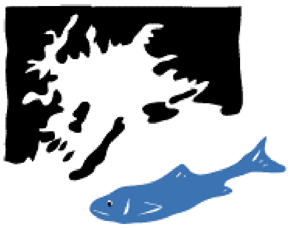
FOURTH QUARTERLY PROJECT REPORT TO EVOSTC

Period: October-December, 2010

An Ecosystem Model of Prince William Sound Herring: A Management & Restoration Tool

(Grant FY07: 070810)



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Progress during the fourth quarter of 2010

This quarterly project report reviews the status of work for the Prince William Sound (PWS) Herring Modeling project from October through December, 2010. We have conducted two final tasks:

- We have developed and applied the *Unrestricted Cohort Tracking Algorithm* to analyzing Alaska Fish and Game's annual surveys of herring in Prince William Soound and Sitka Sound.
- We have also incorporated our bioenergetics model of herring in a *Nursery Model* of juvenile metabolism and schooling.

The Unrestricted Cohort Tracking Algorithm

The *Unrestricted Cohort Tracking Algorithm*, which was developed by Vince Patrick , describes the abundance of herring born in a given year as they age and mature from age 0 juveniles that enter coastal nursery grounds to age 9 adults. This model draws upon the time series of adult population size as estimated from aerial surveys of milt and augmented by coastal egg surveys and acoustic surveys. It also draws upon the age distribution of fish in adult spawning schools found in sectors of PWS. This time series has been gathered over the last 34 years by AF&G to provide input to their Age Structured Analysis Model (ASA) for setting quotes or closing the fishery. We have reviewed ASA code and found that several assumptions or applications of the routine are questionable. These include the assumption that adult natural mortality rates are constant, and that juvenile maturation rates are constant. (However they have at times been adjusted when the ASA appeared to drift from reality.)

The algorithm consists of a comprehensive search routine for retrospective analysis of the ASA survey data. The algorithm is designed to reduce the number of assumptions (such as the two mentioned above) and constraints found in the ASA. This algorithm not only provides the means to assess annual variability in adult mortality and the apparent maturation rate of juveniles, but it also provides an interpolation scheme to assess variability in the survival probability of juvenile cohorts. The algorithm helps provide an objective analysis of the differing hypotheses as to why PWS herring have not returned to a high and stable abundance. For example there have been recent publications or presentations that the current low abundance state of PWS herring is caused by *current factors* such as *VHS* and *Ichthyphonus* epizootics that broke out in the early 1990s, whale predation, or pink salmon fry predation upon herring larvae and metamorphs. Alternatively, there is the hypothesis that the current low abundance state is a residual effect of the collapse of the herring population in the early 1990s caused by the oil spill, over-fishing, and forage depravation. It has been proposed by our consultant, Evelyn Brown and others that recovery from this collapse has been prevented by loss or disruption spawning and nursery grounds in the early 1990s. Recovery can of course be further hindered by the issues of predation and disease listed above. These alternatives are not easily tested without a flexible and objective analysis.

The dark colored lines in Figure 1 show the algorithm's predicted abundance of PWS adult herring of different ages from cohorts born in a given year and the abundance measured during AF&G's field surveys. The lighter colored lines show the annual abundance of cohorts obtained during field surveys from 1976 to 2010, and the ages of cohorts are indicated by the numbers on the colored lines. The fit is good and considerably better than the fit provided by Fish and Game's ASA. The black and gray lines at the top of the figure show the annual, total adult population sampled at different times of the year. The green line and associated numbers at the bottom of the graph is the annual natural survival probability (fishing mortality is excluded) of all adult predicted by our algorithm. Finally, at the bottom of the graph we show 3 rows of additional information. The top row shows the annual total abundance of age 3 juveniles, the sum of both mature and mature 3 year olds. The mature 3 year olds are those that joined adult spawning schools in the early spring of that year and immature 3 year olds are those that did not. The bottom of the graph provides information on the algorithm's prediction of the apparent maturation rate of juveniles… i.e. the distribution of ages of juveniles that first join adult spawning schools. The upper row is the average age at which 50% of that year's cohort matured, and the lower line is the average age at which 91% that year's cohort matured.

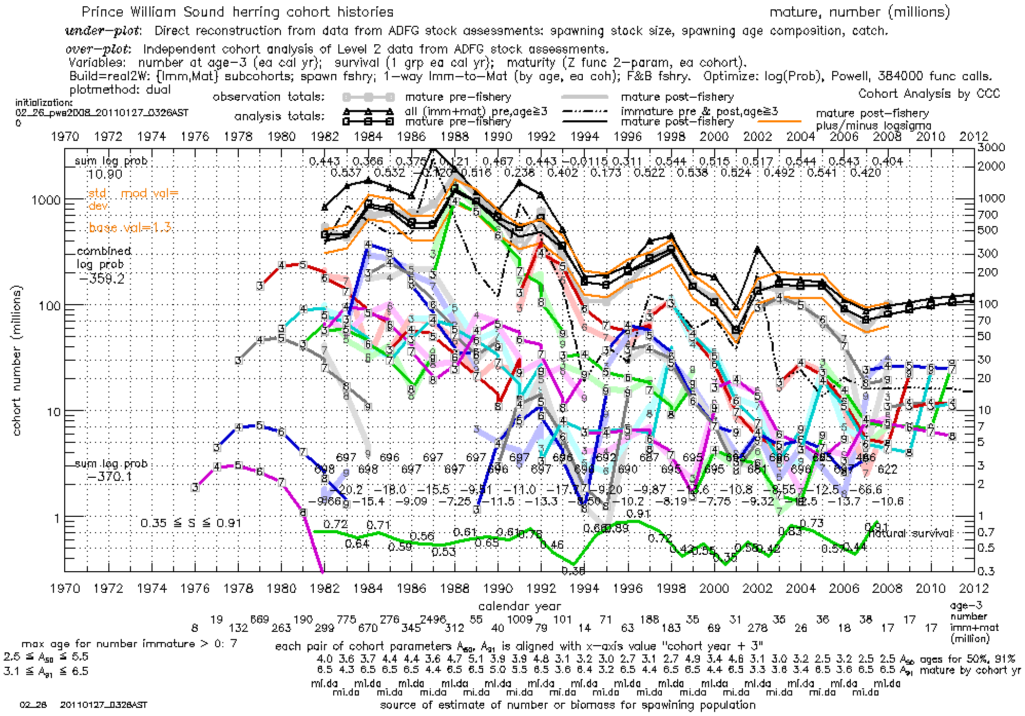

Figure 1. Cohort tracking of adults in PWS.

The algorithm also provides insight into annual changes in juvenile abundance. Figure 2 and 3 plots the biomass of eggs (indicated by 0), and age 1, 2, and 3 juveniles of each cohort in the time series. PWS is shown in figure 2 and Sitka Sound is shown in figure 3. The egg biomass is simply calculated as 12% of adult spawning biomass of the year class. The hatched lines, which connect egg biomass with the biomass of age 2 juveniles, clearly indicates that the survival probability (and to a much lesser extent growth rate) of eggs to age 2 juveniles clearly varies greatly from year to year. The 4 year oscillation in the 80s is most clearly expressed by the cycles in the survival of eggs to age 2 juveniles. This is also true for Sitka Sound. The patterns in survival of eggs to age 1 juveniles in the last 2 decades are much less predictable, but surprisingly this complex pattern is generally similar in both Sounds. Finally, we note that the hatched red line plots the total biomass of age 1 and age 2 juveniles. Age 1, 2, and 3 juveniles are major sources of negative feedback on the survival probability of eggs to age1 juveniles, presumably via competition for food and cannibalism. One notes that most often when the nurseries of the sounds are filled with juveniles the probability that eggs survive to age 2 juveniles is much reduced.

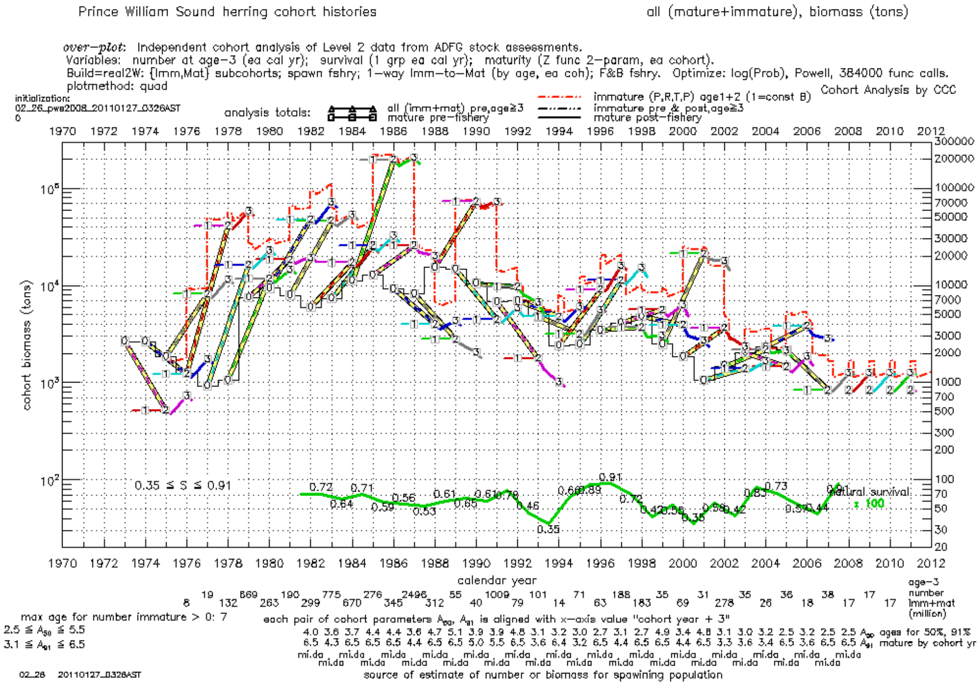

Figure 2 Cohort tracking of juveniles in PWS: from eggs to age 3.

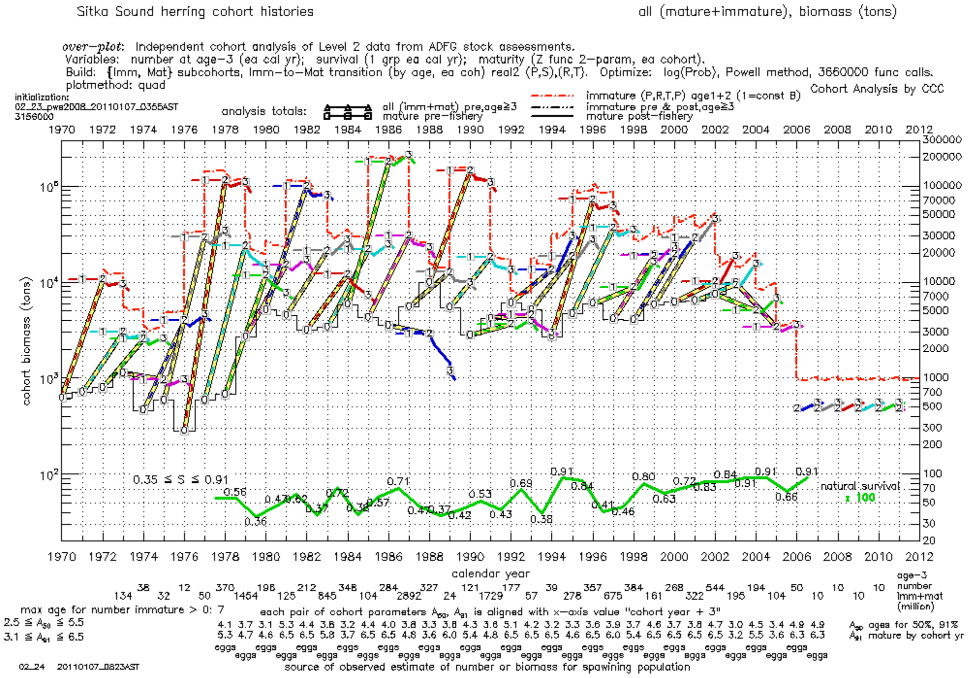

Figure 3. Cohort Tracking of juveniles in Sitka Sound: from eggs to age 3.

Although the details and interpretation of this analysis will be found in our final report, we summarize our findings and speculations from the unconstrained algorithm here:

1. The process of cohort dominance within nursery grounds explains the 4 year cycle in recruitment that occurred in the 1980s. Stated most simply, the juveniles of a strong year class will greatly reduce the survival of age 0 juveniles in younger year classes as long as this strong year class resides within or regularly visits their nursery. Since most juveniles leave the nursery by age 3, the nursery is effectively closed by a strong year class for 3 years and then opened on the 4th year. This cycle was trigged by several years of exceptional recruitment in the mid 1970s that was driven by the Pacific Decadal Oscillation. The cycle was suppressed in the early 1990s most likely because of several years of reduced zooplankton forage. This conjecture is supported by both the drop in adult survival in from mid-1991 to mid-1993 and the large drop in the recruitment of the expected strong 1992 year class. These same patterns occurred in synchrony with those in Sitka Sound.

2. Despite the fact that the 4 year oscillation in recruitment ended around 1992, the population of juveniles occupying a nursery ground may still have continued to present but more evidence is needed to verify this.

3. The "apparent age of maturation" of juveniles varies with year class and appears to follow a pattern in which the juveniles of a strong year class mature earlier than weaker year classes. Specifically, a binomial statistical analysis of data shown in figure 4, which shows rates of maturation for the time series with figure 4 with the data shown in figure 2 supports this pattern. This feature suggests to us that the maturation of juveniles depends to some extent on the abundance of age classes of juveniles. Variations in apparent maturation rates also are seen in SS, and the patterns, although different from those in PWS, are more clearly characterized in terms of interactions between juvenile cohorts. We use the term "apparent age of maturation" because the survey data upon which our analysis is based not sufficiently comprehensive to identify whether the observed variability is actually due to changes in the age of maturation or to changes in the mortality rates of juveniles. For example, an increase in apparent maturation of a cohort could be the result of an increase in the mortality rate of juveniles and vice versa. Thus, the increase in apparent maturation of strong year classes may be an expression of increased contagion of VHS and ichthyophonus. Such cyclic outbreaks of disease in PWS have been documented by Marty and co-workers.

4. The annual natural survival of adults during the 1980s is generally higher than during the following 2 decades. This is particularly true from 1997-2004.

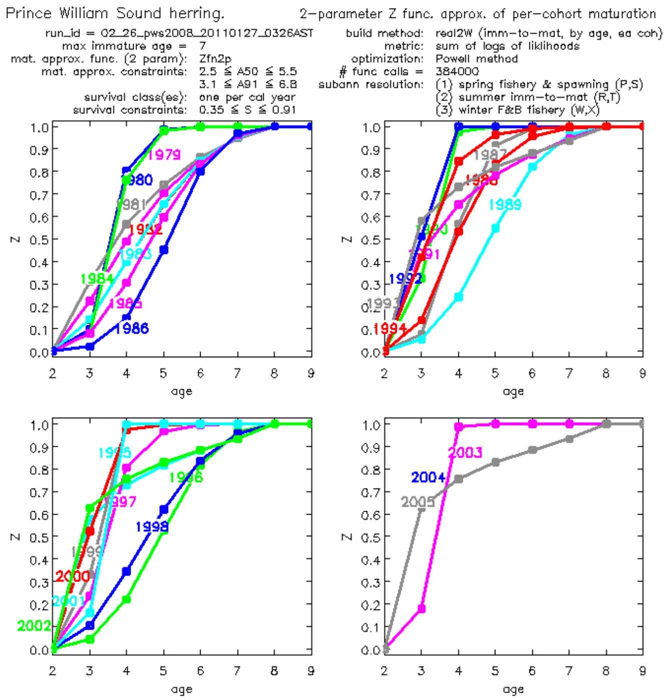

Figure 4. Apparent maturation rates of cohorts by year.

Nursery Model

Dale Kiefer has initiated work on nursery model because as described in # 1 above that the large annual variations in recruitment appear to be closely tied to food supply in the nurseries and the associated competition for food between juvenile cohorts for a limited supply of food. We also initiated the model because patterns in the spatial distribution of nurseries and spawning grounds observed from aerial surveys suggested that they are not rigidly tied to a given shoreline and that the age composition of juveniles within the nurseries varied with location.

Figure 5 is a schematic of our model of a herring nursery. The model describes the dynamics of two major components, the population of zooplankton foraged by juveniles and the juveniles themselves. The juveniles consist of cohorts of age 0 through age 4. As shown, the population of zooplankton forage within the nursery is supplied by advection and turbulent exchange between the nursery and ambient offshore waters, and the forage is depleted by predation of the population of juvenile herring (as well as other foraging species). The rate of supply of zooplankton will depend upon the volume exchange rate between the nursery and the offshore waters as well as the gradient in zooplankton concentration between the nursery and the offshore waters. The rate of depletion of the zooplankton will be largely influenced by the size of the juvenile cohort populations and their respective predation efficiency. The population of a juvenile cohorts will be determined by prior seeding of the bay by metamorphs of that year class (not shown) and their survival probability- presumably determined by starvation, predation, and disease.

We see in the diagram two types of interactions within and between cohorts. They compete with each other for zooplankton forage. It is reasonable to assume that the younger and smaller juveniles are at a disadvantage. We also note that the younger and smaller juveniles are at a disadvantage with regard to starvation. Cohorts also interact with each other by processing information on their rates of encounter with each other and other cohorts. Here we have chosen to call this process quorum sensing, which is a means by which individuals or independent groups signal or communicate with each other to achieve a coordinated action. Species that have demonstrated such communication range from bacteria which draw upon chemical signaling to social insects that draw upon behavioral communication. We propose that quorum sensing in juvenile (and adult herring) help direct schooling and swimming behavior. To our knowledge this process has not been invoked in studies of herring. In our model herring use quorum sensing to adjust their swimming and schooling behavior in an attempt to achieve a desired rate of encounter with other members of their cohort or with members of other cohorts that are close in age and size. If the schools diverge (see next paragraph) from the desired encounter rate, we assign a cost that increases with the size of the divergence.

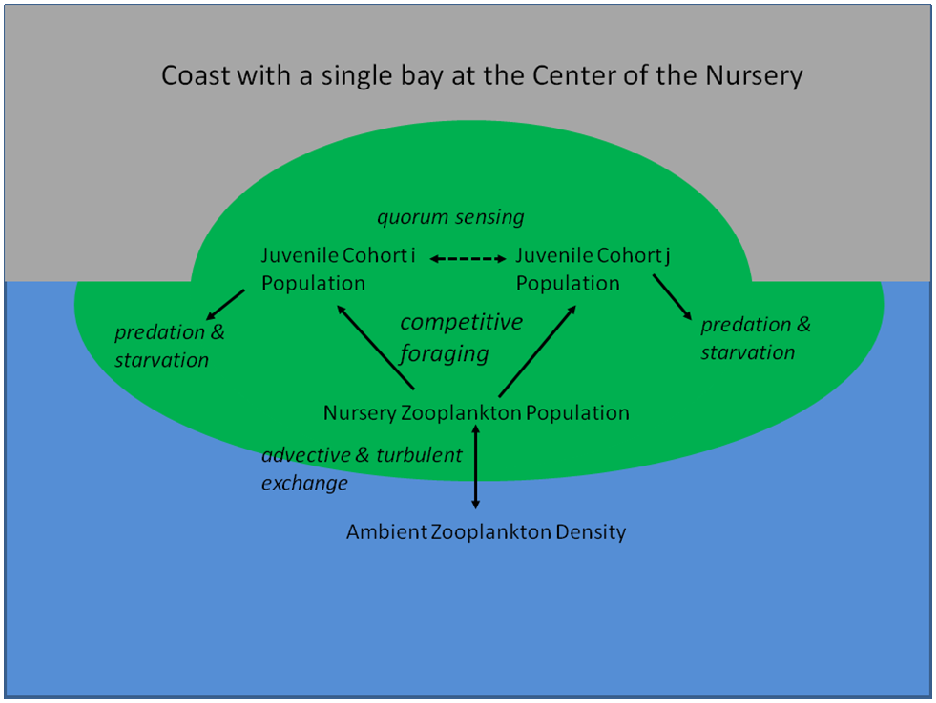

Figure 5. The Nursery Model

Finally, the model includes a bio-energetic model of herring growth and metabolism. Specifically, the system of equations describes ingestion, egestion, respiration, and growth of fish as a function of food supply, their age or size, water temperature, and swimming speed. In our model herring schools try adjust their swimming behavior to achieve maximal growth rates. If the schools diverge from their desired encounter rate with forage, we assign a cost that increases with the size of the deficit in growth rate. One should note immediately that the goal to achieve maximal growth rates and the goal of encountering other juvenile herring at a desired rate will likely conflict over a range of environmental conditions. For example, if the supply of zooplankton forage to a nursery is low, then schools will tend to forage over a greater area in order to achieve higher encounter rates with zooplankton and thus higher growth rates. However, such spatial expansion of the nursery will inevitably reduce herring-herring encounters, driving the schools away from their targeted encounter rate. We propose that this conflict is ultimately resolved through a cost-benefit assessment of the departure from the two goals. Such resolution will shape not only the size of the nursery but also shape the age composition of individuals in schools within the nursery and even in adult populations. The details of this theory and the results of our simulation will be presented in the final report.

What is Next?

We will now complete our herring model by assembling the components that we have coded and write our final report.