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

Project Number and Title

21120111-C Modeling and stock assessment of Prince William Sound herring

Primary Investigator(s) and Affiliation(s)

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Date Proposal Submitted

August 14, 2020

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, project 21120111-E), 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 Management Strategy Evaluation.
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
$124,300	**$288,300**	**$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 (Quinn et al. 2001, Marty et al. 2003, Marty et al. 2010). 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 (ADMB, 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 was used to assess the value of past information collected in the program (Muradian et al. 2019), is the underlying basis for the second set of five years of the long-term herring monitoring project.

In previous years, the BASA model has a slight tendency to estimate higher biomasses than survey points in the most recent 1-2 years. Investigations into this model misspecification have 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. This year, additional checks included down-weighting age composition data, an alternative model of disease, and estimating a regime shift in mean recruitment. Down-weighting the age-composition data resulted in much better fits to biomass indices and lower estimated biomass. Incorporating a shift in mean recruitment also lowered the biomass estimate, but to a lesser extent. Analyses are ongoing to improve fits and reduce estimation bias in the model.

The most recent BASA assessment based on data to the end of 2019 (the "2019 model") can be seen in model fits to the survey time series (Fig. 1), and to numbers-at-age data (Fig. 2) (John Trochta, unpublished). In 2019 the hydroacoustic survey and mile-days of milt were slightly higher than in 2018, although still low by historical levels, resulting in a slight uptick in estimated biomass. The 2019 BASA model added fits to the age-1 aerial survey, which converts counts of age-1 herring schools into an index of recruitment. The age-1 herring school data are quite variable, however, and the model estimates high additional variance for this index that effectively down-weights the influence of these new data in the model assessment. The 2019 model predicts that age-3 recruitment in 2019 is higher than seen since 2002 (Fig. 3), based on a high percentage of age-3 fish observed in 2019 (Fig. 2). Notably, high proportions of age-3 fish were also seen in herring stocks across the Gulf of Alaska in 2019 (S. Dressel, pers. comm.). However, estimates of recruitment based on a single year of data are highly uncertain (Figs. 2-3).

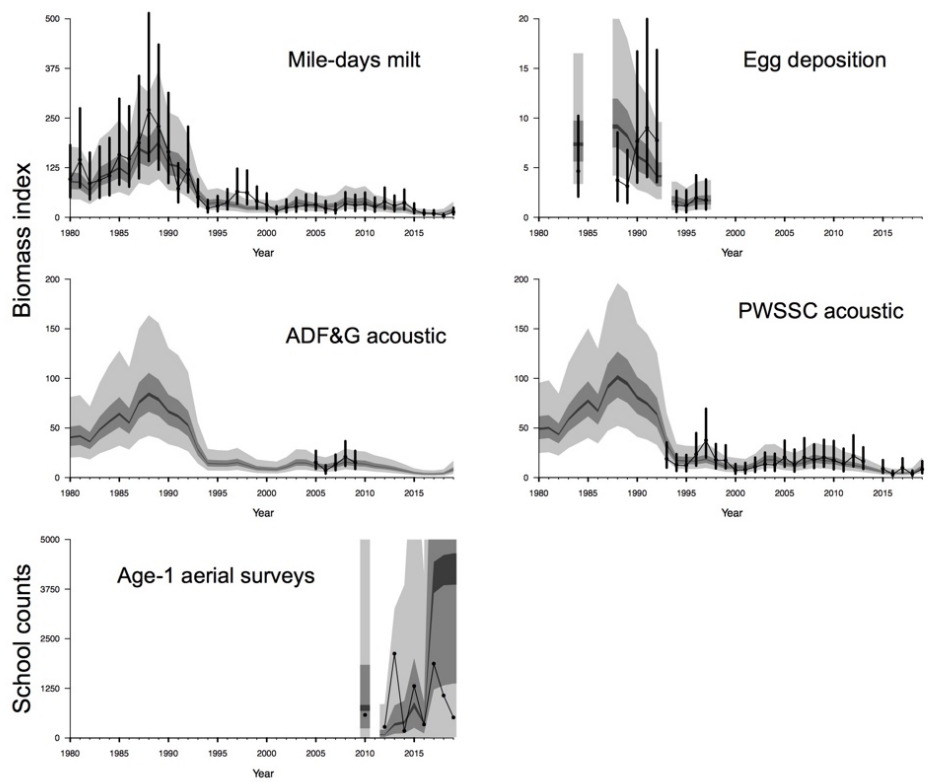

Figure 1. The 2019 Bayesian age-structured assessment (BASA) model estimates of Prince William Sound herring biomass fitted to the five main time series of biomass. The newest addition is the model fit to the counts of schools from the age-1 aerial surveys. Shaded polygons are the model-estimated posterior 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).

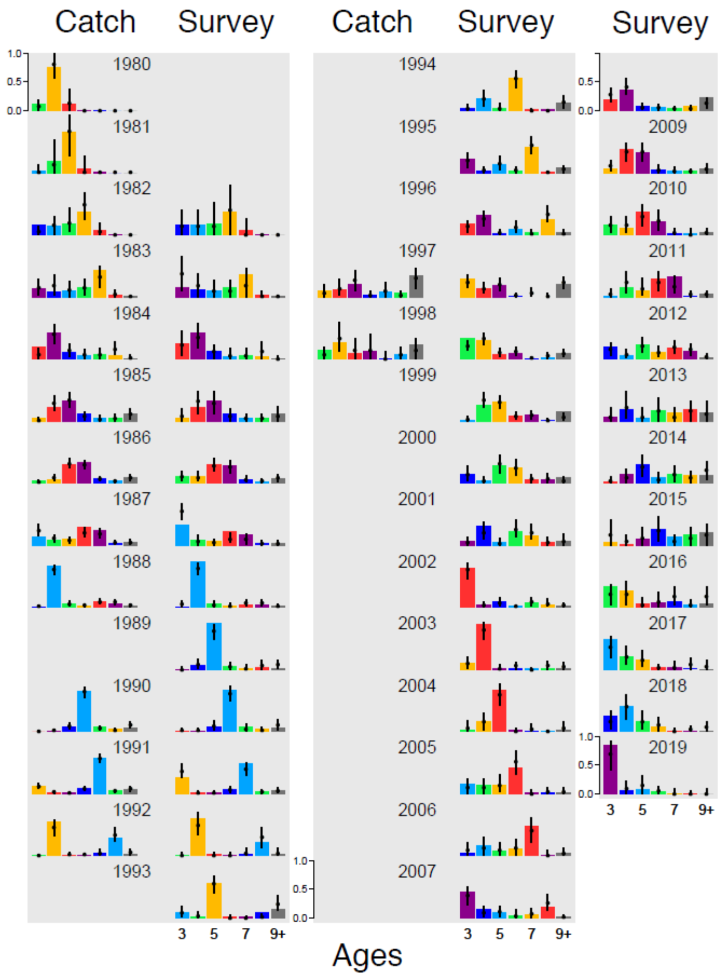

Figure 2. The 2019 Bayesian age-structured assessment (BASA) model fits to the age composition data from purse-seine catches and from the Alaska Department of Fish and Game herring-spawn survey (data from all gears combined). Colors track individual cohorts over time, while points and lines indicate the model posterior median and 95% posterior intervals. Source: John Trochta.

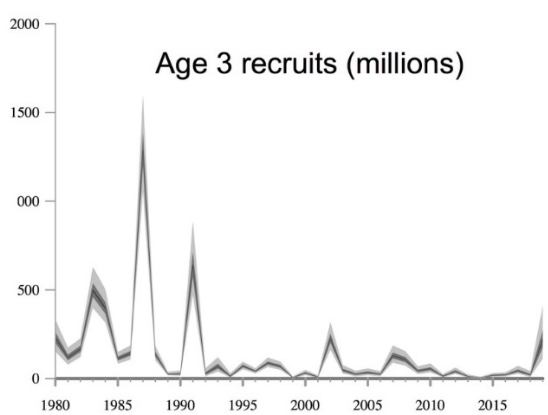

Figure 3. The 2019 Bayesian age-structured assessment (BASA) model estimates of age-3 recruitment in millions, with 95% credibility intervals shown in light gray. Source: John Trochta.

The BASA model has long had an inconsistency in maturity that was addressed this year. In brief, the schools sampled by seine and cast nets are not representative of the entire population because they largely comprise mature pre- and post-spawning individuals, and likely miss many immature fish of the same age that do not participate in spawning schools. Thus, even though maturity estimates are available by age for the sampled fish (which come largely from spawning schools), these are likely not representative of the mature and immature proportions in the entire population. We explored different assumptions about maturity in BASA to examine the effect of getting what maturity represents wrong, including fast vs. slow maturity schedules, one maturity schedule for all years vs. two different schedules split at 1997, estimating availability of immature fish (from the maturity data), assuming a fixed true biological maturity schedule for the total population, and estimating selectivity of seine and cast nets given the maturity data. None of these options had any noticeable impact on estimated spawning biomass and recruitment, but did have some implications for model stability. Based on these findings, we now estimate only one time-period of maturity, with maturity also including availability of herring to sampling.

In 2019, a major new advance was reconfiguring the BASA model so that it could use a more efficient Bayesian algorithm in ADMB called the no-U-turn sampler (NUTS), as implemented in adnuts (Monnahan et al. 2017, Monnahan & Kristensen 2018, Monnahan et al. 2019). This has already cut run time by 60-80% while providing more robust Bayesian convergence, which has allowed for us to run many dozens of model variants to explore the impacts of environmental covariates on mortality and recruitment.

Progress on additional projects

The global herring meta-analysis of 64 herring populations is now published in *Fish and Fisheries* (Trochta et al. 2020). Among the many key results are the finding that PWS herring have experienced unusually long periods of low biomass and low recruitment compared to all other herring populations globally, that at low biomass levels Pacific herring populations are closed to fishing much more often than Atlantic herring populations; and that biomass recovery depends on large recruitment events and is also correlated with sea surface height anomalies and sea surface temperatures.

The project to examine factors that predict PWS herring recruitment and natural mortality is completed 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*. Predictor variables did not show consistent effects (Fig. 4) nor consistently improved model fits in all time periods examined, and across all model selection metrics, although some covariates were selected for particular time periods. Predictors for natural mortality that improved model fits included total pink salmon returns, winter North Pacific Gyre Oscillation, and Gulf of Alaska (GOA) pollock spawning biomass (Fig. 4). No predictors of recruitment improved model fit, although hatchery pink salmon releases and a 1989 regime shift had a non-zero effect when modeled over the entire time period (although this effect is lost over time) (Fig. 4). Additionally, when incorporated as fixed effects into the stock assessment, supported covariates had little effect on estimated spawning biomass or age-3 recruitment (Fig. 5).

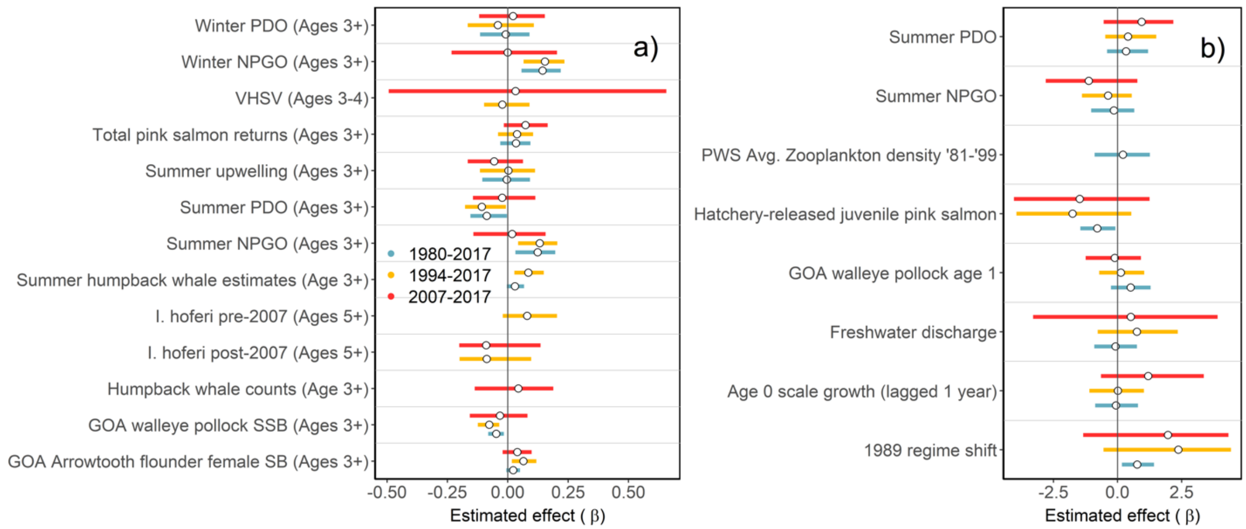

Figure 4. Estimated effects of each covariate and for each time frame with 99.9% credibility intervals. Natural mortality (a) and recruitment (b) specific effects are separated between the two plots. Intervals that do not cross the zero line (vertical black line) imply significant non-zero effects.

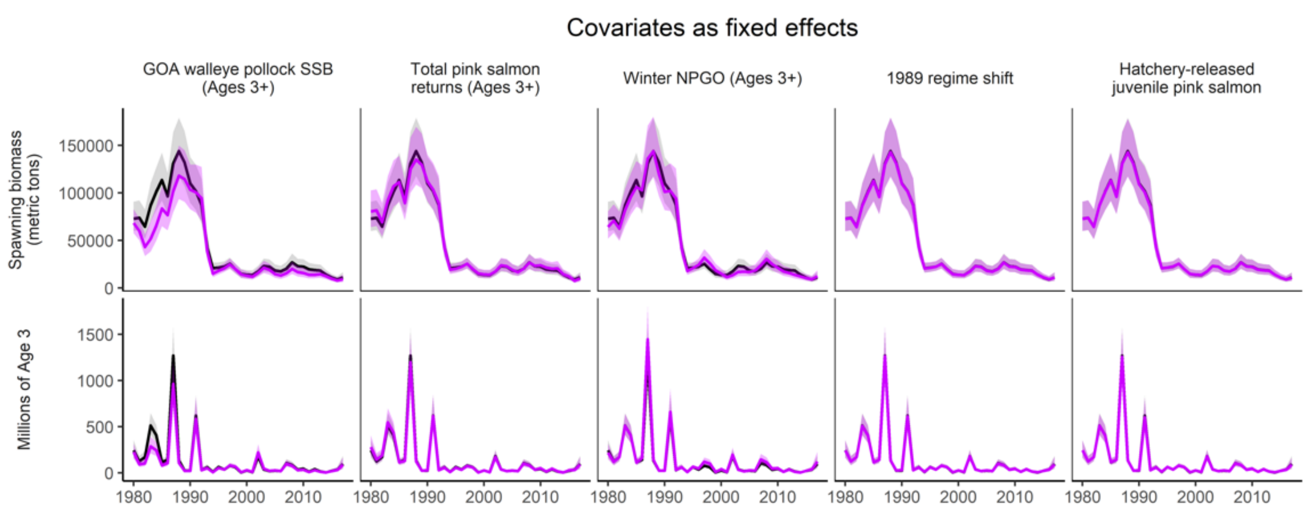

Figure 5. Predictions of spawning biomass (top row) and age-3 recruitment (bottom row) from the most supported covariates incorporated as fixed effects from 1980-2017 (purple lines and areas). Top fixed-effect covariates have model selection values below those for the Null model in at least two out of three model selection criteria and have a significant non-zero effect. The black line and gray shaded area is the base model with no covariates included.

A major ongoing component of the modeling work involves the incorporation of viral hemorrhagic septicemia virus (VHSV) antibody data into the model to better estimate the disease component of natural mortality. Antibody data have never yet been used in fisheries management to estimate the prevalence of disease outbreaks, and disease has been proposed to be one of the major reasons for failed recovery following collapse of the PWS herring population (e.g., Marty et al. 2003, Marty et al. 2010). Age-specific antibody detections have been demonstrated for PWS herring (by PI P. Hershberger), and antibody detections track the proportion of immune fish over time. We have developed a simulator of VHSV disease outbreaks, and an estimation model, to test whether it is possible to use antibody data to estimate disease prevalence and mortality.

The results presented here are very preliminary but promising. Disease is simulated over a 120-day period within each year, resulting in annual patterns similar to those observed in reality, and simulated antibody prevalence by age and year (Fig. 6). A simplified catch-age estimation model with equations explicitly modeling annual infection and disease mortality examines four scenarios: the base model with high sample size of herring examined tested for antibody presence (200 per year), a model where disease is present but not estimated, a model with low sample size (20 per year), and a model where young susceptible fish mingle with older infected fish (the other models effectively assume that only older mature fish can experience infection). The estimation models including disease were unbiased and considerably better than the estimation model ignoring disease (Fig. 7).

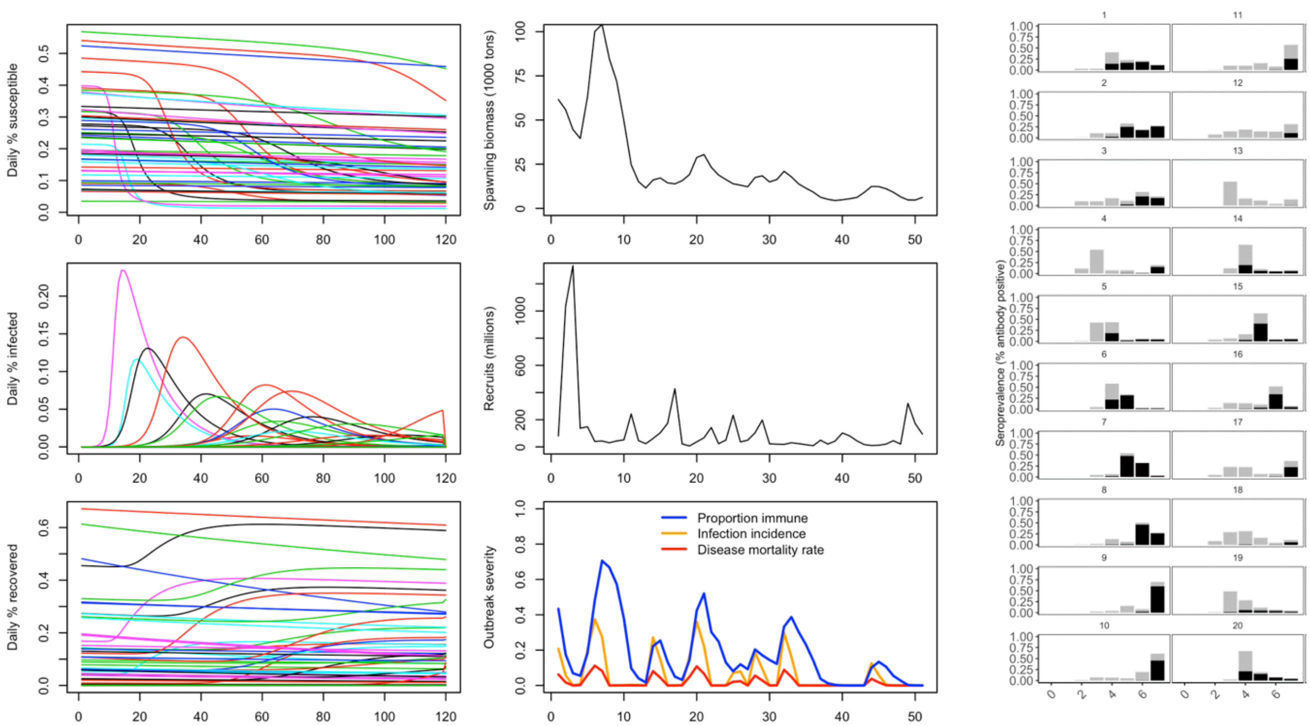

Figure 6. Disease simulator. The left column is the proportion of susceptible fish, infected fish, and recovered fish during the 120-day period in each year (one color per year); the middle column is the time trend over years of spawning biomass, recruitment, and outbreak severity in each year; and the right column is predicted proportion of fish at age in years 1-20 (one panel per year), with black representing those with antibodies and gray those without antibodies.

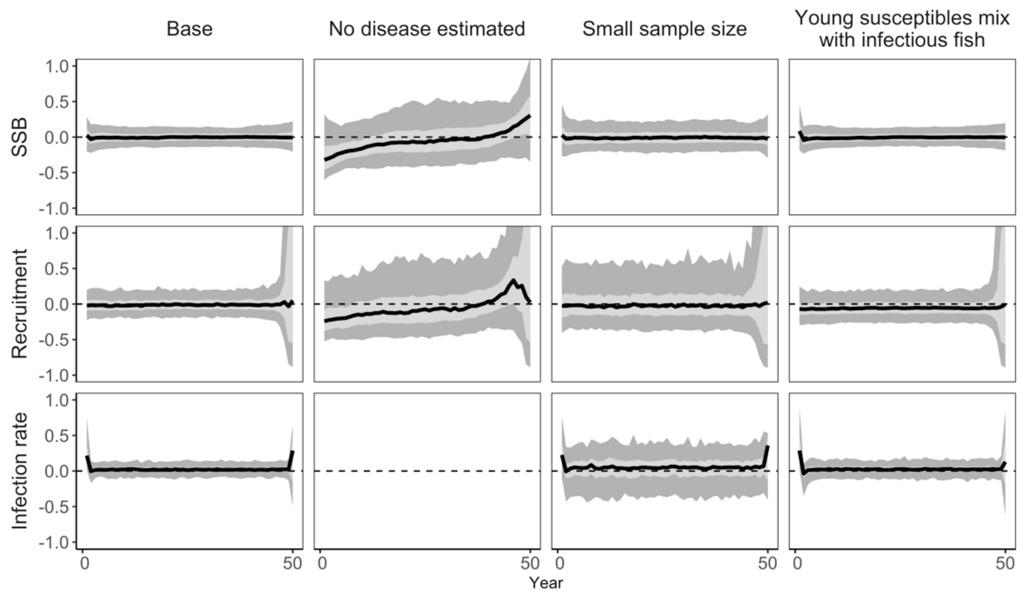

Figure 7. Estimation model including simulated antibody data (base model), showing that it provides unbiased estimates of spawning stock biomass, recruitment, and infection rate, with both large and small sample sizes, regardless of scenario, but is biased when disease is ignored (second column).

These results based on simulated data are very promising, but still preliminary and have not yet been submitted for peer review. Estimates of actual antibody prevalence in PWS herring is nearing completion, and will come from the seroprevalence data being processed by Paul Hershberger's lab. When available these should be able to be straightforwardly incorporated as a reliable predictor for annually-variable natural mortality in populations where disease outbreaks are a major component of natural mortality (the holy grail in fisheries management) in BASA.

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.

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 & Thomas 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 (such as the Gulf-wide high proportion of age-3 herring in 2019) 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).

Dr. McGowan began in the 1st quarter of FY18 and left the project at the end of FY20 for a permanent position with the National Oceanic and Atmospheric Administration position. Post-doc Dr. Dias started in May 2020. Progress to date includes 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 2020-21. 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 description of PWS herring spawn locations and timing used aerial survey data collected by ADF&G from 1973 to 2019. During this period, there have been pronounced spatial and temporal shifts in spawning habitat use within and between different regions of PWS (Fig. 8). Spawning occurred in all regions during the 1980s, primarily concentrating in the Northeast (NE) Shore, along the North Shore, and northwestern Montague Island (Fig. 9). In 1991, herring abruptly stopped spawning along the North Shore and Naked Island, as well as in the northern areas of the NE Shore. This resulted in a rapid decline in total spawn (Fig. 9) that preceded the population collapse in 1993. Since the early 1990s, spawning has only occurred sporadically in these areas, and more recently has declined gradually along Montague Island. In contrast, spawning activity increased along the Southeast (SE) Shore 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 2019. Indices of spawn timing were calculated for five regions in PWS (Fig. 8) based on the day-of-year 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. Three spatial hypotheses were examined (Fig. 10) for coherence in spawn timing trends. 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. 10). 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.

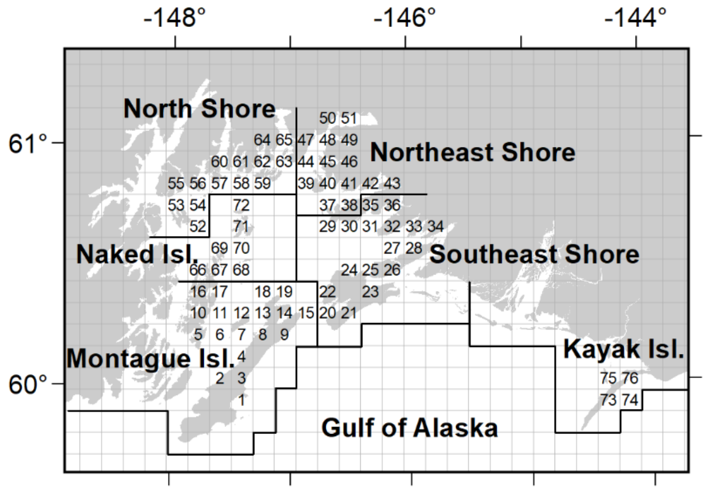

Figure 8. Boundaries for Prince William Sound regions and the Gulf of Alaska adapted from Appendix G4 in Russell et al. (2017). Numbers in 10×10 km grid cells indicate areas within each region where herring spawning was observed between 1973 and 2019 (see Fig. 9).

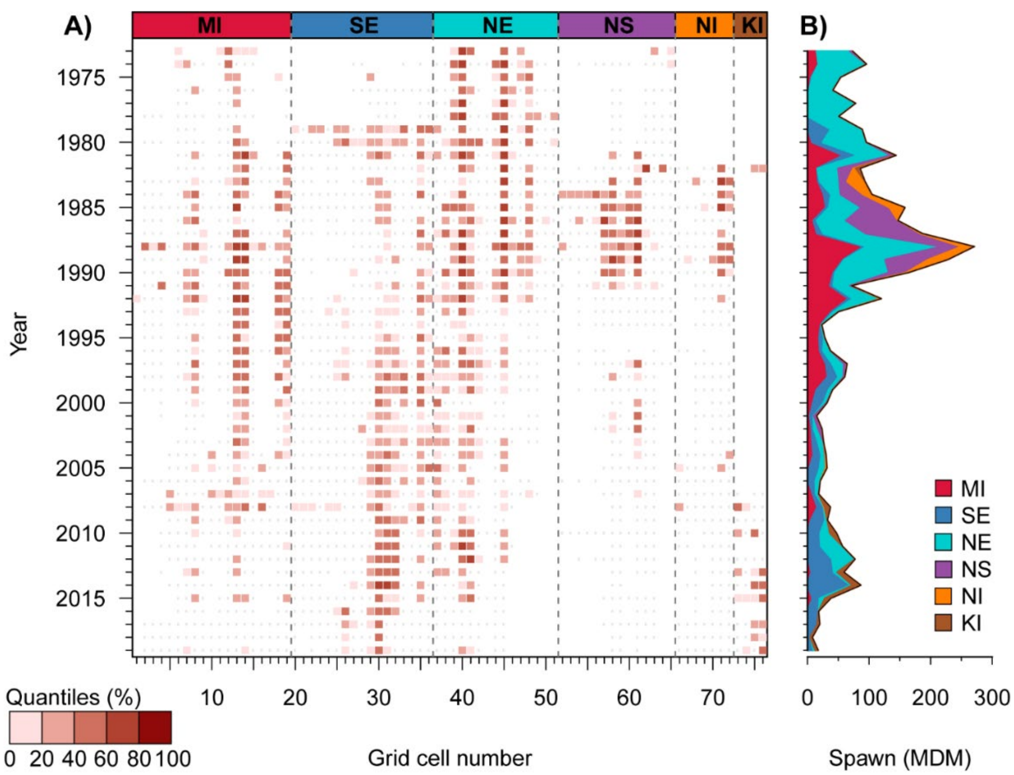

Figure 9. Distribution of spawning from 1973 to 2019 by year. Spawn patterns are represented as (A) quantiles of mile-days of milt by 10×10 km grid cell and year (note, quantiles were calculated across all years), and as (B) cumulative spawn within each region (MI = Montague Island; SE = Southeast Shore; NE = Northeast Shore; NS = North Shore; NI = Naked Island; KI = Kayak Island). Grid cell numbers (1-76) correspond with cell locations identified in Fig. 8. Gray dots indicate grid cells with survey coverage but no observed spawning; blank cells had no survey coverage in that year.

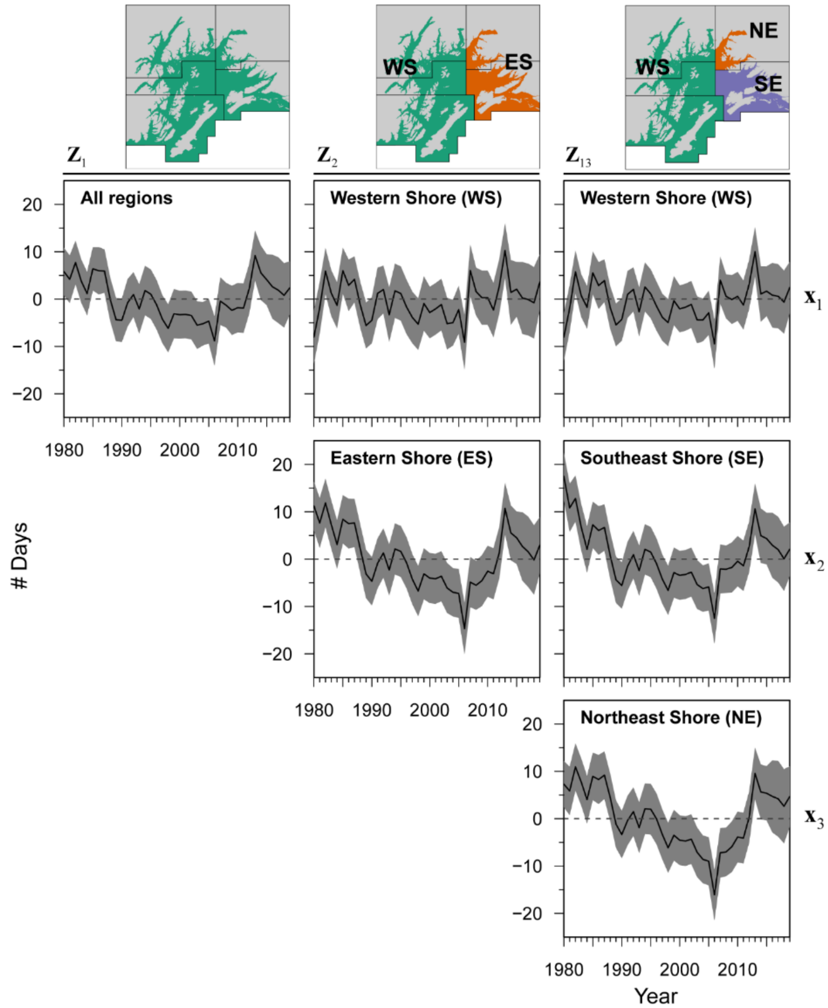

Figure 10. Estimated time series of spawn timing based on three MARSS models (rows), with shaded area representing 95% confidence intervals. Time series are centered by their mean for all years (dashed line) to indicate earlier (-) and later (+) median spawn date. The three spatial hypothesis are those depicted in each column.

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. For example, spawn timing may be related to the condition of fish (the relative fatness of fish from one year to the next), as shown in Fig. 11, or environmental factors. As spawn timing could affect young-of-the-year overwinter survival, detecting the physical and population factors that produce interannual variability is relevant to models predicting PWS herring recovery. The relation between these factors and spawn timing are currently being investigated by Dr. Dias.

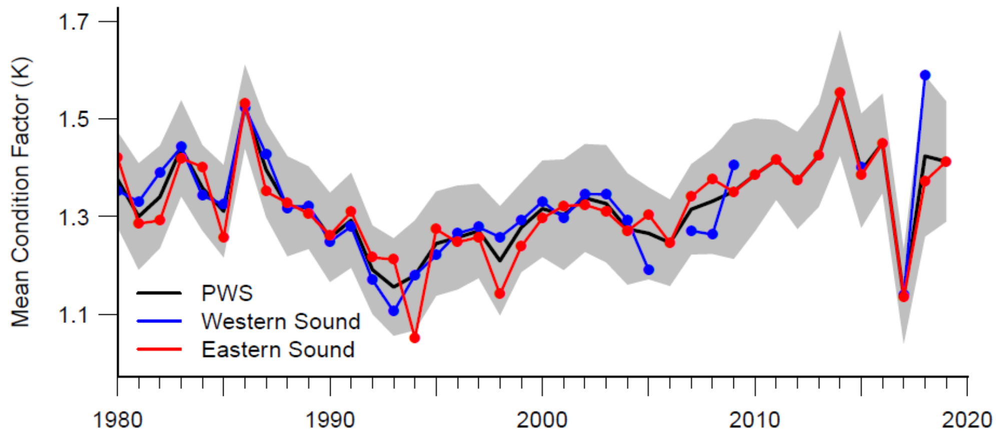

Figure 11. Condition factor for Prince William Sound (PWS) herring age 3 and older, showing the close correspondence between the Eastern and Western Sound, and the abrupt decline in 2017. Outliers were filtered by excluding points outside the 0.5% and 99.5% quantiles for the entire time-series (1980-2019).

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. C = completed, X = planned or not completed. 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										
Environmental factors influencing recruitment and natural mortality																		X		
Preliminary analysis of harvest control rules																			X	
Submit model results and code to Workspace and ADFG				C				C				C				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				C				X			
Milestones: post-doc																				
Obtain oceanographic, biological, and climate data											C									
Pattern description of PWS spawning											C									

Milestone/Task	FY17				FY18				FY19				FY20				FY21			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Time series analysis of environmental & population linkages to PWS spawn timing																X				
Coherence in spawn timing among coastal herring populations in the GOA																	X			
Identify environmental factors to facilitate expansion of BASA model																	X			

B. Explanation for not completing any planned milestones and tasks

Covid-19 will have obvious drains on productivity due to the lack of in-person meetings, affecting both the overall project and the individual aspects involving supervision of students and post-docs. Overall impacts are unknown at this time.

Post-doc David McGowan moved from the project to a full-time position at the National Oceanic and Atmospheric Administration Alaska Fisheries Science Center in February 2020, resulting in some of the extra planned analyses for FY20 being dropped from the table above. A new post-doc Beatriz Dias started on the project in May 2020, and is anticipated to complete some of the planned work, but given the limited time available from funding (12 months), and inevitable time required to understand a new system, data, and previous work, will only be able to complete part of the originally proposed work.

C. Justification for new milestones/tasks

None.

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 annual meetings. With the advent of covid-19, in-person meetings are highly unlikely, which will hinder some of the more collaborative aspects of the project. Nevertheless, 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.

Gulf Watch Alaska

The post-doc will continue collaborating with R. Campbell (project 21120114-G) and other Gulf Watch Alaska (GWA) principal investigators (PIs) on analyses related to herring spawning and first-year survival. Coordination via email and phone calls 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.

Herring Research and Monitoring

The PI and J. Trochta have collaborated with S. Pegau and K. Gorman (project 19170111-D) on work to 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 (project 21120111-E) 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 and processed by HRM 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 Research 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, Chris Siddon, and Bill Templin) for internal review and comments in the form of HRM proposals, reports, and 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 GOA. Coordination via email and phone calls entails the transfer and use of data series for herring spawning, age-weight-length, and temperature loggers collected 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 infected by and recovered from VHSV in each year in the past.

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 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

A number of planned objectives for the post-doc project have been removed given the change in personnel and impacts of covid-19 on productivity. The revised objectives are:

1. Quantify the influence of environmental and population factors on spawning timing in PWS
2. 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
3. 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, including investigating the relative role of different factors such as the oil spill, fishing, and environmental factors.

5. PROJECT PERSONNEL – CHANGES AND UPDATES

The personnel are PI Trevor Branch, PhD student John Trochta, and post-doc Beatriz Dias. During this period the former post-doc David McGowan left for a permanent position in February 2020, and Dr. Bias joined the group in May 2020 and will stay until ~April 2021. A CV for Dr. Dias follows.

Beatriz S. Dias

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eco.umass.edu/people/graduate-students/dias-beatriz-s/ | *Updated:* July 20, 2020

EDUCATION

Ph.D. in Environmental Conservation, *UMass Amherst, US* — 2019

Concentration: Wildlife, Fish and Conservation Biology

Dissertation title: Analysis spatio-temporal of marine ecosystems

M.S. in Marine and Coastal Sciences, *Autonomous University of Baja California Sur, Mexico* — 2011

Thesis title: Black Sea Turtle *Chelonia mydas*(Linnaeus 1758) abundance through mark-recapture at forage areas of BCS, Mexico.

B.S. in Oceanography, *Federal University of Para, Brazil* — 2008

SKILLS

- Programming and software: R, LaTeX, ArcGIS, Excel, Ecopath with Ecosim, Program MARK, Adobe Illustrator, Python/Anaconda, MATLAB
- Experience with long-term data set management
- Experience operating small vessels
- Experience with passive and active fishing gears
- English, Spanish and Portuguese fluency

EMPLOYMENT

Postdoctoral Scholar *School of Aquatic and Fishery Sciences, University of Washington* — 2020-present

Assistant Researcher Scientist *Monterey Bay Aquarium* — 2019-2020

Temporary - Outreach Assistant *Extractive Marine Reserve (RESEX) of Soure, ICMBio, Brazil* — 2013

Researcher Collaborator *Federal University of Para/NAEA, Bazil* — 2011–2014

Temporary - Operation Coordinator *TOMAGE - Sea Turtles of Equatorial Guinea* — 2011–2012

Temporary - Field Researcher *RED Sustainable Tourism, Mexico* — 2010–2011

Intern *Southwest Fisheries Science Center, NOAA, San Diego, US* — 2010

In-water Data Base Manager *Grupo Tortuguero de las Californias A.C., Mexico* — 2009–2011

Full time - Field Biologist *ASVO- Matapalo Sea Turtle Project, Costa Rica* — 2009–2010

PUBLICATIONS

Journal Articles

Dias, B.S., Frisk, M.G. and Jordaan, A. "Evaluating fishing effort reduction and habitat restoration as management strategies to promote alewife (Alosa pseudoharengus) recovery using an ecosystem model." *In review*

Dias, B.S., Martins, B.M.L., Sousa, M.E.M., Cardoso, A.T.C., Jordaan, A. 2020 "Prioritizing species of concern monitoring using GIS-based fuzzy models." *Ocean & Coastal Mngt* https://doi.org/10.1016/j.ocecoaman.2019.105073

Dias, B.S., Frisk, M.G. and Jordaan, A. 2019 "Opening the tap: Increased riverine connectivity strength- ens marine food web pathways." *PLOS ONE* https://doi.org/10.1371/journal.pone.0217008

Dias, B.S., Barbosa, J. F., Jordaan, A. 2019 "Sea turtle records at the Environmental Protection Area of Algodoal-Maiandeua, Para State, Brazil."

Cohen, M.C.L., Lara, R.J., Smith, C.B., Angelica, R.S., **Dias, B.S.**, & Pequeno, T. (2008). "Wetland dynamics of Marajo Island, northern Brazil, during the last 1000 years." *Catena* 76(1): 70-77. https://doi.org/10.1016/j.catena.2008.09.009

PRESENTATIONS

Dias, B.S., Martins, B.M.L., Sousa, M.E.M., Cardoso, A.T.C. and Jordaan, A. (2019). Identification of monitoring priority areas for species of concern using GIS-based fuzzy models: The case of Soure Marine Extractive Reserve on the Amazon Coast. ISTS, Charleston, US (Oral Presentation).

Dias, B.S. and Jordaan A. (2018). Incorporating historical baselines to test management strategies for anadromous forage fish. ICES Working Group on the History of Fish and Fisheries Meeting, Brest, France (Oral Presentation)

Dias, B.S. and Jordaan, A. (2018). Testing Management Strategies to Promote Alosine Recovery in the Gulf of Maine Marine Ecosystem. AFS 148, Atlantic City, US (Oral Presentation).

Dias, B.S. (2018). Temporal and spatial management tools for marine ecosystems: Case studies from the Northeastern United States and Northern Brazil. IMBeR ClimEco6 Summer School. Yogyakarta, Indonesia (Poster presentation).

Dias, B.S. and Jordaan, A. (2017). A marine ecosystem perspective of anadromous forage fish. ICES ASC Fort Lauderdale, US (Oral Presentation).

Dias, B.S., Martins, B.M.L., Sousa, M.E.M., Cardoso, A.T.C. and Jordaan, A. (2017). First steps towards including sea turtle research in Extractive Marine Reserve of Soure management plan. ISTS, Las Vegas, US (Oral Presentation).

Dias, B. S., A Jordaan. (2016). Going with the flow: Employing network analysis to explore Northeast US shelf ecosystem consequences of alternative anadromous forage biomass scenarios. ICES ASC, Riga, Latvia (Oral Presentation).

Jordaan, A., Klein, E.S., Alexander, K., Leavenworth, W.B., Mattocks, S., **Dias, B.S.**, and Frisk, M.G. (2016). What four years of ecosystem modeling using historical data has told us about changes to the Northeast Atlantic ecosystem. ICES ASC, Riga, Latvia.

Dias, B.S., Mattocks, S., Jordaan, A. (2016). The effects of anadromous forage fish biomass restoration on NE US marine ecosystem. ISEM, Townson, Maryland, US (Poster presentation).

Dias, B.S., Jordaan, A., Mattocks, S. (2016). What if? The effects of anadromous forage fish biomass restoration. CCFFR/SCL, St. John's, Newfoundland, Canada (Oral presentation).

Dias, B.S. and Jordaan A. (2014). Sea turtles of the Amazon: First steps towards a conservation network. 34th International Sea Turtle Symposium. New Orleans, LA, US (Poster Presentation).

Dias, B., Rodriguez-Baron, J., Koch, V. (2012). Then years of black sea turtle research and conservation at two coastal lagoons in Northwest Mexico. What do we know? 32nd International Sea Turtle Symposium. Huatulco, Oaxaca, Mexico (Oral Presentation).

Najera-Hillman, E., **Dias,B.**, Koch, V., Hinojosa,G. (2011). Survival and abundance estimates for green turtles (Chelonia mydas) in Estero Banderitas, Baja California Sur, Mexico. 31st International Sea Turtle Symposium. San Diego, California, USA.

Dias, B., Koch, V., Najera-Hillman,E., Hinojosa,G., Wang,J. H., Fisler, S., Swimmer,Y. (2011). Growth rates and body condition index of East Pacific green turtle (*Chelonia mydas*) at four monitoring sites in Baja California Sur. 31st International Sea Turtle Symposium. San Diego, California, USA (Oral Presentation).

Dias, B., Koch, V., Lucero, J. (2011). Mark-recapture for evaluating the status of green sea turtle *Chelonia mydas* (Linnaeus 1758) in Baja California Sur, Mexico feeding grounds . I Conservation Science Symposium. Loreto, Baja California Sur. Mexico (Oral presentation).

AWARDS

2019 *John Boreman Fisheries Award*, ECo Department, University of Massachusetts Amherst, US.

2019 International Sea Turtle Symposium 2019 Travel Grant

2018 Recipient of OCB Travel Grant to attend ClimEco6 summer school University Gadjah Mada, Yogyakarta, Indonesia.

2018-2019 Recipient of ECo Department Fellowship University of Massachusetts Amherst, US.

2017 IMBIZO5 OCB Workshop registration grant

2017 ICES Annual Science Conference 2017 Travel Grant

2017 International Sea Turtle Symposium 2017 Travel Grant

2016 ICES Annual Science Conference 2016 Travel Grant

2013–2017 *Recipient, Science without Borders Scholarship- CAPES*

2011 *Graduated Magna Cum Laude* Autonomous University of Baja California Sur (UABCS), Mexico.

2009–2011 *Recipient, CONACyT scholarship* Autonomous University of Baja California Sur (UABCS), Mexico.

2010 *Recipient, CONACyT Mixed scholarship* UABCS-SFSC NOAA, San Diego, US.

2006–2017 *Recipient, CAPES/CNPq Scholarship* UFPA-Federal University of Para, Brazil.

CONFERENCES

- Organizer Environmental Conservation Department Graduate Student Symposium (ECoGSS) 2018
- AFS 2020 Symposium Forage Fish and Climate Adaptation: Updates on Science and Management Co-chair (https://afs.confex.com/afs/2020/webprogrampreliminary/Session9449.html)
- International Sea Turtle Symposium 2021, Workshops and Regional Meetings Co-chair

6. PROJECT BUDGET

A. Budget Forms

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. FY17-20 PROJECT PUBLICATIONS AND PRODUCTS

Publications (in prep and submitted)

Dias, B., D.W. McGowan, R. Campbell, M. Scheuerell, and T.A. Branch. (in prep). Influence of environmental and population factors on herring spawn timing in Prince William Sound. Canadian Journal of Fisheries and Aquatic Sciences.

Trochta, J.T., M.L. Groner, P.K. Hershberger, and T.A. Branch. (in prep). Using seroprevalence data of disease in fish improves estimates of natural mortality: A simulation study. Canadian Journal of Fisheries and Aquatic Sciences.

McGowan, D.W., T.A. Branch, S. Haught, and M. Scheuerell. (In ADF&G internal review). Multi-decadal shifts in the distribution and timing of Pacific herring (*Clupea pallasii*) spawning in Prince William Sound, Alaska. Canadian Journal of Fisheries and Aquatic Sciences.

Trochta, J.T., and T.A. Branch. (in prep). Consensus and inconsistency of support for ecological covariates in stock assessment using multiple metrics from Bayesian model selection. ICES Journal of Marine Science.

Publications (latest first)

Trochta, J.T., T.A. Branch, A.O. Shelton, and D.E. Hay. 2020. The highs and lows of herring: A meta-analysis of patterns in herring collapse and recovery. Fish and Fisheries 21:639-662.

Hilborn, R., R.O. Amoroso, C.M. Anderson, J.K. Baum, T.A. Branch, C. Costello, C.L. de Moor, A. Faraj, D. Hively, O.P. Jensen, H. Kurota, L.R. Little, P. Mace, T. McClanahan, M.C. Melnychuk, C. Minto, G.C. Osio, A.M. Parma, M. Pons, S. Segurado, C.S. Szuwalski, J.R. Wilson, and Y. Ye. 2020. Effective fisheries

management instrumental in improving fish stock status. Proceedings of the National Academy of Sciences U.S.A. 117:2218-2224.

Muradian, M.L., T.A. Branch, and A.E. Punt. 2019. 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 76:2102-2113.

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 76:1477-1488.

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 2019 BASA stock assessment has been uploaded to the AOOS research workspace, together with the model formulation and underlying data.

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

<u>Presentations</u>

Trochta J.T., T.A. Branch, W.S. Pegau. 2020. Challenges to estimating maturity in stock assessment: a case study of Pacific herring in Prince William Sound, AK, presented at SAFS Think Tank. April, Seattle, WA.

Trochta J.T, and T.A. Branch. 2020. A Bayesian Analysis of the Utility of Ecosystem Information in a Stock Assessment Model of Prince William Sound Herring, oral presentation, Alaska Marine Science Symposium. January, Anchorage, AK.

McGowan, D.W. and T.A. Branch. 2019. Large multi-decadal space and time shifts in Pacific herring spawning in the Gulf of Alaska. October, PICES 2019 Annual Meeting, Victoria, BC, Canada. Oral presentation.

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

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

Trochta J.T, and T.A. Branch. 2017. 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, Seattle, WA.

Trochta J.T., T.A. Branch, A.O. Shelton, and D.E. Hay. 2017. 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, Victoria, British Columbia, Canada.

Outreach

Branch continues to maintain an active science outreach program on a wide variety of fisheries-related topics on social media (Twitter, @TrevorABranch), with 12,500 followers, and 23.4 million views of his tweets since the start of the 5-year program (Feb 2017). Branch and Trochta recorded an interview for the *Field Notes* podcast program produced by the PWS Science Center in 2017. Trochta spent two days in Juneau working with ADF&G biometricians, researchers, managers, and fishery scientists sharing results and insights from EVOSTC funded activities. Trochta contributed articles to the 2017-2018, 2019-2020, and 2020-21 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 articles to the *Delta Sound Connections* 2019-20 and 2020-21 issues.

8. 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.

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.

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.

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, T., and C. Thomas. 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. 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.

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 package. 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.

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 76:1477-1488.

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.

Muradian, M.L., T.A. Branch, and A.E. Punt. 2019. 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 76:2102-2113.

Musgrave, D.L., M.J. Halverson, and W.S. 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 Grant, Anchorage, AK.

Russell, C.W., J. Botz, S. Haught, and S. Moffitt. 2017. 2016 Prince William Sound Area Finfish Management Report. ADF&G, Anchorage, AK.

Trochta, J.T., T.A. Branch, A.O. Shelton, and D.E. Hay. 2020. The highs and lows of herring: A meta-analysis of patterns in herring collapse and recovery. Fish and Fisheries 21:639-662.

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.