Exxon Valdez Oil Spill
Long-Term Herring Research and Monitoring Program Final Report

Modeling and stock assessment of Prince William Sound herring

Exxon Valdez Oil Spill Trustee Council Project 21120111-C
Final Report

Trevor A. Branch

School of Aquatic and Fishery Sciences
Box 355020, University of Washington
Seattle, Washington 98195

June 2023

Exxon Valdez Oil Spill
Long-Term Herring Research and Monitoring Program Final Report

Modeling and stock assessment of Prince William Sound herring

Exxon Valdez Oil Spill Trustee Council Project 21120111-C
Final Report

Trevor A. Branch

School of Aquatic and Fishery Sciences
Box 355020, University of Washington
Seattle, Washington 98195

June 2023

Modeling and stock assessment of Prince William Sound herring

Exxon Valdez Oil Spill Trustee Council Project 21120111-C
Final Report

Study History: In the first five years of the modeling project (2012-2017, Branch 2018), we developed a modern Bayesian stock assessment model of Prince William Sound herring in AD Model Builder (Muradian et al. 2017), used it to assess the value of past data collected for the stock assessment (Muradian et al. 2019), and conducted a meta-analysis of global herring populations to put the decline of Prince William Sound herring into context (Trochta et al. 2020).

This report covers the second period of the modeling project (2017-2022, with a no-cost extension to January 2023), in which a variety of modifications were made to the stock assessment model, including extending the start age back from age-3 to age-0, incorporating scientific aerial surveys of age-1 fish into the model, and assessing whether disease seroprevalence data (antibodies to viral hemorrhagic septicemia virus) can be incorporated into the stock assessment model (Trochta et al. 2022). In addition, in 2020 an alternative Bayesian algorithm was incorporated that reduced run time from many hours to just a few minutes (Monnahan et al. 2019), which enabled us to create a framework to conduct Management Strategy Evaluations of harvest control rules for Prince William Sound herring, work that is underway with *Exxon Valdez* Oil Spill Trustee Council funding for 2022-2027. One final project examined factors that might have influenced recruitment and natural mortality in Prince William Sound herring (Trochta et al. 2021). This work resulted in the training of a Master's student (Muradian 2015) and a PhD student (Trochta 2021).

Two postdoctoral scholars were also employed, who showed that spawning of Prince William Sound herring has shifted both in space and time since monitoring began (McGowan et al. 2021) and identified environmental and population factors that might have contributed to changes in spawn timing (Dias et al. 2022).

Abstract: We created a rapidly-converging Bayesian age-structured assessment model to provide annual updates on the status of Prince William Sound herring, showing that this population collapsed shortly after the *Exxon Valdez* oil spill and has remained at low levels for almost 30 years—justifying the continued moratorium on commercial fishing on this population. This long period of continued low abundance and recruitment are rare when compared to other herring populations, with no clear factor explaining higher mortality and lower recruitment, except for ambiguous evidence for impacts of pink salmon on mortality. Disease has long been implicated in the initial decline, thus seroprevalence data for viral hemorrhagic septicemia virus was included in the model, allowing estimates of the magnitude and impacts of past outbreaks. Prince William Sound herring have shifted spawning both in time and space, with some evidence for both population and environmental factors explaining these shifts. The stock assessment generally predicts that the population will rebuild, but in the absence of high recruitment, commercial fisheries remain closed. To plan ahead for reopening, we developed a management strategy evaluation framework to test harvest control rules for a future fishery on Prince William Sound herring.

Key words: *Clupea pallasii*, modeling, management strategy evaluations, NUTS algorithm, Pacific herring, Prince William Sound, recruitment, stock assessment

Project Data: Underlying data for the stock assessments, model code, and inputs are archived by Axiom Data Science, a Tetra Tech Company, 1016 W 6th Ave., Anchorage, AK 99501.

Data are available through the Gulf of Alaska Data Portal: https://gulf-of-alaska.portal.aoos.org/#metadata/4aaecfe2-de4b-4b6b-ba8e-bb715d26c6f1/project/folder_metadata/2515720, or through the DataONE catalog: https://doi.org/*10.24431/rw1k1t*.

The data custodian is Carol Janzen, Director of Operations and Development, Alaska Ocean Observing System, 1007 W. 3rd Ave. #100, Anchorage, AK 99501, 907-644-6703. janzen@aoos.org.

Citation:

Branch, T. A. 2023. Modeling and stock assessment of Prince William Sound herring. Long-term Herring Monitoring Program Final Report (*Exxon Valdez* Oil Spill Trustee Council Project 21120111-C), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

TABLE OF CONTENTS

LIST OF FIGURES

EXECUTIVE SUMMARY

Five major projects were completed during the modeling component of the Prince William Sound herring program: (1) Annual stock assessments of Prince William Sound herring, using updated and revised versions of the Bayesian stock assessment model. (2) Simulation testing and implementation of disease data within the assessment model. (3) Testing different factors affecting natural mortality and recruitment in Prince William Sound herring. (4) Examining changes in spawn timing and location in Prince William Sound herring. (5) Testing hypotheses for changes in spawn timing. A sixth project (management strategy evaluations) is underway, but is not outlined here.

Bayesian age-structured assessment model (BASA)

The heart of the herring modeling project is the Bayesian age-structured assessment model (BASA) that we developed from the previous age-structured assessment (ASA) model used by the Alaska Department of Fish and Game (ADF&G) to assess Prince William Sound herring for many years. Several modifications were made to BASA to improve performance and generality. Notably, it was extended to start at age-0 instead of age-3 (the age at spawning and fishing), so that it could be fit to the new aerial time series of age-1 schools, and also better model the impacts of disease on the population. In addition, although it had already ran in the efficient model-fitting software AD Model Builder, each run still took 6-8 hours to reach convergence. A modification allowed the use of a new Bayesian algorithm called the No-U-Turn Sampler (NUTS), which typically allows for convergence in 2-3 minutes, improving model efficiency more than 100-fold.

Each year, we ran the BASA model to provide advice to ADF&G on whether Prince William Sound herring is recovering sufficiently to reopen commercial fishing. The fishery has been closed in almost all years since it collapsed in 1994. A new summary format for the assessment results was created in 2021 that allows for the easy porting of results into a standard eight-page summary. In the most recent assessment (based on 2021 data), median spawning biomass was estimated to be 18,100 metric tons (mt), with a 67% probability of being below minimum management threshold of 19,958 mt. The 2016 cohort (age 5 in 2021) continues to be the strongest recent cohort but is still well below the strong cohorts in the 1980s. Based on recent trends, Prince William Sound is projected to recover to the levels in the mid-2000s while still remaining far below biomass levels in 1980–1992, shortly after the *Exxon Valdez* oil spill.

Including disease antibody data in the assessment model

Fisheries stock assessments usually assume that natural mortality is constant, and none have previously included information on disease outbreaks. However, Prince William Sound herring has a unique long-standing program focused on disease prevalence, and previous work has implicated viral hemorrhagic septicemia virus (VHSV) as one of the key reasons for the

population collapse in the early 1990s. Previously, BASA included a crude index of detected total disease as a factor in mortality, but this index only measures disease in living herring, and not how many died, nor the prevalence of past outbreaks. A new measure developed by the herring disease program (project 21120111-E Principal Investigator Hershberger) detects the presence of antibodies for VHSV (seroprevalence) for many years after infection. We modeled disease outbreaks (on a daily scale) and herring populations (annual age structure) to simulate realistic seroprevalence data and were able to show that modifying BASA to include seroprevalence data allowed for the estimation of the timing and severity of past disease outbreaks. When this modification of BASA was applied to Prince William Sound seroprevalence data, it estimated that disease mortality in recent years has been relatively low, and the population currently has relatively little immunity to VHSV.

Factors affecting natural mortality and recruitment in Prince William Sound herring

The hardest parameters to estimate in fisheries are natural mortality and recruitment, but Prince William Sound herring offer a remarkable opportunity to predict these parameters given the long time series available for biological, oceanographic and atmospheric variables. We included covariates for natural mortality and recruitment into BASA and used four Bayesian model selection criteria to identify predictors. Three of the four criteria identified adult pink salmon returns as increasing natural mortality, but there was only ambiguous support for effects of other factors.

Changes in spawn timing and location in Prince William Sound herring

We assembled and digitized a long time series (1973–2019) of spawning locations and timing from ADF&G aerial surveys of Prince William Sound herring, finding that there were abrupt shifts in spawning location before the collapse in the 1990s, and then spawning shifted towards the southeastern parts of the Sound, while the proportion of occupied spawning areas declined dramatically. Spawning shifted 2-4 weeks earlier between 1980 and 2006 before shifting later over a seven-year period.

Examining hypotheses for changes in spawn timing in Prince William Sound herring

The dramatic shifts in spawn timing of Prince William Sound herring could be due to biological or population factors. We used generalized linear models to examine the possible effect of 15 different factors on spawn timing, finding that earlier spawning was most closely associated with mean age and environmental factors such as weaker downwelling and meridional winds.

INTRODUCTION

Prince William Sound (PWS) herring (*Clupea pallassii*) are an iconic species that in the past played a key role as both predators and prey in this ecosystem, as well as supporting a fishery with catches that exceeded 40,000 metric tonnes (mt) in the 1930s, and more than 20,000 mt in the early 1990s. In 1993, however, their biomass collapsed and the fishery was closed, and has remained closed since relatively small commercial catches were taken in 1996-1998. The severity of the collapse in recruitment, catches and biomass was extreme, and has lasted for an unusually long time compared to other herring populations around the world, as outlined in a meta-analysis we conducted during the first five years of *Exxon Valdez* Oil Spill Trustee Council (EVOSTC) funding (Trochta et al. 2020). Many hypotheses have been suggested for their decline, including after-effects of the *Exxon Valdez* oil spill, disease, predation from humpback whales, competition with large hatchery releases of pink salmon, and environmental regime shifts (e.g. Deriso et al. 2008, Hilborn and Eggers 2000, Hulson et al. 2008, Marty et al. 2010, Pearson et al. 2012, Teerlink et al. 2015, Trochta and Branch 2021, Ward et al. 2017).

The status of this population has been assessed annually using an age-structured assessment (ASA) model, initially coded in Excel and developed by the Alaska Department of Fish and Game (ADF&G), and since adapted using EVOSTC funding to run in a Bayesian framework (Muradian et al. 2017) running in AD Model Builder (Fournier et al. 2012), with additional modifications to use a faster Bayesian algorithm called the No-U-Turn sampler (NUTS, Monnahan and Kristensen 2018, Monnahan et al. 2017, Monnahan et al. 2019). The Bayesian assessment model (BASA) is described in Muradian et al. (2017) and Trochta (2021).

In this five-year project, we ran annual assessments of PWS herring using BASA. We also used BASA to test which covariates best explain patterns in natural mortality and recruitment (Trochta et al. 2021), and modified BASA to test whether antibody data provide useful information for the magnitude of disease outbreaks affecting natural mortality (Trochta et al. 2022). Additional projects by two postdoctoral scholars were undertaken using three years of synthesis funding, examining changes in herring spawning in space and time (McGowan et al. 2021, Dias et al. 2022).

OBJECTIVES

The original objectives of the project are outlined below. Modifications are briefly described in italics.

Objective 1: Maintain and update the BASA model based on the ASA model used by ADF&G, including annual assessment updates of PWS herring and the revision of BASA to fit to new data sources such as the age-0 aerial survey, condition data, and updated age at maturity.

Objective 2: Adapting the BASA model to better model the disease component of natural mortality. Specifically, this would be based on new methods for detecting antibodies of viral hemorrhagic septicemia virus (VHSV) in archival and planned future collections of herring serum.

Objective 3: Continued collection and expansion of catch, biomass, and recruitment time series from all herring populations around the world to place the lack of recovery of PWS herring into context given patterns of change in herring populations around the world.

Objective 4: An initial exploration of factors that may be used to predict herring recruitment, including oceanography, climate, competition, and predation. *We expanded this objective to a full analysis of factors relating to recruitment and natural mortality (Trochta & Branch 2021).*

Objective 5: A management strategy evaluation (MSE) 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. *Work was started in 2022 after COVID-19 disruptions, and is nearing completion under the 2022-27 modeling project. It is not discussed here.*

Objective 6: Simulations to evaluate which data sources are the most useful in assessing future herring biomass, based on an MSE of the impact of each form of data on the accuracy of the BASA model. *Given COVID-19, the loss of funding of many of the original data sources, and the longer timeline to develop an MSE, this is now included in the 2022-27 modeling project.*

In addition to these original objectives, the modeling project received three years of funding for a postdoctoral scholar to work on synthesis activities, which was split between two postdocs (McGowan and Dias), who worked on two additional projects described below: the timing and location of herring spawning, and factors influencing the change in herring spawn timing.

METHODS

The modeling study was based on Pacific herring, which is assumed to be a single population occupying the entire PWS for the purposes of fisheries management and assessment, although there are distinct spawning sites within PWS (McGowan et al. 2021).

Maintaining and updating BASA

The stock assessment model is outlined in detail in Muradian et al. (2017), with subsequent modifications outlined in Trochta (2021). The key revisions included expanding the model so that it started at age-0 instead of age-3. In previous years there was no need to include ages 0-2 in the model since the fishery and all survey data were for age-3 and above. However, with the development of the age-1 aerial survey index, the model needed to also fit predicted numbers at age-1 to this index. In addition, disease data could be obtained for the earlier ages. The age-1 aerial survey provides valuable predictions for likely recruitment of fishery-age fish to the population with a two-year forecast window. Time series of condition data were not available for inclusion in the model in predicting over-winter mortality, so these were not included, and a lengthy analysis of different methods of parameterizing age-at-maturity concluded that this made no noticeable difference to the stock assessment outputs. Therefore age-at-maturity was simplified in the model to a single assumed age for all years, instead of two different ages in different time periods.

BASA was run annually on the new data collected for the fishery, and the results reported at the principal investigator meetings, to ADF&G, and in the annual EVOSTC reports. A more formal process was developed in late 2021 (Trochta et al. 2022), involving the automatic generation of an 8-page stock assessment summary report using RMarkDown, which creates a streamlined process for running the assessment and creating a document with the key figures and tables. This also allows for a preliminary stock assessment to be run in November each year based on data from the aerial age-1 survey, the aerial milt survey, and the hydroacoustic survey, together with a partial sample of the age composition data from the surveys. This should provide advance warning should the stock appear to be rapidly declining or at a high enough biomass to allow for a commercial fishery. The final assessment is then planned for February each year when the complete age-sex-length data are available.

Including disease antibody data in the assessment model

Full methods are included in Trochta et al. (2022), and in brief consisted of building a novel epidemiological model to simulate both fisheries population dynamics and the daily infections of disease outbreaks. This allows us to simulate the sampling of fish and testing for antibodies (seroprevalence), and thus generate realistic seroprevalence data by age and year such as can be obtained for PWS herring. Having done this, we modified BASA to include parameters for age- and year-specific mortality from disease, and ran the model to estimate the year and size of disease outbreaks, and their effect on herring mortality. The data available for VHSV seroprevalence in the fishery were obtained from Paul Hershberger (U. S. Geological Survey), and the stock assessment run with the actual disease data (Trochta 2021).

Factors affecting natural mortality and recruitment in PWS herring

Full details are included in Trochta et al. (2021), but the BASA model was modified so that a variety of alternative hypotheses could be tested. In short, recruitment or natural mortality was allowed to vary from year to year as a function of one or more covariates, such as disease prevalence, pink salmon abundance, humpback whale trends, and the oil spill. Hypothesis testing was conducted on the effects on annual recruitment (number of age-3 fish) and natural mortality. Various environmental data representing bottom-up controls (freshwater discharge, temperatures, sea level, upwelling) and ecosystem components acting through predation (humpback whales, adult pink salmon) or competition (juvenile pink salmon) are incorporated into the model as covariates for which we determine the posteriors on their effects. These covariates are represented in individual models that are fit and further grouped into recruitment and mortality hypotheses. Four types of Bayesian model selection criteria were used to determine the best fitting models.

Changes in spawn timing and location in PWS herring

Aerial survey data for PWS herring were compiled from surveys conducted by ADF&G between 1973 and 2019, and then the regions with observed spawning were plotted. For analysis these data were partitioned into 10 km ×10 km grid cells to characterize interannual and decadal changes in spawning spatial patterns while accounting for cells with and without survey effort, and then time series models (MARSS models) were fit to determine which spatial structure in spawn timing best explains the trends in spawn timing. Full details of the methods are contained in McGowan et al. (2021).

Examining hypotheses for changes in spawn timing in PWS herring

To explain the patterns in spawn timing in PWS herring, we gathered 15 environmental and population-level time series of data (covariates) and used these to predict spawn timing in either the entire PWS, or the eastern vs. western Sound (Dias et al. 2022). This division had been determined to be the best for the spawning patterns of herring (McGowan et al. 2021). Included in the covariates was an analysis to identify regime shifts in spawning biomass and surplus production in herring, using the sequential t-test analysis of regime shift (STARS) approach (e.g., Rodionov 2004, Vert-pre et al. 2013).

RESULTS

Stock assessment model results from BASA

The BASA assessment model provides good fits to the mile-days of milt survey, age-1 aerial survey, hydroacoustic survey, and the historical egg deposition surveys that provide anchor points for absolute biomass (Fig. 1, Trochta et al. 2022). The assessment estimates that spawning biomass has recovered to 18,100 mt (95% interval 12,100–27,800 mt) from its lowest point of 5,400 mt in 2018, but has remained low (<27,000 mt) since 1994, at just a small fraction of the 46,800–141,800 mt spawning biomass present in the system during 1980–1993. The probability of being below the lower regulatory threshold of 20,000 t was 67% in 2021.

The 2016 cohort (age-5 in 2021) continues to dominate the population (Fig. 2), comprising the majority of the fish sampled during the herring-spawn survey. Preliminary results from 2022 also continue to show most fish comprising of the 2016 cohort.

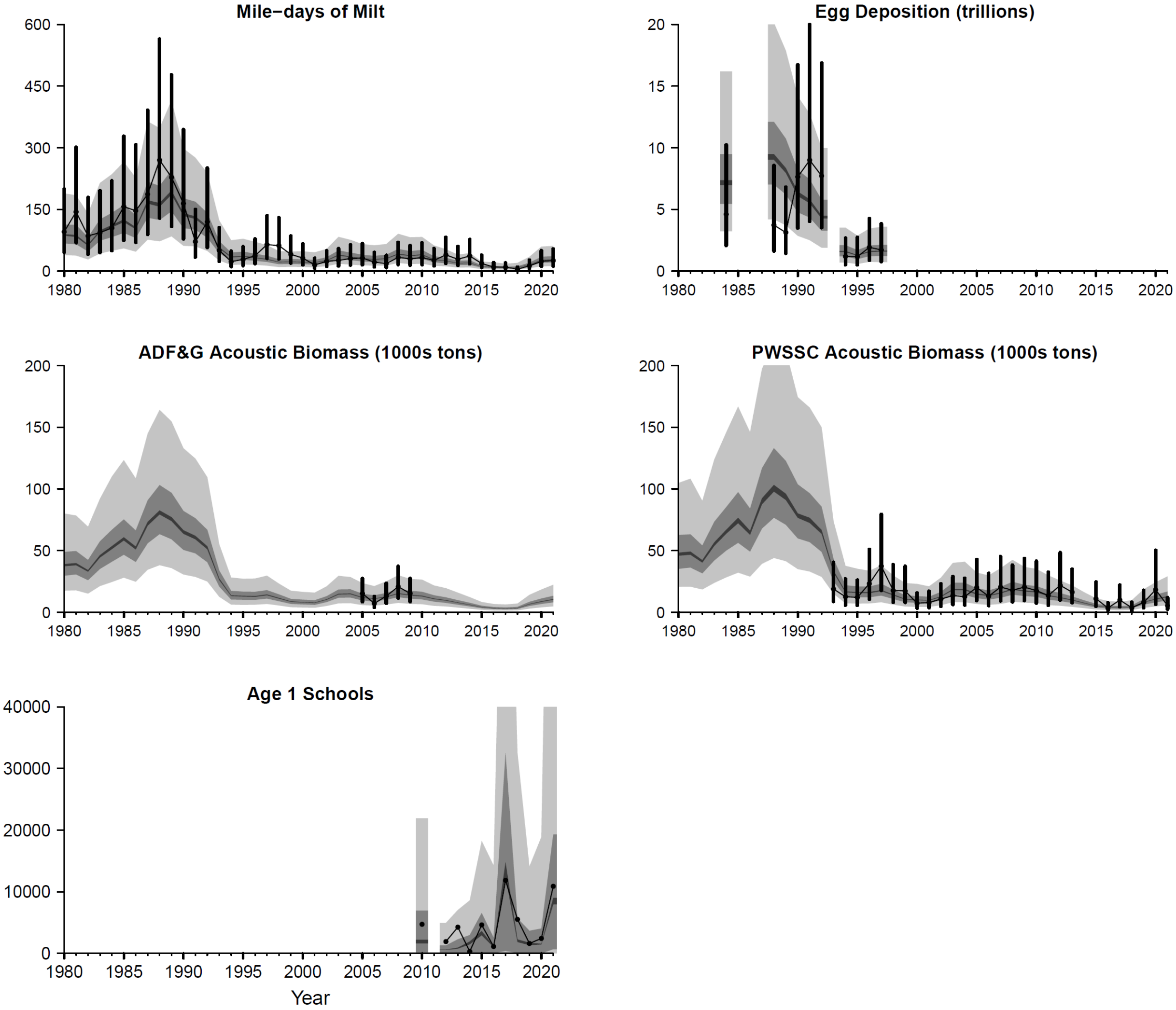

Figure 1. Bayesian Age Structured Analysis model fits to survey data up to 2021, based on data from the Alaska Department of Fish and Game (ADF&G) and Prince William Sound Science Center (PWSSC). Source: Trochta et al. (2021).

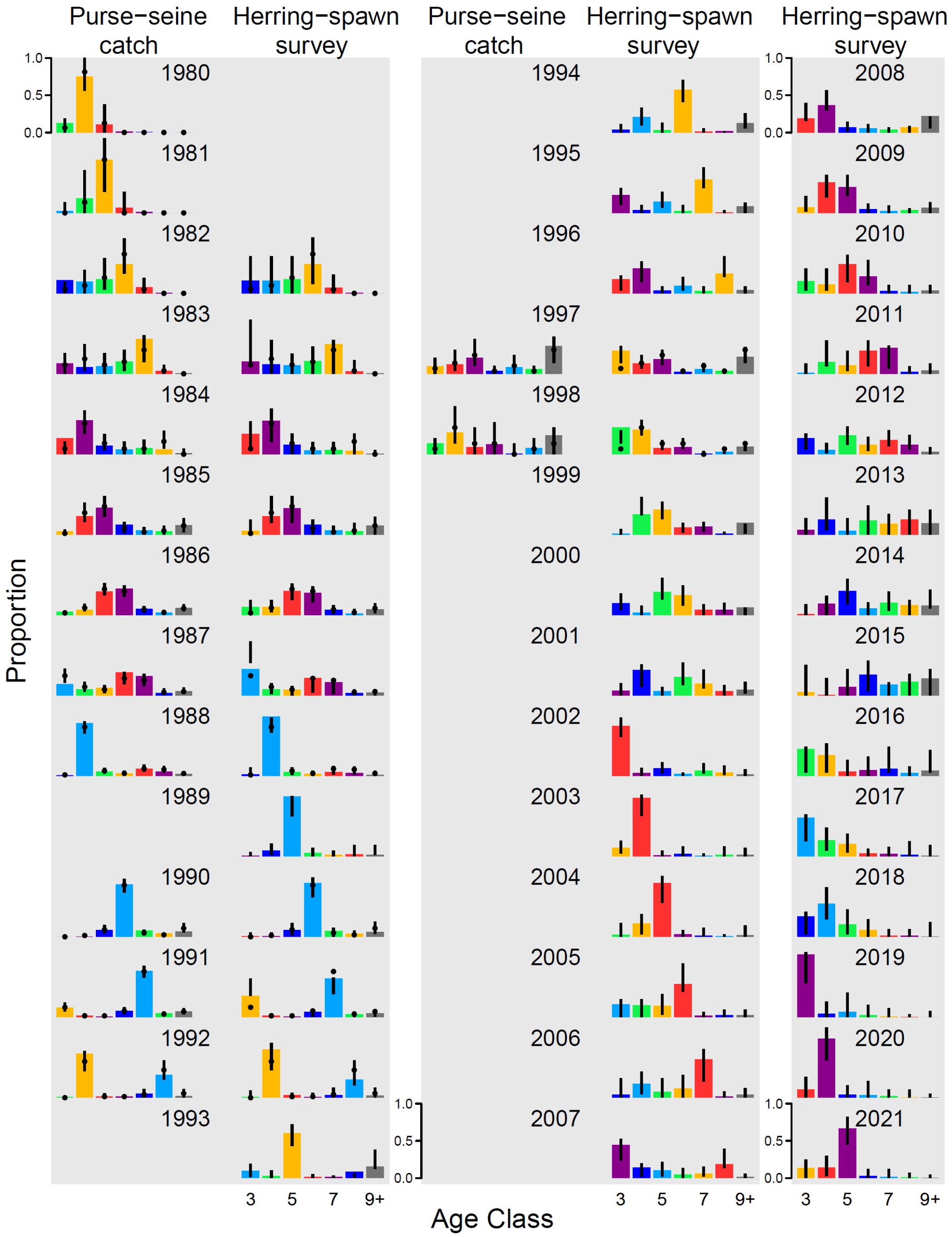

Figure 2. Observed (bars) and predicted (points and lines) proportions at age in the survey and catch for Prince William Sound herring. Source: Trochta et al. (2021).

Including disease antibody data in the assessment model

Simulations were able to reproduce both the daily cycle within the main spawning season, and the annual effects on spawning biomass and the percent of fish that survived each outbreak, contain antibodies, and were infected (Fig. 3, Trochta et al. 2022).

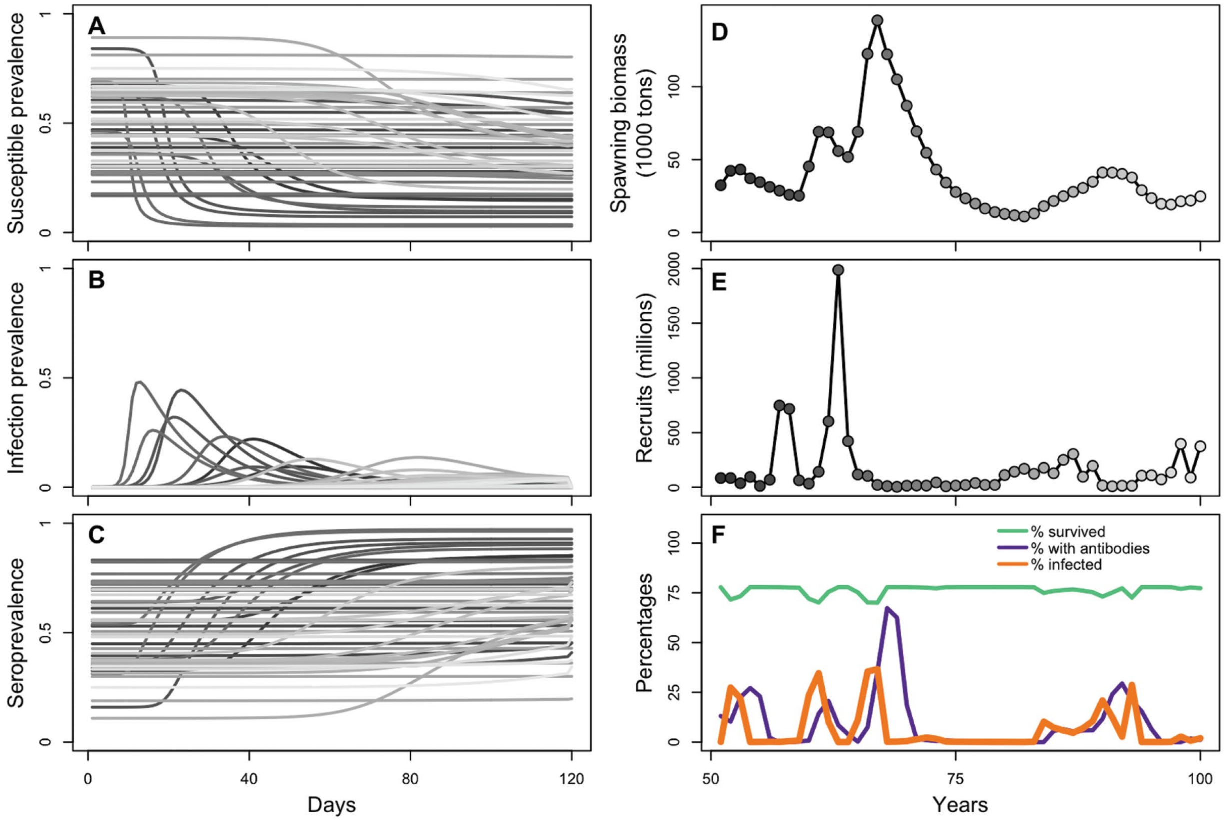

Figure 3. Disease and herring dynamics from one simulation run. Left: daily proportions that are susceptible, infected, and positive for seroprevalence; one line per year. Right: annual spawning biomass, recruitment, and percent in each disease category. Source: Trochta et al. (2022).

Stock assessment models fitted to the resulting simulated seroprevalence data were able to produce unbiased estimates of biomass, recruitment, and disease infection rates, which exceed the performance of the model when seroprevalence data are excluded (Trochta et al. 2022).

When the actual seroprevalence data collected from PWS herring in 2012–2020 were included in BASA (Fig. 4, Trochta 2021), peak immunity to VHSV occurs in 2015-16 and then gradually wanes. Infection rates are estimated to be low throughout this period, averaging 6% with a peak of 21% on 2014, and generally low total mortality on spawning herring even though the model estimates that 65% of herring infected by VHSV die (albeit with large uncertainty). Overall, the low rates of seroprevalence in the population (<40% for any age or year except for age-7 in 2020), suggests that no large recent VHSV outbreaks have affected this population.

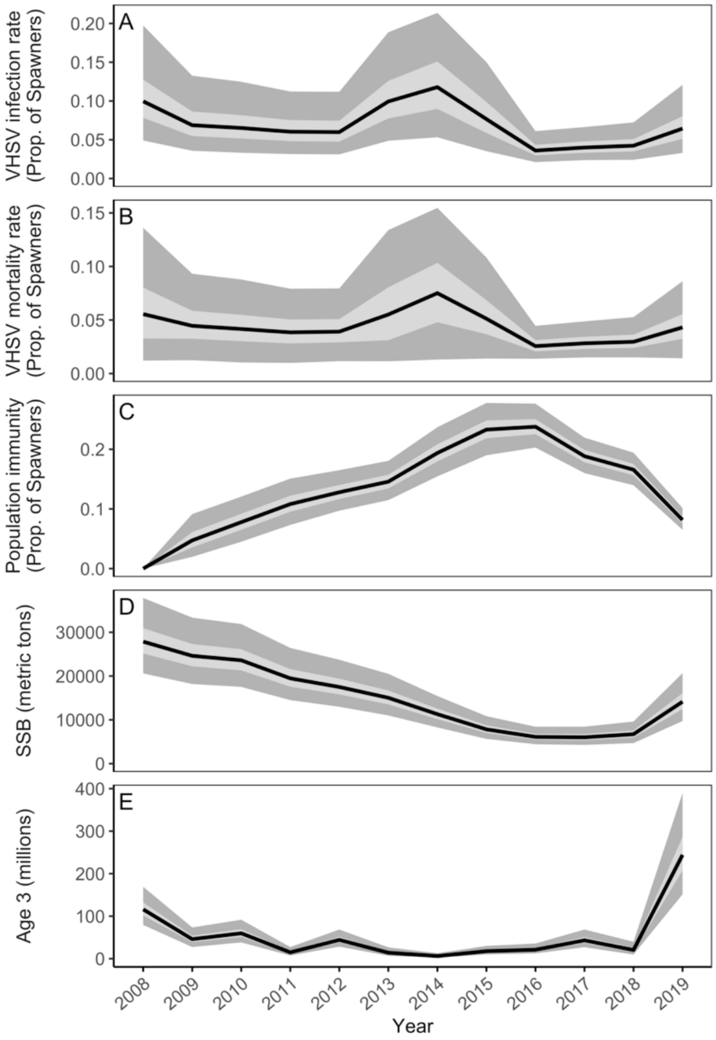

Figure 4. Assessment including disease estimation from seroprevalence, showing proportion of spawners infected with viral hemorrhagic septicemia virus (VHSV), mortality rates, proportion that have immunity, and spawning biomass and recruitment (at age-3) in the bottom two panels. Source: Trochta (2021).

Factors affecting natural mortality and recruitment in PWS herring

Only one covariate had support across more than two Bayesian model selection criteria (for 3 of 4 criteria): higher adult pink salmon numbers were associated with higher adult herring natural mortality (Fig. 5, Trochta and Branch 2021). There was ambiguous support for other fixed effects on natural mortality (walleye pollock [*Gadus chalcogrammus*] and the North Pacific Gyre Oscillation) and recruitment (hatchery-released juvenile pink salmon and a 1989 regime shift). Generally, similar criteria values among covariates suggest no clear evidence for a consistent effect of any covariate.

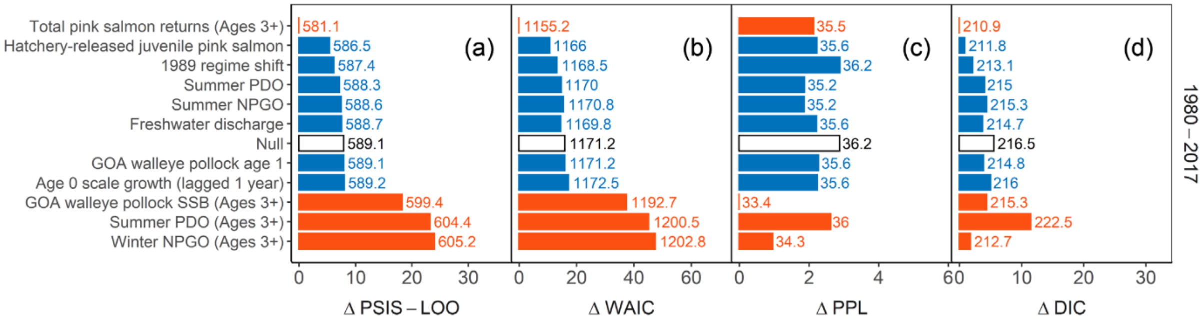

Figure 5. Model selection values for covariates explaining natural mortality (red) or recruitment (blue), for four model selection criteria (panels). Better models have smaller values than the Null model. The criteria are Pareto-smoothed importance-sampled leave-one-out cross-validation scores (PSIS-LOO), Watanabe-Akaike Information Criterion (WAIC), posterior predictive loss (PPL), and Deviance Information Criterion (DIC). PDO = Pacific Decadal Oscillation, NPGO = North Pacific Gyre Oscillation; GOA = Gulf of Alaska; and SSB = spawning stock biomass. Source: Trochta & Branch (2021).

Changes in spawn timing and location in PWS herring

We found abrupt shifts in spawn distribution that preceded both rapid increases in population size in the 1980s and its later collapse (Fig. 6, McGowan et al. 2021). After the collapse, spawning shifted away from historical regions and contracted into a smaller area in the southeastern part of PWS, while the proportion of occupied spawning areas declined from 65% to <9%. Spawn timing also varied, and there was a spatial component to this change as well. The best explanatory model showed that spawn timing differed between the eastern and western portions of PWS: the median spawn date shifted earlier by 26 days in eastern areas and 15 days in western areas of PWS between 1980 and 2006, and then shifted later by 25 (eastern) and 19 (western) days over a seven-year period (Fig. 7, McGowan et al. 2021, Dias et al. 2022).

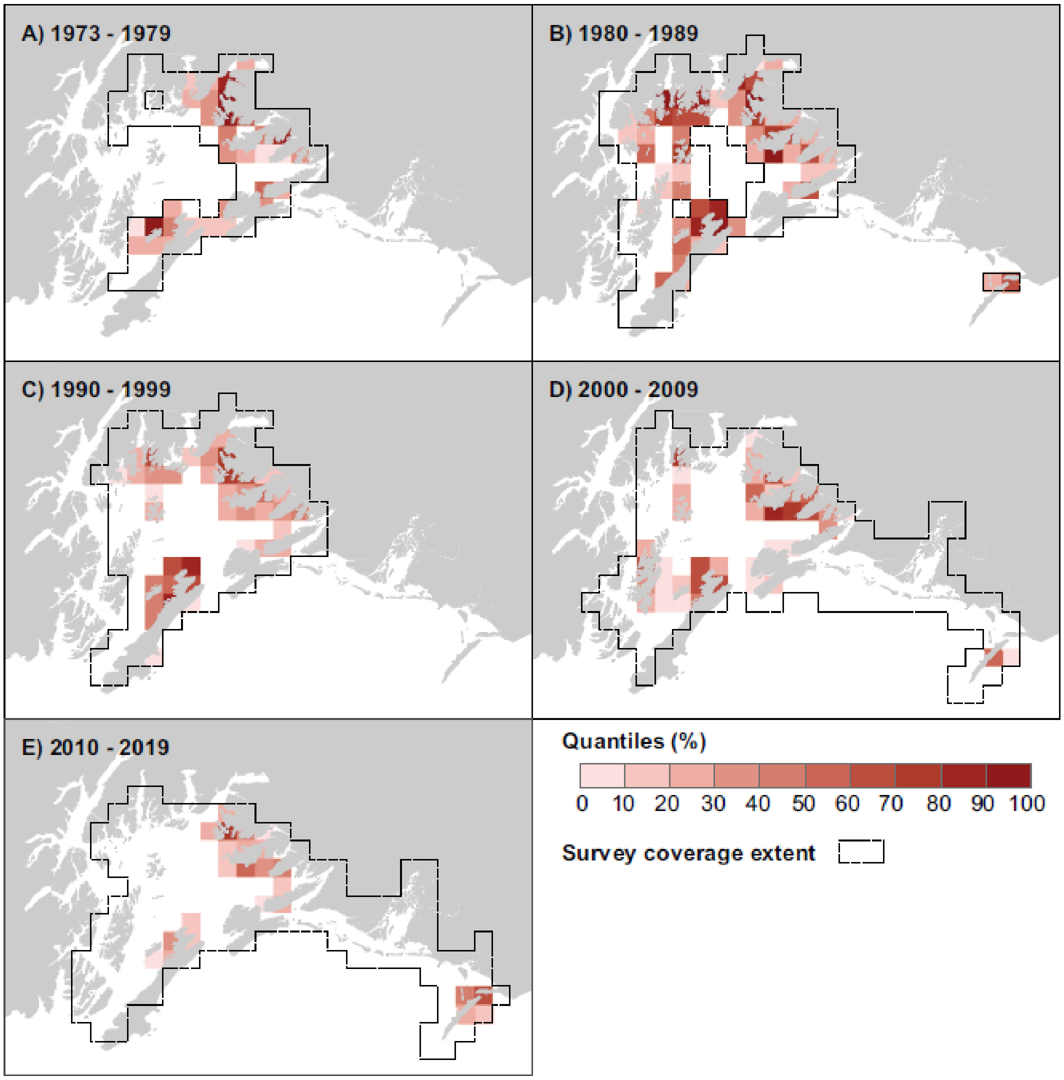

Figure 6. Distribution of PWS herring spawning (red cells) and extent of survey coverage (black boundaries) from 1973 to 2019 by decade. Spawn patterns are represented as quantiles of mile-days of milt summed within each 10×10 km grid cell by decade, although patterns in the 1970s may be biased due to gaps in coverage. Source: McGowan et al. (2021).

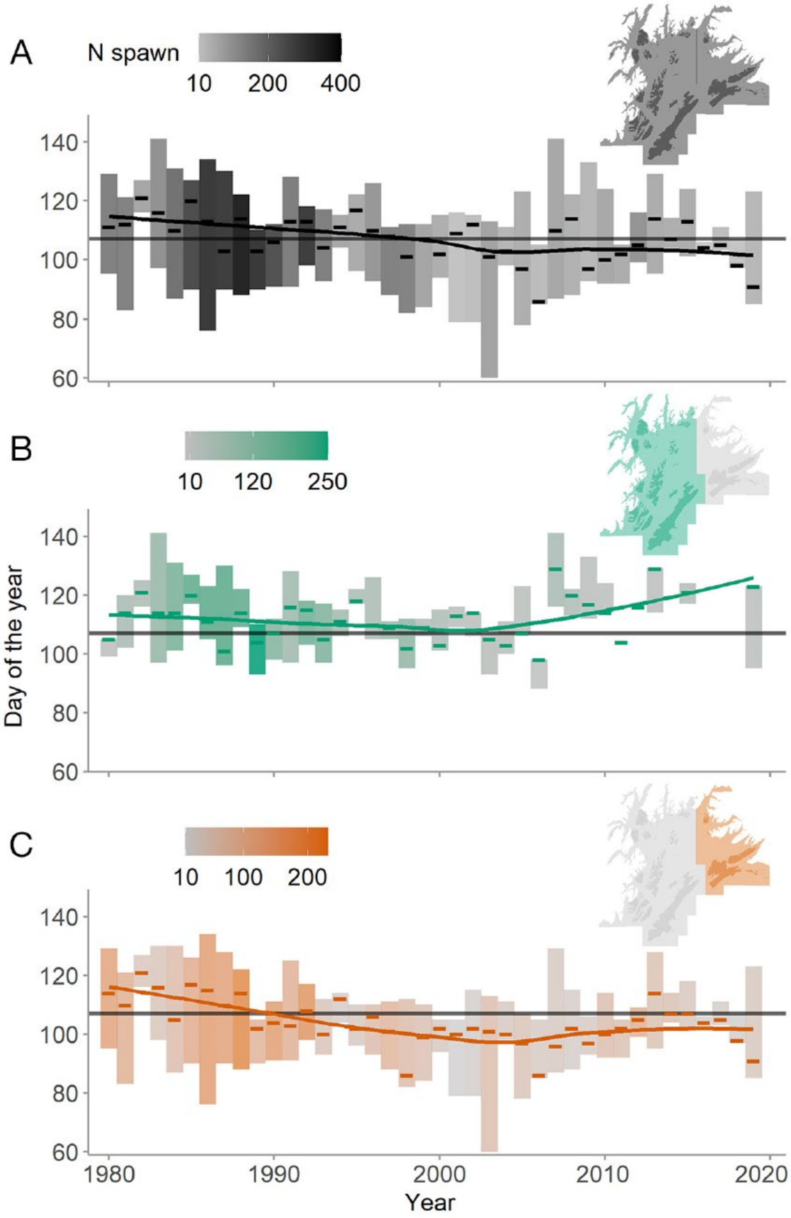

Figure 7. Changes in spawn timing of PWS herring for two scenarios: Sound-wide, and split into eastern and western portions of the Sound. Bars show the start and end of observed spawning, and color the number of observed spawning events. Source: Dias et al. (2022).

Hypotheses for changes in spawn timing in PWS herring

Earlier spawn timing was associated with higher biomass in the eastern Sound and older mean age in the western Sound (Fig. 8). Across the entire sound, earlier spawning was associated with weaker downwelling, weaker meridional winds, and the positive phase of the Pacific-North American teleconnection pattern, which is characterized by warmer North Pacific waters (Fig.

9). We also found that PWS herring have undergone three regime shifts in surplus production (Fig. 10), with initial (1980–1988) high surplus production (and high biomass), followed by large negative surplus production and population collapse (1989–1993), and finally a long period of near-zero surplus production and low biomass (1994–2020). However, these regimes in surplus production (and the regimes in biomass) did not predict changes in spawn timing in the model.

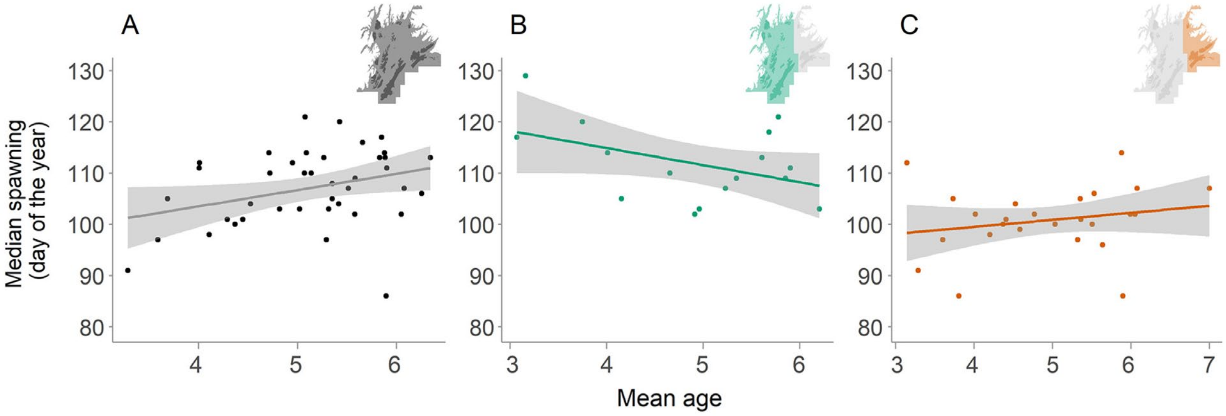

Figure 8. Mean herring spawn date compared to mean age in the herring population, for (A) the entire Prince William Sound, and (B) western, and (C) eastern regions.

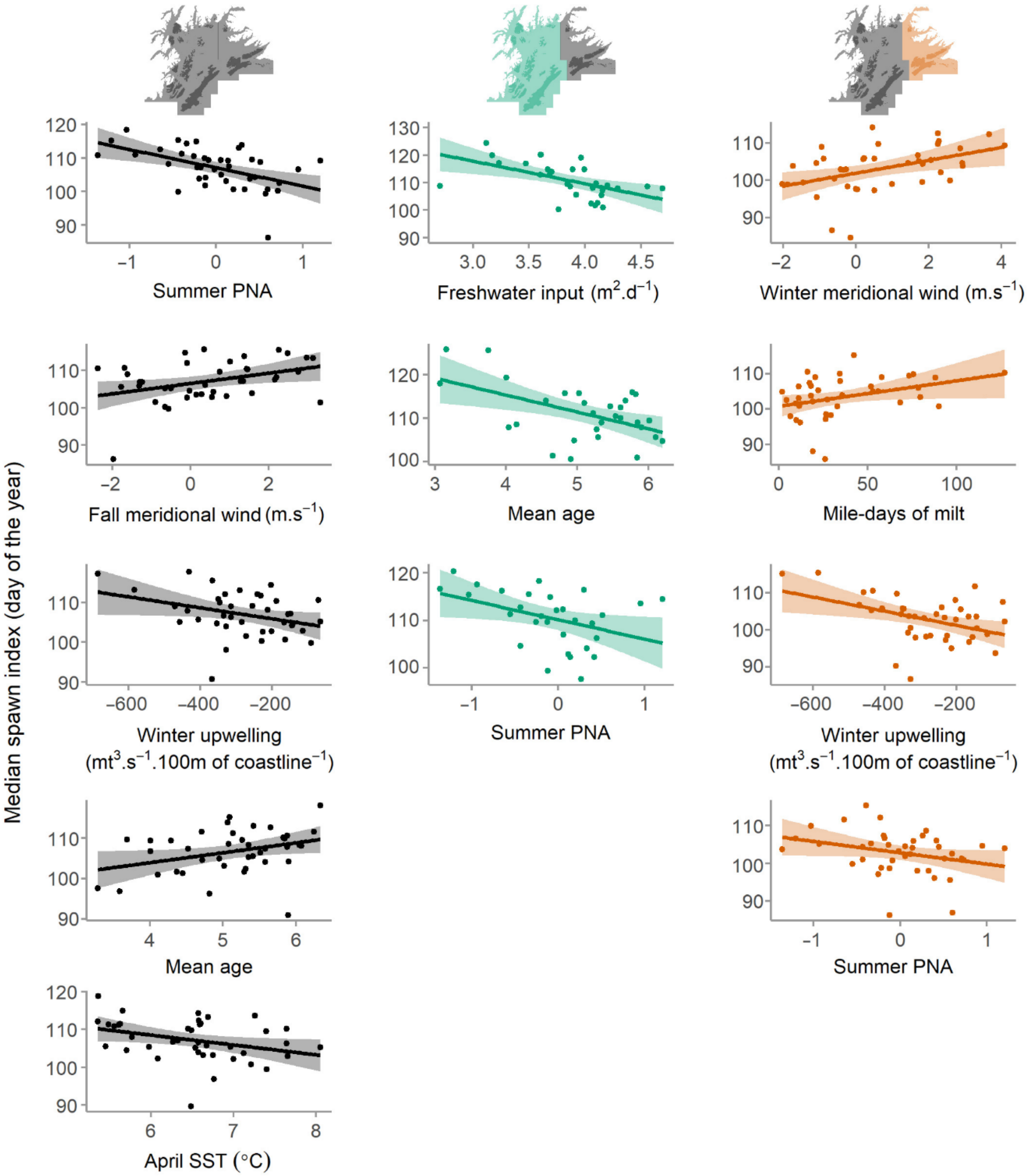

Figure 9. Estimated relation between spawning date across PWS (gray), and the western (green) and eastern (orange) regions. Variables are ordered from top to bottom by their explanatory power. SST = sea surface temperature, PNA = Pacific-North American teleconnection pattern. Source: Dias et al. (2022).

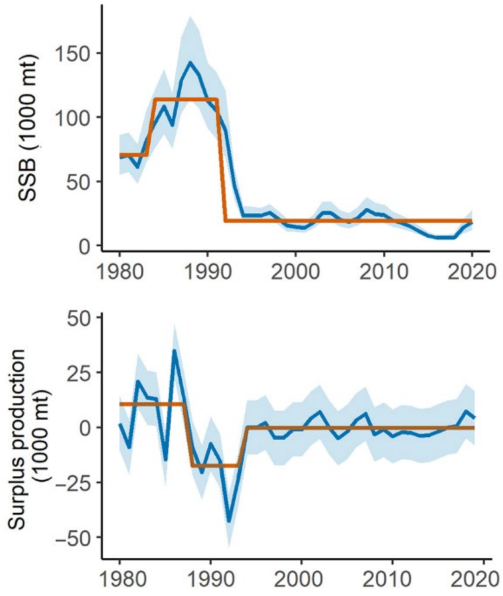

Figure 10. Regimes in spawning stock biomass (SSB) and surplus production for PWS herring, estimated with a five-year moving window. Source: Dias et al. (2022).

DISCUSSION

The regular BASA assessment of PWS herring continue to affirm that this population collapsed in the early 1990s and has since remained in a regime with low recruitment, spawning biomass and surplus production. Annual estimates of spawning biomass show a high probability of being below the lower regulatory threshold for reopening the fishery. This is true even though the 2016 cohort continues to comprise most of the spawning fish. Future assessments will be based on fewer data sources and likely be more uncertain, because of the end of EVOSTC funding to the hydroacoustic survey (project 21120111-G), which together with the aerial milt survey (project 21160111-F), provided estimates of relative biomass each year. In this context, funding is most needed for advance notice of a likely rebuilding of the stock, which can only happen with a very strong recruitment event. The aerial age-1 schools index provides this need with a two-year advance notice, which is sufficient time for the fishery to plan for reopening. Future work will use the management strategy evaluation started under this funding, to test which datasets are the most valuable moving into the future.

Including the disease data in BASA (Trochta 2021, Trochta et al. 2021) marks a landmark in fisheries stock assessment modelling: the first stock assessment that can estimate the magnitude of disease outbreaks, mortality from disease, and the resulting impact on natural mortality. Current estimates show relatively low disease impact on the population, but also a cautionary note that the proportion of the population with positive seroprevalence is low, suggesting that the population could be susceptible to a VHSV outbreak. Continued work is needed to update the stock assessment so that the base results reported each year are fully integrated with the new seroprevalence data collected as part of Paul Hershberger's EVOSTC-funded disease project (project 21120111-E). Our previous simulation work showed that past disease prevalence data is relatively cheap and provides highly valuable information for the assessment (Muradian et al. 2019), and it is likely that the newer seroprevalence data will be similarly valuable.

Our investigation into the causes for the decline and continued low abundance of PWS herring did not reveal any particular smoking gun, but highlighted factors that have long been considered important. Notably, higher pink salmon numbers in PWS were associated with lower herring numbers, suggesting an avenue for further investigation. The 2022-27 funding from EVOSTC includes three projects of high relevance to herring: pink salmon and herring interactions; pollock and herring interactions; and our modeling project to build a model of intermediate complexity (MICE model) that includes humpback whales, pink salmon, pollock, and herring.

In addition to interactions with possible competitions and predators, our projects identified a wide variety of oceanographic and climatic factors as being possible determinants of higher herring mortality, lower herring recruitment, and changes in herring spawn timing. As is common in such investigations, however, highlighting which factors are the most important leads to ambiguous results, with some factors identified as important using one metric, while other factors are important when a different metric is used (Trochta & Branch 2021, Dias et al. 2022). Indeed, trying to predict recruitment from environmental factors has long bedeviled fisheries scientists (Myers 1998). The basic problem is that most fisheries time series are relatively short, interactions are highly complex, and successful high recruitment likely relies on a confluence of multiple factors all being at optimal levels.

Nevertheless, we continue to believe that PWS herring provide the very best opportunity possible to tease out key factors in predicting changes in recruitment, natural mortality, and spawn timing. Few regions, if any, in the world contain such a rich dataset of biological, oceanographic, and climate indexes that has been maintained for such a long period of time. If fisheries science ever will solve these problems, it will be because of the data collected here.

CONCLUSIONS

PWS herring remain at low levels with no sign of recovery, decades after recovery would be expected given trends in other herring populations around the world (Trochta et al. 2020), and our analysis of regimes revealed that the population has been in a low biomass and low surplus production regime since 1994 (Dias et al. 2022). Continued monitoring and stock assessment is needed to ensure that the population does not decline further, and for advance warning to allow for fishery reopening should recovery be imminent. No single factor explains the decline and continued failure to recover in this population, but new investigations into possible competitors and predators (pink salmon, pollock, and humpback whales), disease, and environmental factors, could yet provide a satisfactory explanation.

ACKNOWLEDGEMENTS

This project is part of the Herring Research and Monitoring program. These findings and conclusions presented by the author(s) are their own and do not necessarily reflect the views or position of the *Exxon Valdez* Oil Spill Trustee Council.

LITERATURE CITED

Branch, T. A. 2018. Modeling the population dynamics of Prince William Sound herring. *Exxon Valdez* Oil Spill Long-Term Herring Research and Monitoring Program Final Report (*Exxon Valdez* Oil Spill Trustee Council Project 16120111-Q), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

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.

Dias, B. S., D. W. McGowan, R. Campbell, and T. A. Branch. 2022. Influence of environmental and population factors on Prince William Sound herring spawning phenology. Marine Ecology Progress Series 696:103-117.

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.

Hilborn, R. and D. Eggers. 2000. A review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. Transactions of the American Fisheries Society 129:333-350.

Hulson, P.-J. F., S. E. Miller, T. J. Quinn II, 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.

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., T. A. Branch, S. Haught, and M. D. Scheuerell. 2021. 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 78:1611-1627.

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.

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.

Muradian, M. L. 2015. Modeling the population dynamics of herring in the Prince William Sound, Alaska. 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.

Myers, R. A. 1998. When do environment-recruitment correlations work? Reviews in Fish Biology and Fisheries 8:285-305.

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.

Rodionov, S. N. 2004. A sequential algorithm for testing climate regime shifts. Geophysical Research Letters 31:L09204.

Teerlink, S. F., O. Von Ziegesar, J. M. Straley, T. J. Quinn II, C. O. Matkin, and E. L. Saulitis. 2015. First time series of estimated humpback whale (*Megaptera novaeangliae*) abundance in Prince William Sound. Environmental and Ecological Statistics 22:345-368.

Trochta, J. T. 2021. Modeling population collapse and recovery in herring. Dissertation. University of Washington, Seattle.

Trochta, J. T., and T. A. Branch. 2021. Applying Bayesian model selection to determine ecological covariates for recruitment and natural mortality in stock assessment. ICES Journal of Marine Science 78:2875-2894.

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.

Trochta, J. T., M. L. Groner, P. K. Hershberger, and T. A. Branch. 2022. A novel approach for directly incorporating disease into fish stock assessment: a case study with seroprevalence data. Canadian Journal of Fisheries and Aquatic Sciences 79:611-630.

Trochta, J. T., J. A. Zahner, and T. A. Branch. 2022. 2021 Bayesian Age-structure Stock Assessment (BASA) results for Prince William Sound (PWS) herring. 8 pp.

Vert-pre, K. A., R. O. Amoroso, O. P. Jensen, and R. Hilborn. 2013. Frequency and intensity of productivity regime shifts in marine fish stocks. Proceedings of the National Academy of Sciences U.S.A. 110:1779-1784.

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.

OTHER REFERENCES

This section includes peer reviewed publications, EVOSTC reports and other significant report contributions, publicly available datasets, scientific presentations, and outreach associated with the project.

Peer reviewed publications

Only publications directly related to Prince William Sound herring are included.

Dias, B. S., D. W. McGowan, R. Campbell, and T. A. Branch. 2022. Influence of environmental and population factors on Prince William Sound herring spawning phenology. Marine Ecology Progress Series 696:103-117.

McGowan, D. W., T. A. Branch, S. Haught, and M. D. Scheuerell. 2021. 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 78:1611-1627.

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.

Trochta, J. T. and T. A. Branch. 2021. Applying Bayesian model selection to determine ecological covariates for recruitment and natural mortality in stock assessment. ICES Journal of Marine Science 78:2875-2894.

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.

Trochta, J. T., M. L. Groner, P. K. Hershberger, and T. A. Branch. 2022. A novel approach for directly incorporating disease into fish stock assessment: a case study with seroprevalence data. Canadian Journal of Fisheries and Aquatic Sciences 79:611-630.

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.

Reports

Branch, T. A. 2018. Modeling the Population Dynamics of Prince William Sound Herring. *Exxon Valdez* Oil Spill Long-Term Herring Research and Monitoring Program Final Report (*Exxon Valdez* Oil Spill Trustee Council Project 16120111-Q), *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. https://evostc.state.ak.us/media/7220/16120111-q-branch-2018-final-report.pdf

Branch, T. A. 2018. Modeling and stock assessment of Prince William Sound herring. Annual Report, Project 17120111-C. *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.. https://evostc.state.ak.us/media/2117/2017-17120111c-annual.pdf

Branch, T. A. 2019. Modeling and stock assessment of Prince William Sound herring. Annual Report, Project 18120111-C. *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. https://evostc.state.ak.us/media/2143/2018-18120111c-annual.pdf

Branch, T. A. 2020. Modeling and stock assessment of Prince William Sound herring. Annual Report, Project 19120111-C. *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. https://evostc.state.ak.us/media/7110/19120111-c-annual-report.pdf

Branch, T. A. 2021. Modeling and stock assessment of Prince William Sound herring. Annual Report, Project 20120111-C. *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. https://evostc.state.ak.us/media/7483/20120111-c-annual-report.pdf

McGowan, D. W., T. A. Branch, S. Haught, and M. Scheuerell. 2020. Chapter 3 Multi-decadal shifts in the distribution and timing of Pacific herring spawning in Prince William Sound, Alaska. *In* W. S. Pegau, and D. R. Aderhold, editors. Herring Research and Monitoring Program Synthesis Report. Herring Research and Monitoring Science Synthesis Report

(*Exxon Valdez* Oil Spill Trustee Council Program 20120111). *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. https://pwssc.org/wp-content/uploads/2022/11/HRM-Synthesis-Report.pdf

Pegau, W. S., J. Trochta, K. Gorman, T. A. Branch. 2020. Chapter 2 Maturity. *In* W. S. Pegau, and D. R. Aderhold, editors. Herring Research and Monitoring Program Synthesis Report. Herring Research and Monitoring Science Synthesis Report (*Exxon Valdez* Oil Spill Trustee Council Program 20120111). *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska. https://pwssc.org/wp-content/uploads/2022/11/HRM-Synthesis-Report.pdf

Trochta, J. T. 2021. Modeling population collapse and recovery in herring. Dissertation. University of Washington, Seattle.

Trochta, J. T., J. A. Zahner, and T. A. Branch. 2022. 2021 Bayesian Age-structure Stock Assessment (BASA) results for Prince William Sound (PWS) herring. Report. https://www.researchworkspace.com/project/283170/folder/41873621/current-results

Publicly available datasets

Branch, T. A. & Trochta, J. T. 2017. Bayesian Age-Structured-Analysis (ASA) Model and Results for Herring Population Dynamics in Prince William Sound, EVOS Herring Program. DataONE doi: 10.24431/rw1k1t Available from: https://gulf-of-alaska.portal.aoos.org/#metadata/4aaecfe2-de4b-4b6b-ba8e-bb715d26c6f1/project/folder_metadata/2515720

Trochta, J. T., J. A. Zahner, and T. A. Branch. 2022. Model code and data for 2021 Bayesian Age-structure Stock Assessment (BASA) results. Available from: https://www.researchworkspace.com/project/283170/folder/41873621/current-results

Scientific Presentations

Trochta, J. T., and T. A. Branch. 2021. A framework for incorporating and evaluating environmental hypotheses using Bayesian stock assessments. Oral presentation. ICES Annual Science Conference, Virtual, Denmark, September.

Trochta, J. T., and T. A. Branch. 2021. Using Bayesian model selection to evaluate different ecosystem effects on natural mortality in stock assessment of Prince William Sound herring. Oral presentation. Center for the Advancement of Population Assessment Methodology, Workshop on Natural Mortality: Theory, Estimation, and Application in Fishery Stock Assessment Models. Seattle, WA, June.

Dias, B. S., D. W. McGowan, R. Campbell, and T. A. Branch. 2020 What affects spawning phenology of herring (*Clupea pallasii*) in Prince William Sound? Oral presentation. Alaska Marine Science Symposium, Anchorage, AK, January.

Dias, B. S., D. W. McGowan, and T. A. Branch. 2020 Influence of environmental and population factors on herring spawn timing in Prince William Sound. Oral presentation. PICES Workshop VW6, Research priorities for understanding the population dynamics of small pelagic fish in the North Pacific, Vancouver, October.

Trochta, J. T., M. L Groner, P. K. Hershberger, and T. A. Branch. 2021. Using antibody data to quantify disease impacts in fisheries stock assessment. Oral presentation. Alaska Marine Science Symposium, Anchorage, AK, January.

Trochta, J. T., M. L. Groner, P. K. Hershberger, and T. A. Branch. 2020. Using antibody data to improve estimates of natural mortality in fisheries stock assessment. Invited talk. Quantitative seminar. School of Aquatic and Fisheries Science, Seattle, WA, October.

Trochta, J. T. 2020. The rise of Bayesian: A stock assessment story. Invited talk. American Fisheries Society 150th Annual Meeting, Virtual, September.

Trochta, J. T., and T. A. Branch. 2020. Challenges to estimating maturity in stock assessment: a case study of Pacific herring in Prince William Sound, AK. Invited talk. Think Tank Seminar Series. School of Aquatic and Fisheries Science, Seattle, WA, April.

Trochta, J. T., and T. A. Branch. 2020. Hard of herring: Detecting effects on herring survival from a noisy environment in the Gulf of Alaska. Invited talk. Alaska Department of Fish and Game, Juneau, AK, February.

Trochta, J. T. 2020. A Bayesian analysis of the utility of ecosystem information in a stock assessment. Oral presentation. Alaska Marine Science Symposium, Anchorage, AK, January.

McGowan, D. and T. A. Branch. 2019. Large multi-decadal space and time shifts in Pacific herring spawning in the Gulf of Alaska. Oral presentation. PICES, Victoria, BC. 21-24 October.

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

Trochta, J. T., A. MacCall, D. McGowan, and T. A. Branch. 2019. Incorporating spawn surveys in a semi-spatial stock-recruitment model. Center for the Advancement of Population Assessment Methodology (CAPAM) conference on Spatial Stock Assessment Models, La Jolla. Oral presentation, 1-5 October 2018.

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

Trochta, J. T. and Branch T. A. 2018 Insights into the dynamics of Atlantic and Pacific herring following population collapse. Alaska Marine Science Symposium, Anchorage, AK, January.

Outreach

Principal investigator Trevor Branch communicates widely about science including this project on social media at @TrevorABranch on Twitter. He has 17,400 followers and has posted more than 50,000 times. During this project (February 2017 to January 2022) his tweets were viewed 40.2 million times.

Dias, B.S. 2022. What is causing herring early spawning? Delta Sound Connections 2022-2023. https://pwssc.org/wp-content/uploads/2022/06/DSC-2022-WEB.pdf.

Dias, B. S. 2021. About time. Delta Sound Connections 2021-2022. https://pwssc.org/wp-content/uploads/2021/06/DSC-2021-LR.pdf.

Trochta, J. T. 2020. Herring in their home environment: What matters? Delta Sound Connections 2020-2021. https://pwssc.org/wp-content/uploads/2020/07/DSC-2020-web.pdf.

McGowan, D. W. 2020. Big changes in where herring spawn in Prince William Sound. Delta Sound Connections 2020-2021. https://pwssc.org/wp-content/uploads/2020/07/DSC-2020-web.pdf.

McGowan, D. W. 2019. Spatial patterns of capelin in the Gulf of Alaska. Delta Sound Connections 2019-2020. https://pwssc.org/wp-content/uploads/2019/05/DSC-2019_WEB.pdf.

Trochta, J. T. 2019. Herring models: why and how they are used? Delta Sound Connections 2019-2020. https://pwssc.org/wp-content/uploads/2019/05/DSC-2019_WEB.pdf.