.

Woodhead, A. D. (1979). Senescence in fishes. Fish phenology; anabolic adaptiveness in teleosts, London, Symposium of the Zoological Society of London.

Table 1. Summary of current EVOSTC herring research projects in PWS.

Modeling / data management
Kiefer DA. Project 070810. An ecosystem model of Prince William Sound herring: a management and restoration tool.

Moffit S. Project 070822. Herring data and information portal.

Abiotic factors
Gay SM III. Project 070817. Physical oceanographic factors affecting productivity in juvenile Pacific herring nursery habitats.
Weingartner T. Project 070340. Long-term oceanographic monitoring of the Gulf of Alaska ecosystem.

Biological factors
Primary and secondary productivity
Batten S. Project 070624. Acquisition and application of continuous plankton recorder data.

Food / energetics
Kline TC. Project 070811. Prince William Sound herring forage contingency.
Vollenweider JJ. Project 070806. Are herring energetics in PWS a limiting factor?

Predation
Bishop MA, Kuletz K. Project 070814. Seabird predation on juvenile herring in Prince William Sound.
Rice SD. Project 070804. Significance of whale predation on the natural mortality rate of Pacific herring in PWS.

Essential habitat
Lindeberg M. Project 070805. Shorezone mapping for Prince William Sound.
Meuret-Woody H. Project 070834. Identification of essential habitat for Pacific herring in Sitka Sound for comparison to Prince William Sound.

Distribution and abundance
Bickford N, Norcross B. Project 070782. Herring restoration in PWS: identifying natal and nursery habitats.
Thorne, R. Project 070830. Trends in adult and juvenile herring distribution and abundance in PWS.

Stock discrimination
Otis T, Heinz R, Bickford N. Project 070769. Using otolith chemistry to discriminate Pacific herring stocks in Alaska.

Disease
Hershberger P, Kocan R, Hansen J, Elliott D, Emmenegger E, Kurath G, LaPatra S, Winton J. Project 070819. Prince William Sound herring disease program.

Hatchery culture
Linley T. Project 070821. Development of culture technology to support restoration of herring in Prince William Sound: use of *in vitro* studies to validate and optimize restoration actions.

APPENDIX B – ENHANCEMENT REVIEW

Final Report – September 2007

Herring enhancement in Prince William Sound: feasibility, methodology, biological and ecological implications

Doug Hay

Nearshore Research

2510 Holyrood Drive

Nanaimo BC V9S 4K9

hay.doug@shaw.ca

250 758 4568

1 Overview and synopsis

The subject matter within this report is very broad. Some topics included in this report have received a lot of attention from researchers. Other topics have received very little. Not all topics are strictly scientific. The potential background information for examination of herring enhancement is substantial and includes hundreds of scientific papers and books on herring biology and enhancement of marine fish. There is almost no literature specifically on the topic of herring enhancement. Many of the issues involved with the subject of marine fish enhancement are not resolved. Also there are many unresolved issued concerned with the Prince William Sound herring population. Any attempt to summarize or distill all the available information into a single report demands severe condensation. That is the case in this report.

The issue of enhancement of marine fish populations is controversial. There is an influential part of the fisheries science community, mainly from the ecological side, that is steadfastly opposed to the concept of marine finfish enhancement. There is another component, mainly the practitioners, who are comfortable with the concept and worry little about biological implications. However, even the detractors of the concept suggest that the activity may be warranted when all other conventional management procedures fail. Even then there are reservations about the efficacy of the approach if density-dependent factors regulating recruitment occur after the release of cultured fish. This is a focal point for this issue in Prince William Sound.

The available information about herring in Prince William Sound indicates that some limitation to abundance occurs at early life stages, prior to recruitment which occurs mainly at age 3. Recent work on juvenile herring ecology within Prince William Sound indicates that some herring, especially those residing in specific bays or inlets, have inadequate nutritional resources to survive their first winter. If such mortality is a factor limiting recruitment to the adult spawning stock, then perhaps enhancement could promote better survival of this stage. There are several distinct life history stages of herring however, and they interact spatially and temporally. Also, there are interactions (predation and competition for food) with other species. Therefore a conceptual matrix is developed to show the intra-cohort and inter-cohort interactions, and also interactions between herring and other species. Based on a review of available data on survival of specific life history stages, this report suggests that enhancement activity, if it proceeds, probably should retain cultured herring until the end of the 'fall juvenile' stage. At this time, well-nourished herring juveniles may withstand a relatively good chance of surviving the winter period when feeding opportunities are limited.

This report avoids advocacy but the concluding sections present a review of the current fisheries management and ecological factors that should be addressed prior to the initiation of enhancement activity. The decision about whether enhancement should proceed, or should not proceed, is not addressed explicitly in this report. However, this report is designed to assist those charged with making such a decision. The report points out the failures of previous attempts at marine fish enhancement, especially for Atlantic cod in Atlantic waters. The report also describes the results of recent Japanese research. Their results of mass rearing of herring are impressive – even startling – but it is not clear whether their obvious success at herring culture is actually having any positive effects on the wild herring populations. This statement is based on reviews of such activity by some Japanese scientists who question the validity of the approach. Nevertheless, if enhancement activity is undertaken in Prince William Sound, the Japanese experience would be a source of invaluable technical protocols. Acquisition of such technical details, however, would require direct contact with the Japanese agencies engaged in this work because only brief technical summaries are available at the present time.

Several major scientific reviews about marine fish enhancement activities are unanimous on one key point: it is futile to release young cultured animals into the wild prior to the time when intense density-dependent processes may result in intense mortality. There is no doubt that this point is valid and it is emphasized, and perhaps over-emphasized, in the following text. Although this is a valid and useful comment it may be difficult to identify the point in the life history of herring in Prince William Sound where such density-dependence might occur. Based on the experience with Atlantic cod rearing, it seems clear that release of herring larvae, after a short culture period, would precede the impact of density-dependent processes. Instead, based on the considerable work on herring juveniles in Prince William Sound, it seems that a release time approximately at the end of the first summer feeding period may be the best time to avoid possible density-dependent mortality associated with food limitation and winter survival.

Readers not familiar with biological and fisheries literature may have difficulty understanding why concepts like density-dependence can invoke so much discussion and so little consensus. Probably that is the case with herring in Prince William Sound and perhaps other issues related to herring in Prince William Sound. Density dependence interactions in herring can be complex because there are several distinct life history stages that may, or may not, occupy different parts of the regions (i.e., different depths) and eat different food. It is possible however, that all life history stages within Prince William Sound may overlap, spatially and temporally, at some times of the year. A major uncertainty about Prince William Sound herring biology concerns the role of the shelf waters as summer feeding areas for adults. In other areas of the eastern Pacific the adult component of large herring populations are migratory, and feed intensely during the summer on shelf waters. Juvenile herring tend to reside close to sheltered, nearshore waters. Presumably Prince William Sound herring have the same migratory habits but this aspect has not been explicitly documented or described. It is important because the shelf feeding waters would provide the major source of food for adult herring (age 3 and older). Such feeding migrations would lessen the potential for density-dependent interactions between adults and juveniles within Prince William Sound. This report recommends clarification of this issue.

Another factor affecting density-dependence is the potential for competition from other species. In Prince William Sound there are several large populations of other major species. The role of inter-specific competition for food with herring is not clear. To assist with any decision about the efficacy of herring enhancement, it would be useful to clarify the potential for competition for food between herring and other species. It would be especially useful to understand spatial and temporal variation of such potential interactions. If enhancement activity were undertaken, decisions must be made about the time and location of releases. Such decisions would benefit from knowledge of the location-specific risks for food competition and possible predation.

A review of factors leading to the low biomass of herring in Prince William Sound, or related issues such as biomass surveys or assessments, are not included in this report. Instead, after a brief review of the present state of herring in Prince William Sound, the report reviews relevant literature and information (unpublished reports and some personal communication) that are mainly from Norway, Canada, United States and Japan. Relevant Norwegian work is concerned mainly with the history of mass larviculture and implementation of experimental and mass production mesocosms for larval rearing. Canadian and American work is related to early life history and larval rearing, reproductive and spawning biology and ecology and impoundment of spawning herring. Japanese work on herring enhancement has been conducted for over 20 years but, until recently, little has appeared in the mainstream literature. Some of the most relevant information in this report has been provided through personal communication with Japanese researchers. The report makes a number of recommendations. Mainly the recommendations are suggestions about the merits and limitations of certain technical approaches, such as how to move eggs, incubation, feeding, marking, etc.

There are some sections of the following report which are, admittedly, tedious and banal. Some readers may balk at wading through text that seems to be long on speculation and short on conclusions. This may be especially so for non-biological readers. For this reason I have added a distinct section called 'Prologue'. The prologue consists of questions and answers. The questions raise points that I think many readers may ask. The answers try to avoid technical terms and jargon but retain accuracy. Still, it is clear from some helpful preliminary reviews that some answers provided here may generate debate and discussion. If so, that could be a useful outcome.

The header of this report states '***Final Report – September 2007***'. This version made a number of small editorial and formatting corrections to the previous version dated June, 2007. Helpful comments by reviewers and others were incorporated into earlier versions but the author takes full responsibility for any errors or omissions. This final version has corrected a number of typographical and syntax errors. A few points have been clarified but no substantial deletions were made to the text of earlier versions.

2 Prologue: to enhance or not to enhance - questions and answers

Herring enhancement, through the culture of eggs, larvae and juveniles may seem straightforward, but the concept has profound and complex biological implications. There are technical challenges related to mass production of marine fish but, based on Japanese experience, probably these can be mastered. Such massive production, however, does not necessarily imply successful enhancement. Attempts at enhancement of marine fish started over 100 years ago, but all early attempts were unsuccessful. These early attempts did not recognize that the concept of enhancement makes certain implicit assumptions about ecosystems and factors that limit marine fish abundance – specifically the relationship between the abundance of adult fish (the 'stock') and the numbers of younger fish (the 'recruits') that join their ranks each year – usually known as a 'density-dependent' relationship called 'stock-recruitment'. Some interested readers may not be familiar with these concepts, yet still be interested in the feasibility and problems related to the enhancement of herring. For such readers the following questions and answers may provide some better understanding of the issues. These questions and answers may also reveal something about the present state of knowledge, limitations of knowledge, and technical capacity to do enhancement.

QUESTION: Is it possible to raise large numbers of herring larvae and juveniles in captivity and release them into Prince William Sound?
ANSWER: Yes, it is relatively simple.

QUESTION: How long would you have to raise them before they are released?
ANSWER: Probably a minimum of 6 months, and perhaps longer.

QUESTION: Will the released fish survive and join the spawning population in Prince William Sound?
ANSWER: Yes, it is almost certain that ***some*** cultured herring will join the wild spawning population. This has been done successfully in Japan.

QUESTION: Will these released fish help to increase the herring population in Prince William Sound?
ANSWER: It is not clear whether cultured herring will add to the existing population or merely displace wild herring that are competing for limited resources.

QUESTION: Are there ways that enhancement can be evaluated?
ANSWER: Yes. The released fish can be marked. Survival of released fish can be compared to the survival of wild (natural) fish – but this requires a lot of work. A potential concern with marking programs, however, is that there usually must be some form of fishery to capture the marked individuals.

QUESTION: What are the most important things to learn before enhancement is considered?
ANSWER: One is the time or age when 'density-dependent' factors limit survival. Another is clarification of the herring stock structure in Prince William Sound – how many populations exist there? Yet another is the geographical range of Prince William

Sound herring in the summer. Specifically, do some or most adult herring migrate out of the Sound to feed on shelf waters?

QUESTION: What is 'density-dependence'?
ANSWER: The growth of every animal population is limited by something. When population growth is restricted by the population size or density, this is called 'density-dependence'. Fishery ecologists still argue about the nuances of the definition.

QUESTION: When does density-dependence occur in Prince William Sound?
ANSWER: Nobody knows for certain. In Prince William Sound there is evidence that it happens during the first year of life – mainly in the winter.

QUESTION: How does density-dependence limit herring survival?
ANSWER: In many areas within Prince William Sound there is not enough food for herring to survive over the first winter of life.

QUESTION: Why would enhancement be required now and not earlier, say 20 years ago?
ANSWER: That is not clear. Recent research indicates that food may limit the survival of age 0+ herring. Presumably this was a not a severe limiting factor 20 years ago.

QUESTION: Can there be limiting factors that occur at other times, say for the egg stage?
ANSWER: Usually even the most severely depressed herring stocks produce sufficient eggs and larvae to allow recovery. For example, during the 1960's and 1970's the spawning biomass of the Norwegian spring spawning herring declined to about one percent of its biomass, but the population recovered rapidly when fishing stopped. The decline in Prince William Sound is not yet that severe.

QUESTION: Can there be limiting factors that occur at adult stage?
ANSWER: Yes, and perhaps these are important at the present time. However, the critical adult habitats are usually on shelf waters, where many herring populations feed. If there were some general decline in ocean feeding conditions, or a decline related to increased predation on the adults, we might expect to see similar impacts on all Gulf of Alaskan stocks, but stocks adjacent to Prince William Sound appear to be doing well.

QUESTION: Are there any key biological issues that need to be examined?
ANSWER: It would be useful to know if adults feed on shelf waters. There appears to be uncertainty about the distribution of adult herring relative to the shelf waters adjacent to Prince William Sound. It would be unusual if Prince William Sound herring did not migrate to these shelf waters to feed – but if they really do not utilize this habitat for summer feeding, then their distribution may be confined mainly to the waters within Prince William Sound. If so, adults, pre-recruits and juveniles may be competing for the same zooplankton food (especially copepods) within Prince William Sound.

QUESTION: What is the implication of the time of 'density-dependence' for enhancement?
ANSWER: Releases of cultured herring prior to the period of density-dependence will not help to increase the total abundance of herring.

QUESTION: Would enhancement be expensive?
ANSWER: Yes, but enhancement should not be considered only as a short-term activity.

QUESTION: Is enhancement a remedy for recovery of the Prince William Sound herring population?
ANSWER: It may be, but it may still be too early to consider as an option.

QUESTION: When should enhancement be considered?
ANSWER: Only as a last resort, when all other conventional approaches have failed and after a review of the rationale for enhancement indicates that it is warranted and feasible. Probably, in Prince William Sound, the 'conventional' approaches, that consist mainly of catch controls and fishing gear controls, already have been fully implemented.

QUESTION: Can enhancement create new problems?
ANSWER: There is a possibility of negative ecological impacts on wild fish (i.e., competition for food, alterations of genetic diversity, and risk of increased disease).

QUESTION: Can the uncertain aspects of enhancement be identified based on existing information?
ANSWER: Probably the main points can be identified – and a key one is the time of density-dependence or life history stage of density-dependence. The second aspect concerns required scale of operations. Probably this is among the largest type of marine fish enhancement project ever contemplated.

QUESTION: Is herring enhancement in Prince William Sound a concept worth consideration?
ANSWER: This depends on the motivation and willingness to undertake an expensive project with no promise of success - but it might work.

QUESTION: What will determine success?
ANSWER: Success will depend on the willingness to follow some well-established principles concerning biological and technical procedures. Many aspects about enhancement are not clear, and the most important is whether it should be attempted at all.

QUESTION: Is more review required?
ANSWER: Some greater clarification about spatial variation within Prince William Sound is advisable, especially about stock structure issues. For instance, if there are spatially discrete populations (that might not be genetically distinct) then it would be essential to know how enhancement efforts would apply to each population (or sub-population).

QUESTION: Do we understand the biology well enough to proceed?

ANSWER: There are many unknowns, and all seem important. It would be comforting to better understand the roles of food, predation, intra- and inter-specific competition for food in the survival of age zero herring, during the first year of life. These are relevant to the density-dependence issue.

QUESTION: Disease is an issue for Prince William Sound herring. How could that affect enhancement activity?

ANSWER: The impact of disease on an enhancement program is not clear. At worst, the confinement of herring in high density situations could exacerbate the problem. At best, it may be possible that cultured herring, after exposure to disease at young life history stages (and probably suffering increased mortality following such exposure), may develop some resistance to disease.

QUESTION: Do we understand enough about enhancement technology?

ANSWER: Yes. Most of the necessary detailed information is available, although not necessarily in the scientific literature. Especially important is the technology for marking cultured fish prior to release. This is essential. This process needs more investigation and probably could follow Japanese experience.

QUESTION: How might an enhancement project begin?

ANSWER: Because of the many uncertainties, if it were to start it probably should begin in relatively small, incremental steps. Such steps could be used to provide feedback about the direction and efficacy of the concept.

QUESTION: What are the next procedural steps?

ANSWER: First, the basic question of whether herring should, or should not be subjected to enhancement efforts should be formally addressed prior to initiation of any major enhancement activity. For instance the present paper does not present a rationale for enhancement. The rationale needs be done elsewhere and should address socioeconomic and conservation biology concerns. Second, pilot scale projects should be initiated to address technical problems, such as the number of eggs required, survival rates of cultured fish, food requirements and successful application of chemical marks to young released fish.

3 Introduction

This report reviews scientific literature on marine fish enhancement in general, and herring enhancement in particular, relative to the possible enhancement of herring in Prince William Sound, Alaska. Preparation of this report has been a struggle to reconcile two opposing perspectives about marine fish enhancement. It is clear from the literature that there are strong differences of opinion about the scientific merits and biological rationale for the concept. Skeptics focus on the problems and pitfalls of enhancement programs and are adamant that conventional approaches to stock recovery, such as those described by Caddy and Agnew (2004), must be tried first. Advocates point to the failures of conventional management and the apparent successes of the rapidly expanding mariculture industry.

The interest in stock enhancement and related forms of activity such as marine fish aquaculture and sea ranching has rapidly expanded in recent years. Some researchers do not endorse enhancement activity and dismiss the concept while others advocate careful, precautionary approaches to this subject. Advocates of Prince William Sound herring enhancement should understand the biological and management problems related to this task and should not underestimate the severity of many of the basic concerns. On the other hand, if herring enhancement must be done, it should benefit from the results of relevant research and experience elsewhere, especially in the work conducted on the west coast of Canada, United States, Japan and Norway during the last 30-40 years. The report attempts to explain the factors which require a cautionary approach and discuss the technical approaches used elsewhere.

3.1 Brief background to Prince William Sound herring

A major oil spill occurred in Prince William Sound in 1989, and this is known as EVOS (Exxon Valdez Oil Spill). This spill was followed by an enormous volume of biological work that examined impacts of the spill (see for example the AFS volume edited by Rice et al. (1996) or the series of papers in the Canadian Journal of Fisheries and Aquatic Sciences, Volume 59 (2002). There also has been considerable debate about the severity and duration of the impact on herring. Post-spill estimates of spawning biomass seem to have been contentious, but there is general agreement that there was a major decline of herring in 1993, four years after EVOS. There is general agreement that (1) spawning biomass declined since 1993 and has remained low and (2) recruitment since 1993 has been unusually low (Fig. 1). The causes of the decline and the subsequent low abundance levels have been examined in many studies since 1993 but the explanation for both the decline and lack of herring recovery remains uncertain.

3.2 What is enhancement and what is herring enhancement?

There is potential for ambiguity in the term 'enhancement' as it has been used and defined in recent fisheries literature. For example Bell et al. (2006) define 'stock enhancement' as the 'process of releasing cultured animals to increase yields beyond levels supported by natural recruitment'. The generality of this definition is widely accepted but it is possible to distinguish between releases of cultured animals as 'mitigation' or 'restoration' activity versus releases to 'augment' natural production. For instance Radke and Davis (cited in Table 1 by Molony et al. 2003) use the term 'enhance' as the 'production and release of fish to increase stocks <u>above</u> original levels'. In this context, the implication is that the results of enhancement will provide an increase in numbers or biomass to levels exceeding natural carrying capacity. Hay and McCarter (2006) use the term 'enhancement' in a very different way: in a spatial or geographical context as the 're-establishment' of herring to discontinued spawning areas or 'introduction to new areas'. They state "there are also many potential spawning locations which have never been documented as spawning areas but still appear to have all the appropriate vegetative substrates and local oceanographic conditions that are found in heavily utilized areas". Based on spawn data analyses and herring spawn transplant experiments, Hay and Marliave (1988) state that herring "enhancement" or "re-establishment" does not appear to be possible at the present time. Further, they suggest that if herring spawning habitat is lost, we cannot necessarily expect the impacted stocks to spawn in other locations nor can we realistically expect that new spawning habitat can be created by habitat manipulation. Therefore when used in the context of spatial analyses of herring spawning, the term 'enhancement' has a different meaning than that proposed by either Bell et al (2006) or Molony (2003).

In the present report the term 'enhancement' is used to mean 'the release of cultured herring to supplement natural recruitment so as to assist recovery or restoration of the population to historical levels'. In this sense, the use of the term enhancement refers explicitly to the biomass (or numbers) of the herring spawning stock biomass (SSB) and there are no implicit assumptions about the geographic distribution of spawning areas as noted by Hay and McCarter (2006).

This definition of enhancement is not complex, although some could argue that the present biomass levels are within the range of normal variation, and if so, such attempted enhancement would be a form of 'augmentation'. On the other hand, if present levels of spawning biomass are too low to allow for normal recruitment, and especially if the present low levels are associated with anthropogenic activity, then enhancement of recruitment would clearly be a 'mitigation' process. For the purposes of this report, no further reference to this distinction will be made, except for brief mention in the concluding sections. Readers with an appetite for more definitions, however, should consult Molony et al. (2003, Table 1) that have listed definitions from published literature.

3.3 The biological issues: if enhancement is a solution, what is the problem?

The suggestion of enhancement of Prince William Sound herring could be seen as a specific solution to an undefined problem. There is no dispute that present abundance of Prince William Sound herring is low (Fig. 1). The 'problem' is the uncertainty for the cause(s) of the herring decline: there is not unanimity about the reason(s) for the decline and failure to recover (see, for example the review by Carls et al. (2002) or Pearson et al. (1999). More recent but brief commentary by local experts such as Moffitt (2005), confirm the uncertainty of the explanations for the decline, but point out that there are several interacting factors including environmental factors and disease. This uncertainty has a direct bearing on the rationale for any potential enhancement. In the views of many skeptics, this uncertainty may be sufficient reason to preclude further consideration of this approach. Such skepticism is well founded. Overly-eager proponents of marine enhancement projects should be aware of the spectacular failures in earlier approaches. The most noteable is the multinational, century-long project attempting to enhance Atlantic cod (*Gadus morhua*) (Solemdal et al. 1984) and this is described below. These earlier flawed efforts have led some to question the validity of such approaches (i.e., Grimes 1998) or categorically reject them (MacCall 1989).

This paper does not attempt to identify the biological problem related to the causes(s) of the herring decline but it does try to focus on aspects of biology that proponents of enhancement should be aware of – specifically the issue of the life-history stage in which density-dependent mechanisms limit survival. The ecological factors that limit herring abundance can be elusive (Lasker 1985). Walters and Martell (2004) and Blaxter (2000) point out that, relative to enhancement programs, if the carrying capacity is limiting at a stage or age that occurs <u>after</u> the time of release, then probably enhancement efforts will be worthless because they will not produce 'additional fish'. At best they will result in the replacement of 'naturally produced' fish with 'cultured' fish. This is a vital issue. Therefore a close examination of the different life history stages of herring follows in the next section.

4 Relevant herring biology

4.1 Life history stages and density-dependence

Herring have several different life history stages that differ in duration, size and temporal location (Hay and McCarter 1997). There are over-lapping generations so there is potential for both 'intra-cohort' and 'inter-cohort' interactions – mainly predation and competition – as well as interactions of all herring life history stages with other species. These life stages are depicted in Table 1 that shows the 'within-cohort' interactions as a cohort develops from egg to adult. There are four stages shown in six rows: (1) the egg stage; (2) the larval stage; (3) age 0+ and age 1+ juvenile stages; (4) the pre-recruit and adult stages.

4.2 The egg stage (Row 1, Table 1)

During the egg stage there may be intra-cohort density-dependent 'competition' for oxygen. Maximal survival from fertilization to hatching occurs at moderate egg densities (Galkina 1971, Hourston et al. 1984, Stevenson 1962). On the other hand, the *rate* of egg mortality by scavenging predators may be higher in very low densities (i.e., << 100,000 eggs/m2), such as those that occur in parts of Puget Sound (Palsson 1984) and elsewhere. Therefore in most spawning areas, there will be a scavenging community of benthic grazers that may eliminate some but not all eggs. The optimal egg density is probably a trade-off between the highest density that will minimize the loss to scavenging predators and the minimal density that will provide optimal gas exchange.

4.3 The larval stage (Row 2, Table 1)

The next life history stage is the yolk-sac larval stage that, after about 5-10 days (duration is temperature-dependent) becomes a feeding yolk-sac larva. For most fish species this is a period of extraordinarily high mortality (by predation) and rapid growth among the survivors (Houde 1989). Sometimes there is potential for 'within-cohort' predation, by the largest individuals eating the smallest, as documented in Norwegian enclosures (Wespestad and Moksness 1989) but the frequency of this in natural settings is uncertain. There also may be a risk of predation by juveniles of the older generation, and, in some circumstances, adults – but mainly cannibalism would be limited because (1) larval distribution soon becomes dilute and (2) each life history stage tends to have different spatial niches – older juveniles are deeper and slightly farther offshore.

An unresolved issue is the role of competition for food among larvae – or whether larval food availability limits population growth. In a seminal paper Cushing (1983) advised that, in most larval fish populations, the larvae were 'too dilute' to graze down their food supply. On the other hand, food limitation – or ability to feed - is generally thought to be a key factor regulating larval survival in some clupeid species such as anchovy. For instance, the role of turbulence and wind in regulating access of larvae to patches of food has been embraced as a key hypothesis known as 'Lasker's Windows' (named after the prominent scientist Reuben Lasker). The topic of food availability for herring could fill volumes but there appears to be a consensus that starvation in Pacific herring larvae is not common. For instance, Robinson and Ware (1988) found no evidence of this. Rather, predation appears to be a factor controlling Pacific herring larval survival. Predation by jellyfish (Aurelia) can reduce larval populations by up to 10 % a day (Purcell 1989, 1990; Purcell et al. 2000, Arai and Hay 1983). Jellyfish are only one of many species that prey on larval herring.

The biological literature is awash with papers on larval fish feeding and survival in laboratory settings. Many of these papers are on herring but very few are useful for understanding the issue of Prince William Sound herring enhancement. The exceptions are the papers that comment on feeding rates and methods of mass culture (sometimes called 'larviculture'). The most useful practical literature is mainly from Norway and concerns the rearing of herring in 'mesocosms' or very large containers that allow for mass rearing in plastic cages or bags, as well as concrete and semi-natural outdoor enclosures.

4.4 The juvenile stages (Rows 3-4, Table 1)

This stage develops after 2-3 months of life when herring larvae 'metamorphose' from anguilliform (or 'eel-like') larvae into creatures that resemble small versions of adult herring. There are two stages. The age 0+ (sometimes called age 'zeros') begin at weights that are only a small fraction of a gram and finish their first summer, at an age of about 6-7 months, usually with a size of about 80-100 mm and weight of about 5-10 grams. The age 1+ juveniles are considerably larger and usually there are distinct, non-overlapping size modes of each age group (Stokesbury et al. 1999a). There also may be variation in the weight of juveniles that varies 'within locations and among years' and 'within years and among locations'.

The age 1+ juvenile stage seems to reside in different depths and location than age 0+ herring. Routine juvenile surveys in the Strait of Georgia (Haegele 1997) shows that most – but not all - have moved out of the area by mid-summer. In British Columbia (BC), they move to offshore shelf areas where they have access to rich feeding opportunities in upwelling areas. Probably the migration patterns of herring in Prince William Sound are similar.

The age 0+ juvenile stage warrants careful examination relative to enhancement of Prince William Sound herring. Studies of juvenile herring in the Strait if Georgia (Haegele 1997), like those of Norcross et al. (2001) and Stokesbury et al. (1999 a, b) show that there is spatial variation in the growth of age 0+ (or age 'zero') juveniles in Prince William Sound. This is attributed to spatial differences in food availability. Further, Prince William Sound studies that have examined the energy content of this stage have concluded that food is limited (Paul and Paul 1998, 1999, Paul et al. 1998). It is interesting that Swedish work makes a similar conclusion about juveniles in the Baltic – specifically that sometimes food is limiting at the age 0+ stage (Arrhenius and Hansson, 1999).

Other studies also implicate the age 0+ stage as potentially interesting because juvenile surveys show that indices of the abundance of age 0+ juveniles are significantly correlated to the size of the recruiting cohorts. This has been described in the Baltic (Axenrot and Hansson 2003) and by Hay et al. (2002) for the Strait of Georgia. As discussed later, if estimates of the abundance of the age 0+ stage provide adequate information for the prediction of the recruiting cohort, then it appears that this would be a stage representing the minimum size for release from enhancement. In the case of the Strait of Georgia (Hay et al. 2002) the positive and significant correlation is between the juvenile abundance and the estimated number of individuals about 2.5 years later when they recruit at age 3 (36 months and estimated by age-structured analyses). This was a log:log comparison and the correlation, while significant, was not striking. Rather, it seems that the best prediction came from years when the juvenile abundance was very low – in such years the corresponding abundance of recruiting cohorts also was low. ***The implication is that the size (and age) of juveniles by the time of mid-summer of their first year of life, may be a minimum target for the required period of enhancement.***

4.5 The pre-recruit and adult stages (Row 5-6, Table 1)

Recruitment to the adult (spawning) stock occurs at about age 3 (36 months) although this may be a year earlier for a few individuals (especially males) and later, at age 4 or 5 for others, especially females. The present literature on Prince William Sound herring does not describe seasonal migrations in and out of the Sound to coastal shelf waters. In most areas of the Pacific coast, including San Francisco Bay (Spratt 1976) and other locations, herring move to shelf waters to feed in the summer and fall. Many return to inside waters, (such as the Strait of Georgia) to over-winter. Similar migrations occur in northern BC waters. Also, it seems that in the Bering Sea, adult herring stocks move away to deeper shelf waters in the south-west, and away from the shallower spawning areas in Bristol Bay. *What happens in Prince William Sound?*

Presumably there must be some utilization of the shelf because, based on simple comparisons or available 'habitat', Prince William Sound would not be large enough to support the abundance of herring that were seen there in the 1970's and 1980's (Woodby et al. 2005). This assertion is based on the simple analysis made by Hay and McCarter (1997) that adult herring 'habitat' may be simply defined as the available space between 0-200 m. For example, the Strait of Georgia has only about 30 % of its area that would be suitable for continuous adult feeding habitat (Table 1 in Hay and McCarter 1997). Based on a maximum high density of about $10 g/m^2$ (or 10 mt/km^2) the Strait of Georgia should be able to maintain an adult herring population of about 30,000 mt (metric tons). This estimate is much lower than recent biomass estimates which frequently exceed 100,000 mt (Schweigert 2004). The simplest explanation for the difference is that most herring migrate from the Straight of Georgia to shelf waters off the west coast of Vancouver Island to feed during the summer.

The distributions of depth strata of the Strait of Georgia and Prince William Sound are quite similar. Therefore it seems reasonable to assume that the biomass of herring in Prince William Sound might be approximately similar to that of the Strait of Georgia, and generally this is what the stock assessments of the 1980's and 1990's indicate (Woodby et al. 2005). Therefore it also seems reasonable to assume that Prince William Sound herring also move to shelf waters to feed in the summer.

5 Herring habitat and density-dependence

Herring habitat is determined by the composite of abiotic and biotic factors affecting herring. Often, however, the term habitat is used in the context of a single factor, such as food or temperature. In this report the term habitat is sometimes used in the context of food or space. To be suitable habitat for herring there must be a suite of suitable conditions including water temperature, oxygen concentration, depth range and so on.

5.1 Habitat areas and density-dependence – is any stage-specific habitat limiting?

A common position among most commentators on marine fish enhancement is that it is not a worthy activity if density-dependence mechanisms are prominent after the time of fish release (i.e., Blaxter 2000, Walters and Martel 2004). In general, it seems that most commentators believe that this is the situation for species such as herring that inhabit large ocean areas. This common reservation is simple and sensible: if there is a point in the life history where the carrying capacity of the environment or habitat restricts survival, then efforts to expand a population beyond the carrying capacity are pointless at best – and harmful and wasteful at worst (MacCall 1989).

Some scientific reviews on marine fish enhancement (i.e., Blaxter 2000) preclude consideration of species like herring - probably because it seems unreasonable to consider manipulating populations like the Norwegian spring spawning herring or the Bering Sea herring that inhabit such vast ocean areas. In these populations the relative numbers of recruiting fish in many years is phenomenally large compared to the real (or imagined) capacity of culture operations that would be required to produce them. Herring populations in the eastern Pacific, however, are different than those of the Atlantic or western Pacific because the maximal population sizes are relatively small (< 100,000 t) and they have a tight ecological connection to nearshore habitats. For Pacific herring it is usual to think of stock:recruit relationships as population-specific interactions between the mature, adult stock and the new recruits joining them each year (Williams and Quinn 2000a, 2000b).

Hay and McCarter (1997a) describe the apparent relationship between available habitats for different life history stages of Pacific herring. They point out that in most populations a limiting factor to maximal population size (SSB) is shelf area. Although their analysis is simple, they point out that the available shelf area (defined as the surface area between 0 and 200m) for Prince William Sound is about 17,000 km^2 (Table 1, p 562, Hay and McCarter 1997). Surveys of larval distributions show large inter-annual variation in the Strait of Georgia. Larval distributions may change substantially among years, with some years having most concentrations on the east side or north (Hay and McCarter 1997b). The key point is that the larval distribution was substantially greater that the spawn distribution, and extended to many areas where spawning did not occur. ***A relevant conclusion from these studies is that spawning habitat or larval rearing habitat was NOT a limiting factor in the Strait of Georgia.*** This also might apply to Prince William Sound.

5.2 Lessons from the Strait of Georgia

Juvenile surveys (Haegele 1997) showed that juveniles were more abundant around the perimeter of the Strait of Georgia and there were substantial size differences among juveniles from different areas, similar to results described for Prince William Sound. The conclusion is that Prince William Sound, like the Strait of Georgia, has adequate spatial habitat to support the nearshore-resident juvenile stages of the spawning stock.

The ***within-cohort juvenile*** density-dependence factors may not be the same as the density-dependence factors that operate ***between the adult SSB and the size of the recruiting cohort*** – unless the adult cohort can graze down the available food used by juveniles during their first summer. Therefore, as suggested by Lorenzen and Enberg (2001), much of the density-dependent factors that operate at the adult stage in herring may be on growth – occurring after recruitment. This assertion is consistent with the observation of relatively consistent sizes of juveniles as they recruit (estimated by the size of scales) followed by increased cohort-specific variation in size in older ages (Hay et al. 2001).

5.3 Lessons from Prince William Sound

Foy (2001), Norcross et al. (2001), Norcross and Brown (2001), Foy and Norcross (1999a, 1999b) and Paul and Paul (1998a, 1998b, 1999) provide evidence that (1) herring juveniles may not feed sufficiently during the summer to accumulate sufficient energy to see them through their first winter. *This observation is very relevant to the issue of enhancement in Prince William Sound.* (2) There is spatial variation in the nutritional state of herring juveniles in different parts of their range (within Prince William Sound). Specifically, the energy content of herring juveniles, at the end of their first summer of life, varies geographically within Prince William

Sound. The geographical differences in energy content appear to be relatively consistent over time (Norcross et al. 2001).

The implication from the results of Foy (2001), Norcross et al (2001) and others is that the juvenile carrying capacity may be limiting in some locations of Prince William Sound and that it also may vary over time, within locations. It may be useful, however, to distinguish between the nearshore carrying capacity of juveniles versus the offshore shelf-feeding carrying capacity of the adult stock. In some years, the carrying capacity of the juvenile stage may be restrictive, so that the recruiting cohorts may be small. In a year, or a succession of years, when large numbers of juvenile cohorts are produced, one would expect classical density-dependence between SSB and recruiting year class, similar to that described by Myers (2004) and others. On the other hand, if there were years, or succession of years with bad recruitments, then perhaps other forms of population limitation are operating, such as a limitation of the carrying capacity of some (or most or all) of the juvenile rearing areas – and especially the areas that support large numbers of age 0+ herring in their first year. *An implication of this is that any enhancement activity should stress the age 0+ juvenile period and that enhancement should only be considered when the spawning stock is low relative to historical levels.*

5.4 Depth strata, herring habitat and density

The question of available spatial habitat for herring may be important and it may be instructive to compare the spatial distribution of habitats between Prince William Sound and the Strait of Georgia (Table 2). The rationale for this comparison is that adult herring (those that are recruited to the adult spawning stock and usually are age 3 or older) spend the summer months feeding on waters off the continental shelf. This is the post-recruitment stage of sexually mature (or maturing) individuals otherwise known as the spawning stock biomass (SSB).

The significance of the potential utilization of shelf waters for feeding is simply that Prince William Sound probably comprises only part of the habitat used by adult herring. Summer feeding migration of adults from the Sound would reduce potential competition for limited food resources – because adult herring can feed on the same zooplankton (copepods) that are consumed by juvenile herring. Conversely, if Prince William Sound herring did not migrate from the Sound, then the density of herring (prior to the 1993 crash) would have been extraordinarily high. For instance Hay and McCarter (1997a, Table 1) list the maximum density of Prince William Sound herring as 8.8 g/m^2 (or 8.8 mt/km^2). This estimate is based on a maximum spawning biomass (plus catch of 150,000 mt in 1991) and a presumption of a spatial habitat of about 17,000 km^2 which includes the adjacent shelf waters. Although the maximum estimate of 150,000 mt (from Funk and Harris, 1992, cited in Hay and McCarter 1997a) may now seem unreasonably high, it is reasonable to assume that Prince William Sound may sometimes have had a spawning biomass of at least 100,000 mt. If so, and if the available spawning habitat were about 9000 km^2 (from Table 2), then the maximum density of Prince William Sound herring would be over 11 g/m^2 (11 mt/km^2) making it the most dense of any herring population in the world. However adjacent herring populations in Southeastern Alaska and BC also have a high density at about 10 g/m^2. The point is, however, that in the absence of contrary information, it is probable that Prince William Sound herring also use the adjacent shelf waters for feeding. Such shelf feeding would reduce the potential for intra-specific and inter-cohort competition for food, as shown in Table 1. In particular, the seasonal departure of some or most of the adult component of the stock would reduce competition between adults and age 0+ juveniles in the late summer and fall (when they are large enough to take the same copepod prey as the older age 1+ juveniles and adults) and age 1+ juveniles. If the adult component of the Prince William Sound herring stock followed the migratory patterns seen in BC herring, then they probably would leave the Sound immediately after spawning and not return until the fall, around October or November.

5.5 Habitat limits on herring abundance

Hay and McCarter (1997a) also suggest that the distribution of herring populations is determined by the availability of the habitat for key life history stages: the egg stage (spawning habitat), larval stage (retention areas), juvenile habitat (nearshore, shallow protected habitats), adult feeding habitat (usually shelf waters with high zooplankton density related to oceanographic factors, especially upwelling) and over-wintering habitat (usually nearshore quiet areas). For example, along the Pacific coast of North America herring spawn only in relatively sheltered areas – and almost never in open waters. This is a major difference between Pacific and Atlantic herring that spawn in shallow open shelf waters. If spawning in such protected areas is a requirement for Pacific herring, this would explain the distribution of herring populations between California and Northern Washington State that are usually associated with small coastal indentations, usually river mouths and estuaries. San Francisco Bay is an example of a large estuary – and in most years has maintained a substantial herring population (> 20,000 mt).

5.6 Continental shelf as the ultimate limiting factor

An important ecological limit to herring abundance on the coasts of BC, SE Alaska and the Gulf of Alaska may be the geographical area of the shelf waters where adult herring feed – and not necessarily the spawning habitat or the geographic area (km^2) of juvenile habitat. In BC, there appears to be ample herring spawning habitat: herring have, at one time or another, utilized almost 25% of the BC coast for spawning (Hay and McCarter 2006). Similarly, there may be more larval herring habitat than is required, although this is harder to define. Replicate field surveys showed herring larvae were broadly distributed relative to their spawning areas, although they appeared to stay in the vicinity of the shore (Hay and McCarter 1997b). Perhaps even more important is that larger larvae seemed to move inshore, close to shallow waters. The evidence for this is based on the unexpectedly high incidence of large larvae captured with small nets fished in shallow nearshore areas that are ordinarily not sampled with the larger, open water plankton nets used in systematic surveys (Hay and McCarter 1997b). Similar observations have been made about the distribution of large herring larvae in the Baltic and in the southern North Sea. This implication is that in some areas, such as the eastern Pacific, the absence of large herring larvae in field samples may not represent only larval avoidance of sampling gear by larger, faster larvae, but rather the movement of these larvae towards shallow, macrophyte-rich areas where herring begin the juvenile phase of their life. Therefore the relative abundance of nearshore shallow areas may provide critical habitat for herring larvae as they metamorphose into herring juveniles.

5.7 Questions about shelf waters and Prince William Sound herring

The role of the continental shelf as a possible feeding area for Prince William Sound herring is not clear. There is very little reference in the literature to the occurrence of herring on the adjacent shelf waters. To some this may seem like an arcane point but it may be important. In most areas of the North Pacific, the adult component of large herring populations move to shelf waters to feed in the summer. Presumably this also occurs in the water adjacent to Prince William Sound. Access to the adjacent shelf waters probably would expand feeding opportunities by a factor several times greater compared to the potential to feed only within the Sound. For instance, the total area of the "Prince William" district (Fig. 2) is 7885 km^2 for depths from 1-100m , and 8990 km^2 for depths from 101-200 m (Table IV-1 in Ronholt et al. 1978). In contrast, Table 2 (this report) shows that the total area within the Sound is 9059 km^2 with about 3400 km^2 for depths of 0-100 m and about 5300 km^2 for depths from 101-200 m. Therefore, if habitat is simply defined as the preferred depth range of herring, access to the shelf waters adjacent to Prince William Sound would nearly double the available habitat for adult herring, - and it would triple the available habitat between 1-100m. It seems very likely that herring do use this habitat and this author (Hay) has observed adult herring captured as incidental bycatch during research surveys conducted in the Gulf of Alaska in the early 1960's. The research survey conducted at that time, a survey of demersal resources in the Gulf of Alaska and Bering Sea, has been described by Rohholt et al. (1978). They do not report explicitly on the numbers or locations of herring catches but they do note (in their Table V-3) that herring were captured in all six surveys conducted throughout the area. Rounsefell (1930) describes locations of herring catches in the 1920's in the extreme south-west of Prince William Sound, (Manning Bay, Macleod Harbor, and Elrington and Prince of Wales Passages and Puget Bay). These seem to have been areas supporting summer fisheries. Some locations (i.e., Puget Bay) were well outside of Prince William Sound. These observations suggest that some herring do move from the Sound into adjacent coastal waters.

6 Review of enhancement – related work

A considerable amount of research has been conducted relative to laboratory culture and rearing of larval marine fish, including herring. Usually the work on herring was directed at some purpose other than enhancement. Regardless, some of the results are applicable to this review. Much, but not all of the work was conducted in Norway, Japan, Canada, the United States of America and the United Kingdom.

6.1 Global activity – general considerations

The global activity related to marine finfish enhancement and sea ranching has increased rapidly in the last ten years. Born et al (2004) provide an impressive list of the numbers of countries undertaking enhancement projects and they also show lists of species and other information related to the duration of projects, numbers of individual fish released, etc. They also make a plea for better reporting so that the efficacy of 'stock enhancement' can be better evaluated. They provide a review of some of the biological and methodological requirements related to this rapidly developing field – specifically the need for standardized nomenclature and reporting. Further they briefly discuss the issue of whether enhancement is an appropriate approach relative to more conventional approaches (input and output controls) to fisheries management. In the case of Prince William Sound, where nearly all herring fishing has been suspended, some of these issues are not applicable. Born et al (2004) point out that the FAO Code of Conduct for Responsible Fisheries, to which the United States is a signatory, provides technical guidelines (through Article 9, FAO, 1995) that apply to the development of aquaculture and culture-based fisheries. Probably this FAO report would not be an obstacle to future enhancement efforts in Prince William Sound but proponents should be aware that there are general internationally-accepted protocols for such activity. General protocols that provide basic guidelines to all enhancement projects are provided by Bartley and Leber (2004), but these do not comment specifically on herring.

At the conclusion of this report there is a checklist, adapted from Walters and Martell (2004). This checklist covers all of the aspects of enhancement considered in the FAO reports, and more,

6.2 Review of applied technology and applications

Many countries, or research agencies within various countries, have embarked on marine fish enhancement programs. Norway has been involved with fish culture and related work for over a century. The Norwegian work with the culture of marine larvae (larviculture) provides some useful information relative to Prince William Sound herring enhancement. The long Norwegian experience with larval rearing of Atlantic cod, and the participation of other countries in the same exercise, may represent one of the most revealing failures in fisheries science. It would be regrettable if herring enhancement proponents were to naively advocate and resurrect such a failed approach – so in the text below, there is a section that briefly explains the Norwegian failure (and the same failure as repeated in Canadian, American and British agencies).

Summarizing research activities that have relevance to herring enhancement could be done according to country (mainly but not exclusively Norway, Canada, United States and Japan). Alternately it might be done according to life history stage, beginning with egg stages followed by larval stages, juvenile stage and so on. This life-history-stage is the approach taken in the following pages except for the Japanese work which is unique and difficult to dissect into stages. Also, most of the Japanese work is not accessible through the conventional scientific literature. Only the Japanese agencies have attempted to raise large quantities of juvenile herring for mass release, as an attempt to enhance local herring stocks. These attempts, while scientifically interesting, still are not a demonstrable success – or failure. Nevertheless, the results to date are very useful for the purposes of understanding issues related to enhancement in Prince William Sound.

6.3 Sources of eggs

Compared to many other marine fish species, access to fertile, viable herring eggs is simple. For nearly every conceivable type of enhancement activity that might develop in Prince William Sound, all would involve securing eggs (from a 'donor site') and moving them to a new location (a 'recipient' site) for incubation. There are four general ways this can done. Each is listed below with some comments.

6.3.1 Method 1. Stripping and artificial fertilization

Eggs can be extracted from live, ripe females and artificially fertilized. All parental stock is killed in this process so this method is suitable only for small scale experimental work. The major disadvantage is that it is difficult to be certain of the spawning readiness of females. If they are slightly immature, they may still have eggs that can fertilize, but the overall fertilization rate may be relatively low. Also, there is some indication that during the preparation of sperm solutions, the presence of blood from the surgical removal of testes could contaminate eggs with blood thereby limiting viability of the egg (D. Alderdice, pers. comm.).

If artificial fertilization methods are used it is important to avoid exposing eggs to seawater prior to fertilization. Maximal fertilization rates can be achieved by introducing eggs into a previously prepared sperm solution. Herring have extremely adhesive eggs so one method of mass culture is to extrude eggs from the female onto an artificial substrate such as a plastic screen or Nitex ™ (a fabric used for plankton nets). This was a successful artificial substrate used in experimental work (Hay 1986). Before eggs were placed onto this screen material, the screens were soaked in fresh sperm-containing seawater. Fertilization occurred instantly as the eggs were extruded from the female.

6.3.2 Method 2. Naturally spawned eggs

Moving eggs from natural spawns will provide an excellent source of eggs for experiments, and possible pilot-scale enhancement experiments. The main problem with this approach is that some naturally spawned eggs will be lost to the environment. Also, there may be habitat damage as eggs are removed. Such removals, if small, are not a conservation concern although there could be some negative impacts on spawning areas.

There is a risk of a serious impact on natural spawning areas if naturally spawned eggs were the main source of eggs used for enhancement. First, there would be direct loss of eggs (even a small enhancement project would involve billions of eggs). Second, there would be damage to the spawning habitat – and remaining eggs. Probably there would be considerable direct mortality to eggs that would be squashed, or dislodged or uprooted during this phase.

6.3.3 Method 3. Impounded herring

Eggs could be used from operations like 'spawn-on-kelp' fisheries in which impounded or semi-impounded captive, spawning fish, are forced to spawn on suspended or removable substrate. Perhaps material such as web netting from purse seine webbing, or vegetation natural substrate – such as *Laminaria* used for 'spawn-on-kelp' operations could be used for the purposes of acquiring eggs for enhancement. In these situations, captive herring spawn on natural or artificial substrate that is prepared and suspended in ponds or cages.

Probably this approach may be the most reliable and the least controversial for potential enhancement projects. There is a roe-on-kelp fishery in Prince William Sound and the technical expertise at establishing impoundments exists in the area. There is a substantial 'grey' literature on experimental impoundments in BC during the 1980's when these were under consideration as possible alternatives to the roe fishery. Two of the most useful reports are by Kreiberg et al. (1986) that present designs and methodology for 'towable netpens' and Kreiberg and Solmie (1987) that provide a basic biological guideline for impounding herring.

It is unclear if disease may be a factor to consider when planning a potential enhancement project. If so, it seems probabe that disease issues might arise more frequently from impounded herring. This issue of disease is discussed briefly as a separate topic.

6.3.4 Method 4. Wind drift - opportunistic sources

Eggs that are blown ashore, following storms, may form 'wind drift'- or 'windrows' of eggs on beaches. Usually these eggs are alive and can be moved easily. This was the source of eggs used for two years of consecutive egg transfer experimentation in Southern British Columbia (Hay and Marliave 1988). Finding useful quantities of such eggs can be a problem. Hay and Marliave used a small aircraft to scout spotter planes and a network of local informants, mainly Fisheries and Oceans Canada Fishery Officers. Usually this source of eggs became available following intense storms - and there always are storms during herring spawning - but the available eggs usually are found only over a few hundred m. Each year in the Strait of Georgia the cumulative spawn may be several hundred km of spawn, and the perimeter of the Strait of Georgia is about 3700 km. Further, these windrows are difficult to see during a high tide. During high tides, herring egg windrows usually consist of a slurry of loose eggs and vegetation. When the tide recedes, the loose eggs and vegetation may accumulate into piles along the shore, sometimes reaching depths of 30 cm or more. Surprisingly, if these windrows are found soon after a storm, most of these eggs are alive. The exposure to air is not a problem. In fact, during our first trials at moving windrow eggs, we found that eggs left in air, but kept cool and damp, were much more likely to survive that those immersed in water in buckets and aquaria. In the two years of the egg transfer work we moved about 20 billion eggs each year – approximately equivalent to a spawning stock of about 20 metric tons.

6.3.5 Wet egg weight

This paragraph is more of an aside about a useful but rare statistic on wet egg weight. Remarkably, the estimate of the weight of a herring in nature is difficult to find. There may be only one grey reference by Hay and Miller (1982) who studied wind drift spawn in Georgia Strait. To estimate the quantities, they took sub-samples to determine the wet weight of a single, live, incubating egg. Their estimated weight, for a single egg, was 2.38 mg. This weight is much greater than the weight of an unfertilized egg from a female. At the time of spawning, when eggs are exposed to seawater, they take up water and expand their volume. Therefore egg weights estimated from fecundity analyses (i.e., the ovary weight divided by the fecundity weight) will be much less than the weight of a live, fertilized egg in nature. This estimate of egg weight from a Strait of Georgia herring may be roughly applicable to a Prince William Sound herring, but probably is not adequate for any detailed work in the future. Wet egg weight could vary with salinity and therefore depth, because inter-tidal eggs may be exposed to different salinities than sub-tidal eggs. This simple statistic is essential for potential herring enhancement work. Therefore some additional data are advisable.

6.3.6 Recommendations about egg source(s)

In some ways, windrow eggs as a source for herring enhancement are ideal, because they can be taken without deleterious impacts on spawning habitat. If such a source of eggs is available each year, as it was in the Strait of Georgia, then it would be a good choice for enhancement. The major risks are (1) the sources of eggs are not predictable and the timing is unknown; (2) the location of windrows may be inconvenient for enhancement-related work; (3) collecting and relocating the windrow eggs is labor-intensive and requires vessels, such as barges, that can reach the shore – or areas close to the shore; (4) the loose eggs are more difficult to incubate that those firmly attached to substrate.

Even if wind-drift eggs were not available, then the access to eggs from operations like 'roe-on-kelp' operations may be the best. The collection of eggs would be almost identical to the processes used presently to encourage captive herring to lay their eggs on suspended kelp. There are many options that may be developed, however. One is the use of artificial substrate, such as the webbing from purse seines or trawls. Herring readily spawn on such material. One proposal, developed years ago in BC, was to suspend netting from logs, either in impoundments or on natural spawning areas. Then after the eggs have become well-fastened to the material, and have lost their stickiness, the netting could be gently rolled up on the logs so the logs could be towed to other locations.

6.4 Egg incubation

Probably this is the simplest enhancement activity. Under most conditions, herring eggs are robust. The exception can arise in laboratory settings where the eggs are artificially fertilized by killing and stripping females. Often such eggs may not be at the exact point of readiness, so low fertilization rates may follow. Normally, nearly all herring eggs in nature are fertilized. Rates less than 90 % are suspect.

6.4.1 Egg density

Hourston et al. (1984) report on hatching experiments of Pacific herring captured in southern BC. Although few quantitative data are provided, they noted that hatching rates were high for most of 14 different substrates (mainly naturally occurring macrophytes). They also examined egg deposition intensity and used females from three sources (different collections). The general conclusion was that the main factor affecting hatching success was egg intensity: hatching was lower at high intensity. They also noted however, that the measure of egg intensity varies with the properties of the substrate. They did not provide any advice about the optimal egg density – or egg layers – but they noted that the very high mortality of herring eggs found by Galkina (1971) was probably attributable to the high egg density (~ 20 layers).

6.4.2 Egg incubation duration

At ambient temperatures the duration of egg incubation will be about three weeks. The time can be estimated approximately by the equations of Alderdice and Velsen (1971) that relate temperature to the time required to hatch. Probably eggs should not be relocated until a few days after spawning, to allow them all to harden, and also allow the eggs and substrates to be colonized by the microscopic grazing community. This grazing community will control fungus on dead eggs. In naturally spawned eggs there always are some unfertilized eggs, even among healthy females, because a small proportion of eggs will not fertilize. For instance, fertilization will not occur if the micropyle is blocked. Unfertilized eggs will eventually die and probably become infected with fungus. Once well established, fungus can attach to healthy eggs and kill large numbers. Fungal outbreaks are rare among naturally spawned eggs deposited in suitable locations and normal conditions. The reason for this low infection rate is that the grazing community consumes fungus as it develops, thereby enhancing egg survival to hatching.

6.4.3 Estimates of survival to hatching

Unlike the eggs of many pelagic marine species, herring eggs have relatively high survival rates. Usually the exceptions are noted, and sometimes there may be instances of mass mortality, but in general these are rare. Such instances can occur when unusual conditions occur, such as freezing of eggs in the inter-tidal zone, or exposure to sunlight and desiccation in the inter-tidal zone. Sedimentation also can lower survival. Experimental exposure of incubating eggs to lower oxygen levels, when eggs were suspended below salmon netpens, also resulted in decreased survival.

In general, if incubating eggs from naturally spawned areas are protected from predation, then high survival rates from fertilization to hatching might be expected, probably at least 80% or more. The literature provides a mixed range of egg survival estimates but it is important to note that estimates of egg survival rates vary with location of the various studies. For instance, Norcross and Brown (2001) estimated natural egg survival to be about 25%. Rooper et al. (1999) estimated egg loss to predation and abiotic factors to be about 31% for an estimated survival rate of 69%. Palsson (1984), in Puget Sound, reported relatively high rates, but most of the Puget Sound spawning areas have relatively low densities of eggs, usually not more that a few hundred thousand per m^2. In contrast, Strait of Georgia egg densities are higher, often 500,000 eggs per m^2, or greater (Hay 2006). During the incubation period a loss of 50,000 eggs per square meter to local invertebrate predators (such as small snails, crabs, etc) would result in a 50% morality if original density was 100,000 eggs per m^2 but only 10% if the original density was 500,000 eggs per m^2.

6.5 Herring Larviculture

The term 'larviculture' is not common, but the implication is that it involves the feeding of captive larvae. Large research efforts have been devoted to this task, mainly because it was commonly believed that the feeding of young larvae of marine fishes was the key to understanding factors that controlled year class success. There is far too much literature on this topic to include here.

6.5.1 History in Europe and North America

Meyer (1878) reared herring eggs in the Baltic in an attempt to investigate methods for delaying development and hatch so that the eggs might be shipped to other countries for 'artificial raising'. Meyer successfully shipped live herring eggs to the Kiel laboratory but did not report on survival or growth rates. It is interesting that a translation of Meyers report was presented in an annual Report of The Commissioner, United States Commission of Fish and Fisheries, (Part 4) in 1878. The two main topics of the report were (i) an inquiry into the decrease of food-fishes and (ii) the propagation of food-fishes in the waters of the United States.

In experiments conducted in 1966 and 1967, Talbot and Johnson (1972) reared San Francisco Bay herring from eggs to more than two years of age. They observed that at 4 days after hatching, when their yolk sacs were almost depleted, larvae were too small to ingest newly hatched brine shrimp (*Artemia)* nauplii but the larvae were able to consume brine shrimp after 6 days. In June, when the herring had developed into juveniles, they were successfully fed live brine shrimp, but an attempt to feed some with pellets (Oregon Moist™) was not successful. Pellets sank to the bottom of the aquaria and were ignored by the juveniles. In November, at about ten months of age, the herring were successfully fed on frozen brine shrimp. Talbot and Johnson (1972) noted that metamorphosis, from the anguilliform larval shape to the normal herring shape, was complete at about 80 days of age and a total length of about 33 mm. They also noted that the sizes of the reared herring were slightly smaller than the herring of the same age that grew naturally in San Francisco Bay.

6.5.2 Larviculture – history in Norway

Norway has conducted a considerable amount of scientific research concerned with fish culture, both from a theoretical and applied perspective. Although there are many papers, reports and theses that are concerned with herring in particular, no research has specifically addressed the issue of herring culture for profit (farming) or the mass rearing of herring for stock enhancement. There are several areas of research that are directly applicable to the issue of herring enhancement in Prince William Sound, Alaska. Specifically, Norwegian research has addressed germane issues concerned with reproductive biology of herring, egg incubation and larval culture. Probably the most useful contribution concerns the extensive amount of work conducted using mesocosms, large containers, bags or enclosures suitable for rearing larvae and juveniles.

The earliest interest in larviculture in Norway was concerned with Atlantic cod. Over one hundred years ago Norway initiated a huge program to artificially spawn, incubate and grow Atlantic cod larvae for short periods prior to release. The work was eventually emulated by Scotland, Canada and the United States – and the potential benefits of the approach led other countries, such as Australia, to release larvae of other species. In retrospect, the popularity of the approach and the relatively large and expensive scale of operations seems remarkable because there was no definitive evidence that the cod larviculture was successful. There was, however, a lot of acrimonious debate about the issue, in Norway and elsewhere.

6.5.3 The Flödevigen experience

The chapter by Solemdal et al. (1984) provides a fascinating review of the history of the cod enhancement project and the Flödevigen laboratory which was pivotal in this work. It started in

1882 with private funds. The laboratory was constructed in 1884. For nearly ninety years, until 1971, the hatchery released yolk-sac larvae of cod, up to 400 million per year. After 20 years, private interests lost faith in the project and it was taken over by the government, leading to the establishment of the Flödevigen laboratory which continues to this day. In addition to cod, the laboratory released several other species including lobster. At the onset, the main biological proponent of the work was a prominent zoologist, G.O. Sars, who convinced a sea captain, Gunder Dannevig, to promote the development of this approach. He succeeded, both within Norway and internationally, and the laboratory was constructed and functioned. After a decade or two, however, the viability of the project was not confirmed and detractors began to speak out. These included other prominent Norwegian scientists some of whom subsequently achieved international fame, including Einar Lea, Johan Hjort, and others. These scientists pointed out that there was no convincing evidence of success of this larval rearing approach. In particular, Hjort believed that the key to larval survival was the available level of food for larvae after they resorb their yolk sac – so he did not endorse the release of yolk sac larvae. Instead they advocated a longer rearing period and release of older larger larvae. One early attempt to demonstrate the success of the project (of releasing yolk sac larvae) was to release them in a large enclosure that mimicked the natural environment.

Regardless of the criticism, the larviculture programs at Flödevigen and elsewhere in the world continued for decades and ended in Flödevigen in 1971. It is only within the last 25 years that clear objective analyses presented in peer reviewed literature has shown the futility of the endeavor – as a technique (of releasing *yolk sac* larvae) for enhancing Atlantic cod. There were some positive spin-offs from this work however, especially related to increased knowledge of the early life history of marine fish.

6.5.4 Perspective on herring larviculture in BC and elsewhere

Newly hatched brine shrimp (*Artemia*) eggs, called 'nauplii', are easily raised and are widely used for experimental and commercial rearing of marine fish larvae. The successful use of brine shrimp for herring is relatively recent. At the annual meeting of the early Life History Section of the American Fisheries Society, held in Vancouver, BC in 1984, some European scientists privately expressed exasperation with the claims about larval fish survival made by some of the Norwegian participants – who claimed high rates of larval survival. Some even suspected results were wrong, even fabricated. We know now that high survival is possible – and it is related mainly to the quality of food. Herring larvae from BC and Alaska will feed on *Artemia* nauplii soon after hatching. Herring larval guts are transparent and the tiny bolus of food – usually discrete nauplii - can be seen and counted in the gut in live larvae. Larvae feed in lighted conditions but not in the dark (Alderdice and Velsen, 1971). When food is abundant larvae feed to satiation and their guts appear to be continuously full. In contrast, when the light is dim or during the night their guts are empty. This observation can be made after the lights are suddenly switched on in a darkened laboratory. It is a simple matter to discern whether larval herring are feeding simply by looking at them.

Blaxter (1968), and others experimented with varied diets in attempts to rear herring to juvenile stages. Blaxter reported an increase in survival using *Artemia* supplemented with barnacle nauplii, but larval survival in Blaxter's experiments was low relative to the much higher survival rates achieved in later years by Norwegian and Japanese researchers in the 1970's and subsequent years. For instance, Blaxter (1968) reports that a combination of food types yielded higher survival rates than single-food diets, but this higher rate was only about a 10% survival rate from hatching to metamorphosis, and a 3-4% survival rate from fertilization to metamorphosis.

6.5.5 Experimental larval culture at the Pacific Biological Station, Nanaimo, BC

At the Pacific Biological Station in Nanaimo, BC, we were able to access high quality eggs, either from artificial fertilization or from natural sources. Laboratory incubation for the period before feeding was rarely a problem, even with varying temperature and salinity. Hatching rates and production of viable larvae were high, usually exceeding 95%. (See comments elsewhere on factors affecting fertilization rates and incubation survival). Maintaining active, feeding larvae through to the absorption of their yolk sac was simple. Virtually all larvae started feeding successfully and consumed food until their guts were full. Early growth rates (estimated by analyses of length and dry weight) were rapid. After about five days, larval feeding rates began to decline, and usually by 10-20 days after first feeding, most had stopped feeding. At these early stages death by starvation to the 'point of no return' (or when starvation was irreversible), occurred in all larvae in about 20 days. As the era of experimental physiology and ecology in the 1970's and 1980's was ending at the Pacific Biological Station, we tried a food enrichment product, 'Super Selco™', recommended by Jeff Marliave of the Vancouver Public Aquarium. Newly hatched *Artemia* nauplii were soaked in the 'fish based' product for a few hours prior to presentation to the herring larvae. Survival of the larvae, when fed with this product, was excellent, and virtually all of the larvae fed with the enriched larval food continued to feed and grow.

6.5.6 Larval food culture

Technological aspects of *Artemia* enrichment have been described in various reports (i.e., Lavens and Sorgeloos 1996). Unfortunately, this aspect of larval herring husbandry has been overlooked in literature concerned with larval culture of herring. There is a lot of information and research activity about rotifer culture, as a first food for marine fish larvae. Probably this would be an optional consideration for culture of Prince William Sound herring larvae that, like BC herring, would be able to feed directly on *Artemia*. On the other hand, it is clear that plain (not enriched, see below) *Artemia* are not adequate as the sole food source for herring larvae, so the nutritional benefits of additional food items, such as rotifers, for first-feeding herring larvae might make the additional efforts of mass-rearing of rotifers worthwhile.

6.5.6.1 Enrichment of Artemia

Enrichment of *Artemia* nauplii with a product like Super Selco™ (Artemia Systems N.V., Baarode, Belgium) can result in remarkable improvements in larval survival.

6.5.6.2 Quantities

The correct feeding levels of *Artemia* may be important. After a day or two, the nauplii grow and utilize much of their yolk sac. The result is a prey item that is less nutritious and without the benefit of the exposure to Selco which, to be effective, seems to adhere to the nauplii, but the beneficial impact may be lost with time. Therefore it probably is important to develop larval rearing systems or feeding levels that do not allow for the accumulation of uneaten, less nutritious, older *Artemia* nauplii as larval herring prey.

6.5.6.3 Contamination

It is necessary to avoid contamination of larval herring rearing containers with unhatched *Artemia* eggs. Many larger larvae will feed on these but they merely pass through the fish undigested, in the original form. The unhatched *Artemia* egg capsule is, therefore, an impediment for optimal feeding.

6.5.6.4 Water and flow

Larval herring need cool, well oxygenated water, so completely static systems are not appropriate for mass culture where the larvae or their food have a significant BOD (biological oxygen demand). Some form of flow-through system is required but it is important to eliminate the potential for entrainment within drains. Perhaps this is obvious, but the problem is simplified in large containers that have large openings and closures that permit slow water exchange. Such inlets and outlets can be covered with fine mesh screens (i.e., 350 µm) that allow slow passage of water without risk of larval impingement.

6.5.6.5 Algal growth

Some natural algal growth seems to be beneficial. We noticed that larvae seem to do well in 'green water' tanks but we have no explanation for this. Boehlert and Morgan (1985) noticed that Pacific herring larvae fed more effectively in 'murky water'. Pacific herring larvae seem to be mainly visual feeders so prey may be more visible to larvae in some conditions.

6.6 Field observations of larval feeding

It is difficult to detect or quantify larval feeding from field samples of larvae collected in nets, or from large outdoor enclosures, because herring larvae usually void their gut contents when impinged against a net (Hay 1981). However, larval feeding in nature can be observed directly at certain times. At night, larvae are attracted to lights so careful observation of larvae in field conditions is relatively simple if the physical conditions permit. Such observation is possible on the wharf at the Pacific Biological Station, Nanaimo, BC. When observed early in the evening, while they still retain food in their guts, some larvae can be examined directly. We observed that wild herring larvae take a variety of food. Probably the eggs of copepods and other invertebrates were the most common food but we noticed that sometimes they consumed inedible items such as pollen (especially the round pollen from conifers or maple trees) or small round air bubbles. Sometimes the buoyancy of the bubbles, in the larval guts, seemed to impair the swimming movement of larvae. The potential significance of these observations is that herring larvae appear to take a range of prey items, although they seem to select items that are approximately round and that have high visual contrast. In informal (and unpublished) experiments in the laboratory, we provided herring larvae with fresh barnacle nauplii that are almost transparent. Fresh barnacle nauplii were obtained by smashing the adult barnacles. We also used food dye to color the barnacle nauplii. Herring larvae took more dyed nauplii than the natural, transparent larvae.

Readers should regard the preceding paragraph as more of an informal (and hopefully useful) narrative and not a detailed set of specific recommendations for larval rearing. There are a number of sources for planning large scale larval food production. See, for example, an FAO report that provides detailed information on the mass production of live food (FAO 1996). There also is an earlier report on large-scale larval fish rearing (FAO 1986). This report, while now a bit dated, provides a number of practical, technical methods useful for rearing marine larvae.

7 Norwegian larviculture work and development of mesocosms

Norwegian science in the last one hundred years has contributed substantially to our understanding of herring reproductive biology. In terms of enhancement, the experimental work on mesocosms is the most relevant to the issue of herring enhancement in Prince William Sound. Mesocosms are relatively large cages or semi-natural enclosures of varying size. Usually fish larvae are reared with natural food (zooplankton) that also exists within the mesocosms, although in many experiments larval fish diets are supplemented with other foods, including wild-captured zooplankton, brine shrimp (*Artemia*) nauplii and pellets. Mesocosms are relevant to herring enhancement because some form of enclosure will be required for rearing larvae during the first months of their post-hatching life.

7.1 Semi-natural mesocosms

An enduring legacy of the Flödevigen work was the construction of large seawater ponds – small land-locked basins, several m above sea level. Water levels were controlled by pumping (and discharging) sea water from the pond into the adjacent ocean water. These enclosures or mesocosms, could hold thousands of larvae, including larval herring. An especially useful result from rearing larvae in these enclosures was the demonstration of high rates of survival, from egg to large larva – rates that exceeded fifty percent survival. In the 1960's and 1970's most laboratory researchers working with herring struggled with much lower survival rates. Norwegian experiments conducted in these large mesocosms demonstrated that herring larvae survival could indeed be reasonably high. Only brief details of the size and dimensions of the mesocosms are presented in published literature but Øiestad (1983) presents illustrations and these are copied in Fig. 3. Such semi-natural enclosures may be a useful approach for herring enhancement in Prince William Sound.

Øiestad (1982) provides a descriptive overview of the development of bags, ponds and mesocosms used in Norway. Mainly these were experiments to study herring larvae ecology and not mass rearing. Studies included the trophic habits of larvae and evaluation of the effects of larval predation on micro-zooplankton. Of the nine different studies summarized by Øiestad, most were mesocosms consisting of large plastic bags ranging in size from 4 m^3 - 2500 m^3 that were used for experimental durations of up to 125 days. Maximal experimental duration in the ponds was 180 days.

7.2 Mesocosms and larval fish growth and survival

In a 1982 review paper Øiestad (1982) made two basic conclusions about marine fish larvae reared in mesocosms. One is that they can survive at feeding densities that previously were believed to be too low. The second is the larval numbers were very sensitive to predation in the bags. Subsequently, Moksness and Øiestad (1987) reared herring larvae in basins for up to 4 months with smaller capelin larvae. Of 25,000 eggs introduced at the beginning of the tests, 7000 survived to an age of 30 days and 4400 survived to an age of 100 days. They noted that herring larvae began schooling at 50 days and metamorphosis occurred at 60 days when they were 34 mm long.

Wespestad and Moksness (1990) used the same enclosures to rear Pacific herring *Clupea pallasi*. A total of 4891 larvae survived for 63 days after hatching, for a daily survival rate of about 2.7%. Some mesocosm work was conducted with other species using much greater initial numbers. For instance Øiestad et al. (1985) placed about 2.5 million cod larvae into an enclosure. They estimated that after one month (in April) about 500,000 metamorphosed into larvae and depleted the natural food by mid-May. An interesting point for this review is that the basin could support such a large number of larvae (>>500,000) without additional feeding. They also found that the metamorphosed fish were able to feed on pellets and some wild copepods captured from areas outside the enclosure. Moksness (1990) also used the Flödevigen outdoor enclosure to rear cod larve to juveniles – which were later used to test the survival of artificially reared cod that were tagged and released at about 2 years of age. The conclusion was that the observed recapture rates were too low to consider larger scale rearing and subsequent release of cod as a technique to support the commercial fishery.

Kvenseth and Øiestad (1984) describe experiments raising cod *Gadus morhua* in very large outdoor or enclosed ponds (surface area of 22,000 m^2 and volume of 60,000 m^3) in western Norway. They also used hydrographic monitoring and serial sampling of phytoplankton, zooplankton and fish larvae. Automatic feeding systems were used in the ponds. Approaches such as this are necessary for rearing large numbers of larvae and juveniles, such as herring in Prince William Sound.

7.3 Juvenile rearing and Mesocosms

Houde and Berkeley (1979, 1982) investigated feeding and growth of age 0+ juvenile herring in 1300 m^3 enclosures called CEPEX (Controlled Ecosystem Populations Experiment) enclosures. These enclosures were in Saanich Inlet, in southern BC. These enclosures were 10 m in diameter and 23.5 m deep. One hundred juvenile herring, approximately 3 grams each, were introduced into the enclosures and reared for one month. Food was not added, but there was an abundant zooplankton fauna present in the bag at the beginning of the experiment. Periodic samples were collected to determine growth and feeding capacity. Growth rates in the CEPEX enclosures were slow relative to control fish maintained in smaller (2 m^3) tanks on an adjacent research barge. These 'control' fish that were fed regularly with wild zooplankton collected in plankton nets. The specific growth rate (weight) was low (0.7% per day) in the mesocosm fish but high in the control (barge) fish at 5.35% per day.

The papers by Houde and Berkeley (1979, 1982) provide some potentially useful information about feeding stomach evacuation rates. For example, the relationship between dry weight of food contents and herring (wet) weight was:

$$F = 5.92 + 5.55W$$

where F = dry wt of food (mg) and W = wet weight in (g). They also found that digestion was 95% complete after 15 h (at 16 °C). The ration of wild herring collected in the adjacent waters of Saanich Inlet (southern Strait of Georgia, BC) was about 0.037 g/d for a fish weighing 2.6 g – for a mean of 0.0142 g of food per g of fish (total wet weight) or a consumption of 4.9% of their *dry* body weight per day. These data could be roughly applicable to Prince William Sound herring although temperature differences in juvenile rearing habitat probably have considerable effects on feeding and evacuation rates. Subsequently, more comprehensive data sets on wild and captive juvenile herring feeding and evacuation rates have been estimated from Baltic herring (Arrhenius 1995, 1996; Arrhenius and Hansson 1996a, 1996b).

7.4 Rearing to the juvenile stage – how long, how big – the critical questions

Field studies of juvenile herring feeding in Prince William Sound provide evidence of food deprivation leading to poor survival over the winter. Preceding parts of this report have commented that a fundamental ecological requirement of enhancement is to avoid release of cultured fish before density-dependent processes begin.

Clearly, release of larvae is ineffective for herring enhancement. To be effective, enhancement must continue to the juvenile stage, but for how long? Suppose the enhanced juveniles were fed rapidly so they grew well. Once released would these bigger, fatter, enhanced individuals survive better than smaller, thinner, naturally raised juveniles? Perhaps, especially if they could feed well. The important question, however, is whether such enhanced fish would add to the population, or merely displace the small, naturally produced, herring juveniles? Although there is much uncertainty regarding these questions, it would seem logical that the longer the enhanced herring were raised, the bigger they would become. From the cost perspective, the sooner the juveniles were released, the better. From an ecosystem perspective, the later the release, the better. Somewhere between the end of the first summer/fall (say October) and the middle of the first winter (say February) would appear to be the optimal time of release. A winter release – or a release <u>after</u> most of the rich summer/fall feeding occurs, presumes that very little food would be available to any juvenile herring, enhanced or natural. Therefore it seems likely that this is a period when density-dependent competition for food would not be a key factor. However, it also would be advisable to ensure that any enhanced herring are not so large that they might prey on the naturally raised members of the same cohort. This comment is based on the Japanese experience that has seen astounding growth of well-fed juveniles (see comment about Japanese enhancement in later sections).

Therefore perhaps the key question for herring enhancement in Prince William Sound, if it were to proceed, is the duration of juvenile rearing.

8 Japanese experience with enhancement

Japanese research appears to have made substantial progress rearing marine fish larvae, including herring. For instance Kurata (1959) reports on many aspects of larval feeding ecology. Since then there have been technical developments that have resulted in extraordinarily high rates of larval survival. Japanese work in this field seems to have developed *in situ*, without much scientific communication with work going on elsewhere. Much of the recent work has direct and significant implications for potential herring enhancement work in Prince William Sound. This review of Japanese work was facilitated by direct communication with several key people with experience in this area. One potentially important paper, which is in press, was not available for inclusion here.

8.1 Lake Furen

Probably one of the best and most accessible reports on Japanese enhancement of herring is that of Morita (1985). At the end of a paper describing the demise and present status of the massive Hokkaido-Sakhalin herring stock, there is a three-page summary of Japanese experience with herring enhancement, as it was practiced up to 1985. Morita describes procedures that were used to gather spawning fish from a brackish lake, artificially spawn the eggs, incubate the eggs and raise the eggs and larvae on a combination of food organisms, including rotifers, and *Artemia* as well as small 'pellets' that were the sole food used after 73 days of feeding.

The reference by Morita (1985) to artificial food is interesting and worthy of further investigation. Unfortunately, there is nothing in the accessible literature that describes such food. Personal experience, however, would indicate that any artificial food (such as a pellet) would require a specific gravity similar to the rearing water – so that it stays in suspension. Herring, at any age, do not forage on the bottom, and in general they do not seem to strike at floating items.

8.2 High Lake Furen survival rates

Morita (1985) describes very high survival rates, estimated at nearly 50% after 100 days of rearing. *At this time the juveniles reached a mean length of about 70 mm (with a range of 40-90 mm)*. The juvenile herring were released into Lake Furen, a small brackish lagoon on eastern Hokkaido. There is no subsequent mention of the fate of these juveniles but Kobayashi (2001) reports that in subsequent years (1993-2000) about 300,000 juveniles have been tagged (at a length of 6-8 cm) and released into Lake Furen each year. From there they enter into the Akkeshi Bay area of eastern Hokkaido. These tagged herring have been recaptured inside and outside of Lake Furen. Growth rates of herring from Lake Furen are very high, reaching 15.5 cm after one year and 21.0 cm at age 2, when they mature sexually. Also remarkable is the apparent homing of herring back to Lake Furen. After release some were recaptured more than 300 km to the west (Cape Erimo) and others about 100 km to the north (Cape Shiretoko). This indicates that some herring move away from the immediate vicinity of Lake Furen in adjacent coastal waters. Presumably some or most find their way back to Lake Furen for spawning. If so, cumulative recapture rates for tagged Lake Furen herring were sometimes high (12.5% for the 1995 cohort, 4% for the 1998 cohort) but in most years the recapture rate was about 1%. Kobayashi (2000) concludes that the attempt at enhancement has not been fully successful.

Suzuki and Fukunaga (2004) summarize the number of releases in the Akkeshi Bay area that range from 130,000 to 578,000 annually. The average length at the time of release is 68-69 mm. Some of these herring are recovered in the Akkeshi Fish market, so there is little doubt that these artificially reared herring juveniles survived and joined wild stocks. The maximal return rate of marked fish was 12% in 2000. Although there are some uncertainties regarding the computation of 'recovery rates', this short communication shows a striking relationship between the size of the release and the recapture rate (Fig 4).

8.3 Size-at-release and survival – implications for Prince William Sound

Figure 4 shows that rearing larvae and juvenile to a size of about 70-80 mm (compared to the shortest size of about 60 mm) seems to improve return rates, presumably by improving their survival - although the results also could be an improvement in the geographic fidelity as a consequence of longer enhancement duration. Regardless, if this relationship holds for Prince William Sound, and if enhanced larve grew there at approximately the same rates as they do in Japan, they probably would be much larger than naturally reared herring in Prince William Sound. Figure 5 shows the growth rate of wild herring larvae and juveniles from surveys in the Strait of Georgia. At 100 days of age they are smaller (about 50 mm) compared to the mean length of 70 mm for the Akkeshi Bay herring shown in Fig. 4.

The implications of this are not clear, and conclusions from such comparisons are speculative. Nevertheless it seems likely that enhanced herring grow much faster than naturally reared herring, similar to the results of Houde (1979, 1982). Although tentative, the potentially promising aspect of this (somewhat speculative) result is that enhanced fish may be able to survive well, once released. The worrisome aspect is that if naturally available food is limiting, as it seems to be for juveniles in Prince William Sound, enhanced herring may be able to out-compete smaller, wild herring.

8.4 Miyako Stock Enhancement Center at Miyako Bay

Okouchi and Nakagawa (2006) and Okouchi (2007 pers. comm.) describe similar herring rearing and release projects conducted at the Miyako Stock Enhancement Center at Miyako Bay, in western Honshu. At latitude of 39°N, this is close to the southern limit of the range of herring in the western Pacific. As in the Lake Furen project, work involving rearing, tagging and release experiments has been conducted since 1984. Feeding technology never seems to have been an issue with Japanese researchers, perhaps because they just borrowed technologies developed for other species, such as the popular Sea Bream.

8.5 ALC marking

Okouchi (per comm. 2007) advised that it took six years of experimentation to develop the ALC (alizarin complexone) otolith marking technology. Since 1994 they have applied ALC otolith marks annually to large numbers of juveniles, ranging from 13-71 million fish although not all are herring.

The ALC otolith marks are applied early, to larvae, when they are immersed in a 20 ppm ALC medium for 24 hours (i.e., ALC must be added to their incubation water for 24 hours). (Begg et al. 2005, in an introductory/summary paper for an international symposium on otoliths, discuss recent advances in otolith technology. For more details of otolith marking, see other papers in the same volume.)

The main emphasis of the Miyako Bay experimentation has been the confirmation of homing. Over the years they found evidence that released herring migrate away from the area before they return to their general release area. Some recovery information from incidentally-captured fish is complicated because there are no corresponding data on fishing or catch rates, etc. In any event, a key conclusion is that if the total recaptures of marked herring are aggregated from six different spawning grounds in the Miyako Bay area (an indentation on the north-eastern shore of Honshu Island with approximate dimensions of about 5 km by 20 km), the fidelity rate (or homing rate) is 71.5%.

A curious aspect of this work was the experimental marking of eyed eggs (pre-hatch) with ALC markers. The mark was successful. This result is surprising because the otolith of larval fish is very small and the size of a chemical mark must be extraordinarily small. Also the egg capsule is thought to be impenetrable to many chemicals, perhaps including ALC. However, the results of the Japanese work are very interesting and potentially very useful. If such otolith marking can be applied at the late egg stage, then this would enable a number of experimental/research possibilities – that extend beyond enhancement-related research.

8.6 Evaluation of enhancement in Japan

Kitada and Kishino (2006) review four case studies of Japanese enhancement projects. They suggest that limited carrying capacity may limit the ultimate expansion of enhancement activities. They found evidence that in some programs, enhanced fish replaced wild fish – so they advise that enhancement programs should proceed cautiously. Their review did not comment on the Japanese herring projects.

This paper was not available for inclusion at the time of writing:
Sugaya, T., M. Sato, E. Yokoyama, Y. Nemoto, T. Fujita, H. Okouchi, K. Hamasaki and S. Kitada (2007 in review). Population genetic structure and variability of Pacific herring *Clupea pallasii* in the stocking area along the Pacific coast of northern Japan. Aquaculture.

9 Disease and the potential impact on enhancement

High incidence of disease in Prince William Sound herring has attracted considerable research attention (for example see Carls et al 1998; Hershberger et al 1999; Kocan et al 1996, 1997, 1999; Marty et al 1998, 2003; Meyers et al 1994). The two diseases of concern are the viral hemorrhagic septicemia virus (VHSV) and the parasitic fungus *Ichthyophonus hoferi*. The exact role of disease in the population decline of 1993 remains uncertain but VHSH appears to be implicated with poor recruitment (Marty et al. 1993). These diseases are ubiquitous in the marine environment, in Prince William Sound and elsewhere, but infection rates vary in time and space and disease outbreaks are unpredictable. The persistence of a high incidence of disease in Prince William Sound seems exceptional among herring populations but perhaps that may be a function of the intense scientific scrutiny of Prince William Sound herring. Perhaps if there were more detailed monitoring of other populations, they too would have high infection rates. However, severe epizootic incidences, leading to mass mortality, are known in other herring populations.

The recent problems and concern with disease of herring in Prince William Sound pose a significant issue for potential enhancement activity. Suggestions for solutions of directions are beyond the scope of this paper except to point out some elementary aspects of the problem. One is that disease outbreaks seem to be associated with density confinement, similar to that seen in spawn-on-kelp fishery operations (Hershberger et al. 1999). Therefore the collection and holding of pre-spawning adults, as possible egg sources for culture (for enhancement), could lead to unanticipated problems if disease erupted in the parental stock. It seems best to avoid such confinement, if possible. Such avoidance could be accomplished by the collection and use of naturally deposited eggs (on natural substrate) or from suspension of artificial substrate to collect eggs from naturally spawning herring. Such practice, however, defeats any attempts to have enhancement operations occur in pathogen free environments.

9.1 Should enhancement facilities be pathogen free?

A basic question for enhancement activity is whether the rearing habitat should be natural, using untreated marine water from Prince William Sound, or whether it should occur in pathogen-free laboratory-style settings. For many reasons it seems that rearing eggs, larvae and juveniles in a natural environment seems preferable. Larvae and juveniles would be exposed to disease and probably many would succumb to the disease. The survivors, however, might be those who have some resistance to the disease or have acquired some degree of immunity. The alternative is the rearing of many juveniles in a disease-free environment, perhaps for a period of six months, and then releasing these naïve fish to a disease-ridden environment. Based on the laboratory results described in many of the papers on disease (listed above) where naïve, laboratory reared herring juveniles are exposed to disease and then experience catastrophic mortality, it seems preferable to risk disease exposure as soon as possible during enhancement, with the hope that such early exposure to disease would preclude a later, and potentially devastating mortality loss by disease, following release.

The impact of disease on any proposed herring enhancement may depend on the timing of exposure and perhaps the duration of confinement. Based on the work to date it seems preferable to use natural rearing environments with possible early exposure of larvae or juveniles to pathogens. This is only a tentative conclusion, however, and if enhancement proceeds, it may be useful to have a group of disease experts prepare specific protocols on the risks and impacts of disease at different herring life history stages, within enhancement facilities.

10 Issues of scale: size of a herring enhancement project

How many fish, produced through enhancement, would be required to make a significant difference in Prince William Sound spawning biomass? Any answer is speculative but Fig. 1b (from Moffit 2005) shows that recruitment in recent years has been about 200,000,000 (two hundred million) fish in several of the years since 1994, and usually lower. **Therefore, for a starting objective, an estimate of 20,000,000 (twenty million) additional herring recruits would seem like a reasonable objective – this number would be only about 10% of present recruitment levels which are considered to be low.**

10.1 How many eggs are required for enhancement?

The quantitative estimates in the following text are meant only to be illustrative and not definitive. Prior to any enhancement activity there must be an estimate of the required number of wild eggs that must be extracted from the natural environment. It is highly probable that this number will be very large, perhaps unacceptably large, if the starting number must withstand very high mortality in the cultured eggs, larvae or juveniles. Based on the Japanese experience, however, total survival rates may be as high as 30%, from eggs to young juveniles. Better estimates of mortality during mass rearing of Prince William Sound herring would require pilot-scale experiments. For the present, however, some approximations may be made based on existing information.

From Fig. 1b, we see that the approximate mean recruitment in recent years is about 200 million fish. An additional 20,000,000 (twenty million) fish produced through enhancement would provide a ten percent increase in recruitment. The estimation of the number of eggs required to produce twenty million recruits would be simple – *if* mortality between the egg stage and recruit stage were low or minimal. This is explained in the following section (10.1.1). The estimation of the numbers of required eggs, when mortality is considered, is much more difficult. Making such an estimate requires understanding of mortality at each life-history stage, from egg to larva, larva to juvenile, and from juvenile to new recruit, at age 3 (or 36 months).

10.1.1 Relative fecundity: the number and weight of spawning fish required to produce twenty million recruits, assuming no mortality

One metric ton of spawning herring produces about 100,000,000 eggs (10^8/mt). This estimate is based on the observation that the mean relative fecundity of herring females, throughout most of their range from California to the Gulf of Alaska, is about 200 eggs/g (Hay 1985). This estimate of relative fecundity tends to hold over a broad range of sizes, from the smallest newly recruiting females to the larger, older females. Larger females have relatively larger ovaries (often about 30% of their total weight at spawning) whereas smaller females tend to have relatively smaller ovaries (often about 20% of the total weight at spawning). However, egg size also varies: larger females tend to have larger eggs and vice versa. Therefore the estimate of relative fecundity, of about 200 eggs/g is robust (probably accurate within $\pm$10%) and useful for the calculations used here.

Herring populations have a nearly exact 50:50 sex ratio, and the age-specific weights of the sexes are approximately similar. Therefore the estimate of relative fecundity for female Pacific herring, of 200 eggs/g, can be adjusted to reflect the egg production of the total population (both sexes) and is about 100 eggs/g. Because this estimate is about 100, some readers may incorrectly assume that this estimate is only a rough approximation, say within an 'order of magnitude'. Actually, this estimate is much better than that and probably as accurate as the estimate of relative fecundity (explained above) and accurate within about 10%. Therefore the range of estimates of egg production for Prince William Sound herring probably varies between 90-110 eggs/g of spawning fish (both sexes included).

With perfect survival and assuming one gram of spawning fish produces 100 eggs (10^2 eggs), it follows that one kg of spawning herring produces 100,000 (10^5 eggs) and one metric ton (mt) produces 100,000,000 (10^8 eggs). Twenty million eggs (2 x 10^6) would require <u>200 kg</u> of spawning fish (i.e., 20 x $10^6/10^5$ egg/kg) or <u>0.2 mt.</u>

Ardent proponents of enhancement may be encouraged by the estimate of 200 kg of spawning fish as a requirement for producing 20 million recruits. This estimate is unrealistic however because it is obvious that mortality at all early life stages cannot be ignored. However the estimation of mortality, over the three year period, between fertilization and recruitment, is not simple, as shown is the next section.

10.1.2 Stage-specific survival

For the purposes of estimating stage-specific mortality (or survival) in the following analyses, nine life-history stages are distinguished, of which five are adapted from the classification used by Norcross and Brown (2001). The survival model used by Norcross and Brown (2001) assumes that the survival to any specific stage is simply the product of the survival of previous stages. For instance, if S represents survival, then survival to age 1 would be:

$$S_{age\text{-}1} = (S_{egg})(S_{larva})(S_{fall\ juvenile})(S_{winter\ juvenile})$$

The following analysis assumes that the age (and duration) of each stage is as follows:
(1) unfertilized eggs (age 0 days)
(2) fertilized eggs (age 0 days, duration 0.001 days)
(3) the egg or embryonic (pre-hatch) period (age 0-20 days)
(4) hatch and post-hatch period (age 21-30 days)
(5) the larval drift stage (age 31-179 days)
(6) fall-juveniles (up to 180 days of age)
(7) winter juveniles (between 181 and 365 days)
(8) age 2 juveniles (age 366 to 730 days)
(9) age 3 recruits (age 731-1095 days)

The ages and durations of these stages are approximate. Probably most investigators familiar with herring biology could argue that there are other stage classifications that are preferable, and they may be correct. However the list used here is designed to expand on the information and extend the survival model provided by Norcross and Brown (2001). This list extends the 'post-hatch' stage to a slightly longer period, to 10 days, which may be slightly longer than that implied by Norcross and Brown (2001). Also, some additional stages are added and the rational for each stage is discussed briefly.

10.1.2.1 The unfertilized and unfertilized egg stages

The distinction between the 'unfertilized egg' and 'fertilized' egg stages provides a simple way of estimating fertilization success (at about 99% successful). Some may argue that this estimate is too high, but it matches what I have observed in nature – but not in laboratories. Fertilization rates in laboratories are often much lower, especially when artificial substrates are used for eggs and when eggs have been surgically removed from females. In any event, recognizing this as a distinct stage allows for clarity of this estimation and assumption. Minor changes in the assumptions about the rates of fertilization have little impact on estimates of overall survival.

10.1.2.2 Egg stage

Egg survival in nature,, from fertilization to hatching, appears to be affected by a combination of biotic and abiotic factors. Survival estimates from the literature vary widely but several sources report measured survival rates of about 50% (Haegele 1993; Haegele and Schweigert 1989, 1991; Rooper et al. 1998, 1999). In Prince William Sound, Norcross and Brown (2001) indicate a survival range between 24% and 45%. Factors affecting survival include predation and weather, with mortality associated with storm action and dehydration. The duration of this stage in Prince William Sound is about 20 days.

10.1.2.3 Hatch and post-hatch period

This is not necessarily a distinct stage, but it is described by Norcross and Brown (2001) as a period when some abnormalities can be detected in live larvae. It also is a period when larvae exhaust their yolk sac (about 5 days post-hatching) and begin to feed (5-10 days post-hatching). Brown and Norcross estimate survival to be between 50% and 100% during this period. Probably they assumed that this stage was shorter than 10 days, because these are high estimates of survival at this stage. Regardless, for the purposes of the estimates in this report, the minimum survival is assumed to be 50% and maximum survival is 100% during this period.

10.1.2.4 Larval drift stage

This is a period when herring larvae feed voraciously and grow rapidly. It also is a period of intense mortality and may reach 10% per day (Arai and Hay 1982, and others) – so after a period of about 40 days, total survival would reduce the initial number to about 1% of the starting number. This estimate is based on research in other areas, but such low survival rates have been observed in many marine species. Therefore natural herring larval populations may decline by about 99% during this time. This is consistent with the Norcross and Brown (2001) estimates of 1% (minimum) and 7% (maximum) survival during the larval drift stage.

10.1.2.5 Fall juvenile stage

Post metamorphic survival to the juvenile stage in nature is presumably mainly determined by predation, although predation rates could be impacted by disease and food availability. Once the fish have reached the juvenile stage, approximately beginning in the early and middle months of their first summer, then feeding becomes important to allow them to survive through their first winter when availability is limited (Norcross et al. 2001). Norcross and Brown show survival rates between 2% and 21% during this period, although the duration of the period they use is not explicitly described. In the present paper this stage is assumed to be relatively long (120 days) so relatively low survival rates would be expected.

10.1.2.6 Winter juvenile stage

Norcross and Brown (2001) show a range of site-specific rates for this stage, which is assumed here to occur approximately for six months, from about November to April (although Norcross et al. consider this stage to occur between October and March). They report total survival ranges from 5% to 99% during this stage, but these are the extremes for sub-sections (individual bays) within Prince William Sound. The high and low annual extremes for the data aggregated among the different areas would raise the minimum and lower the maximum estimates of survival during this period. For the purposes of this report I estimated the maximum average survival simply as the approximate average of the ranges of the annual estimates for the years reported: the 1995-1996 range is 39-86%, the 1996-1997 range is 18-86%, and the 1997-1998 range is 39-64%. The annual means from these estimates are 62%, 52% and 50% respectively. Therefore a minimum of 50% and a maximum of 62% survival during this period may provide useful annual summaries of these data, although a minimum survival rate of 50% during this period seems high – even if it is based roughly on the available data. Better estimates might be made from the available data if the survival estimates were weighted approximately by the relative numbers of juveniles occurring in each of the areas examined.

10.1.2.7 Age 2 and age 3 stages (older juvenile and pre-recruit years)

These stages are not well understood. Based on observations in the Strait of Georgia (BC) most juveniles migrate out of the area during the second summer, approximately between the ages of 12-18 months, although in some of the most remote bays and inlets, it seems that some herring are non-migratory and resident in the same general areas throughout the year. It is not clear if there is a similar mix of migratory and non-migratory herring in Prince William Sound. Further, it is not clear whether some areas of Prince William Sound might be more likely to retain non-migratory herring. In any event, the survival of these stages is poorly understood in Prince William Sound and all other Pacific herring populations. For the purposes of this report I assumed that a maximum survival rate might be about 50% in each year of these two stages. A minimum estimate of 5% (one-tenth of the maximum survival rate) was arbitrarily chosen – although it is the same as the minimum survival rate for the earlier juvenile stages reported by Norcross and Brown (2001).

10.1.3 Estimates of survival from egg to recruit

The stage-specific survival rates for each of the eight stages described above is shown in Table 3. Table 3 also shows an estimate of the approximate weight of individuals at the conclusion of each stage. Following the model of Norcross and Brown (2001), the survival at each stage is the product of the minimum and maximum survival rates of the previous stages. A problem with this approach, however, is that it is unlikely that specific cohorts would encounter conditions leading to either consistently low or consistently high rates as they develop through each stage. A more realistic estimate might be better represented by the mean or median estimates. Therefore Table 3 shows the mean mortality as the midpoint between the minimal and maximal rate for each stage.

The estimated numbers and biomass of each stage is shown in Table 4. A starting number of one hundred million eggs (10^8) is used – as a proxy for the approximate egg production of one mt of spawning fish. The estimates of the minimum and maximum number of survivors at the end of the winter juvenile stage is nearly identical with those presented by Norcross and Brown (2001). (Note that Norcross and Brown began their calculations with ten million (10^6) instead of the one hundred million used in Table 4 of this paper – so the estimated numbers-at-stage here are 10 times greater than they show.

Table 4 also shows an average estimate of stage-specific survival, that might be more realistic than either the products of the consecutive minimum estimates for each stage or consecutive maximum for each stage. Table 4 shows an estimate of about 117,000 survivors at the end of the fall juvenile stage, and about 65,000 at the end of the first winter. As a very rough approximation, these calculations indicate that about 1% survive during the first year of life.

10.1.4 Estimation of pre-release survival rates in an enhancement project

Table 5 shows the same stage-specific stages as Table 3, but also shows the estimated survival rates that might be encountered in an enhancement project. For each stage a minimum and maximum estimate are shown. It must be understood that the estimate of survival used in these calculations (50% at each major stage) is little more than a guess. *These survival estimates are much higher than those* occurring in natural populations (see Table 3) but the cumulative survival is lower than the estimates reported in Japanese herring enhancement research (estimates at about 50% in the Lake Furen project – see Section 8.1). With the assumption of a starting number of one hundred million eggs (10^8), the minimal estimates of survival to the end of the fall juvenile stage was about 6.12 million (or also about 6% survival) and the maximal maximum estimates of survival was 57.18 million (or about 57% survival).
The end of the fall juvenile stage probably is a reasonable time to consider release of enhanced juveniles.

10.1.5 Estimation of post-release survival rates in an enhancement project

Table 6 shows the estimated numbers and survival of herring reared in an enhancement project and released at approximately 6 months (180 days) of age. The range of pre-release survival estimates up to this stage was estimated to be between 6% and 57% corresponding to about 6 million and 57 million survivors based on a starting number of one hundred million eggs. Once released these herring juveniles could encounter survival rates applicable to wild herring. These are shown in Table 6 as estimates of the minimum, maximum and average probability (p) of survival for three stages (winter juveniles, age 2 and age 3). Like some of the previous estimates, these estimates are only 'guesses' about probable survival rates. ***In general, survival rates of adult (post-recruit) herring are usually greater than 50% per year so an estimate of a maximal survival of 50% and a minimal survival of 5% (used in Table 6) may be reasonable, and perhaps even conservative.*** Such estimates however, assume that total annual survival is not affected by intense fishing or other forms of mortality. Table 6 also shows an 'average' estimate of survival, which is simply the arithmetic mean of the high and low estimates.

10.1.6 The numbers of eggs required to produce 20 million recruits

The three survival scenarios in Table 6 (best case, worst case and average case) show that, of a starting number of 100 million eggs, the worst, best, and average case scenarios would yield a total survival of 733 million, 8.8 million and 1.3 million fish respectively.

Probably, for the purposes of approximate estimation of survival of enhanced fish to the age 3 recruit stage, an estimate of about 1% survival of starting eggs may be reasonable. Therefore production of 20 million recruits would require about 2 billion eggs (i.e., 100 times 20 million). ***Based on the estimated relative fecundity of 100 egg/g of spawning fish, production of 20 million age 3 recruits would require a starting number of about 2 billion eggs – or the egg production corresponding to a spawning biomass of 20 mt of herring.***

If such projected survival estimates (1% from the egg stat to the recruit stage of enhanced herring enhancement for the first six months of life) are reasonable, then the estimate of 20 mt of spawning herring may not be a formidable barrier to initiation of an enhancement project. For instance, this quantity of fish probably is less than many single purse catches – or the numbers used in commercial spawn-on-kelp operations.

10.1.7 Enhancement impacts on spawn deposition

In terms of the estimated area of spawning habitat lost from the use of 2 billion eggs, this area could be the equivalent of 20 km of shoreline spawn (assuming a mean density of 100,000 eggs/m^2 (a very light density) and a mean width of 1 m (very narrow width). If the mean spawn width were 10 m (a more realistic width estimate) then the equivalent shoreline distance of 2 km would be required. Using estimates of higher spawn densities of 1,000,000 eggs/m^2 (probably a relatively high but not uncommon egg density) then the shoreline distances corresponding to 2 billion eggs would be between 200 m and 2 km respectively - if the mean spawn widths were

1m and 10 m, respectively. Probably under most conditions of a spawn deposition, use of 2 billion eggs for enhancement would be about 400 m (i.e., mean density of about 500,000/m^2 and mean width of 10 m).

It is essential to stress that the estimates used in some of the preceding calculations are guesses and many are not based on real data. Some could be misleading or wrong and such error could have a major impact on the estimates of total survival used here. The assumption of a total survival of about 1% could be wrong by a factor of 10. Probably the distribution of error estimates is not symmetrical – so there would be a greater change of the real number being closer to 0.1% survival than 10% survival. Therefore it would be incorrect to assume that the estimates derived in this report are robust. Instead, they are merely intended as guides and should be subject to re-examination and revision if an enhancement project were initiated.

10.2 Implications of larviculture mortality for duration of herring enhancement

These preceding estimates are intended to be illustrative although hopefully the survival and mortality estimates are roughly realistic. The previous examples show that if enhancement is a realistic option, then the duration of larval and juvenile culture periods may be vital. A potentially important observation is the low survival rates associated with the larval drift stage that Norcross and Brown (2001) estimated to have a maximum stage-specific survival rate of 7%.

Ignoring, for the moment, the earlier comments about the futility of release of enhanced fish prior to periods of intense density-dependent mortality, it may be informative to consider short enhancement durations, say of about two months, corresponding to the approximate end of the larval stage (Table 3). How many eggs would be required to produce 20 million recruits if the release occurred at 60 days of age?

One way to approach this is to assume that the products of a month-long enhancement (i.e., feeding larvae) would, once released into the wild, have the same survival potential as wild-reared herring larvae. From Table 6 we see that the survival of enhanced herring, to the end of the 'post-hatch' stage, varies between 24%-89% with average mortality at 57%. Then if these surviving larvae, at an age of about 30 days were released to the wild and experienced the same mortality estimates as wild larvae at each stage, then the 'average' survival to age 3 would be 0.00019 (the products of the age-specific survival estimates for each stage subsequent to release). If so, how many herring would be required to produce 20 million age 3 recruits if the survival rate were 0.00019? Using the relative fecundity estimate of 10^8 eggs/mt, the answer is about 1.05×10^{11} - or roughly about 1000 mt. Clearly, in the present context of the herring issues in Prince William Sound, this would be an unacceptably large number of herring to commit to an enhancement project. This estimate of required eggs would decrease substantially if survival were assumed to be maximum throughout all life stages following release – but such an assumption is not warranted for the purposes of these calculations. ***The conclusion is that if an enhancement project were to proceed, the duration of culturing should exceed the first month of life of a herring*.**

Maximal natural survival rates during the larval drift stage have been shown to be low at 7% (Norcross and Brown 2001) so it seems clear that this may be a life history stage where an enhancement project could provide higher survival estimates. This, and the next stage -'fall juveniles' - also may be a stage where some density-dependent process may affect survival. ***Therefore, it seems clear that an enhancement project should avoid release times prior to the 'winter-juvenile' stage.***

10.3 Other estimates of survival

Some readers may object to the way these estimates of mortality were estimated. Probably many valid objections could be raised. Perhaps a better way would be to ignore life history stages and estimate the probable survival directly between eggs to recruits. In general, we might make a reasonable guess about the number of eggs deposited (from spawn surveys). Age-structured stock assessment analysis can provide annual estimates of the numbers of recruits. For the purposes of this report however, where the intention is only to establish some approximate guidelines that might help focus pilot scale experiments, we might assume that the total recent egg production of the Prince William Sound spawning biomass (say about 20,000 mt or about 2 x 10^4 mt) multiplied by the approximate relative fecundity (10^8 eggs/mt of SSB, Hay 1985) would yield an estimate of total annual egg production of 2 x 10^{12} eggs. The approximate survival from egg to recruit, assuming an annual average recruitment of about 200 million fish (Fig. 1b) would be about 0.0001 ([2 x 10^8 age 3 recruits]/ [2 x 10^{12} eggs] reduces to about $1/10^4$) - or one recruit surviving from ten thousand eggs. If mortality were constant over time then the daily survival rate would be in excess of 99% per day – or a mortality rate less than 1% per day. Clearly this daily survival rate is much higher than some observed field estimates. For instance Arai and Hay (1982) calculated mortality to be about 10% per day for yolk sac larvae (daily 'survival' rates would be about 90%) so mortality must decrease in older, larger size groups. The implication for a possible herring enhancement project is that mortality is variable during early development (a fact widely known) so that stage-specific estimates of mortality, even rough estimates, are preferable to assumptions that mortality rates are constant during the period between egg incubation and recruitment.

It is a problem, however, to measure actual mortality rates – especially among juveniles. In the Strait of Georgia annual surveys of juveniles, made in September of each year, estimated juvenile density by surface area and volume. When extrapolated to the whole area of the Strait, the results always were under-estimated – the total estimated number of age 0+ juveniles was less than the numbers of age three fish recruiting to the adult populations. The reason for these low estimates in not clear but in part it is related to the widespread distribution of juveniles. They extend their range throughout all areas of the Strait of Georgia and even in Johnstone Strait, especially in tidally active areas where spawning does not occur.

10.4 Implications of the high survival rates seen in Japanese research

The Japanese experience suggests that high survival of cultured eggs, larvae and juveniles could be possible. They report annual survival rates of about 30%, from eggs to juveniles. If so, then the required number of eggs for enhancement probably would be relatively small. The estimated number of eggs required to increase present recruitment levels by 10% (i.e., an additional 20,000,000 recruits) would require the total egg production of only 200 kg of spawning fish – assuming that mortality were zero between egg fertilization and recruitment. Assuming that the 30% survival estimates approaching the Japanese rates might be reached, then the total biomass of spawning fish required as parental stock would then require about 666 kg or 0.6 mt – which might be rounded off to about 1000 kg or 1 mt. Of course this estimate does not allow for post-release mortality between the juvenile and adult stage. Also, this is based on an improvement of only 10%. Higher expectations would require more donor eggs.

10.5 Juvenile survival – is this the vital question?

Some key biological issues related to enhancement concern the mortality during the juvenile periods and the factors affecting recruitment. This latter point has been investigated for more than 100 years – and although there has been progress there still is much uncertainty. This presents both a problem and a challenge for enhancement work. Clearly it would be comforting to see the Prince William Sound herring population resume its former levels of abundance – and that is the basis for the enhancement concept. As the viability of an enhancement project is investigated, perhaps through pilot-scale field investigations, supplemented with laboratory tests, and perhaps retrospective and field analyses of herring growth and survival, there may be other opportunities for valuable scientific by-products.

There is an excellent opportunity to examine some key factors that might affect Prince William Sound herring recruitment. A specific issue concerns the concept of 'self-recruitment' to sub-components of the Prince William Sound population. Are there separate spawning groups (populations?) in Prince William Sound as suggested by O'Connell et al. (1998)? If so do they contribute recruits to the total population, in proportion to their spawning biomass? Are there some areas that contribute more or fewer recruits than other areas? Is larval and juvenile survival the same in all areas? What is the (genetically) effective population size of Prince William Sound? Is it much smaller than the numbers of spawners, based on the assumption that all eggs have a roughly equal probability of survival? Genetic work on Prince William Sound herring by O'Connell et al. (1998) and work on other species by Hauser et al. (2002) indicate that effective population size may be surprisingly low, perhaps orders of magnitude smaller than the numbers of spawners. If so, what is the implication for enhancement work that will, of necessity, produce a lot of young fish from a small component of the gene pool? It would be wise to re-examine the genetic structure of Prince William Sound herring, especially in light of work by Kitada et al. (2000) that suggests previous estimates of effective population size may have been under-estimated.

11 Criteria for enhancement decisions in Prince William Sound

Walters and Martell (2004), in a dedicated chapter on generic 'marine enhancement programs', explain three aspects of enhancement: (1) critical steps in program design; (2) monitoring and experimental requirements; (3) things that can go wrong. Within each of these categories they discuss criteria that can be used to evaluate the efficacy of potential enhancement programs, such as the one under consideration for herring in Prince William Sound. These three main topics are examined in detail at the conclusion of this report but perhaps the paramount issue concerned with Prince William Sound herring enhancement is the time of release of cultured organisms relative to herring life history stages when density-dependence mechanisms limit population size. If density-dependent mechanisms restrict population size at life history stages that develop AFTER the time of release, then it is clear that such releases will not enhance the population size – and it is possible that there could be a negative impact by displacing naturally-produced 'wild' fish or by altering the genetic structure of the population.

11.1 Critical steps in program design

Each of the main points that follow are taken or adapted from Chapter 12 (Marine Enhancement Programs) from Walters and Martell (2004). Beneath each point is a '***Comment***' that attempts to interpret the existing situation, or information, relative to the potential for herring enhancement in Prince William Sound.

11.1.1 Make management priorities and trade-offs clear and acceptable

Comment: Has there been a serious evaluation of possible resource trade-offs? The cause of the herring collapse is not clear, nor is the explanation for the continued high incidence of disease. Probably the closures of the sac-roe fishery are evidence that conservation of the herring stock is a paramount concern for the management of herring. It is less clear if hard management decisions will follow if it became clear that part of the problem with the low herring abundance was related to fisheries programs for other species, such as the large pink-salmon hatchery system. This critical step asks 'what if the Prince William Sound herring stock cannot co-exist at high levels of abundance with other stocks'? Perhaps the population has now adjusted to a new ecological regime related to other fisheries or other anthropogenic factors. Maybe there is another, more fundamental explanation related to predator pits (i.e., Bakun and Weeks 2006).

Another management priority that needs clarification is the duration of herring enhancement, especially if it proves successful. Will managers be satisfied to cease enhancement activity if and when herring abundance increases?

11.1.2 Demonstrate recruitment overfishing or unsuccessfully rearing in the wild

Ensure stock assessments to show that the target stock is recruitment overfished or can no longer successfully rear in the wild.
Comment: This step is fully met. Annual stock assessments are done annually. There is no fishery, so there is no concern with recruitment-overfishing, unless herring are taken in significant quantities and bycatch (or killed by collateral damage) in other fisheries. This seems unlikely.

11.1.3 Show that enhanced fish can successfully recruit in the wild

Comment: This has been shown by Japanese work. It is highly probable that this step will be fully met.

11.1.4 Show that total abundance is increased by the enhancement contribution

Comment: This step has NOT yet been shown by Japanese work. Although the enhancement methods used in Prince William Sound may resemble those used in Japan, the objectives are not necessarily the same. The best way to meet this objective is to extend the culture time as long as necessary to reduce, or eliminate, density-dependent competition with wild juveniles.

11.1.5 Prevent continued overfishing

Ensure that fishery regulations are adequate to prevent continued overfishing of the wild population (unless there has been a policy decision to 'write-off' the wild population.

Comment: This step is not applicable at the present time. The fishery is closed. This step is only relevant if and when the stock 'recovered' to a level that supported a fishery. If that happened however, presumably the enhancement efforts would cease. If they did not end, but continued, then management rationale for enhancement would have changed – from a 'conservation and restoration' exercise to a 'production' exercise.

11.1.6 Show that the hatchery production system is sustainable over time, if it is to be permanent

Comment: This step is not applicable at the present time. The fishery is closed so enhancement is being considered for purposes of restoration, not production.

11.2 Monitoring and experimental requirements

Comment: Two key monitoring requirements exist. The first is to conduct broad marking programs to assess the survival of enhanced and wild herring. Probably the Japanese ALC marking procedure may be the most reasonable approach.

The other basic monitoring requirement is ongoing genetic analyses to ensure that the possible addition of recruits, from relatively few spawners, does not compromise the genetic integrity of Prince William Sound herring. In the case of Prince William Sound, there may be some uncertainty about the effective population size, as determined from microsatellite DNA analyses (O'Connell et al. 1998).

11.3 Things that can go wrong

11.3.1 Failure to produce fish that successfully recruit to the spawning population

Comment: Japanese work indicates that cultured herring can compete and spawn. It is essential, however, to have a marking system for released fish. The Japanese work should provide good protocols for this. Also, this field is developing rapidly (see review by Niva et al. 2005).

11.3.2 Direct exploitation of wild fish to provide hatchery seed stock

Comment: This is a real, but relatively small concern with the assumption that, following Japanese practices, there can be relatively good survival from hatching to the juvenile stage.

11.3.3 Post-release competition between hatchery and remaining juvenile fish

Comment: This may be the most pressing concern. Monitoring and research should attempt to determine the optimal release time. Based on the information in this report, later releases of larger juveniles may reduce possible competition for scarce food resources in the late fall and early winter.

11.3.4 Increase in predation and disease risk for remaining wild fish

Comment: This is a major concern, given the present high incidence of disease in Prince William Sound herring. It is especially troubling that the viral disease (VHS) tends to break out in crowed conditions.

11.3.5 Selection under enhancement conditions for traits that are inappropriate

Comment: This is only a concern if enhancement activities had a long duration.

11.3.6 Attraction of fishing effort by unregulated fisheries

Comment: Probably this is not an issue.

12 Facilities, Operations, Research and Costs

12.1 Facilities

It is obvious that the cost would vary with the size and scope of any enhancement operation. Probably equally important would be the location(s) of operations. Remote locations without convenient access to support facilities would cost more.

12.1.1 Salmon hatchery costs as a model?

Although one of the key recommendations in this report is for a cautious, modest start (if there is to be a start), in some ways it is simpler to estimate the cost of a full-blown enhancement project that would raise 20 million, or more, juveniles annually. It seems probable that the total costs may be roughly similar to the total costs of similar hatchery production of pink salmon in Prince William Sound that releases over 600 million pink salmon fry at a weight of about 0.5 g each (Cross et al. 2005). Probably the weights of released herring juveniles would be roughly similar, but perhaps lower. Estimates from Table 6 (and see text in Section 10.1.5) indicate an average post-release survival of about 5% (based on the 'average' estimate). If so, the required number of released juveniles (at age of 6 months) would be twenty times greater than the expected number of recruits (at age 3 years). Therefore production of 20 million age 3 recruits could require release of a number twenty times greater – or 400 million. If so, this would require that herring enhancement operations might be on approximately the same operational scale as the Prince William Sound pink salmon hatcheries.

Although pink salmon and herring rearing facilities are different (fresh water versus marine, etc.), a comparison of the costs of potential herring hatcheries probably would be roughly similar (say within an order of magnitude) to salmon hatcheries. Both types of operations require some expensive capital investment. Both would require periods of labor-intensive work and therefore need a combination of seasonal and full-time staff. Both would require significant expenditure for food. Both require pre- and post-release monitoring. The major difference with herring operations (at the initial stages) is that there would be a greater proportion of time spent on research to establish protocols for egg collection, larval food preparation and early feeding, disease monitoring, juvenile feeding, and *especially* experimental mass marking. Unfortunately, simple estimates of the costs of salmon hatcheries were not available as a potential guide to the total costs. Also, it is one thing to estimate annual operating costs and another to factor in the initial capital costs of facilities. For the purposes of estimating the costs of herring enhancement, both capital and operational costs must be considered. Nevertheless the total costs, if pro-rated over several years, would be many millions of dollars, perhaps tens of millions.

12.2 Pilot scale cost estimation

Costs of pilot scale operations would depend greatly on the approach but would be considerably less than full-scale implementation. As mentioned above, if the decision were to rear herring in pathogen-free facilities, in laboratory-like settings, then costs may be substantial. Even rearing a few million juveniles would require extensive facilities. On the other hand, rearing eggs, larvae and juveniles in natural or semi-natural settings could be considerably less expensive.

12.2.1 Egg acquisition

The costs of collecting eggs on real or artificial substrate would be relatively modest. Assuming that this process would require charter of vessels and staff for a period of about 6-8 weeks (this length of time is required for preparation and set-up, etc.), the costs probably would be in the tens of thousands of dollars, but probably less than one hundred thousand dollars.

12.2.2 Larval rearing and tanks, cages or mesocosms

The costs of larval rearing would depend greatly on the site. If it were possible to establish large semi-natural mesocosms, perhaps similar to that used in Flödevigen, Norway, then the costs of expensive tank facilities might be avoided. Alternatively, perhaps there is somewhere in Prince William Sound where some portion of the shoreline, such as a small bay or inlet, might be sequestered for herring enhancement. This would require some form of screening to reduce or eliminate key larval herring predators such as jellyfish, arrow worms (chaetognaths), some predatory zooplankton and juvenile fishes. Such a location also would need to be amenable to food supplementation, with artificially reared rotifers and/or *Atremia* nauplii. Yet another possibility would be lagoon-type locations, even with lower salinity water, similar to some of the Japanese facilities – where the larval and juvenile herring are reared in brackish lagoons (which they refer to as 'lakes'). A possible advantage of such lower-salinity areas may be a reduction in marine predatory fish that avoid low-salinity areas. The early life history stages of herring, however, usually are very tolerant of lower salinities, to 15 ppt (or lower.

12.2.3 Juvenile density – in nature and in enhancement facilities

If suitable semi-natural mesocosm facilities could be located, this might result in considerable cost reduction. Alternatively the costs of tank facilities could be substantial. The key question is how much area of volume would be required? (The following attempt to address this is very speculative and perhaps there may be better ways).

Suppose the initial number of herring juveniles in Prince William Sound is 100 times greater than the approximate number of average recruits. If the annual number of juveniles is about 200 million or 2×10^8 (see Fig. 1b) then this estimate would be 20 billion - or 2×10^{10}. This would require 99% mortality between the youngest juvenile stage and the age of recruits, about 2 years and 10 months later. This estimate of young (age ~2 months) juveniles is about 100 times less than the number of eggs (2×10^{12}) deposited by a spawning stock biomass of 20,000 metric tons (i.e., 2×10^4 mt with a relative fecundity of 10^8eggs/mt = 10^{12} eggs). So perhaps this estimate is roughly realistic. Now suppose these 20 billion juveniles are confined mainly to the nearshore water of Prince William Sound, between the inter-tidal zone and a depth of 10 m. From Table 2, the estimated area of such water is 709 km^2 or about 7×10^8 m^2. If the average depth were 5 m, then the total volume of this shallow 'juvenile' habitat would be about 35×10^8 m^3 or (3.5×10^9 m^3). Therefore the average volume of water per juvenile would be estimated as the total volume of the habitat (3.5×10^9 m^3) divided by the numbers of juveniles (2×10^{10}). The result is 0.175 m^3 per juvenile, or 175 liters per juvenile.

Juvenile herring begin to school at a young age and it is obvious that they do not occupy all potential areas of available habitat. Therefore their density in nature must be considerably greater. For the purposes of estimating the required volume of containers used for enhancement, we might begin with an assumption that each juvenile requires between 1 and 10 liters each. Then, if the starting number of juveniles in a pilot-scale facility were one million (10^6), the required volume would be between 10^6 and 10^7 liters – or 1000-10,000 cubic m (10^3-10^4 m^3). At a minimum this would correspond to a cubic tank with dimensions of 10 m on each side (depth x length x width). More realistically it could be a large container (or the cumulative volume of many containers) with a depth of one m, that would extend 30 m (i.e., about 100 feet) for both length and width. This would be a substantial volume of water, roughly equivalent to a large swimming pool. Based on the calculations above, which are acknowledged to be crude, such a pool would provide the minimum volume for one million juveniles. Such tanks or containers would be expensive. As a first approach, some modification of cages used in modern fish-farms might be used, if they could be lined with fine-mesh screen material. If so, the costs of a single facility would probably be in the 'tens of thousands' of dollars or perhaps \$100,000 or more, but this is a guess. If such a single cage/container provided a minimum rearing volume, then it would take ten such cages to provide a rearing volume, assuming 10 liters per juvenile, to reach the 'maximum' volume estimated above. Therefore, for a pilot-scale facility rearing one million juveniles, it may take the equivalent of between one and ten specialized netpens, each of which may cost \$100,000 or more. A full scale enhancement project may require many of these. It is vital, however, to appreciate that these are very rough estimates. Their main purpose may serve only as a guide to developing more accurate estimates.

12.2.4 Food costs

Aside from the cost of rearing facilities, there also would be substantial food costs. The costs of food may be estimated, approximately by determining the total weight of juveniles reared prior to release, and assuming a conservative conversion efficiency. Suppose, for instance, that in a pilot-scale facility, one million juveniles were reared to a weight of about 0.5 g. Then the total fish weight would be 5 million g (or 5000 kg or 5 mt). If the conversion efficiency (adjusting for the loss of uneaten food) was 10%, then it may require about 50 tons of food to raise one million juveniles. The approximate cost of pellet food used for salmonids is about \$2000/ton (Chris Beattie, Product Manager, Skretting Canada, pers. comm.). Therefore the cost of feeding one million juveniles to a release weight of 0.5 g would be about \$100,000. This estimate could be lower by a factor of two (or more) depending on the size or time of release and the actual conversion efficiency. Therefore if a minimum estimate were about 2 mt, then total feed costs would be about \$50,000-\$100,000 for one million enhanced juveniles, and ten times greater (or much more) than that of a full-scale project raising hundreds of millions of juveniles.

12.2.5 Fishing – to recover marked fish

If the present fishery is closed, how will sufficient recruit fish be captured to allow for monitoring of marked fish? Presumably, some fishing operations would be required to do this. If so, perhaps the sale of captured fish could be a source of revenue to offset the costs of the experimental culture. If not, then the cost of a dedicated vessel charter and other expenses would probably require several hundred thousand dollars per year.

12.2.6 Staff

Probably a staff of 5-10 would be sufficient for a pilot scale facility, but this would vary with the location and types of facility. Probably salary and benefits would cost $500,000-$1,000,000 per year.

12.2.7 Mass-marking research

A key issue is marking and mark recovery. Probably research grants could be used to start this and preliminary work could begin with modest funding (< $100,000) but soon would require substantially more, perhaps $500,000 or more. Full technological development of mass marking procedures, which is essential, might be very expensive. Therefore a complementary research program, at the initial stages of a pilot-scale project, could require $100,000-$500,000.

12.2.8 Strategic planning, cooperative and collaborative research

Prior to start up of any field activity, it would be essential to develop robust strategic and research plans that, for instance, could investigate different options for various facilities. A specific requirement may be development of cooperative or collaborative relationships with Japanese agencies and researchers. This would require both travel and hospitality budgets, although activities such as reciprocal trips to Japan to investigate methodology, etc., might be required to produce deliverables in the form of informative methodological reports. Probably any serious attempt at enhancement, even at the pilot scale, would require substantial funding for several major projects a year. An allocation of at least $400,000-$500,000 per year, during the early years of the project, seems essential.

12.2.9 Discretionary funding

Aside from the anticipated costs (facilities, egg acquisition, food, staff, etc) there could be substantial unpredictable costs that require discretionary funding. Probably this should be at least 10-20% of the total allocation.

12.3 Estimate of total costs for pilot-scale project

The breakdown of costs is as follows (with numbers representing dollars, in thousands):

egg acquisition	$50	-	$100
rearing facilities	$100	-	$500
food	$50	-	$100
fishing	$50	-	$100
staff	$500	-	$1000

strategic planning, research	$400	-	$500
discretionary	$200	-	$400
Total	$1350	-	$2700

Therefore how much would a pilot-scale project cost? Based on the speculation above it might be approximately between $1.3 and $3.0 million dollars. This cost would be required to initiate what might be one of the largest marine enhancement projects of its kind and certainly larger than anything previously attempted for herring. Two important caveats about these cost estimates are as follows. (1) The estimates are based on very preliminary and incomplete information. They require considerable refinement, and perhaps correction, prior to the initiation of any enhancement activity. (2) The cost of a pilot scale project, raising about one million juveniles, would not be 10% of a larger, full-scale program to rear and release, for instance, 20 million juveniles. There are economies of scale that would be considerable so a project that would be tens times the size of the pilot scale work would not require that research effort, although monitoring work would increase.

13 Summary and Recommendations

Prior to initiation of any enhancement activity there should be review of the existing circumstances to ensure that enhancement is warranted and that it is the only way to proceed. Based on the guidelines presented by Walters and Martell (2004) this could be done by a distinct, separate project that evaluates the condition of the present stock, and the methods used to evaluate the present stock. This could include an external review of assessment procedures and key biological aspects used in the assessments.

Enhancement activity, if it were to proceed, should begin slowly, with pilot scale activity. As much as possible the work should try to be developed so that results will have multiple benefits. For instance, Japanese work on enhancement, while still of questionable value as a means of improving recruitment, has made some valuable contributions to the understanding of herring biology, particularly homing and migration.

The time of release is a critical aspect of any marine fish enhancement work. There is general agreement that it is futile to release enhanced fish at a size or age that is still subject to density-dependent effects. This can happen if their survival is determined by the carrying capacity of the habitat they require when released. The probable implication for Prince William Sound herring is that enhancement would be required to maintain herring until the end of their first summer or growing season. In this way, they would not compete with naturally reared herring.

The scale of enhancement operations will depend on survival rates between the time of fertilization and the time of release, which could be at an age of about 6 months, or possibly longer. Based on survival and mortality estimates from the scientific literature, the numbers of eggs required to produce enough juveniles to impact recruitment could be formidable, but this would depend on the scale of operations and the duration of the enhancement program. The most troubling scenarios could require the equivalent of many tons of spawning herring and require significant quantities of eggs, so there could be deleterious impacts to natural spawning areas as eggs were collected and transferred. On the other hand, the very high survival rates seen in Japanese work, if emulated in Prince William Sound, would require only modest use of naturally deposited eggs or spawners.

The duration of captivity, between the time of first feeding and release, is a key issue requiring further investigation. There is a trade-off between rearing large numbers for a short duration (early release) versus rearing of smaller numbers for a longer duration.

The 'large number, short duration' option could:

(i) have adverse impact on natural spawn during the collection of herring spawn,
(ii) require large amounts of larval food such as rotifers and *Artemia,*
(iii) encounter higher post-release mortality through predation,
(iv) present high risk of competition for food with natural herring,
(v) be less expensive in terms of required rearing facilities and food,
(vi) be technologically easier,
(vii) have a lower probability of success.

The 'small number, long duration' option could:

(i) have small impacts on donor sites during spawn collection,
(ii) require moderate amounts of food for larvae but significantly more food for juveniles,
(iii) encounter lower post-release mortality through predation,
(iv) present low risk of competition for food with natural herring,
(v) be more expensive in terms of staff and facilities,
(vi) be more technologically challenging,
(vii) have a higher probability of success.

The technological requirements for enhancement are best determined through pilot scale experiments. A large challenge would be the housing and feeding of millions (or billions) of juvenile herring. Some rearing in mesocosms could be tried. The Norwegian experience with large semi-natural mesocosms might provide examples of useful prototypes.

Supplemental feeding with a food source like *Artemia* will be required. Mass rearing of *Artemia*, and other potential fish foods, is both an art and a science. It will require time to set up facilities and have technicians learn the procedures.

Mass marking programs are an essential part of enhancement. It appears that the Japanese experience with ALC otolith marks is successful. Prince William Sound herring enhancement initiatives should build on the Japanese achievements.

Scientific cooperation and collaboration with Japanese agencies and researchers would provide valuable technical information for the initial stages of enhancement.

The rôle of disease in any enhancement activity in Prince William Sound is uncertain. Disease could be a serious problem. A basic decision will be required about the types of facilities used and the exposure of cultured fish to disease. The choice will be between: (i) rearing fish in pathogen-free facilities (if possible) before releasing them to the wild, (where they might experience severe disease-related mortality, or (ii) letting the larval and juvenile stages be exposed to disease, knowing that some mortality of enhanced fish will occur prior to release, but subsequent mortality in the wild may be lower. It seems preferable to have exposure to disease early in the life of herring, with the hope that the survivors may acquire some resistance. In any event, this is a specific issue that requires more attention from disease experts.

A qualifier: a decision to 'investigate' enhancement is not a commitment to 'conduct' enhancement.

A decision to investigate the feasibility of enhancement does not necessarily mean that the EVOS Trustee Council is committed to the concept or determined to engage in enhancement activity. Instead, the intention is to examine the implications of the concept, as it applies to herring in Prince William Sound. Full scale enhancement activity would require several years of preparation, mainly to develop and determine some technological issues, such as mass marking of young fish prior to release. Mass marking and other technological activities are fundamental pre-requisites of enhancement activity. Therefore, because the development of these technological issues will take time, it is important that some investigations begin immediately. It also is important to understand that these investigations also could result in a definitive conclusion the enhancement of herring is impractical or far too expensive.

We suggest a sequential three-phase plan that could lead to full scale enhancement within five years. Each phase consists of several concurrent steps of complementary activities. Phase I will consist of three activities, each of which could resulting a conclusion that enhancement of herring is not warranted, because of technological or biological issues. Therefore we reiterate: the first components of a restoration plan are to determine the technological and logistical feasibility of the plan. These steps will not necessarily lead to enhancement activity.

Phases and activity of a herring restoration plan.

Herring restoration in PWS could proceed in three distinct consecutive phases, each of which has several distinct but concurrent activities or 'steps'. The three phases and suggested durations are: (1) Justification, decision rules and feasibility – one year; (2) Pilot scale enhancement and methodology tests – four years; (3) Full scale enhancement – initiated in five years. Each phase would have several steps or activities that could be conducted concurrently within the duration of each phase. The text below provides some background and

Phase one - step one: Justification, decision rules and feasibility

1. First step: develop decision rules and reference points.

It is certain that any restoration or enhancement will be very expensive and, at the onset, the results will be uncertain until shown otherwise. Critics and skeptics of enhancement will point out that the requirement for enhancement must be clear and demonstrable. Therefore it follows that there must be clear criteria (or decision rules) related to the abundance or condition of the Prince William Sound herring population that should be established prior to any enhancement activity. These decision rules could be developed in a dedicated report that could be used as a guide to enhancement activity, in much the same way that decision rules are used to manage a fishery. The criteria used to support decision rules would be related to some estimate of total herring abundance, although other demographic/ecological, such as specific cohort sizes, or sequences of weak cohorts. Also some spatial attributes could be incorporated when decisions rules are being developed.

Ideally, decision rules would be developed that would provide clear benchmarks for when enhancement activity might be initiated, or suspended or stopped. For instance, at an extreme, if the herring population trend population trend to decline were to continue, with extirpation anticipated to occur within a decade, then it would be clear that enhancement should be initiated. Likewise, if the PWS herring population reached some pre-determined level of the estimated virgin population biomass, either before or subsequent to enhancement activity, then enhancement would not be warranted. Such a pre-determined level would presumably be low, well below the lowest point natural variation expected for the population over a sustained period. Therefore the decision rule could also incorporate trends in changes in absolute abundance and the temporal durations of such trends.

This step requires that the decision about whether enhancement should, or should not proceed be based on specific criteria about the PWS population. Specifically, what metric(s) will determine whether enhancement is warranted? If the metric is based on abundance, then biological criteria must be defined about how low the population must go *before* enhancement is implemented. For instance, must the population decline to 10 percent, or 5 percent, or 1 percent of the pre-crash (in 1993) levels of abundance? The criteria, however also could be related to annual patterns of recruitment. For instance, if two, three, or more years of poor recruitment occurred consecutively then this might also be considered as rationale for enhancement. Further, in some special instances, the spatial distribution might be considered.

A related issue is the metric when enhancement is no longer warranted, or when the population has increased to a level that natural reproduction and survival are sustainable. This also can be defined as a metric, say when the population abundance is within the range of normal variation, or when any increments related to enhancement activity are not effective.

Yet another metric could consider the worst scenario, when the population may be headed for extinction. In thus case *conservation hatcheries* may be warranted. In the event of such a dire situation the artificial propagation of herring might not really be an 'enhancement activity' but rather an essential conservation activity. Regardless, it would be useful to develop criteria that would define abundance levels that would define the situation when conservation actions wound be warranted.

The development of metrics that would be used to initiate suspend or halt enhancement activity for herring in Prince William Sound is a vital pre-requisite to any action. The formulation of these metrics will requires input from several sources, representing different perspectives on the present situation. Primary sources of input would be from the Alaska Department of Fish and Game that conduct the annual age-structured assessments. Additional input could come from the commercial fishing community, coastal communities, plus the academic and the biological consulting community that has worked on herring issues in PWS. The mechanisms for developing these decision rules and metrics need careful consideration but probably the most efficient way would be to have one person (or team), under contract, lead a committee to prepare a report that investigates and defines the metrics and decision rules. Following this report, a workshop discussing the metrics and decision rules may be appropriate.

Synopsis: Write and define a contract to prepare a report that: (i) presens data on the past and present state of Prince William Sound herring, with comments on the strengths and weaknesses of the information; (ii) defines criteria, such as abundance levels, that would be a basis for initiating enhancement activity and suspending or stopping such activity following favorable responses of the population; (iii) defines criteria where possible extinction is a concern and that would warrant implementation of 'conservation hatcheries.

Phase one – step two: assessment and development of mass marking technology

An essential requirement for initiation of enhancement activity would be a means for the evaluation of success or failure – or measuring the relative survival of enhancement fish compared to wild, naturally produced herring. Such evaluation requires that enhanced fish can be identified. Compared to salmonids, identification of hatchery fish is a challenge for marine fish species such as herring that have many more, smaller eggs and that lack precise natal homing. In salmonid hatcheries, the verification of the survival is seen through the return of released fish back to the point of release – a phenomenon of natal homing through olfaction. Most marine fish do not appear to have the same capability to home with the same precision, perhaps mainly because the olfactory characteristics of their spawning habitats in marine spawning coastal areas are less distinct. Also, and perhaps more important, the residence time for the early life history stages of marine fish in their natal habitats is much shorter (days or weeks) than salmonids that live in freshwater spawning habitats and juvenile nursery areas for months or years, prior to open sea migrations. Therefore compared to salmonids herring have less time to imprint and because they are much smaller (by a factor of about one thousand times), herring larvae have a much less developed physiological and anatomical capabilities that might support imprinting capability. In any event, they do not home with the same geographic precision as salmonids so natal homing cannot be used as a mechanism to verify successful enhancement.

Mass marking of enhanced herring appears to be the only potential method for evaluating success of enhancement. Mainly this is related to marking of herring eggs or larvae in PWS. For certain potential restoration approaches, however, mass marking of age 0+ juveniles may also be a requirement. The work in this step would involve a combination of laboratory and field work, supported by detailed technical reports showing methods, data, results and conclusions.

Ideally this work should investigate several different marking options relative to potential screening methods. This might include investigation of the implications of otolith marking substances such a Alizarin, than can be detected with relatively simple, visual-based florescent screening using microscopic analyses of otoliths. Another promising approach would be marking otoliths with specific elements or isotopes and screening using laser mass-spectrometry. Accurate cost estimates for such marking must be developed to reflect different potential enhancement scenarios. At one extreme the potential enhancement scenarios range from rearing a relatively large number of eggs and larvae for short periods (< 2 months) prior to release. At the other extreme, a smaller number would be reared for reared for longer periods (~6 month).

Synopsis: Write and define a contract to prepare a report that will provide definitive approaches and/or methodology to mass marking. This report would include detailed review and analysis of the Japanese work and experience with mass marking of herring.
The report(s) should comment on the success rates for establishing marks and the costs related to different marking scenarios, at both ends of the process (marking and reading the marks at later stages).

Phase one – step three: Recapture and mark-detection methodology – a pre-application statistical guide concerned with issues of scale.

Mass marking of enhanced fish is an essential requirement to demonstrate the efficacy of any enhancement or restoration work. A complementary activity is determining the numbers of marked fish and recapture rates that must be made to demonstrate the capacity for survival of enhanced (marked) fish. When mass marking is considered for Prince William Sound, some key issues will be related to the numbers of marked fish that are released and the numbers that can be subsequently recaptured and screened. There may be significant costs related to the recapture and screening of marked fish. These costs will vary according to the numbers released, the estimated post-release survival and the efforts related to recapture. The costs of recapture and screening will be, approximately, inversely related to the numbers of release. For instance if a relatively high proportion of the total population can be marked and released, the effort related to recovery and screening is reduced. If the number of marked and released herring is proportionally small relative to the numbers of wild fish, then the efforts related to recapture and screening could be substantial and impractical.

For instance, if the proportion of marked fish in the population is only 0.001 (one in a thousand) then estimating the survival rates of enhanced fish with require examination of hundreds of thousands, or millions of fish. Probably this is impractical. However with an average recruitment of about twenty million herring per year in PWS, having a mark frequency of one fish in a thousand will require that twenty thousand marked fish survive to age three. If the mark frequency were higher, say one per hundred, then over two hundred thousand would have to survive to age three. Even if the frequency of marked herring were one per hundred at age three, the screening effort to assess the survival of marked fish would be considerable, requiring examination of thousands of fish – just to get single-digit estimates of survival, with wide (i.e., unreliable) confidence limits. Similarly a frequency of one in ten herring surviving to age thee would require survival of two million fish to age three. However, it seems probably that the required screening to assess survival, if ten percent of the population were marked, would be possible.

In each of these simplistic three mark-rate scenarios (0.001, 0.01 and 0.1 mark frequencies) substantial post-release mortality would require that the actual number of marked herring be much greater than the actual number estimated to be alive at age three. Probably the numbers of marked herring, prior to release, would be much greater by a factor of ten or a hundred. For example, assuming a one percent survival for each mark-rate scenario (0.001, 0.01 and 0.1 mark frequencies) the release numbers would have to be: two million fish, twenty million and two hundred million herring – released after an initial rearing period. Two hundred million herring would represent the progeny of roughly about 2 tons of herring, based on the approximate relative fecundity of about 10^8 eggs per tons of spawning herring. Therefore acquisition of sufficient eggs is not a problem with rearing such a number because this is a relatively small amount relative to the total population, even at present low levels of abundance. Instead the main issue of concern would be the cost and effort related to rearing such a large number of young herring prior to release.

Synopsis. There is a need for a dedicated report that comments on the feasibility of marking and different mark-recapture rates. Some relatively simple modelling and statistical analyses should investigate the options and financial costs of several release-recapture scenarios and relate this to the cost of rearing herring, prior to release.

References

Alderdice, D. F. and F. P. J. Velsen. 1971. Some effects of salinity and temperature on early development of Pacific herring (*Clupea pallasi*). Journal Fisheries Research Board Canada 28:1545-1562.

Arai, M.N., and Hay, D.E. 1982. Predation by medusae on Pacific herring (*Clupea harengus pallasi*) larvae. Canadian Journal of Fisheries and Aquatic Sciences 39: 1537-1540.

Arrhenius, F. 1995. Feeding ecology of Baltic Sea herring (*Clupea harengus* L.) field and model studies of a dominant zooplankton. Ph.D. thesis. Stockholm University, Stockholm, Sweden.

Arrhenius, F. 1996. Diet composition and food selectivity of 0-group herring (*Clupea harengus L.*) and sprat (*Sprattus sprattus* (L.)) in the northern Baltic Sea. ICES Journal of Marine Science 53:701-712.

Arrhenius F. and S. Hansson. 1996a. Food consumption of larval, young and adult herring and sprat in the Baltic Sea. Marine Ecology Progress Series 96: 125-137.

Arrhenius F. and S. Hansson. 1996b. Growth and seasonal changes in energy content of young Baltic Sea herring (*Clupea harengus* L.) ICES Journal of Marine Science 53: 792-801.

Arrhenius, F. and S. Hansson. 1999. Growth of Baltic Sea young-of-the-year herring Clupea harengus is resource limited. Marine Ecology Progress Series 191:295-299.

Axenrot, T. and S. Hansson. 2003. Predicting herring recruitment from young-of-the-year densities, spawning stock biomass, and climate. Limnology and Oceanography 48:1716–1720.

Bakun, A. and S.J. Weeks. 2006. Adverse feedback sequences in exploited marine systems: are deliberate actions warranted? Fish and Fisheries 7: 316-333.

Bartley, D.M. and Leber, K.M. (eds). Marine ranching. FAO Fisheries Technical Paper 429. FAO. Rome. 2004. 213p.

Begg, G.A., S.E. Campana, A.J. Fowler and I.M. Suthers. 2005. Otolith research and application: current directions in innovation and implementation. Marine and Freshwater Research 56: 477-483.

Bell, J.D., D.M. Bartley, K. Lorenzen, N.R. Loneragan. 2006. Restocking and stock enhancement of coastal fisheries: potential, problems and progress. Fisheries Research 80: 1-8.

Blaxter, J.H.S. 1968. Rearing herring larvae to meta-morphosis and beyond. Journal Marine Biological Association U.K. 48: 17-28.

Blaxter, J.H.S. 2000. The enhancement of marine fish stocks. Advances in Marine Biology 38:1-54.

Born, F., A.J. Immink and D.M. Bartley. 2004. Marine and coastal stocking: global status and information needs. In Marine Ranching. FAO Technical Paper 429. FAO. Rome. 213 p.

Caddy, J.F. and D.J. Agnew. 2004. An overview of recent global experience with recovery plans for depleted marine resources and suggested guidelines for recovery planning. Reviews in Fish Biology and Fisheries 14: 43-112.

Carls, M.G, G.D. Marty and J.E. Hose. 2002. Synthesis of the toxicological impacts of the Exxon Valdez oil spill on Pacific herring (*Clupea pallasi*) in Prince William Sound, Alaska, U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 59: 153-172.

Carls, M.G., G.D. Marty, T.R. Meyers, R.E. Thomas and S.D. Rice. 1998. Expression of viral hemorrhagic septicemia virus in pre-spawning Pacific herring (*Clupea pallasi*) exposed to weathered crude oil. Canadian Journal Fisheries Aquatic Science 55: 2300-2309.

Cross, A.D., D.A. Beauchamp, J.L. Armstrong, M. Blikshteyn, J.L. Boldt, N.D. Davis, L.J. Haldorson, J.H. Moss, K.W. Myers and R.V. Walker. 2005. Consumption demand of juvenile pink salmon in Prince William Sound and the coastal Gulf of Alaska in relation to prey biomass. Deep-Sea Research II, 52: 347–370.

Cushing, D.H. 1983. Are fish larvae too dilute to affect the density of their food organisms? Journal Plankton Research 5: 847-854

FAO. 1986. Production in Marine hatcheries. B. Loix (ed). FAO. Rome. 350 p.

FAO. 1996. Manual on the production and use of live food for aquaculture. P. Lavens and P Sorgeloos (eds). FAO Fisheries Technical Paper 361. FAO. Rome. 1996. 295p.

Foy R.J. and B.L. Norcross. 1999a. Spatial and temporal variability in the diet of juvenile Pacific herring (*Clupea pallasi*) in Prince William Sound, Alaska. Canadian Journal of Zoology 77 :697-706.

Foy R.J. and B.L. Norcross. 1999b. Feeding behavior of herring (Clupea pallasi) associated with zooplankton availability in Prince William Sound, Alaska. Pages 129-135 in: Ecosystem Approaches for Fisheries Management. University of Alaska Sea Grant College Program Report 99-01. Fairbanks, Alaska, USA.

Foy, R.J. 2001. Temperature effects on zooplankton assemblages and juvenile herring feeding in Prince William Sound, Alaska. Pages 21-36 in: Funk F, J. Blackburn, D. Hay, A.J. Paul, R. Stephenson, R. Toresen and D. Witherell (eds). Herring: Expectations for a New Millenium. Proceedings of the 18th Lowell Wakefield Fisheries Symposium, February

23-26, 2000. Anchorage, Alaska. University of Alaska Sea Grant Program Report No. 01-04, Fairbanks, Alaska, USA.

Galkina, L.A. 1971. Survival of spawn of the Pacific herring (*Clupea harengus pallasii* Val.) related to the abundance of the herring stock. Rapp. P.-V. Reun. Cons. Explor. Mer. 160: 30-33.

Grimes, C.B. 1998. Marine stock enhancement: sound management or techno-arrogance? Fisheries 23: 18–23.

Haegele, C.W. 1997. The occurrence, abundance and food of juvenile herring and salmon in the Strait of Georgia, British Columbia in 1990 to 1994. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2390: 124 p.

Haegele, C.W. and J.F. Schweigert. 1989. Egg loss from pacific herring spawns in Barkley Sound in 1988. Canadian Management Report of Fisheries and Aquatic Sciences 2037. 37 p.

Haegele, C.W. and J.F. Schweigert. 1991. Egg loss in herring spawns in Georgia Strait, British Columbia, Canada. pp 309-322. *In*· Westpestad V. J. and E Collie (eds). Proceedings of the International Herring Symposium, October 23-25, 1990, Anchorage, Alaska. Alaska Sea Grant College Program Report No. 91-01. Alaska Sea Grant College Program, University of Alaska, Fairbanks, Alaska, USA.

Haegele, C.W. 1993. Seabird predation of Pacific herring, *Clupea pallasi*, spawn in British Columbia. Canadian Field Naturalist 107:73-82.

Hauser, L., G.J. Adcock, P. J Smith, J.H.B. Ramirez and G. R. Carvalho. 2002. Loss of microsatellite diversity and low effective population size in an overexploited population of New Zealand snapper (*Pagrus auratus*). Proceedings National Academy Science. USA 99: 11742–11747.

Hay, D.E. 1981. Effects of capture and fixation on gut contents and body size of Pacific herring larvae. Rapp. P.-v. Reun. Cons. Int. Explor. Mer. 178:395-400.

Hay, D.E. 1985. Reproductive biology of Pacific herring (*Clupea harengus pallasi*). Canadian Journal of Fisheries and Aquatic Sciences 42: 111-126.

Hay, D.E. 1986. Effects of delayed spawning on the viability of eggs and larvae of Pacific herring. Transactions American Fisheries Society 115:155-161.

Hay, D.E. and J.R. Brett. 1988. Maturation and fecundity of Pacific herring: an experimental study with comparisons to natural populations. Canadian Journal of Fisheries and Aquatic Sciences 45: 399-406.

Hay, D.E. and M.J. Marliave, 1988. Transplanting Pacific herring spawn: a stocking experiment. American Fisheries Society Symposium 5:49-59.

Hay, D.E., and D.C. Miller. 1982. A quantitative assessment of herring spawn lost by storm action in French Creek, 1980. Canadian Manuscript Report of Fisheries and Aquatic Sciences 1636.

Hay, D.E. and P.B. McCarter. 1997a. Continental shelf area, distribution, abundance and habitat of herring in the North Pacific. Wakefield Fisheries Symposium. Alaska Sea Grant College Program 97-01: p 559-572.

Hay, D.E. and P.B. McCarter. 1997b. Larval retention and stock structure of British Columbia herring. Journal Fisheries Biol. 155-175.

Hay, D.E. and P. B. McCarter. 2006. Herring spawning areas of British Columbia. A review, geographic analysis and classification. http //www pac dfo-mpo gc ca/sci/herring/herspawn/pages/project_e htm Revised edition from original (Hay, D.E., P.B. McCarter, R. Kronlund and C. Roy. 1989. Spawning areas of British Columbia herring: a review, geographical analysis and classification. Volumes 1-6. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2019.)

Hay, D. E., J .F. Schweigert, M. Thompson, C.W. Haegele and P. Midgley. 2002. Analyses of juvenile surveys for recruitment prediction in the Strait of Georgia. PSARC Working Paper 2002-03. 33p.

Hay, D.E., M.J. Thompson, and P.B. McCarter. 2001. Anatomy of a strong year class: Analysis of the 1977 year class of Pacific herring in British Columbia and Alaska. Pp. 171-198. In Funk, F. J. Blackburn. D. Hay, A.J. Paul, R. Stephenson, R. Toresen, and D. Witherall. (eds). Herring: expectations for a new millennium. University of Alaska Sea Grant, AK-SG-01-04, Fairbanks. 773p.

Hershberger, P.K., R.M. Kocan, N.E. Elder, T.R Meyers and J.R. Winton. 1999. Epizootiology of viral hemorrhagic septicemia virus in Pacific herring from the spawn-on-kelp fishery in Prince William Sound, Alaska, USA. Diseases Aquatic Organisms 37:23-31.

Houde, E.D. 1989. Comparative growth, mortality, and energetics of marine fish larvae: Temperature and implied latitudinal effects. Fishery Bulletin 87(3) 471-495.

Houde, E.D. and S.A. Berkeley. 1979. Juvenile Pacific herring *Clupea harengus pallasi:* feeding in CEPEX enclosures. C.M. 1979/L:23. Biological Oceanography Committee, Ref. Pelagic Fish Committee.

Houde, E.D. and S.A. Berkeley. 1982. Food and growth of juvenile herring Clupea harengus pallasi in CEPEX enclosures. p 239-249. *In* Marine mesocosms. G.D.Grice, and M.R. Rove (eds). Biological and chemical research in experimental ecosystems. Springer-Verlag. NY.

Hourston, A.S., H. Rosenthal and H. von Westernhagen. 1984. Viable hatch from eggs of Pacific herring (*Clupea harengus pallasi*) deposited at different intensities on a variety of substrates. Canadian Technical Report Fisheries Aquatic. Science 1274. 19 p.

Kitada, S and H. Kishino. 2006. Lessons learned from Japanese marine finfish stock enhancement programmes. Fisheries Research 80: 101-112.

Kitada, S., T. Hayashi and H. Kishino. 2000. Empirical Bayes procedure for estimating genetic distance between populations and effective population size. Genetics:156: 2063-2079.

Kitakado, T., S. Kitada, H. Kishino and H.J. Skaug. 2006. An integrated-likelihood method for estimating genetic differentiation between populations. Genetics 173: 2073-2082.

Kobayashi, T. 2001. Biological characteristics and stock enhancement of Lake Furen herring distributed in northern Japan. In Funk, F. J. Blackburn. D. Hay, A.J. Paul, R. Stephenson, R. Toresen, and D. Witherall. (eds). Herring: expectations for a new millennium. University of Alaska Sea Grant, AK-SG-01-04, Fairbanks. 773p.

Kocan, R.M., G.D. Marty, M.S. Okihiro, E.D. Brown and T.T. Baker. 1996. Reproductive success and histopathology of individual Prince William Sound herring 3 years after the *Exxon Valdez* oil spill. Canadian Journal Fisheries Aquatic Science 53: 2388-2393.

Kocan, R. M., P.K. Hershberger, T. Mehl, N. Elder, M.Bradley, D. Wildermuth, and K. Stick. 1999. Pathogenicity of *Ichthyophonus hoferi* for laboratory reared Pacific herring *Clupea pallasi* and its early appearance in wild Puget Sound herring. Diseases of Aquatic Organisms 35:23–29.

Kocan, R.M., Bradley, M., Elder, N., Meyers, T., Batts W., and Winton, J. 1997. The North American strain of viral hemorrhagic septicemia virus is highly pathogenic for laboratory reared Pacific herring. Journal Aquatic Animal Health, 9: 279–290.

Kreiberg, H., J. R. Brett, A. Solmie, and R. A. Carter. 1986. A handbook on impounding sac-roe herring. Canadian Industry Report Fisheries Aquatic Sciences 168: 46 p.

Kreiberg, H. and A. Solmie. 1987. A production scale towable netpen for efficient high-volume transport of Pacific herring: design and comparative performance. Aquacultural Engineering 6:289-299.

Kurata, H. 1959. Preliminary report on the rearing of the herring larvae. Bulletin of the Hokkaido Regional Fisheries Research Laboratory 20: 117-138. (In Japanese with English abstract).

Kvenseth, P.G . and V. Øiestad. 1984 . Large-scale rearing of cod fry in an enclosed pond on the natural food production. In E. Dahl, D.S. Danielssen, E. Moksness and P Solemdal (eds). The propagation of cod *Gadus morhua* L. Flodevigen Rapportser1: 645-655.

Lasker, R. 1985. What limits clupeoid production? Canadian Journal of Fisheries and Aquatic Sciences 42: 31-37.

Lavens, P; and P. Sorgeloos. (eds). Manual on the production and use of live food for aquaculture. FAO Fisheries Technical Paper. No. 361. Rome, FAO. 1996. 295p.

Lorenzen, K. and K. Enberg. 2001. Density-dependent growth as a key mechanism in the regulation of fish populations: evidence from among-populations comparisons. Proceedings Royal Society London (B) 269:45-54.

MacCall, A. D. 1989. Against marine fish hatcheries: ironies of fisheries politics in the technological era. California Cooperative Fisheries Investigation Report 30: 46–48.

Marty, G. D., E.F. Freiberg, T.R. Meyers, J. Wilcock, T.B. Farver and D.E. Hinton. 1998. Viral hemorrhagic septicemia virus, *Ichthyophonus hoferi*, and other causes of morbidity in Pacific herring *Clupea pallasi* in Prince William Sound, Alaska, USA. Diseases of Aquatic Organisms 32:15–40.

Marty, G.D., T.J. Quinn II, G. Carpenter, T.R. Meyers and N.H. Willits. 2003. Role of disease in abundance of a Pacific herring (*Clupea pallasi*) population. Canadian Journal of Fisheries and Aquatic Sciences. 60: 1258–1265.

Meyer, H.A. 1878. Biologische Beobachtungen bei Künstlicher Aufzucht des Herins westlichen Ostee. (Translation by Herman Jacobsen). Presented in United States Commission of Fish and Fisheries. 1878. Report of the Commissioner. Part 4. Washington Government Printing Office. pp 629-831.

Moffit, S. 2005. Prince William Sound Pacific herring. In APPENDIX C . Ecosystem Considerations for 2006. J. Boldt. (ed). Alaska Fisheries Science Center, Seattle. Wash.

Moksness, E. 1990. A tagging and release experiment of 2-group artificially reared coastal cod (*Gadus morhua*). Flødevigen rappoertser 1: 33-41.

Molony, BW., R. Lenanton, G. Jackson and J. Norriss. 2003. Stock enhancement as a fisheries management tool. Reviews in Fish Biology and Fisheries 13: 409–432.

Morita, S. 1985. History of the herring fishery and review of artificial propagation techniques for herring in Japan. Canadian Journal of Fisheries and Aquatic Sciences 42: 222-229.

Myers, R.A. 2002. Recruitment: understanding density-dependence in fish populations. In Hart, P. and J.D. Reynolds. (eds). Fish and Fisheries handbook. Volume 1: 123-148.

Niva, T., P. Keränen, J. Raitaniemi and H.M. Berger. 2005. Improved interpretation of labeled fish otoliths: a cost-effective tool in sustainable fisheries management. Marine and Freshwater Research 56: 705–711.

Norcross, B.L. and E.D. Brown. 2001. Estimation of First-Year Survival of Pacific herring from a Review of Recent Stage-Specific Studies, pp. 535-558. In Funk, F. J. Blackburn. D. Hay, A.J. Paul, R. Stephenson, R. Toresen, and D. Witherall. (eds). Herring: expectations for a new millennium. University of Alaska Sea Grant, AK-SG-01-04, Fairbanks. 773p.

Norcross, B.L., E.D. Brown, R.J. Foy, M. Frandsen, S. Gay, T. Kline, D.M. Mason, E.V.Patrick, A. Paul, and K.D.E. Stokesbury. 2001. A synthesis of the life history and ecology of herring in Prince William Sound, Alaska. Fisheries Oceanography (suppl. 1)10: 42-57.

O'Connell, M., M.C. Dillon, J. M. Wright, P. Bentzen, S. Merkouris, and J. Seeb. 1998b. Genetic structuring among Alaskan Pacific herring populations identified using microsatellite variation. Journal Fisheries Biology 53:150-163.

Okey, T.A. and D. Pauly. 1998. Trophic Mass-Balance Model of Alaska's Prince William Sound Ecosystem, for the Post-Spill Period 1994-1996. 2nd Edition. In Okey, T.A. and D. Pauly. *(eds)*. University of British Columbia Fisheries Centre Research Report Volume 6 Number. (Exxon Valdez Oil Spill Trustee Council. Annual Report. Restoration Project 98330-1. ISSN 1198-6727

Øiestad, V. 1983. Growth and survival of herring larvae and fry (*Clupea Harengus* L.) exposed to different feeding regimes in experimental ecosystems: outdoor basin and plastic bags. Unpublished report. 299 p.

Øiestad, V. and E. Moksness. 1981. Study of growth and survival of herring larvae (Clupea harengus L.) using plastic bag and concrete basin enclosures. Rapp. P.-v Reun. Cons. int. Explor. Mer 178: 144-149.

Øiestad, V. 1982. Application of enclosures to studies on the early life history of fishes. In Marine mesocosms. G.D. Grice and M.R. Reeve. ed. Springer-Verlag. New York.

Okouchi, H. and N. Masahiro. 2006 (Abstract). Homing of herring released in Miyako Bay. Third International Symposium on stock enhancement and sea ranching. Seattle, Washington.

Palsson, W. A. 1984. Egg mortality upon natural and artificial substrata within Washington state spawning grounds of Pacific herring *(Clupea harengus pallasi*). Masters Thesis, Univ. Washington, Seattle, WA. 191 p.

Paul, A.J. and J.M. Paul. 1998a. Comparisons of whole body energy of captive fasting age zero Alaskan Pacific herring (*Clupea pallasi Valenciennes*) and cohorts over-wintering in nature. Journal of Experimental Biology and Ecology 226(1):75-86.

Paul A.J. and J.M. Paul. 1998b. Spring and summer whole body energy content of Alaskan juvenile Pacific herring. Alaska Fisheries Research Bulletin 5(2):131-136.

Paul A.J. and J.M. Paul. 1999. Interannual and regional variations in body length, weight, and energy content of age 0 Pacific herring from Prince William Sound, Alaska. Journal Fish Biology 54:996-1001.

Paul, A.J., J.M. Paul and E.D. Brown. 1998. Fall and spring somatic energy content for Alaskan Pacific herring (*Clupea pallasi Valenciennes 1847*) relative to age, size and sex. Journal Experimental Marine Biology and Ecology 223:133-142.

Pearson, W.H., R.A. Elston, R.E. Bienert, A.S, Drum, and L.D. Antrim. 1999. Why did the Prince William Sound, Alaska, Pacific herring (*Clupea pallasi*) fisheries collapse in 1993 and 1994? Review of hypotheses. Canadian Journal of Fisheries and Aquatic Sciences 56: 711-737.

Purcell, J.E., E.D. Brown, K.D.E. Stokesbury, L.H. Haldorson and T.C. Shirley. 2000. Aggregations of the jellyfish *Aurelia labiata*: abundance, distribution, association with age-0 Pollack, and behaviors promoting aggregation in Prince William Sound, Alaska, USA. Marine Ecology Progress Series 195: 145-158.

Purcell J.E., 1989. Predation by the hydromedusa *Aequorea victoria* on fish larvae and eggs at a herring spawning ground in British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46: 14 15- 1427.

Purcell J.E., 1990. Soft-bodied zooplankton predators and competitors of larval herring *(Clupea harengus pallasi)* at herring spawning grounds in British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 47:505-515.

Rice S.D. R.B. Spies, D.A. Wolfe and B.A. Wright. (eds) Proceedings of the Exxon Valdez Oil Spill Symposium. American Fisheries Society Symposium No. 18. American Fisheries Society, Bethesda, Maryland, USA.

Robinson S.M.C. and D.M. Ware. 1988. Ontogenetic development of growth rates in larval Pacific herring, *Clupea harengus pallasi,* as measured with RNA-DNA ratios in the Strait of Georgia, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences. 45:1422-1429.

Ronholt, L.L., H.H. Shippen and E.S. Brown. 1978. Demersal fish and shellfish resources of the Gulf of Alaska from Cape Spencer to Unimak Pass 1948-1976. (A historical Review). Northwest and Alaska Fisheries Center. Processed Report. Volume I. 277 p.

Rooper, C. L.J. Haldorson, and T.J. Quinn. 1998. An egg-loss correction for estimating spawning biomass of Pacific herring in Prince William Sound, Alaska. Alaska Fisheries Research Bulletin 5:137-142.

Rooper, C., L.J. Haldorson, and T.J. Quinn. 1999. Habitat factors controlling Pacific herring (*Clupea pallasi*) egg loss in Prince William Sound, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 56(6):1133-1142.

Rounsefell, G.A. 1929. Contribution to the biology of the Pacific herring *Clupea pallasii*, and the condition of the fishery in Alaska. Bulletin of the Bureau of Fisheries. 45:227-320.

Sasaki, M., R. Isheda and T. Shiro. 2001. Distribution and feeding habits of juvenile herring (*Clupea pallasii*) in Northern Japan. p101-116. In Funk, F. J. Blackburn. D. Hay, A.J. Paul, R. Stephenson, R. Toresen, and D. Witherall. (eds). Herring: expectations for a new millennium. University of Alaska Sea Grant, AK-SG-01-04, Fairbanks. 773p.

Schweigert, J. 2004. Stock assessment for British Columbia herring in 2004 and forecasts of the potential catch in 2005. Canadian Science Advisory Secretariat 2004/84: 89p.

Solemdal, P., E. Dahl, D.S. Danielssen and E. Moksness. 1984. The cod hatchery in Flødevigen – background and realities pp17-45. In E. Dahl,. D.S. Danielssen E. Moksness and P. Solemdal. (eds). The propagation of cod Gadus morhua L. An international symposium, Arendal 14-17 June 1983. Flødevigen rappoertser Vol. 1. 439 p.

Spratt, J.D. 1976. The Pacific herring resource of Tomales and San Francisco Bays: its size and structure. California Fish & Game Marine Research Technical Report 33.

Stevenson, J. C. 1962. Distribution and survival of herring larvae (*Clupea pallasi*, Valenciennes) in British Columbia waters. Journal Fisheries Research Board Canada 19:735-810.

Stokesbury K.D.E., R.J. Foy and B.L. Norcross. 1999a. Spatial and temporal variability in juvenile Pacific herring, *Clupea pallasi*, growth in Prince William Sound Alaska. Environmental Biology of Fishes 56(4):409-418.

Stokesbury, K.D.E., J. Kirsch, E.D. Brown, G.L. Thomas and B.L. Norcross. 1999. Spatial distributions of Pacific herring, *Clupea pallasi*, and walleye pollock, *Theragra chalogramma*, in Prince William Sound, Alaska. Fishery Bulletin 98:400-409.

Suzuki, S. and K. Fukunaga. 2004. Stocking effectiveness of Pacific herring (Clupea pallasi) in the Akkeshi Bay Area, Hokkaido. Technical report of Stock Enhancement Center 1: 95-98.

Talbot, G.B. and S.I Johnson. 1972 Rearing Pacific herring in the laboratory. The Progressive Fish-Culturalist 34(1):2-9.

Walters, C.J. & Martell, S.J.D. (2004) Fisheries Ecology and Management. Princeton University Press, Princeton.

Wespestad, V., G. Bargmann and D.E. Hay. 1994. Opportunities for the enhancement of the lingcod, *Ophiodon elongatus* Girard in Puget Sound and Georgia Strait. Aquaculture and Fisheries Management 25: 189-197.

Wespestad, V and E . Moksness. 1990 . Observations on the early life history of Pacific herring (*Clupea harengus pallasi*) from Bristol Bay, Alaska, in a marine mesocosm. Fishery Bulletin 88: 191-200 p.

Williams, E.H., and T.J. Quinn, II. 2000. Pacific herring *Clupea pallasi* recruitment in the Bering Sea and north-east Pacific Ocean, I: relationships among populations. Fisheries Oceanography 9: 285-299.

Williams, E.H., and T.J. Quinn, II. 2000. Pacific herring *Clupea pallasi* recruitment in the Bering Sea and north-east Pacific Ocean, II: relationships to environmental variables and among populations. Fisheries Oceanography 9:285-299.

Woodby, D., D.Carlile, S. Siddeek, F. Funk, J.H. Clark and L. Hulbert. 2005. Commercial fisheries of Alaska. Alaska Department of Fish and Game. Special Publication No. 05-09.

(a)

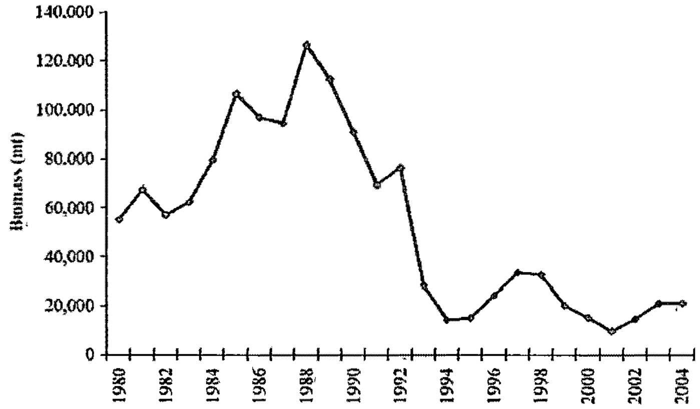


Figure 50 Prefishery run biomass (metric tons) of adult Pacific herring in Prince William Sound, 1980-2004 The biomass values are calculated from the age-structured model used to produce the 2005 projections

(b)

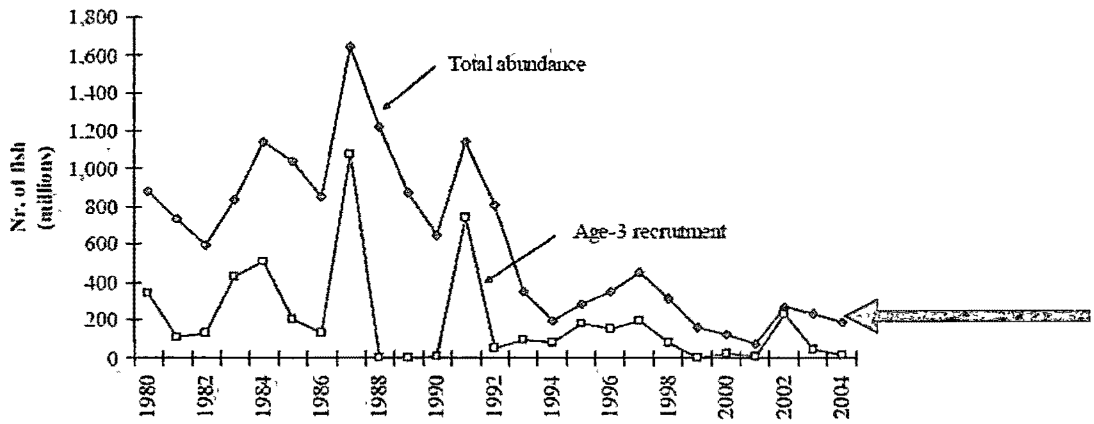


Figure 49 Age-3 recruitment and total prefishery abundance of Pacific herring in Prince William Sound, 1980-2004. The abundance values are outputs of the age-structured model used to produce the 2005 projections

Fig. 1. Herring abundance trends in Prince William Sound.

(a) (Copied from Moffit 2005). Prefishery run biomass (metric tons) of adult Pacific herring in Prince William Sound, 1980-2004. The biomass values are calculated from the age-structured model used to produce the 2005 projections. (b) (Copied from Moffit 2005). Total numbers of herring (age 3 and older) and numbers of age 3 recruits in Prince William Sound. The arrow to the right shows the approximate present level of recruitment at about 200,000,000 fish/y.

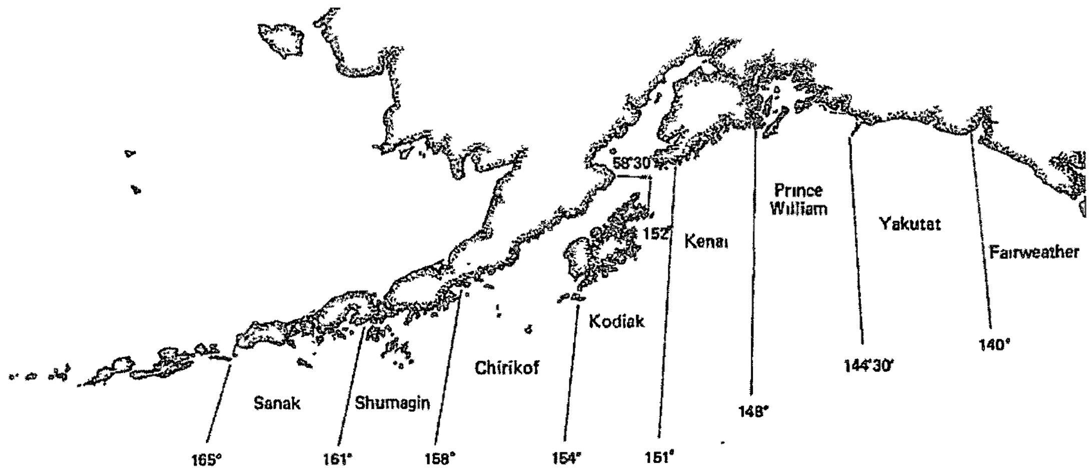


Fig. 2. The Gulf of Alaska showing different districts.

The Prince William district contains both the inside waters of Prince William Sound and the adjacent waters. (Copied from Ronholt et al. 1978). See text for explanation.

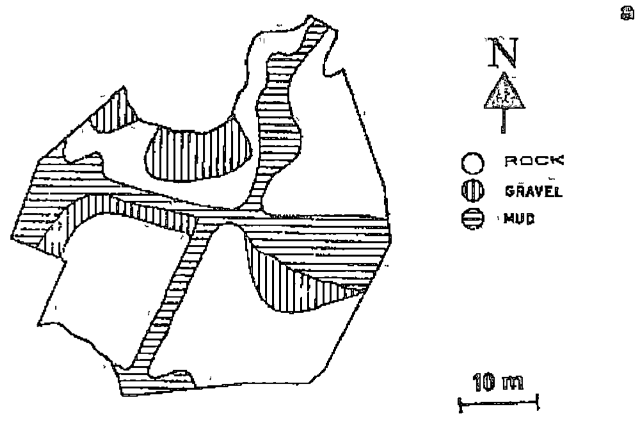


Fig. 1a. The basin, with main bottom types indicated.

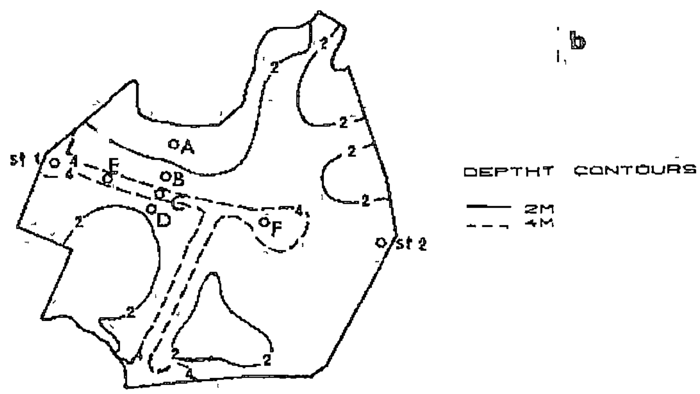


Fig. 1b. The basin, with depth contours and sampling stations indicated. 1: weekly monitoring of hydrography, nutrition salts, and phytoplankton; 1 and 2: weekly monitoring of zooplankton (pump sampling); 2 → 1: net sampling for fish larvae and zooplankton; A,B,C,D and 1,E,C,F,2: zooplankton sampling along transects (pump sampling).

Fig. 3. Illustration of outdoor mesocosms used for larval fish rearing in Flödevigen, Norway. (Copied from Øiestad 1983). Outdoor enclosures such as this may be suitable for larval and juvenile rearing projects in Prince William Sound.

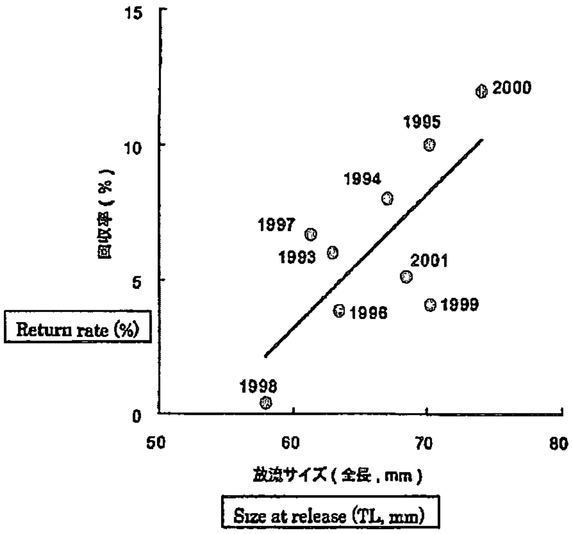
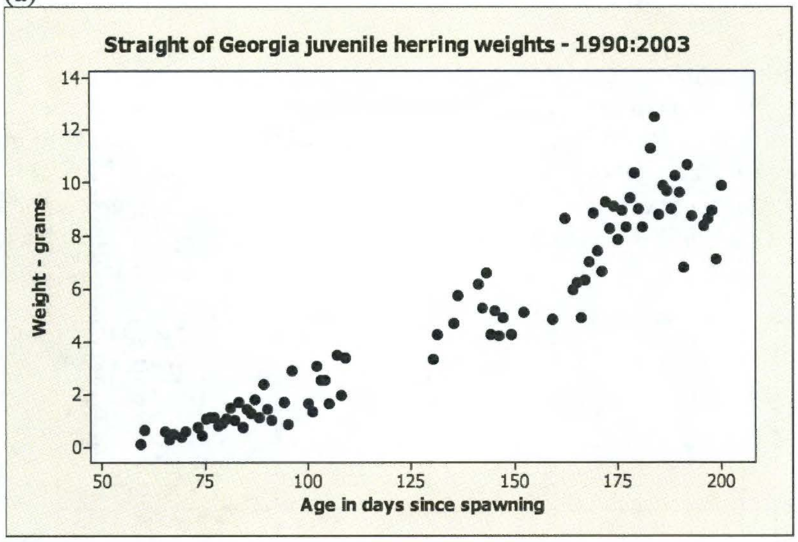


Fig. 4. Relationship between the size at release of age 0 herring juveniles.

The line shows the estimated percentage of returning spawners relative to the size of release (mm) to Akkeshi Bay, eastern Hokkaido. Copied from Suzuki and Fukunaga (2004). (See text for explanation).

(a)



(b)

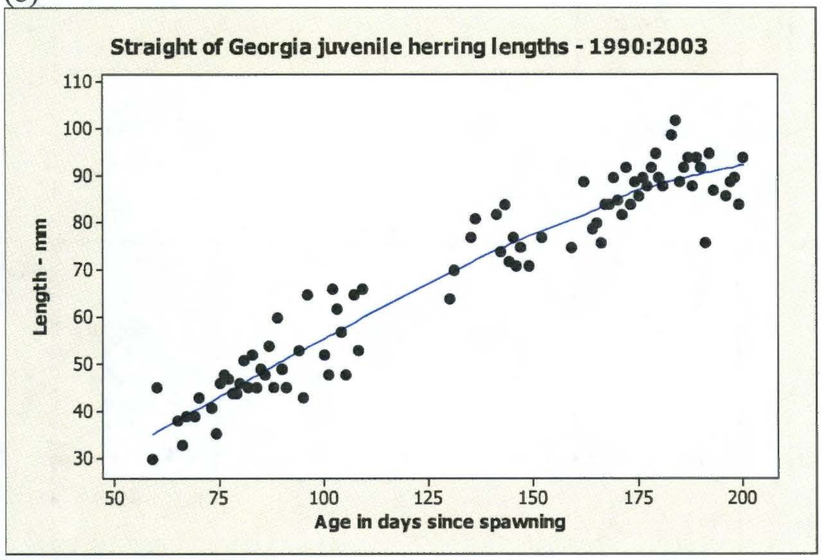


Fig. 5. (a) Weight (g) and (b) length (mm) by age (days) for juvenile herring in the Strait of Georgia. The data were aggregated over sample years from approximately 1990-2003.

Table 1. Simplified life history stages of Pacific herring in Prince William Sound.
The table shows 'within' cohort interactions in column A, as the cohort ages from eggs to adults – progressing from Row 1-6. 'PWS-Gulf' refers to possible adult herring migrations to adjacent shelf waters in the Gulf of Alaska. Columns B-D show 'between-cohort' interactions, with eth stop symbol indicating little or no interactions. The shaded boxes show the largest interactions. For instance age 1+ herring will complete for food with age 0+ juveniles (column-row B3). Column E shows interactions between different stages of herring and other species.

		Within Cohort	Between Cohorts	Between Cohorts	Between Cohorts	Between species
		A	B	C	D	E
	Stage		1+ Juvenile	2+ Pre-recruit	Adult	Other species
1	Egg$_{(y)}$ PWS	Oxygen and abiotic factors PWS 1			Eggs = SSB x 10^{8}- PWS 12	Predation, disease PWS 18
2	Larvae$_{(y)}$ PWS	Spring-Food Competition PWS 2	Spring-summer Predation PWS 7	Spring-summer Predation PWS 9	Spring-summer Predation PWS 13	Spring-summer Predation PWS 19
3	0+ Juvenile$_{(y)}$ PWS	Summer-fall-winter food competition PWS 3	Late summer - fall food competition PWS 8	Late summer - fall food competition PWS 10	Late summer - fall food competition PWS 14	Predation Late summer - Fall Food Competition PWS 20
4	1+ Juvenile$_{(y+1)}$ PWS-GULF	Summer-fall-winter food competition PWS-GULF 4		Food competition PWS-GULF 11	Food competition PWS-GULF 15	Predation food competition PWS-GULF 21
5	2+ Pre-recruit$_{(y+2)}$ PWS-GULF	Summer-Fall-winter food competition PWS-GULF 5			Food competition PWS-GULF 16	Predation food competition PWS-Gulf 22
6	Adult$_{(y+3+)}$ PWS-GULF	Predation food competition PWS-GULF 6			Food competition PWS-GULF 17	Predation food competition PWS-GULF 23

Table 2. Comparison of depth strata between Prince William Sound (PWS) and the Strait of Georgia (SOG). PWS data are from Table 1 (Okey, 1998) in Okey and Pauly, 1998. The SOG depth strata data were derived from GIS (Arcview©) analyses of BC Statistical areas for all areas of the Straight of Georgia (Statistical Areas 14-19, 28-29 and part of 13, but excluding all of Puget Sound). The SOG depth strata intervals were adjusted to match those presented for PWS.

Depth stratum (m)	PWS		SOG	
	Area (km^2)	%	Area (km^2)	%
intertidal (+ - 0)	300	3 31	215	2 37
0-10	709	7 83	597	6 57
10-20	709	7 83	312	3 43
20-100	2018	22 28	2591	28 53
>100	5325	58 76	5364	59 08
TOTAL	9059	100 00	9080	100 00

Table 3. Estimates of stage-specific survival.

For each of nine life history stages (first column) the table shows the estimated duration of the stage (in days) and approximate weight (grams) of each individual (at the conclusion of each stage). Based on information described in the text, the six columns to the right show the minimum, maximum and average estimates of survival (p). The underlined numbers show estimates taken from Norcross and Brown (Table 4) 2001. The survival rates shown in the last three columns are in exponential format (E), and are identical to the previous three columns that are shown in arithmetic format.

Life History Stage	Durations *days*	Age at stage end *days*	Approx. weight at each stage *grams*	Minimum age-specific survival *p*	Maximim age-specific survival *p*	Average age-specific survival *p*	Minumum age-specific survival *rate*	Maximum age-specific survival *rate*	Average age-specific survival *rate*	Minumum age-specific survival *rate*	Maximum age-specific survival *rate*	Average age-specific survival *rate*
unfertilized eggs	0											
fertilized eggs	1	1	0 001	0 99	0 99	0 99	0 990000000	0 990000000	0 990000000	9 900E-01	9 900E-01	9 900E-01
eggs	20	20	0 001	0 24	0 45	0 345	0 237600000	0 445500000	0 341550000	2 376E-01	4 455E-01	3 416E-01
posthatch	10	30	0 02	0 5	1	0 75	0 118800000	0 445500000	0 256162500	1 188E-01	4 455E-01	2 562E-01
larval_drift	30	60	0 5	0 01	0 07	0 04	0 001188000	0 031185000	0 010246500	1 188E-03	3 119E-02	1 025E-02
fall_juveniles	120	180	8	0 02	0 21	0 115	0 000023760	0 006548850	0 001178348	2 376E-05	6 549E-03	1 178E-03
winter_juveniles	185	365	10	0 5	0 62	0 56	0 000011880	0 004060287	0 000659875	1 188E-05	4 060E-03	6 599E-04
age 2	365	730	40	0 05	0 5	0 275	0 000000594	0 002030144	0 000181466	5 940E-07	2 030E-03	1 815E-04
age 3	365	1095	120	0 05	0 5	0 275	0 000000030	0 001015072	0 000049903	2 970E-08	1 015E-03	4 990E-05

Table 4. Numbers and biomass at each life history stage in natural populations.

The first four columns show the same information as Table 3 (life history stage, duration, age at the end of the stage and the weight of individuals at the end of the stage). The table tracks the stage-specific survival of each stage according to three estimates of age-specific survival. minimum, maximum and average survival. The beginning number of eggs is one hundred million (10^8) – corresponding to the numbers of eggs produced by one mt of spawning herring. The underlined numbers, describing the minimum and maximum numbers of survivors, are identical to the estimates presented in Norcross and Brown (2001, Table 4) after adjusting for the 100-fold difference in starting numbers. The last six columns, showing estimated biomass (in grams and metric tons) show mixed responses Relative to the starting biomass, which is the cumulative weight of all one hundred million individual eggs, the cohort biomass decreases under the minimum survival scenario, increases under the maximum survival scenario and fluctuates under the average survival scenario.

Life History Stage	Durations *days*	Age at stage end *days*	Approx. weight at each stage *grams*	Cohort number minimum survival *number*	Cohort number maximum survival *number*	Cohort number average survival *number*	Cohort biomass - minimum survival *grams*	Cohort biomass - maximum survival *grams*	Cohort biomass - average survival *grams*	Cohort biomass - minimum survival *m tons*	Cohort biomass - maximum survival *m tons*	Cohort biomass - average survival *m tons*
unfertilized eggs				100000000	100000000	100000000						
fertilized eggs	1	1	0 001	99000000	99000000	99000000	99000	99000	99000	0 099	0 099	0 099
eggs	20	20	0 001	23760000	44550000	34155000	23760	44550	34155	0 024	0 045	0 034
posthatch	10	30	0 02	11880000	44550000	25616250	237600	891000	512325	0 238	0 891	0 512
larval_drift	30	60	0 5	118800	3118500	1024650	59400	1559250	512325	0 059	1 559	0 512
fall_juveniles	120	180	8	2376	654885	117835	19008	5239080	942678	0 019	5 239	0 943
winter_juveniles	185	365	10	1188	406029	65987	11880	4060287	659875	0 012	4 060	0 660
age 2	365	730	40	59	203014	18147	2376	8120574	725862	0 002	8 121	0 726
age 3	365	1095	120	3	101507	4990	356	12180861	598836	0 000	12 181	0 599

Table 5. Estimated survival in a hypothetical enhancement project.

The columns show the estimated minimum and maximum stage-specific survival rates in a hypothetical enhancement project. The life history stages follow those used in the Tables 3 and Table 4. A minimum and maximum survival estimate is estimated for each stage. These survival estimates, shown as probability of survival (p), are assumed to be much higher than those occurring in natural populations but the cumulative survival is lower than the estimates reported in Japanese herring enhancement research. These survival estimates are used to estimate the survival of one hundred million (10^8) eggs at the pre-fertilization stage to the 'fall juvenile' stage. The underlined numbers show the minimal estimates of survival (6.19 million or also about 6.19% survival) and maximal estimates of survival (57.18 million or about 57.18% survival) at the end of the fall juvenile stage, at an age of 6 months. Similar estimates are made for the end of the winter juvenile stage (shown in Italics). No further estimates are shown for survival in enhancement based on the assumption that release would occur at some time between during the winter juvenile stage – a stage when intra-specific density-dependent effects may be minimal.

Life History Stage	Duration *days*	Age at stage end *days*	Approx. weight at each stage *grams*	Minimum stage specific survival *p*	Minimum stage specific survival *numbers*	Minimum stage specific survival *numbers (millions)*	Maximum stage specific survival *p*	Maximum stage specific survival *numbers*	Maximum stage specific survival *numbers (millions)*	Biomass with minimum survival *grams*	Biomass with maximum survival *grams*	Biomass with minimum survival *m tons*	Biomass with maximum survival *m tons*
pre-fertilization					100,000,000			100,000,000					
fertilized	1	1	0 001	0 99	99,000,000	99	0 99	99,000,000	99	99,000	99,000	0 099	0 099
embryo	20	20	0 001	0 5	49,500,000	49 5	0 95	94,050,000	94 05	49,500	94,050	0 0495	0 09405
posthatch	10	30	0 02	0 5	24,700,000	24 7	0 95	89,347,500	89 3475	494,000	1,786,950	0 494	1 78695
larval_drift	30	60	0 5	0 5	12,375,000	12 375	0 8	71,478,000	71 478	6,187,500	35,739,000	6 1875	35 739
fall_juveniles	120	180	8	0 5	6,187,500	<u>6 1875</u>	0 8	57,182,400	<u>57 1824</u>	49,500,000	457,459,200	49 5	457 4592
winter_juveniles	*185*	*365*	*10*	*0 05*	*3,093,750*	*3 09375*	*0 99*	*56,610,570*	*56 61057*	*30,937,500*	*566,105,700*	*30 9375*	*566 1057*
age 2	365	730	40	—	—	—	—	—	—	—	—	—	—
age 3	365	1095	120	—	—	—	—	—	—	—	—	—	—

Table 6. Estimated survival following enhancement and release.

The estimated numbers and survival of herring reared in an enhancement project and released ('HEP Release') at approximately 6 months (180 days) of age. The life history stages follow those of Tables 3-5 but the estimates of stage-specific survival rates for wild herring (*prior to release*) are not used for these calculations but are included to illustrate how herring reared in an enhancement project may be subject to stage-specific survival rates, depending on the time of release. The estimated numbers of herring, surviving from an initial number of 100 million (from Table 5) is shown in the last three columns for the 'worst', 'best' and 'average' survival scenarios. In these scenarios the numbers of juveniles surviving to the point of release are about six million for the worst case scenario, 57 million for the best case scenario, and 31 million for the average case scenario. Once released these herring juveniles would then encounter survival rates applicable to wild herring, shown here as the minimum, maximum and average probability (p) of survival for three stages (winter juveniles, age 2 and age 3). The large ***bold Italic*** numbers at the lower right show the impact of these three 'post-release' survival scenarios imposed on three of the 'pre-release' survival scenarios that apply during enhancement.

Life History Stages	Durations *days*	Age at stage end *days*	Time of Release	Minimum age-specific survival *p*	Maximim age-specific survival *p*	Average age-specific survival *p*	scenario minimum HEP and lowest natural survival *numbers*	scenario maximum HEP and highest natural survival *numbers*	scenario average and average natural survival *numbers*
unfertilized eggs							100,000,000	100,000,000	100,000,000
fertilized eggs	1	1		0 99	0 99	0 99	99,000,000	99,000,000	99,000,000
eggs	20	20		0 24	0 45	0 345	49,500,000	94,050,000	71,775,000
posthatch	10	30		0 5	1	0 75	24,700,000	89,347,500	57,023,750
larval_drift	30	60		0 01	0 07	0 04	12,375,000	71,478,000	41,926,500
fall_juveniles	120	180	*HEP Release*	0 02	0 21	0 115	6,187,500	57,182,400	31,684,950
winter_juveniles	185	365		***0.5***	***0.62***	***0.56***	3,093,750	35,453,088	17,743,572
age 2	365	730		***0.05***	***0.5***	***0.275***	154,690	17,726,544	4,879,482
age 3	365	1095		***0.05***	***0.5***	***0.275***	***733***	***8,863,272***	***1,341,858***

Prince William Sound Herring Management

This chapter will outline 1) the current population status of Pacific herring *Clupea pallasii* in Prince William Sound (PWS), 2) the current regulatory management plan, 3) historical and current strategies employed in PWS for the commercial fisheries, 4) a review of the current regulatory threshold and exploitation rate policy, 5) compare and contrast the PWS management and strategies with other Pacific coast herring fisheries, 6) discuss possible recovery criteria, and 7) make suggestions for possible regulatory or other changes to the fisheries to help ensure long-term sustainability.

Current Prince William Sound Population Status

The Alaska Department of Fish and Game (ADF&G) has completed herring stock assessments in PWS since harvesting herring for roe or harvesting of roe-on-kelp began in 1969. Population trends were initially monitored with aerial surveys and beach surveys to estimate biomass and the linear extent of beach used for spawning (Brady 1987), and have continued almost without interruption. Age, sex, and size data has been collected from most fisheries and spawning aggregations since 1973 (e.g., Sandone 1988; Baker et al. 1991). Dive surveys to estimate spawning biomass began with feasibility studies in 1983 and 1984 and continued in 1988-1992 (Brown and Baker 1998) and 1994-1997 (Willette et al. 1998). In 1993, ADF&G in cooperation with the Prince William Sound Science Center (PWSSC) began fall acoustics surveys (e.g., Thomas and Thorne 2003). Spring (March/April) acoustics surveys have been conducted 1995-2007. Age structured models have been used since 1993 to estimate historical population parameters and project future biomass, recruitment, and abundance (e.g., Funk 1994). The current biomass trends are tracked with three measures of abundance: 1) aerial survey biomass estimates, 2) aerial survey mile-days of spawn, and 3) hydroacoustics survey estimates of the prespawning biomass.

The aerial survey biomass is estimated from small plane surveys conducted from late March through late April or early May. Survey methods are outlined by Brady (1987), and were little changed until recently. In 2006, ADF&G began using a tablet computer, a GIS application, and a GPS unit to collect survey track, biomass estimates, and the linear shoreline extent of spawn. A data collection application was written for the GIS software and used for the first time for the 2007 field season.

Mile-days of spawn are the sum of the daily survey estimates of the linear shoreline extent of milt in the water (Brady 1987). The peak biomass estimates are the sum of the peak daily estimates from the southeast, northeast, northern, Naked Island, and Montague Island areas of PWS. The historical time series (1973-2007) of mile-days of spawn were recalculated in 2007 after all maps were reexamined and digitized. The historical time series of biomass estimates is currently being recalculated as all data sheets are being examined and the biomass observations digitized. The recalculated mile-days of spawn and the historical peak biomass observations generally match changes in direction (Figure 1; $r = 0.606$). Aerial estimates of biomass are probably more variable than estimates of the linear extent of spawn. Biomass estimates are dependent on water depth, turbidity, school size, and the length of time that herring stage prior to spawning (Brady 1987).

APPENDIX C – MANAGEMENT REVIEW

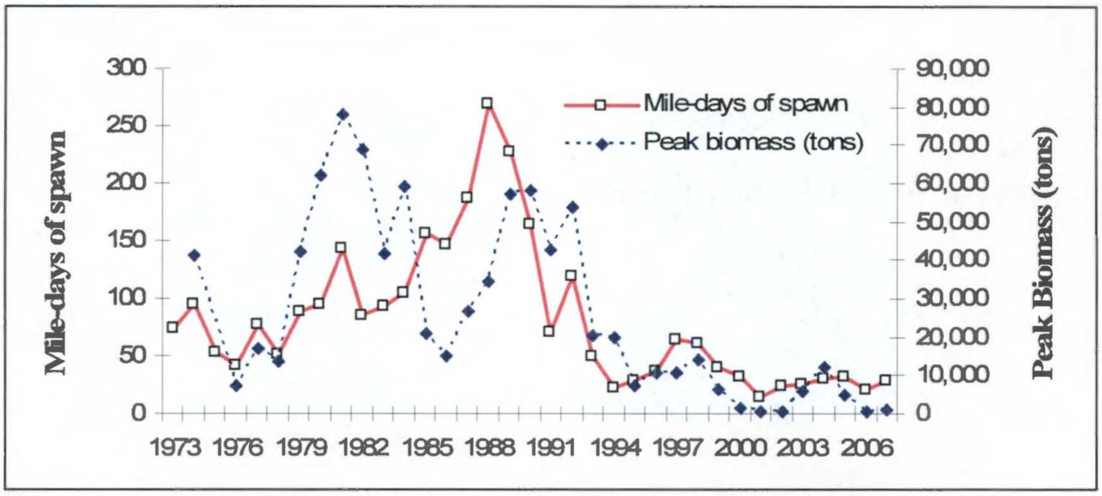


Figure 1. Historical time series of mile-days of spawn and peak biomass (tons) estimates from aerial surveys of Prince William Sound herring, 1973-2007.

Abundance trends are also tracked through hydroacoustics surveys conducted by ADF&G and PWSSC. Acoustics estimates have similar problems to aerial surveys. First the survey vessel has to locate fish aggregations and PWS is a large area to search without additional information. Additionally, the herring must be found when they are aggregated prior to spawning and not actively moving. The search is generally started in historical prespawn concentration areas in Port Gravina, Port Fidalgo, and northern Montague Island. Observations from aerial surveys or vessels transiting PWS often significantly reduce the search time. To obtain appropriate estimates of the spawning biomass (total biomass adjusted for age and maturity), samples for age, sex, and size must be obtained or estimated from other samples from nearby locations. The acoustics estimate trends generally follow those shown by the aerial survey estimates of mile-days of spawn (Figure 2; r = 0.675).

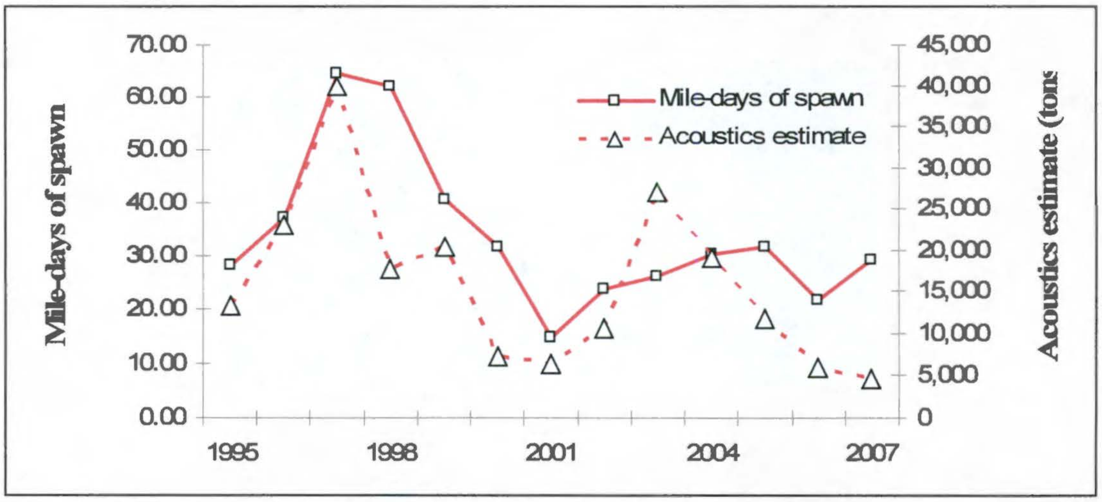


Figure 2. Mile-days of spawn and acoustics estimates of spawning biomass, 1995-2007.

The current stock assessment tool used for preseason forecast is an age structured assessment (ASA) model. The current model is a modified version of the Funk (1994) model adjusted to allow the integration of disease information (e.g., Quinn et al. 2001) and hydroacoustics estimates (Hulson et al. *in press*). The 2007 model output for the historical time series of abundance and biomass estimates that the total biomass and abundance are at their lowest level since 1980 even without any commercial fishing harvest since 1999 (Figure 3).

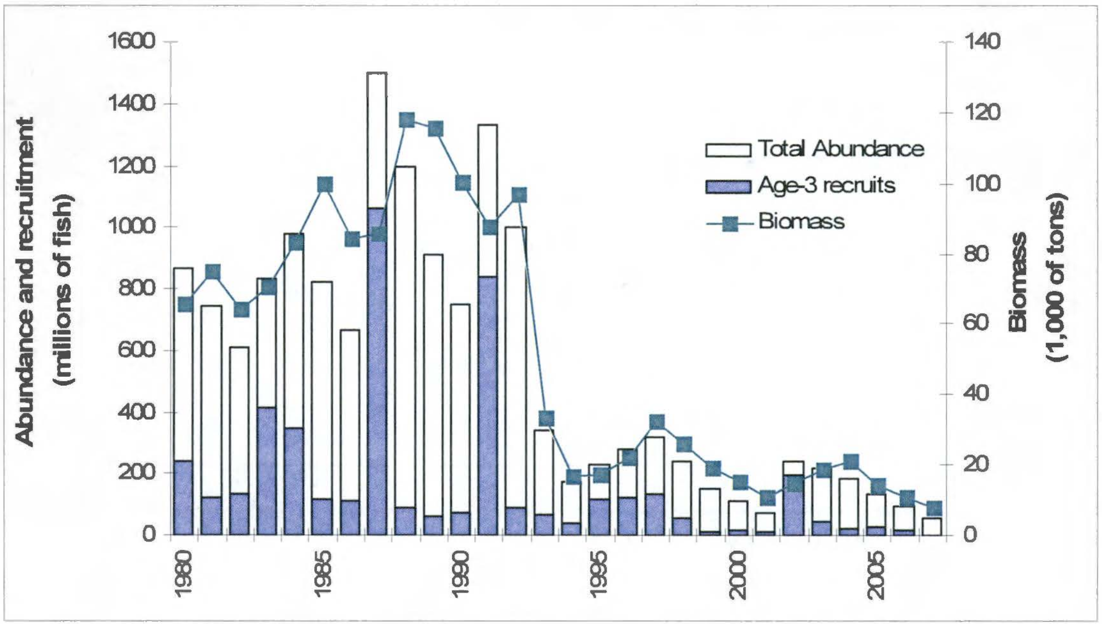


Figure 3. Total abundance, age 3 recruitment, and estimated prefishery run biomass from the 2007 version of the ASA model for Prince William Sound herring.

The estimated total prefishery run biomass for 2008 is 10,252 tons (9,301 metric tons). This much less than the 22,000 ton spawning biomass threshold required in regulation prior to any commercial fishing (5 AAC 27.365). However, there was a significant abundance of juvenile herring (< age 3) documented in PWS this summer during ADF&G surveys of juvenile salmon. Additional work in November 2007 documented large schools of juvenile herring in two locations in PWS.

Prince William Sound Management Plan

This section is intended to summarize the PWS management plan and associated regulations that may influence the health of the resource. As such this section does not review regulations that relate to items such as the size of the sign required on a pound structure.

The PWS management area (Registration Area E) is described in 5 AAC 27.300 as follows: "The Prince William Sound Area has as its western boundary a line extending south from Cape Fairfield, as its eastern boundary a line extending south from Cape Suckling and as its southern boundary 59° N. lat." (Figure 4).

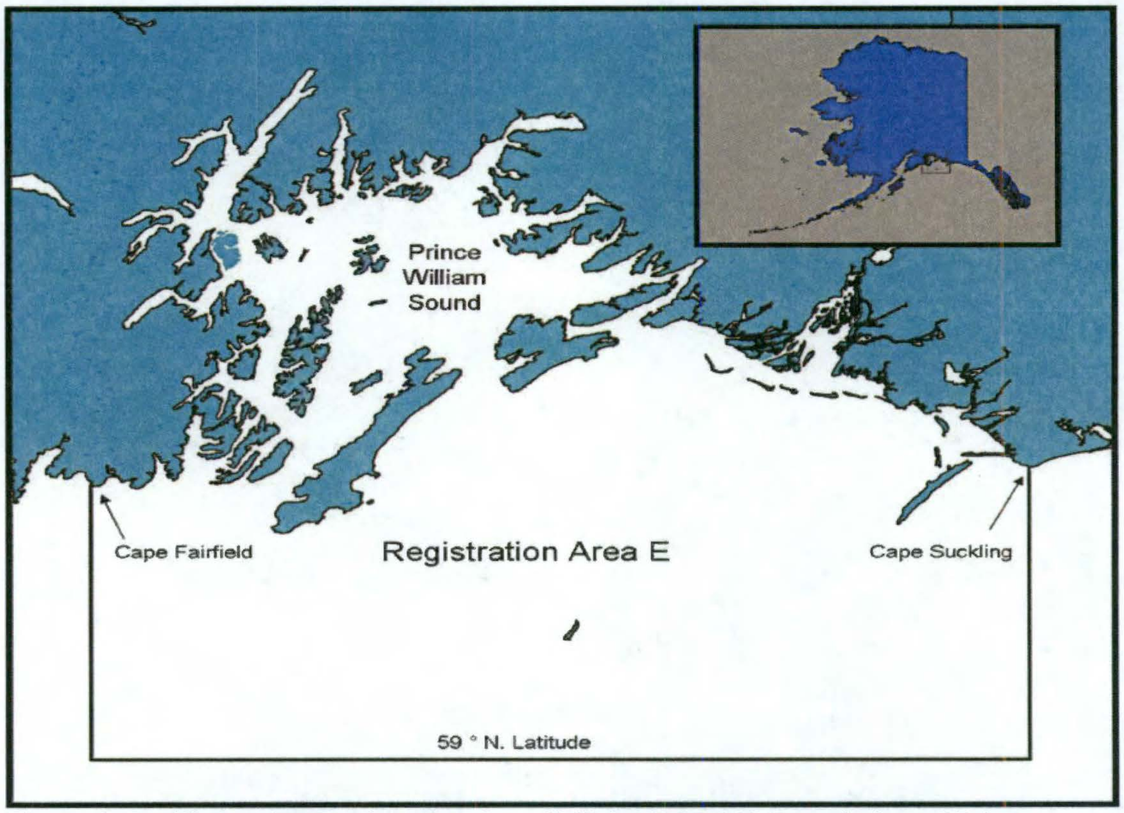


Figure 4. Pacific herring Registration Area E (5 AAC 27.300 Description of Prince William Sound Area).

Prince William Sound has a history of commercial exploitation of Pacific herring dating back to the early 1900s. (Rounsefell and Dahlgren 1932). Commercial markets in the 1920s through the 1940s were for fish oil, fertilizer, or fish meal; pickled fish, dry salted fish, or halibut bait.

The modern era of herring exploitation in PWS began with increased demand for herring roe from Japanese markets in the late 1960s. By the 1980 there were five separate fisheries for herring in PWS including two fisheries for sac roe: 1) spring purse seine sac roe, and 2) spring drift gillnet sac roe; two fisheries for spawn-on-kelp: 1) spring wild harvest of spawn-on-kelp, and 2) spring impoundment or "pound" spawn-on-kelp; and finally a fall/winter food and bait fishery. (Randall et al. 1981).

Fishing seasons are set in regulation for the food and bait and sac roe fisheries; however, fishery open periods are established using ADF&G's emergency order authority. The management year for herring is from 1 July through 30 June, so the first fishery that occurs in a management year is the fall/winter food and bait fishery. The food and bait fishing season is from 1 October through 31 January, and the sac roe fishing season is from 1 March through 30 June. Spawn-on-kelp fisheries do not have a season in regulation and open periods are established by emergency order.

The Prince William Sound Herring Management Plan, 5 AAC 27.365, has as objectives to 1) provide for an optimum sustained yield and 2) provide an equitable allocation among all user groups. The fishery is managed for a minimum spawning biomass of 22,000 tons (20,020 metric tons); no fisheries will open if stock assessments indicate the predicted biomass will be below this threshold. The management plan allows for an exploitation rates from 0 to 20% when the predicted biomass is between 22,000 and 42,500 tons (38,220 metric tons). The exploitation rate can be adjusted based on the anticipated age class strength. The department may allow a maximum exploitation rate of 20% when the projected spawning biomass exceeds 42,500 tons. For management purposes, herring in all locations of PWS are assumed to be one stock.

The projected prefishery run biomass is based on the final spawning biomass estimate from the previous year, cohort analysis, and projected recruitment. The plan allocates the projected available herring surplus among the five herring fisheries (Table 1).

Table 1. Percentage of the guideline harvest level allocated to each of the five fisheries for Pacific herring in Prince William Sound.

Fishery	Percentage of the guideline harvest level
Purse seine sac roe fishery (spring)	58.1%
Gillnet sac roe fishery (spring)	3.4%
Food and bait fishery (fall/winter)	16.3%
Spawn-on-kelp not in pounds (spring)	8.0%
Spawn-on-kelp in pounds (spring)	14.2%

The spawn-on-kelp fisheries are not harvesting fish, so the quota percentages are adjusted to spawn-on-kelp product from the actual fish biomass. For the spawn-on-kelp not in pounds fishery (wild roe-on-kelp fishery), one ton of spawn-on-kelp product may be harvested for every eight tons of herring allocated to the fishery. The spawn-on-kelp in pounds fishery harvests an estimated one ton of product for every 12.5 tons of herring allocated to the fishery. The herring allocation for this fishery is divided among the number of permit holders and the department establishes the maximum number of blades of kelp a permit may maintain in the pound.

Of the four spring fisheries in PWS, only the wild spawn-on-kelp harvest is open entry. For the remaining spring fisheries there are 104 permanent and 2 interim purse seine sac roe permits, 24 drift gillnet sac roe permits, and 128 herring pound permits in PWS. The fall/winter food and bait fishery is open entry; however, there are vessel restrictions. A vessel used to harvest herring in registration Area E (Prince William Sound) between 1 July and 28 February may not harvest herring in any other registration area during the same time period. Additionally, any vessel used to harvest herring in any other registration area from 1 July to 28 February may not harvest herring in registration Area E during the same time period.

Purse seines used in the spring sac roe and spawn-on-kelp in pounds fisheries can be 150 fathoms (274.4 m) long and 1,000 meshes deep, and mesh size is not regulated. Gillnets used for the spring sac roe fishery are limited to 100 fathoms (30.5 m) in aggregate length and 120 meshes (9.15 m) in depth. Gillnet mesh size may be from a minimum of 2 1/8 inches (53.9 mm) to a maximum of 3 inches (76.2 mm).

Beginning in 1997, spawn-on-kelp in pounds permit holders could use pound structures in either closed or open pound configurations. Permit holders selecting a closed pound configuration use purse seines to capture fish and then tow them (in a tow pound) to the pound site before transferring fish into the pound structure. Purse seine size limitations for the pound fishery are the same as for the purse seine sac roe fishery. The department can manage open and closed pound fisheries separately or in combination, e.g., an area may be opened for closed or open pounding only, or both. Pound spawn-on-kelp is harvested by either 1) confining herring within a rectangular net pen structure containing suspended kelp (closed pounding), or 2) by moving a rectangular structure with suspended kelp that is not completely enclosed by web into an area where herring are naturally spawning, (open pounding). The size of a closed pound structure cannot exceed 2,000 square feet (185.12 m^2) at the surface and walls cannot be more than 30 feet (9.15 m) deep. Additionally, the webbing of a closed pound cannot be used as the webbing of another closed pound structure.

Spawn-on-kelp in pounds permit holders must register with the Cordova office of ADF&G by 15 March of a year that fishing will be open. Prior to the fishing season, the department must determine the maximum amount of herring and the number of blades of kelp that each permit holder may use. Additionally, permit holders that notify the department before 1 April that they will use an open pound structure receive an increase in the maximum amount of kelp that they can use consistent with the wild spawn-on-kelp expansion factor (1 ton of product for 8 tons of herring). After notifying the department that a permit holder intends to fish with an open pound, they cannot change to a closed pound for the remainder of the season.

Fishing for a closed pound starts when fish are first introduced into the pound. Once fish are introduced into a closed pound, they can't be released without departmental authorization. More fish cannot be introduced into a pound more than five days after herring were first placed in the pound. Herring may not be kept in a pound more than seven days after the day they are first introduced. Fishing for an open pound begins when kelp is first placed in the water within the pound. Kelp for use in pounds may be harvested anywhere in PWS; however, most permit holders use *Macrocystis* sp. kelp harvested in Southeast Alaska. After release of the adult herring, the pound structure must be left in the water at the fishing location for not less than 4 weeks to allow eggs deposited on the webbing to hatch. The complete structure must be completely removed from the water not later than 6 weeks after harvest of the kelp.

Closed pounds are restricted to north and east of a line from Porcupine Point to Point Freemantle unless the department opens other areas using its emergency order authority. Open pounds are allowed anywhere in Area E in areas opened by emergency order.

The wild spawn-on-kelp fishery harvests existing PWS kelp species. Harvest areas are opened by emergency order after major spawning events on marketable kelp species. Wild kelp is harvested using SCUBA or hookah dive gear or by hand picking. Market requirements determine what type of kelp is desirable and subsequently the type of harvest gear required. The wild harvest of spawn-on-kelp product is conducted by divers or by hand picking, depending upon markets and the kelp species available for harvest.

The fall/winter food and bait fishery allow purse seine gear with no length limit or mesh size restriction. Additionally, trawl gear is allowed and gillnets with an aggregate length of less than 150 fathoms (274.4 m) may also be used.

Management History

Management Objectives

The management objectives are similar for all of the PWS herring fisheries and include conservation and economic objectives. The management objectives for herring fisheries in PWS are to 1) keep the harvest within the preseason guideline harvest level (GHL), 2) avoid fishing on recruit aged fish (age 3 and 4), 3) provide a quality product, and 4) conduct an orderly fishery. Overall the department would like to maximize the economic value of the fisheries without taking unnecessary risks with long-term conservation of the herring stocks.

Stock assessment and preseason projections

Currently, the department uses an age structured analysis (ASA) model to forecast the size of the prefishery run biomass (e.g., Funk and Sandone 1990; Funk 1994), When the spring sac roe fishery began in 1969, the department used aerial and beach surveys, age composition data, and harvest data for both preseason and inseason evaluations of stock status (Randall et al. 1983a). In 1975, the department began conducting winter hydroacoustics surveys to evaluate stock status; however, these were generally not very successful in providing quantitative data for management (Pirtle et al. 1975; Randall et al. 1983a; Randall et al. 1983b). The biomass assessments made prior to the initiation of the spawn deposition program and recruitment models required a significant amount of judgment by management and research biologists. Given the demand for herring in the 1980s, ADF&G made a significant effort to improve stock assessments. In 1987 ADF&G began using models that used the previous years' escapement biomass adjusted for growth, mortality, and recruitment to project the prefishery run biomass for the next year (Sandone 1988; Brannian 1989; Baker 1990; Baker and McCracken 1991). Additionally, the department began dive surveys to estimate the spawning biomass with pilot studies in 1983 and 1984. (Biggs and Funk 1988). The first ASA model forecast was completed for the 1993 season (Funk 1994).

The ASA model provides a best fit to the time series of historical data including purse seine harvests, purse seine harvest age compositions, spawning escapement age compositions, spawn deposition survey spawning biomass estimates, and aerial survey miles of spawn estimates (Funk 1994). After the population level problems with disease became evident in 1993, the model was adjusted to account for disease mortality (Quinn et al. 2001; Marty et al. 2003, Marty et al. 2004). Additionally, ADF&G in conjunction with the Prince William Sound Science Center (PWSSC) began conducting hydroacoustics surveys again in 1993 (Thomas and Thorne 2003). These assessments have been conducted annually and the ASA model was adjusted to include the hydroacoustics assessment data directly into the model (Hulson et al. *in press*).

Threshold and maximum exploitation rate policy

Another aspect of the current management is the threshold spawning biomass level and sliding scale exploitation rate policy outlined in 5 AAC 27.365. The fishery is managed for a minimum spawning biomass of 22,000 tons and no fisheries will open if the ASA model forecast indicates the projected biomass will be below this threshold. If the projected biomass is greater than the threshold level, the exploitation rate can be set on a sliding scale from 0% to 20% and the maximum exploitation rate allowed is 20%. This threshold and maximum exploitation rate policy was established and placed into regulation in 1994. Prior to 1986, the fishery was managed for guideline harvest levels (7,500 to 8,500 tons for 5 fisheries) that were considered conservative (fixed harvest policy). Beginning in 1986, a threshold was set at 8,500 tons and a maximum exploitation rate of 20% if the estimated biomass was above the threshold (threshold and fixed exploitation rate policy). A threshold and maximum exploitation rate policy is a compromise between maximizing yield and providing stable yields through time (Funk and Rowell 1995). The threshold is set at 25% of the average unfished biomass should allow fairly quick recoveries from perturbations. The 20% exploitation rate when the biomass is above the threshold while not maximizing yield, would provide good yields that are more stable than at the maximum sustained yield exploitation rate level (Zheng et al. 1993).

Stock structure and management

The current ADF&G management plan considers all herring in PWS to consist of one stock (5 AAC 27.365). When ADF&G began managing for significant herring sac roe harvests in the early 1970s, the department had little stock structure information. Therefore, a precautionary approach was used to manage the fishery and each spawning concentration was assumed to be a separate stock group. Between 1970 and 1976, the fishery was managed so that spawning aggregations were left in each general concentration area. Management strategies and ideas about the stock structure developed with the fisheries. In 1977 fishing districts were put into regulation that assumed there were at least two major stocks based on differences in the timing of peak spawning events (Pirtle 1979). The purse seine sac roe fishery was managed to split the quota between the two major districts (Northern and Montague districts).

Although the management plan states that PWS herring will be managed as a single stock, ADF&G uses a precautionary approach to management decisions that hinge on possible local stock structure. For example, in 1997 the department had a 3,277 ton GHL for the purse seine fishery, but decided against a purse seine fishery in northeastern PWS when aerial surveys indicated that only 2,000 to 3,000 tons were available (Morstad et al. 1998).

An examination of the genetic structure and diversity of PWS herring indicated there was possibly some genetic structuring (O'Connell et al. 1998). Additional research on stock structuring for different spawning stocks with in PWS using fatty acid analysis and otolith chemistry are currently being examined. The results of these studies may influence future management plans and inseason decision making. More information is required on possible local spawning stock structure in PWS, but ADF&G intends to continue precautionary management that allows for such a possibility.

Sac roe fisheries management

Although the season is started with a preseason forecast of abundance and GHL, ADF&G will make inseason adjustments to time, area, and GHL as conditions warrant. The harvest guidelines are currently established prior to the fall/winter food and bait fishery using an age structured assessment model. ADF&G wants to avoid fishing on recruit aged herring until they are fully recruited to the spawning population. Daily sampling by purse seine or gillnet boats is used to identify fish schools that meet processors fish weight and roe maturity standards and avoid recruit aged fish. The sampling allows the department to target the most economically valuable fish. Aerial and sonar surveys are used to determine appropriate boundaries for openings to keep the harvest within the GHL or within processing capacity limits. Assessments of the tender fleet and processing capacity are made on a daily basis and adjustments are made to the area and length of fishery openings to match the available capacity and keep the harvest below the GHL.

The management strategies used for inseason assessment of biomass and adjustments fisheries time and area have evolved as the fishery developed. Between 1969 and 1974, the fishery opened 1 March and was closed by emergency order when the harvest quota was achieved. Aerial surveys of herring biomass and harvest information were used inseason to close each area when management staff determined that no more harvest should be allowed. The fleet would then move to other areas and began fishing.

In 1974 there were multiple problems with the purse seine sac roe fishery including 1) fisheries operating for hours or days without notification of ADF&G staff, 2) a fleet that almost tripled in size, 3) tenders without scales, so timely harvest estimates were not available, 4) lack of communication with tenders and processors, and 5) harvests occurring on fish prior to roe maturing (Pirtle et al. 1974). Therefore, ADF&G requested from the BOF and received the ability to open the fisheries using emergency order authority beginning in 1975. Also beginning in 1975, tenders were required to provide the number of deliveries and harvest weight prior to leaving the area, and test fishing for roe maturity was instituted prior to fishery openers. The fishery openers went back to a fixed date in 1979 and then back to using emergency order authority in 1983. Since 1983 all sac roe fisheries have been opened with the department's emergency order authority.

Since the sac roe fisheries began in 1969, the department has generally gone into the season with a either a set GHL or a biomass forecast based on a recruitment model or ASA model. Once the season begins, aerial surveys and boat surveys have been used to evaluate the available biomass by area and inseason adjustments are made. The department has had to depart from this strategy of using the preseason GHL forecast several times, e.g., 1993 and 1999 (Donaldson et al. 1995; Sharp et al. 2000). It was apparent in 1993 (aerial and boat surveys) and 1999 (preseason acoustics survey) that the biomass was not as large as the preseason forecast. Therefore, the department proceeded very cautiously in evaluating areas for a possible fishery. It was possible in both years that prespawning herring were staging outside PWS, so boat and aerial surveys continued until most purse seine boats moved on to other fisheries.

ADF&G would like to avoid fishing on recruit aged fish, and this is outlined specifically in regulation 5AAC 27.059 Management Guidelines for Commercial Herring Sac Roe Fisheries. This increases the economic value of the fishery in both the short term and the long term. Processors generally establish minimum weight and roe percentage standards prior to the fishery. However, the standards depend on the abundance and size of herring from other fisheries along the Pacific coast (Sharp et al. 2000). In PWS, the processor minimum requirements for purse seine sac roe fish are generally about 125 to 130 grams with 10% mature roe. Because gillnets are more selective, they generally harvest larger fish with higher proportion of mature roe. There are many fewer gillnet permits and their harvest efficiency is much less than that of the purse seine fleet. This allows ADF&G to manage the gillnet fishery to more efficiently target higher quality fish. In most years, the processor minimum weight standards preclude the harvest of recruit aged fish because they generally weigh less than 125 grams.

Limited entry for the sac roe fisheries also began in 1977, and the districts were also intended to separate the gear types. The purse seine sac roe fishery was restricted to the Northern and Montague districts. All waters exclusive of the Northern and Montague districts were called the General District. The open entry food and bait fishery was only allowed in the General District. An additional district (Eastern District) was created in 1980 to allow the purse seine sac roe harvest of spawning aggregations outside of the existing districts (Randall et al. 1981). Additionally, the gillnet sac roe fishery was established as a fishery and restricted to the Northern District. In 1985, the districts for sac roe fisheries were removed from regulation, but the food and bait fishery was still restricted to the General District. By 1988, the consensus was that the commercial fishery targeted a single major stock that spawned from mid-April to early May and that there several other smaller spawning stocks (Brady et al. 1990). Because the management plan assumed that all PWS herring were one stock and ADF&G was not using the districts for management, the State of Alaska Board of Fisheries (BOF) removed the districts from the commercial fishing regulations at the 1994 BOF meeting.

Roe-on-kelp not in pounds (wild spawn-on-kelp) management

This fishery began in 1969, and has been through some significant changes. The fishery is open entry and requires much less initial investment for equipment than the other fisheries. Many participants used small skiffs and SCUBA or hookah gear; therefore, some years attracted a significant number of participants (1,100 permits in 1972; Pirtle 1979). The fishery began in the Port Fidalgo area where many of the preferred species of kelp were available. The most marketable kelp species was ribbon kelp *Laminaria saccharina*, but processors also bought roe on *L. groenlandica*, sieve kelp *Agarum cribrosum*, and some hair kelp *Desmarestia* sp. (Pirtle 1979).

Roe-on-kelp product from this fishery is graded on the thickness and uniformity of egg coverage on kelp and the kelp blade size. Market conditions influence the species of kelp that processors are willing to accept. Additionally, processors require clean product without any contamination by silt or sand. In some years the egg coverage was spotty, or there was no coverage on the preferred species, or the product had silt on it from storms or beach wash.

The fishery has generally been managed by opening an area with marketable kelp species after several days of spawn. The fishery grew quickly even with more stringent quality requirements by the processors beginning in 1972. The BOF instituted new regulations in 1977 intended to protect kelp stocks. These regulations included limiting the harvest to handheld, unpowered cutting devices and requiring kelp to be cut at least 4 inches (10.16 cm) above the stipe. This eliminated harvesters that were using grapple hooks and limited the fishery to SCUBA or hookah divers. The BOF also created a roe-on-kelp quota of 165 tons—much less than the 1975 harvest of 458.5 tons (Pirtle 1979).

Beginning in the mid 1970s, ADF&G conducted prefishery dive surveys to assess the standing crop and species composition of kelp at five sites near the historical roe-on-kelp harvest areas. (Rosenthal 1977). These surveys and other research improved the understanding of the time required to regenerate kelp in areas that were heavily harvested in the mid 1970s.

The BOF changes that limited this fishery to divers for the preferred species of kelp reduced effort and allowed fisheries to precede in some years when marketable kelp with good coverage was minimal. However, even with this restriction, the number of possible participants as measured by permits issued, made the department cautious about opening small areas because of the possibility of denuding the kelp beds.

In 1991, a market developed for spawn on popweed (*Fucus* sp.). *Fucus* is intertidal and can be harvested at low tide without dive equipment. Most of the harvest since 1989 has been off Montague Island and most of the product harvested has been on *Fucus*. There are few areas with good coverage of the kelp species, e.g., Ribbon kelp, around Montague Island.

Management of the wild roe-on-kelp fishery requires emphasizing to the permit holders that they check with their buyer/processor about kelp species and quality requirements prior to harvesting any product. The uncertainty in this fishery because of changes in spawning locations, spawning density, and problems with silty kelp were some of the reasons for the development of the roe-on-kelp in pounds fishery.

Roe-on-kelp in pounds management

The BOF passed regulations creating the roe-on-kelp in pounds fishery in 1978, and the first pound structures harvested product in 1980 (Randall et al. 1981). The roe-on-kelp in pounds fishery began because of the uncertainties in the wild roe-on-kelp fishery. The fishery developed rapidly and by 1987 more than 100 permits were issued and >100 pound structures harvested roe-on-kelp (Brady et al. 1990). The fishery became a limited entry fishery in 1992 with 128 permanent permits.

The rapid development of this fishery led to annual changes in the regulations and subsequently the fishery was managed with a commissioner's permit rather than by codified regulations from 1982 until 1994. ADF&G staff members were concerned about this fishery and as early as 1983 complained that many of the permit requirements were unenforceable and the fishery required a large amount of monitoring to ensure permit compliance (Randall et al. 1983b). Significant changes to the commissioner's permit were made since 1983 to reduce the possible problems. Additionally, subsequent research answered questions about 1) product weight loss from harvest weight to final product weight, 2) tons of herring required to produce a ton of final product, 3) average proportion of eggs deposited on kelp and pound webbing, and 4) egg retention in female herring in pounds (Morstad et al. 1992; Morstad and Baker 1995).

Current management for roe-on-kelp in pounds requires the department to determine the quota for the fishery and the appropriate number of kelp blades that permit holders could use for open and closed pounds. Permit holders must inform ADF&G by 1 April which configuration they intend to fish or they will be given the smaller blade quota allowed for closed pounds. Permit holders choosing the closed pound quota can decide to fish an open pound configuration instead, but permit holders that specified they would be using an open pound cannot change to a closed pound configuration.

The department manages the closed pound fishery similarly to the purse seine sac roe fishery. Aerial surveys are used to estimate the biomass available, and test fishing occurs to determine when to allow seining for introduction of herring into closed pounds. If it appears that insufficient biomass will be available in the traditional areas of Landlocked, Boulder, and Galena bays, the department may open other areas to seining for introduction into pounds.

Comparison with other management plans

The PWS Pacific herring fisheries are managed similarly to those for similar gear and fishery types from southern British Columbia through Bristol Bay.

Recovery criteria

These draft recovery criteria were proposed by Mark Carls for discussion purposes. They include criteria for both abundance and recruitment.

The population of PWS Pacific herring will be considered recovered when:

1) The spawning biomass has been above 43,000 tons for 6-8 years,

2) There have been two "strong" recruitments of age-3 fish in those 6-8 years, where "strong" is ≥ 220 million fish (log deviation ≥ 0.567).

These criteria are draft. We also talked to Dr. Terry Quinn about possible methods to determine recovery criteria. There are many ways that recovery criteria can be set and this needs more evaluation.

Possible Changes to Improve Long-Term Sustainability

The Alaska Department of Fish and Game has taken the first step in helping PWS herring to recover by closing all fisheries since 1999. Currently, the management plan only applies to commercial fisheries, so any changes will have no affect until the PWS increases in abundance to above the threshold level of 22,000 tons. Some of the possible changes are not possible through a simple regulatory management plan change.

Possible changes could help 1) reduce fleet efficiency, 2) conduct cooperative purse seine fisheries, 3) reduce the probability of disease transmission, and 4) review the threshold and maximum exploitation rate policy.

It became apparent to ADF&G staff early in development the purse seine sac roe fishery that a fleet of >100 boats could be very efficient. For example, in 1991 the purse seine sac roe fleet harvested almost 8,400 tons of herring in a single 20 minute open period (Brady et al. 1991). Of course the fishery location, bathymetry, stage of the tide, and size of the open area all contributed to the large harvest. But the point is that the efficiency of the fleet demands that management biologists have to be very careful when planning a competitive fishery opener with >100 boats. A smaller purse seine fleet may allow longer fishing openers and testing to increase the quality and value of fish harvested. More analysis would be required to determine the optimum fleet size.

The Sitka sac roe fleet has conducted more cooperative fisheries at times. A cooperative fishery would allow all fishers to have an equal share, and would allow the department better control of the harvest. The cooperative fishery could be for the whole season or just for any remaining quota after some open periods. This might allow the fleet to get some value out of a small quota amounts that the department may think are too small to harvest in a competitive fishery. An earlier survey indicated that >40% of the PWS purse seine sac roe limited entry permit holders strongly disagreed with the possibility of a equal quota sharing or an individual fishing quota management system in their fishery (Stearns and Huppert 2001).

Since the PWS herring population collapse in 1993, sampling for possible disease vectors such as viral hemorrhagic septicemia virus (VHSV) and erythrocytic necrosis virus (ENV) have discovered activities that increase the possibility of disease outbreaks. Several of these discoveries have management implications, especially for the roe-on-kelp in pounds fishery Hershberger et al. (2001) made several suggestions related to the roe-on-kelp in pounds fishery: 1) develop accurate methods of estimating biomass of herring placed into pounds, and 2) establish minimum pound volumes. These two suggestions are meant to reduce crowding which increase the stress on pounded fish that subsequently can increase the expression of VHSV and egg retention.

They also suggested not allowing roe-on-kelp in pounds fishing when the majority of the biomass is projected to be recently recruited fish (age 3 and age 4). The newly recruited fish are more susceptible to VHSV and the older fish have likely already been exposed and are immune. Additionally, the older fish have higher fecundity and lower egg retention rates.

The last management option suggested by Hershberger et al. (2001) was to do away with the closed pound fishery and replace it with an open pound fishery. The BOF made regulatory changes to allow open pounds in 1997, but unless there is a significant biomass spawning, it will be difficult to locate kelp in spawn and produce a quality product.

Summary

The Alaska Department of Fish and Game, Division of Commercial Fisheries, has been the sole management agency for Pacific herring commercial fisheries in PWS since statehood. The market for herring sac roe improved in the late 1960s, and the first harvests for sac roe and wild roe-on-kelp occurred in 1969. The fisheries developed rapidly until by 1980 there were five separate fisheries: 1) fall/winter food and bait, 2) spring purse seine sac roe, 3) spring gillnet sac roe, 4) spring wild roe-on-kelp, and 5) spring roe-on-kelp in pounds. Only the fall/winter food and bait and wild roe-on-kelp fisheries are open entry. The regulatory structure, stock assessment, and inseason management strategies developed and evolved along with the fisheries. The main objectives of the inseason management are to 1) keep harvests below the GHL, 2) maximize the economic value, 3) keep fishery pressure off recruit aged fish, and 4) conduct orderly fisheries. The current regulatory management plan assumes that all herring in PWS are from one stock. A minimum threshold abundance level must be achieved before any fisheries can occur and the maximum exploitation rate that can be used when the abundance forecast is above the threshold level is capped at 20% (threshold and maximum exploitation rate policy). The management plan outlines the allocation among the five fisheries and provides a framework for inseason management. The opening times and areas for all five fisheries are established using the ADF&G emergency order authority. Most of the management strategies employed in PWS are standard to the major herring fisheries along Pacific coast. Objective criteria about what would constitute recovery are currently in draft form and need further refinement. Research on disease cycling in herring after the collapse of the PWS herring stocks in 1993 may provide information that could be used to adjust commercial management after the stocks recover.

Literature cited

Rounsefell, George A. and Edwin H. Dahlgren (1932) Fluctuations in the supply of herring, *Clupea pallasii*, in Prince William Sound, Alaska. Bulletin United States Bureau of Fisheries, Vol. XLVII, Washington.

Brown, E.D., and T.T. Baker. 1998. Injury to Prince William Sound herring following the *Exxon Valdez* oil spill, *Exxon Valdez* State/Federal Natural Resource Damage Assessment Final Report (Fish/Shellfish Study Number 11), Alaska Department of Fish and Game, Division of Commercial Fisheries Management and Development, Cordova, Alaska.

Baker, T.T., J.A. Wilcock, and B.W. McCracken. 1991. Stock assessment and management of Pacific herring in Prince William Sound, 1990. Alaska Department of Fish and Game, Division of Commercial Fisheries. Technical Fisheries Data Report No. 91-22, Juneau.

Brady, J.A. 1987. Distribution, timing, and relative biomass indices for Pacific Herring as determined by aerial surveys in Prince William Sound 1978 to 1987. Alaska Department of Fish and Game, Division of Commercial Fisheries, Prince William Sound Data Report 87-14, Anchorage.

Marty, G. D., T. J. Quinn II, S. A. Miller, T. R. Meyers, and S. D. Moffitt. 2004. Effect of Disease on Recovery of Pacific Herring in Prince William Sound, Alaska, *Exxon Valdez* Oil Spill Restoration Project Final Report (Restoration Project 030462), University of California, Davis, California.

Marty, G. D., T. J. Quinn, II, G. Carpenter, T. R. Meyers, and N. H. Willits. 2003. Role of disease in abundance of a Pacific herring (*Clupea pallasi*) population. Can. J. Fish. Aquat. Sci. 60:1258-1265.

Thomas, G.L., and R.E. Thorne. 2003. Acoustical-optical assessment of Pacific herring and their predator assemblage in Prince William Sound, Alaska. Aquatic Living Resources 16(2003) 247-253.

Quinn, T. J., Marty, G. D., Wilcock J., and Willette, M. 2001. Disease and population assessment of Pacific herring in Prince William Sound, Alaska. *In* Herring Expectations for a new Millennium, pp. 363–379. Ed. by F. Funk, J. Blackburn, D. Hay, A. J. Paul, R Stephenson, R. Toresen, and D. Witherell. Alaska Sea Grant College Program, AK-SG-01-04.

Funk, F. 1994. Forecast of the Pacific herring biomass in Prince William Sound, Alaska, 1993. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 5J94-04, Juneau.

Hulson, Peter-John F., S. E. Miller, T. J. Quinn, G. D. Marty, S. D. Moffitt, and F. Funk. *In press.* Incorporating hydroacoustics data into the Prince William Sound Pacific herring assessment model. Journal of Marine Science.

Hershberger, P. K., R. M. Kocan, N. E. Elder, G. D. Marty, and J. Johnson. 2001. Management of Pacific herring spawn-on-kelp fisheries to optimize fish health and product quality. North American Journal of Fisheries Management Vol. 21:976-981.

Baker, T. T. 1990. Forecast of the Pacific herring biomass in Prince William Sound, Alaska, 1990. Regional Information Report No. 2C90-05. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage.

Baker, T. T. and B. W. McCracken. 1991. Forecast of the Pacific herring biomass in Prince William Sound, Alaska, 1991. Regional Information Report No. 2C91-06. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage.

Brannian, L. K. 1989. Forecast of the Pacific herring biomass in Prince William Sound, Alaska 1989. Regional Information Report No. 2A89-01. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage.

Sandone, G. J. 1988. Prince William Sound 1988 herring biomass projection. Regional Information Report No. 2A88-05. Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau.

Biggs, E. D. and F. Funk. 1988. Pacific herring spawning ground surveys for Prince William Sound, 1988, with historic overview. Regional Information Report No. 2C88-07. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage.

Zheng, J., F. C. Funk, G. H. Kruse, and R. Fagen. 1993. Evaluation of threshold management strategies for Pacific herring in Alaska. Pages 141-166 in G. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn II, editors. Proceedings of the international symposium on management strategies for exploited fish populations. University of Alaska Fairbanks, Alaska Sea Grant College Program Report 93-02.

O'Connell, M., M. C. Dillion, J. M. Wright, P. Bentzen, S. Merkouris, and J. Seeb. 1998. Genetic structuring among Alaskan Pacific herring populations identified using microsatellite variation. Journal of Fish Biology. V53, 150-163.

Rosenthal, R. J. 1977. Herring spawn on kelp fishery, Prince William Sound, 1977. Final contract report to the Department of Fish and Game, Division of Commercial Fisheries, Cordova.

Morstad, S., T. T. Baker, and J. A. Brady. 1992. Pacific herring pound spawn-on-kelp fishery in Prince William Sound, Alaska, 1990. Regional Information Report 2A92-02. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage.

Morstad, S. P., and T. T. Baker. 1995. Pacific herring pound spawn-on-kelp fishery in Prince William Sound, Alaska, 1991. Regional Information Report 2A95-21. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage.

Willette, T.M., G.S. Carpenter, K. Hyer, and J.A. Wilcock. 1999. Herring natal habitats, *Exxon Valdez* Oil Spill Restoration Project Final Report (Restoration Project 97166), Alaska Department of Fish and Game, Division of Commercial Fisheries, Cordova, Alaska.

Funk F., and G. Sandone. 1990. Catch-age analysis of Prince William Sound, Alaska, herring, 1973-1988. Fishery Research Bulletin No. 90-01, Juneau.

Funk F., and K. A. Rowell. 1995. Population model suggests new threshold for managing Alaska's Togiak Fishery for Pacific herring in Bristol Bay. Alaska Fishery Research Bulletin Vol. 2 (2): 125-136.

Pirtle, R. B., P. J. Fridgen, K. Roberson, and J. Bailey. 1974. Annual Management Report, 1974. Alaska Department of Fish and Game, Division of Commercial Fisheries, Cordova.

Pirtle, R. B., P. J. Fridgen, K. Roberson, M. McCurdy, and J. Bailey. 1975. Annual Management Report, 1975. Alaska Department of Fish and Game, Division of Commercial Fisheries, Cordova.

Pirtle, R. B. 1979. Annual Management Report, 1978, Prince William Sound Area Region II. Alaska Department of Fish and Game, Division of Commercial Fisheries, Cordova.

Randall, R. P. Fridgen, M. McCurdy, and K. Roberson. 1981. Prince William Sound Area Annual Finfish Management Report, 1980. Alaska Department of Fish and Game, Division of Commercial Fisheries, Cordova.

Randall, R. P. Fridgen, M. McCurdy, and K. Roberson. 1983a. Prince William Sound Area Annual Finfish Management Report, 1982. Alaska Department of Fish and Game, Division of Commercial Fisheries, Cordova.

Randall, R. P. Fridgen, M. McCurdy, and K. Roberson. 1983b. Prince William Sound Area Annual Finfish Management Report, 1983. Alaska Department of Fish and Game, Division of Commercial Fisheries, Cordova.

Brady, J. A., K. Schultz, E. Simpson, E. Biggs, S. Sharr, and K. Roberson. 1990. Prince William Sound Area Annual Finfish Management Report, 1988. Regional Information Report No. 2C90-02. Alaska Department of Fish and Game, Division of Commercial Fisheries, Cordova.

Brady, J. A., S. Morstad, E. Simpson, and E. Biggs. 1991. Prince William Sound Area Annual Finfish Management Report, 1990. Regional Information Report No. 2C91-14. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage.

Donaldson, Wayne, Steve Morstad, Daniel Sharp, John Wilcock, and Sam Sharr. 1995. Prince William Sound Management Area 1993 Annual Finfish Management Report. Regional Information Report No. 2A95-20. Alaska Department of Fish and Game, Commercial Fisheries Management and Development Division, Anchorage, Alaska.

Morstad, Steve, Daniel Sharp, John Wilcock, Tim Joyce, and J. Johnson. 1998. Prince William Sound Management Area 1997 Annual Finfish Management Report. Regional Information Report No. 2A98-05. Alaska Department of Fish and Game, Commercial Fisheries Division, Anchorage, Alaska.

Morstad, Steve, Daniel Sharp, John Wilcock, Tim Joyce, and J. Johnson. 1998. Prince William Sound Management Area 1998 Annual Finfish Management Report. Regional Information Report No. 2A99-20. Alaska Department of Fish and Game, Commercial Fisheries Division, Anchorage, Alaska.

Sharp, Daniel, Tim Joyce, J. Johnson, Steve Moffitt, and Mark Willette. 2000. Prince William Sound Management Area 1999 Annual Finfish Management Report. Regional Information Report No. 2A00-32. Alaska Department of Fish and Game, Commercial Fisheries Division, Anchorage, Alaska.

Stearns, G. and D. Huppert. 2001. Attitudes toward current and alternative management practices in Alaska's limited entry commercial herring roe fisheries. Washington Sea Grant Program Publication, WSG-AV 02-01.

12.06.09 Proposed IMS Infrastructure Improvement Project, Scoping Report, May 1994
12.06.10 Draft FY 1995 Work Plan Supplement Volume 2 Brief Project Descriptions July 1994
12.06.11 Draft FY 1995 Work Plan Supplement Volume 3 Detailed Budgets July 1994
12.06.12 Proposed IMS Infrastructure Improvement Project, Final EIS, September 1994
12.06.13 Draft Environmental Impact Statement, June 1994
12.06.14 Summary of the Draft Environmental Impact Statement, June 1994
12.06.15 Final Environmental Impact Statement, September 1994
12.06.15e Errata Letter for Final Environmental Impact Statement, Dear Interested Citizen October 6, 1994
12.06.16 Summary of Final Environmental Impact Statement, September 1994
12.06.17 Executive Summary EIS for Proposed IMS Infrastructure Improvement Project September 1994
12.06.18 Record of Decision for the *Exxon Valdez* Oils Spill Restoration Plan, October 1994
12.06.19 *Exxon Valdez* Oil Spill Restoration Plan November 1994
12.06.19a Restoration Plan and FY 1995 supporting documents from 94 workshop
12 06.20 Habitat Acquisition by Region/Report to the Public Advisory Group, October 1994
12.06.21 Science for the Restoration Process, Proceedings of the Workshop, April 13 - 15, 1994
12.06.22 Proceedings, Five Years Later, March 1994
12.06.23 Report of the Executive Director Concerning Habitat Acquisition, November 28, 1994
12.06.24 FY 1995 Final Work Plan, December 1994

12.07 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 1995

12.07.01 Invitation to Submit Restoration Projects for Federal Fiscal 1996 & Draft Restoration Program & Beyond, March 24, 1995
12.07.02 Draft Restoration Program: FY 1996 & Beyond
12.07.03 Draft Fiscal Year 1996 Work Plan
12.07.04 Final Fiscal Year 1996 Work Plan, December 1995
12 07 05 1995 Status Report on EVOS
12.07.06 Report of the Executive Director Concerning Habitat Acquisition, October 1995

12.08 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 1996

12.08.01 Shuyak Island Revised Program 11-6-9993 January 8, 1996
12.08.02 FY 1996 Work Plan Detailed Budgets, Approved Projects
12.08.03 Invitation to Submit Restoration Proposals for FY 1997
12.08.04 1996 Status Report
12.08.05 Exxon Valdez Oil Spill Restoration Plan Draft Update on Injured Resources & Services April 1996 & Update on injury & Recovery Status,

September 1996 (update to Recovery Objectives, Chapter 5)
12.08.06 Fiscal Year 1997 Draft Work Plan
12.08.07 Fiscal Year 1997 Work Plan, December 1996 *Note Addendum & Supplementation Criteria Inside Front Cover of Work Plan
12.08.08 EVOS Research & Restoration Information Project CD-ROM

12.09 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 1997
12.09.01 Invitation to Submit Restoration Proposals for FY 1998
12.09.02 1997 Status Report

12.10 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 1998
12.10.01 Abstracts of 1997 Restoration Projects, 1/20/98
12.10.02 1998 Status Report

12.11 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 1999
12.11.01 Restoration Plan Update on Injured Resources & Services (3/99)
12.11.02 Sand Lance: A Review of Biology & Predator Relations & Annotated Bibliography (9/99)
12.11.03 1999 Status Report

12.12 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2000
12.12.01 2000 Status Report

12.13 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2001
12.13.01 2001 Status Report

12.14 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2002
12.14.01 Gulf of Alaska Ecosystem Monitoring (GEM) and Research Program brochure
12.14.02 2002 Status Report
12.14.03 The Status of Alaska's Oceans & Watersheds 2002

12.15 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2003
12.15.01 2003 Status Report

12.16 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2004
12.16.01 2004 Status Report
12.16.02 Then and Now – A Message of Hope, 15th Anniversary of the *Exxon Valdez* Oil Spill. 2004
12.16.03 DVD - Then and Now – A Message of Hope, 15th Anniversary of the *Exxon Valdez* Oil Spill, 2004

12.17 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2005

12.18 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2006
12.18.01 2006 Status Report (published on the web only, no hard copies printed by professional printer)

12.19 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2007
12.19.01 2007 Status Report (published on the web only, no hard copies printed by professional printer)

12.20 TRUSTEE COUNCIL SPONSORED PUBLICATIONS 2008

13. CORRESPONDENCE
13.01 CORRESPONDENCE FROM THE TRUSTEE COUNCIL

20.01.01 Proposed SEA (Sound Ecosystem Assessment) Budgets (#94320)
20.01.02n FY 96 Budget Instructions for Non-Trustee Organizations
20.01.02t FY 96 Budget Instructions: Index to Excel Files

21. ***EXXON VALDEZ* OIL SPILL RESTORATION PLAN: UPDATE ON INJURED RESOURCES AND SERVICES, September 1996**

21.01 PRELIMINARY DOCUMENTATION

21.01.01 Chapter 5 Revision, Original, April 1996
21.01.02 Preliminary Revised Draft of Chapter 5 (Recovery Objectives), December 29, 1995
21.01.03 Revisions of Restoration Objectives (early drafts), November-December 1995
21.01.04 Public Comments at or Related to the 1996 Restoration Workshop on Preliminary Revised Recovery Objectives in Chapter 5
21.01.05 General Public Comment on Draft Update on Injured Resources & Services
21.01.06 Post Workshop Drafts on Chapter 5 Revisions
21.01.07 *Exxon Valdez* Oil Spill Restoration Plan: Update on Injured Resources & Services September 1996
21.01.08 *Exxon Valdez* Oil Spill Restoration Plan Update on Injured Resources and Services March 1999