EVOSTC FY17-FY21 INVITATION FOR PROPOSALS
FY20 CONTINUING PROJECT PROPOSAL SUMMARY PAGE

Project Number and Title

20120111-C

Modeling and stock assessment of Prince William Sound herring

Primary Investigator(s) and Affiliation(s)

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Project Abstract

Prince William Sound (PWS) herring collapsed shortly after the *Exxon Valdez* oil spill and has yet to recover. Here, we propose to continue the modeling component to the long-term herring monitoring project, which has as its chief goal an understanding of the current status of PWS herring, the factors affecting its lack of recovery, and an assessment of research and fishery needs into the future. Key products are the following (items 6-8 are related to the postdoctoral fellow):

1. The core product of the modeling project is the maintenance and updating of the new Bayesian age-structured assessment (BASA) model based on the ASA model used by the Alaska Department of Fish and Game (ADF&G), including annual assessment updates of PWS herring and the revision of BASA to fit to new data sources.
2. Adapting the BASA model to better model the disease component of natural mortality. Planned work includes simulation modeling of information that can be obtained from antibodies of viral hemorrhagic septicemia virus (VHSV) in herring (described by Hershberger), to examine whether such data can be used to estimate annual outbreak size, the susceptibility of different ages to VHSV, and the estimation of additional mortality due to VHSV.
3. Collation of catch, biomass, and recruitment time series from herring populations around the world to place the lack of recovery of PWS herring into context.
4. An initial exploration of factors that may be used to predict herring recruitment, including oceanography, climate, competition, and predation.
5. Management strategy evaluation to test alternative harvest control rules for managing the fishery in the future, given realistic variability in productivity over time, and the possibility that the population has moved into a low productivity regime. Ecological, economic and social factors would be considered in the MSE.
6. Examination of physical and ecological processes linked to PWS herring spawning, spawning survival, and survival of juvenile life stages.
7. Examination of physical and ecological processes on recruitment to the PWS and Sitka Sound herring populations.
8. Identifying environmental inputs for incorporation into the BASA model to improve recruitment predictions.

EVOSTC Funding Requested* *(must include 9% GA)*

FY17	FY18	FY19	FY20	FY21	TOTAL
Auth: $124,300	Auth: $288,300	Auth: $297,000	$303,300	$148,900	$1,161,900

Non-EVOSTC Funds to be used, please include source and amount per source: (see Section 6C for details)

FY17	FY18	FY19	FY20	FY21	TOTAL
0	0	0	0	0	0

1. PROJECT EXECUTIVE SUMMARY

The herring modeling project is intended to improve predictive models of Prince William Sound (PWS) herring through synthesizing the data collected by the other components of the overall Herring Research and Monitoring (HRM) program and hence assessing the current status of the population.

Annual assessment model updates

Muradian (2015, MS thesis) reviewed the available literature during the first five years of the long-term herring monitoring project; a brief summary is included here. PWS herring are the key forage fish species in PWS and have been harvested commercially for at least a century, with catches over 40,000 t in the 1930s (Muradian 2015). After the *Exxon Valdez* oil spill in 1989, which occurred during a period of high herring abundance, the herring population remained high for three years until collapsing in 1992-93 (Quinn et al. 2001). Since then, the fishery has been closed, except for a brief period during 1996-98. The fishery is managed by the Alaska Department of Fish and Game (ADF&G) which keeps the fishery closed if the pre-fishery spawning biomass is less than 22,000 short tons (19,958 mt), has the discretion to set a catch limit of 0-20% if the spawning biomass is 22,000–42,500 short tons, and may open the fishery with a catch limit of 20% of the pre-fishery spawning biomass if this is over 42,500 short tons (Muradian 2015).

In 1988, an age-structured assessment model (the "ASA Model") was developed by ADF&G that fitted to catch-at-age data and mile-days-of-milt and used egg deposition data as an absolute estimate of biomass (Funk and Sandone 1990). Later developments included the incorporation of disease data to explain the rapid declines in the population in 1992 (Marty et al. 2003, Marty et al. 2010, Quinn et al. 2001). As hydroacoustic survey biomass estimates became seen as more reliable, they too were added to the model, helping to address the conflict between the trends in mile-days-of-milt and the egg deposition data (Hulson et al. 2008); and a Ricker stock-recruit relation was added to the model to stabilize estimates of recruitment (Hulson et al. 2008). The ASA model is fit to data by minimizing sums of squares using Solver in Excel, but is no longer run annually by ADF&G.

In the first five years of the HRM program, an updated version of the ASA model was developed at the University of Washington (Muradian et al. 2017). The key new features included (1) a translation of the model into AD Model Builder (Fournier et al. 2012), (2) the use of likelihoods to allow a natural statistical weighting of data sets instead of sums of squares, (3) freely estimating recruitment in each year instead of using a Ricker stock-recruit relation, since the data did not support a Ricker model, and (4) converting the model to a Bayesian model to allow statistically-based estimates of uncertainty in model parameter estimates and estimated biomass (e.g. Punt and Hilborn 1997), instead of the bootstrapped estimates used in the ASA model. This Bayesian version of the ASA model (which we name "BASA") provides similar median estimates of pre-spawning biomass as the ASA model, but also reports uncertainty in model estimates. The new BASA model is the underlying basis for the second set of five years of the long-term herring monitoring project.

The most recent BASA assessment based on data to the end of 2018 can be seen in model fits to the survey time series (Fig. 1), numbers-at-age data (Fig. 2), recruitment estimates and biomass relative to management quantities (Fig. 3) (John Trochta, unpublished). Notably, in 2018 the hydroacoustic survey and mile-days of milt were both historically low, resulting in model estimates among the lowest in the time series. However, the BASA model has a slight tendency to estimate higher biomasses than survey points in the most recent 1-2 years, resulting in a one-year lag before very low data points are accepted as reasonable by the model. Thus, the actual status of the stock is likely somewhat worse than the BASA model would suggest. Investigations into this model mis-specification included placing different priors on survey coefficient of variation (CV; fixing the CV to 0.15, 0.2, 0.3, and 0.4), allowing for autocorrelated recruitment, and fixing the sex ratio. As expected, the lower the survey CV was set, the more closely the model fitted to those data points, and the lower the recent biomass was (Fig. 4).

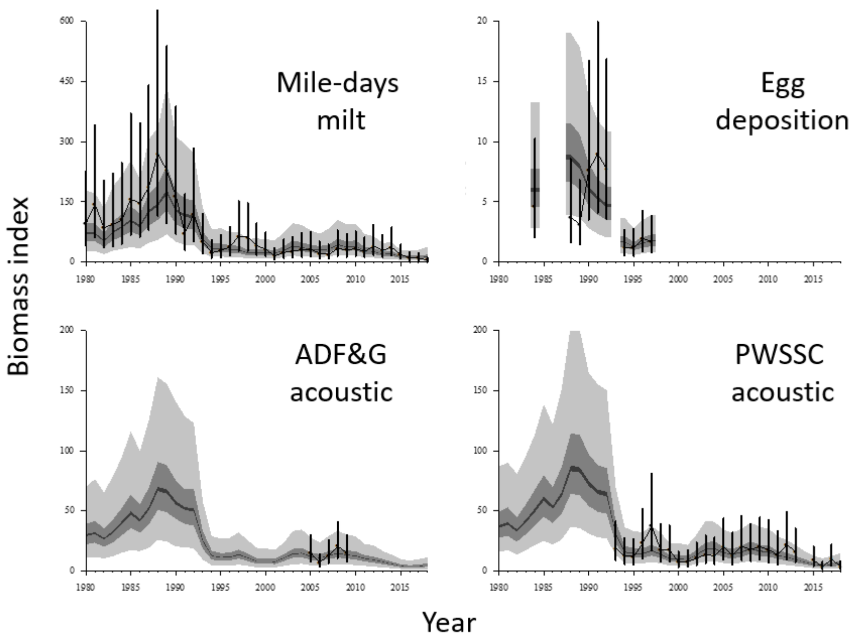

Figure 1. The 2018 Bayesian age-structured assessment (BASA) model estimates of Prince William Sound herring biomass fitted to the four main time series of biomass. Shaded polygons are the model-estimated posterior predictive intervals: 5th percentiles (black), 50th percentiles (dark gray) and 95% percentiles (light gray). Small dots are the median of the data, and lines are the 95th percentiles including additional variance estimated by the model. Source: John Trochta, using the model described in Muradian et al. (2017).

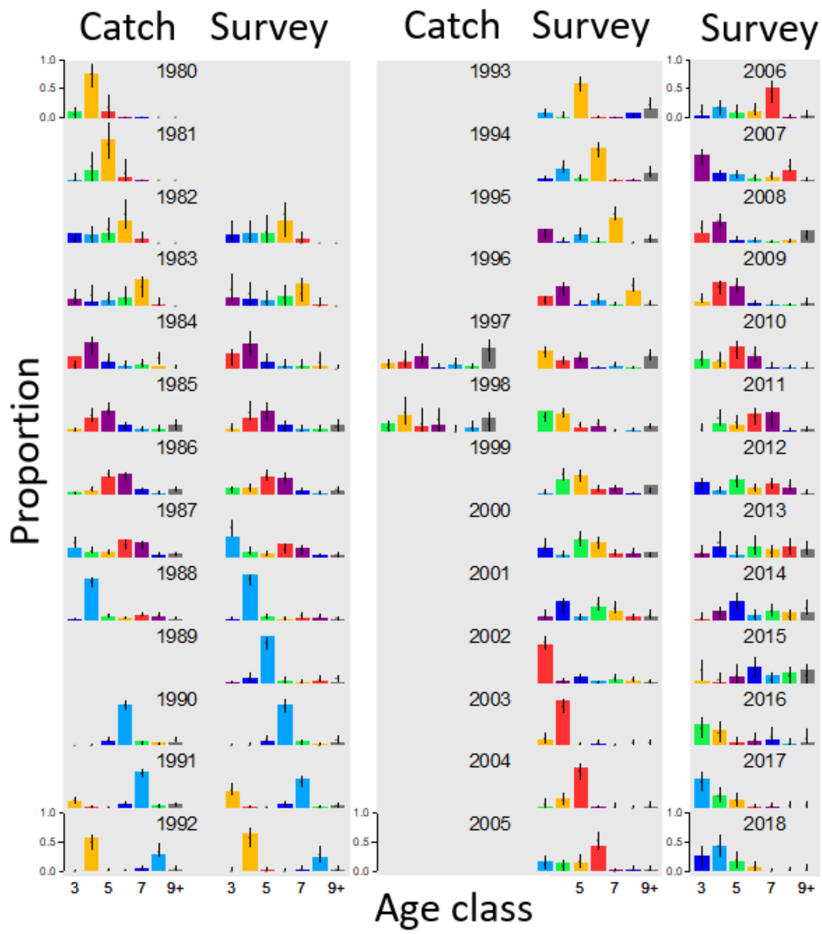

Figure 2. The 2018 Bayesian age-structured assessment (BASA) model fits to the age composition data from purse-seine catches and from the Alaska Department of Fish and Game herring-spawn survey (data from all gears combined). Colors track individual cohorts over time, while points and lines indicate the model posterior median and 95% posterior intervals. Source: John Trochta, using the model described in Muradian et al. (2017).

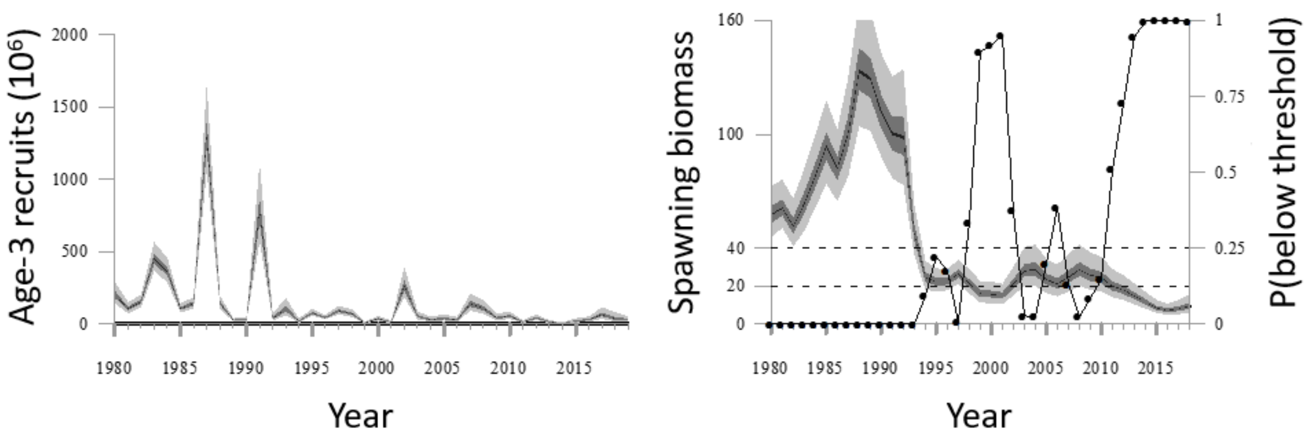

Figure 3. Estimates of age-3 recruitment (left), spawning biomass (shading, right), and the probability that biomass falls below the management threshold of 22,000 short tons in each year (points, right) from the 2018 Bayesian age-structured assessment (BASA) model. Source: John Trochta.

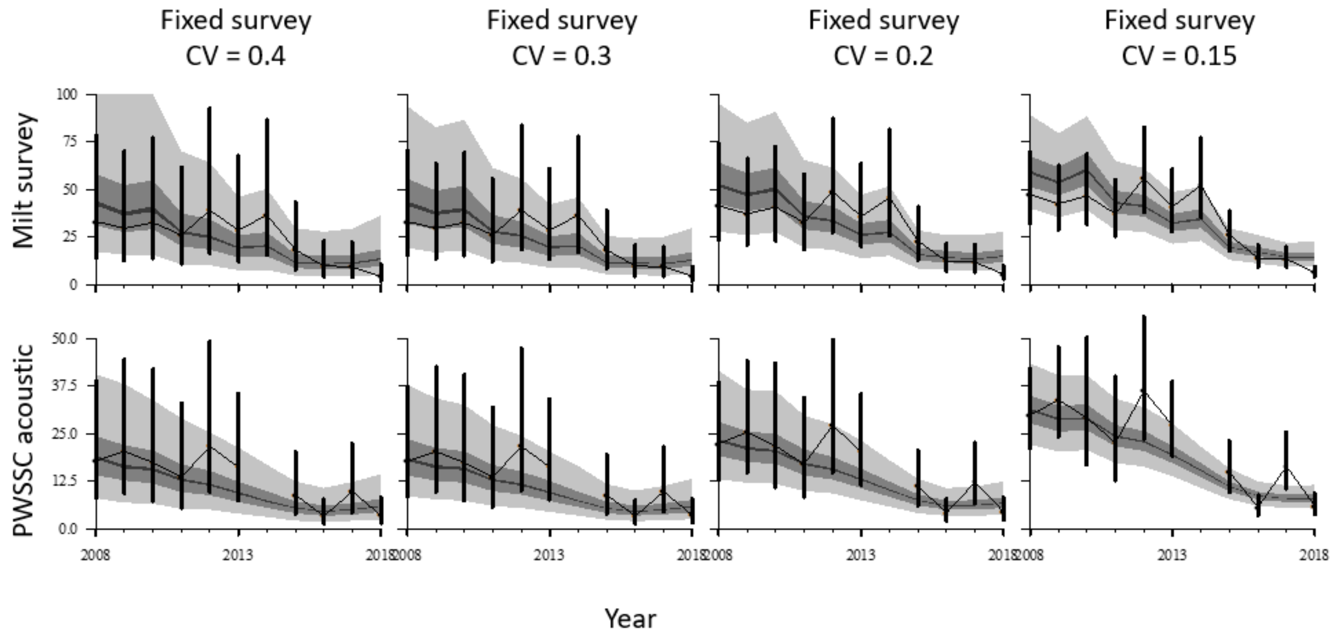

Figure 4. The effect on biomass estimates from the Bayesian age-structured assessment (BASA) model of fixing the CV (uncertainty) assumed for the milt survey and the Prince William Sound Science Center hydroacoustic survey at different levels. Model-predicted biomass was still above the milt survey in 2018 at the lowest CV, but the model trend was no longer upward. Shading and points have the same meaning as Fig. 1.

The incorporation of maturity at age in the model is an ongoing source of uncertainty. In the current formulation, spawning fish are treated as being 100% mature, and the maturity proportions represent a combination of both proportion mature and proportion absent from spawning aggregations. A newer formulation is planned that separately accounts for the small proportion of immature fish in the spawning aggregations, and also the availability of fish to the surveys (i.e., the proportion of fish at each age not present in the spawning aggregations).

In ongoing model development, the BASA model has been reconfigured to use a more efficient Bayesian algorithm in ADMB called the no-U-turn sampler (NUTS), as implemented in adnuts (Monnahan & Kristensen 2018, Monnahan et al. 2017). This has already cut run time by 50% while providing more robust Bayesian convergence, and further improvements in run time may be possible (Monnahan et al. 2019).

Progress on additional projects

The global herring meta-analysis was extensively revised and rewritten in response to reviewer comments, and resubmitted to *Fish and Fisheries*, where it remains under review. Results continue to highlight the unusually long period of low biomass and low recruitment in PWS herring compared to other herring populations around the world.

The project to examine factors that predict PWS herring recruitment and natural mortality is almost finished and ready for submission. Bayesian model selection was used to compare alternative forms of BASA with different predictor variables for recruitment and natural mortality, and the resulting manuscript is in preparation for submission to *ICES Journal of Marine Science*.

Work continues on a simulation study that examines the usefulness of viral hemorrhagic septicemia virus (VHSV) antibody data for estimating the disease component of natural mortality. We are coding an age-structured assessment/susceptible-infection-recovery model (SIR) hybrid to use simulations to test what kind of information these data are likely to supply. While early simple simulations demonstrated the feasibility of estimating VHSV severity from antibody data, review of these preliminary results revealed this approach to be overly simplistic. We are currently collaborating with Maya Groner to develop a better model within an age-structured assessment (i.e., a separate simulation model as well as BASA) that sufficiently captures disease dynamics in herring. Antibody data has yet to be incorporated into the BASA model. The delay is due to ongoing revisions on incorporating disease dynamics as well as issues with the seroprevalence data that are currently being reprocessed by Paul Hershberger's lab. Currently the BASA model continues to use disease prevalence estimates as a proxy for disease, although disease prevalence has been negligible in recent years.

A collaboration was started between John Trochta, Alec MacCall, and David McGowan last fall to incorporate spatial information from aerial spawning surveys (i.e., gridded milt data) into BASA and evaluate its utility for improving predictions of recruitment. Work is ongoing.

Postdoctoral projects

Hypotheses vary on the primary causes of the herring population collapse (Hulson et al. 2008, Thorne and Thomas 2008, Pearson et al. 2012) and continued low population size and poor recruitment (Deriso et al. 2008, Pearson et al. 2012, Ward et al. 2017). High recruitment is needed for the population to recover to pre-1993 abundance, but this population has not experienced any high recruitment events during the last three decades (Muradian et al. 2017), creating uncertainty as to which environmental conditions will be favorable to the population’s long-term recovery.

While the PWS herring population has not had a strong year class since 1988, it is possible to gain insight from high recruitment events that have occurred in other local herring and groundfish populations that historically had synchronized recruitment with the PWS population. From 1978-1993, recruitment in the Sitka Sound herring population, along with other smaller populations within Southeast Alaska, was closely related to PWS herring recruitment (Williams and Quinn 2000). Similarly, recruits-per-spawner estimates for PWS herring were positively related to walleye pollock (*Gadus chalcogrammus*) young-of-year abundance in the GOA from 1980 to 2009 (Sewall et al. 2018). Since 1993, both the Sitka herring and GOA pollock populations have had multiple strong year classes, most recently in 2012 (Dorn et al. 2018, Hebert 2019).

Given that herring and pollock typically recruit to their populations at age-3 and age-5, respectively, observed synchrony in recruitment success among different populations indicates that large-scale oceanographic processes operating across the Gulf of Alaska (GOA) and Northeast Pacific are potentially influencing spawning and/or survival through the critical first year of life. Although the 2012-year class did not result in high recruitment to the PWS herring population (Haught et al. 2017, Muradian et al. 2017), there is evidence that the 2012 cohort initially experienced relatively high survival through the first year. The PWS juvenile herring aerial survey estimated that the relative abundance of age-1 fish in June 2013 was the highest among all surveyed years (1996-99, 2010-2016) (S. Pegau pers. comm.). This suggests that conditions in 2012 across the GOA and within PWS were favorable to spawning and survival through the first year of life for both herring and pollock, but that age-1 and age-2 herring in PWS incurred higher mortality within PWS between summer 2013 and spring 2015 that resulted in low recruitment as age-3 fish.

Most oceanographic and biological time series available from ongoing PWS monitoring efforts are relatively short in duration (< 10 years), preventing direct comparison with herring abundance and condition before the population crash. Strong connectivity between PWS and the northern GOA shelf (Kline 1999, Wang et al. 2001, Halverson et al. 2013, Musgrave et al. 2013) indicates that climate and oceanographic drivers operating across the GOA and Northeast Pacific influence physical and biological conditions within PWS. Integrating longer time series from the GOA and Northeast Pacific may be used to infer conditions within PWS that influence the abundance, growth, and condition of PWS herring (e.g., Batten et al. 2016). Similarly, comparative studies between the PWS and Sitka herring populations may provide insight as to large-scale processes that favor spawning, as well as local processes whose impact on mortality varies between populations (e.g., Moran et al. 2018).

The HRM program has hypothesized that herring recruitment is driven by bottom up forcing, while mortality (i.e., the population level) is primarily determined by disease and predation (HRM proposal to EVOSTC FY17-FY21). Based on recent observations of high first year survival of the 2012 year class that did not lead to high recruitment (S. Pegau per. comm.), and recognized bio-physical connectivity between PWS and the GOA, we expand upon the HRM hypothesis and propose that spawning and survival of herring during their first year of life is determined by bottom up processes that operate across the northern Gulf of Alaska (GOA) and broader Northeast Pacific, as seen for herring in the North Sea (Gröger et al. 2010), while survival of juvenile fish after their first winter is determined by local ecological processes within PWS.

Dr. McGowan began in the 1st quarter of FY18. Progress to date has entailed conducting a literature review to become familiarized with historical herring- and oceanographic-related work conducted in PWS and the broader Northeast Pacific, quantifying spatial and temporal variability in PWS herring spawning over a 45-year period, and preparing covariate data for time series and spatio-temporal analyses that will be conducted in fall 2019. The literature review has led to the ongoing identification of available data from historical and current *Exxon Valdez* Oil Spill Trustee Council-funded studies, ADF&G, National Oceanic and Atmospheric Administration, and other sources that will be used as potential covariates to explain spatial and temporal variability in herring spawning and first-year survival.

The pattern description of PWS herring spawning used aerial survey data collected by ADF&G from 1973 to 2017. During this period, there have been pronounced spatial and temporal shifts in spawning habitat use within and between different regions of PWS (Fig. 5). Spawning occurred in all regions during the 1980s, primarily concentrating in the Northeast (NE) Sound, along the north shore, and northwestern Montague Island (Fig. 6A). In 1991, herring abruptly stopped spawning in the north shore and Naked Island regions, as well as in the northern areas of NE Sound. This resulted in a rapid decline in total spawn (Fig. 6B) that preceded the population collapse in 1993 (Fig. 1). Since the early 1990s, spawning has only occurred sporadically in these areas, and more recently has declined gradually in the Montague Island region. In contrast, spawning activity increased in the Southeast (SE) Sound in the 1990s, and is now the primary spawning area for PWS. These findings show the PWS population has undergone a pronounced shift in spawning habitat use.

Spawn timing within PWS has also shown high interannual variability during periods of high and low spawning activity from 1980 to 2017. Indices of spawn timing were calculated for each region based on the day-of-year (DOY) when 50% of total spawn (i.e., mile-days of milt) for that year had been observed, which corresponds with the peak of spawning activity in most years. To quantify spatial and temporal shifts in spawn timing for PWS herring, time series of spawn timing for each region were fitted to a multivariate auto-regressive state-space (MARSS) model. Spawn timing trends were different between hydrologically distinct areas of PWS: peak spawning shifted 3 weeks earlier between 1980-2006 in eastern PWS where oceanographic exchange with the GOA is weaker and freshwater inputs from glaciers is lower, whereas there was no clear trend in other areas during this period (Fig. 7). Starting in 2007, the peak spawn date shifted later in the season across all PWS areas by 2-3 weeks during a 7-year period of relatively cold temperatures in the GOA. To determine if these patterns occurred more broadly, ongoing work is quantifying coherence in spawn timing among PWS herring and other coastal herring populations in the GOA (Sitka Sound, Craig, Revilla Channel, Kamishak Bay). In addition, the relative influence of environmental processes operating at local (10s of km) and larger (100s-1000s of km) scales on spawn timing is being assessed for each population to provide a mechanistic understanding driving these patterns. These topics will be further investigated in fall 2019 as part of the 5-year Synthesis report.

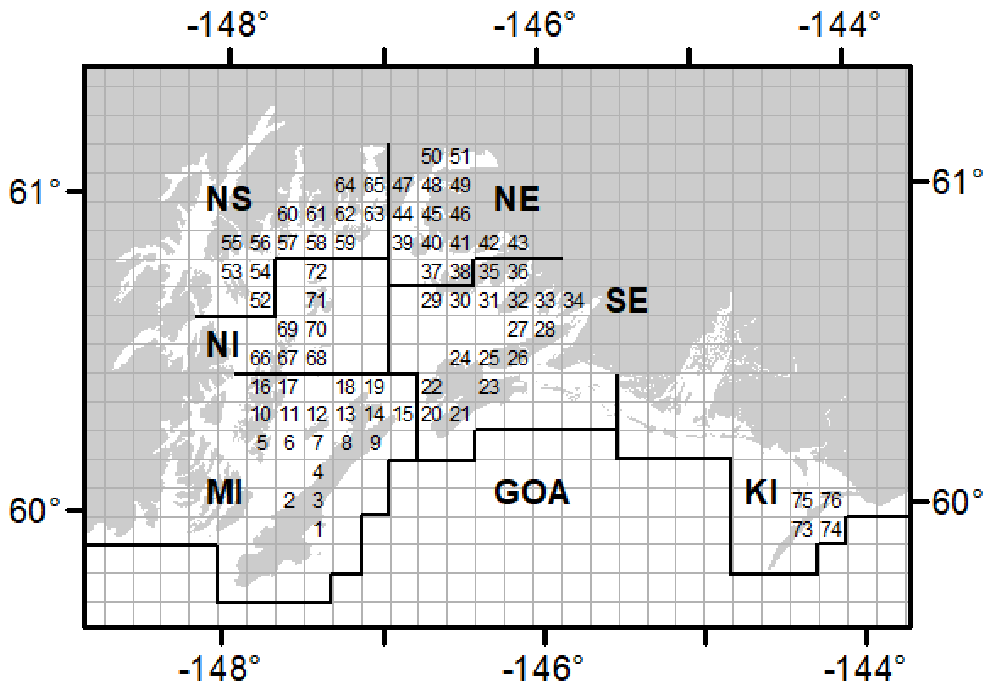

Figure 5. Boundaries for PWS regions (MI = Montague Island; SE = Southeast Sound; NE = Northeast Sound; NS = North Shore; NI = Naked Island; KI = Kayak Island) and the Gulf of Alaska (GOA) adapted from Appendix G4. in Russell et al. (2017). Numbered 10×10 km grid cells indicate areas within each region where herring spawning was observed between 1973 and 2017 and correspond with the x-axis in Fig. 6A.

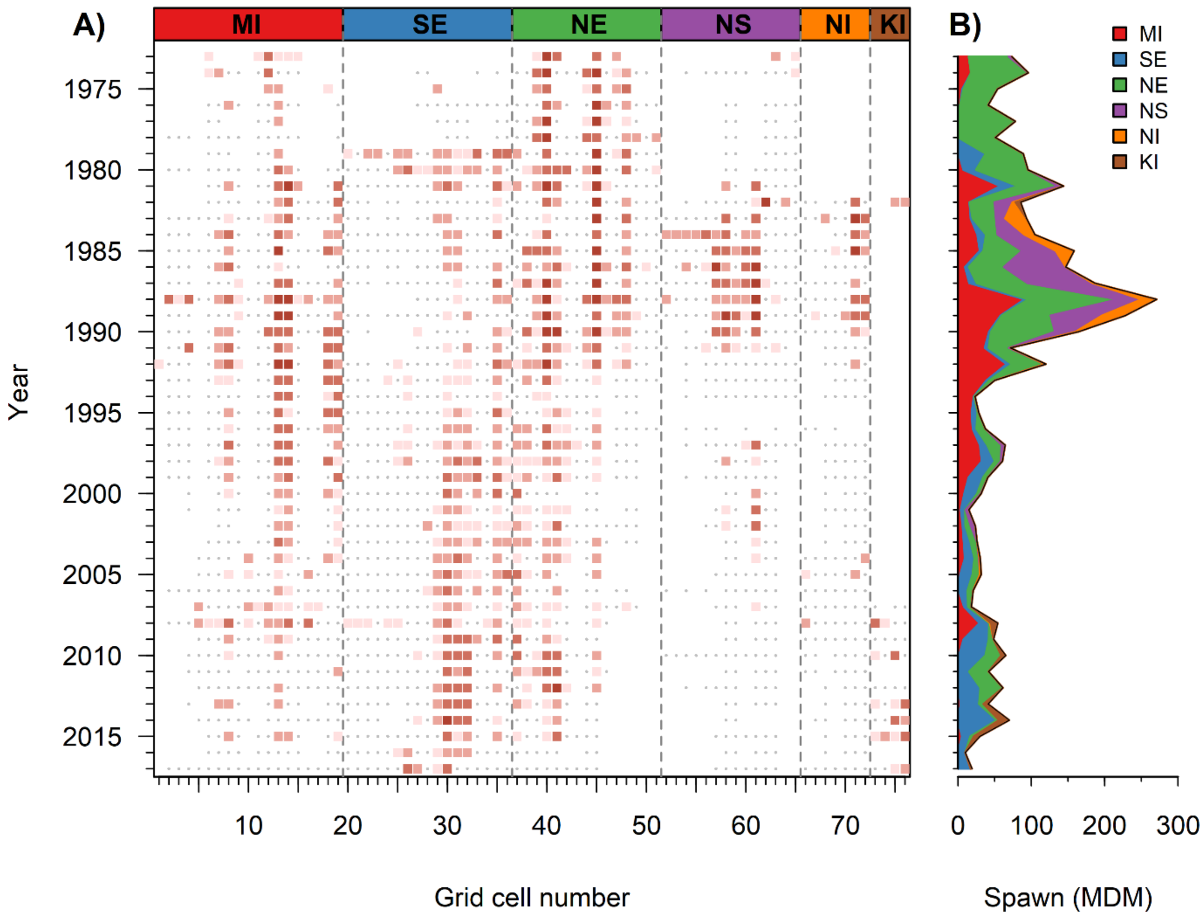

Figure 6. Distribution of spawning from 1973 to 2017 by year. Spawn patterns are represented as (A) quantiles of mile-days of milt (MDM) by 10×10 km grid cell and year (note, quantiles were calculated across all years), and as (B) cumulative spawn within each region (MI = Montague Island; SE = Southeast Sound; NE = Northeast Sound; NS = North Shore; NI = Naked Island; KI = Kayak Island). Grid cell numbers (1-76) correspond with cell locations identified in Fig. 5.

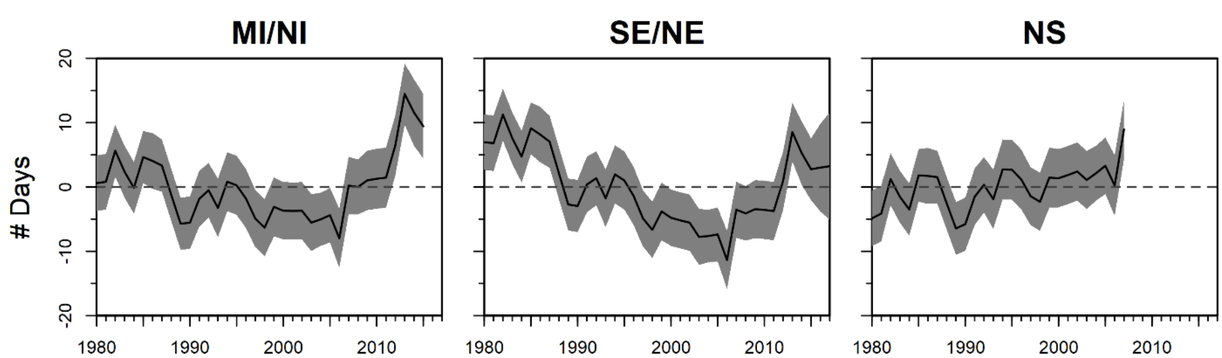

Figure 7. Estimated spawn timing trend (solid line) with 95% confidence intervals (shaded area) by grouped regions: MI/NI = Montague Island and Naked Island regions; SE/NE = Southeast Sound and Northeast Sound regions; NS = North Sound. Trends are standardized by their mean for all years (dashed line).

2. PROJECT STATUS OF SCHEDULED ACCOMPLISHMENTS

A. Project Milestones and Tasks

Table 1. Project milestones and task progress by fiscal year and quarter, beginning February 1, 2017. Additional milestones and/or tasks have been added in red. Yellow highlight indicates proposed fiscal year workplan. C = completed, X = not completed or planned. Fiscal year quarters: 1 = Feb 1 – April 30; 2 = May 1 – July 31; 3 = Aug. 1 – Oct. 31; 4 = Nov. 1 – Jan. 31.

	FY17				FY18				FY19				FY20				FY21			
Milestone/Task	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Milestones: model																				
Identify graduate student	C																			
Simulation study on feasibility of estimating annual VHSV infection rate from antibodies in serum														X						
Obtain antibody data from herring serum 2012-17 for inclusion in model																X				
Preliminary examinations of environmental factors affecting recruitment										C										
Preliminary analysis of harvest control rules																		X		
Submit model results and code to Workspace and ADFG				C				C				X				X				X
Update on global herring meta-analysis and relevance to PWS herring										C										
Update BASA model with antibody disease component															X					
Annual assessment update from BASA model					C				C				X				X			
Milestones: post-doc																				
Obtain oceanographic, biological, and climate data											C									
Pattern description of PWS spawning											C									
Time series analysis of environmental & population linkages to PWS spawn timing												X								
Coherence in spawn timing among coastal herring populations in the GOA												X								
Spatiotemporal analysis of environmental linkages to PWS spawning													X							
Analysis of environmental linkages to 1st year survival of PWS herring														X						
Analysis of environmental linkages to recruitment to PWS and Sitka populations															X					
Identify environmental factors to facilitate expansion of BASA model															X					

B. Explanation for not completing any planned milestones and tasks

The post-doc has made changes to his milestones and tasks listed under "Post-doc" in the FY19 workplan. To accommodate additional analyses related to herring spawning (see Section 2C below), the task "Preliminary analysis relating PWS data series to longer time series from the GOA and NE Pacific" from the original proposal has been dropped. Timetables for obtaining covariate data have been pushed back to the 3rd quarter of FY19 to accommodate the availability of updated data series through 2017 that will be included in the spawning analyses. The timetable has also been revised to include the new spawning analyses being completed for the Synthesis report (3rd quarter FY19) that will then be prepared as manuscripts for submission to peer-review journals (4th quarter FY19). These changes include shifting completion of the analysis of factors influencing 1st-year survival back to the 2nd quarter of FY20, and environmental linkages to recruitment and identifying environmental factors for the BASA model to the 3rd quarter of FY20.

C. Justification for new milestones/tasks

The post-doc has made changes to his milestones and tasks listed under "Post-doc" in the FY19 workplan. After completing a preliminary analysis of spawn patterns, it was determined this topic warranted a more in-depth examination. The revised spawning analysis now includes 3 elements: a pattern description of spatial and temporal variability (see Section 1, Project Executive Summary, above), identification of environmental and population factors that influence PWS spawn timing, and quantifying coherence in spawn timing among coastal herring populations in the GOA. The last element is designed to assess if interannual variations in spawn timing for each population are primarily explained by local or large-scale processes operating across the GOA. Collectively, these three analyses will comprise the post-doc's primary contribution to the 5-year Synthesis report. A fourth spawning analysis is designed to quantify the influence of environmental factors (e.g., freshwater inputs) on spawning in PWS using a vector auto-regressive spatio-temporal (e.g., McGowan et al. 2019), but it has yet to be determined if there is sufficient spatially-explicit covariate data available for this study.

3. PROJECT COORDINATION AND COLLABORATION

A. Within an EVOSTC-funded Program

Within the program, coordination takes place through regular data transfer, emails, phone calls, and two in-person meetings per year. Each of the components of the herring plan has a close connection to the model, from the acoustic survey, to the disease work, to aerial surveys, and assessment of age at maturity.

Herring Research and Monitoring

The post-doc will be collaborating with K. Gorman and S. Pegau on analyses related to herring first-year survival. The PI and J. Trochta are collaborating with S. Pegau and K. Gorman on ongoing work that will improve the maturity model, namely prioritizing the type of data required to inform maturity estimates. The PI and J. Trochta are also collaborating with P. Hershberger and M. Groner on developing an appropriate model of VHSV epidemiology. Coordination via email, phone calls, and in-person meeting entails the transfer and use of data series for herring condition, energy density, seroprevalence data, seine and cast net data of spawning aggregations, and aerial survey-based counts of juvenile abundance collected &/or processed by HRM PIs as model inputs, and collaborative writing and revising of manuscripts.

Gulf Watch Alaska

The post-doc will continue collaborating with S. Campbell and other Gulf Watch Alaska (GWA) PIs on analyses related to herring spawning and first-year survival. Coordination via email, phone calls, and in-person meeting entails the transfer and use of oceanographic and predator data series collected &/or processed by GWA PIs as model inputs, and collaborative writing and revising of manuscripts.

Data Management

Data collected and used in each component of the modeling project are managed and uploaded to the Workspace in coordination with Axiom. Project data requirements are reviewed annually with Axiom and updated as necessary (November-December of each fiscal year), particularly for the assessment model. BASA input data are processed and provided by ADF&G by the 3rd quarter and the model subsequently ran by the 4th quarter of each fiscal year.

B. With Other EVOSTC-funded Projects

This project does not directly coordinate with other EVOSTC-funded projects.

C. With Trustee or Management Agencies

Input data for the assessment model (ADF&G survey, age composition, weight at age, etc.) comes from ADF&G, which requires close coordination to understand how the data were collected and how they should be used in the model. Results are transmitted to lead ADF&G scientists (Sherri Dressel) for comments and review in the form of HRM proposals and reports, in addition to pre-submission versions of manuscripts.

The post-doc is actively collaborating with ADF&G staff (S. Haught, K. Hebert, T. Otis) on multiple analyses related to herring spawning within PWS and other coastal populations in the Gulf of Alaska. Coordination via email, phone calls, and in-person meeting entails the transfer and use of data series for herring spawning, age-weight-length, and temperature loggers collected &/or processed by ADF&G as model inputs, and collaborative writing and revising of manuscripts.

J. Trochta is collaborating with Alec MacCall and D. McGowan on developing a semi-spatial stock assessment model for herring with the potential incorporate this model into BASA if proven useful. Coordination via email, phone calls, and in-person meeting entails the transfer and use of data series for herring spawning collected &/or processed by ADF&G as model inputs, and collaborative writing and revising of manuscripts.

4. PROJECT DESIGN

A. Overall Project Objectives

For the modeling component, the two primary objectives are to conduct annual stock assessment for PWS herring and to work on including the new antibody data from herring serum, which will tell us what percent of the herring at each age have been exposed to VHSV disease in each year in the past. Work will continue on the global herring meta-analysis to provide informative Bayesian priors for the assessment, and to explore factors used to predict herring recruitment.

For the post-doc project the original objectives were:

1. Measure coherence between PWS data series and related time series from the GOA and Northeast Pacific with greater spatial and temporal coverage to identify oceanographic, biological, and climate covariates that can be used in subsequent analyses as potential predictors of PWS herring spawning, survival, and recruitment
2. Identify physical and/or ecological processes linked to PWS herring spawning

3. Identify physical and/or ecological processes linked to survival of age-1 PWS herring
4. Identify physical and/or ecological processes linked to survival of age-2 PWS herring
5. Quantify the influence of environmental factors linked to PWS herring spawning and/or juvenile survival on recruitment to PWS and Sitka Sound herring populations
6. Provide environmental factors linked to PWS herring spawning and/or juvenile survival to the modeling and stock assessment project to assess if expanding the BASA model to include these environmental inputs improves the accuracy of the recruitment predictions

This study is designed to synthesize available data series collected over the past four decades to improve our understanding of how environmental variability has influenced, and potentially suppressed, PWS herring recruitment and population size. It builds upon decades of research and monitoring following the *Exxon Valdez* oil spill: this includes recent efforts by Batten et al. (2016) to examine the relationship between temperature and prey availability to PWS herring first year growth, and by Sewall et al. (2017) and Ward et al. (2017) to identify environmental and anthropogenic connections to PWS herring recruitment. By examining the influence of environmental factors related to bottom up and top down forcing on herring during subsequent life stages that ultimately determine recruitment success, this study is designed to shed light on stage-specific bottlenecks that are potentially constraining recovery of PWS herring.

Final products from this project are expected to result in 3-4 scientific papers describing results for Objectives 2-5 (results from Obj. 3 and 4 will be submitted as either 1 joint paper or 2 separate papers). In addition, relationships identified by Obj. 1 are expected to support other HRM and GWA projects by identifying new environmental covariates relevant to their respective analyses.

B. Changes to Project Design and Objectives

The primary objectives for the post-doc project have been revised as follows:

1. Characterize spatial and temporal variability in herring spawning in PWS
2. Quantify the influence of environmental and population factors on spawning timing in PWS
3. Examine coherence in spawn timing among coastal herring populations in the GOA to assess if variations in spawn timing are primarily explained by local or large-scale processes
4. Quantify the influence of environmental factors on spatio-temporal variability in PWS spawning
5. Identify physical and/or ecological processes linked to survival of age-1 PWS herring
6. Identify physical and/or ecological processes linked to survival of age-2 PWS herring
7. Quantify the influence of environmental factors linked to PWS herring spawning and/or juvenile survival on recruitment to PWS and Sitka Sound herring populations
8. Provide environmental factors linked to PWS herring spawning and/or juvenile survival to the modeling and stock assessment project to assess if expanding the BASA model to include these environmental inputs improves the accuracy of the recruitment predictions

These changes allow for a more in-depth examination of observed shifts in the location and timing of spawning in PWS over the past four decades. The population largely abandoned spawning areas in the northern Sound prior to the population collapse that accounted for much of the total spawn in the 1980s, and more recently has ceased spawning around Montague Island after nearly 40 years. The current spawning areas in SE Sound (Fig. 6) were not widely used prior to the population collapse (Fig. 1), and we believe the potential impact of this shift in habitat use on the population warrants closer examination.

5. PROJECT PERSONNEL – CHANGES AND UPDATES

Personnel remain PI Trevor Branch, PhD candidate John Trochta, and postdoc David McGowan.

During FY19, John Trochta applied for a bypass from the MS to the PhD program, and completed his PhD qualifying and PhD general exams. His stipend is now being paid at the higher PhD-candidate level rate.

6. PROJECT BUDGET

A. Budget Forms (See HRM FY20 Budget Workbook)

***EXXON VALDEZ* OIL SPILL TRUSTEE COUNCIL**
PROGRAM PROJECT BUDGET PROPOSAL AND REPORTING FORM

Budget Category:	Proposed FY 17	Proposed FY 18	Proposed FY 19	Proposed FY 20	Proposed FY 21	TOTAL PROPOSED	ACTUAL CUMULATIVE
Personnel	$48.7	$138.2	$144.3	$152.4	$64.8	$548.4	
Travel	$6.4	$13.7	$12.1	$9.3	$6.9	$48.4	
Contractual	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	
Commodities	$25.1	$25.7	$26.1	$25.0	$24.2	$126.1	
Equipment	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	
Indirect Costs (*will vary by proposer*)	$33.8	$86.9	$90.0	$91.6	$40.7	$343.0	
SUBTOTAL	$114.0	$264.5	$272.5	$278.3	$136.6	$1,065.9	
General Administration (9% of subtotal)	$10.3	$23.8	$24.5	$25.0	$12.3	$95.9	N/A
PROJECT TOTAL	$124.3	$288.3	$297.0	$303.3	$148.9	$1,161.9	
Other Resources (Cost Share Funds)	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	

B. Changes from Original Project Proposal

None.

C. Sources of Additional Project Funding

None.

7. FY17-19 PROJECT PUBLICATIONS AND PRODUCTS

<u>*Publications (in prep and submitted)*</u>

McGowan, D. W., T. A. Branch, and S. Haught. (In prep). Multi-decadal space and time shifts in Pacific herring spawning in Prince William Sound, Alaska. Canadian Journal of Fisheries and Aquatic Sciences.

Muradian, M. L., T. A. Branch, and A. E. Punt. (in review). A framework for assessing which sampling programs provide the best trade-off between accuracy and cost of data in stock assessments. ICES Journal of Marine Science.

Trochta, J. T., T. A. Branch, A. O. Shelton, and D. E. Hay. (in review). The highs and lows of herring: A meta-analysis of patterns in herring collapse and recovery. Fish and Fisheries.

Trochta, J. T., and T. A. Branch (in prep). Bayesian analysis of oceanographic and ecological drivers of Pacific herring population dynamics. ICES Journal of Marine Science.

<u>*Publications (latest first)*</u>

Brown, C. J., A. Broadley, M. F. Adame, T. A. Branch, M. P. Turschwell, and R. M. Connolly. 2019. The assessment of fishery status depends on fish habitats. Fish and Fisheries 20:1-14.

Gephart, J. A., H. E. Froehlich, and T. A. Branch. 2019. To create sustainable seafood industries, the United States needs a better accounting of imports and exports. Proceedings of the National Academy of Sciences U.S.A. 116:9142-9146.

Monnahan, C. C., T. A. Branch, J. T. Thorson, I. J. Stewart, and C. S. Szuwalski. 2019. Overcoming long Bayesian run times in integrated fisheries stock assessments. ICES Journal of Marine Science https://doi.org/10.1093/icesjms/fsz059.

Trochta, J. T., M. Pons, M. B. Rudd, M. Krigbaum, A. Tanz, and R. Hilborn. 2018. Ecosystem-based fisheries management: Perception on definitions, implementations, and aspirations. PLoS One 13:e0190467.

Ward, E. J., M. Adkison, J. Couture, S. C. Dressel, M. A. Litzow, S. Moffitt, T. Hoem Neher, J. Trochta, and R. Brenner. 2017. Evaluating signals of oil spill impacts, climate, and species interactions in Pacific herring and Pacific salmon populations in Prince William Sound and Copper River, Alaska. PLoS One 12:e0172898.

Muradian, M. L., T. A. Branch, S. D. Moffitt, and P.-J. F. Hulson. 2017. Bayesian stock assessment of Pacific herring in Prince William Sound, Alaska. PLoS One 12:e0172153.

<u>Published and updated datasets</u>

The 2018 BASA stock assessment has been uploaded to the AOOS research workspace, together with the model formulation and underlying data.

<u>Presentations</u>

McGowan, D. W. Poster. Spatial and temporal variations in Pacific herring spawning in Prince William Sound, presented at AMSS. January 2019, Anchorage, AK.

Trochta J. T, and T. A. Branch. Evaluating the effects of a changing ecosystem on Pacific herring (*Clupea pallasii*) in Prince William Sound, Alaska, presented at AMSS. January 2019, Anchorage, AK.

Trochta J. T., A. D. MacCall, D. W. McGowan, and T. A. Branch. Incorporating spawn surveys in a semi-spatial stock-recruitment model, presented at CAPAM Spatial Workshop. October 2018, La Jolla, CA.

Trochta J. T, and T. A. Branch. An investigation of popular hypotheses on the survival of Pacific herring in Prince William Sound, Alaska using Bayesian model selection, presented at SAFS Think Tank. April 2017, Seattle, WA.

Trochta J. T., T. A. Branch, A. O. Shelton, and D. E. Hay. Insights into the Dynamics of Atlantic and Pacific Herring Following Population Collapse, presented at the PICES International Symposium on Drivers of dynamics of small pelagic fish resources. March 2017, Victoria, British Columbia, Canada.

<u>Outreach</u>

Branch continues to maintain an active science outreach program on a wide variety of fisheries-related topics on social media (Twitter, @TrevorABranch), with 10,800 followers, and 6.3 million views of his tweets during FY19 to date. Branch and Trochta recorded an interview for the *Field Notes* podcast program produced by PWSSC in 2017. Trochta contributed articles to the 2017-2018 and 2019-2020 issues of the *Delta Sound Connections*. Trochta also gave a talk on herring population dynamics for the *UW Science Now* lecture series at Town Hall Seattle in 2016. McGowan contributed an article to the *Delta Sound Connections* 2019-2020 issue.

LITERATURE CITED

Batten, S. D., S. Moffitt, W. S. Pegau, and R. Campbell. 2016. Plankton indices explain interannual variability in Prince William Sound herring first year growth. Fisheries Oceanography 25:420–432.

Deriso, R. B., M. N. Maunder, and W. H. Pearson. 2008. Incorporating covariates into fisheries stock assessment models with application to Pacific herring. Ecological Applications 18:1270–1286.

Dorn, M., K. Aydin, B. Fissel, W. Palsson, K. Spalinger, S. Stienessen, K. Williams, and S. Zador. 2018. Assessment of walleye pollock stock in the Gulf of Alaska. Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Gulf of Alaska, North Pacific Fishery Management Council, Anchorage, AK.

Fournier, D. A., H. J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M. N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods & Software 27:233-249.

Funk, F. C., and G. J. Sandone. 1990. Catch-age analysis of Prince William Sound, Alaska, herring, 1973-1988, Fishery Research Bulletin No 90-01. Alaska Department of Fish and Game, Division of Commercial Fisheries. Available at http://www.sf.adfg.state.ak.us/fedaidpdfs/frb.1990.01.pdf.

Gröger, J. P., G. H. Kruse, and N. Rohlf. 2010. Slave to the rhythm: how large-scale climate cycles trigger herring (*Clupea harengus*) regeneration in the North Sea. ICES Journal of Marine Science 67:454–465.

Halverson, M. J., C. Bélanger, and S. M. Gay. 2013. Seasonal transport variations in the straits connecting Prince William Sound to the Gulf of Alaska. Continental Shelf Research 63:S63–S78. Coastal Ocean Observing System: Retrospective Reanalysis and Real-Time Forecasting.

Haught, S., J. Botz, S. Moffitt, and B. Lewis. 2017. 2015 Prince William Sound Area Finfish Management Report. Alaska Department of Fish and Game, Anchorage, Alaska.

Hebert, K. 2019. Southeast Alaska 2018 Herring Stock Assessment Surveys. Regional Operational Plan, Alaska Department of Fish and Game, Anchorage, Alaska.

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

Kline, Jr., Thomas C. 1999. Temporal and spatial variability of 13C/12C and 15N/14N in pelagic biota of Prince William Sound, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 56:94–117.

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.

Marty, G. D., P.-J. F. Hulson, S. E. Miller, T. J. Quinn II, S. D. Moffitt, and R. A. Merizon. 2010. Failure of population recovery in relation to disease in Pacific herring. Diseases of Aquatic Organisms 90:1-14.

McGowan, D. W., J. K. Horne, and L. A. Rogers. 2019. Effects of temperature on the distribution and density of capelin in the Gulf of Alaska. Marine Ecology Progress Series 620:119–138.

Monnahan, C. C., T. A. Branch, J. T. Thorson, I. J. Stewart, and C. S. Szuwalski. 2019. Overcoming long Bayesian run times in integrated fisheries stock assessments. ICES Journal of Marine Science https://doi.org/10.1093/icesjms/fsz059.

Monnahan, C. C., and K. Kristensen. 2018. No-U-turn sampling for fast Bayesian inference in ADMB and TMB: Introducing the adnuts and tmbstan R packag. PLoS One 13:e0197954.

Monnahan, C. C., J. T. Thorson, and T. A. Branch. 2017. Faster estimation of Bayesian models in ecology using Hamiltonian Monte Carlo. Methods in Ecology and Evolution 8:339-348.

Moran, J. R., R. A. Heintz, J. M. Straley, and J. J. Vollenweider. 2018. Regional variation in the intensity of humpback whale predation on Pacific herring in the Gulf of Alaska. Deep Sea Research Part II 147:187–195.

Muradian, M. L. 2015. Modeling the population dynamics of herring in the Prince William Sound, Alaska. M.S. thesis, University of Washington, Seattle.

Muradian, M. L., T. A. Branch, S. D. Moffitt, and P.-J. F. Hulson. 2017. Bayesian stock assessment of Pacific herring in Prince William Sound, Alaska. PLOS ONE 12:e0172153.

Musgrave, D. L., M. J. Halverson, and W. Scott Pegau. 2013. Seasonal surface circulation, temperature, and salinity in Prince William Sound, Alaska. Continental Shelf Research 53:20–29.

Pearson, W. H., R. B. Deriso, R. A. Elston, S. E. Hook, K. R. Parker, and J. W. Anderson. 2012. Hypotheses concerning the decline and poor recovery of Pacific herring in Prince William Sound, Alaska. Reviews in Fish Biology and Fisheries 22:95–135.

Punt, A. E., and R. Hilborn. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. Reviews in Fish Biology and Fisheries 7:35-63.

Quinn, T. J., G. D. Marty, J. Wilcock, and M. Willette. 2001. Disease and population assessment of Pacific herring in Prince William Sound, Alaska. Pages 363-379 in F. Funk, J. Blackburn, D. Hay, A. J. Paul, R. Stephenson, R. Toreson, and D. Witherell, editors. Herring: expectations for a new millennium. University of Alaska Sea Gran, Anchorage, AK.

Sewall, F., B. Norcross, F. Mueter, and R. Heintz. 2018. Empirically based models of oceanographic and biological influences on Pacific Herring recruitment in Prince William Sound. Deep Sea Research Part II 147:127–137.

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

Wang, J., M. Jin, E. V. Patrick, J. R. Allen, D. L. Eslinger, C. N. K. Mooers, and R. T. Cooney. 2001. Numerical simulations of the seasonal circulation patterns and thermohaline structures of Prince William Sound, Alaska. Fisheries Oceanography 10:132–148.

Ward, E. J., M. Adkison, J. Couture, S. C. Dressel, M. A. Litzow, S. Moffitt, T. H. Neher, J. Trochta, and R. Brenner. 2017. Evaluating signals of oil spill impacts, climate, and species interactions in Pacific herring and Pacific salmon populations in Prince William Sound and Copper River, Alaska. PLOS ONE 12:e0172898.

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