Survival of Fraser River Sockeye – Multi-Stage Stock-Recruit Analyses

Final report to the Pacific Salmon Commission
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Executive Summary

The MSSRA project involved scientists from DFO/PBS and PSC in a series of bi-weekly brain-storming exercises for eight months in 2014 to find new approaches to stock-recruit analyses. This was successful. We improved understanding of how environmental effects can be included to improve management ("success maximizing fisheries management"). We developed methods to include historical metadata such as proportion of CU returns in a run, as a variance factor to correct for relative accuracy of observations. We developed a multi-level model to include lake areas as a guide when fitting capacity (with productivity) to stock-recruit data. We extracted an annual "shared survival" pattern from 17 CUs in various ways, with similar results. We related that to marine indicators at short and long time scales, with correction for shared autocorrelation. We discovered that one habitat variable (effect of spawning channel on Chilko Lake fry migrating past that channel) changed both productivity and capacity parameters. In response we created a revised stock-recruit model that separates density independent and density dependent survival and applied that. Lastly we speculated on new approaches to salmon management.

Please notice financial statement in Appendix 1 and the summaries of 17 MSSRA reports in Appendix 2.

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Introduction

Objectives of this Southern Fund project (copied from proposal):

Table 1

Task	Status
Working with a group of experts on sockeye salmon biology and systems analyses, it will develop and document a set of tools for multi-stage, multi-habitat S/R analysis (MSRA). Upon completion of this project, MSRA will be available for use by the scientists and managers of PSC and DFO.	Complete. Collaboration successful. Tools developed, applied, and documented.
Assemble important data sets from Fraser sockeye salmon. Most of these data sets are maintained by participants in this project and include: abundance, outmigration timing, age composition, length frequencies, and weights (Chilko outlet, lower Fraser, Strait of Georgia); S/R statistics (multiple populations); population specific marine distribution and abundance with length-at-age frequencies, sex and age composition; diversion rates through Juan de Fuca Strait; abundance, length and weights by age for adult returns or escapement; and abundance and fecundity of spawners (multiple populations).	Complete. Extensive list of marine indicators assembled. Analyses were limited to 17 Eggs and Returns series for Fraser CUs plus similar time series from Osoyoose Lake, Great Central Lake, and Naidna Lake. Entemsive analysis of Chilko smolts. Deliverable as the MSSRA dataset.
Review and assess the relevance of data sets assembled for non-Fraser sockeye salmon such as: spawner-fry, fry-smolt, spawner-smolt, smolt-return survivals (Okanagan, Barkley, Long Lake);	Not attempted. Smolts data other than Chilko Lake was not provided by DFO and PSC participants.
Clean, load, organize, summarize, and plot the assembled data on salmon abundance and condition by length, by location, and by life-history stage.	Limited to eggs (as EFS) and returns data, and to Chilko smolts. Length and condition data were not provided by DFO and PSC participants.
Evaluate the importance of spatial heterogeneity to early marine survival by comparing Fraser population survival patterns with non-Fraser populations that do not pass through the Fraser River estuary, Strait of Georgia, Johnstone and Queen Charlotte Straits.	Ongoing. Analysis was limited to comparing Fraser to Osoyoos, Great Central and Nadina. A subsequent project planned for summer–fall 2015 will continue this task.
Estimate the productivity and capacity of occupied habitats by fitting the growth, condition, migration speed, and mortality of modeled sockeye to the data available. Environmental signals will be the annual component of residuals from this fitting, essentially describing the salmons' response to ocean conditions. Compare climatologists' indices of ocean conditions to those extracted from salmon data by MSRA.	Completed. A dynamic simulation of growth and location was prepared in advance but the project chose not to pursue this. A "shared survival" signal was extracted from PCA of 17 Fraser sockeye CUs and compared to 100+ marine indices. Correction for shared autocorrelation and separation into high and low frequency components produced different results

	than previously seen.
Develop a fully parameterized MSRA by evaluating the significance of major environmental effects at various life-history stages (eggs, fry, smolts, juveniles, adults, spawners) and at the place and time that each habitat is occupied by each stage. Focus on early marine period. The path through various habitats will differ among stocks and ecotypes of Fraser River sockeye salmon; Stuart Lake and Stellako River stocks, for example, appear to veer offshore after leaving Queen Charlotte Strait and are not found on the Central Coast in fall with other Fraser sockeye[1]. MSRA includes consideration of compensatory (density dependent) and depensatory mechanisms that may be influencing growth and survival within and among life-history stages.	Not attempted. On the other hand, a revision of the B&H model produced a better tool to analyze habitat quality changes within life stage of Fraser sockeye.
By excluding recent data (after brood 2006) and by cross-validation, test the ability of the model to predict salmon growth and survival with and without environmental effects.	Completed. Specifically by effect of spawning channel, returns accuracy, and shared survival on survivals by life stage for Chilko Lake CU.
Draft one or more manuscripts describing the research for a peer-review journal.	Completed. Draft of primary accepted for presentation at NPAFC in Japan 2015 May 18. Two further primaries are planned.
Document the MSRA models and data, prepare a User Guide, and prepare a Final Report for PSC that evaluates, among other things, the importance of the early marine environment for Fraser sockeye.	Completed. See draft primary, interim report, and final report. Documented R scripts and accompanying Stan code (for Bayesian fits) available.

[1] Tucker, S., M. Trudel, D.W. Welch, J.R. Candy, J.F.T. Morris, M.E. Thiess, C. Wallace, D.J. Teel, W. Crawford, E.V. Farley, Jr., and T.D. Beacham. 2009. Seasonal stock-specific migrations of juvenile sockeye salmon along the west coast of North America: Implications for growth. *Trans. Am. Fish. Soc.* 138: 1458-1480.

Collaboration and Programmer/Analyst Support

This Southern Fund project will employ Mr. Scott Akenhead to focus on this project during the 2014-2015 fiscal year. Mr. Akenhead will work from the Pacific Biological Station (PBS) to:

Task	Status
Organize, facilitate, and report meetings of the Steering Committee and Technical Panel as well as one-on-one meetings and shared-work sessions.	Complete. Biweekly meetings April to December 2014. 19 MSSRA internal reports.
Assemble, clean, load, organize, and summarize datasets.	Complete. MSSRA data table has 267 columns.
Draw attention to data issues, *e.g.* outliers in age composition, incomplete sampling, calibration shifts, *etc*.	Completed. Important result from fitting effect of variance factors from metadata such as accuracy of returns from proportion of run.
Build prototypes for MSRA in R, debug with test data. Present preliminary results from real data and post these on the collaboration website (see below) for comments and discussion. MSRA prototypes will variously use R/nlm, R/odesolve, or R/adbm as required by the Steering Committee.	Complete. 109 R scripts (2.2 Mbytes) 43 Rdata files (243 Mbytes) 52 Stan models (1 Mbyte) ADMB is obsolete, replace by Stan.
Refine the models and create/automate the graphical and tabular output required for scientists and fisheries managers to fully understand the results.	Complete. 582 plot files (210 Mbytes) many tables
Organize and document R scripts, data tables, and models and prepare a User Guide so our accomplishments can be reapplied easily by fisheries biologists.	Ongoing. Initial preparations for web-based collaboration were met with zero enthusiasm. R scripts and Stan models are well documented. A User Guide has been started but there is no audience.
Draft text for Interim and Final Reports as well as for the Methods and Results sections in papers for scientific journals, according to outlines vetted by the Steering Committee. Improve these documents by reviews and contributions from the Technical Panel and Advisors.	Complete. Interim report accepted. Near-final results presented as PSC seminar 2015 February. Draft primary paper circulated to coauthors. Presentation to NPAFC 2015 May.

Support all communications via a new collaboration website (visible to all team members) in order to increase efficiency. The website will hold: [abbreviated] reference library, rafts, graphs, data library, chronology and reports, project management items, User Guide, etc.	Rejected as unnecessary by committee. No interest in working collaboratively. No evidence that “New users may wish to incorporate more detailed life history information and environmental indicators, enabling the comprehensive cumulative effects framework envisioned by Healey (2012)[13]

Methods

Quality Assurance / Quality Control

The breadth and depth of knowledge and skills of the scientists active in MSSRA were be its greatest strength. There were three categories of collaboration:

(1) a Steering Committee of scientists with expertise in sockeye salmon or modeling;
(2) a Technical Panel of individuals who offered advice and data; and
(3) Advisors who commit to providing data (when appropriate) and the review of interim reports.

This aspect of the project was successful, with 15 participants at the start, and the list of people requesting regular updates expanded to 20. A core team of 6 participants participated throughout the project: J. Irvine, K. Hyatt, S. Johnson, S. Grant, C. Michelsens, and S. Akenhead. We received critical support from J. Hume (now a co-author for NPAFC paper).

Monitoring and evaluation - is this being done ?

The assembled scientists received a series of internal reports in addition to the biweekly meetings. Co-authors comments on results represent evaluation and monitoring. Peer review of primary papers will provide the final and ultimate evaluation.

Results

Project Deliverables - were the stated Objectives met ?

Deliverable	Status
Manuscript describing the Multi-stage Stock Recruit Analysis (MSRA).	Complete.
Project software, data, and associated documentation.	Complete. Available upon request.
A Final Report to PSC that summarize the work, includes the results of major runs of MSRA, discusses the value of the MSRA approach to salmon management, and recommends next steps.	Complete.

The project schedule adhered to that proposed.

Project Schedule - did the project run according to schedule ?

The project schedule adhered to that proposed.

Discussion

Benefits - what tangible benefits have resulted from the project ?

There were two important results with value to the PSC, among many minor advances:

1. We demonstrated that stock-recruit curves applied in the conventional manner were not reliable for Fraser sockeye, but this can be remedied by applying historical metadata such as: lake area as a guide for capacity, information on spawning channels and fertilization as a factor for productivity and capacity, proportion of run as a factor that is fitted to down-weight outliers (and equally dangerous in-liers), and "shared survival" as a factor to further reduce scatter around stock-recruit curves. The results, applied to Chilko Lake, were dramatic.
2. Because productivity and capacity parameters for stock-recruit curves both react to a single habitat change, we realized that a revised model was required and reconstructed a variant of the Beverton-Holt model that is based directly on density-independent and density dependent mortality rates. This is more appropriate when considering stock-habitat-recruit instead of stock-recruit. More work on this is planned, but we did isolate 27 annual values of DIM and 17 CU-specific values of DDM from the Fraser CUs. The DDM estimates are expressed as DDM per area, and include the effect of competition between CU within shared lakes, although the natural history behind this needs more work.

Conclusion

See Benefits

Recommendations

These are the remarks of one person, Scott Akenhead, and do not represent the opinion of MSSRA committees and participants, and have not been reviewed by anyone.

New paradigm: Habitat-based salmon management

The Ricker model for stock and recruitment has apparently been treated more religiously and less scientifically than desirable over the past 50 years. A new approach is emerging, one that is focused on how changes to habitat quantify and quality affect salmon growth, location, and survival instead of being focused on invisible, density-dependent effects ascribed to "stock." This is a more but more realistic model, and will be more reliable. The tools for knowledge management and analysis are already available to study and apply the effects of salmon on their habitats and the effects of those habitats on salmon.

Population management instead of CU (stock) management

This new approach is likely to lead to two large changes. First, there will be a shift to dealing with populations (spawning sites) instead of CUs (which are essentially species), made possible by inexpensive DNA identification of parentage at the population (and individual!) level. Tracking these populations through several habitats and life stages will be part of this, aided by emerging technology such as tags that record salmon location and activity.

Success-maximization

Second, the recognition of trends, regime shifts, and habitat quality "events" as critically important to salmon management will lead to a new salmon escapement policy that optimizes about 75% of broods (years) with good production at the expense of closed and reduced fisheries in about 25% of broods that will have poor production. I have simplified this to a binary system for clarity, and have skipped an explanation of the abundance X environment interactions that underly this conclusion (but see the MSSRA reports). If making successful years more successful does in fact greatly increase total economic yield from the Fraser sockeye resource, i.e. outweighs the (probable) effect of making the bad years worse, then the importance of pre-season forecasts will be increased so that businesses can avoid start-up costs for fisheries that do not occur and possibly switch to fishing other species.

Collaboration and Open Access.

Lastly, it might be in the interest of the PCS to move the science that it participates in from a paradigm of "career first, salmon second" to one that is open, collaborative, and inclusive, i.e. "salmon first." PSC might consider requiring open access to data collected with its money (that means public access via searchable websites) as a condition for receiving PSC support.

Appendix 1. - Financial Statement of Expenditures

Attention: Victor Keong, Program Assistant: Restoration & Enhancement Funds
Pacific Salmon Commission, Ph: 604-684-808ext. 613

This project, Multi-Stage Stock Recruit Analysis, was support by the PSC by contracting directly with the coordinator /programmer-analyst Scott Akenhead, via his consulting company S4S Solutions, Inc. The following table records the transaction. PSC has to date paid $55,800, on a grant that totaled $62,000. Balance owed is $6,200.00. Receipts submitted separately.

Date	Payments PSC to S4S	PSC Balance	Payments by S4S	S4S Balance	Description	Receipt
		62,000.00		0.00		
	30,000.00	32,000.00		30,000.00		
			30,000.00	0.00	payment to S. Akenhead	
	25,800.00	6,200.00		25,800.00		
			25,800.00	0.00	payment to S. Akenhead	
Mar 20			12.92	-12.92	Canada Post	1
Aug 18			123.63	-136.55	External Hard Drive	2
Aug 12			11.15	-147.70	Gabriola ferry, meeting Skip McKinnell	3
Aug 12			33.57	-181.27	lunch for S. McKinnel, J. Irvine	4
Jul 8			354.00	-535.27	Harbour Air, PSC meeting. S.Akenhead and J. Irvine	5
Feb 25			416.04	-951.31	Harbour Air, PSC meeting. S.Akenhead and J. Irvine	6
Jul 8			105.62	-1056.93	Lunch for PSC Meeting. J. Irvine, S. Grant, others	7
Mar 21			1245.89	-2302.82	Air Canada Vancouver Osaka return NPAFC conference	8
			3897.18 pending	-6,200.00	payment to S. Akenhead	
	6,200.00 pending	0.0		0.0		

Approved:
Scott Akenhead, President, S4S Solutions Inc.

Appendix 2. - Summaries of MSSRA Reports.

Report	Title	Summary
1	Model Differences	Compares two *proposed* models for salmon science and management being developed by two teams: (1) DFO/PSC MSSRA (technical contact Scott Akenhead[2]) and (2) DFO/SFU Cumulative Effects (technical contact Eduardo Martins[3]). An "elevator pitch" for each is supported by a table that compares specific aspects of these initiatives.
2	Proposed Analysis by K Hyatt and J Irvine	Kim Hyatt and Jim Irvine shared some of their thinking about the opportunities presented by the MSSRA project. This report summarizes that conversation.
3	First Look at Fraser Sockeye Stock and Recruit patterns	Principal Components Analysis of 17 Fraser Stocks with plots and R code.
4	Trends and Extremes in Fraser Sockeye Returns per EFS	Charles Hannah asked three questions, based on the following figure (PCA of 10 Fraser CUs, 58 years), that address fundamental assumptions of our approach. (1) Would anyone care if we could explain the smoothed curve through the data? (2) Would anyone care if we could explain the top 10 or 20% of the deviations from the curve? (3) Is there pattern to the deviations if you break them out by 4 year return groups?
5	Environmental Indices	a haphazard collection of environmental time series conceivably related to the productivity of Fraser River sockeye salmon, with R code to download, reshape, and plot the data. Most but not all of these indicators are in the MSSRA data table.
6	pre1960 Chilko Escapement and Returns	Reconstruction of data for Chilko Lake sockeye stock-recruit plot for brood years 1938-1953 shows no evidence of density dependent survival despite escapements over 0.6×10^6 (approximately 0.3×10^6 EFS). Productivity, as returns per escapement, was 2.5(se=.23) or about 5(0.5) returns/EFS. These results are similar to DFO data for brood years 1947-1960, which shows productivity of 4.8(0.9) without significant density dependence.

[2] scott@s4s.com
[3] egmartins@gmail.com

Report	Title	Summary
7	Clusters and MDS-PCA Fraser sockeye Environmental Indices	From total returns (R) and effective female spawners (EFS) by 27 broods by 17 CUs of Fraser sockeye salmon, log(R/EFS) by year was normalized within each CU. These are not Ricker residuals. A distance matrix was the basis for applying a density-based cluster algorithm published this month in Science.[4] Clustering was compared to multidimensional scaling for each (PCA based on the distance matrix). Two clusters of years and 5 outlier years were identified. Dropping four outlier CUs resulting in one cluster with 2 outliers (broods 2003, 2005). The first time series for the MDS axis for 13 stocks and 27 years explains 51% of the total variance.
8	Ellipses: Fraser sockeye log(R) vs log(EFS)	Plots of log(returns) versus log(EFS) were compared across 17 Fraser sockeye stocks for broods 1950 to 2006. Ellipses describing 95% confidence limits had aligned centroids (same productivity) and similar widths (similarity of non-stock effects). log(EFS) explains $\mathbf{r^2}$ = 76% of the variance in log(R). Including an x^2 term) is a slight but significant improvement. Applying the log-log quadratic relationship on a CU-by-CU basis produced curves similar to applying a Ricker curve but allowing $\beta > 0$. The overall $\mathbf{r^2}$ was 80% with 51 parameters, little gain overall but a better fit for a few stocks that showed an asymptote for R at high EFS. The details of stock-recruit curves are lost when ¾ of the variation in log(R) is due to a linear effect of log(EFS) and almost all of the remainder is due to environmental and observational variance. Until scatter is addressed effectively, debating the shape of stock-recruit curves is medieval rationalism.
9	Great Central Lake Sockeye: returns vs escapement	Low survival events are extracted from Great Central Lake to show possibilities for success maximizing fisheries management.
10	Osoyoos Lake sockeye: returns vs escapement	Two productivity regimes are extracted from Returns and Escapement data for Osoyoos Lake CU of sockeye salmon.

[4] Rodriguez, A., and A. Laio. 2014. Clustering by fast search and find of density peaks. Science 344(6191):1492-1496. doi:10.1126/science.1242072

Report	Title	Summary
11	Comparison of Eggs to Returns Survival in Three California Current Sockeye Stocks.	Sockeye from Sproat Lake and Great Central Lake have correlated (72%) egg to returns survival rates due to three "low survival events" involving 8 out of the 31 years of available data. Sockeye from Osoyoos Lake (Okanogan and Columbia Rivers) share 30% of the variation in survival rate with these distant CUs, but they all enter the California Current Ecosystem, in contrast to Fraser sockeye stocks. The productivity of Osoyoos sockeye is lower that the others, but there is so much residual variance (unaccounted by escapement) that seemingly large differences are statistically insignificant. Examining the conventional fit for a Ricker curve, log(survival) ~ escapement may be a significant regression ($\mathbf{r}^2$ of 50% and 31% for Sproat and Great Central, insufficient range in Returns and Escapement for Osoyoos) but the $\mathbf{r}^2$ for resulting Ricker curve prediction of Returns from Escapement can have a low $\mathbf{r}^2$ (7% for Sproat) or show negative skill (-5% for Sproat) which means worse than using the mean as a predictor.
12	Egg to Smolt and Smolt to Returns survival Sproat, Great Central, Chilko	Smolt abundance (S) data for Sproat and Great Central Lakes sockeye smolts, from plots in government publications, was compared to similar data from Chilko Lake. Escapement (E) and Returns (R) data for the WCVI sockeye CUs were previously available. Time series plots and correlations of S/E and R/S are presented and discussed briefly.
13	Variance model for metadata when fitting Stock-Recruit curves	When fitting a Chilko Stock-Recruit curve, the expected standard deviation of residuals was a function of "variance factors" for stock size and for accuracy of Returns, i.e. we fitted weights for this regression. We added "productivity factors" to account for a 3X increase in egg-to-smolt survival starting 2004, and to examine the effect of fertilizer added 1988-1994, including the possibility of the fertilizer accumulating. Fitting used STAN for Bayesian statistics from sampling the posterior joint distribution of parameters. Note: This analysis was subsequently redone.
14	Bayesian multi-level model for Fraser stocks' productivity and capacity	A report on the development of a model that uses a capacity versus lakes regression simultaneously with fitting productivity and capacity to 17 stocks. We start by recovering known value from made-up data. Then annual productivity (across 17 stocks) and CU-specific capacities (across 27 years) are recovered.
15	Review of Work and Discoveries	Slightly improved report derived from the Interim Report to the Pacific Salmon Commission. An update of the previously circulated PowerPoint was included. This report is the basis for presentation of MSSRA results as a seminar at PSC HQ in February. We are trying to switch from exploring new models to formalizing our findings, from brainstorming to publishing, e.g. abstract accepted by the NPAFC for the Kobe conference 2015 May 17.

Report	Title	Summary
16	Rethinking Stock-Recruit Curves to Include Environmental Covariates	**Question**: Which stock-recruit parameter does an environmental indicator affect, productivity or capacity? **Answer**: Both, because density-independent mortality (DIM) affects both productivity and capacity, whereas density-dependent mortality (DDM) affects only capacity. An old but possibly never-used version of the Beverton-Holt curve is applied in a Bayesian multi-level model to extract DDM by stock as a function of lake area and "shared DIM" by year across stocks. DIM looks exactly like simple survival across stocks. DDM suggests high capacities but reflects incomplete understanding on how habitat quality in lakes is affected by abundance.
17	Salmon Stock-Recruit Models Require a Stock X Environment Interaction Term	The increasing variance of returns as stock size increases implies that high stock sizes amplify habitat quality effects. A simulation model is used to examine this idea and to look for a better way to examine the effect of habitat variables. The best result (so far) was extending the Ricker regression to become (log Returns)-log(Stock) versus stock + stock × habitat. Note: this is preliminary numerical experiment and much work remains. Good idea, though.