The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River

April 2011

TECHNICAL REPORT 6

Fraser River sockeye salmon: data synthesis and cumulative impacts

David Marmorek, Darcy Pickard, Alexander Hall, Katherine Bryan, Liz Martell, Clint Alexander, Katherine Wieckowski, Lorne Greig and Carl Schwarz

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Preface

Fraser River sockeye salmon are vitally important for Canadians. Aboriginal and non-Aboriginal communities depend on sockeye for their food, social, and ceremonial purposes; recreational pursuits; and livelihood needs. They are key components of freshwater and marine aquatic ecosystems. Events over the past century have shown that the Fraser sockeye resource is fragile and vulnerable to human impacts such as rock slides, industrial activities, climatic change, fisheries policies and fishing. Fraser sockeye are also subject to natural environmental variations and population cycles that strongly influence survival and production.

In 2009, the decline of sockeye salmon stocks in the Fraser River in British Columbia led to the closure of the fishery for the third consecutive year, despite favourable pre-season estimates of the number of sockeye salmon expected to return to the river. The 2009 return marked a steady decline that could be traced back two decades. In November 2009, the Governor General in Council appointed Justice Bruce Cohen as a Commissioner under Part I of the *Inquiries Act* to investigate this decline of sockeye salmon in the Fraser River. Although the two-decade decline in Fraser sockeye stocks has been steady and profound, in 2010 Fraser sockeye experienced an extraordinary rebound, demonstrating their capacity to produce at historic levels. The extreme year-to-year variability in Fraser sockeye returns bears directly on the scientific work of the Commission.

The scientific research work of the inquiry will inform the Commissioner of the role of relevant fisheries and ecosystem factors in the Fraser sockeye decline. Twelve scientific projects were undertaken, including:

Project	
1	Diseases and parasites
2	Effects of contaminants on Fraser River sockeye salmon
3	Fraser River freshwater ecology and status of sockeye Conservation Units
4	Marine ecology
5	Impacts of salmon farms on Fraser River sockeye salmon
6	Data synthesis and cumulative impact analysis
7	Fraser River sockeye fisheries harvesting and fisheries management
8	Effects of predators on Fraser River sockeye salmon
9	Effects of climate change on Fraser River sockeye salmon
10	Fraser River sockeye production dynamics
11	Fraser River sockeye salmon – status of DFO science and management
12	Sockeye habitat analysis in the Lower Fraser River and the Strait of Georgia

Experts were engaged to undertake the projects and to analyse the contribution of their topic area to the decline in Fraser sockeye production. The researchers’ draft reports were peer-reviewed and were finalized in early 2011. Reviewer comments are appended to the present report, one of the reports in the Cohen Commission Technical Report Series.

Executive Summary

Purpose of This Study and Methods Used

The overall goal of this study was to synthesize the results of Cohen Commission research projects into an assessment of the cumulative impacts of various factors potentially affecting the Fraser River sockeye fishery over the recent period of declining productivity. Salmon biologists calculate *total productivity* as the number of mature adults produced per spawner[1]. Over the last two decades, there has been a general decline in both Fraser sockeye productivity and the rate of survival of returning adults from the estuary to the spawning ground. However, some Fraser sockeye stocks have not shown productivity declines (i.e., Harrison and Late Shuswap) and some years (e.g, 2010) have shown notable increases in productivity.

We organized our work around five objectives: a workshop involving all Cohen Commission researchers; synthesis and integration of data on stock productivity and potential explanatory factors acquired from these researchers; integrative analyses of cumulative impacts based on the ten technical reports completed to date for the Commission (the aquaculture report is still in progress); quantitative analyses of cumulative impacts based on the available data; and completion of this report.

Prior to considering potential causes of declining productivity, we first summarized the observed patterns of change in various attributes of the Fraser sockeye fishery. We then systematically analyzed potential causes of these patterns, using a framework adapted from the literature on cumulative effects/impacts and retrospective ecological risk assessment. This framework considered the cumulative impacts of all of the factors potentially affecting each of five life history stages, as well as possible interactions across life history stages. We explicitly recognize that combinations of factors are likely responsible for observed effects, and that these combinations will vary in complex, usually unknown ways across years and stocks. The intent of this analysis is to make the best use of the available evidence to improve our understanding of changes to Fraser sockeye populations over the last two decades.

Within each life stage, we considered whether each of the hypothesized stressors:

1. could affect sockeye survival through a plausible mechanism;

[1] Mature adults (or recruits) are estimated as the number of fish returning to the coast *before* the onset of fishing. This estimate is derived by working backwards from the numbers of adults that eventually reached the spawning ground, plus any en-route mortality between the mouth of the Fraser and the spawning ground, plus harvest. Biologists also estimate *juvenile productivity* (fry or smolts per spawner), and *post-juvenile* productivity (mature adults per fry or spawner).

2. has generally exposed Fraser sockeye to increased stress over the period of productivity declines;
3. is correlated with variations in sockeye productivity (i.e. over space, time and stocks); and,
4. has other corroborating evidence from cause-effect studies.

Based on the available evidence, we then came to a conclusion whether the factor was *unlikely* (representing the lowest level of confidence), *possible, likely,* or *very likely* (representing the highest level of confidence) to have been a **primary driving factor** behind the overall pattern of declining productivity in Fraser sockeye. Factors that were unlikely to have been primary drivers to the overall pattern may still have contributed to changes within particular stocks and years. In some cases, major data gaps led us to the outcome that *no conclusion was possible.* Our synthesis of evidence from the Cohen Commission technical reports was supported by our own statistical analyses to determine the relative ability of various factors (representing different combinations of stressors) to explain changing patterns of productivity in Fraser sockeye.

The Pattern We Seek To Explain

Based on the Cohen Commission's technical reports (Peterman and Dorner 2011, Hinch and Martins 2011), we can describe five key attributes of change in Fraser and non-Fraser sockeye populations:

1. Within the Fraser watershed, 17 of 19 sockeye stocks have shown declines in productivity over the last two decades (the two exceptions are Harrison and Late Shuswap sockeye).
2. Most of 45 non-Fraser sockeye stocks that were examined show a similar recent decrease in productivity. Thus, declining productivity has occurred over a much larger area than just the Fraser River system and is not unique to it.
3. Of the nine Fraser sockeye stocks with data on juvenile abundance, only Gates sockeye have showed declines in juvenile productivity (i.e., from spawners to juveniles) but 7 of the 9 stocks showed consistent reductions in post-juvenile productivity (i.e., from juveniles to returning adult recruits).
4. There have been three separate phases of decline in productivity since 1950. The first started in the 1970s, the second in the mid-1980s, and then the most recent one in the late 1990s or early 2000s, with individual stocks showing these trends to various extents.

5. Over the last two decades there has been an increasing amount of en-route mortality of returning Fraser sockeye spawners (i.e., mortality between the Mission enumeration site and the spawning ground). This results in reduced harvest, as fishery managers do their best to ensure enough spawners return to the spawning ground in spite of considerable mortality along the way.

Conclusions Regarding Potential Causes of This Pattern

We present our conclusions for each life history stage, recognizing that there are interactions both within and between life history stages. These results do not consider aquaculture (report in progress) or other factors not considered by the Cohen Commission (except for a brief consideration of interactions between sockeye and pink salmon).

Stage 1: Incubation, Emergence and Freshwater Rearing

With the exception of **climate change**, which we consider to be a *possible* factor, and **pathogens** (for which *no conclusion is possible* due to data gaps), it is *unlikely* that the other factors considered for this stage, taken cumulatively, were the *primary* drivers behind long term declines in sockeye productivity across the Fraser Basin. These factors included **forestry**, **mining**, **large hydro**, **small hydro, urbanization, agriculture, water use, contaminants, density dependent mortality, predators,** and effects of **Lower Fraser land use** on spawning and rearing habitats. We feel reasonably confident in this conclusion because juvenile productivity (which integrates all stressors in this life history stage except over-wintering in nursery lakes) has not declined over time in eight of the nine Fraser sockeye stocks where it has been measured. We would be even more confident if more stocks had *smolt* enumeration rather than *fry* estimates (only Chilko and Cultus stocks have smolt estimates). Though not primary drivers of the Fraser sockeye situation, each of these factors may still have had some effects on some Fraser stocks in some years (the data are insufficient to reject that possibility). We suspect, based on qualitative arguments alone, that **habitat** and **contaminant** influences on Life Stage 1 were also not the *primary* drivers responsible for productivity declines occurring to most non-Fraser stocks assessed by Peterman and Dorner (2011). However, given the absence of any exposure data and correlation analyses for non-Fraser stocks, it is not possible to make conclusions on the relative likelihoods of factors causing their declining productivities. None of the factors considered for Stage 1 are likely to have been much worse in 2005 and 2006 for Fraser sockeye stocks, sufficient to have significantly decreased egg-to-smolt survival in the salmon that returned in 2009. Similarly, none of these factors are likely to have been much better in 2006 and 2007, sufficient to have substantially improved egg-to-smolt survival in the salmon that returned in 2010.

Stage 2: Smolt Outmigration

We analyzed the same factors for Stage 2 as for Stage 1 and came to the same conclusions. There are however three key differences in our analyses for these two stages. First, regardless of differences in their spawning and rearing habitats, all sockeye stocks pass through the highly developed Lower Fraser region. Second, migrating smolts are exposed to the above-described stressors for a much shorter time than are eggs and fry, which reduces the likelihood of effects. Third, since smolt migration occurs subsequent to enumeration of fry and smolts in rearing lakes, we have no analyses relating survival rates to potential stressors during this life history stage. Thus our conclusions have a lower level of confidence than for Stage 1. While there are some survival estimates for acoustically tagged smolts, these data (which only cover a few stocks) were not analyzed by any of the Cohen Commission technical studies. None of the factors considered for Stage 2 is likely to have been much worse in 2007 for downstream migrating smolts (affecting the 2009 returns), or to have been much better in 2008 (affecting the 2010 returns).

Stage 3: Coastal Migration and Migration to Rearing Areas

There are almost no data on exposure for **pathogens** making *no conclusion possible.* The evidence presented suggests that sockeye salmon in the Strait of Georgia have little direct exposure to **human activities and development**[2], leading to a conclusion that it is *unlikely* that these factors have contributed to the decline of Fraser River sockeye salmon. Sockeye salmon have been exposed to predators, marine conditions, and climate change during this early marine phase. However, there has been no evidence presented on any correlations between key predators and sockeye salmon survival. Some important predators appear to be increasing in abundance, and some potentially important alternate prey appear to be decreasing, but many other known predators are decreasing or remaining stable. It therefore remains *possible* that **predators** have contributed to the observed declines in sockeye salmon. Based on plausible mechanisms, exposure, consistency with observed sockeye productivity changes, and other evidence, **marine conditions** and **climate change** are considered *likely* contributors to the long-term decline of Fraser River sockeye salmon. It is also *very likely* that poor **marine conditions** during the coastal migration life stage in 2007 contributed to the poor returns observed in 2009. Marine conditions were much better in 2008 (much cooler temperatures), which benefited returns in 2010. **Aquaculture** was not considered in our report as the Commission Technical reports on this potential stressor were not available, but will be considered in an addendum to this report.

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[2] "Human activities and development" refers specifically to those activities and developments considered within Technical Report #12 (Fraser River Sockeye Habitat Use in the Lower Fraser and Strait of Georgia), which do not include salmon farms. Exposure to salmon farms will be covered in the technical report on aquaculture, which is currently in progress. The present report does not provide any conclusions regarding salmon farms.

Stage 4: Growth in North Pacific and Return to Fraser

Our conclusions on this life history stage are similar to those for Stage 3, though we conclude that **marine conditions** and **climate change** remain *possible* contributors to the long-term decline of Fraser River sockeye salmon (whereas in Stage 3, we considered them to be likely contributors).

Stage 5: Migration back to Spawn

While the timing of increased **en-route mortality** coincides generally with the Fraser sockeye situation, the Fraser sockeye productivity indices already account for en-route mortality (i.e., recruits = spawners + harvest + en-route mortality). Therefore, there is no point in examining correlations between en-route mortality and life cycle or post-juvenile productivity indices within the same generation. The only possible effects on productivity are inter-generational effects, for which the evidence is limited and equivocal. We therefore conclude that it is *unlikely* that en-route mortality (or pre-spawn mortality[3], which has only increased for Late Run sockeye) are a primary factor in declining indices of Fraser sockeye productivity. However, en-route mortality has *definitely* had a significant impact on the *sockeye fishery* and the *numbers of adult fish reaching the spawning ground*, particularly for the Early and Late runs. **Pre-spawn mortality**, **habitat changes**, and **contaminants** are *unlikely* to be responsible for the overall pattern of declining sockeye productivity. *No conclusion is possible* regarding **pathogens** due to insufficient data. None of the factors assessed for this life history stage are likely to have shown significant changes between 2009 and 2010.

The above conclusions are based on qualitative and quantitative analyses of existing information. There are two important caveats on these conclusions. First, there are major gaps in both our fundamental understanding of how various factors interact to affect Fraser River sockeye salmon, and in the data available to quantify those factors. Second, all Cohen Commission researchers have had a limited amount of time to analyze existing information; future data syntheses and analyses may provide deeper and different insights. Below, we summarize our recommendations for research, monitoring and synthesis activities.

Recommendations for Research, Monitoring and Synthesis

Researchers at the Cohen Commission workshop agreed with the PSC report (Peterman et al. 2010) that the 2009 and long-term declines in sockeye productivity were likely due to the effects

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[3] Pre-spawn mortality is defined as females that have arrived on spawning grounds but die with most of their eggs retained in their body.

of multiple stressors and factors, and that a strong emphasis should be placed on studying the entire life cycle of sockeye salmon along with their potential stressors. Unlike the PSC report, participants felt that research efforts should be expanded outside the Strait of Georgia as a priority area, as well as increasing efforts inside the Strait.

Section 5.2 of this report describes 23 recommended research and monitoring activities, organized by life history stage, based on four sources: the PSC report (Peterman et al. 2010), the Cohen Commission's research workshop, the Commission's Technical reports, and this cumulative effects assessment. We have highlighted 12 of these 23 recommendations as particularly high priority, but the others are also essential to provide the information needed to properly manage Fraser sockeye. The three dominant themes are: 1) coordinated, multi-agency collection of data on sockeye stock abundance, survival and stressors for each life history stage; 2) development of an integrated database and cumulative assessments both within and across multiple life history stages; and 3) transparent dissemination of information annually to scientists and non-scientists. Since the early marine environment appears to be a major potential source of declining productivity, it is particularly important to improve information on potential stressors affecting sockeye along their migratory path from the mouth of the Fraser River through Queen Charlotte Sound, including food, predators, pathogens, and physical, chemical, and biological ocean conditions. Further efforts to prioritize, sequence and refine our recommendations will require a careful consideration of several factors: the ultimate uses of the information; given those uses, the appropriate space and time scales and required/achievable levels of accuracy and precision; and the most cost-effective, well-integrated designs for the overall monitoring and research program.

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1.0 Introduction

1.1 Project Objectives

Our work was organized around five objectives: workshop facilitation, data synthesis and integration, integrative analyses of cumulative impacts based on the ten technical reports completed to date for the Commission (the Aquaculture Report is still in progress), quantitative analyses of cumulative impacts, and clear communication. Each of these objectives is described below.

1. Workshop Facilitation. We organized and facilitated a science workshop (Nov. 30 – Dec. 1, 2010) including presentations from all research groups, feedback and discussion from all researchers and peer reviewers, and interactive discussion of linkages and interactions among all research projects. The results of this workshop are summarized in Appendix 6.

2. Data Synthesis and Integration. Our first task under this objective was to assemble data on productivity[4] and stressor metrics from all research projects, through development of a data template sent to all researchers, and assistance to these scientists on organizing their data.. Once received, we then organized these data into an integrated format to support statistical analyses (i.e., a linked database associating productivity indices for different stocks with data on stressors from appropriate locations, stocks, years and time periods). This database was designed to be expandable in future to include other data sets that were not available in time for this project (e.g., information on aquaculture).

3. Integrative Analyses of Cumulative Impacts. We first developed integrative frameworks for organizing and analysing potential cumulative impacts, based on a life history approach. Our second task was to summarize patterns in Fraser Sockeye productivity over time and space, and other indicators relevant to the Fraser sockeye fishery, building on the work of Peterman and Dorner (2011) and other Cohen Commission technical reports. Third, we synthesized the key findings from all Cohen Commission technical reports (representing over 2400 pages) within

[4] Salmon biologists calculate *total productivity* as the number of mature adults produced per spawner. Mature adults (or recruits) are estimated as the number of fish returning to the coast *before* the onset of fishing. This estimate is derived by working backwards from the numbers of adults that eventually reached the spawning ground, plus any en-route mortality between the mouth of the Fraser and the spawning ground, plus harvest. The total abundance of returning adult Fraser sockeye salmon is a product of the number of spawners in the parent generation times their productivity. Biologists also estimate *juvenile productivity* (fry or smolts per spawner), and *post-juvenile* productivity (mature adults per fry or spawner).

these integrative frameworks, converging to conclusions about the relative likelihood of different factors explaining observed patterns in Fraser sockeye productivity. One difficulty in this process is that each researcher used their own approach for synthesizing and organizing information. Thus we recognized that the third step would involve mining key findings within each technical report that fit our integrative framework, and then assess potential cumulative impacts within and between life history stages.

4. Quantitative Analyses of Cumulative Impacts. We first determined reasonable hypotheses worth testing, given plausible mechanisms of impact on sockeye as outlined in the Cohen Commission Technical Reports. To the extent possible given available data, we then completed statistical analyses to determine the relative ability of various factors (representing different combinations of stressors) to explain changing patterns of productivity in Fraser sockeye. Where feasible, we incorporated quantitative analyses into the Integrative Analyses of Cumulative Impacts (objective 3 above).

5. Clear Communication. This is a cross-cutting objective, namely to clearly communicate how the stressors examined by the Cohen Commission research projects could interact to affect Fraser River sockeye. The intent of this objective is to develop methods of presenting and reporting key findings that will be accessible to the diverse audiences interested in the work of the Cohen Commission, including Judge Cohen and the Cohen Commission scientific and legal staff, Cohen Commission Participants, interested members of the public, research contractors, and peer reviewers.

1.2 Report Overview

This technical report is organized into the following sections:

Section 2.0: Cumulative Impacts or Effects
This section introduces the concept of cumulative impacts or cumulative effects, some key ideas associated with this concept, and their application to this project.

Section 3.0: Complexity, Caveats and Overall Approach
This section describes the approach we used to synthesize and integrate evidence across other associated technical reports, first identifying some of the overarching limitations on this type of analysis (e.g., the inherent complexity of the underlying ecological system, the significant gaps in our knowledge), and how these limitations enact constraints on the ability to make definitive conclusions about cause-effect relationships.

Section 4.0: Results, Synthesis and Discussion
This section provides the results of our qualitative cumulative impact analysis, integrating evidence across other Cohen Commission technical reports by life history stage, as well as some of the important results from our quantitative cumulative impacts analyses. This section covers the breadth of the evidence presented within the suite of Cohen Commission technical reports, but refers to those reports, and the appendices of this report, for greater details on the depth of evidence available.

Section 5.0: Conclusion
This section summarizes Section 4.0 along two themes. First, given existing knowledge, what overall conclusions can be drawn about the importance of different potential contributors to the decline of Fraser River sockeye salmon? Second, what future research and monitoring activities might best reduce critical uncertainties in our existing knowledge?

Appendices:
Appendix 1: Statement of Work provides the original Statement of Work from the Commission for this technical report.

Appendix 2: Reviewer Evaluations and Responses provides the reviewers' evaluations of our draft report, and our responses to their comments, including revisions that we incorporated into this final report.

Appendix 3: Data and Methods describes the data we received, how we organized it, and our approach to qualitative and quantitative analyses. We also suggest possible future quantitative approaches that could not be implemented in our project due to time limitations.

Appendix 4: Quantitative Results presents the results of our quantitative analyses.

Appendix 5: Data Template User Guidelines provides the guidelines that accompanied the data template we developed to guide Commission contractors supplying us with data.

Appendix 6: Workshop Report contains the agenda, summary report and detailed minutes from the two day, Cohen Commission Scientific and Technical Workshop, November 30 – December 1, 2010.

2.0 Cumulative Impacts or Effects

2.1 What are Cumulative Impacts or Effects?

One of the primary goals of this project is to examine the potential cumulative impacts on Fraser River sockeye salmon productivity, of multiple stressors acting at different times and places. The terms cumulative effects and cumulative impacts are frequently used interchangeably. In Section 2.0 we use the term "cumulative effects" to respect the convention of the literature to which we refer; however, throughout the rest of the report, we generally use the term "cumulative impacts" to respect the language with which our original assignment from the Cohen Commission was described.

We start by exploring what is meant by "cumulative effects". Unfortunately, while there is no universal definition of "cumulative effects", there are some general concepts worthy of review. What is *an effect*? Greig (2010) defines an environmental effect as, "a change in a component, property or function of an ecosystem." In the present project we are concerned specifically with adverse environmental effects that "diminish a desirable component, property, or function of an ecosystem" (Greig 2010), namely, the ecosystems that support Fraser sockeye, and the sockeye stocks themselves.

What is it that is being *affected*? To assess the consequences of particular stressors, we need to define the Valued Ecosystem Component (VEC), the focal component that society wishes to protect, conserve or enhance. These are the sockeye stocks occupying the 36 Conservation Units in the Fraser River watershed.

Which effects are being examined cumulatively? There are various conceptualizations relevant to this question. Cumulative effects could be conceived as:

- **the total impact of a single type of stress that has occurred repeatedly over time**, possibly increasing in frequency or magnitude (e.g., the cumulative effect of water pollution in the Fraser River estuary over the past four decades);
- **the total impact of a single type of stress that occurred repeatedly over space** (e.g., the cumulative effect of multiple mountain pine beetle outbreaks across the entire Fraser River watershed);
- **the total impact of many different types of stressors at one point in time or over a period of time** (e.g., the cumulative effect of changing climate, increased mammal predation, and increased harmful algal blooms).

Even when multiple stressors are examined together, there is a distinction between examining the *relative magnitude* of impacts of each stressor, versus examining the *mechanisms by which* *stressors interact or combine* to affect sockeye. The first type of analysis might examine all stressors to determine which factors made the largest independent contribution to a change in the VEC. For example, what has had a larger relative effect on sockeye productivity: increases in predators, increases in diseases and parasites, decreased food resources, or increased competition for food? Such a question explores the relative importance of each individual factor.

The second kind of analysis looks at how multiple effects might *combine* (i.e., how multiple stressors might interact to produce a combined impact different (in form or magnitude) from each stressor acting independently). For example, how might increasing ocean temperatures have affected predators, diseases and parasites in a way that changes their overall impact? There are many ways in which individual effects might combine to form types of “cumulative effects”. Sonntag et al. (1987) classified cumulative effects into the following types: linear additive effects, amplifying or exponential effects, discontinuous effects, and structural surprises. Greig et al. (2003) suggested an alternative categorization of types of cumulative effects: additive, compensatory, synergistic, and masking.

2.2 Cumulative Effects Assessment

“Cumulative Effects Assessment” (CEA) specifically refers to the process in which the effects of a proposed project are assessed together with the effects of other past, present or future projects to determine the overall cumulative effects on Valued Ecosystem Components (VECs). Under the Canadian Environmental Assessment Act (CEAA) CEA is required for all projects where the Act applies and is thus a part of the project approval process. The issue at hand, a retrospective investigation into the potential causes underlying the decline of Fraser River sockeye salmon, is in many ways fundamentally different from the forward-looking Environmental Impact Assessment process. However, there are many important shared concepts about how “cumulative effects” are defined and used, or rather how they should be, that are critical to understand.

According to current practice, two criteria may be used to determine if CEA is required for a proposed project. First, in some cases it has been argued that the effects of the individual project must be significant on their own (L. Greig, pers. comm.). If the effects of an individual project are insignificant, it is assumed that the project’s contribution to potential cumulative effects will also be insignificant and a CEA will not be required for project approval. This is inappropriate since effects that are individually insignificant when combined with other effects can result in significant impacts. Second, some practitioners take the view the proposed project and other relevant developments/projects must have effects of the same type, with the same timing, at the same location. If multiple projects have effects that differ by type or timing or location, it is assumed that there is no potential for cumulative effects and a CEA will not be required (Greig 2010, Golder Associates Ltd. 2008).

Greig and Duinker have argued repeatedly that this narrow definition of cumulative effects is inherently flawed (e.g. Duinker and Greig 2006, 2007; Greig and Duinker 2008). They argue that individual projects with insignificant effects or different types, timing, or location of effects, may still contribute to significant cumulative effects (also Berube 2007). CEA should be focused on VECs rather than projects because ultimately the cumulative effects on VEC sustainability are the effect of greatest concern. The aggregate stress on a VEC includes all projects and developments (whether or not they meet the requirements for EIAs or CEAs) as well as many natural drivers – a VEC must endure all these stressors cumulatively. It is the net consequence of the aggregate stresses that determines the status and sustainability of a VEC (Greig et al. 2003). Cumulative effects are the "only real effect worth assessing" and need to be assessed at the scale of ecological regions (Duinker and Greig 2006).

Although the present research project is not an environmental impact assessment project, it does address several of the criticisms of the standard approach to "cumulative effects" in Canada. First, this project is definitively centered on a focal VEC – Fraser River sockeye salmon. Second, this project uses the relevant ecological regions as a study area – the Fraser River watershed and estuary, the Strait of Georgia, and the marine migratory extent of Fraser River sockeye. Third, the analyses include a large range of factors hypothesized to be contributors to the decline in the VEC and these factors are all considered to potentially contribute to cumulative impacts on the VEC even though they differ substantially in type, timing and location of their primary effects.

Another major difference between a CEA and the present research is the temporal direction of focus. A CEA is explicitly future focused. Environmental assessment is an exercise in determining different possible future scenarios and examining the potential impacts of actions taken today across those possible futures. In environmental assessment, past actions cannot be changed and are only useful for discovering and calibrating cause-and-effect relationships among actions and VEC-consequences. However, the Cohen Commission is explicitly focused on the past. It is inherently concerned with retrospective analyses to determine the magnitude and nature of those cause-and-effect relationships. The ultimate goal of such knowledge is *prospective* - to facilitate more strongly informed future management decisions. However, the critical first step is to improve our *retrospective* understanding of the fundamental relationships between impact factors and VEC sustainability (Fraser sockeye productivity and recruitment).

2.3 Present Cumulative Effects Analysis

The present cumulative effects analysis relies on data provided by each of the independent research projects investigating a different potential category of stressor. Some of the analyses examine potential interactions among different types of stressors, but most of our quantitative work focuses on the *relative* impact of these different factors. Our analyses are be limited by: 1) the quality and extent of the data that are actually available; and 2) the degree of complexity in the "true" underlying causes of the recent decline in productivity of Fraser River sockeye.

We first address the issue of complexity. Figure 2.3-1 illustrates four different hypothetical paths by which an individual sockeye salmon could be exposed to stressors over its lifetime, yet all leading to the same outcome - death as an adult. For the sake of simplicity, we have assumed it is possible to integrate all stress factors into a single measure of cumulative stress where 0.0 represents perfect health and 1.0 represents mortality. There are four scenarios described in Figure 2.3-1:

- **A1**: the sockeye is severely affected by stressors as a fry (e.g., acquiring a disease that almost killed it and permanently affected its health), but does not suffer any further stress until, as an adult, a minor incremental impact results in death.
- **A2**: the stressor that almost killed the sockeye as a fry killed off many other fry, reducing competition for food at the smolt stage, improving the health of surviving individuals;
- **B:** the sockeye suffers moderate stress from many separate incidents over its lifetime, eventually dying at the same age as under the other scenarios even though none of the stressors experienced were even moderately severe.
- **C:** the sockeye is only moderately affected by stressors over its lifetime until, as an adult, it is impacted severely by stressors that quickly result in death (e.g., low food, abundant predators, high temperatures).

In scenarios A and C, the rapid induction of severe stress could be either one severe stressor or many stressors occurring simultaneously but within a similarly constrained window of time. In scenario B, the slow induction of moderate stress could be either continued exposure to one stressor over the entire lifetime, or many different stressors occurring variably over time and space.

If scenario A or C accurately represent the "true" pathway, this relationship might be detected by testing the fit to productivity indices of models that only include sets of factors limited to fry (A) and adult (C) life history stages. If scenario B represents the "true" pathway with one key stressor, this relationship might be detected by testing model sets limited to particular stressors or classes of stressors. However, if scenario B represents the “true” pathway with many stressors combining and interacting over time and space, this relationship may be very difficult to detect.

The quality and extent of available data severely limits the range of analyses that can be performed, as we discuss later.

The scope of the present cumulative effects analysis is limited to the scope of the Cohen Commission technical research projects as a whole. Our cumulative effects analysis has been conducted within the universe of the other technical projects and the data available from within those projects. This is not a cumulative effects study of Fraser River sockeye salmon within the broader realm of all available scientific literature, research and reports.

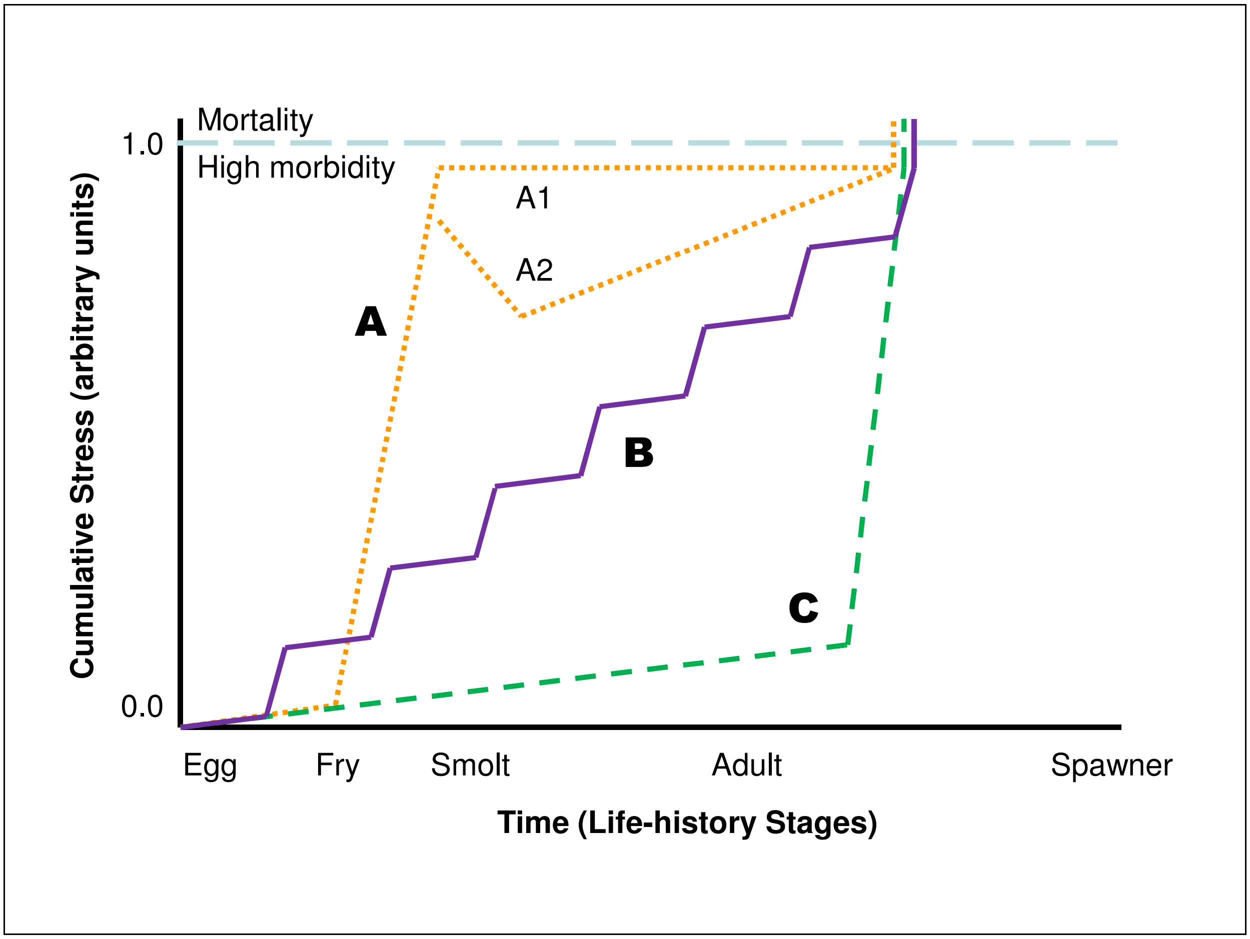

Figure 2.3-1. Cumulative stress model. Lines illustrate four scenarios through which an **individual** sockeye salmon might suffer from the cumulative impacts of exposure to stressors over its lifetime. Each scenario illustrates a different pattern in the number, severity and timing of stressors experienced, yet the timing of mortality is the same for all three scenarios. For both Scenarios A and C, it is evident that eventual mortality is primarily the result of one particular period of substantial stress, though in Scenario A this is not the proximate reason for death. Scenario A2 reflects the possibility that density-dependence effects on the population might occur within a single generation (as compared to density-dependent effects that may also occur across generations), which could benefit surviving individuals. That is, in Scenario A2, the stressor that almost kills this hypothetical individual may actually kill a substantial portion of the rest of the population. If so, the surviving individuals may encounter improved conditions as smolts due to lower density and less competition for resources. However, in Scenario B mortality is the result of many subsequent impacts over the individual's entire lifetime, none of which would have resulted in mortality on their own or even as a small subset of the cumulative impact. A roughly similar conceptual model could be developed for an entire sockeye population, though it would be more appropriate to use overall survival rates, which would decrease over time and life history stages.

Concepts of cumulative effects are embedded throughout this report. First, we have already discussed above discuss the theory of cumulative effects. Second, the conceptual model (Figure 3.3-1) embodies several characteristics of cumulative effects analyses: it provides a graphical representation of how the valued ecosystem component (i.e., sockeye salmon) is potentially affected by many stressors over its lifetime; these stressors may be independent factors occurring simultaneously or the interaction of several factors; and stress may accumulate over multiple life history stages, as long as the salmon survives. Third, we consider the *integrated* responses of each life history stage to multiple potential stressors, rather than examining each stressor independently, which was the focus of several of the other technical reports (e.g., climate change, contaminants, pathogens, Lower Fraser and Strait of Georgia habitat, predators). Fourth, our quantitative analysis (introduced in Section 3.3.6; described in detail in Appendix 3 (Section A3.5.2) examines the correlation between groups of stressors and total productivity, rather than examining these factors independently.

3.0 Complexity, Caveats, and Overall Approach,

3.1 Complexity of the Ecological System

Over the 4 to 5 years of their life cycle, salmon encounter largely unmonitored variations in physical and chemical conditions, food, competitors, predators, and disease, over several thousand kilometres from high in the Fraser Basin to the Gulf of Alaska, with cumulative and interactive effects (most unknown), occurring over multiple life history stages in ways that vary from year to year. Gaps exist not only in data (limited time series and spatial coverage for many factors), but also in fundamental understanding. Under these circumstances, it is extremely difficult for fisheries managers to accurately predict the expected returns of different salmon stocks in advance of their arrival. Indeed, pre-season predictions of sockeye returns are not reliable for 7 of 18 Fraser sockeye stocks (English et al. 2011; Executive Summary). Previous work (Walters and Collie 1988, Walters 1989, Myers 1998) has emphasized the difficulties of predicting recruitment of fish populations for the purposes of fisheries management, including the lack of persistence of environment-recruitment correlations.

Rocket science is commonly used as a benchmark when describing the relative difficulty of other subjects (e.g., "It isn't rocket science."). Fisheries science also isn't rocket science, but it is nonetheless very challenging. Rocket scientists rely on repeatable laws of physics, whereas ecological interactions are much more variable over time and space, and much less understood. If a rocket scientist had equivalent challenges to a fisheries scientist, s/he would be launching and landing rockets with all the key variables determining outcomes (gravity, atmospheric pressure, temperature, solar radiation, fuel quality, cosmic rays) radically changing from year to year and place to place, with little ability to monitor this variation, and considerable uncertainty about the basic theory behind each of these variables and their interactions.

Given the above uncertainties, attributing causes to observed effects is very difficult. Peterman and Dorner (2011, pg. 13-14) express this challenge well:

> An important concept for readers to keep in mind when considering the evidence presented in this and other scientific reports to the Cohen Commission is that ecological systems are dynamic and constantly change across time and space. They are composed of complex sets of components that interact to generate responses to concurrently operating disturbances arising from both natural processes (e.g., ocean conditions) and human activities (e.g., fish farming). Because of such simultaneously occurring natural and human processes, it can be very difficult to attribute single dominant causes to observed ecological changes, and while it is important to investigate each potential cause individually, it is important to be aware that it might have been the interaction of several factors, rather than one factor per se, that caused the changes. Two well-known case

> examples illustrate this problem -- the collapse of Canada's Northern cod populations in the early 1990s and the virtual disappearance of California sardine in the 1960s -- both of which fueled long debates about the relative importance of fishing, environmental changes, and government regulations in causing those collapses.

The sockeye stocks within the Fraser Basin have widely varying life history, genetic and habitat characteristics that create different levels of vulnerability to the stressors each stock encounters (described in Nelitz et al. 2011). Effects of stressors on survival at any life history stage depend on both the magnitude of the stress and the vulnerability of the salmon. Characteristics that vary across stocks include: spawning habitat (inlets, outlets, lake shore, flow rates, substrate conditions, environmental conditions), nursery lakes (area, size, productivity, temperature, ice break-up, duration of rearing), smolt out-migration (distance, timing, temperatures, arrival at estuary, residence time in estuary), coastal migration (timing, duration, route), and adult migration (return route, age of return, timing, estuary residence time, timing of upstream migration, upstream distances and duration, river temperatures and other environmental characteristics, pre-spawn mortality rates). Many Fraser sockeye stocks are strongly cyclical (e.g., Late Shuswap, Quesnel, Scotch) whereas others are less so. Once mobile, each salmon has a recurring choice – eat or hide. Sockeye stocks (and sub-populations within each stock) have developed complicated and varying life histories that include moving between ranges of habitats varying in the risks they represent (Christensen and Trites 2011, pg. 5). Finally, we are observing large scale effects of climate change in both freshwater and marine environments, with influences on many of the above attributes and their interactive relationships.

3.2 Unknowns, Unknowables, Knowledge Gaps, and Data Limitations

Given all of the above challenges, what can fisheries science achieve that is helpful to both the Cohen Commission and fisheries managers? First, science can test hypotheses, rejecting those that are unlikely or false. Even with considerable gaps in data and understanding, and mostly indirect evidence, contrasts over space and time in both salmon stock productivity and the potential stressors allow us to judge certain stressors to be unlikely to have been the *primary* factors causing declines in sockeye productivity or abundance. Other factors may be possible or even likely, provided that they fulfill most or all of various criteria (i.e., have a plausible mechanism by which survival could be affected; have generally exposed Fraser sockeye to increased stress over the period of productivity declines; correlate over space, time and stocks with variations in productivity; and (ideally) have other corroborating evidence from cause-effect studies). The procedure by which we evaluate alternative hypotheses is described below in section 3.3. Two key principles are: 1) hypotheses can be rejected as false or unlikely, but cannot be accepted as true (only relatively more likely); and 2) correlation does not equal causation (one also needs an underlying mechanism that can logically (and defensibly) link the cause with observed effect).

There are several challenges in this process of evaluating alternative hypotheses. The first challenge is data limitations, which include incomplete time series of information (both within each stage of the life cycle and over multiple years), incomplete spatial coverage for all stocks, poor quality data (imprecise or inaccurate measurements), crude indicators that do not really reflect the condition of interest (e.g., air temperatures rather than the water temperatures where salmon eggs are incubating), and inconsistent methods of measurement. There are 36 Conservation Units in the Fraser Basin (CUs). We only have estimates of spawning abundance and en-route mortality for about half of these CUs, and juvenile production estimates for about one quarter of these CUs. With the exception of a few detailed studies (available for only a few years and stocks), we do not have any estimates of survival rates or abundance between the time that fry or smolts are sampled, and the time that adults return to be counted at Mission two to three years later. When it comes to explanatory factors, we would ideally have data that are inter-generational (i.e., across 40 years to provide a pre-decline base period), intra-generational (across life history stages and locations), and inter-stock (to explain why some have done well while others declined). Statistical analyses of multiple factors (to see which ones are best correlated with productivity patterns) require data on all of the factors for all of the stocks and years included in the analysis. As difficult as it is to retrospectively deduce which factors were more or less likely to have caused historical patterns, the one advantage that we have over predicting the future is that there is only one past.

The second challenge is gaps in basic knowledge or understanding. We generally do not know how, where or when sockeye die. The few situations in which we can definitively determine the causes of mortality are comparatively rare (i.e., fish harvests, stomach analyses of predators, intensive telemetry studies showing that fish died while experiencing conditions beyond established thresholds). In most cases, mortality must be inferred indirectly based on information on the sockeye's exposure to different stresses, but there are uncertainties in both fish migration patterns and the stresses experienced by each group of fish. McKinnell et al. (2011; pg. 4) point out:

> "During the period of years of interest to the Commission, there are virtually no observations of Fraser River sockeye salmon during about 75% of their life at sea, and the value of coincidental samples taken during their emigration from the Strait of Georgia is debatable."

Little is known about the potential impact that abundant predators may have on relatively rare prey. In such situations, it may be possible for the abundant predator to have a very large impact on, for example, a weak and declining sockeye stock, despite that prey being a minor and possibly even negligible component of the predators diet. This type of predator-prey relationship may be fundamentally important to the prey while being of virtually no importance to the predator.

The third challenge (really an extension of the second) is unknowables. We cannot know the explanatory influence of a factor that has not been monitored in a given year or location. When there are no data, one cannot make any inferences either in favour or opposed to a given hypothesis.

3.3 Current Framework

3.3.1 Overview

Our approach to cumulative impacts analysis comprises three components:

1. Understand the patterns of change in the productivity of Fraser River sockeye salmon stocks (and other sockeye stocks) over the past several decades. This is the pattern that we are seeking to explain. This component is the primary focus of Project 10 (Peterman and Dorner, 2011), and is summarized in section 4.1 of this report.
2. Identify factors that could feasibly have contributed to the observed patterns of changing productivity in Fraser sockeye salmon. These potential explanatory factors do not necessarily need to be mutually exclusive (i.e., there may be multiple causes of the observed patterns). The various factors are the focus of other Cohen Commission Technical Reports and are covered in much greater detail therein.
3. Assess the relative likelihood of feasible explanatory factors and their potential interactions, the focus of sections 4.2 to 4.7 of this report. We have compiled the evidence presented within other Cohen Commission Technical Reports into a weight of evidence approach.

3.3.2 Conceptual model

We developed a conceptual model illustrating the factors potentially affecting each life stage (Figure 3.3-1), so as to:

1. organize the factors identified within the Technical Reports as being potential contributors to the Fraser sockeye productivity declines, and indicate the life stages possibly affected by each factor;.
2. represent some of the key interactions among factors, both within and across Technical Reports;

3. provide the Cohen Commission with some insights into the underlying complexity of this ecological system[5]; and
4. provide an organizational framework for the analysis of cumulative impacts, identifying all of the factors to be integrated into qualitative and quantitative analyses of each life history stage, and across the overall life cycle.

Figure 3.3-2 illustrates a simplified version of the conceptual model projected over the geographic habitat range of Fraser River sockeye salmon. This representation of the sockeye salmon life history does not show details of specific mechanisms or all interactions among factors, but instead is intended to represent the general movement patterns of Fraser River sockeye salmon throughout their habitat range and indicate the broad spatial scales over which different factors may influence sockeye salmon health and survival.

Further details on the value of conceptual models as a central component of analytical frameworks and the development of this particular model are provided in Appendix 3.

[5] Though reasonably complex, our conceptual model is certainly not an exhaustive representation of all primary and intermediate factors that influence sockeye salmon productivity.

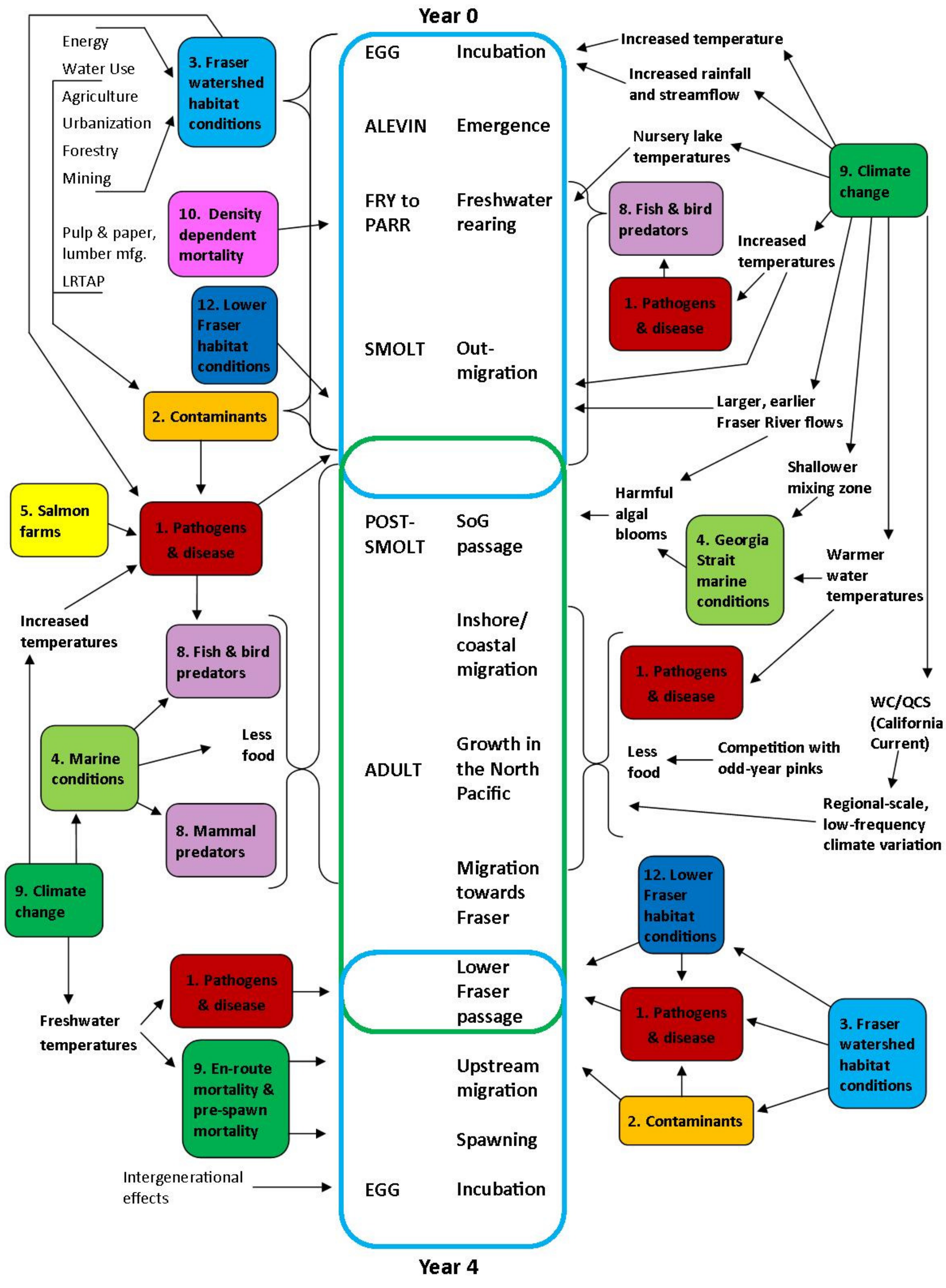

Figure 3.3-1. The conceptual model of the life history of Fraser River sockeye salmon and potential stressors affecting each life stage. The life history processes and developmental stages are shown in the centre column. The blue and green outlines signify the freshwater and marine components, respectively. To avoid any more complexity, we have excluded many feedbacks and interactions from this diagram (e.g., decreases in sockeye may affect predators; stressors that cause mortality at an earlier life history stage may lead to less competition and improved survival at a later life history stage; the nature of some interactions and feedbacks may be conditional upon other factors).

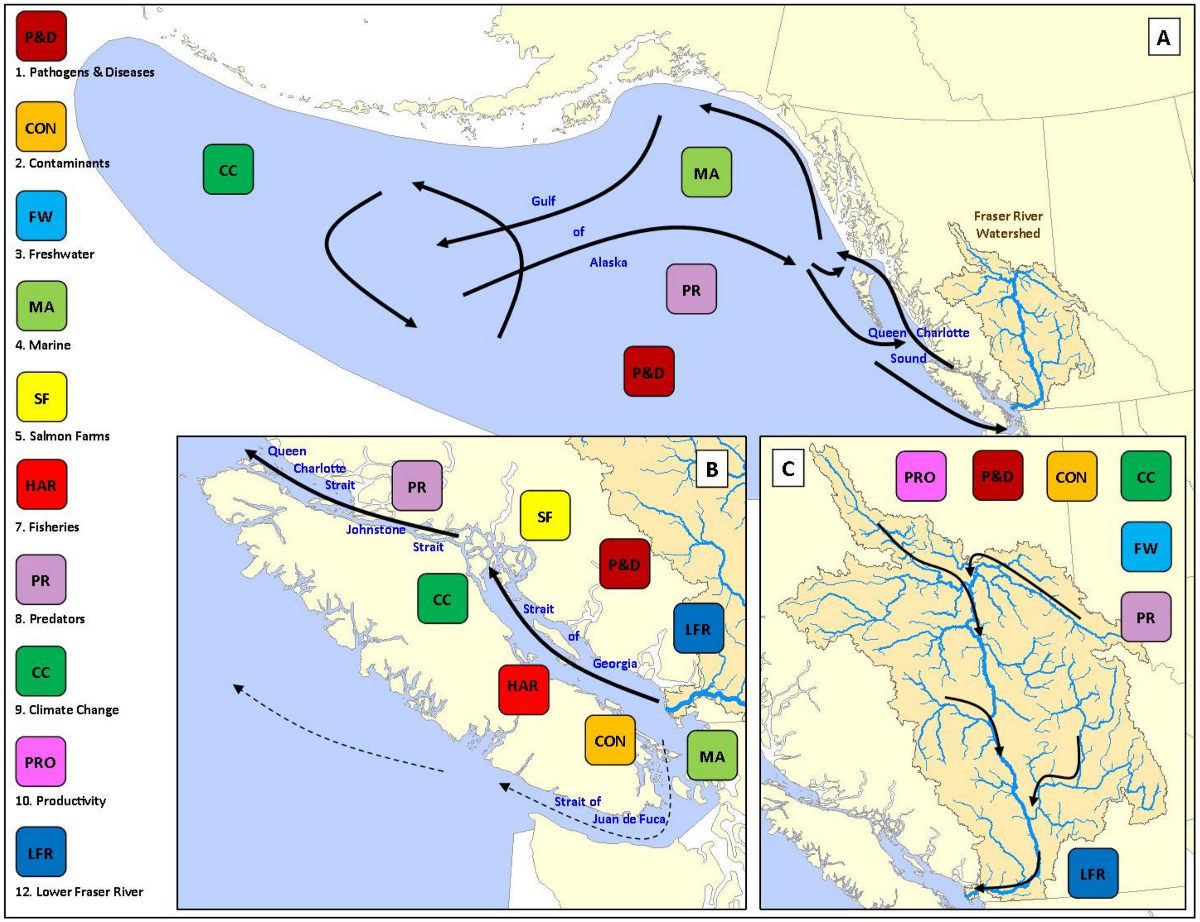

Figure 3.3-2. Life history of Fraser River sockeye salmon illustrating generalized movement patterns among habitats. Arrows represent movements up to the return to the coast but do not show return passage through the Strait of Georgia and upstream migration to spawning grounds. Potential stressors are assigned to general areas/life stages, not specific locations. Box C shows the Fraser River watershed, in which spawning, incubation, emergence, nursery lake rearing, and outmigration occur. Box B shows the Lower Fraser River, Strait of Georgia, Johnstone Strait, and Strait of Juan de Fuca, through which post-smolts pass on during their migration to the Gulf of Alaska, and returning adults pass on their journey back to the Fraser River. The dotted line indicates that there is limited evidence for the use of Juan de Fuca by post-smolts. Box A shows the Northeast Pacific Ocean, where maturing sockeye salmon spend two winters after completing their migration up the coast then return to the Fraser River. The movement patterns within the ocean are highly generalized, but based on McKinnell et al. (2011, Figure 4). Refer to McKinnell et al. (2011) for further details on ocean distribution and patterns.

3.3.3 Life history perspective/approach

The present project takes a life history approach to the compilation, synthesis and evaluation of the evidence contained in other Cohen Commission Technical Reports. Each project focused on particular factors (e.g., contaminants, pathogens, freshwater habitat, predators, ocean conditions). The present project cuts across factors and synthesizes the stressors that sockeye salmon encounter within each life history stage. This perspective more closely resembles the manner in which sockeye salmon actually experience the world they live in; as they progress through their lifetime, they experience the world stage by stage, not factor by factor. Within each life stage or at any point in time, sockeye salmon experience many potential stressors in whatever combination they arrive. This reflects the essence of cumulative effects – that the Valued Ecosystem Component (i.e. sockeye salmon) must endure the aggregate stress of human and natural drivers as a cumulative impact, not as individual impacts.

3.3.4 Types of evidence

To evaluate the relative likelihood of potential factors, we pulled together qualitative and quantitative evidence presented by other contractors, as well as doing our own quantitative analyses in this project. The Cohen Commission Technical Reports include descriptions of key processes and mechanisms, data summaries, reviews of published literature and previous data analyses, new data analyses, and major conclusions, including ways to improve our understanding and fill data gaps. Additional lines of evidence emerged from the Cohen Commission Scientific and Technical Workshop (held Nov. 30 and Dec. 1, 2010), including contractor presentations, expert feedback on the conceptual model, and expert evaluation of the relative likelihood of broad categorical factors. We also examined the Expert Panel Report to the Pacific Salmon Commission (PSC) on the Decline of Fraser Sockeye (Peterman et al., 2010). However, our primary sources of information were the Cohen Commission Technical Reports, and data sets on important potential stressors provided by the authors of these reports. We used these data to perform statistical analyses across all factors. These statistical analyses complement other analyses performed within some of the factor-specific projects and represent another important piece of evidence for the cumulative impacts assessment.

3.3.5 A weight of evidence approach to retrospective ecological risk assessment

We apply a weight of evidence (WOE) approach to synthesize evidence presented across the Cohen Commission Technical Reports and assess the overall likelihood that a particular factor has made a substantial contribution to the decline of Fraser River sockeye salmon. The foundation for this approach is covered in greater detail in Appendix 3.

The two key objectives defining our WOE approach are:

1. Use the full breadth of evidence presented within the Cohen Commission projects.
2. Synthesize and evaluate the evidence within a logical and systematic framework.

Whereas it is not realistic to use every single piece of evidence presented in this body of scientific work, the intent is to incorporate the *breadth* of evidence presented, recognizing that the weight of evidence synthesis cannot possibly capture the *depth* of evidence presented within each project. The framework used to evaluate the evidence is based on publications in the field of Retrospective Ecological Risk Assessment (RERA), specifically Forbes and Callow (2002), and Burkhardt-Holm and Scheurer (2007). Their approach is considered appropriate when four criteria are met, all of which apply in the case of Fraser sockeye:

1. The adverse ecological impact has already occurred.

   Fraser River sockeye salmon productivity <u>has been</u> declining over recent decades and the 2009 returns <u>were</u> exceptionally poor.

2. The evidence for this impairment already exists.

   Data on the abundance Fraser River sockeye salmon recruits and spawners confirms the declines in both returns and productivity.

3. Factors that could potentially be causal agents of this impairment have been identified.

   The Cohen Commission identified a selection of broad factors that could feasibly have contributed to the decline of Fraser River sockeye salmon, and within each of the Cohen Commission Technical Reports a range of specific potential stressors are identified. The Pacific Salmon Commission workshop in June 2010 (Peterman et al.) identified a similar, though not identical, set of factors.

4. The evidence available to evaluate the likelihood of each possible factor is limited.

   The constraints on the quantity and quality of the evidence available with which to evaluate potential contributors to the decline of Fraser River sockeye salmon are representative of many ecological problems: 1) quantitative data are usually short, incomplete, sparse, or simply non-existent; 2) where quantitative data do exist, they are likely to be complex, variable, ambiguous, and/or noisy, making rigorous statistical analysis difficult or impossible; and 3) available evidence is correlative at best, and complicated by the interaction of multiple confounding factors that are uncontrollable, or even unknown.

Forbes and Callow (2002) state that "the primary challenge in retrospective risk assessment is to make best use of the available evidence to develop rational management strategies and/or guide additional analyses to gain further evidence about likely agents as causes of observed harm", which precisely describes the challenge of the present project as well.

The WOE approach to retrospective ecological risk assessment that we have utilized challenges the available evidence for each potential factor with the same sequential set of questions as employed by Burkhardt-Holm and Scheurer (2007) in their evaluation of the decline of brown trout in Swiss rivers, though we have grouped several questions into one step. One of our challenges is that we are applying this approach retrospectively to a series of projects that themselves did not utilize a formal RERA framework. We cannot answer questions that were not asked in the projects themselves. Within each life stage we examine the major potential causative agents identified within the other Cohen Commission Technical Reports. For each factor, we synthesize the evidence by addressing the following questions:

1. Plausible mechanism:
   "Does the proposed causal relationship make sense logically and scientifically?"
2. Exposure:
   "Is there evidence that sockeye populations are, or have been, exposed to the causal factor?
3. Correlation/Consistency:
   "Is there evidence for association between adverse effects in sockeye populations and presence of the causal factor, either in time or space?"
4. Other Evidence:
   Is there further evidence available to support the likelihood of that a factor has made a substantial contribution, such as answers to the questions below?
   - Thresholds: *"Do the measured or predicted exposure levels exceed quality criteria or biologically meaningful thresholds?"*
   - Specificity: *"Is there an effect in the population known to be specifically caused by exposure to the stressor?"*
   - Experiments: *"Have the results from controlled experiments in the field or laboratory led to similar effects?"*
   - Removal: *"Has the removal of the stressor led to an amelioration of the effects in the population?"*

Within each step of this evaluation, we emphasize both what is known and what is not known, and within each life stage we identify the key things that need to be known better. Within Question 3, we synthesize the evidence on any relationship with observed patterns in Fraser

River sockeye salmon but also, where possible, the observed patterns in non-Fraser River sockeye salmon (though this evaluation is limited since the Cohen Commission did not collect stressor data for non-Fraser sockeye stocks). Based on the evidence available, a relative likelihood is assigned to each broad category of stressor (e.g., contaminants, predators, etc.) at each life stage, according to the framework shown in Figure 3.3-3. The conclusions from each life stage apply to the contribution of each broad impact factor to the overall pattern of change observed in Fraser River sockeye stocks. There may be cases in which the relative likelihoods of particular stressors do not all align perfectly with the relative likelihood assigned to the parent stressor category. For example, the evaluation of the overall impact of predators may not match the evaluation of particular predators. There may also be cases in which the results from this evaluation framework might be different for individual stocks. However, the focus of the present project is to evaluate the likelihood that each broad factor has made a significant contribution to the *overall* observed decline in the Fraser River sockeye salmon stock complex.

Because this method is an inherently retrospective form of analysis, the results cannot be used to make future predictions. Both Forbes and Callow (2002) and Burkhardt-Holm and Scheurer (2007) emphasize that it is unrealistic to expect these methods to be definitive in terms of ascribing causation. While such an approach may be able to explain retrospectively which factors most likely contributed to past patterns of change in productivity, the importance of particular factors may be more or less important in the future and will vary within any given year in both magnitude and relative importance. Even if we had complete data on all of the factors potentially affecting sockeye over the entire period of record for the stock productivity data, we would not be able to necessarily predict in advance how these factors will combine in the future to affect productivity. This is particularly true in the era of climate change, where the biophysical structure and functioning of ecosystems may move beyond the range of historical conditions. As mentioned above in section 3.1, environment-recruitment correlations generally do not persist over time (Walters and Collie 1988, Walters 1989, Myers 1998).

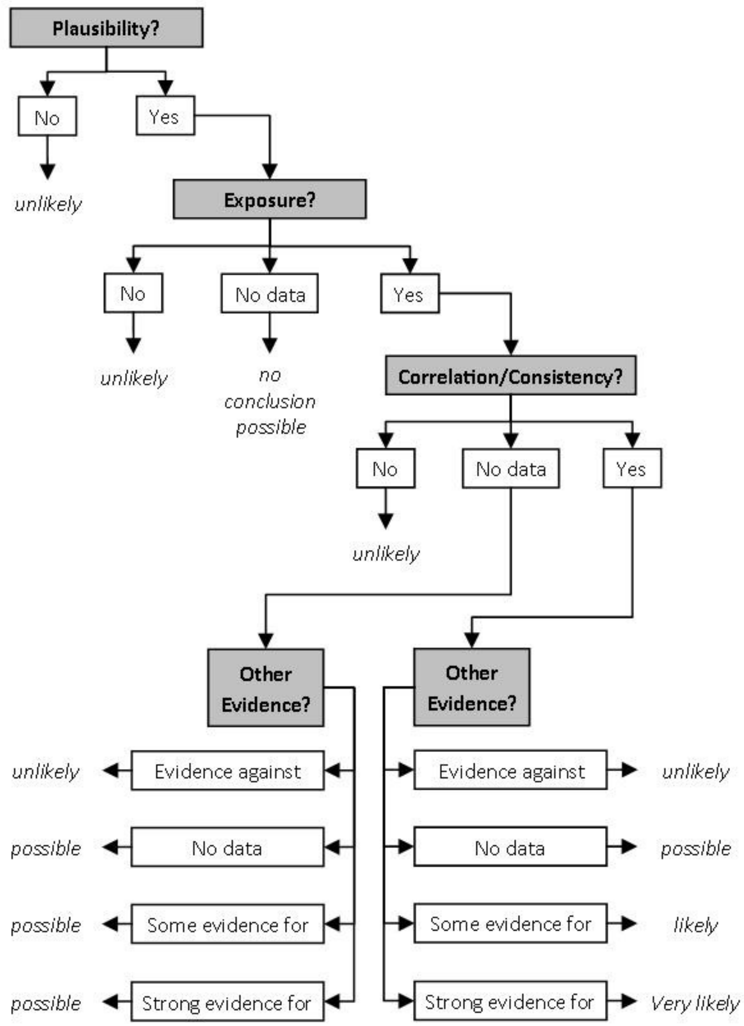

Figure 3.3-3. Flow diagram used to assign the relative likelihood that a particular factor has made a substantial contribution to the decline of Fraser River sockeye salmon, based on the answers to the questions used to challenge the available evidence. This structure is adapted from Burkhardt-Holm and Scheurer (2007, Figure 1).

3.3.6 Quantitative analyses

Regression analysis was the primary method used in our quantitative analyses. This section provides a high level summary of regression intended to inform all readers (regardless of background) about the general approach and the limitations of the analysis. Appendix 3 (Section A3.5.2) provides a technical description of this approach, including details on data reduction, creation of model sets, candidate models, model structure, and model selection. Detailed results of our analyses are presented in Appendix 4, with selected summaries in Sections 4.4 and 4.7.

Multiple regression can be used to determine the relative importance of each covariate for explaining the variability in sockeye productivity. Non-linear relationships between covariates and sockeye productivity can be explored. Covariates that are hypothesized to have an additive cumulative impact on sockeye productivity (i.e., each factor on its own may have an insignificant biological impact but when encountered together the sum of the effects may be biologically important) can be analyzed in groups rather than one at a time. Regression can also be used to test hypothesized interactions between covariates (i.e., multiplicative cumulative impacts). Multiple regression is valuable tool for addressing the primary objective of this analysis (i.e., understanding the cumulative and relative impact of all of the stressors).

Regression analysis is used to understand how different variables relate to one another. Typically there is one response variable (i.e., dependent variable) of interest and one or more predictor variables (i.e., independent variables or covariates). In this case the dependent variable is an annual stock specific index of total productivity (ln (R/S), the natural logarithm of recruits/spawner[6]). The independent variables are all factors identified as likely to be important by each of the other Cohen Commission Technical Reports (e.g., sea surface temperature). Regression analysis entails specifying a mathematical model that describes the functional form of the relationship between the covariates and the response variable and using the observed data to estimate the parameters in the model. The model parameters provide information on the direction and strength of the relationship between the covariates and the response variable.

Many different models are possible. For example, models may include different covariates, linear and non-linear covariates, and/or interactions among different covariates. As long as there are sufficient data, parameters for any model can be estimated, but this does not mean that the model is sensible. Not surprisingly there is a vast amount of literature dedicated to the subject of model selection and comparison. We use the Burnham and Anderson (1998) hypothesis-driven approach to model selection and inference. In hypothesis-driven analyses, the only factors that would be allowed to enter the analyses would be those that are connected to a logical, and in this case, biologically justified hypothesis. This reduces the potential that some variables will emerge as significant simply by chance and not as a result of any underlying mechanism, which is quite likely to happen in a project where there are large numbers of covariates and hence potential models. Standard practice is to select multiple feasible candidate models, fit each model (i.e., estimate the parameters), and then compare the performance of each model. There are many approaches for comparing model performance; we used the small sample size corrected Akaike's information criterion (AIC_c) (Burnham and Anderson, 1998).

[6] Using the natural logarithm of (R/S) transforms the Ricker spawner-recruit model into a linear form which makes it easier to apply regression analysis.

This project is unusual in its scope. While the response variable, ln(R/S), is available for 19 stocks across B.C. and approximately 50 years of data are available for each stock, the number of potential covariates is very large. A total of 126 quantitative and 5 qualitative data sets were provided to us from the other technical reports (Table A3.4-9). We then calculated an additional 32 data sets (i.e., derived variables based on the data provided) that were more appropriate for our analyses.

It is possible for a single data set to be linked to (i.e., hypothesized to impact) multiple life stages of Fraser River sockeye. In addition, there are up to 4 different age types (i.e., 4sub2, 5sub2, 4sub1, and 3sub1). These links result in a total of 1058 possible covariates to include in the analysis. However, not all covariates are available for all years and stocks. Models can only be compared when the models are fit using the same data. The implication of this is that we cannot compare all models of interest on the full data set but instead must identify time periods with complete data for different subsets of the covariates.

For example, there is a small subset of the covariates (e.g., sea surface salinity for the Strait of Georgia) that have data extending back to 1950, but there are other covariates that only have data starting in 1996 (e.g., chlorophyll a). If we wish to compare models with these two covariates (i.e. salinity and chlorophyll), we would have to either reduce the data set to those years with data for both covariates (i.e., limit the model to 1996-present and sacrifice the earlier data for salinity), or exclude covariates with limited years of data (i.e., limit the model to only salinity and ignore chlorophyll a, but extend the analysis back to 1950). Choosing any particular set of covariates forces you to truncate longer time series to the length of the shortest data set. Choosing any particular time period forces you to limit your analyses to those covariates with a period of record that is sufficiently long.

We chose to evaluate different time-periods independently because each time period presents a different trade-off between the length of the data and the number of covariates that can be included. Within each time-period we generated different model sets. A model set represents a set of covariates that have complete data over the chosen time-period. Within each model set, different models (i.e. combinations of variables) can be tested to determine their ability to explain the observed variability in the dependent variable, sockeye productivity in this case. Expressed another way, a 'model set' is simply a suite of candidate models within a given time-period that are organized to address a particular question. For example, one question of interest is whether the set of factors affecting a particular life stage are more important than others.

Key points:

- Models may differ in the number and type of covariates, linear vs. non-linear terms, and the presence of interaction terms.
- Many models are possible, but we should only test models that have biologically justified hypotheses.
- In order to compare the relative performance of different models using Akaike's Information Criterion (AIC_c), models should be fit using the same data.
- Comparison of AIC_c scores does not tell us the *best model possible*, but rather helps us to understand the relative support for the *models we have estimated*.
- You need more data than parameters in order to be able to estimate the parameters.

4.0 Results, Synthesis and Discussion

4.1 The Pattern We Need to Explain

The Cohen Commission is interested in the causes of both longer term declines in Fraser sockeye productivity over the last 2-3 decades, as well as the poor survival of sockeye returning to spawn in 2009 (Figure 4.1-1). Another important part of the overall pattern is the surprisingly large returns of Fraser sockeye in 2010, which were the highest returns over the last six decades. Prior to exploring the relative likelihood of different factors (i.e., *why* the productivity declines occurred), we need to understand *where* and *when* these declines occurred (i.e., which stocks? which years? which life history stages?). Analyzing patterns in both Fraser and non-Fraser stocks is helpful for two reasons. First, including data on sockeye populations outside of the Fraser River helps to determine whether the Fraser's situation is unique, or whether other sockeye populations were suffering the same fate. Second, including more stocks increases the amount of contrast in the exposure to different stressors, which helps in drawing conclusions about the possible causes of observed patterns.

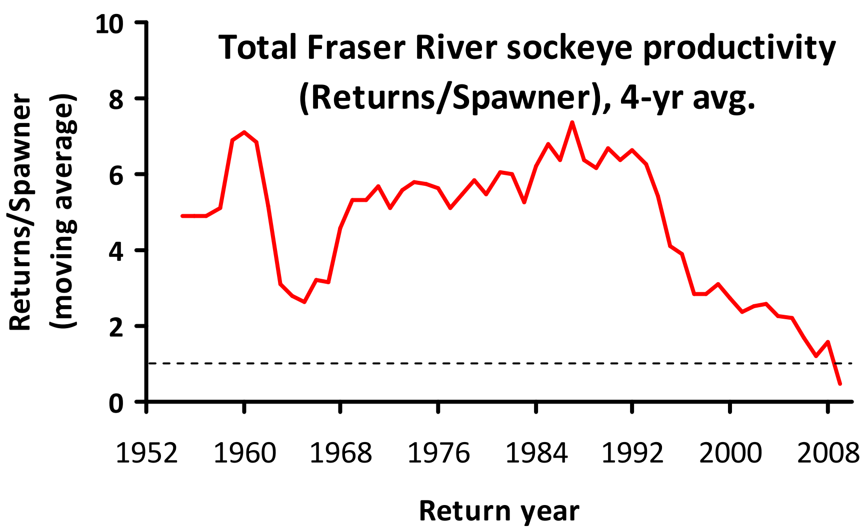

Figure 4.1-1. Returns per spawner for all Fraser sockeye stocks combined. Graph shows the four-year moving average of total adult returns across all Fraser River sockeye stocks (not including the minor jacks component) divided by total spawners 4 years before. The moving average removes much of the year to year variability in productivity created by some large, strongly cyclical stocks. Return year is the last year of the four used to produce the moving average. The horizontal dashed line indicates the productivity at which the population can replace itself, i.e., returns/spawner = 1. The graph mainly reflects time trends of the most abundant stocks, but most Fraser stocks show similar decreasing trends, with the exception of the Harrison and Late Shuswap stocks (see Figure 4.1-2). Source: Peterman et al. (2010). Preliminary data indicate that returns per spawner in 2010 were close to the long term average over the last six decades, and similar to levels observed in the 1980’s (Anon., Fraser Sockeye 2010 Think Tank).

Peterman and Dorner (2011) analyzed data sets on the abundance of spawners and their resulting returns for a total of 64 populations ("stocks") of sockeye salmon, including 19 from the Fraser River, and the rest from other parts of British Columbia, Washington state, and Alaska (Figure 4.1-2). Only 4 of these 64 stocks were substantially affected by other potentially confounding factors (Pitt, Cultus – hatcheries; Great Central Lake and Sproat - lake fertilization) so the overall productivity patterns are representative of natural wild sockeye populations. Peterman and Dorner also obtained data on juvenile abundance in fresh water for 24 of these and other sockeye populations to determine if problems were mainly in fresh water or the ocean. They used three measures of productivity: 1) the number of returning adults (recruits) per spawner[7], which includes the effects of spawner abundance on productivity; 2) annual residuals in productivity, which describes how productivity diverged from what would have been expected each year just based on spawner abundance; and 3) Kalman filter estimates of long term trends in productivity, which extract productivity trends from year-to-year noise.

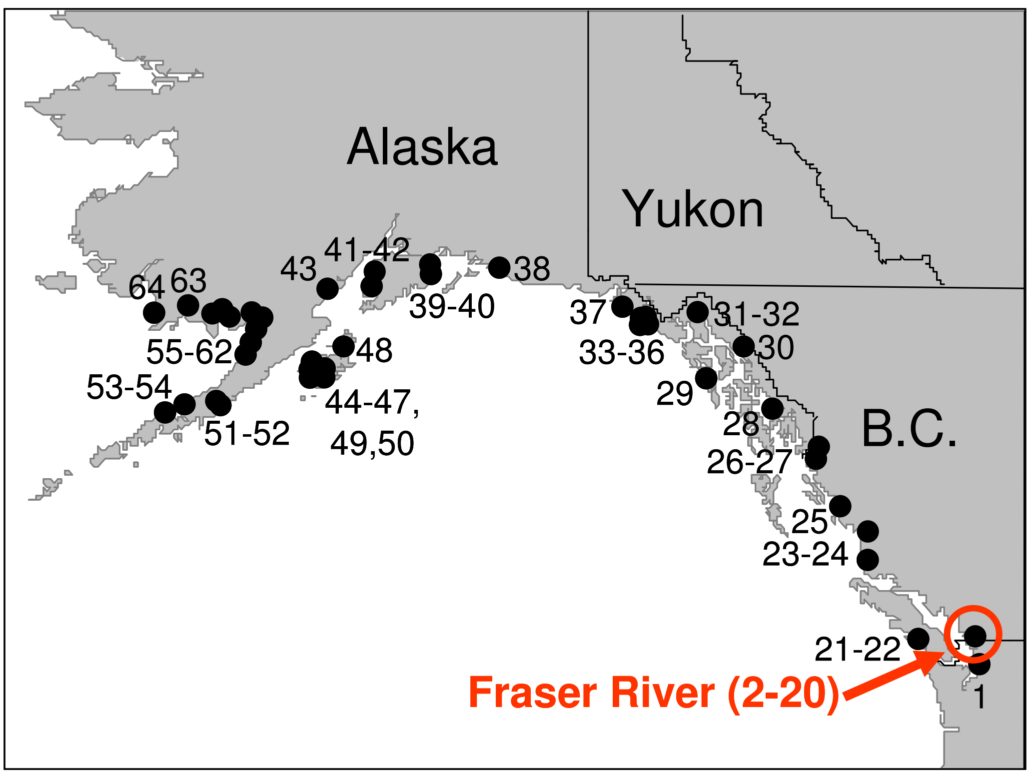

Figure 4.1-2. Locations of ocean entry for seaward-migrating juveniles of the 64 sockeye salmon populations with time series data on annual abundances of spawners and the resulting adult returns or recruits. Source: Peterman and Dorner (2011).

7 Recruits are estimates of the abundance of returning spawners in coastal fishing areas *prior* to harvest and post-Mission en-route mortality, estimated for each stock as: [(estimated adults on the spawning ground) + (estimated marine and freshwater harvest) + (estimated post-Mission en-route mortality)].

Peterman and Dorner (2011) have three key findings regarding the patterns of change in sockeye productivity:

1. **Life history stages of Fraser sockeye showing declining productivity.** Of the nine Fraser sockeye stocks with data on juvenile abundance (Figure 13 in Peterman and Dorner 2011), only Gates sockeye have showed declines in **juvenile productivity** (i.e., from spawners to juveniles) but 7 of the 9 stocks showed consistent reductions in **post-juvenile productivity** (i.e., from juveniles to returning adult recruits). These results indicate that either: 1) the primary mortality agents causing the decline in Fraser River sockeye occurred in the post-juvenile stage (i.e. after fry or smolts were enumerated), or 2) that certain stressors that affected juveniles were non-lethal in fresh water but caused mortality later in the marine sockeye life stage. Note that mortality during over-wintering in nursery lakes (for most stocks), or during pre-smolt and smolt downstream migration would be ascribed to the post-juvenile stage. Unfortunately, juvenile data series for non-Fraser stocks are either very short or not available at all, making it difficult to judge to what degree similarities in juvenile-to-adult survival rates are shared among B.C. stocks outside the Fraser (Appendix P3 in Peterman and Dorner 2011).

2. **Stocks showing declining productivity.** Within the Fraser watershed, 17 of 19 sockeye stocks have shown declines in productivity over the last two decades. Both Fraser and many non-Fraser sockeye stocks, in Canada and the U.S.A., show a similar recent decrease in productivity. Thus, this trend has occurred over a much larger area than just the Fraser River system and is not unique to it. This is a very important new finding. Specifically, based on smoothed estimates of productivity trends via a Kalman filter (the third productivity measure described above), there have been relatively large, rapid, and consistent decreases in sockeye productivity starting in the late 1990s in many areas along the west coast of North America including the following stocks (from south to north): Puget Sound (Lake Washington), Fraser River, Barkley Sound on the West Coast of Vancouver Island (Great Central and Sproat Lakes), Central Coast of B.C. (Long Lake, Owikeno Lake, South Atnarko Lakes), North Coast of B.C. (Nass and Skeena), Southeast Alaska (McDonald, Redoubt, Chilkat), Yakutat (northern part of Southeast Alaska; East Alsek, Klukshu, Italio). These patterns are illustrated in Figures 4.1-3 and 4.1-4.

3. **The timing of productivity declines.** There have been three separate phases of decline in productivity since 1950. The first started in the 1970s, the second in the mid-1980s, and then the most recent one in the late 1990s or early 2000s, with individual stocks showing these trends to various extents. Furthermore, periods of low productivity in southern

sockeye stocks tended to coincide with periods of high productivity in western Alaskan stocks, and vice versa.

The Cohen Commission is interested in factors affecting the Fraser sockeye fishery, not only Fraser sockeye productivity. Over the last two decades there has been an increasing amount of en-route mortality of returning Fraser sockeye spawners (i.e., mortality between the Mission enumeration site and the spawning ground), as illustrated for late run sockeye in Figure 4.1-5. This results in reduced harvest, as fishery managers do their best to ensure enough spawners return to the spawning ground in spite of considerable mortality along the way. Since en-route mortality is already included in estimates of recruits, it does not affect estimates of productivity, but it does affect the fishery.

Other patterns noted by McKinnell et al. (2011) have particular relevance to the low 2009 returns (2007 ocean entry for most sockeye), and provide some interesting contrasts among stocks with different life history patterns and migratory pathways:

- most Fraser River sockeye stocks had very poor returns/spawner in 2009, but;
- Columbia River sockeye had double their average returns in 2009 (recruits/spawner not available),
- hatchery-reared sockeye from Cultus Lake showed typical survival rates through the Strait of Georgia in 2007 (estimated from tracking acoustic tags), and
- there were record high returns of Harrison River sockeye in 2010, from underyearlings that reared in the Strait of Georgia in 2007.

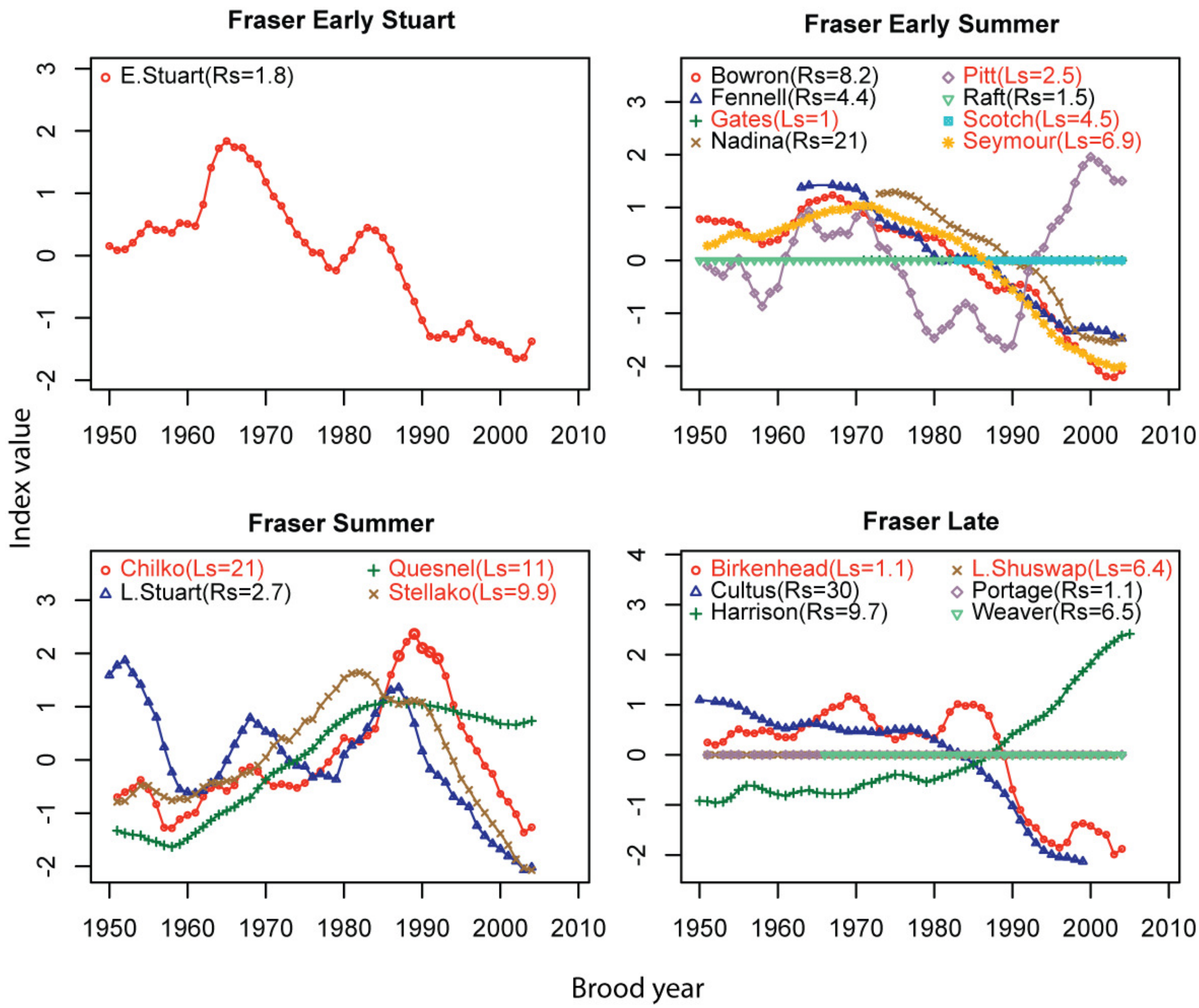

Figure 4.1-3. Estimates of long term trends in total life cycle productivity for the four Fraser sockeye run timing groups, by brood year. The graph is based on productivity estimates for each stock, using a smoothed Kalman filter, using the stock-recruitment model that best fit the data (methods explained in Peterman and Dorner 2011). Brood year is year of spawning. The productivity estimates are in the same units for all stocks, plotted relative to each stock's mean and standard deviation. Four stocks show no trend in this smoothed Kalman filter indicator (i.e., Raft, Scotch, Portage, Weaver). This may be due to the absence of any long term trend, a masking of the underlying trend by high year to year variability, and/or gaps in the time series. Annual residuals in productivity for these four stocks have however been well below their long term means in several brood years since 2000. Source: Peterman and Dorner (2011)

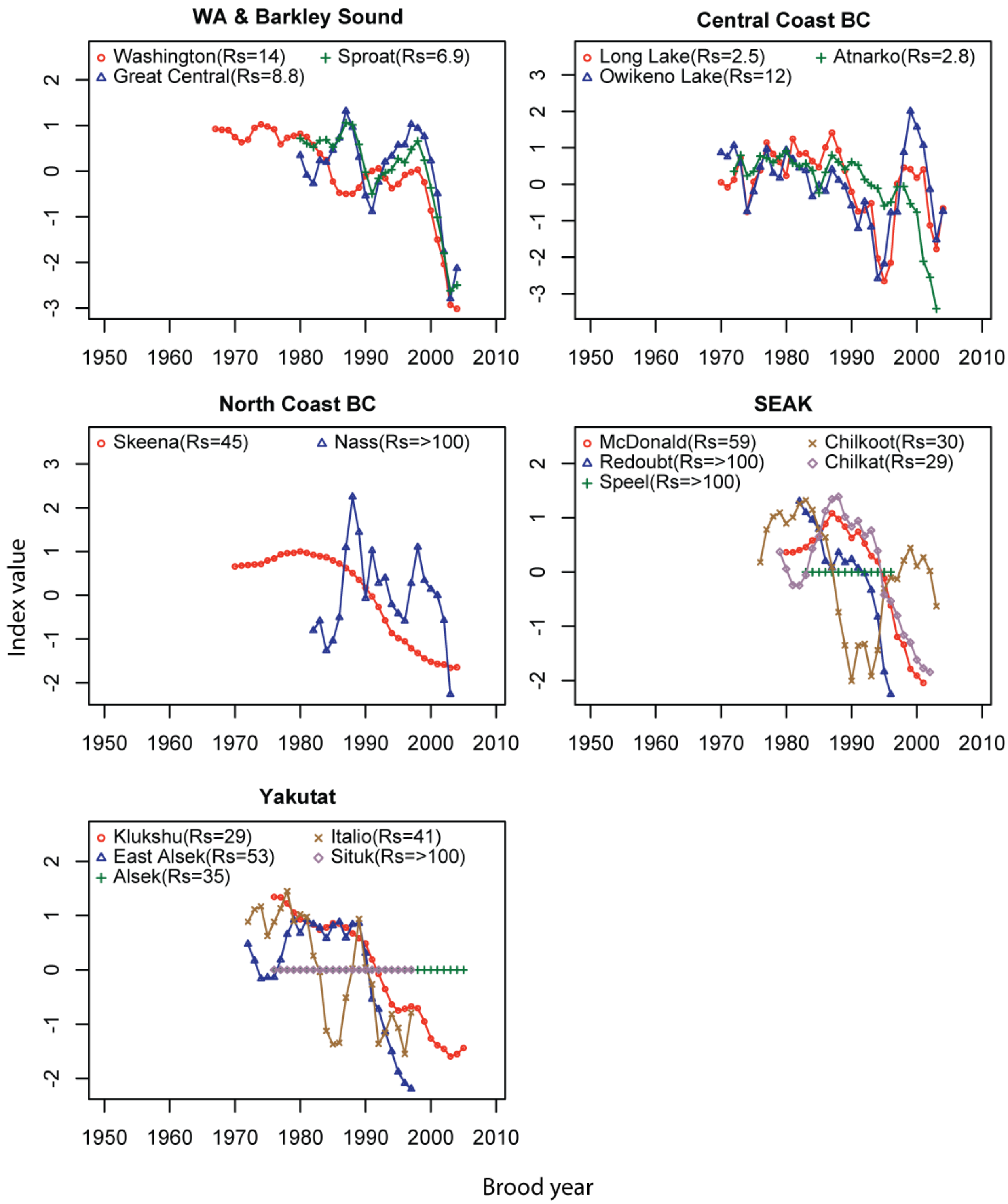

Figure 4.1-4. Estimates of long term trends in total life cycle productivity for non-Fraser sockeye stocks, by brood year. Brood year is year of spawning. The productivity estimates are in the same units for all stocks, plotted relative to each stock's mean and standard deviation. Three stocks show no trend in this smoothed Kalman filter indicator (i.e., Speel, Alsek, Situk). This may be due to the absence of any long term trend, a masking of the underlying trend by high year to year variability, and/or gaps in the time series. Source: Peterman and Dorner (2011)

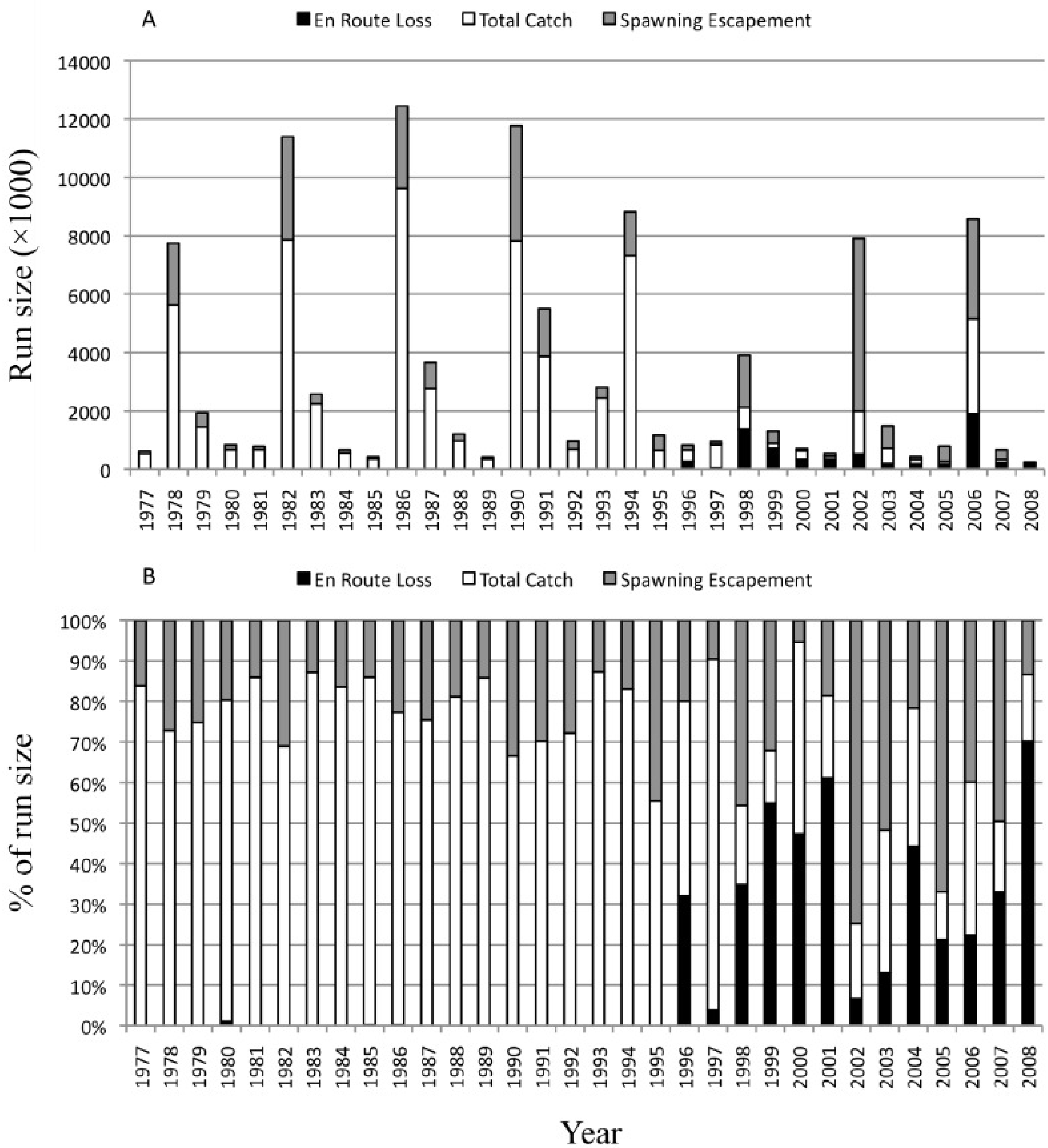

Figure 4.1-5. A) Total run size of adult Late-run sockeye salmon from 1977 to 2008 with fish fate categorized into total catch, *en route* loss and spawning escapement. B) The same data as presented in panel A but with fate categories expressed as percentages of the total run size. Source: Hinch and Martins (2011)

We conducted independent statistical analyses of the timing of changes in recruit per spawner indices (the first productivity measure described above) for each Fraser stock, using a method called change point detection. We found declining productivity (recruits/spawner) for 15 of the 19 Fraser sockeye stocks (all except for Harrison, Late Shuswap, Raft and Weaver). While nine of the 15 stocks with declining productivity showed declining trends throughout the time series, the other six (Early Stuart, Birkenhead, Quesnel, Stellako, Chilko, Pitt) showed a change in the slope of the productivity trend line part of the way through the time series (in 1965, 1983, 1983, 1984, 1988, and 1999, respectively). Similar to Peterman and Dorner (2011), we found declining productivity in most Fraser sockeye stocks, and variability across stocks in when those declines occurred. Details are contained in Appendix 4.

The returns or recruits in any given year (R) are a function of the number of spawners (S) in the brood year (generally four years earlier) and the productivity or number of returns/spawner (R/S). Or, mathematically, $R = S * (R/S)$. Many Fraser sockeye stocks are strongly cyclical, with a substantial variation in the number of spawners (S) over each of the four brood years in a cycle. Strong brood years generally produce strong brood years four years later. Even if productivity (R/S) remained constant, the variation in S would cause substantial year to year changes in both the total returns, and their stock composition. These patterns are strongly apparent in Figure 4.1-6, which shows the number of total sockeye recruits to the Fraser from each brood year, their stock composition, and overall productivity (R/S). Stock composition can vary substantially from year to year (e.g., returns from the 1985, 1989, 1993, 1997 and 2001 brood years were dominated by Quesnel sockeye, whereas returns from the 1986, 1990, 1994, 1998 and 2002 brood years were dominated by Late Shuswap sockeye). The above brood years are the peak years (respectively) for the Quesnel and Late Shuswap stocks, and in general provided stronger aggregate returns to the Fraser than the intervening years.

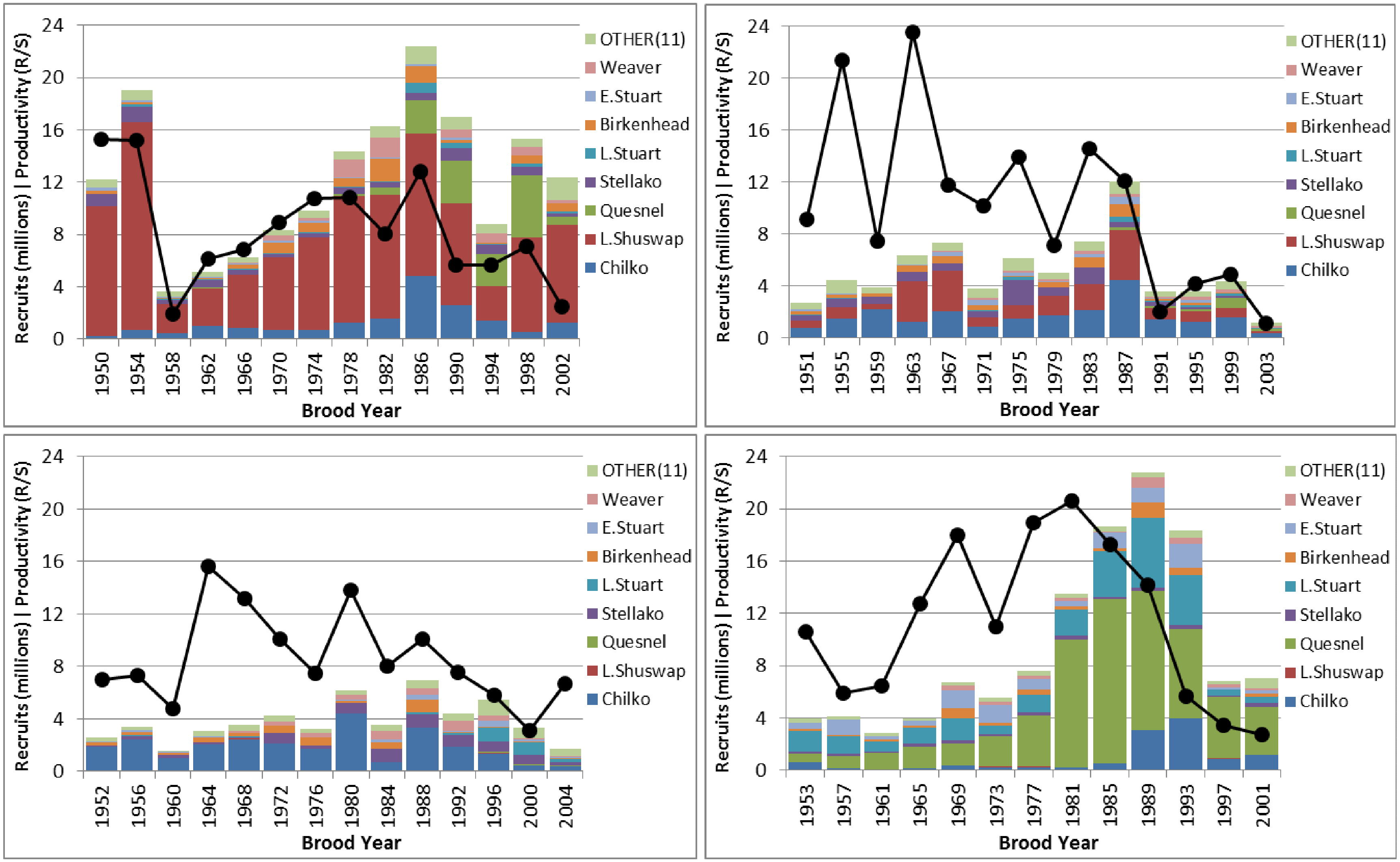

Figure 4.1-6. Aggregate returns to the Fraser Basin (height of bars), recruits/spawner (line) and stock composition (colours within each bar), for each brood year. The data are shown in 4-year intervals, reflecting the 4-year life cycle of sockeye, and illustrating the general consistency in relative abundance and stock composition every 4 years.

Implications of Observed Patterns in Productivity for Analysis of Factors Causing the Decline

If just Fraser sockeye stocks had shown declines in productivity, while non-Fraser stocks were more or less stable, that would point to stressors unique to the Fraser stocks. However, the widespread common patterns of declining productivity suggests that the simplest explanation of the dominant or primary driving forces behind the declines are factors operating on a large scale, affecting both pristine and developed watersheds. While that does not exclude other local factors from contributing to the overall pattern as secondary influences, or the possibility that different factors could cause declines in different stocks, the most parsimonious explanation of the overall pattern would be a large scale stressor, extending from Washington to SE Alaska, over the last two decades. Peterman and Dorner (2011) state:

> The large spatial extent of similarities in productivity patterns that we found across populations suggests that there might be a shared causal mechanism across that large area. Instead, it is also possible that the prevalence of downward trends in productivity across sockeye stocks from Lake Washington, British Columbia, Southeast Alaska, and the Yakutat region of Alaska is entirely or primarily caused by a coincidental combination of processes such as freshwater habitat degradation, contaminants, pathogens, predators, etc., that have each independently affected individual stocks or smaller groups of stocks. However, the fact that declines also occurred outside the Fraser suggests that mechanisms that operate on larger, regional spatial scales, and/or in places where a large number of correlated sockeye stocks overlap, should be seriously examined in other studies, such as the ones being done by the other contractors to the Cohen Commission. Examples of such large-scale phenomena affecting freshwater and/or marine survival of sockeye salmon might include (but are not limited to) increases in predation due to various causes, climate-driven increases in pathogen-induced mortality, or reduced food availability due to oceanographic changes. Further research is required to draw definitive conclusions about the relative influence of such large-scale versus more local processes.

The above observations, plus other productivity trends included in Peterman and Dorner (2010), suggest that the combination of factors that were *primarily* responsible for declines in Fraser River sockeye productivity over the last 2-3 decades should have the following attributes:

- were generally worse during the last 2-3 decades (as compared to prior decades) for 11 of the 19 Fraser stocks: Early Stuart, Bowron, Fennell, Gates, Nadina, Seymour, Chilko, Late Stuart, Stellako, Cultus, Birkenhead;
- were generally worse, though highly variable, during the last two decades (as compared to prior decades) for 5 Fraser stocks: Quesnel, Weaver, Portage, Raft, and Scotch;
- improved or did not change during the last two decades for two Late Run sockeye stocks (the Harrison, Shuswap)[8];

[8] The Pitt River stock is excluded from the list of non-declining stocks due to possible hatchery influence.

- were generally worse during the last 2-3 decades (as compared to prior decades) for most of the non-Fraser stocks;
- showed a major improvement for some Fraser stocks (particularly Harrison, Chilko, Adams) that led to large returns in 2010.

4.2 Stage 1: Incubation, Emergence and Freshwater Rearing

The stage covers sockeye salmon from egg to the beginning of their outmigration to the ocean.

4.2.1 Plausible mechanisms

As shown in the conceptual model (Figure 3.3.-1) plausible mechanisms affecting Stage 1 include: 1) Fraser watershed habitat conditions (particularly the effects of forestry, mining, hydroelectricity, urbanization, agriculture, and water use); 2) delayed density dependent mortality; 3) predation, 4) disease and 5) climate change. There are cause-effect mechanisms by which each of these factors could at least *potentially* affect sockeye egg-to-fry, or egg-to-smolt survival rates, as described below.

The potential effects of **Fraser watershed habitat conditions** on Stage 1 are discussed in Nelitz et al. (2011; section 3.0), and are summarized below:

- The activities associated with **forestry** (particularly road construction, stream crossings, and upslope harvesting) can alter the amount and timing of delivery of water and sediment to streams, potentially affecting spawners, eggs and juveniles. The **mountain pine beetle** outbreak in BC's Interior (due in part to warmer winters caused by **climate change**) has led to extensive salvage logging, expanding the area potentially affected by forestry. Unlogged watersheds with mountain pine beetle have hydrological patterns intermediate between a mature forest and a clearcut.
- **Mining** can potentially affect sockeye spawning through permanent loss of habitat, disruption of the stream bed, sedimentation on incubating eggs, or contamination by acid drainage, heavy metals and other toxic substances.
- **Large scale hydroelectric facilities** (in particular the Bridge/Seton River power project and Alcan's Kemano project on the Nechako) can potentially affect Fraser sockeye through physical barriers to migration, increased stress/disease, greater vulnerability to predators and direct turbine/spillway mortality.
- **Smaller scale hydro facilities**, including Independent Power Projects or IPPs generally divert water from fishless stream channels, but can potentially affect downstream spawning areas and migration corridors through changes to total gas pressure, gravel

supply or water temperature. Unless interbasin transfers of water occur, effects on sockeye nursery lakes are unlikely.

- **Urbanization** creates impervious surfaces that perturb natural streamflow patterns, altering the quantity, quality and accessibility of riparian habitats, and impairing water quality; all of these effects can potentially affect sockeye egg-to-fry/smolt survival.
- **Agriculture** can affect spawning and rearing habitats by physically altering stream channels, riparian zones and floodplains; direct removal of surface and ground water, and degradation of water quality.
- **Water withdrawals** for industrial, commercial, domestic and agricultural uses can reduce access to sockeye spawning, rearing and migratory habitats, and also affect their quality.

MacDonald et al. (2011) conducted a comprehensive inventory of **contaminants**, or **chemicals of potential concern (COPCs)**, within the Fraser Basin. Their inventory includes contaminants originating from point sources (e.g., pulp and paper mills, sawmills, wood preservation facilities, cement and concrete plants, seafood processing facilities, mines, oil and gas developments, storage and shipping facilities, contaminated sites and spills, municipal wastewater facilities, landfills, salmonid enhancement facilities), non-point sources (e.g., runoff from forest management areas, agriculture operations, municipal stormwater and linear developments) and atmospheric sources (e.g., forest fires; volcanoes; emissions into the air from vehicles, industries, and agriculture; long range transport of atmospheric pollutants). Some of these sources of COPCs could potentially affect spawning and rearing habitats, while others are restricted to migratory corridors. MacDonald et al. (2011) systematically whittled down their long list of COPCs through analyses of contaminant pathways and exposures relative to thresholds affecting sockeye, as described in the Executive Summary of their report.

The spawners in one brood year can potentially affect the total life cycle productivity (adult recruits per spawner) of the next three brood years. If these effects are negative, then this is called **delayed density dependent mortality**. As described in Peterman et al. (2010; section 4.7), the proposed mechanisms are that a large number of spawners in one year will produce a large number of fry the subsequent spring, which increases competition among juvenile salmon for limited food resources in the rearing lake, increases incidence of disease in salmon, and/or leads to increased predation on juvenile salmon in the rearing lake or elsewhere in the life cycle. Conversely, declining abundances of sockeye result in less nutrients being transferred from marine to freshwater ecosystems, with potential negative effects on both subsequent generations of sockeye and other ecosystem components (reviewed by Nelitz et al. 2006).

Freshwater predators on juvenile sockeye could potentially increase in response to large fry production (discussed above), or could increase in response to other natural or anthropogenic factors that shift the species composition of fish or wildlife communities. Christensen and Trites (2011) cite studies from along the Pacific Coast indicating that various predators can potentially consume significant numbers of sockeye in freshwater, including coho, chinook, cutthroat trout, rainbow trout, steelhead, Northern pikeminnow, Yellow perch, common mergansers, Caspian terns, and double-crested cormorants. They later shrink this list of suspects based on trends in the abundance of these predators.

Disease is another potential form of delayed density dependent mortality (discussed above), or could increase for other reasons. In his review of potential candidate diseases, Kent (2011, Executive Summary) noted that the IHN virus is well recognized as a lethal pathogen to fry, and rated IHN as "High Risk". He also summarized studies indicating that warming temperatures, pollution and habitat alteration can potentially increase both the susceptibility of salmon to disease, as well as the abundance of certain pathogens (Kent 2011; pgs. 21-22).

As discussed in Hinch and Martins (2011, Section 1.4) **climate change** can potentially affect the survival of eggs, alevins and fry by: shifting temperatures above the thermal optimum to which each stock has adapted (sockeye populations in the interior of B.C. prefer cooler water than coastal stocks); increasing late fall stream flows and expanding the wetted area available for spawning (a positive effect); increasing winter stream flows and scouring more eggs from the gravel (a negative effect); and increasing rates of predation on sockeye fry rearing in lakes. In addition to these direct impacts on sockeye spawning and rearing, climate change can potentially exacerbate the impacts from other stressors (e.g., disease (discussed above); more extreme storm events increasing forestry impacts on water and sediment delivery; climate-induced changes to seasonal patterns in stream flow combining with water withdrawals to worsen conditions for eggs, fry and smolts).

The above stressors all have plausible mechanisms for potential impacts on Stage 1 of the sockeye life cycle. However, for the above factors to jointly affect egg-to-fry/smolt survival, these early life history stages must be exposed to some combination of these stressors in actual spawning and rearing locations within the Fraser Basin, and at levels that cumulatively combine to affect survival. This is much more difficult to determine, as discussed below. Levels of exposure and survival must be inferred indirectly from incomplete information.

4.2.2 Exposure of Fraser River sockeye to stressors

The intrinsic characteristics and form of a watershed, as well as the location and intensity of stressors (i.e., forestry, mining, agriculture, hydropower facilities, water withdrawals, urbanization) affect the level of exposure of sockeye **spawning and rearing habitats** to these stressors. Nelitz et al. (2011) estimated the intrinsic habitat vulnerability of the spawning and rearing habitats in each of the 36 Conservation Units within the Fraser Basin, using three indicators: (1) migration distance; (2) total area of nursery lakes; and (3) ratio of lake influence to total spawning extent. The CUs with the greatest relative habitat vulnerability (i.e., have long migration distances, a low ratio of lake influence to total spawning extent, and a small to moderate nursery lake area) include Early Stuart – Stuart, Takla/Trembleur; Early Summer – Bowron, Fraser; and Summer – Mckinley. Nelitz et al. (2011) also developed indices of the disturbances within each Conservation Unit, including spatial analyses that estimated the percent of disturbed area within each sockeye watershed and along migration corridors, and the cumulative level of stress on different habitat types. Most indices of exposure to potential habitat stress represent current conditions; there are few data sets with trends through time. The highest levels of stress exposure are generated by forest harvesting, roads, water use and large scale hydro facilities.

MacDonald et al. (2011; Chapter 4) used a very thorough, conservative (risk averse) procedure for assessing **contaminant exposures and hazards** to sockeye. They estimated the maximum observed concentration of each contaminant as the exposure point concentration (or EPC) in each area of interest from existing data. From the literature they determined a 'no effect' level of each contaminant, called the toxicity screening value (or TSV), which in some cases was the lowest observed background level. They then calculated a hazard quotient (HQ) equal to the ratio of EPC/TSV. Any contaminant with an HQ value greater than 1 was flagged as having a potential risk, and more closely examined to determine if these potential risks were likely to truly affect sockeye. To match exposures to life history stages, they sorted water chemistry data by types of habitats and periods of exposure for four life history stages based on the timing of sockeye life history stages. For example, contaminant exposure of eggs and alevins for the 1991 brood year used contaminant data from August 1991 to May 1992 for the appropriate sites for each stock. Exposure of fry from the 1991 brood year used contaminant data for nursery lakes from April 1992 to March 1993. Sediment chemistry is not sampled as often, and therefore were sorted into pre and post-1990 periods to test whether they correlated with a change from generally healthy to generally poor sockeye productivity.

In freshwater spawning and rearing habitats, the **contaminants** posing the highest risk to salmon included total suspended solids, turbidity, phosphorus and seven metals (aluminum, chromium, copper, iron, mercury and silver). However, these risks may be overestimated due to underestimating the background conditions for total suspended solids and turbidity (which would lead to an overestimate of the hazard), uncertainties on the actual effects of phosphorus, likely contamination of many samples analyzed for metals, and inadequate information on the form of contaminants (e.g., dissolved forms are more toxic than when they are attached to sediment particles). Notwithstanding these caveats, MacDonald et al. (2011) stress that total suspended sediment could potentially affect egg-to-fry survival rates, particularly in areas with increasing rates of logging during the last 20 years (e.g., Bowron, Chilko, Nechako, North Thompson, Quesnel).

The potential exposure of sockeye stocks to **delayed density dependent mortality** is considered by determining if the abundance of spawners in each of the previous three years negatively affects the overall productivity of the subsequent brood year, and in particular whether such negative effects are associated with large spawning abundances (Peterman and Dorner 2011).

Christensen and Trites (2011) found that there were data on the relative abundance of only 4 of 14 candidate **freshwater fish predators**, and trend data for only one fish species. Data on candidate bird predators are a bit better due to Christmas Bird Counts. There are virtually no data to estimate the relative exposure of eggs, alevins, fry or smolts to **disease** across different Fraser stocks and time periods. Hinch and Martins show that temperature and flow data within the Fraser Basin and nearby regions show evidence of increasing exposure of these life history stages to the effects of **climate change**, including the following patterns:

- summer water temperatures in the Fraser River are 2.0°C warmer compared to 60 years ago, with roughly a 0.7°C average increase during the last two decades (Figure 4.6-1);
- temperatures in the Adams River during the time of spawning increased by 1.5°C from 1950 to 1989; and
- over the Pacific Northwest Region as a whole, snowmelt and the spring freshet are now occurring 1-4 weeks earlier than in the 1950s.

4.2.3 Correlation/consistency with patterns in Fraser River sockeye productivity

Freshwater Habitat Factors. Nelitz et al. (2011) searched for correlations across both space (contrasts among different stocks) and time (contrasts over different stocks and years), though many indicators of habitat stressors are not available over time. Looking across space, Nelitz et al. (2011) developed a cumulative index of the relative intensity of habitat stressors (i.e., forest harvesting, mountain pine beetle, road density, urban area, agricultural area, water allocation, small-scale hydro, place mines; see Tables 11-14 in Nelitz et al. 2011). This cumulative index did not correlate well with differences in productivity among different Fraser Basin stocks. For example, the two Fraser sockeye stocks that have done well over the last two decades (Harrison and Late Shuswap) have shown, respectively, moderate and high relative indices of cumulative habitat stress on spawning and rearing habitats (Table 18 in Nelitz et al. 2011). Furthermore, Nelitz et al. (unpub. analyses) found that indices of the intensity of habitat stressors and habitat vulnerability were not consistent with estimates of the current status of conservation units based on Pestel and Cass (2009), that is, stock status did not decline with increasing indices of habitat stress and vulnerability.

Looking across time, Neltiz et al. found that trends in overall sockeye productivity[9] across 17 sockeye stocks were **not correlated** with either the intensity of habitat stressors on nursery lakes or their core measures of habitat vulnerability.[10] The only variable correlated with trends in sockeye productivity was migration distance (i.e., stocks with longer migration distances showed greater rates of decline), which may reflect other correlated factors (e.g., watershed position, nursery lake elevation) rather than being a direct causative factor. Juvenile productivity (i.e., juveniles/spawner) was unrelated to indices of forest harvesting and mountain pine beetle disturbance, but showed some indications of negative associations with spring air temperatures at nursery lakes (i.e. juvenile productivity decreases as spring temperatures increase). Finally, the stability over time in juvenile productivity despite declines in overall life cycle productivity suggests that freshwater habitat factors are not a primary driving factor in the observed productivity declines, though it is possible that some non-lethal effects during spawning and rearing affect later life history stages. These results are similar to those found in the PSC report (Peterman et al. 2010; Section 4.6).

Johannes et al. (2011; Table 2) found that there was either no risk or low risk of impacts to spawning and rearing habitats in the **Lower Fraser** from population growth, industrial and infrastructure projects, liquid and solid wastes, ships and vessels, dredging and diking, contaminated materials and exotic species. They assigned a moderate risk level to agriculture and forestry activities in Lower Fraser watersheds where there is a longer duration and greater magnitude of potential interactions.

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[9] trends in annual residuals in returns/spawner, relative to the expected life cycle productivity based on the numbers of spawners in the brood year, indicator #2 in section 4.1; data from Peterman et al. (2010)

[10] Predictor variables included those relating to habitat vulnerability (migration distance, ratio of lake influenced:total spawning extent, area of all nursery lakes) and habitat stress (total water license allocations, municipal area, forest harvested area within the last 15 years, road density, water licence restrictions, agricultural area, and area disturbed by Mountain Pine Beetle). Source: Table 16 in Nelitz et al. (2011).

Several analyses by MacDonald et al. suggest that **contaminants** are not a primary factor in the declining productivity of Fraser sockeye stocks (MacDonald et al. 2001; Executive Summary, Section 5.4). First, over the last 20 years, there is either no trend in the frequency of contaminants exceeding toxicity screening values, or a decreasing trend. If contaminants were an important cause of declining sockeye productivity, contaminant concentrations should have been increasing over time. Second, various measures of sockeye productivity (freshwater, post-juvenile, overall life cycle) were not significantly correlated with a water quality index (incorporating conventional variables, major ions, nutrients, metals and phenols). Third, while the results of a sediment risk assessment showed that the concentrations of iron and nickel were elevated at various locations within the basin, exposure to these contaminants of concern in sediment is unlikely to be sufficient to adversely affect the survival, growth or reproduction of sockeye salmon. However, the concentrations of selenium and dioxins occurred in salmon eggs at concentrations sufficient to adversely affect sockeye salmon reproduction, though the magnitude and extent of such effects could not be determined with existing data.

Delayed Density Dependence. With the exception of the Quesnel sockeye stock, Peterman and Dorner (2011; pg. 33-45) found little evidence in the Fraser system for increased spawner abundance (and delayed density dependence) being the primary cause of declining productivity. They found little support for the idea that extremely large spawner abundances of sockeye (i.e., "over escapement") reduced subsequent sockeye stock productivity. These analyses were based on various analyses of indices of total productivity over the whole life cycle (i.e., recruits/spawner), and therefore reflect the net effects across all life history stages.

Christensen and Trites (2011) found that most of the candidate **freshwater predators** described in section 4.2.1 are unlikely to have increased substantially during the period of declines in sockeye productivity; the only possible remaining suspects are Caspian terns and double-crested cormorants, as they do feed on sockeye smolts in freshwater and may be increasing in abundance. Data on freshwater predators are however very limited.

Hinch and Martins (2011) did not conduct any statistical analyses relating **temperature conditions** to indices of sockeye juvenile or life cycle productivity. Based on temperature conditions and trends, as well as thermal optima for different sockeye life history stages, Hinch and Martins (2011) concluded that survival of eggs has *possibly* increased as a result of **climate change** (but not in all stocks); survival of alevins is *unlikely* to have been affected; and survival of fry in lakes has *possibly* decreased.

While temperature changes or other factors may have resulted in changes in the abundance of **pathogens** in spawning and rearing habitats, or sockeye susceptibility to such pathogens, the data are insufficient to perform any systematic assessment of these hypotheses. Miller et al. (2010, presentation at June 2010 PSC Workshop) found that sockeye smolts contained a genomic signal indicative of physiological stress *prior* to entering the ocean, which she attributed to stress in freshwater. However, the genomic signal detected by Miller et al. was present in smolts during both 2007 and 2008 (Miller, handout provided to June 2010 PSC Workshop), yet those years of entry apparently had very different marine survival rates (based on the very large difference in observed vs expected adult returns in 2009 vs. 2010).

4.2.4 Correlation/consistency with patterns in non-Fraser River sockeye productivity

The Cohen Commission studies did not include assembly of data on potential stressors for sockeye stocks outside of the Fraser Basin. Therefore we cannot quantitatively analyze the level of correlation of stressors with productivity trends in non-Fraser stocks. However, we can make some qualitative arguments, admittedly speculative regarding the consistency of hypothesized stressors with observed productivity declines. First, it is very likely that **freshwater habitat** conditions (including **contaminants**) vary greatly across the 64 stocks analyzed by Peterman and Dorner (2011), yet most of these stocks show broadly similar patterns of decline. Second, it is very likely that most non-Fraser stocks on the central and north coast of B.C, and in SE Alaska have equal or better habitat conditions than most watersheds in the Fraser Basin, simply based on population density. Third, with increasing efforts at regulation of land use activities and habitat restoration over the last two decades, salmon habitats in most non-Fraser watersheds are likely to have shown less degradation than in prior decades with less regulation. Therefore, our expectation is that it is unlikely that habitat conditions would be correlated with declining productivity in most of the non-Fraser stocks. However, given the absence of any exposure data and correlation analyses for these stocks, no rigorous conclusion is possible.

Peterman et al. (2010; Section 4.7) noted that stocks outside of the Fraser Basin usually do not have such strong and regular fluctuations in abundance; they therefore concluded that delayed density dependence was not a likely mechanism for observed declines in non-Fraser sockeye stocks. Peterman and Dorner (2011; Tables 2 and 3, Appendix P2) looked at 46 non-Fraser sockeye stocks. They examined the level of support in the data for two spawner-recruit models: the Ricker model (without delayed density dependence), and the Larkin model (with delayed density dependence). While the Larkin model had more support than the Ricker model in 10 out of 46 non-Fraser stocks, the results indicate that the declines in these non-Fraser stocks were not caused by over-escapement, for two reasons (B. Dorner, pers. comm.). First, there are not that many cases where spawner abundance was unusually high over the period of declining productivity. Second, in the cases where there were years with unusually high spawner abundances (Sproat, Klukshu, Chilkat, Alsek) there was either no support for delayed density dependence or no substantial difference between the productivity trends inferred by the Ricker and Larkin models.

Disease, predators and climate change were not quantitatively evaluated for non-Fraser stocks for Stage 1 of the sockeye life history.

4.2.5 Other evidence

Other evidence includes literature demonstrating thresholds, an understanding of the specific form of response of sockeye to certain stressors (i.e., helping to accept or reject different suspected causes), experiments demonstrating cause-effect linkages, or positive sockeye responses following the removal of a stressor. For the factors discussed above, such evidence is strongest for the effects of elevated **temperatures** and some **contaminants**, which have been well studied in laboratory and field experiments (see Hinch and Martins 2011, MacDonald et al. 2011). The physiology of **diseases** has been well studied in various experiments, more with hatchery fish than wild fish, but the thresholds causing mortality are less well understood (Kent 2011). It is much more difficult to define thresholds for **habitat** conditions (e.g., the proportion of clear-cut watershed area that triggers negative impacts on sockeye spawning and rearing), as these thresholds are very dependent on each watershed's attributes, which determine the vulnerability of the spawning and rearing habitats therein (Nelitz et al. 2011; section 2.2.4). Evidence for **density dependence** is largely based on indirect insights from spawner and recruit data, as there are very few sites with continued monitoring of the various ecosystem components that might transmit such effects (i.e., predators, disease, food supply), and their relative responses to years with high spawner abundance.

4.2.6 Conclusions

Table 4.2-1 follows the logic of the flow chart in Figure 3.3-1, showing our conclusions regarding the effects of each stressor on life history stage 1 (including eggs, alevins, fry, and parr). Our conclusions relate to the **overall trends** in sockeye productivity over the last two decades.

Table 4.2-1. Evaluation of the relative likelihood that potential stressors encountered by Fraser River sockeye salmon during life history stage 1 (including eggs, alevins, fry, and parr), have contributed to overall declines in productivity in recent decades. Some factors may have had effects on some stocks in some years (e.g., density dependence affecting Quesnel sockeye), but are unlikely to have been responsible for the overall pattern across all Fraser sockeye stocks. See section 4.7 for further discussions of correlations.

Factor	Mechanism	Exposure	Correlation/Consistency	Other Evidence	Likelihood
Forestry[b]	Yes	Yes	No	No[a]	Unlikely
Mining	Yes	Low	Not done	No[a]	Unlikely
Large hydro	Yes	Yes	No	Against	Unlikely
Small hydro	Yes	Low	No	No[a]	Unlikely
Urbanization above Hope	Yes	Yes	No	No[a]	Unlikely
Agriculture[b]	Yes	Yes	No	No[a]	Unlikely
Water Use	Yes	Yes	No	Yes	Unlikely
Contaminants	Yes	Yes	No	Yes	Unlikely
Density Dependent Mortality	Yes	Some stocks	No	No	Unlikely
Pathogens	Yes	Few data	Not done	Yes	No conclusion possible
Predators	Yes	Few data	No	No	Unlikely
L. Fraser land uses	Yes	Yes for ag/for; No for others	No	No	Unlikely
Climate Change	Yes	Yes	Weak evidence	Mixed evidence	Possible

[a] It is difficult to establish hazard thresholds for the proportion of watershed area above which there are negative impacts on sockeye spawning and rearing. Such thresholds are better defined for contaminants and water use.
[b] Agriculture and forestry rows include evidence from both Technical Reports 3 (Nelitz et al. 2011) and 12 (Johannes et al. 2011). Forestry includes logging, Mountain Pine Beetle and log storage.

With the exception of climate change, which we consider to be a *possible* factor, and pathogens (for which no conclusion is possible due to data gaps), it is *unlikely* that the above factors (i.e. forestry, mining, large and small hydro, urbanization, agriculture, water use, contaminants, density dependent mortality, predators, and Lower Fraser land use), taken cumulatively, were the *primary* drivers behind long term declines in sockeye productivity across the Fraser Basin. We feel reasonably confident in this conclusion because juvenile productivity (which integrates all stressors in this life history stages) has not declined over time in the eight of the nine Fraser sockeye stocks where it has been measured. We would be even more confident if more stocks had smolt enumeration rather than fry estimates (only Chilko and Cultus stocks have smolt estimates). Though not primary drivers of the Fraser sockeye situation, each of these factors may still have had some effects on some Fraser stocks in some years (the data are insufficient to reject that possibility). We suspect, based on qualitative arguments alone, that habitat and contaminant influences on Life Stage 1 were also not the *primary* drivers responsible for productivity declines occurring to most non-Fraser stocks assessed by Peterman and Dorner (2011). However, given the absence of any exposure data and correlation analyses for non-Fraser stocks, it is not possible to make conclusions on the relative likelihoods of factors causing declining productivities in non-Fraser stocks.

None of the factors considered in this section is likely to have been much worse in 2005 and 2006 for Fraser sockeye stocks, sufficient to have significantly decreased egg-to-smolt survival in the salmon that returned in 2009. Similarly, none of these factors is likely to have been much better in 2006 and 2007, sufficient to have substantially improved egg-to-smolt survival in the salmon that returned in 2010.

4.2.7 Key things we need to know better

The various scientists working on projects for the Cohen Commission completed their analyses to the greatest degree possible given the limitations of data and time. The above conclusions, while reliable given the diverse lines of evidence, are nevertheless constrained by serious data gaps. For the spawning and rearing phase of sockeye life history, some of the critical needs for better data and understanding include:

1. increased numbers of stocks with quantitative assessments of **smolt outputs and condition** (currently only available for Chilko and Cultus lakes), to distinguish survival rates in pre and post-juvenile life stages and evaluate the likelihood of alternative hypotheses, and <u>for these same stocks</u>;
2. better estimates of both **watershed and in-lake conditions over time** (including the cumulative effects of multiple stressors) using consistent methods, for a cross-section of stocks with varying conditions (e.g., migration distance, levels and types of watershed disturbance), to better understand current status, causative mechanisms and risk thresholds;
3. better understanding of the status of **smaller conservation units**, consistent with implementation of the Wild Salmon Policy; and

4. better **integration of existing and future data sets** affecting freshwater spawning and rearing habitats (a more general need, discussed in section 9.2)

4.3 Stage 2: Smolt Outmigration

This stage covers sockeye from the time they leave their nursery lake (as fry, pre-smolts or smolts) to the time they reach the mouth of the Fraser River.

4.3.1 Plausible mechanisms

Most of the plausible mechanisms discussed for stage 1 (egg-to-smolt stage) also apply to stage 2, since migrated smolts can be exposed to degraded habitats, contaminants, pathogens, elevated temperatures and the effects of delayed density dependence. Nelitz et al. (2011) point out that sockeye salmon smolts are cued to migrate towards the ocean in response to changing environmental conditions, which includes responding to day length, lake springtime temperatures (related to the timing of ice break-up in nursery lakes), and springtime peak flows, all of which are influenced by year to year climate fluctuations and **climate change**. Earlier outmigration could lead to a mismatch between the arrival of salmon smolts in the Fraser estuary and Strait of Georgia, and the timing of plankton blooms that are essential for growth and survival in Stage 3 (coastal migration).

4.3.2 Exposure of Fraser River sockeye to stressors

There are four key points to consider regarding the exposure to stressors during this stage. First, the *duration of potential exposure* to stressors is much less in Stage 2 than in Stage 1. Whereas sockeye spend on average 1.75 years in stage 1 (e.g, spawning in August-November of 2004 and leaving their rearing lake in May of 2006), they generally spend only two months in Stage 2 migrating downstream the ocean (e.g., during May and June 2006), and will be exposed to a wide range of conditions during this migration. Second, both the duration of exposure and the stressors experienced (i.e., the vulnerability of a stock's migratory habitat) vary with the distances over which sockeye smolts must migrate. There is a 10-fold variation in migratory distances across the Fraser Conservation Units, from 111 km for Cultus Lake sockeye, to 1182 km for Nadina sockeye (Nelitz et al. 2011, Table 18). Third, all sockeye stocks pass through the *Fraser estuary*, and are exposed (though briefly) to the cumulative effects of habitat disruption in this region (Johannes et al. 2011). Fourth (and counter to the third point), while "dilution is not the solution to pollution", the substantial volumes of water in the lower Fraser River have an important dilution effect on contaminant concentrations (MacDonald et al. 2011; Johannes et al. 2011).

Nelitz et al. (2011; Table 18) found that their index of **cumulative habitat stress[11] to migratory habitats** (which included the zone within a 1 km buffer along migratory habitats) was **relatively high** for all sockeye conservation units with a migration distance greater than 750 km. The stress index was however also relatively high for some conservation units with short migratory distances but exposed to more intensively disturbed regions (e.g., Cultus (111 km migration), Chilliwack (156 km), Kakawa (164 km), Nahatlatch (255 km)). Two stocks of particular interest because of their relatively healthy trends in productivity, the Shuswap (487 km migration) and Harrison (127 km), had (respectively) relatively high and moderate levels of the migration stress index.

MacDonald et al. (2011) assessed the exposure to **water contaminants** during downstream migration by selecting data during May and June for the appropriate migratory routes for each stock. For **sediment contaminants**, they grouped sites into pre and post-1990 periods.

4.3.3 Correlation/consistency with patterns in Fraser River sockeye productivity

We do not know smolt survival rates for most of the Fraser River stocks. There are some estimates of velocities and survival rates of sockeye smolts migrating downstream from various Fraser watersheds, based on acoustic tags (e.g., Melynchuk et al. 2010). However, these data sets were not included in any quantitative analyses conducted for the Cohen Commission, due to time limitations. Our analyses of migratory stage stressors (and those conducted by other Cohen Commission technical reports) used indices of post juvenile or full life cycle productivity as the dependent variable to be explained. These indices do not allow us to clearly separate effects on survival in the downstream migration from effects occurring in the ocean, though we do explore whether stressor indices in different life history stages are better correlated with full life cycle productivity.

Nelitz et al. (2011; Table 16) found that overall life cycle sockeye productivity was negatively associated with **migration distance** (the <u>only</u> factor with a strong association), but they have no direct explanation for why this occurred. It might relate to differential exposure to a suite of stressors along the migration route, or could be capturing parallel influences on total productivity that are unrelated to stresses associated with human activities, since migration distance is

[11] This index of cumulative habitat stress was developed by first applying cluster analysis to each of the land use stressor indices, scoring each conservation unit as 1 (low), 2 (moderate) or 3 (high) *relative* levels of stress, with a score of 0 assigned in cases where a habitat had no spatial overlap with a stressor. The scores across all stressor indices were then summed to give an overall index of cumulative habitat stress for each CU.

correlated to other factors reflecting watershed position, including elevation and latitude, as noted by Selbie et al. (2010).

The available evidence does not support the hypothesis that exposure to **water contaminants** during the downstream migration could be a contributing factor to declines in Fraser sockeye productivity (MacDonald et al. 2011, Section 5.4). The post-juvenile index of sockeye productivity declined with increasing values of a water quality index for the migration period and zone (i.e. the opposite pattern from what one would expect if contaminants were a cause of the productivity declines). There was no relationship between the water quality index and the full life cycle index of productivity. While the results of the sediment risk assessment showed that the concentrations of iron and nickel were elevated at two locations within the basin (Lower Fraser and South Thompson Rivers), and have likely increased in the Lower Fraser, exposure to these contaminants of concern in sediment is unlikely to be sufficient to adversely affect the survival, growth or reproduction of sockeye salmon.

Hinch and Martins (2011) did not examine the effects of **temperature** on downstream migration, though section 1.5.1 of their report describes increasing temperatures in the Fraser River in late spring and early summer, and earlier timing of the spring freshet (about 6 days earlier than in the 1950's). Nelitz et al. (2011; Section 4.2; Table 17) used springtime air temperature as an indicator of the timing of ice break-up in nursery lakes (one of the cues of smolt outmigration), and tested the hypothesis is that if lake ice breaks up significantly earlier than experienced historically, smolts would leave sooner, arrive in the Fraser estuary at the wrong time, and experience lower productivity. They found that years with warmer spring time air temperatures in nursery lakes were indeed associated with lower life cycle productivity in 14 of 18 Fraser stocks, but these negative correlations were weak and not statistically significant. The absence of statistical significance could be due either to the absence of a real relationship, or the fact that fairly crude indicators (air temperatures) were used as predictors. In the recent PSC report on Fraser sockeye, Peterman et al. (2010; section 4.6) found no change in the **migration timing** of smolts from Chilko Lake, and in Cultus Lake the median date of outmigration has shifted *later* by about 13 days over the past 80 years (i.e., contrary to the expected response to climate change). Better data are needed to assess trends in the timing of smolt outmigration relative to changing climate conditions, and how this influences later survival once smolts enter the ocean.

Harrison River sockeye have a different life history from the rest of Fraser River sockeye populations. They leave their rearing habitats as fry (sometimes called underyearling smolts) in the year after spawning occurs (rather than in the second year after spawning), and reside in the Fraser estuary for up to 5 months before entering the ocean. This life history would cause Harrison smolts to experience considerably greater exposure to contaminants and other stressors in the Lower Fraser than other Fraser sockeye, yet this stock is the only one of 19 with increasing productivity. This implies that conditions in the Lower Fraser River were not sufficiently stressful to cause productivity declines in Harrison sockeye, and suggests that Lower Fraser conditions were unlikely to be a primary driver of observed productivity declines in the other Fraser stocks that pass through the Fraser estuary much more quickly.

4.3.4 Correlation/consistency with patterns in non-Fraser River sockeye productivity

We do not have indicators of potential stressors for non-Fraser sockeye stocks during the smolt migration stage. Similar arguments to those presented in section 4.2.4 apply to habitat and contaminant stressors during the smolt migration stage (i.e., we suspect they are not primary drivers of observed productivity declines, but have no stressor data to test this hypothesis).

4.3.5 Other evidence

Other evidence includes literature demonstrating thresholds, an understanding of the specific form of response of sockeye to certain stressors (i.e., helping to accept or reject different suspected causes), experiments demonstrating cause-effect linkages, or positive sockeye responses following the removal of a stressor. In general, the level evidence for Stage 2 is less than for Stage 1, due primarily to the challenges of experimentally evaluating responses of rapidly migrating smolts to a continuing gradient of stressors. Evidence is strongest for such stressors as **contaminants** and **temperature**, which are amenable to experimentation. As discussed above, MacDonald et al. (2011) compared water contaminant concentrations during the smolt migration period with thresholds established from laboratory and field studies, and found no evidence that contaminants encountered by smolts contributed to declining sockeye productivity. Studies of smolt health conducted in other rivers (e.g., Columbia River and other studies reviewed in Marmorek et al. 2004) are generally not applicable to the Fraser situation. Therefore, we are left with little other evidence to evaluate stressor hypotheses.

4.3.6 Conclusions

Table 4.3-1 shows our conclusions regarding the effects of each stressor on life history stage 2 (smolt migration from rearing habitats to the Fraser Estuary). Again, our conclusions relate to the **overall trends** in sockeye productivity over the last two decades. This table is identical to Table 4.2-1 for Stage 1, except that migrating smolts are judged to have no exposure to either mines or small hydro, compared to low exposure for eggs, alevins and fry.

Table 4.3-1. Evaluation of the relative likelihood that potential stressors encountered by Fraser River sockeye salmon during their smolt migration from rearing habitats to the Fraser Estuary (Stage 2) have contributed to overall declines in productivity in recent decades. See section 4.7 for further statistical analyses relevant to the correlation/consistency column.

Factor	Mechanism	Exposure	Correlation/Consistency	Other Evidence	Likelihood
Forestry[b]	Yes	Yes	No	No[a]	Unlikely
Mining	Yes	No	Not done	No[a]	Unlikely
Large hydro	Yes	Yes	No	Against	Unlikely
Small hydro	Yes	No	No	No[a]	Unlikely
Urbanization above Hope	Yes	Yes	No	No[a]	Unlikely
Agriculture[b]	Yes	Yes	No	No[a]	Unlikely
Water Use	Yes	Yes	No	Yes	Unlikely
Contaminants	Yes	Yes	No	Yes	Unlikely
Density Dependent Mortality	Yes	Some stocks	No	No	Unlikely
Pathogens	Yes	Few data	Not done	Yes	No conclusion possible
Predators	Yes	Few data	No	No	Unlikely
L. Fraser land uses	Yes	Yes for ag/for; No for others	No	No	Unlikely
Climate Change	Yes	Yes	Weak evidence	Mixed	Possible

[a] It is difficult to establish hazard thresholds for the proportion of watershed area above which there are negative impacts on sockeye spawning and rearing. Such thresholds are better defined for contaminants and water use.
[b] Agriculture and forestry rows include evidence from both Technical Reports 3 (Nelitz et al. 2011) and 12 (Johannes et al. 2011). Forestry includes logging, Mountain Pine Beetle and log storage.

As for Stage 1, we conclude that with the exception of climate change, which we consider to be a *possible* factor, and pathogens (for which no conclusion is possible due to data gaps), it is *unlikely* that other factors (i.e., forestry, mining, large and small hydro, urbanization, agriculture, water use, contaminants, density dependent mortality, predators, and Lower Fraser land use) taken cumulatively, were the primary drivers behind long term declines in sockeye productivity across the Fraser Basin. A major reason for this conclusion is the short time period over which migrating smolts are exposed to the above stressors. Though not primary drivers of the Fraser sockeye situation, each of the factors considered for Stage 2 may still have had some effects on some Fraser stocks in some years (the data are insufficient to reject that possibility).

However, since smolt migration occurs subsequent to enumeration of fry and smolts in rearing lakes, we have no analyses relating survival rates during this life history stage to potential stressors. Thus our conclusions have a lower level of confidence than for Stage 1. While there are some survival estimates for acoustically tagged smolts, these data (which only cover a few stocks) were not analyzed by any of the Cohen Commission technical studies.

As we found for Stage 1, none of the factors considered for Stage 2 is likely to have been much worse in 2007 for downstream migrating smolts, sufficient to have significantly decreased smolt survival **prior to entering the ocean**, and affecting the 2009 returns. Ocean conditions in 2007 are a very different story, discussed in the next section. Similarly, none of the factors affecting smolt survival during their downstream migration are likely to have ben much better in 2008, sufficient to have substantially improved smolt to adult survival in the salmon returning in 2010. For example, Rensel (2010, Figure 4 in Appendix C of Peterman et al. 2010) found that Fraser River flows in May were higher than normal in **both** 2007 and 2008.

4.3.7 Key things we need to know better

Sockeye smolt survival from rearing to the estuary is a significant gap in the current assessment. In the Columbia River, extensive PIT-tagging (Passive Induced Transponders) of hatchery fish (mostly chinook and steelhead) have provided precise estimates of in-river smolt survival rates, as well as smolt to adult survival rates, leading to considerable advancements in understanding (e.g., Schaller et al. 2007). The PSC Panel on Fraser sockeye declines (Peterman et al. 2010) had the following recommendations, with which we concur:

> "The survival rate of sockeye juveniles during their migration downstream within the Fraser River cannot currently be estimated separately from the overall juvenile-to-adult survival rate. To identify the timing and location of sockeye mortalities, this limitation should be (and can be) corrected. In the absence of correcting this issue, focusing research mainly on marine conditions may be insufficient for improving understanding, forecasting, and management. The Panel recommends research to assess sockeye smolt survival between lakes and the Fraser River estuary. The priority is rated higher for future management actions because corrective actions could be taken for disease and/or contaminant problems, for example." (Peterman et al. 2010; pg. 21)

4.4 Stage 3: Coastal Migration and Migration to Rearing Areas

This stage covers the journey of sockeye salmon from the mouth of the Fraser River to the Gulf of Alaska.

4.4.1 Plausible mechanisms

As shown in the conceptual model (Figure 3.3-1) potential factors affecting Stage 3 include: 1) **pathogens and disease**; 2) **predators**, 3) **marine conditions**, 4) Strait of Georgia habitat conditions (including marine conditions and **human activities and development** in the surrounding area), 5) **climate change**, and 6) **salmon farms** (note: the salmon farms technical report is not yet available). There are cause-effect mechanisms by which each of these factors could at least *potentially* affect the health and survival of sockeye salmon post-smolts after leaving the Fraser River and progressing through their coastal migration to the North Pacific Ocean, as described below.

This stage is particularly important to Fraser River sockeye salmon. McKinnell et al. (2011, Section 2) explain that for Fraser River sockeye salmon in particular, this stage may equate to a "race northwards to find better feeding conditions". The sockeye salmon populations that enter the ocean in the more southern portions of sockeye habitat range have longer ocean migrations to the Gulf of Alaska, with lower average growth rates and lower ocean survival than those entering from more northern rivers. Therefore, Fraser River sockeye salmon may be particularly sensitive to any increases in stress through this critical stage.

Pathogens and disease could potentially lead to increased mortality of sockeye salmon post-smolts. Kent (2011) provides a list of potentially important pathogens and indicates that there are many potential pathogens that could cause mortality in wild salmon. He identifies the following pathogens as potentially "high risk" over the entire life of sockeye salmon: the IHN virus, three bacteria (*Vibrio anguillarum*, *Aeromonas salmonicida*, *Renibacterium salmoninarum*), and two parasites (Ich -*Ichthyophtheirus multifillis* and the myxozoan *Parvicapsula minibicornis*). IHN is important for fry but also occurs in the marine environment and there have been outbreaks in pen-reared Atlantic salmon. Kent (2011) reports that although sockeye salmon post-smolts appear to be less susceptible, recent evidence suggests that virulence is variable and therefore it is conceivable that some strains may be more pathogenic to sockeye salmon in the ocean.

Kent (2011) describes several important **interactions with pathogens and disease** that may increase the impact on sockeye salmon. **Temperature** influences the immune status of fish and most pathogens increase with temperature either due to a direct response to warmer conditions or an indirect response to increases in invertebrate hosts and other intermediate vectors. **Organic pollutants** can increase intermediate hosts and opportunistic fungi and bacteria, and **toxic contaminants** may impair fish immune systems but may also increase the mortality of invertebrate hosts. Some research suggests that **land use** practices also have an indirect effect on pathogens. **Aquaculture** was not considered in our report as the Commission Technical reports on this potential stressor were not available, but will be considered in an addendum to this report. Unfortunately, there are insufficient data to evaluate the extent to which these potential interactions of pathogens and other stressors are (or are not) causing sockeye smolt mortality during their coastal migration.

There are many **marine predators** that may consume sockeye post-smolts as they migrate from the mouth of the Fraser northward along the coast. Christensen and Trites (2011) identify spiny dogfish, coho salmon, chinook salmon, juvenile sablefish, humbolt squid, and arrowtooth flounder as potential **fish predators.** Potential **bird predators** include common tern, arctic tern, pelagic cormorant, Brandt's cormorant, gulls, and common murre. Mortality due to predation is likely to have always been high during this life stage as the sheer abundance of post-smolts migrating up the coast would have always attracted a diversity of predators, but if the level of predation has increased in recent decades, the impact on the sockeye salmon population may have also increased. **Marine mammal predators** (including pinnipeds and cetaceans) have been documented eating salmon post-smolts but there is no evidence of marine mammal predation on sockeye salmon post-smolts (Christensen and Trites, 2011). However, knowledge on the diet, abundance, distribution and biology of potential predators is often scarce. For example, little information is known on the diet of Pacific white-sided dolphins, but salmon might represent 30-60% of their diet during June through November (Christensen and Trites, 2011). Salmon is also known to be an important prey species for Steller sea lions, although the evidence suggests that Steller sea lions predominantly eat adult salmon rather than juveniles. Knowledge of specific predator-prey associations is largely based on diet information for predators but such information is largely qualitative and often non-existent for particular predators of interest (Christensen and Trites, 2011). Overall, Christensen and Trites (2011) emphasize that even if it could be shown that the aggregate rate of predation on sockeye salmon has increased substantially over the past several decades, it would likely still not be possible to determine whether predation itself was contributing to the decline of sockeye salmon or predators are simply acting as the "executioners" of sockeye salmon that were already less healthy and slower due to some other underlying driver.

Christensen and Trites (2011) also put forth an alternate theory regarding the potential impact of predation on sockeye salmon. They suggest that if there have been substantial declines in the populations of **alternate prey** species that are physically comparable to sockeye salmon, predators that might otherwise not eat or not prefer sockeye salmon might increase their consumption. In this situation, it would be possible for predators to have an increased impact on sockeye salmon while not actually increasing in abundance.

Competition is another plausible mechanism of potential importance discussed by Christensen and Trites (2011). Ruggerone et al. (2010) summarize trends in wild and hatchery populations in the North Pacific, and discuss the potential for a "tragedy of the commons" effect due to increased numbers of fish competing for a finite pool of food resources. In section 4.7, we consider the extent to which total pink salmon abundance (wild plus hatchery) can explain changes in Fraser sockeye stock productivity. As discussed in section 4.7, these effects are most likely to occur in Stage 4 (growth in the North Pacific and return to the Fraser).

McKinnell et al. (2011) investigate how **marine conditions** along the coast may potentially have affected Fraser River sockeye salmon over recent decades and the 2005 brood year (2009 returns) in particular. The **physical conditions** examined include wind, river discharge, salinity, temperature, water density, and water column stability. The primary **biological conditions** examined were the timing and magnitude of chlorophyll production. Broad scale climate drivers can influence river discharge and wind regimes, which may then influence the salinity of coastal waters. Salinity and temperature interact to affect water density, water column stability and therefore surface mixing, which impacts the productivity of the surface layer and its potential to increase in temperature. Fraser sockeye salmon are negatively affected by warmer and less productive ocean conditions. McKinnell et al. (2011, Sections 6.1, 6.2) explore the oceanography and climate of the Strait of Georgia and Queen Charlotte Strait/Sound.

Johannes et al. (2011) explore how **human activity and development** in the areas surrounding Strait of Georgia may potentially have had a negative impact on **habitat quality** for sockeye salmon as they leave the Fraser River estuary. Changes in the human population may be a proxy for many feasible mechanisms by which human activity and development might directly impact sockeye salmon habitat quality. Increasing contaminants in the Strait of Georgia from mills, industrial facilities, chemical inputs to farming, and liquid and solid waste inputs could potentially degrade habitat quality. Forestry is a major land use in the areas surrounding the Strait of Georgia. Although forestry has been shown to often have a negative effect on freshwater and estuary habitats for salmon, the potential impact on inshore marine habitat is uncertain (Johannes et al., 2011). Increased marine traffic may also create transient disturbances upon the surface and contribute further contaminants to the water.

Climate change could potentially have driven broad scale changes to the entire ecosystem (Hinch and Martins, 2011). It is plausible that climate change may have contributed to changes in the timing, magnitude, patterns, trends and variability in physical and biological habitat conditions along the coast. The potential impacts to sockeye salmon could be direct, such as increases in sea surface temperature, or indirect, such as changes in predation, disease, or food abundance and quality.

4.4.2 Exposure of Fraser River sockeye to stressors

Most of the evidence on exposure to particular stressors during this life stage is based on an understanding of the general migration route and timing of Fraser River sockeye salmon and an assumption that exposure occurs where there is spatial and temporal overlap of potential factors with the post-smolts. As sockeye salmon pass through the Strait of Georgia, Queen Charlotte Sound, and along the coast they are exposed to the physical and biological conditions of the season.

Strong evidence of exposure would require a much more precise knowledge of the spatial and temporal patterns of both the sockeye salmon and each specific potential stressor, recognizing that migration timing varies among stocks. The mere presence of a potential stressor does not necessarily mean that exposure has occurred. For example, finding a particular contaminant at one sampling location in the Strait of Georgia does not mean that sockeye salmon were exposed to it. If an infection is detected in fish, that may implicate exposure to that pathogen, but overlap with the pathogen alone may not. Furthermore, "exposure" in a general sense to potential sources may not necessarily correspond with exposure to actual detrimental conditions. Johannes et al. (2011) show that farm area and total farm inputs (i.e. chemical fertilizers and insecticides) have been increasing around the Strait of Georgia, yet improved management practices have reduced runoff from farms waste, which is the element that is most likely to directly affect sockeye salmon.

Exposure to many **predators** can only be assumed based on the likely overlap in space and time because knowledge of the distribution and diet of many predators is lacking. Christensen and Trites (2011) have searched the scientific literature for diet information for potential predators but the data are often relatively sparse, old or only available for particular species. Physical evidence that particular predators have consumed sockeye salmon post-smolts provides convincing evidence of exposure, but a lack of such data does not support any conclusions about exposure - most sockeye that are eaten are simply never seen again and thus exposure cannot be confirmed. The importance of potential predators is often based on knowledge about the composition of a predator's diets and whether or not sockeye salmon is a preferred prey species. However, it is possible that a relatively abundant predator could have a substantial impact on sockeye, even if sockeye comprised only a small, possibly undetectable fraction of the predator's diet (Christensen and Trites, 2011). For example, if 0.1% of the diet of spiny dogfish were sockeye smolts, spiny dogfish would consume 14.5 million smolts within the Strait of Georgia and yet over a thousand dogfishes might need to be sampled before finding one containing sockeye salmon smolts (Christensen and Trites, 2011, p. 77). To provide some frame of reference, the average number of smolts leaving Chilko Lake from 1997-2005, prior to accounting for any mortality while outmigrating to the ocean, was approximately 22.5 million. The key point here is that a predator could have a substantial impact on a prey species even if that prey is a negligible proportion of the predator's diet. For example, the existing evidence shows that juvenile salmon represents a very small proportion of the diet of Steller sea lions. The more important question is: what is the net impact of Steller sea lions on sockeye salmon? However, predation is a major part of sockeye salmon's natural lifecycle; substantial exposure to predation should be expected even if predation has not substantially contributed to the decline of Fraser River sockeye salmon.

Very little is known about the exposure of Fraser River sockeye salmon to **pathogens and disease**. Relatively few outbreaks of disease have ever been documented in BC sockeye salmon (Kent, 2011). However, this is not strong evidence against exposure to potentially important diseases because there is simply very little research on wild fish; most research focuses on hatchery fish and there is minimal data on the marine phase at all (Kent, 2011). There is currently poor understanding of the prevalence, geographic distribution, and virulence of pathogens that wild sockeye salmon might be exposed to in the marine environment (Kent, 2011).

Johannes et al. (2011, Section 4) have concluded that the potential exposure of sockeye salmon in the Strait of Georgia to impacts from **human activity and development**[12] (evaluated in terms of geographic overlap and magnitude of interaction) are “nil” to “low” for the following categories of potential stressors: population growth and urbanization; agriculture and forestry land use; large industrial and infrastructure projects; solid and liquid waste; and dredging, diking, and disposal at sea; contaminated materials; and, nonindigenous species introductions. The geographic overlap is evaluated as a moderate only for shipping and vessel traffic, but the magnitude of interaction is still only evaluated as low (Johannes et al., 2011).

Another poorly understood factor is the extent to which the **Strait of Juan de Fuca** is occasionally used by post-smolts leaving the Strait of Georgia, and how this behavior may vary over time and among specific stocks. McKinnell et al. (2011) provide a summary of the available evidence on the use of this alternate migration route. Any sockeye salmon that use this route might avoid exposure to potential stressors in the northern Strait of Georgia and Johnstone Strait, but it appears that the use of this route has been relatively rare in sockeye salmon.

McKinnell et al. (2011, section 7.1.1) explain how the resolution of most **marine** data does not correspond with the fine scale variability that sockeye salmon actually experience as they migrate up the coast. Regional data is often inferred from only a single or relatively few point

[12] “Human activities and development” refers specifically to those activities and developments considered within Technical Report #12 (Fraser River Sockeye Habitat Use in the Lower Fraser and Strait of Georgia), which do not include salmon farms. Exposure to salmon farms will be covered in the technical report on aquaculture, which is currently in progress. The present report does not provide any conclusions regarding salmon farms.

observations that are then averaged across time and/or space to capture broad scale variation; however, the specific conditions encountered by migrating sockeye salmon in a specific location at a specific time may not be reflected in regional data (McKinnell et al., 2011, section 7.1.1). Given the absence of more spatially precise data and knowledge of sockeye location, one must assume that sockeye salmon passing through a particular region are exposed to the regionally averaged conditions.

4.4.3 Correlation/consistency with patterns in Fraser River sockeye productivity

Kent (2011) reports that the limited survey data available on **pathogens and disease** do not indicate any increase over time; however, it is impossible to determine whether these sparse data are representative of broader trends across other pathogens. Almost no data exist with which to assess changes in the abundance of different pathogens over time, the prevalence of diseases over time, or the spatial distribution of important pathogens (Kent, 2011). This makes it impossible to assess whether diseases are correlated with Fraser sockeye productivity.

Christensen and Trites (2011) did not test for any statistical relationships between **predator** abundance and the observed patterns in sockeye salmon abundance or productivity. One factor that complicates such analyses is that changes in predator abundance are only a rough proxy for potential changes in the magnitude of sockeye consumed; the ultimate impact of the sockeye salmon population is going to be a product of both predator abundance and consumption rates. Christensen and Trites (2011) note that several key fish predators (including spiny dogfish, coho salmon, chinook salmon, juvenile sablefish), and key marine bird predators have been declining, or at least not increasing, over recent decades. Conversely, arrowtooth flounder, which is believed to be a potentially important predator of sockeye salmon, appears to be increasing in abundance. However, data on abundance over time do not generally exist for most fish and bird predators except for a few commercially important species (Christensen and Trites, 2011). Marine mammals such as Steller sea lions and harbour seals have increased substantially over recent decades. Christensen and Trites (2011) report that juvenile salmon do not represent a significant proportion of the diet of these marine mammals, but as the spiny dogfish example cited in the previous section indicates, this does not definitively exclude such predation from possibly having an impact on salmon populations. Several important, abundant prey species have decreased substantially over time, which might drive predators that would otherwise not favor sockeye salmon to increase their consumption (Christensen and Trites, 2011).

McKinnell et al. (2011) demonstrate that the cohort from the 2005 brood year may have endured extreme **physical and biological ocean conditions** in Queen Charlotte Sound during their 2007 coastal migration. Anomalous climate conditions in 2007 resulted in exceptional snowpack accumulation in the mountain ranges of western BC during the winter, then a delayed but rapid snowmelt in the spring that produced extreme levels of discharge into Queen Charlotte Sound. As a result of this large influx of freshwater into the Sound, salinity measurements were found to be at or near record lows throughout the area. This anomaly was then maintained by an atypical wind regime that kept these fresher waters "backed up" in Queen Charlotte Sound. The sea level anomalies observed in Prince Rupert provide further support for this mechanism. The products of these factors were a fresher surface layer and a more stable ocean column that inhibited mixing, allowing the surface layer to warm to higher than average temperatures and potentially become depleted of nutrients. The spring of 2007 marked a year of very poor chlorophyll production in Queen Charlotte Sound, a factor that has been associated over time with poor survival rates of sockeye salmon from Chilko Lake. The combination of a substantial reduction in food supply and the higher energetic costs of migrating through warmer waters could potentially have led to increased mortality of the cohort of Fraser River sockeye salmon that returned in 2009. However, by contrast, McKinnell et al. (2011) found that while some of these same physical and biological measures were higher than average in the Strait of Georgia in 2007, none of them exhibited extreme levels. Although long records of many physical ocean properties are available, there exists only a limited record for biological properties such as chlorophyll concentration (i.e. since 1998). McKinnell et al. (2011; page ix and 135) noted that in 2007 there was typical survival of acoustically-tagged hatchery-reared sockeye salmon from Cultus Lake northward through the Strait of Georgia in 2007, which is consistent with the non-extreme physical conditions discussed above.

McKinnell et al. (2011; page 110) emphasize that conditions in Queen Charlotte Sound were very different in 2008 (affecting the 2010 returns) as compared to conditions in 2007 (affecting the 2009 returns):

> "The summer of 2008 was the opposite of 2007. Sea surface temperatures along the North American coast were cool following what was the coldest year in the Gulf of Alaska since 1972, and these cool anomalies persisted along the coast through September. Unlike the Strait of Georgia, migrating sockeye salmon in 2008 would have had a very different thermal experience during their migration in 2008 compared to 2007 once leaving the coastal straits. The temperature of surface seawater along the coast is often an indicator of major ecological changes that accompany the warmer/colder ocean."

The much improved marine survival rates of Fraser sockeye in 2008 (relative to 2007) are consistent with the hypothesis that sea surface temperatures strongly affect marine survival.

Johannes et al. (2011) demonstrate that although the human population surrounding the Strait of Georgia has consistently increased over the past two decades, trends observed in **human activity and development** have been more variable (e.g., liquid and solid waste stable, substantial decrease in the number of new large developments per decade, agricultural area increased 10%, livestock more than doubled, fertilizer inputs remained stable, insecticide inputs increased roughly 100%, forest harvesting decreased 50%, ship movements stable, cruise ship traffic steadily increased, concentrations of contaminants decreased substantially).

Hinch and Martins (2011; section 1.4.3) summarize studies indicating an inverse relationship between sockeye salmon early marine survival and **increasing sea temperature**. This suggests that there is strong evidence for a direct impact of climate change on sockeye salmon. However, because coastal sea surface temperatures experienced by Fraser River sockeye salmon remain within their tolerable range, it is suggested that temperature is a proxy for other regional mechanisms or interactions affected by climate change (Hinch and Martins, 2011).

4.4.4 Correlation/consistency with patterns in non-Fraser River sockeye productivity

Other sockeye stocks overlap with portions of the coastal migration of Fraser River sockeye salmon. Stocks that share both geographic and temporal overlap will likely encounter similar pathogens, predators and ocean conditions during this stage. The extent to which such stocks show similar trends in productivity to those of the Fraser River (see Peterman and Dorner, 2011) would provide evidence supporting the importance of these stressors. In examining the productivity patterns over 64 Fraser and non-Fraser sockeye populations from Washington to SE Alaska, Peterman and Dorner (2011; pg. 3) comment that: "The large spatial extent of similarities in productivity patterns that we found across populations suggests that there might be a shared causal mechanism across that large area.", though they acknowledge that further work is required to test this hypothesis. The Cohen Commission technical reports do not however include analyses of the relationships between stressors at this stage and productivity indices for non-Fraser River sockeye.

4.4.5 Other evidence

In terms of factors potentially contributing to the poor 2009 returns, McKinnell et al. (2011) provide detailed evidence of physical and biological ocean properties that exceeded their historical records thus exceeding the known range of natural variability, which we consider to be an exceedance of an implicit threshold. With respect to the overall relationship between sea surface temperatures and Fraser sockeye smolt survival, Hinch and Martins (2011; section 1.4.3) summarize the following evidence of how warmer temperatures indirectly affect sockeye (references cited in their report):

- along the British Columbia coast, warm SSTs are associated with reduced upwelling and hence low food availability (i.e. zooplankton) for young sockeye salmon;
- the peak timing of the copepod *Neocalanus plumchrus*, the main zooplankter in the Strait of Georgia, has advanced up to 30 days in the past decades and the peak duration has shortened in response to warming;
- the observed advance in timing of the Fraser River spring freshet may also be contributing to an earlier peak in zooplankton density in the Strait of Georgia;
- changes in food availability as well as high metabolic rates incurred by warm waters are consistent with the observation that early marine growth of Fraser River sockeye salmon is reduced when coastal SST is warm;
- reduced growth would make juveniles more vulnerable to predation mortality;
- the abundance of non-resident predatory fish in coastal waters off British Columbia increases in warm years; and
- resident predatory fish increase food consumption so as to offset high metabolic rates incurred by warm waters

Conditions in Queen Charlotte Sound versus the Strait of Georgia

One of the most striking differences between the conclusions reached at the Cohen Commission workshop (Appendix 6) and the PSC report (Peterman et al., 2010) concerned the relative importance of ocean conditions inside versus outside the Strait of Georgia (SoG) during the coastal migration of sockeye salmon to the Gulf of Alaska. Peterman et al. (2010) concluded that it was "very likely" that physical and biological ocean conditions inside SoG during this life stage had been a "major factor" contributing to the overall decline in productivity and "likely" that they had been a major factor contributing to the poor returns in 2009[13]. By comparison, the panel concluded that it was "possible" that ocean conditions outside SoG had been a "contributing factor" to both the overall and 2009 patterns in sockeye salmon. However, the majority of the expert participants in the Cohen Commission workshop evaluated ocean conditions inside SoG as being only a "likely" contributor to both the overall and 2009 patterns, but that ocean conditions outside SoG, within Queen Charlotte Sound (QCS) in particular, were a

[13] The approaches used by Peterman et al. (2010) to assess the relative likelihood of different hypothese, as well as the approaches used at the Cohen Commission Scientific and Technical workshop, were less formal than those we applied in this technical report, and are not directly comparable. There were also differences in the group of experts involved in making these assessments. For example, Peterman et al. (2010) gave ocean conditions inside the Strait of Georgia their highest possible likelihood rating and ocean conditions outside the Strait of Georgia a lower likelihood rating, whereas the participants at the Cohen Commission workshop concluded the reverse.

“likely” contributor to the overall pattern and a “very likely”, potentially major, contributor to the poor 2009 returns.

Using the data collected from the other Cohen Commission technical projects, we have conducted quantitative analyses over several time periods. The analyses use multiple regression to compare the ability of several different oceanographic and climatic variables (measured in QCS and SoG) to explain the observed variability in Fraser River sockeye salmon productivity (i.e., ln(recruits/spawner)). A brief overview of the approach used is provided in Section 3.3.6 and the details of the methodology and results are described in Appendices 3 and 4, respectively.

We tested three model sets with the data available for marine conditions in QCS and SoG (Table 4.4-1). Each model set represents a set of covariates or independent variables that have complete data over a specified period of time. Within each model set, different models (i.e., combinations of variables) can be tested to determine their ability to explain the observed variability in the dependent variable. In the present case, the dependent or response variable is sockeye salmon productivity (ln (recruits/spawner)). Models can only be directly compared to other models in the same model set (i.e., using the same set of data) but not to models in other model sets. The time frames of the three model sets tested in this section are brood years 1969-2004, 1980-2004, and 1996-2004. The key differences among the model sets examined are that sea surface temperatures were not available for QCS until 1980, and chlorophyll was not available until 1996. The conclusions of these results are presented below, with details in Appendix 4.

For 1969-2004 (Table 4.4-2), the results show that the SoG temperature model (M8) and the QCS salinity and discharge model (M4) were the two models with the most support, but neither performed substantially better than the “global” model, which is the model that contains all the variables in the model set (i.e., M1 in Table 4.4-2). For SoG during this period, temperature (M8) is more valuable for explaining the observed variability in Fraser River sockeye salmon productivity than salinity (M7). Overall, the analysis of this time period shows that there is support for both QCS and SoG models – the top ranked model was for SoG, the second for QCS, and the third was the global model, including both regions. These results show that for these particular variables, over this particular time period, there is no clear evidence of any difference between the explanatory value of the two regions; however, the absence of temperature data for QCS is a substantial shortcoming of this model set, and chlorophyll is not included in any model.

Table 4.4-1. Variables used in the quantitative analyses of marine conditions in Queen Charlotte Sound (QCS) and the Strait of Georgia (SoG). All of the data included in this table were available to at least 2004 (in terms of brood year). In many cases, even more recent data is available but the period of analysis was limited by the data for productivity (i.e. the dependent variable), which was currently only available up to brood year 2004. The 2004 brood year produced adults that would have predominantly returned in 2008, with 5-yr olds returning in 2009.

Variable Type	Variable	Location	Data Metrics	Start of available data (brood year)
Dependent	Productivity	n/a	ln (recruits/spawner)	1950
Independent	Sea surface temperature (SST)	QCS	Average SST, July-August	1980
		SoG	Average SST, April-August	1934
Independent	Sea surface salinity (SSS)	QCS	Average SSS, April-August, Egg Island	1968
		SoG	Average SSS, April-August, Entrance Island	1934
Independent	Chlorophyll a	QCS	Average concentration of cholorphyll a, April Average concentration of cholorphyll a, May	1996
		SoG	Average concentration of cholorphyll a, April, northern SoG Average concentration of cholorphyll a, May, northern SoG	1996
Independent	Discharge	QCS	Average discharge, July, Wannock River (Rivers Inlet)	1959
		SoG	Average discharge, May, Fraser River Average discharge, June-July, Fraser River	1968
Independent	Wind	QCS	Average summer wind regime, June-July; principal component of north-south and east-west vectors	1946

Table 4.4-2. Model specifications for the 1969-2004 (brood years) model set. This table shows the variables included in each of the 8 models tested (i.e., M1 to M8) within this model set. Table 4.4-1 explains which specific data sets were used for each of these variables. "Rank of model" reflects the AIC_c score showing level of support (#1 ranked model had the highest level of support and lowest AIC_c score).

Region	Variable	M1	M2	M3	M4	M5	M6	M7	M8
QCS	Salinity	X	X		X		X		
QCS	Discharge	X	X		X				
QCS	Wind	X	X						
SoG	Temperature	X		X					X
SoG	Salinity	X		X		X		X	
SoG	Discharge	X		X		X			
Rank of model		**3**	**4**	**5**	**2**	**7**	**8**	**6**	**1**

For 1980-2004 (Table 4.4-3), the three models with the lowest AICc scores were M4 (QCS SST, SSS and discharge), M5 (QCS SST and SSS), and M2 (QCS SST, SSS, discharge, and wind) (Table A4.3-16). Together they indicate that the QCS models have greater explanatory value than SoG models for Fraser River sockeye salmon productivity during 1980-2004. This conclusion is supported further by the fact that the models with the next two lowest AICc scores are M7 (QCS SSS) and M9 (QCS SST). This finding is an important new result because it is alters the conclusion of Peterman et al. (2010) based on new data and analyses that were not available at the PSC workshop.

Table 4.4-3. Model specifications for the 1980-2004 (brood years) model set. This table shows the variables included in each of the 10 models tested (i.e. M1 to M10) within this model set. Table 4.4-1 explains which specific data sets were used for each of these variables. "Rank of model" reflects the AIC_c score showing level of support (#1 ranked model had the highest level of support and lowest AIC_c score).

Region	Variable	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
QCS	Temperature	X	X		X	X				X	
QCS	Salinity	X	X		X	X		X			
QCS	Discharge	X	X		X						
QCS	Wind	X	X								
SoG	Temperature	X		X			X				X
SoG	Salinity	X		X			X		X		
SoG	Discharge	X		X							
Rank of model		**6**	**3**	**10**	**1**	**2**	**8**	**4**	**9**	**5**	**7**

Within both of the model sets discussed above (i.e. 1969-2004 and 1980-2004), and across all models for both QCS and SoG, temperature demonstrated a negative or inverse relationship with the productivity of Fraser River sockeye salmon. Salinity also had a consistent relationship across all models within both of the model sets discussed above; however, the direction of the relationship is in the opposite direction for the two regions, positive for QCS, and negative for

SoG. This may be due to regional differences in mechanisms, the confounding impact of other factors that interact with sea surface properties, or issues regarding the precise location of measurements versus the precise migration routes of the sockeye. We cannot offer a definitive explanation for why this might be the case or suggest any underlying mechanism.

For 1996-2004, it was not possible to test a model set with both QCS and SoG because the time period was too short for the number of variables to be included for the two regions. The alternative approach was to develop two model sets, one for each region, to test the importance of chlorophyll against the other variables independently within each region (Tables 4.4-4 and 4.4-5). The results show that QCS chlorophyll may be an important metric in explaining the variation in sockeye salmon productivity over the period of 1996-2004, whereas QCS temperature and salinity are relatively uninformative parameters. To the contrary, within SoG during this timeframe, salinity has strong support and the remaining parameters are found to be uninformative, except when they are all included together in the global model. One should be very cautious about drawing conclusions from patterns observed over such a very short period of time, but these results do at least indicate that there may be strong regional differences in the importance of the potential drivers examined. During the data processing steps of this project, it was noted that the variance in chlorophyll measured in the Northern SoG was substantially greater than that measured in the Central SoG across all months where data were provided (Appendix 3). It may be worth examining these regional differences more closely.

Table 4.4-4. Model specifications for the 1996-2004 (brood years) model set for Queen Charolotte Sound. This table shows the variables included in each of the 9 models tested (i.e. M1 to M9) within this model set. Table 4.4-1 explains which specific data sets were used for each of these variables. “Rank of model” reflects the AIC_c score showing level of support (#1 ranked model had the highest level of support and lowest AIC_c score).

Region	Variable	M1	M2	M3	M4	M5	M6	M7	M8	M9
QCS	Chlorophyll	X	X	X	X	X				X
QCS	Temperature	X	X	X	X		X		X	
QCS	Salinity	X	X	X		X	X	X		
QCS	Discharge	X	X							
QCS	Wind	X								
Rank of model		**9**	**6**	**4**	**2**	**3**	**8**	**5**	**7**	**1**

Table 4.4-5. Model specifications for the 1996-2004 (brood years) model set for the Strait of Georgia. This table shows the variables included in each of the 8 models tested (i.e. M1 to M8) within this model set. Table 4.4-1 explains which specific data sets were used for each of these variables. “Rank of model” reflects the AIC_c score showing level of support (#1 ranked model had the highest level of support and lowest AIC_c score).

Region	Variable	M1	M2	M3	M4	M5	M6	M7	M8	M9
SoG	Chlorophyll	X	X	X	X				X	
SoG	Temperature	X	X	X		X		X		
SoG	Salinity	X	X		X	X	X			
SoG	Discharge	X								X
Rank of model		**3**	**9**	**8**	**6**	**2**	**1**	**5**	**4**	**7**

4.4.6 Conclusions

Table 4.4-6 shows a summary of the results of the weight of evidence evaluation of potential contributing factors at this life stage. All of the potential factors in this life stage have plausible mechanisms. There are almost no data on exposure for **pathogens** making *no conclusion possible*. The evidence presented suggests that sockeye salmon in the Strait of Georgia have little direct exposure to **human activities and development**, leading to a conclusion that it is *unlikely* that these factors have contributed to the decline of Fraser River sockeye salmon. Sockeye salmon have been exposed to predators, marine conditions, and climate change during this early marine phase. However, there has been no evidence presented on any correlations between key predators and sockeye salmon survival. Some important predators appear to be increasing in abundance, and some potentially important alternate prey appear to be decreasing, but many other known predators are decreasing or remaining stable. It therefore remains *possible* that **predators** have contributed to the observed declines in sockeye salmon. Based on plausible mechanisms, exposure, consistency with observed sockeye productivity changes, and other evidence, **marine conditions** and **climate change** are considered *likely* contributors to the long-term decline of Fraser River sockeye salmon. Peterman and Dorner's analyses of **delayed density dependence** were applied to total productivity over the whole life cycle. Therefore, their conclusion that delayed density dependence is unlikely to have been a primary factor causing productivity declines (discussed in section 4.2 for life stage 1) reflects the net effect across all life history stages. **Aquaculture** was not considered in our report as the Commission Technical reports on this potential stressor were not available, but will be considered in an addendum to this report.

Table 4.4-6. Evaluation of the relative likelihood that potential stressors encountered by Fraser River sockeye salmon during their coastal migration and migration to ocean rearing areas have contributed to overall declines in productivity in recent decades. See section 4.7 for further statistical analyses relevant to the correlation/consistency column.

Factor	Mechanism	Exposure	Correlation/Consistency	Other Evidence	Likelihood
Pathogens	Yes	Few data	-	-	No conclusion possible
Predators	Yes	Yes	No data	No data	Possible
Marine Conditions	Yes	Yes	Yes	Yes	Likely
Human Activity and Development (SoG)	Yes	No	-	-	Unlikely
Climate Change	Yes	Yes	Yes	Yes	Likely

The only technical report to present evidence from this life stage specifically associated with the 2009 returns was the report on **marine factors**, which outlined a set of extreme conditions encountered by this cohort that demonstrates plausibility, exposure, correlation, the exceedance of the observed historical range of variability for several metrics, and the differential survival of certain stocks and age-types. The conclusion is thus that it is *very likely* that **marine conditions** during the coastal migration life stage contributed to the poor returns observed in 2009.

4.4.7 Key things we need to know better

There are several major elements about the life history of Fraser River sockeye salmon that are poorly understood and prevent a better understanding of the contribution of key stressors in this life stage to the overall decline in the population. These include:

1. estimates of number of smolts leaving the Fraser River (preferably by stock) would indicate how many sockeye salmon might actually be dying during their outmigration before even encountering the stressors they face in their marine environment. Presently, there are only some estimates available for Chilko and Cultus.
2. information on the health and condition of smolts leaving the Fraser River, including size, contaminant and disease burdens, signs of temperature stress, would provide valuable insight into the contribution of freshwater stressors prior to reaching the ocean. Even if a high proportion of smolts survive until the ocean, they may be extremely vulnerable to only small changes in the stressors they will face during their coastal migration if they are already in poor condition when they arrive.

3. survival rates within key portions of the coastal migration would help determine where the highest levels of mortality occur, for example in the Strait of Georgia, Johnstone Strait, or Queen Charlotte Strait/Sound.
4. increased knowledge of stock-specific migration routes and timings would increase the ability to look for contrast in space and time among the stressors that different sockeye salmon stocks encounter (e.g., how often and to what extent do certain age-types within certain stocks use the Strait of Juan de Fuca).
5. increased knowledge of the migration route and timing of the **Harrison stock** would provide a particularly valuable contrast to other Fraser River sockeye stocks for two reasons: 1) the life history of the Harrison stock is quite different from all of the other stocks, and 2) this stock has demonstrated an increase in productivity while almost all other stocks have shown decreasing productivity.
6. estimates of the total consumption of sockeye salmon by particular species of marine mammals should be calculated, based on the current knowledge about the consumption rates of sockeye salmon and other prey species, the bioenergetics of those marine mammals, and their population. Such calculations would provide a better indication of the cumulative potential impact of predation by marine mammals on sockeye salmon populations.

All of these elements represent critical gaps in our understanding of the life history of Fraser River sockeye salmon, where neither the current situation nor historical conditions are well understood. Knowing the natural baseline for these elements would better inform our understanding of how patterns have changed, but data collected now can only inform our understanding of the current reality.

4.5 Stage 4: Growth in North Pacific and Return to Fraser

This stage covers the growth and maturation of sockeye salmon in the North Pacific Ocean and their return back to the Fraser River.

4.5.1 Plausible mechanisms

As shown in the conceptual model (Figure 3.3-1) potential factors affecting Stage 4 include: 1) **pathogens and disease**; 2) **predators**, 3) **marine conditions**, 4) **climate change**, and 5) Strait of Georgia habitat conditions (including marine conditions and **human activities and development** in the surrounding area). There are cause-effect mechanisms by which each of these factors could at least *potentially* affect the health and survival of immature and mature sockeye salmon in the North Pacific Ocean and adults returning to the Fraser River, as described below. In general, the potential mechanisms in this stage are similar to those described for Stage 3 (Section 4.4) above.

The high risk **pathogens** described earlier are known or suspected to potentially affect both juveniles and adults. However, although *Parvicapsula minibicornis* has been documented to be highly prevalent in sockeye salmon smolts, it is not found in adults, which suggests that mortality due to this pathogen occurs within the early marine phase (Kent, 2011). Overall, very little is known about pathogens and disease in the marine environment (Kent, 2011).

The potential mechanisms for **predators** to affect sockeye salmon populations are the same as above (increased abundance, increased predation rate, or decreases in alternate prey) but the assemblage of potential predators is different. Christensen and Trites (2011) identify salmon shark and daggertooth as key predators of adult sockeye salmon that could plausibly have had an increasing impact on sockeye salmon populations. Sockeye salmon is known to comprise a large portion of the diet of salmon sharks. Blue sharks do not specialize on sockeye salmon, but do eat salmon in general and are much more abundant than salmon sharks. On the return journey back to the Fraser, there are many **marine mammals** that will prey on adult salmon. In some cases, sockeye salmon do not appear to be a substantial portion of any of their diets but, as illustrated by the spiny dogfish example in Section 4.4.2, this does not necessarily imply that such predators do not have an impact on sockeye salmon. The effect of any predator on sockeye depends on the predator's abundance, the proportion of the predator's diet which consists of sockeye salmon, and the resulting total biomass of sockeye consumed by the predator. Data collected by P.F Olesiuk (unpublished) on Steller sea lion scat samples was presented at both the PSC workshop and the Cohen Commission workshop. These data show that adult salmon is a common component of the diet of Steller sea lions, being found in approximately 12-30% of samples, varying by season (Peterman et al. 2010, A. Trites, workshop presentation). These samples were not identified by species. Other research has suggested that salmon represent approximately 10% of the overall diet of Steller sea lions, and that sockeye salmon contribute to 9% of that portion (i.e. 0.9% of the total diet; A. Trites, workshop presentation). However, since Steller sea lions consume a large amount of biomass, a small proportion of that consumption could still plausibly have a meaningful effect on sockeye salmon. The technical report on predators did not include estimates of total sockeye consumed by Steller sea lions. The bird predators described above are not relevant to this life stage. Returning adult sockeye salmon are a very different prey then their earlier post-smolt forms: larger, but fewer and faster.

The biological and physical **ocean conditions** are fundamentally important for the health and survival of maturing sockeye salmon in the North Pacific Ocean. For example, ocean temperature has a critical influence on bioenergetics for sockeye salmon (McKinnell et al., 2011). The thermal limit hypothesis describes the role that ocean temperature has in limiting the geographic range of sockeye salmon in the North Pacific, and suggests how this range may be reduced by warming ocean temperatures due to climate change. But McKinnell et al. (2011, Section 3.5) critique this theory because it does not consider the ability of sockeye salmon to seek cooler ocean temperatures simply by moving deeper. Inter-annual and inter-decadal variation in ocean temperature and biological productivity are known to have substantial impacts on many marine species (McKinnell et al., 2011).

Such variability in ocean conditions may be further exacerbated by **climate change**. For example, in recent decades the Pacific Decadal Oscillation has been exhibiting more frequent oscillations between phases (Hinch and Martins, 2011, Section 1.5). Hinch and Martins (2011) suggest that "it seems that interannual variations in climate conditions have contributed to the extreme variation in the abundance of returning adults that were observed in 2009 and 2010".

Habitat conditions in the Strait of Georgia, including marine conditions and **human activities and development** are obviously not factors during the open ocean phase, but the same mechanisms described in Section 4.4 are relevant for returning adults. Returning adults may potentially be more resilient to some of the stressors encountered through the Strait of Georgia, especially since returning individuals are those that have survived the early marine phase and two winters in the open ocean.

4.5.2 Exposure of Fraser River sockeye to stressors

The ability to assess the exposure of Fraser River sockeye salmon to various potential stressors in the open ocean and return journey to B.C. coastal waters is severely limited by lack of knowledge of the distribution of sockeye salmon during this stage. McKinnell et al. (2011, Section 1.3) describe the lack of systematic monitoring and report that "there are virtually no observations of Fraser River sockeye salmon during about 75% of their life at sea and the value of coincidental samples taken during their emigration from the Strait of Georgia is debatable". Aside from the following case where there is some information with which to evaluate exposure, one must simply assume that the Fraser River sockeye salmon have been exposed to the mechanisms described above.

The evidence presented by Christensen and Trites (2011) shows that for **marine mammal predators** there has not been exposure to California sea lions because they are not present along the southern coast of BC during the summer. However, Steller sea lions have a large population distributed along with the northern and western coasts of Vancouver Island during the summer and the total population for BC and southeast Alaska may be upwards of 60,000 (Peterman et al.

2010) and the Strait of Georgia has the highest harbor seal density anywhere in the world, implying exposure to both of these potential predators.

The data on Fraser River sockeye salmon recruits, by stock and by age-type (i.e. differentiating among fish that enter the ocean or return from the ocean earlier or later than the dominant behavior pattern), suggest that since the mid-1970s or early 1980s, the variability in the proportion of sockeye salmon returning at age-5 (rather than the dominant age-4) has been increasing. Figure 4.5-1 shows the proportion of adults returning in year 5 for the Early Stuart stock, as one example of this pattern. This particular example demonstrates several general patterns: 1) after 1980, the proportion of the stock returning in year 5 is never zero; 2) the average proportion of sockeye spending an additional year in the ocean before returning to spawn appears to be increasing over time, especially after approximately 1980; 3) the year-to-year variability also appears to be increasing after approximately 1980; and 4) there are occasional years where the proportion of Year-5 sockeye is several times greater than average. Rigorous statistical analyses of this potential phenomenon have not been conducted in the present project, but preliminary investigations have found that to varying degrees these types of patterns also appear to occur within many other Fraser River sockeye salmon stocks. This warrants further analysis, because if these patterns are shown to be consistent across stocks, it would present evidence suggesting that Fraser River sockeye salmon have been increasing the duration of their exposure to potential stressors encountered in the open ocean.

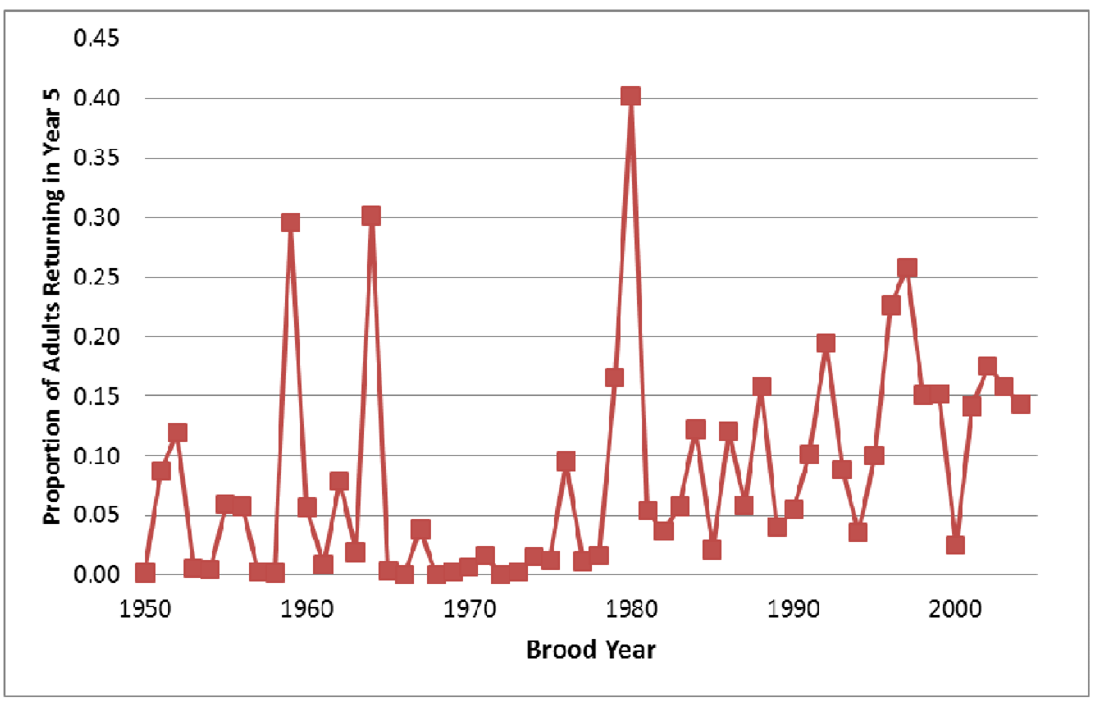

Figure 4.5-1. The proportion of Early Stuart sockeye returning as 5-year old adults.

Historically, the majority of returning adults migrated through the Strait of Juan de Fuca on the return journey to the Fraser River, whereas a smaller portion would return via the "northern diversion" through Johnstone Strait. Returning via the Strait of Juan de Fuca potentially results in reducing the duration of exposure to potential stressors within the Strait of Georgia and eliminating exposure to potential stressors within Queen Charlotte Strait and Johnstone Strait on the return journey. However, the balance of these alternate behaviours also appears to have changed substantially over the past few decades. Figure 4.5-2 demonstrates that the proportion of sockeye salmon returning via the "northern diversion" has increased markedly over time, from approximately 10-20% in the 1950s and 1960s, to upwards of 80% in many of the years since the late 1970s. The obvious increase in the variability evident in Figure 4.5-2 suggests that some underlying driver changed in the late 1970s. The reason that sockeye salmon might "decide" to take one route versus the other and the point at which the decision is made both remain unknown, but it appears that greater use of the northern diversion may be associated with warmer coastal ocean temperatures (McKinnell et al., 2011, Section 4.6).

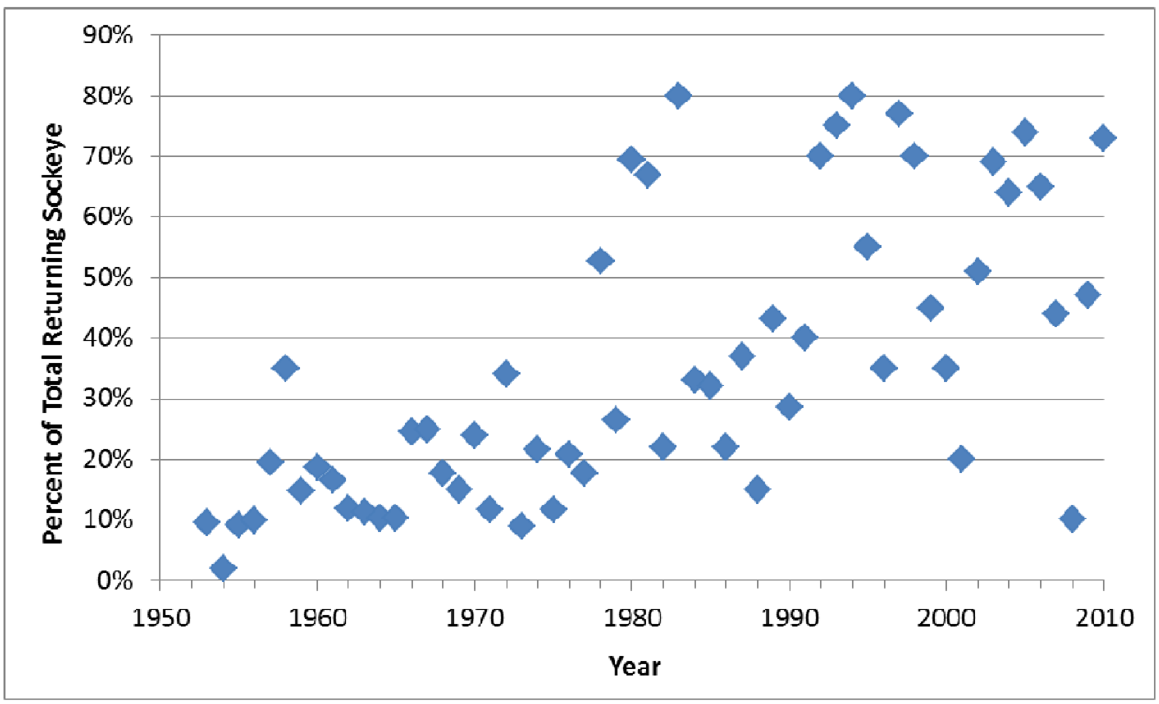

Figure 4.5-2. Time series of the percentage of Fraser River sockeye salmon that migrate via the northern diversion (Johstone Strait). Source: Pacific Salmon Commission unpublished data.

Whereas the Cohen Commission scientific projects are looking at changes in sockeye productivity and returns as the primary response variable, changes in both ocean residency and migration route are other potential responses that may be driven by similar factors and conditions. Understanding how these other response patterns have been changing over time, and the mechanisms responsible, may help to clarify some of the underlying mechanisms contributing to changes in the Fraser River sockeye productivity.

4.5.3 Correlation/consistency with patterns in Fraser River sockeye productivity

Virtually no data exists to assess changes in the abundance, prevalence, or spatial distribution of important **pathogens and diseases** over time (Kent, 2011).

Christensen and Trites (2011) did not test for any statistical relationships between **predator** abundance and the observed patterns in sockeye salmon abundance or productivity. The concerns expressed in Section 4.4.3 regarding using predator abundance as a proxy for predator impact apply equally in this stage, as does the issue regarding the difficulty in accessing the potential impact that a relatively abundant predator might have on a relatively rare prey. Christensen and Trites (2011) report data that show that blue shark abundance has been increasing over recent decades. The abundance of salmon sharks and daggertooth, which are both potentially much more important predators, are thought to have been increasing over recent decades, possibly in a similar pattern to blue sharks, although there are no data on their abundance (V. Christensen, pers. comm.). Marine mammals have increased substantially over the past several decades and many species have now returned to historic highs; however, the effect of these large increases on sockeye salmon are uncertain and will vary among species depending on their actual consumption of sockeye salmon.. Similar to the previous stage, there is an overall shortfall of data on most fish and bird predators, with the exception of a few commercially important species (Christensen and Trites, 2011). However, there have been substantial declines in populations of walleye pollock, Pacific cod, Pacific jack mackerel, Pacific mackerel, and Pacific hake, the predators of which might consider sockeye salmon as an alternate prey if their preferable prey are becoming less abundant (Christensen and Trites, 2011).

Ocean conditions are subject to high frequency variability superimposed upon lower frequency patterns and thus “oceanographic variability is variable” (S. McKinnell, workshop presentation). This variability means that although the spatial scale of sockeye migrations corresponds with an oceanographic spatial scale, it may be difficult to find cases where there is a clear correlation between sockeye salmon patterns and oceanographic conditions (S. McKinnell, workshop presentation). However, the return timing of Fraser River sockeye salmon stocks has been shown to be associated with large-scale climate patterns in the North Pacific Ocean (McKinnell et al., 2011). In 1991/1992, many oceanographic patterns were observed to change in synchrony, marking the onset of what McKinnell et al. (2011) describe as a persistent oceanographic change, including increases in spring and summer sea surface temperature and increases in sea surface salinity. There is much evidence that very warm years tend to negatively affect certain characteristics of Fraser River sockeye salmon biology (McKinnell et al., 2001, Section 3.5). This broad scale shift in oceanographic conditions coincides with a "shift" in median Fraser River sockeye salmon productivity that may have also occurred in 1992. McKinnell et al. (2011) propose that the underlying pattern of a marked shift in productivity occurring in 1992 provides a better fit to the observed productivity data than does the idea of a gradual decline over time and that there are other comparable sockeye stocks on the west coast that exhibited similar declines beginning in 1992, though many of those stocks subsequently demonstrated recovery with the 1998/99 la Niña. In 2007, the Gulf of Alaska was generally cool, which is not consistent with the poor returns observed in 2009. In terms of **biological ocean conditions**, McKinnell et al. (2011) state that for the open ocean, "there is no trend in average nutrient concentrations in the southern Gulf of Alaska (Station Papa) since the 1950s, no trend in average chlorophyll a since 1998, and no trend in average zooplankton biomass.

Hinch and Martins (2011) report that it is possible that the survival of immature sockeye salmon has decreased in association with **climate change**. Although there are no lab data and little field data on the response of adult sockeye to climate change in the open ocean, it does appear that Fraser River sockeye salmon survival is negatively correlated to the sea surface temperature of their last few months at sea (Hinch and Martins, 2011, Section 1.4). They further report that sea surface temperatures in the Strait of Georgia and the Gulf of Alaska have been consistently increasing since the 1950s, while sea surface salinity and pH have been decreasing over the same period (Hinch and Martins, 2011, Section 1.5). However, there is also evidence that much of the observed warming trend can be attributed to the 1977-1997 positive phase of the PDO, rather than longer-term changes in climate (Hinch and Martins, 2011, Section 1.5).

Returning Fraser River sockeye salmon will encounter the same potential stressors associated with **human activity and development** surrounding the Strait of Georgia as described in Section 4.4, though the extent of this exposure will vary based on the rate of northern diversion, as described above in Section 4.5.2.

4.5.4 Correlation/consistency with patterns in non-Fraser River sockeye productivity

Our comments here are identical to those for Stage 3 in section 4.5.3. Many other sockeye stocks share the same habitat of the North Pacific Ocean with Fraser River sockeye salmon. Stocks that share both geographic and temporal overlap in the open ocean will likely encounter similar pathogens, predators and ocean conditions during this stage. The extent to which such stocks show similar trends in productivity to those of the Fraser River (see Peterman and Dorner, 2011) would provide evidence supporting the importance of these stressors. In examining the patterns over 64 Fraser and non-Fraser sockeye populations from Washington to SE Alaska, Peterman and Dorner (2011; pg. 3) comment that: "The large spatial extent of similarities in productivity patterns that we found across populations suggests that there might be a shared causal mechanism across that large area.", though they acknowledge that further work is required to test this hypothesis. The Cohen Commission technical reports do not however include analyses of the relationships between stressors at this stage and productivity indices for non-Fraser River sockeye.

4.5.5 Other evidence

The relevant technical reports do not present any further evidence for factors contributing to long-term declines in sockeye salmon that fit within the WOE evaluation framework utilized (i.e. thresholds, specificity, experiments, or removals).

4.5.6 Conclusions

Table 4.5-1 shows a summary of the results of the weight of evidence evaluation of potential contributing factors encountered in this stage of growth in the North Pacific and return to the Fraser River. All of the potential factors in this life stage have plausible mechanisms. There are virtually no data on exposure for **pathogens** making *no conclusion possible.* Identical to the previous stage, the evidence presented suggests that sockeye salmon returning through the Strait of Georgia have little direct exposure to **human activities and development**, leading to a conclusion that it is *unlikely* that these factors have contributed to the decline of Fraser River sockeye salmon. Sockeye salmon have been exposed to predators, marine conditions, and climate change during this open ocean phase. There has been no evidence presented on any correlations between key predators and sockeye salmon survival. However, over the same time period that Fraser River sockeye salmon productivity has been decreasing, some important predators appear or are believed to be increasing in abundance, many potentially important alternate prey have been decreasing, and marine mammals have been increasing substantially (although it is believed there is no relationship with the changes in sockeye salmon population). It therefore remains *possible* that **predators** have contributed to the observed declines in sockeye salmon. Both technical reports addressing marine conditions, as well as the report addressing climate change, show or reference research that shows correlations with sockeye salmon patterns, but present no further evidence on thresholds, specificity, experiments, or removals. **Marine conditions** and **climate change** remain *possible* contributors to the long-term decline of Fraser River sockeye salmon. Peterman and Dorner's analyses of **delayed density dependence** were applied to total productivity over the whole life cycle. Therefore, their conclusions that delayed density dependence is unlikely to have been a primary factor causing productivity declines (discussed in section 4.2 for life stage 1) reflects the net effect across all life history stages. **Aquaculture** was not considered in our report as the Commission Technical reports on this potential stressor were not available, but will be considered in an addendum to this report.

Table 4.5-1. Evaluation of the relative likelihood that potential stressors encountered by Fraser River sockeye salmon during their growth and maturation in the ocean and return to the Fraser River (Stage 4) have contributed to overall declines in productivity in recent decades. See section 4.7 for further statistical analyses relevant to the correlation/consistency column.

Factor	Mechanism	Exposure	Correlation/Consistency	Other Evidence	Likelihood
Pathogens	Yes	No data	-	-	No conclusion possible
Predators	Yes	Yes	No data	No data	Possible
Marine Conditions	Yes	Yes	Yes	No data	Possible
Human Activities and Development (Sog)	Yes	No	-	-	Unlikely
Climate Change	Yes	Yes	Yes	No data	Possible

4.5.7 Key things we need to know better

There are several elements about the life history of Fraser River sockeye salmon that are poorly understood and inhibit a better understanding of the contribution of key stressors in this life stage to the overall decline in the population.

1. estimates of the abundance of sockeye salmon reaching the Gulf of Alaska would help distinguish mortality occurring during the open ocean phase from mortality potentially occurring earlier prior to leaving the continental shelf.
2. information on the health and condition of sockeye salmon reaching the Gulf of Alaska, including size, contaminant and disease burdens, signs of temperature stress, would provide valuable insight into whether the population is in such poor condition that it would be vulnerable to even moderate stresses or in such good condition that it would require stressors with very substantial impacts to affect the population in this stage.
3. better understanding of the spatial and temporal distribution of sockeye salmon in the Gulf of Alaska would guide researchers on where to focus greater attention while looking for potential changes in ocean conditions, predators, etc.

4. increased data on biological ocean conditions would increase the ability to determine the broad scale impacts of variability in physical and ocean conditions and changing climate on the whole ecosystem.
5. integrated ecosystem models and bioenergetic models could help increase understanding of relationships among predators, prey, and food resources, under both presumed current conditions and hypothesized future conditions. In most cases there are not enough basic data available to accurately develop such models but often they can still offer insight into which uncertainties are most important to resolve.
6. analyses of differences in the duration of ocean residency as for each of the Fraser River sockeye salmon stocks with data on recruits by age type would show whether or not the proportions of stocks remaining an extra year in the ocean are changing, and how these proportions may very among stocks and years.

Items 1-5 represent critical gaps in our understanding of the life history of Fraser River sockeye salmon, where neither the current situation nor historical conditions are well understood. Knowing the natural baseline for these elements would better inform our understanding of how patterns have changed, but data collected now can only inform our understanding of the current reality. Item 6 is different in that such analyses could be performed with the available data, but have not been done within the Cohen Commission scientific projects.

4.6 Stage 5: Migration back to Spawn

Stage 5 includes the period from the time returning adult sockeye enter the Fraser River to the time that they spawn. En-route mortality is estimated as the difference between spawner abundance estimates at Mission and on the spawning ground, after accounting for in-river harvest upstream of Mission. Pre-spawn mortality is the rate of mortality of female spawners that arrive on the spawning ground but fail to spawn, dying with most of their eggs retained in their body.

4.6.1 Plausible mechanisms

As illustrated in the conceptual model (Figure 3.3.2-1), the stressors of potential concern include: **climate change**, which alters **temperatures** in the Fraser River increasing **en-route** mortality and impacts from **pathogens**; **pre-spawn mortality; habitat conditions** in both the Lower Fraser River and migratory corridors; and **contaminants**.

Some of the above-described mechanisms have well-established interactive effects. Strong river flows and warm temperatures demand considerable energy expenditures for returning spawners.

There is indisputable evidence of the links between **increasing temperatures and en-route mortality**, as summarized by Hinch and Martins (2011), who also note that infection and disease have been implicated as a major cause of migration mortality. English et al. (2011; Executive Summary) note that en-route mortality is highest where high temperatures, river constrictions, and in-river fisheries co-occur. Kent (2011) concludes that if there has been a large increase in mortality caused by the high risk **pathogens** he identified, it is likely due to environmental changes that increase both their prevalence and sockeye susceptibility to such pathogens. He notes that both of these shifts could be triggered by changes in water temperatures. Miller et al. (2011) found that returning spawners with a genomic signature indicative of stress, possibly due to a virus, suffered higher rates of en-route mortality than adult fish without this signature.

Nelitz et al. (2011) and Johannes et al. (2011) summarize the **habitat stressors** experienced along the migratory corridor, and outline the various mechanisms by which sockeye could be affected. MacDonald et al. (2011) summarize the mechanisms by which **contaminants** could potentially affect returning spawners.

4.6.2 Exposure of Fraser River sockeye to stressors

Hinch and Martins (2011) summarize changes in the exposure of returning spawners to high temperatures. Both temperatures and flows have changed over recent decades as a result of climate change, shifting away from the historical ranges and timing to which each stock has evolved. Summer water temperatures in the Fraser River are 2.0^{o}C warmer compared to 60 years ago, with roughly a 0.7^{o}C average increase during the last two decades (Figure 4.6-1). The rate of temperature change is increasing, as 13 of the last 20 summers have been the warmest on record. While there have been no significant changes in the total flow accumulated over the summer season, more of this total flow is arriving earlier in the year. One measure is the date at which the first half of the cumulative summer flows occurs, which is happening a day earlier per decade**.** Temperature tolerance varies among stocks, but in general survival begins to decline above 15^{o}C, and rapidly worsens above 17-18^{o}C. Surprisingly, the Summer stocks that experience the highest temperatures (Figure 4.6-1) have shown the lowest levels of en-route mortality (Figure 4.5-2), presumably because they are better adapted to warmer temperatures.

For several stocks of Late run sockeye, the effects of increasing temperatures have been exacerbated by their tendency in many recent years (since 1995) to enter the river 3-6 weeks earlier than normal (dashed line at top of Figure 4.6-1; from Hinch and Martins 2011). Regardless of the hypothesized factors driving this behaviour (e.g., ocean conditions, advanced maturation, physiological stress from pathogens, Late runs joining Summer run schools), it increases the exposure of these Late run stocks to temperatures up to 5^{o}C higher than their thermal optimum, with longer exposures to freshwater diseases and parasites. Weaver Creek sockeye, one of the Late Run stocks, have lost of 50 to 100% of their total run due to en-route mortality, with higher mortality rates generally occurring in the years with earliest migration (Hinch and Martins 2011, Figure 2.2).

Hinch and Martins (2011; section 1.7.1) cite climate model studies predicting that summer water temperature in the Fraser River may warm by ~ 2.0^{o}C over the next 100 years, with a worsening of en-route mortality. Other research studies predict that the number of days per year exceeding salmonid critical temperatures may triple in the Fraser River over the next 100 years and more than 90% of a stock may be forced to migrate under suboptimal temperatures for physiological performance.

The methods of estimating exposure to contaminants and habitat stressors along the migration corridor have already been described in section 4.3 for Stage 2 (smolts).

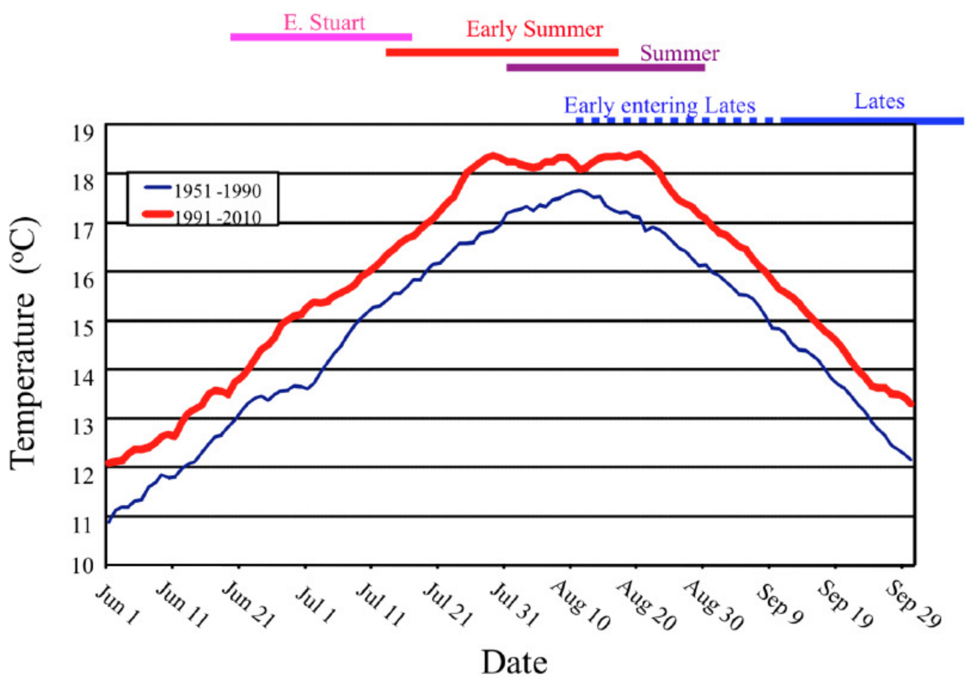

Figure 4.6-1. Daily average temperature in the lower Fraser River averaged among years within two time periods (thick line: 1951-1990; thin line: 1991-2010) over the summer months. The period of entry and passage in the lower Fraser River for the four main run timing groups are indicated by solid lines above the figure. Since 1995, segments of all Late-runs have been entering the river much earlier than usual and this is indicated by the dashed line. Source: Hinch and Martins (2011; Fig. 2.8)

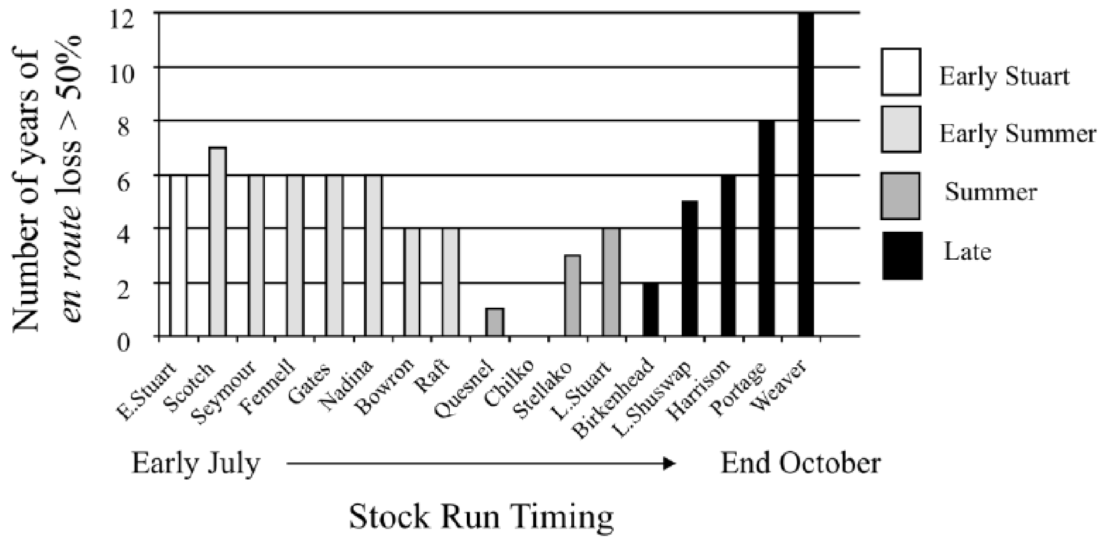

Figure 4.6-2. Number of years that *en route* loss by adults exceeded 50% for the major Fraser River sockeye salmon stocks from 1996-2008. Stocks are ordered based on run timing into the Fraser River with run-timing groups indicated. These data are based on the percent of potential spawners that had migrated past the Mission hydroacoustic facility but were not detected on spawning grounds (i.e. they are based on escapement discrepancies). Source: Hinch and Martins (2011; Figure 2.7)

4.6.3 Correlation/consistency with patterns in Fraser River sockeye productivity

En route mortality began to be reported in 1992 for Early Stuart, Early Summer and Summer runs, and in 1996 for Late-runs, and has increased substantially in recent years with particularly serious impacts on the earlier and later stock groups (Figure 4.6-2). While the timing of en-route mortality coincides generally with the Fraser sockeye situation, the life cycle productivity and post-juvenile productivity indices already account for en-route mortality (i.e., recruits = spawners + harvest + en-route mortality, as described in section 4.1). Declines in these productivity indices therefore reflect factors other than en-route mortality. Therefore, there is no point in examining correlations between en-route mortality and life cycle or post-juvenile productivity indices within the same generation. The only possible effect on productivity indices worth exploring are inter-generational effects, discussed in the next paragraph.

En-route mortality affects **spawning abundance and harvests**, both critical components of the Fraser sockeye fishery, which is the focus of the Cohen Commission. Fishery managers have deliberately reduced harvest to compensate for en-route mortality and allow sufficient spawning. Without en-route mortality, harvests and/or spawning escapements could have been considerably higher during the last two decades (Hinch and Martins 2011; Section 2.10). Hinch and Martins (2011) note that migrating females perish at much higher rates than males during years with stressful conditions, which could substantially affect the numbers of effective female spawners and therefore the total recruits in the following generation (though perhaps not recruits/spawner). It is also possible that sub-lethal but stressful conditions could affect the quality of eggs and fry of the next generation, which could affect recruits/spawner, though results to date exploring this question are limited and equivocal. Therefore, en-route mortality is clearly correlated with the decline in the Fraser fishery, though not with indices of productivity.

With respect to conditions in 2009 and 2010, Hinch and Martins (2011) note that river temperatures were well above average in 2009, exceeding 18^{o}C during the period from a four week period from late July to late August, and that at least 50-60% migrated in-river earlier than their historical timing. While data are not yet available on 2010 en-route mortality, river temperatures were also warm, though not as stressful as in 2009. The big difference between 2009 and 2010 was in the number of returning spawners, which is assessed prior to en-route mortality.

Hinch and Martins (2011) found no clear indication that **pre-spawn mortality**, at the run-timing level, has been increasing over the recent few decades in concordance with increasing en route mortality, with the possible exception of the past 25-year trend in Late-run pre-spawn mortality that shows a general increase but with high variability.

There are not sufficient data to examine correlations between **disease** in returning spawners and various productivity indicators, or with en-route mortality. Hinch and Martins (2011) note that mortality rates from a parasitic kidney disease increase in Weaver Creek Late-run sockeye as they are exposed to higher temperatures (measured as accumulated degree-days), and that bacterial infections causing gill damage are more common as temperatures increase. Thus, Fraser temperature data may be a useful proxy indicator of both en-route mortality and disease impacts.

As for Stages 1 and 2, the available evidence does not support the hypothesis that exposure to **water contaminants** during the upstream spawning migration could be a contributing factor to declines in Fraser sockeye productivity (MacDonald et al. 2011, Section 5.4). The post-juvenile index of sockeye productivity declined with increasing values of a water quality index for the upstream migration period (i.e., the opposite pattern from what one would expect if contaminants were a cause of the productivity declines). There was no relationship between the water quality index and the full life cycle index of productivity.

When examining correlations between **life cycle productivity and summer air temperature** across adult migration, Nelitz et al. (2011; Section 4.2; Table 17) found that 16 stocks of 18 Fraser stocks had negative correlations (i.e., years with warm summer air temperature along the migration corridor tended to be associated with years of lower total productivity), though only 1 correlation was statistically significant. As described in section 4.3 of this report (Stage 2), Nelitz et al. (2011) found that the length of the migratory route was also negatively correlated with life cycle productivity, though the causes of this correlation are unknown. Since the life cycle productivity index already accounts for en-route mortality, it should already account for mortality generated by the duration and magnitude of exposures to high temperatures during the upstream migration. Thus while the patterns in these two negative correlations are consistent with the hypothesis of temperature stress on returning spawners, the true causes of these correlations are unclear, and may reflect other driving forces.

4.6.4 Correlation/consistency with patterns in non-Fraser River sockeye productivity

The Cohen Commission contractors did not examine estimates of en-route mortality, habitat conditions, contaminants or disease for non-Fraser River sockeye stocks. There are good estimates of the survival rates of returning Okanagan sockeye from radio-tracking studies (e.g., Naughton et al. 2003).

4.6.5 Other evidence

Other evidence includes literature demonstrating thresholds, an understanding of the specific form of response of sockeye to certain stressors (i.e., helping to accept or reject different suspected causes), experiments demonstrating cause-effect linkages, or positive sockeye responses following the removal of a stressor. Unlike for many of the stressors discussed for previous life history stages, there is an impressive and convincing body of evidence demonstrating the mechanistic links between increasing temperatures and en-route mortality, which is reviewed by Hinch and Martins (2011). This evidence includes laboratory and field experiments showing temperature thresholds for different stocks (e.g., Figures 2.9 and 2.10 in Hinch and Martins 2011), physiological investigations, and detailed studies of the survival, temperature exposure and health of radio-tracked spawners.

4.6.6 Conclusions

Table 4.6-1 shows our conclusions regarding the effects of each stressor on life history stage 2 (smolt migration from rearing habitats to the Fraser Estuary). Again, our conclusions relate to the **overall trends** in sockeye productivity over the last two decades. In the correlation/consistency column we distinguish between 3 different sets of measures of impact on the Fraser sockeye fishery: a) life cycle and post-juvenile productivity indices; b) harvest; and c) escapement. Peterman and Dorner's analyses of **delayed density dependence** were applied to total productivity over the whole life cycle. Therefore, their conclusions that delayed density dependence is unlikely to have been a primary factor causing productivity declines (discussed in section 4.2 for life stage 1) reflects the net effect across all life history stages.

While the timing of **en-route mortality** coincides generally with the Fraser sockeye situation, the Fraser sockeye productivity indices already account for en-route mortality (i.e., recruits = spawners + harvest + en-route mortality). The only possible effect on productivity indices worth exploring are inter-generational effects, for which the evidence is limited and equivocal. We therefore conclude that it is *unlikely* that en-route mortality or pre-spawn mortality are a primary factor in declining indices of Fraser sockeye productivity. However, en-route mortality has definitely had a significant impact on the sockeye fishery and the numbers of adult fish reaching the spawning ground, particularly for the Early and Late runs. **Pre-spawn mortality**, **habitat**, and **contaminants** are *unlikely* to be responsible for the overall pattern of declining sockeye productivity; *no conclusion is possible* regarding **pathogens** due to insufficient data. None of the factors assessed for this life history stage are likely to have shown significant changes between 2009 and 2010.

Table 4.6-1. Evaluation of the relative likelihood that potential stressors encountered by Fraser River sockeye salmon from the time returning adults enter the Fraser Estuary to when they spawn (Stage 5) have contributed to the overall decline of the population in recent decades. Since various habitat measures are identical to Table 4.3-1, they have been grouped together. Correlation/consistency column includes 3 different sets of measures of impact on the Fraser sockeye fishery: a) life cycle and post-juvenile productivity indices; b) harvest; and c) escapement.

Factor	Mechanism	Exposure	Correlation/Consistency	Other Evidence	Likelihood
Habitat[d]	Yes	Yes	No	No	Unlikely
Contaminants	Yes	Yes	No	Yes	Unlikely
Pathogens	Yes	Few data	Not done	Yes	No conclusion possible
Climate change, temperatures & en-route mortality	Yes	Yes	Yes [b,c] n.a. [a]	Yes No	Definitely [b,c] Unlikely [a]
Pre-spawn mortality	Yes	Yes	No [a, b,c] (only increased in Late run)	Mixed	Unlikely [b,c] Unlikely [a]

[a] life cycle and post-juvenile productivity indices already incorporate en-route mortality, so correlations are not applicable. Available (limited) data does not show that en-route stress has intergenerational effects.
[b] harvest
[c] escapement
[d] Habitat row includes evidence from both Technical Report 3, discussing all Fraser sockeye conservation units (Nelitz et al. 2011) and Technical Report 12 (Johannes et al. 2011) discussing the Lower Fraser. This row summarizes all of the rows reported in Table 4.3-1.

4.6.7 Key things we need to know better

Hinch and Martins (2011) recommend the following improvements in knowledge for this life history stage:

- improved estimates of spawning, both in-season and post-season;
- continued tagging programs for direct and accurate estimates of survival;
- en route mortality estimates for additional stocks;
- research on the extent and consequences of gender differences in upstream survival;
- impacts of fisheries capture and release/escape on en route and pre-spawn mortality;
- cumulative impacts, carry-over and intergenerational effects;
- climate change modelling to quantify the impact of future climate warming on Fraser River sockeye salmon productivity and abundance;
- how sockeye salmon might adapt to climate change; and
- management strategies to maximize the potential for persistence of sockeye under increasing stress from climate change.

In addition, English et al. (2011) recommend the following activities for fisheries management, which pertain largely to this life history stage:

- improving the documentation of harvest by all sectors;
- working with First Nations and recreational fishers to minimize the impact of in-river fisheries on released fish;
- improved escapement goals (by stock and run-timing group) and in-season management models; and
- improved documentation of escapement monitoring

4.7 Effects over Entire Life Cycle

The previous five sections explore the relative importance of different potential contributors to sockeye mortality within each life stage, and also discuss potential interactions among these factors. In this section we build on the previous sections with a qualitative discussion of the potential for cumulative effects over the entire life cycle, and summarize the results of our quantitative analyses, which assess the relative importance of different potential contributors over the entire life cycle.

4.7.1 Qualitative assessment of the potential for cumulative effects over the entire life cycle

The conceptual model (Figure 3.3-1) shows how different factors could combine to affect sockeye survival at each life history stage. The cumulative stress model (Figure 2.3-1) illustrates how effects at different life history stages can accumulate over the whole life cycle, increasing the cumulative stress on an individual salmon to the point where it dies. The accumulation of stress may be concentrated in one life history stage or distributed across multiple life history stages. The stress experienced within each life history stage may be insufficient to cause mortality, but the cumulative effect of stressors in multiple life history stages can cause death. However, mortality events at an early life history stage can also result in a compensatory reduction in competitive stress for those fish which survived, reducing their cumulative stress and increasing their chances of survival. These two sets of processes illustrated in Figure 3.3-1 and 2.3-1 (i.e., cumulative impacts from many stressors within each life history stage, cumulative effects on each fish over its life) occur concurrently within each generation of sockeye.

Table 4.7-1 summarizes the results of our analyses by life history stage. We found only two factors (marine conditions and climate change) which were *likely* to have been a primary factor in the observed declines in Fraser sockeye productivity (recruits/spawner) over the last two decades. While en route mortality has definitely had an impact on the sockeye fishery and numbers of fish reaching the spawning ground, it is *unlikely* to have affected total productivity, since en route mortality is already included in the calculation of total recruits (i.e., recruits = spawners + en-route mortality + harvest). The effects of predators during the marine phase of the salmon life cycle (stages 3 and 4 in Table 4.7-1) were judged to be *possible* primary contributors to these declines. Due to lack of data it is not possible to draw conclusions about the contributions of pathogens, which is a particularly important data gap that we discuss further in our recommendations (Section 5). Aquaculture was not considered in our report as the Commission Technical Reports on this potential stressor were not available, but will be considered in an addendum to this report. All other factors (i.e., forestry, mining, large hydro, small hydro, urbanization, agriculture, water use, contaminants, density dependent mortality, human activity and land uses in the Lower Fraser and Strait of Georgia) were judged to be *unlikely* as primary causes of long term productivity declines, though they may still have been contributory factors. That is, stressors which we consider unlikely to be primary causes of productivity declines, may combine with other factors to create sufficient cumulative stress to kill salmon (i.e., through additive or greater than additive (synergistic) interactions) in some stocks in some years.

The coastal migration phase of the sockeye's life history provides a good example of multiple stressors interacting to cause cumulative impacts. There is indirect evidence that while ocean temperatures were not high enough to directly kill sockeye smolts in the summer of 2007, these warmer temperatures may have decreased the quantity and quality of available food and increased other stressors (e.g., metabolic demands during inshore migration, vulnerability to predators, the level of pathogens and harmful algae); see McKinnell et al (2011) and Peterman et al (2010). The combined effect of all these factors may have caused significant smolt mortality in 2007, while each of them independently would have been insufficient to kill smolts. In laboratory situations there is sufficient experimental control to explore the cumulative effects of multiple factors across the full range of possible stressor combinations. However in the ocean environment, multiple stressors will tend to covary together (like those described above which all increase with warmer temperatures), so it is much more difficult to discern their relative impacts on survival.

Table 4.7-1. Evaluation of the relative likelihood that potential stressors encountered by Fraser River sockeye salmon during each life history stage have contributed to overall declines in productivity in recent decades, based on sections 4.2 to 4.6. n.a. = not applicable to a given life history stage. Note that aquaculture was not considered as the Commission Technical reports were not available, but will be considered in an addendum to this report.

Factor	Life History Stage				
	1. Incubation, Emergence and Freshwater Rearing	2. Smolt Outmigration	3. Coastal Migration & Migration to Rearing Areas	4. Growth in N. Pacific and Return to Fraser	5. Migration back to spawn
Forestry[a]	Unlikely	Unlikely	n.a.	n.a.	Unlikely
Mining	Unlikely	Unlikely	n.a.	n.a.	Unlikely
Large hydro	Unlikely	Unlikely	n.a.	n.a.	Unlikely
Small hydro	Unlikely	Unlikely	n.a.	n.a.	Unlikely
Urbanization above Hope	Unlikely	Unlikely	n.a.	n.a.	Unlikely
Agriculture	Unlikely	Unlikely	n.a.	n.a.	Unlikely
Water Use	Unlikely	Unlikely	n.a.	n.a.	Unlikely
Contaminants	Unlikely	Unlikely	n.a.	n.a.	Unlikely
Density Dependent Mortality	Unlikely	Unlikely	Unlikely[b]	Unlikely[b]	Unlikely[b]
Pathogens	No conclusion possible	No conclusion possible	No conclusion possible	No conclusion possible	No conclusion possible
Predators **L. Fraser land uses**	Unlikely Unlikely	Unlikely Unlikely	Possible n.a.	Possible n.a.	Unlikely[b] Unlikely
Strait of Georgia human activity & land uses	n.a.	n.a	Unlikely	Unlikely	n.a.
Climate Change	Possible	Possible	Likely	Possible	Definitely [c] Unlikely [d]
Marine Conditions	n.a.	n.a.	Likely	Possible	n.a.

[a] Forestry includes logging, Mountain Pine Beetle and log storage.
[b] Not addressed directly for these life stages but conclusions from section 4.2 apply across the whole life cycle.
[c] definitely affected harvest and escapement
[d] life cycle and post-juvenile productivity indices already incorporate en-route mortality in definition of recruits, so en-route mortality cannot explain trends in recruits / spawner. Available (limited) data does not show that en-route stress has intergenerational effects.

Cumulative effects may cause significant mortality in some years but not in others. For example, Miller et al. (2011) found that in 2006, returning sockeye salmon with a genomic signal indicative of poor physiological condition (and possibly related to a viral infection) were much more likely to suffer en-route and pre-spawning mortality mortality. The genomic signal detected by Miller et al. was also present in smolts during both 2007 and 2008 (Miller, handout provided to June 2010 PSC Workshop), yet those years of entry had very different marine survival rates (based on the very large difference in observed vs expected adult returns in 2009 vs. 2010). As discussed by McKinnel et al. (2011) ocean conditions in Queen Charlotte Sound and the Gulf of Alaska were much cooler in 2008 than in 2007. It may be that when ocean conditions are poor (as in 2007) disease contributes to mortality, but when ocean conditions are good (as in 2008) the fish survive despite carrying diseases.

As noted by McKinnel et al (2011), biologists rarely observe death by natural causes of Fraser River sockeye at sea. Therefore, unlike with autopsies of humans, we can generally only infer the cumulative causes of mortality through indirect evidence. Even with very detailed information on the exposure of salmon to different stressors (e.g., Petrosky and Schaller 2010), it is difficult to draw strong conclusions on the relative contributions of each factor to observed patterns of survival. Often there are multiple explanations that are generally consistent with the observed data.

4.7.2 Quantitative analyses across the entire life cycle

We performed quantitative analyses across the entire life cycle from two different perspectives – by life history stage and by stressor category. An overview of our methodology is described in Section 3.3.6, a technical description of the methodology is presented in Appendix 3 (Section 3.5.2), and the detailed results are reported in Appendix 4. In this section we provide an overview of the results of our quantitative analyses and a broad discussion of the major conclusions. First, we describe our analysis of the relative importance of different life stages in explaining variation in sockeye productivity. Second, we describe our analysis of the relative importance of categories of potential stressors across all life stages, as organized by the Cohen Commission Technical Reports.

The Relative Importance of Different Life History Stages

We analyzed data across all projects and life stages that were available for brood years 1969-2001. This particular time period was the result of the trade-off between choosing a window of analysis short enough to include a wide selection of variables and long enough to generate meaningful results with respect to the observed decline in the productivity of Fraser River sockeye salmon. To assess the relative importance of each life history stage, multiple models were tested, each of which contained all of the available variables associated with a particular life history stage (Table 4.7-2). The life history stages examined include: incubation and freshwater rearing, outmigration, coastal migration, ocean rearing, return to the Fraser, upstream migration, and spawning. Three additional models were tested within the model set: a "global" model, including all available variables for 1969-2001; an aggregate model of the freshwater life stages preceding ocean-entry; and, an aggregate model of all three marine life stages. These models were then tested using the same data set to determine which models have the greatest amount of relative support (i.e., strongest ability to explain the observed variation in sockeye productivity across years and stocks).

The results show that the aggregate marine model (M10) has the greatest relative level of support. Model M10 includes many more variables than the next two models. The AICc criterion that is used to assess the relative level of support for different models rewards models which do a better job of explaining the variation in the response variable (in our case sockeye stock productivity), but penalizes models for including more variables to explain this variation, since each additional variable requires another model parameter to be estimated. A model with high explanatory power from only a few variables would receive a strong AICc score (AICc scores are like golf; lower is better). The fact that model M10 achieves a high relative level of support despite having so many variables indicates that the extra variables are informative for explaining variation in sockeye productivity, relative to the other models included in Table 4.7-2.

Model M10 represents an aggregate of several life stages with the marine phase. We are also interested in which marine life stages appear to be most important. The models of individual life stages with the highest level of support are coastal migration (M4) and the return to the Fraser (M6). Although coastal migration ranks higher, the results show that there is roughly equal support for these two models, suggesting that both of these life stages are important in explaining the variability in the productivity of Fraser River sockeye salmon. However, the analysis scores also indicate that both of these models have marginal support relative to the aggregate marine model (M10), suggesting that there is a definite benefit to using all of the marine variables to explain variation in sockeye productivity. These results imply that factors within the marine phase are more important relative to the available freshwater factors in explaining the patterns observed in Fraser River sockeye salmon over the 1969-2001 brood years.

Table 4.7-2. Variables included in each model used to test the relative importance of different life-history stages over brood years 1969-2001.Variables in the data set are organized by life history stage. The M2 and M8 models are empty because there were no variables applicable to those life history stages available for the period of 1969-2001; however, they are maintained here in order for consistency in naming models among different time frames. LFR = lower Fraser River. SoG = Strait of Georgia.

Variables			**Models**									
			M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**
Life stage	**Stressor category (i.e. Cohen Commission Technical Report)**	**Variable Description**	**Global**	**Incubation to Lake Rearing**	**Outmigration**	**Coastal Migration**	**Growth in North Pacific**	**Return to the Fraser**	**Upstream Migration**	**Spawning**	**Aggregate Freshwater**	**Aggregate Marine**
Smolt outmigration	Contaminants	Qualitative water quality index. Stock specific.	X		X						X	
Smolt outmigration	Freshwater habitat conditions	Spring air temperature CU specific	X		X						X	
Smolt outmigration	Habitat conditions in LFR & SoG	Discharge, SoG, April total	X		X						X	
Smolt outmigration	Habitat conditions in LFR & SoG	Discharge SoG, May total	X		X						X	
Smolt outmigration	Habitat conditions in LFR & SoG	Lower Fraser total dredge volume	X		X						X	
Smolt outmigration	Predators/ Alternative Prey	Double Crested Cormorant and Common Merganser: Quantile based aggregate estimate	X		X						X	
Coastal migration	Habitat conditions in LFR & SoG	SoG discharge , June-July average (Fraser River)	X			X						X
Coastal migration	Habitat conditions in LFR & SoG	SoG discharge, May average (Fraser River	X			X						X
Coastal migration	Habitat conditions in LFR & SoG	Sea surface salinity. SoG, April-Aug average.	X			X						X
Coastal migration	Habitat conditions in LFR & SoG	Sea surface temperature. SoG, April-Aug average.	X			X						X
Coastal migration	Marine conditions	QCS discharge, June-Sept average (Wannock River)	X			X						X
Coastal migration	Marine conditions	Sea surface salinity. QCS, April-Aug average.	X			X						X
Coastal migration	Marine conditions	Summer wind regime. QCS.	X			X						X
Coastal migration	Predators/ Alternative Prey	5 marine bird species: Quantile based aggregate estimate	X			X						X
Coastal migration	Predators/ Alternative Prey	Arrowtooth flounder biomass	X			X						X

Variables			Models									
			M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Coastal migration	Predators/ Alternative Prey	California sea lion estimate	X			X						X
Coastal migration	Predators/ Alternative Prey	Harbour seal estimate	X			X						X
Coastal migration	Predators/ Alternative Prey	Steller sea lion estimate	X			X						X
Coastal migration	Predators/ Alternative Prey	Alternative prey quantile based aggregate estimate of 8 species/locations.	X			X						X
Growth in North Pacific	Marine conditions	North Pacific Index, Nov-Mar average	X				X					X
Growth in North Pacific	Predators/ Alternative Prey	Alternative prey quantile based aggregate estimate of 8 species/locations.	X				X					X
Return to Fraser	Habitat conditions in LFR & SoG	Sea surface salinity. SoG, May-Sept average.	X					X				X
Return to Fraser	Habitat conditions in LFR & SoG	Sea surface temperature. SoG, Sept average.	X					X				X
Return to Fraser	Marine conditions	Sea surface salinity. QCS, May-Sept average.	X					X				X
Return to Fraser	Predators/ Alternative Prey	California sea lion estimate	X					X				X
Return to Fraser	Predators/ Alternative Prey	Harbour seal estimate	X					X				X
Return to Fraser	Predators/ Alternative Prey	Steller sea lion estimate	X					X				X
Return to Fraser	Predators/ Alternative Prey	Alternative prey quantile based aggregate estimate of 8 species/locations.	X					X				X
Upstream migration	Climate change	Lower Fraser water temperature for returning adults.	X						X			
Upstream migration	Contaminants	Qualitative water quality index. Stock specific.	X						X			
Upstream migration	Freshwater	Summer air temperature. CU specific.	X						X			
Upstream migration	Predators/ Alternative Prey	Bald Eagle abundance.	X						X			

However, an important limitation is that the results only apply to the variables actually included in the analysis. When comparing the relative performance of competing models it is important to consider what factors have been included or excluded from a particular model. For example, within this model set, all of the freshwater life-stages had lower levels of support than all of the marine life-stages, and the aggregrate freshwater model (M9) had the least support of all. But the aggregate freshwater model is comprised only of the following variables: total Fraser River discharge for both April and May (separately), two freshwater bird predators, Fraser River dredging volume, spring air temperature at nursery lakes, and a water quality index for outmigration. The strength of any conclusion that freshwater life stages are not as important as marine life stages can only be as strong as our belief that the assemblage of variables described above is a reasonably accurate representation of the freshwater component of the life history of Fraser River sockeye salmon. The makeup of each model must be considered when interpreting the results. The limitations on data availability were such that, within the Cohen Commission technical reports, this is the best representation possible of the freshwater component over this timeframe. Improvements to the data used for the freshwater component might yield different results from the regression analysis.

The Relative Importance of Different Stressor Categories

We used the same data set as above (i.e. all available data across all projects and life stages for brood years 1969-2001) to test a different set of models, each of which contained all the available variables associated with a particular stressor category (as organized by the Cohen Commission Technical Reports): contaminants, freshwater habitat factors, marine conditions, predators/alternate prey, climate change, and habitat conditions in the lower Fraser River and the Strait of Georgia. We also tested an additional “global” model with all available variables for this timeframe.

Table 4.7-3. Variables included in each model used to test the relative importance of different stressor categories over the period of 1969-2001 (brood years). As described in the text, the first set of analyses performed did not include pink salmon (removed from M1, and no M8 tested). LFR = lower Fraser River. SoG = Strait of Georgia.

Variables			Models							
			M1	M2	M3	M4	M5	M6	M7	M8
Life stage	Life stage	Variable Description	Global	Contaminants	Freshwater habitat	Marine conditions	Predators/alternate prey	Climate change	LFR & SoG habitat	Pink salmon
Contaminants	Smolt outmigration	Qualitative water quality index. Stock specific.	X	X						
Contaminants	Upstream migration	Qualitative water quality index. Stock specific.	X	X						
Freshwater habitat conditions	Smolt outmigration	Spring air temperature CU specific	X		X					
Freshwater habitat conditions	Upstream migration	Summer air temperature. CU specific.	X		X					
Marine conditions	Coastal migration	QCS discharge, June-Sept average (Wannock River)	X			X				
Marine conditions	Coastal migration	Sea surface salinity. QCS, April-Aug average.	X			X				
Marine conditions	Coastal migration	Summer wind regime. QCS.	X			X				
Marine conditions	Growth in North Pacific	North Pacific Index, Nov-Mar average	X			X				
Marine conditions	Return to Fraser	Sea surface salinity. QCS, May-Sept average.	X			X				
Predators/ Alternative Prey	Smolt outmigration	Double Crested Cormorant and Common Merganser: Quantile based aggregate estimate	X				X			
Predators/ Alternative Prey	Coastal migration	5 marine bird species: Quantile based aggregate estimate	X				X			
Predators/ Alternative Prey	Coastal migration	Arrowtooth flounder biomass	X				X			
Predators/ Alternative Prey	Coastal migration	California sea lion estimate	X				X			
Predators/ Alternative Prey	Coastal migration	Harbour seal estimate	X				X			
Predators/ Alternative Prey	Coastal migration	Stellar sea lion estimate	X				X			
Predators/ Alternative Prey	Coastal migration	Alternative prey quantile based aggregate estimate of 8 species/locations.	X				X			
Predators/ Alternative Prey	Growth in North Pacific	Alternative prey quantile based aggregate estimate of 8 species/locations.	X				X			
Predators/ Alternative Prey	Return to Fraser	California sea lion estimate	X				X			
Predators/	Return to Fraser	Harbour seal estimate	X				X			

Variables			Models							
			M1	M2	M3	M4	M5	M6	M7	M8
Alternative Prey										
Predators/ Alternative Prey	Return to Fraser	Stellar sea lion estimate	X				X			
Predators/ Alternative Prey	Return to Fraser	Alternative prey quantile based aggregate estimate of 8 species/locations.	X				X			
Predators/ Alternative Prey	Upstream migration	Bald Eagle abundance.	X				X			
Climate change	Upstream migration	Lower Fraser water temperature for returning adults.	X					X		
Habitat conditions in LFR & SoG	Smolt outmigration	Discharge, SoG, April total	X						X	
Habitat conditions in LFR & SoG	Smolt outmigration	Discharge SoG, May total	X						X	
Habitat conditions in LFR & SoG	Smolt outmigration	Lower Fraser total dredge volume	X						X	
Habitat conditions in LFR & SoG	Coastal migration	SoG discharge , June-July average (Fraser River)	X						X	
Habitat conditions in LFR & SoG	Coastal migration	SoG discharge, May average (Fraser River	X						X	
Habitat conditions in LFR & SoG	Coastal migration	Sea surface salinity. SoG, April-Aug average.	X						X	
Habitat conditions in LFR & SoG	Coastal migration	Sea surface temperature. SoG, April-Aug average.	X						X	
Habitat conditions in LFR & SoG	Return to Fraser	Sea surface salinity. SoG, May-Sept average.	X						X	
Habitat conditions in LFR & SoG	Return to Fraser	Sea surface temperature. SoG, Sept average.	X						X	
Competition with pinks	Growth in North Pacific	Pink salmon abundance (NE Pacific)	X[14]							X[14]
Competition with pinks	Growth in North Pacific	Pink salmon abundance (Russia)	X[14]							X[14]

[14] Two sets of analyses were done with these models. Only the second set included pink salmon, as this potential stressor was not one of the factors covered within the Cohen Commission Technical Reports.

The results show that the global model (M1) had the greatest level of support. The fact that this model was ranked highest even with 18 more variables than the next model indicates that the variables associated with only a single project are not sufficient to explain the pattern in productivity. When comparing the relative performance of models representing individual stressor categories the predators/alternate prey model (M5) has the greatest level of support followed closely by the Lower Fraser/Strait of Georgia project (M7). The predator/alternate prey model reflects two possible mechanisms for affecting Fraser sockeye: changes in the abundance of predators and/or changes in the availability of alternate prey.

As discussed above, each stressor category is only represented by the available data. Many of those categories are not adequately represented. For example, “climate change” (M6) is only represented by a single variable – the delayed effect of lower Fraser River water temperature for returning adults – that does not fully capture the potential impacts of climate change on sockeye salmon over their entire life. A second example is the impact of pathogens and disease, which could potentially be an important factor but are simply not represented within any of these models due to the lack of data. Therefore it is not possible to make any conclusions at all about the relative importance of pathogens and disease compared to other stressors, which is a major weakness.

Overall, we do not believe that organizing the data by stressor category is as useful as organizing the data by life history stage. The boundaries between categories are arbitrary and many of them lack sufficient data. In the analysis organized around stressor category, none of the models had definitively higher support than the global model, which included all available variables. By contrast, when the exact same data were organized by life history stage, several of the models achieved a higher level of support than the global model.

The results of this analysis raise the important issue (mentioned in Section 3.2) about correlation versus causation. An example of this issue is found within the predators model. Christensen and Trites (2011) show that the abundance of both Steller sea lions and Harbour seals have increased substantially over the past few decades. Because the timeframe of that increase corresponds with the period over which Fraser River sockeye salmon have been declining in productivity, these measures are likely to exhibit a high degree of correlation. While it is possible, this does not necessarily mean that the increase in pinnipeds is driving down the sockeye salmon population. Alternative explanations are: some other factor is affecting both populations; or, pinniped populations have been recovering from low abundance since the banning of hunting and culling, and sockeye productivity is being driven by something else. Further study is required to determine which of these possibilities are most likely. Any factor with a strong temporal trend over the same period of time as the strong temporal downtrend in sockeye salmon productivity will likely have a high correlation (e.g., internet usage in the City of Vancouver has likely increased substantially and consistently since the early 1990s, corresponding directly to the period over which there have been substantial declines observed in the productivity of Fraser River sockeye salmon).

We performed a second analysis with one additional stressor category – the abundance of pink salmon both in the Northeast Pacific and from Russia. The analysis was extended to include pink salmon for two reasons: 1) the PSC Report found evidence for competitive effects of pink salmon on Fraser sockeye (section 4.9 in Peterman et al., 2010); and 2) the data were made available to us. The PSC report examined three potential mechanisms by which pink salmon might affect Fraser sockeye, and rejected two of these due to contradictory evidence. The remaining hypothesis is that abundant odd-year pink salmon from Alaska and Russia compete with adult Fraser sockeye on the high seas, which is consistent with the observation that Fraser sockeye spawning in odd years show poorer growth & survival than even-year Fraser sockeye.

The results from this set of analyses show that the pink salmon model (M8) and the global model (M1) appear as the strongest two models. The level of support for both of these models is similar but because they are substantially different models, the interpretation is that they provide legitimately competing models to explain the patterns observed in Fraser River sockeye salmon. The predators/alternate prey model (M5) is third, but with a lower level of support. The fact that the pink salmon model does well is in some ways not surprising: there is a scientifically supported hypothesis, with good data for the attribute that the hypothesis relates to, and the connection is specific to a life history stage.

4.8 Other Potential Factors Not Included in Cohen Commission

The projects comprising the Cohen Commission's Scientific and Technical Research Program represent an extensive but not exhaustive coverage of potential factors that may have contributed to the decline of Fraser River sockeye salmon. Table 4.8-1 lists some additional theories and potential factors that have not been explicitly included within the scope of the Cohen Commission technical reports, or this report. These additional, potentially contributing factors are presented here simply to acknowledge that other theories do exist, beyond the scope of the Cohen Commission and beyond the scope of the present report. The analyses conducted within this project do not (and could not) exhaustively represent all possible factors.

Table 4.8-1. Other factors potentially contributing to the decline of Fraser River sockeye salmon that were not considered within the spectrum of Cohen Commission technical reports. Some of these items are relatively focused questions whereas others are very broad. The list order does not represent any prioritization.

Factor	Question of Interest
Volcanic Ash	Did the 2008 eruption of the Kasatochi volcano in Alaska contribute to the record sockeye returns in 2010 by providing a natural fertilization of the ocean that resulted in greater growth and ultimately higher survival rates?
Competition with Pink Salmon*	Do odd-year pink salmon (the dominant cycle) compete with sockeye salmon for food resources during their migration overlap, resulting in diminished resources for sockeye salmon and therefore lower survival rates?
Hatchery Fish	Do large releases of hatchery fish result in increased predation of wild fish by creating high, localized concentrations of prey that attract increased numbers of predators to a place where wild and hatchery fish are mixed?
Hatchery Fish	Do large releases of hatchery fish affect ocean survival of wild fish through competition or predation?
Competitors and Food Resources	Have sockeye survival rates been reduced by increased competition for resources resulting from increased abundance of competitors and/or reduced food resources?
Early Outmigration	Have sockeye smolts been leaving lakes earlier, driven by changing climate and climate associated factors (e.g., lake thaw), then arriving "too early" to an ocean environment with insufficient resources because the phenology of key ocean characteristics has not advanced by nearly as much ?
Nursery Lake Food Supply	Has the quantity and quality of planktonic food required to maintain historical sockeye productivity declined as a result of climate change?
Unreported Fishing*	Could unreported catches of sockeye on the high seas and in fisheries outside of the Pacific Salmon Treaty fisheries have contributed to Fraser sockeye productivity declines?

* Competition with pink salmon and unreported fishing were addressed in the PSC report (Peterman et al. 2010). Evidence in Peterman et al. (2010; Section 4.9) is consistent with the hypothesis that odd-year pink salmon from Alaska and Russia compete with returning adult Fraser sockeye (Stage 4 in this report). Unreported catch is unlikely to have contributed to Fraser sockeye productivity declines (Peterman et al. 2010; Section 4.1).

5.0 Conclusion

5.1 Important Contributors to the Decline of Fraser River Sockeye

We present our conclusions for each life history stage, recognizing that there are interactions both within and between life history stages. These results do not consider aquaculture (report in progress) or other factors not considered by the Cohen Commission.

Stage 1: Incubation, Emergence and Freshwater Rearing

With the exception of **climate change**, which we consider to be a *possible* factor, and **pathogens** (for which *no conclusion is possible* due to data gaps), it is *unlikely* that the other factors considered for this stage, taken cumulatively, were the *primary* drivers behind long term declines in sockeye productivity across the Fraser Basin. These factors included **forestry**, **mining**, **large hydro**, **small hydro, urbanization, agriculture, water use, contaminants, density dependent mortality, predators,** and effects of **Lower Fraser land use** on spawning and rearing habitats. We feel reasonably confident in this conclusion because juvenile productivity (which integrates all stressors in this life history stage except over-wintering in nursery lakes) has not declined over time in the eight of the nine Fraser sockeye stocks where it has been measured. We would be even more confident if more stocks had *smolt* enumeration rather than *fry* estimates (only Chilko and Cultus stocks have smolt estimates). Though not primary drivers of the Fraser sockeye situation, each of these factors may still have had some effects on some Fraser stocks in some years (the data are insufficient to reject that possibility). We suspect, based on qualitative arguments alone, **habitat** and **contaminant** influences on Life Stage 1 were also not the *primary* drivers responsible for productivity declines occurring to most non-Fraser stocks assessed by Peterman and Dorner (2011). However, given the absence of any exposure data and correlation analyses for non-Fraser stocks, it is not possible to make conclusions on the relative likelihoods of factors causing their declining productivities. None of the factors considered for Stage 1 are likely to have been much worse in 2005 and 2006 for Fraser sockeye stocks, sufficient to have significantly decreased egg-to-smolt survival in the salmon that returned in 2009. Similarly, none of these factors are likely to have been much better in 2006 and 2007, sufficient to have substantially improved egg-to-smolt survival in the salmon that returned in 2010.

Stage 2: Smolt Outmigration

We analyzed the same factors for Stage 2 as for Stage 1 and came to the same conclusions. There are however three key differences in our analyses for these two stages. First, regardless of differences in their spawning and rearing habitats, all sockeye stocks pass through the highly developed Lower Fraser region. Second, migrating smolts are exposed to the above-described stressors for a much shorter time than are eggs and fry, which reduces the likelihood of effects. Third, since smolt migration occurs subsequent to enumeration of fry and smolts in rearing lakes, we have no analyses relating survival rates *during this life history stage* to potential stressors. Thus our conclusions have a lower level of confidence than for Stage 1. While there are some survival estimates for acoustically tagged smolts, these data (which only cover a few stocks) were not analyzed by any of the Cohen Commission technical studies. None of the factors considered for Stage 2 are likely to have been much worse in 2007 (affecting the 2009 returns), or much better in 2008 (affecting the 2010 returns).

Stage 3: Coastal Migration and Migration to Rearing Areas

There are almost no data on exposure for **pathogens** making *no conclusion possible*; this is a major data gap. The evidence presented suggests that sockeye salmon in the Strait of Georgia have little direct exposure to **human activities and development**, leading to a conclusion that it is *unlikely* that these factors have contributed to the decline of Fraser River sockeye salmon. Sockeye salmon have been exposed to predators, marine conditions, and climate change during this early marine phase. However, there has been no evidence presented on any correlations between key predators and sockeye salmon survival. Some important predators appear to be increasing in abundance, and some potentially important alternate prey appear to be decreasing, but many other known predators are decreasing or remaining stable. It therefore remains *possible* that **predators** have contributed to the observed declines in sockeye salmon. Based on plausible mechanisms, exposure, consistency with observed sockeye productivity changes, and other evidence, **marine conditions** and **climate change** are considered *likely* contributors to the long-term decline of Fraser River sockeye salmon. It is also *very likely* that **marine conditions** during the coastal migration life stage contributed to the poor returns observed in 2009. **Aquaculture** was not considered in our report as the Commission Technical reports on this potential stressor were not available, but will be considered in an addendum to this report.

Stage 4: Growth in North Pacific and Return to Fraser

Our conclusions on this life history stage are similar to those for Stage 3, though we conclude that **marine conditions** and **climate change** remain *possible* contributors to the long-term decline of Fraser River sockeye salmon (whereas in Stage 3, we considered them to be likely contributors).

Stage 5: Migration back to Spawn

While the timing of **en-route mortality** coincides generally with the Fraser sockeye situation, the Fraser sockeye productivity indices already account for en-route mortality (i.e., recruits = spawners + harvest + en-route mortality). Therefore, there is no point in examining correlations between en-route mortality and life cycle or post-juvenile productivity indices within the same generation. The only possible effects on productivity indices are inter-generational effects, for which the evidence is limited and equivocal. We therefore conclude that it is *unlikely* that en-route mortality (or pre-spawn mortality, which has only increased for Late Run sockeye) are a primary factor in declining indices of Fraser sockeye productivity. However, en-route mortality has *definitely* had a significant impact on the sockeye fishery and the numbers of adult fish reaching the spawning ground, particularly for the Early and Late runs. **Pre-spawn mortality**, **habitat changes**, and **contaminants** are *unlikely* to be responsible for the overall pattern of declining sockeye productivity. *No conclusion is possible* regarding **pathogens** due to insufficient data. None of the factors assessed for this life history stage are likely to have shown significant changes between 2009 and 2010.

The above conclusions are based on qualitative and quantitative analyses of existing information. There are two important caveats on these conclusions. First, there are major gaps in both our fundamental understanding of how various factors interact to affect Fraser River sockeye salmon, and in the data available to quantify those factors. Second, all Cohen Commission researchers have had a limited amount of time to analyze existing information; future data syntheses and analyses will likely provide deeper and different insights. Below, we summarize our recommendations for improving the data and understanding of Fraser River sockeye salmon.

5.2 Research and Monitoring Priorities

Our summary of research and monitoring priorities includes findings from both the workshop involving all Cohen Commission researchers (held Nov. 30 – Dec. 1, 2010), and our synthesis of the more detailed recommendations contained in the Cohen Commission's technical reports.

5.2.1 Results from the workshop

Workshop participants were asked to examine section 5.3 of the Expert Panel's Report to the Pacific Salmon Commission (PSC report), *Priorities for Monitoring and Research* (Peterman et al. 2010), as a starting point for a plenary discussion. Since each of the twelve projects contains recommendations specific to their topic areas, the purpose of this exercise was to broadly address priorities for monitoring and research beyond project boundaries.

The participants agreed with the PSC Panel that a co-ordinated, multi-disciplinary program should be implemented. There was consensus among the group that a focused oceanographic and fisheries research program targeting the Georgia Strait, Queen Charlotte Sound and extending along the continental shelf to the Alaska border would considerably advance our knowledge of current and future Fraser River sockeye populations. The program should focus on four core areas: 1) data collection, 2) assimilation of these data into a single, central database, 3) integrated analyses, and 4) dissemination of information.

There was widespread agreement with the PSC report that the 2009 and long-term declines in sockeye productivity were likely due to the effects of multiple stressors and factors. Future efforts should focus not only on increasing our basic biological knowledge of sockeye salmon, but should also use information gained from the cumulative effects assessment to determine priority research areas. Certain monitoring needs (research questions) can be answered with a single (one-time, annual) study; however, others require long-term effort and monitoring. A strong emphasis should be placed on studying the entire life cycle of sockeye salmon along with their potential stressors. It was noted that in some cases, additional sample collection would be straightforward to implement by simply augmenting current data collection efforts. Data collection and monitoring efforts could be extended to other salmon species as well, increasing the potential for comparative research. Unlike the PSC report, participants felt that research efforts should be expanded outside the Strait of Georgia as a priority area, as well as increasing efforts inside the Strait.

One of the resounding issues throughout the workshop was researchers' difficulty in obtaining and understanding data from existing databases. Considerable effort should be spent building and maintaining an integrated database, for both Fraser and non-Fraser sockeye stocks, with focused research and monitoring goals in mind. The database should include the historical sockeye data with clear metadata as well as data from current and future monitoring. For the database to be useful to scientists, it would need to be regularly updated and maintained. As mentioned in the PSC report, it would be critical to create a framework that would allow simultaneous coordination of research across disciplines, recognize the potential for cost-effective joint sampling programs, and promote identification of synergistic effects and interactions.

The decline of sockeye salmon in the Fraser River is an issue that has captivated the province of British Columbia. Participants felt that the proposed increase in data collection and monitoring should be followed by transparent dissemination of information to scientists and non-scientists on a regular basis. Given the potential funding of new initiatives and future findings, an annual report on the State of the Salmon should be compiled and made publicly available.

More specifically, the extended research program should be co-ordinated with a U.S. program covering those areas of the Alaskan continental shelf containing high sockeye densities. Since much of the research will augment existing research programs, funding of current programs should be maintained. Further, recommendations for research should be directly compared to current monitoring and research to determine expenditures and assess their relative merits. As emphasized in the PSC Report, new data collection and analysis techniques exist that would facilitate research efforts and increase efficiency in effort and cost.

5.2.2 Synthesis of recommendations from Cohen Commission Technical Reports

Table 5.2-1 is a synthesis of research and monitoring recommendations, based on the PSC report, discussions at the Cohen Commission workshop, the Commission's Technical reports, and this cumulative effects assessment. We have organized these recommendations by life history stage, building on the structure used in the PSC report. However, each recommendation should be seen as a component of a fully integrated, multi-disciplinary research program, essential to understanding the cumulative effects of multiple factors on the abundance of returning salmon. Specific research and monitoring recommendations for uncertainties related to aquaculture are not included in detail in Table 5.2-1, as the Commission Technical reports on this potential stressor were not available. Aquaculture will be considered in an addendum to this report.

In addition to improving the information available for each life history stage, we stress the importance of improving our ability to rapidly organize these data into a geographically and thematically linked form, and to conduct cumulative assessments which integrate effects over the entire sockeye life cycle through an appropriate mix of models and data analyses. We note that the database developed for this project (described in Appendix 3), as well as the databases developed by individual researchers working on Commission Technical Reports, are preliminary but important steps towards the goal of an integrated database. However there are some serious limitations to the types of indicators available for various stressors, in terms of their specificity for various stressors, as well as spatial and temporal coverage.

One practical strategy towards the goal of an integrated database would be to continue existing topic-specific databases (e.g., climate data, ocean conditions, stock information, contaminants, habitat data, pathogens), each maintained by the entities that have collected these data, but link key fields of each one to an integrated, interdisciplinary, geo-referenced database. The integrated database would periodically grab key variables from the topic-specific databases, and store these data within a structure that catalyzed cumulative, rapid assessments across stressors and life history stages. The advantage of this approach is that any updates made to topic-specific databases (e.g., corrections to past estimates of smolt emigration) are automatically corrected in the integrated database. This avoids the problem of having a centralized database with duplicate but out-of-date or incorrect versions of historical data. This approach is gradually being implemented in the Trinity River Restoration Program, and has also been recommended for other rivers in the Western U.S., including the Klamath, Sacramento and San Joaquin.[15] There are considerable technical and institutional challenges in setting up such an approach, but the benefits include fewer errors in data assembly, ease of inter-disciplinary integration, and much more timely application of quantitative analyses.

In addition to improving the data available for understanding both the stressors affecting sockeye and their life-stage specific survival rates, there needs to be improved application of quantitative methods to these data. The goals of these analyses should be to reduce uncertainties critical to fisheries management decisions, and to improve our retrospective understanding of the factors that have affected sockeye survival rates and productivity. The quantitative methods that we applied in this report were the simplest approaches that could be feasibly completed within the time available. A small working group could consider other methods that should be applied to the database that we've assembled (as well as future improvements to it), including: simulation and statistical approaches incorporating non-linear and non-additive interactions; functional regression analyses for continuously measured variables like temperature, salinity and discharge; control chart approaches to examine changes in the variability of both response measures and environmental variables; and Bayesian approaches which assign probability distributions to each factor and their interactions. Potential methods are more fully described in Appendix 3. We emphasize the importance of extending these kinds of analyses to all 64 stocks assessed by Peterman and Dorner (2011), and others not included in their data set (e.g., Okanagan sockeye). The greater contrasts in both stock productivity and stressors provided by larger data sets will yield stronger insights on driving factors.

Due to ecosystem complexity and year to year variability in environment-recruitment correlations (see section 3.1 and English et al. 2011), we think that it will be very difficult to develop reliable *pre-season* models to accurately predict sockeye returns. A more reasonable expectation is that quantitative analyses will be primarily retrospective, and can yield only very general forecasts (e.g., whether marine survival rates over the next two years are likely to be below average, about average, or above average). As discussed in English et al. 2011, *in-season* data and models will likely continue to be the primary tools used to manage harvest.

[15] See http://trrp.net/science/IIMS.htm for more information.

The twelve highest priority recommendations are shown in **bold**, but the entire set of 23 recommendations form a cohesive whole. Since the early marine environment appears to be a major potential source of declining productivity, it is particularly important improve information on potential stressors affecting sockeye along their migratory path from the mouth of the Fraser River through Queen Charlotte Sound, including food, predators, pathogens, and physical, chemical, and biological ocean conditions. Information on pathogens, including potential relationships to aquaculture, is a particularly important data gap.

Further work is required to prioritize, sequence, define and integrated these recommended activities. Management decisions must still be made despite considerable uncertainty, and the information requirements for those management decisions should guide the elaboration, prioritization and integration of our recommendations. In other similar efforts we have found it helpful to apply the Data Quality Objectives (DQO) process developed by the U.S. Environmental Protection Agency (EPA 2006). Adapting some of the guiding principles of the DQO process to the sockeye situation leads to the following questions, which we believe should be applied to each of the recommendations in Table 5.2-1:

1. How exactly will the information be used? Example uses include: increasing our fundamental understanding of what is going on; directing strategic decisions on managing fisheries, hatcheries and other human activities (e.g., land use, pollution, aquaculture); managing expectations on sockeye returns 1 to 2 years later; helping to help make short term in-season harvest management decisions.
2. Given the intended uses of this information, what are the appropriate time and space scales of interest, and the required/achievable levels of accuracy and precision? For example, given the myriad and highly variable factors affecting sockeye, what level of accuracy and precision is required/achievable with pre-season forecasts of run returns? How much effort should be allocated to pre-season forecasts versus in-season forecasts and management?
3. What activities need to be done first? Are there some activities which are contingent upon outcomes of the primary activities (i.e., if we learn X, then we need to do Y), but otherwise can be deferred? Are rigorous adaptive management approaches feasible for key management uncertainties?
4. Given the answers to questions 1-3, what are the most cost-effective research and monitoring designs of a fully integrated, multi-disciplinary program? What pilot studies need to be done to develop such designs?

Table 5.2-1. Recommended research and monitoring priorities listed by sockeye life stage. This table builds on Peterman et al. (2010; Table E-3), as well as the Cohen Commission workshop and technical reports (including this one). The importance of recommended research and monitoring activities is rated by: (1) "Explanatory Importance", i.e., the relative likelihood that the set of hypothesized factors listed in the second column for a given life stage contributed to the sockeye declines (i.e., a synthesis across the stressors affecting that life stage), and (2) "Relevance to Management Actions", i.e., the value that such knowledge has for informing potential management actions. For example, a rating of *High* for "Explanatory Importance" and *Low* for "Relevance to Management Actions" indicates that research and monitoring of this life stage and the associated stressors is valuable in explaining the causes of decreasing productivity, but has little relevance to informing choices about potential management actions. **Boldface items** indicate the highest priority research and monitoring topics.

Life stage for Fraser River sockeye salmon	Relevant report section	Explanatory Importance	Relevance to Management Actions	Comments and recommended research and monitoring activities
Parental spawning success and incubation	4.2	Low	Low	Although an unlikely explanation of past declines, spawning success and incubation could relate to disease concerns and/or become higher priority in the future with climate change. Recommended activities include: 1. better estimates of both watershed conditions over time using consistent methods, for a strategically selected cross-section of stocks with varying conditions (e.g., migration distance, levels and types of watershed disturbance), to better understand current status, causative mechanisms and risk thresholds; **2. better understanding of the status of smaller conservation units, consistent with implementation of the Wild Salmon Policy; and** 3. better integration of existing and future data sets affecting freshwater spawning and rearing habitats
Juvenile rearing, production capacity, and smolt production	4.2	Medium	High	Quantitative assessment of smolt production is essential to estimate survival rates in pre- and post-juvenile life stages, and focus management responses. Only 2 of 19 Fraser stocks currently have smolt estimates (Cultus, Chilko). Recommended activities include: **4. assessments of freshwater smolt production and health for a strategically selected cross-section of stocks** (as described above)**;** 5. studies of conditions and ecosystem dynamics within the rearing lakes for these stocks; and 6. more intensive examinations if problems are detected.
Downstream migration to estuary	4.3	Medium	High	We do not know the survival rate of smolts during their downstream migration, or when they arrive in the Fraser estuary (vital to understanding potential mismatches between arrival times and marine plankton blooms). Smolt survival currently cannot be estimated separately from the overall juvenile-to-adult survival rate. Recommended activities

Life stage for Fraser River sockeye salmon	Relevant report section	Explanatory Importance	Relevance to Management Actions	Comments and recommended research and monitoring activities
				include: **7. research to assess sockeye smolt survival rates and travel time between lakes and the Fraser River estuary, for the strategically selected subset of stocks described above;** 8. estimates of the size and health of smolts arriving in the Fraser estuary (e.g., pathogens, contaminant body burdens, lipid reserves);
Coastal migration	4.4	High	High	Both the Strait of Georgia (highlighted in the PSC report) and Queen Charlotte Sound (highlighted in section 4.4 of this report) are of critical importance to sockeye. Recommended activities (which should be fully integrated with current work by DFO and NOAA) include: **9. A fully integrated oceanographic and ecological investigation of the Strait of Georgia (SoG), the Strait of Juan de Fuca (SJF), Johnstone Strait (JS) and Queen Charlotte Sound (QCS) (including oceanographic conditions, zooplankton, algae, marine mammal predators, alternate prey) to quantify/evaluate factors affecting Fraser sockeye survival, and improve linked physical - ecosystem models;** **10. Studies of residency and migration paths of Fraser sockeye post-smolts through the SoG, SJF, JS and QCS;** **11. Sockeye pathogen and contaminant levels in SoG, SJF, JS and QCS under different marine conditions and exposures to aquaculture activities;** **12. Estimates of the annual relative survival of Fraser sockeye over the period of residency in the SoG, SJF, JS and QCS;** and **13. Studies of the migratory paths of Harrison Lake sockeye.**
Growth in the North Pacific and return to Fraser	4.5	Medium	Low	Open-ocean research may improve understanding of competition (e.g., pink-sockeye), growth, maturity, and over-wintering survival. Recommended activities include: **14. Continued assessments of return abundances, age at return and harvest rates, all very important to future management decisions and sustainability of Fraser sockeye.** 15. estimates of the abundance of sockeye salmon reaching the Gulf of Alaska (and their distribution,

Life stage for Fraser River sockeye salmon	Relevant report section	Explanatory Importance	Relevance to Management Actions	Comments and recommended research and monitoring activities
				health, condition), as well as oceanographic conditions, would help distinguish mortality occurring during the open ocean phase from mortality prior to leaving the continental shelf. 16. Information on non-Fraser populations, useful in narrowing down the processes affecting Fraser sockeye, managing those stocks, and detecting shifting sockeye distributions with climate change.
Migration back to spawn	4.6	Low	High	Recommended activities include: **17. continued evaluation of the accuracy of in-season and post-season sockeye assessments, and improvements in those assessments;** **18. accurate estimates of sockeye in-river mortality (en-route mortality, in-river harvest, pre-spawn mortality);** **19. management strategies to maximize the potential for persistence of sockeye under increasing stress from climate change;** 20. climate change modelling to quantify the impact of future climate warming on Fraser River sockeye salmon productivity and abundance; 21. improved estimates of the spawning escapement for Fraser pink salmon; 22. improved escapement goals for each stock and run-timing group; and 23. research on gender differences in upstream survival, impacts of fisheries capture on en route and pre-spawn mortality, intergenerational effects.

6.0 References

Ainsworth, L.M., Routledge, R., and Cao, J. 2011. Functional Data Analysis in Ecosystem Research: the Decline of Oweekeno Lake Sockeye Salmon and Wannock River Flow. Journal of Agricultural, Biological, and Ecological Statistics. Available online (DOI: 10.1007/s13253-010-0049-z).

Arnold, T.W. 2010. Uninformative Parameters and Model Selection Using Akaike's Information Criterion. Journal of Wildlife Management 74(6): 1175-1178.

Bates, Douglas M. 2010. lme4: Mixed-effects modeling with R (Draft Book Chapters) Springer. http://lme4.r-forge.r-project.org/book/. Accessed on April 13, 2011.

Berube, M. 2007. Cumulative effects assessments at Hydro-Québec: what have we learned? Impact Assessment and Project Appraisal. 25(2): 101-109.

Burgner, R.L. 1991. The life history of sockeye salmon (*Oncorhynchus nerka*). Pages 3-117 in C. Groot and L. Margolis (eds), Pacific Salmon Life Histories. Univ. British Columbia Press.

Cain, J. 2001. Planning Improvements in Natural Resources Management: Guidelines for Using Bayesian Networks to Support the Planning and Management of Development Programmes in the Water Sector and Beyond. Centre for Ecology and Hydrology (CEH), Wallingford, UK, 124 pp.

Burkhardt-Holm, P. and K. Scheurer. 2007. Application of the weight-of-evidence approach to assess the decline of brown trout (*Salmo trutta*) in Swiss Rivers. Aquatic Sciences. 69: 51-70.

Burnham, K.P. and D.R. Anderson. 1998. Model Selection and Inference: A Practical Information-Theoretic Approach. Spring-Verlag, New York.

Christensen, V. and A.W. Trites. 2011. Predation on Fraser River sockeye salmon. Cohen Commission Tech. Rep. 8. Vancouver, B.C. www.cohencommission.ca

Council on Environmental Quality, Executive Office of the President. 1997. Considering Cumulative Effects Under the National Environmental Policy Act.

Counterpoint Consulting Inc. 2011. Status of DFO management and science. Cohen Commission Tech. Rep. 11. In prep. Vancouver, B.C. www.cohencommission.ca

Devore, J.L. 1995. Probability and Statistics for Engineering and the Sciences. Fourth Edition. Duxbury Press, Brooks/Cole Publishing Company, Pacific Grove, CA, USA.

Dixon, P. M., and J. H. K. Pechmann**.** 2005. A statistical test to show negligible trend. Ecology 86:1751-1756.

Draper, N.R. and H. Smith. 1998. Applied Regression Analysis. Third Edition. John Wiley & Sons, Inc., New York, USA.

Duinker, P.N. and L. Greig. 2006. The impotence of cumulative effects assessment in Canada: ailments, and ideas for redeployment. Environmental Management 37:153–161.

Duinker, P.N. and L.A. Greig. 2007. Scenario analysis in environmental impact assessment: improving explorations of the future. Environmental Impact Assessment Review 27:206-219.

English, K.K., T.C. Edgell, R.C. Bocking, M. Link and S. Raborn. 2011. Fraser River sockeye fisheries and fisheries management and comparison with Bristol Bay sockeye fisheries. LGL Ltd. Cohen Commission Tech. Rep. 7. Vancouver, B.C. www.cohencommission.ca

Forbes, V.E. and P. Calow. 2002. Applying Weight-of-Evidence in Retrospective Ecological Risk Assessment When Quantitative Data are Limited. Human and Ecological Risk Assessment 8(7): 1625-1639.

Gelman, Andrew, John B. Carlin, Hal S. Stern, and Donald B. Rubin. Bayesian data analysis, 2nd edition. 2004. Chapman and Hall/CRC. Boca Raton, Florida.

Golder Associates Ltd. 2008. Bruce Nuclear Power Plant Project Environmental Assessment, Methods, Project and Existing Environment Volume 1 September 2008. Submission to Bruce Power by Golder Associates Ltd., 2390 Argentia Rd. Mississauga, ON. 832 pp. Available at: <http://nuclearsafety.gc.ca/eng/readingroom/newbuilds/withdrawnapplications/bruce_tiverton/application_documents.cfm>

Greig, L. 2010. Geospatial Risk Characterization Workshop I: Tools for Ecosystem-based Approaches to Support Integrated Decision Making – Workshop Summary. Prepared by ESSA Technologies Ltd., Richmond Hill, ON for Fisheries and Oceans Canada, Gulf Fisheries Centre, Oceans and Science Branch, [Moncton, NB], 85 pp + Appendices.

Grieg, L. and P. Duinker. 2008. Strengthening Science in Environmental Impact Assessment.

Greig, L.A., P.N. Duinker, R.R. Everitt, and K. Pawley. 2003. Scoping for cumulative effects assessment. Prepared for Indian and Northern Affairs Canada Environment Directorate, Whitehorse, Yukon Territory. ESSA Technologies Ltd., Richmond Hill, Ontario. 51 pp.

Hilborn, Ray and Carl J. Walters. Quantitative Fisheries Stock Assessment. Choice, Dynamics, and Uncertainty. 1992. Kluwer Academic Publishers, Norwell, Massachusetts.

Hinch, S.G. and E.G. Martins. 2011. A review of potential climate change effects on survival of Fraser River sockeye salmon and an analysis of interannual trends in en route loss and pre-spawn mortality. Cohen Commission Tech. Rep. 9. Vancouver, B.C. www.cohencommission.ca

Johannes, M.R.S., R. Hoogendoorn, R.E. Scott, and L. Nikl. 2011. Fraser River sockeye salmon habitat analysis: Lower Fraser and Strait of Georgia. Golder Associates Ltd. Cohen Commission Tech. Rep. 12. Vancouver, B.C. www.cohencommission.ca

Johnson, R.A. and D.W. Wichern. 2002. Applied Multivariate Statistical Analysis. Fifth Edition. Prentice Hall, Upper Saddle River New Jersey.

Kent, M. 2011. Infectious diseases and potential impacts on survival of Fraser River sockeye salmon. Cohen Commission Tech. Rep. 1. Vancouver, B.C. www.cohencommission.ca

Kuikka, S., N. Holden, H. Gislasen, S. Hansson, H. Sparholt and O. Varis. 1999. Modeling environmentally driven uncertainties in Baltic cod (*Gadus morhua*) management by Bayesian influence diagrams. Canadian Journal of Fisheries Management 56: 629-641. http://article.pubs.nrc.gc.ca/RPAS/RPViewDoc?_handler_=HandleInitialGet&calyLang=eng&journal=cjfas&volume=56&articleFile=f98-206.pdf

Levy, D. 2006. BC Sockeye Salmon Population Declines: Probable Causes and Recommended Response Strategies. Prepared for Sierra Club of Canada – B.C. Chapter. North Vancouver, B.C.

MacDonald, D.D., J. Sinclair, M. Crawford, H. Prencipe and M. Meneghetti. 2011. Potential effects of contaminants on Fraser River sockeye salmon. MacDonald Environmental Sciences Ltd. Cohen Commission Tech. Rep. 2. Vancouver, B.C. www.cohencommission.ca

Mantel, N. 1967. The detection of disease clustering and a generalized regression approach. Cancer Research.27:209-220.

Marmorek, D.R., M. Porter , I.J. Parnell and C. Peters, eds. 2004. Comparative Survival Study Workshop, February 11–13, 2004; Bonneville Hot Springs Resort. Report compiled and edited by ESSA Technologies Ltd., Vancouver, B.C. for Fish Passage Center, Portland, OR and the US Fish and Wildlife Service, Vancouver, WA. 137 pp. Available from: http://www.fpc.org/documents/CSS/CSSworkshop_reportfinal.pdf

McKinnell, S.M., E. Curchitser, C. Groot, M. Kaeriyama and K.W. Myers. 2011. The decline of Fraser River sockeye salmon *Oncorhynchus nerka* (Steller, 1743) in relation to marine ecology. PICES Advisory Report. Cohen Commission Tech. Rep. 4. Vancouver, B.C. www.cohencommission.ca

Melnychuk, M.C., D.W. Welch, C.J. Walters. 2010. Spatio-Temporal Migration Patterns of Pacific Salmon Smolts in Rivers and Coastal Marine Waters. PloS ONE 5(9): e12916. doi:10.1371/journal.pone.0012916.

Miller, K.M.. 2011. Genomic Signatures Predict Migration and Spawning Failure in Wild Canadian Salmon. Science 331, 214. DOI: 10.1126/science.1196901

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

Naughton, G.P., C.C. Caudill, M.L. Keefer,T.C. Bjornn, L.C. Stuehrenberg, and C.A. Peery. 2005. Late-season mortality during migration of radio-tagged adult sockeye salmon (*Oncorhynchus nerka*) in the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 62: 30–47. doi: 10.1139/F04-147

Nelitz, M., C. Murray, M. Porter, and D. Marmorek. 2006. Managing Pacific Salmon for Ecosystem Values: Ecosystem Indicators and the Wild Salmon Policy. ESSA Technologies Ltd. Pacific Fisheries Resource Conservation Council. 101 pp.

Nelitz,M., M. Porter, E. Parkinson,K. Wieckowski,D. Marmorek,K. Bryan,A. Halland D. Abraham. 2011. Evaluating the status of Fraser River sockeye salmon and role of freshwater ecology in their decline. ESSA Technologies Ltd. Cohen Commission Tech. Rep. 3. Vancouver, B.C. www.cohencommission.ca

Parsons, T.R., M. Takahashi, and B. Hargrave. 1977. Biological Oceanographic Processes, 2nd Edition. Pergamon Press, Toronto.

Pestal, G. and A. Cass. 2009. Using Qualitative Risk Evaluations to Prioritize Resource Assessment Activities for Fraser River Sockeye. Canadian Science Advisory Secretariat Research Document 2009/071. Available from: http://www.dfo-mpo.gc.ca/CSAS/Csas/Publications/ResDocs-DocRech/2009/2009_071_e.pdf

Peterman R.M., D. Marmorek, B. Beckman, M. Bradford, N. Mantua, B. Riddell, M. Scheuerell, M. Staley, K. Wieckowski, J. Winton, C. Wood. 2010. Synthesis of evidence from a workshop on the decline of Fraser River Sockeye. June 15-17, 2010. A Report to the Pacific Salmon Commission, Vancouver, B.C., 123 pp. + 35 pp. of appendices. Available from www.psc.org

Peterman, R.M. and B. Dorner. 2011. Fraser River sockeye production dynamics. Cohen Commission Tech. Rep. 10. Vancouver, B.C. www.cohencommission.ca

Petrosky, C. and H. Schaller. 2010. Influence of river conditions during seaward migration and ocean conditions on survival rates of Snake River Chinook salmon and steelhead. Ecology of Freshwater Fish 19 (4): 520-536.

R Development Core Team (2010). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/

Ruggerone, G.T., R.M. Peterman, B. Dorner, and K.W. Myers. 2010. Magnitude and Trends in Abundance of Hatchery and Wild Pink Salmon, Chum Salmon, and Sockeye Salmon in the North Pacific Ocean. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 2:306–328, 2010

Schaller et al. 2007. Comparative Survival Study (CSS) of PIT-Tagged Spring/Summer Chinook and Steelhead In the Columbia River Basin: Ten-year Retrospective Analyses Report. BPA Contract # 25247. http://www.fpc.org/documents/CSS/FINAL%20COMPLETE%2010%20YEAR%20CSS%20REPORT-8-31-07withfrontpage.pdf

Schindler, D.E., R. Hilborn, B. Chasco, C.P. Boatright, T.P. Quinn, L.A. Rogers, and M.S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. Nature 465: 609-612.

Selbie, D.T., M.J. Bradford, M.J. Hague, J.M.B. Hume, E.A. MacIsaac, and D.A. Patterson. 2010. Are freshwater habitat conditions in the Fraser River watershed an important contributor to the Fraser sockeye salmon situation? In: Appendix C of Peterman et al. (2010) Synthesis of evidence from a workshop on the decline of Fraser River Sockeye. June 15-17, 2010

Sonntag, N.C., R.R. Everitt, L. Rattie, D.L. Colnett, C.P. Wolf, J. Truett, A. Dorcey, and C.S. Holling. 1987. Cumulative effects assessment: A context for further research and development. Prepared for Canadian Environmental Assessment Research Council (CEARC), Hull, Quebec, 91 pp.

Thompson, B. 2003. Score Reliability: Contemporary Thinking on reliability Issues. Sage Publications, Thousand Oaks, California.

Toms, J.D. and M.L. Lesperance. 2003. Piecewise Regression: A tool for identifying ecological thresholds. Ecology 84:2034-2041.

Walters, C.J. and J.S. Collie. 1988. Is Research on Environmental Factors Useful to Fisheries Management? Canadian Journal of Fisheries and Aquatic Sciences 45: 1848-1854.

Walters, C.J. 1989. Value of short-term forecasts of recruitment variation for harvest management. Canadian Journal of Fisheries and Aquatic Sciences 46: 1969-1976.

Weed, D.L. 2005. Weight of Evidence: A Review of Concepts and Methods. Risk Analysis 25(6): 1545-1557.

U.S. Environmental Protection Agency (EPA). 2006. Guidance on Systematic Planning Using the Data Quality Objectives Process. EPA QA/G-4. http://www.epa.gov/quality/qs-docs/g4-final.pdf

Appendix 1. Statement of Work

Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River

"Fraser River Sockeye Salmon: Data Synthesis and Cumulative Impacts"

SW1 Background

1.1 The Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (www.cohencommission.ca) was established to investigate and report on the reasons for the decline and the long term prospects for Fraser River sockeye salmon stocks and to determine whether changes need to be made to fisheries management policies, practices and procedures.

1.2 The Commission has engaged other Contractors to prepare technical reports covering scientific topics related to the Commission's mandate. A synthesis of this information is required to address cumulative impacts and to evaluate possible causes for the decline of Fraser sockeye salmon.

SW2 Objective

2.1 To provide data synthesis and integration services to the Cohen Commission and to lead the preparation of cumulative impact analysis involving all of the Science Contractors.

SW3 Scope of Work

3.1 Following the submission by Contractors of Progress Reports on November 1, 2010, the Contractor will analyze and organize information on explanatory factors, to assess their correlative strength with patterns of change in sockeye stock productivity during different life history stages. This will involve the preparation of a computer model to track the relative influence of different variables, and their interactions, that can affect Fraser sockeye salmon. This material will be developed and returned to the Contractors by December 15, 2010. The Contractors' Final Reports, which are due January 31, 2010, will be utilized to clarify the full range of factors, and their interactions, that impact Fraser sockeye[16].

SW4 Deliverables

4.1 The Contractor will organize a Project Inception meeting to be held within 2 weeks of the contract date in the Commission office.

4.2 The main deliverables of the contract include the facilitation of 2 workshops and the preparation of 2 workshop reports. The first workshop (Nov. 30 – Dec. 1, 2010) will involve Contractors and the Scientific Advisory Panel to address cumulative effects and their relationship with sockeye declines. The second workshop (Feb. 23-24, 2011) will involve the public, Participants, as well as the other Cohen Commission Contractors.

4.3 The Workshop Facilitators will make themselves available to Commission Counsel and legal staff as required.

Additional Methodological Details:

Cumulative Impact Analysis. The Contractor will take a life history approach to cumulative impact analysis, examining the suite of stressors potentially affecting each life history stage, and how those stressors have changed over the period of interest (i.e., early 1990's until the present). The Contractor will use the results of each investigator's work to illustrate the magnitude of each stressor over space and time, and its potential for delayed effects on subsequent life history stages (e.g., acquisition of a disease at one life history stage may not cause mortality until other stressors such as high temperatures affect a later life history stage). The intent is to illustrate these *potential* cumulative impacts through a series of integrative frameworks, such as:

a) a life history diagram showing the impacts of different stressors, with arrows of different thickness indicating the strengths of different pathways (including both direct and delayed effects);
b) time series graphs showing changes in a series of indicators for different stressors, placed on a map of the sockeye's life history, showing all indicators on a consistent relative scale (e.g., scaled to 1 based on the maximum value over the time series);
c) similar time series graphs of the changes in productivity indicators for different sockeye salmon stocks; and
d) analyses of the evidence for and against different hypotheses, building on the June 15-17 PSC workshop.

Computer Model. Each of the investigators gathering information on different stressors will assemble indicators of those stressors, organized into a spreadsheet with a consistent format (i.e., stressor by year by stock), specifically the 19 Fraser River sockeye stocks for which productivity indicators have been assembled by the Pacific Salmon Commission. For some stressors (e.g., impacts on freshwater spawning and rearing habitat), these indicators may be stock-specific. For other stressors (e.g., fish farms, oceanographic conditions, mammalian predators) many stocks will need to be grouped, as the independent effects on different stressors are unknown. The ability to explain the patterns of change in both Fraser sockeye stocks and other stocks of interest outside the Fraser (valuable to create contrast)

[16] Several of the Commission Participants requested that additional details concerning methodology for cumulative impact analysis be provided. This information is shown after the section SW4 Deliverables.

will be explored using a multiple regression approach or perhaps other multivariate techniques. It is expected that there will be some serious challenges in completing this analysis due to both data gaps, and insufficient degrees of freedom for strong statistical inference. However, this effort will serve to illustrate the challenges in deducing the relative impacts of different stressors.

Appendix 2. Reviewer Evaluations and Responses

<u>**Reviewers:**</u>

1. **Randall M. Peterman**
2. **Sean Cox**
3. **Rick Routledge**
4. **John Reynolds**

The authors' responses to each reviewer's comments are provided in bold below.

Report Title: Fraser River Sockeye Salmon: Data Synthesis and Cumulative Impacts (draft final report)
Reviewer Name: Randall M. Peterman
Date: 12 March 2011

1. Identify the strengths and weaknesses of this report.

<u>Strengths</u>:

a. Most of this report is extremely well written. The hierarchical organization of the material is a very effective way for readers with different levels of understanding of the Fraser sockeye situation to easily access the report to the desired depth. For the most part, tables and figures are clear and useful.

b. In recognition of the variety of backgrounds among readers, sections 2 and 3 do an excellent job of setting out the context and limitations for this type of work, as well as explaining the process for drawing conclusions. I particularly like Fig. 3.3-3 on page 19 as a way of succinctly showing how the categories of relative likelihood were assigned to hypothesized mechanisms. The report also nicely differentiates between explanations of past observations and making forecasts of the future.

<u>Weaknesses</u>:

c. There are two short sections in them main text that are poorly written (pages 58-59 and 77-79). Those are sections that deal with the authors' own analyses of data (as opposed to the summaries of other researchers' analyses that are covered in the rest of the report).

<u>Response</u>: These two sections have been re-organized and rewritten to address both this issue and the more specific criticisms raised below. In particular, a new section (Section 3.3.6) has been added to ensure that an appropriate overview of the quantitative methods is provided prior to any discussion of the results of those analyses. This section is intended to provide a concise, non-technical description of the quantitative methods such that both non-technical and technical readers will be able to clearly understand the basic terminology and overall methods used without needing to refer to the technical details

presented in Appendix 3.

d. Unfortunately, when I finally read Appendix 3 (which I expected to clarify the shortcomings in the main text regarding the description of the authors' statistical methods), I was still unclear what they actually did. There are still no statistical models given. Appendix 3 should therefore be rewritten in the format of a methods section of a journal paper so that readers with statistical backgrounds can understand what the authors did and evaluate the appropriateness of the methods of analysis. Again note, however, that this criticism only applies to the methods used by the authors of this report on their analyses of raw data; it does not to their synthesis of evidence and other analyses provided to them by other contractors.

Response: The sections of Appendix 3 that pertain to our quantitative analyses have been substantially rewritten to address these issues, as well as the more specific criticisms regarding this section raised below.

e. Appendix 4 described more about the methods, but still not enough. More problematic, though, was the poor presentation of results of the authors' own data analyses. My comments and suggestions for improvement are detailed at the end of section 6 of this review.

Response: Appendix 4 has been substantially rewritten to address these issues, as well as the more specific criticisms regarding this section raised below. We acknowledge that the draft version of this appendix made available to the reviewers was quite rough. The time available for conducting the quantitative analyses and describing their results was highly constrained due to long delays in receiving the appropriate data.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

a. The authors used (and clearly explained to readers) a rigorous "weight-of-evidence" approach that helped them deal with the complex set of hypothesized causes of the decline of Fraser River sockeye, as well as the wide range of available data for different hypotheses. This "weight-of-evidence" approach was based on two key publications in the field of "Retrospective Ecological Risk Assessment" (Forbes and Callow 2002; Burkhardt-Holm and Scheurer 2007), but the authors omitted full references to these papers at the back of the report.

Response: The correct, full citations have been added to references section.

b. The authors did a very commendable job at presenting the best scientific interpretation of available data that they obtained from the other contractors. The report also carefully points out cases where no information was available and where no conclusions could be drawn. As well, the report draws legitimate conclusions that put more weight on hypotheses about marine processes outside the Strait of Georgia than the conclusions of the Expert Panel at the workshop in June 2010 sponsored by the PSC (Pacific Salmon Commission) (Peterman et al. 2010). The current report had more data and analyses available to it than the PSC workshop.

Response: Thank you for the positive feedback.

c. The report falls short on interpretation of its own data analyses, though, as I describe at the end of section 6 of this review. I respect the fact that they were extremely complex analyses done in a relatively short time, but even this draft report could have been better at describing those analyses. Given that those analyses drew essentially the same conclusions as found by data from the other contractors, this problem is not as serious as it would have been if the original data analyses described here were the only ones to go on.

Response: The reviewer provides much more specific comments on this issue in Section 6 of this review. We have provided our responses to each of those points in Section 6.

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

There are only a few places where I noted that the evaluations of hypotheses here could be improved. These are noted in section 6 below as specific comments.

Response: We have responded to the comments referred to here in Section 6.

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

a. In general, the recommendations are well supported. The authors have done an excellent job of relatively concisely compiling a complicated set of evidence. The only recommendation that I might add is that management decisions still need to be made, despite the lack of appropriate data on some purported mechanisms affecting the decline of Fraser sockeye salmon. There will always be uncertainties, and although some of the judgments summarized here are qualitative, they at least describe the state of the art and provide everyone with more information than they had before.

Response: The challenge of making decisions under uncertainty is a good point, and we have expanded our discussion of prioritization in Section 5.2.2.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

a. I have nothing to add beyond what has already been included in the various recommendations in the report.

6. Please provide any specific comments for the authors.

1. I realize that this document was produced under considerable time pressure, but it

now needs a thorough copy editing to clean up poor grammar, incomplete sentences, extra or missing words, errors in figure numbers, missing references, repeated page numbers in the Executive Summary and the main text starting with the Introduction, etc.

Response: The final report has now received much more thorough copy editing than was possible for the draft report (given our tight time constraints), addressing the items mentioned by the reviewer above and more.

2. Page 2 of Executive Summary, last paragraph - The sentence starting with "For each life stage, we considered..." should be changed to a numbered or bulleted list; it is too hard to read.

Response: We have changed this sentence to be more readable.

3. Further on in that paragraph, emphasize that your categories "unlikely, possible, likely, or very likely" are listed in order of increasing confidence. Although that is obvious here, much later you have many hypotheses where you state "possible" and it may not be clear to readers at that point where that category sits along the spectrum.

Response: Rewritten to emphasize relationship between classifications and confidence.

4. Page 3 bullet item 1 - You must define what you mean by productivity. Given that one of your objectives is clear communication with non-technical readers, this type of ambiguity should be removed from all jargon terms in the report.

Response: We have provided an explicit definition of what we mean by "productivity" both in the Executive Summary and where the term first occurs in the main report (Section 1.1).

5. The term "inshore migration" should be replaced throughout this document by "coastal migration"; the latter is clearer as well as more common.

Response: We have replaced the term "inshore migration" with "coastal migration" throughout the report.

6. Page 5 of Executive Summary, last paragraph - define "PSC report" and briefly explain the workshop process that it summarizes.

Response: Done.

7. Page 22, 4th line - insert "substantially" between "were" and "affected".

Response: Done.

8. Figures numbered 4.1-3 through 4.1-5 have incorrect figure numbers according to references to them in the main text.

Response: Figure numbers have been corrected.

9. The figure currently numbered 4.1-5 (colored stacked bar plots) has something wrong with the year labels and legends, which makes them appear splotchy and hard to read.

Response: This figure has been reproduced both with higher resolution and larger fonts for the labels to improve its readability.

10. Page 31 - The main heading should be reworded by inserting "of observed patterns in productivity" between "Implications" and "for analysis".

Response: Done.

11. Page 32 - Regarding the italicized note to reviewers: those generalizations seem fine.

Response: Comment removed from final report. Original comment:

> ***"Note to reviewers: The above generalizations inevitably have some over-simplifications, so tweaks are undoubtedly required. We desire a concise summary of attributes."***

12. The summary tables in the conclusions sections on each life stage are very useful (page 40 for example).

Response: Thank you for confirming that these tables have met their intended objective.

13. The Selbie (2010) reference is missing at the back.

Response: Reference added.

14. Your reference to that Selbie paper implies that you also have access to the other papers from the PSC workshop in June of 2010. Therefore, I recommend that you draw upon the evidence presented by John Ford at that workshop concerning the increasing and large population of Steller sea lions (~ 60,000 animals in B.C. and Southeast Alaska in 2009). Ford also pointed out that a substantial part of their diet (~12 to 31%) comes from salmonids (not yet identified down to species). This information on Steller sea lion predation should be inserted into the last paragraph on page 50 and carried through to other similar sections later.

Response: This information has been included. The diet data to which the reviewer refers (presented both by John Ford at the PSC Workshop and Andrew Trites at the Cohen Commission Science Workshop, originally from P.F. Olesiuk, unpublished), measures the proportion of scat samples containing salmonids. That is, approximately 12-31% (varying by season) of the samples contained salmon but that does not mean that salmon make up

12-31% of the diet. The evidence presented by Andrew Trites at the Cohen Commission workshop suggests that salmon comprise approximately 10% of the overall diet of Steller sea lions.

15. Page 52 - insert "Strait of Juan de Fuca" after "Queen Charlotte Strait". Also, you need a map labelling these salt-water locations, as well as the "Queen Charlotte Sound" mentioned on page 57.

<u>Response</u>: Corrected as suggested. We have added labels to Figure 3.3-2 for the major salt-water locations commonly referred to throughout the report.

16. Top of page 53 - The following example of potential predation effects is very important: "...if 0.1% of the diet of spiny dogfish was sockeye smolts, they would consume 14.5 million smolts within the Strait of Georgia (very significant predation)...". Analogous examples for marine mammal predators, particularly Steller sea lions, are conspicuous by their absence. This omission must be corrected here, as well as on page 50 and the bottom of page 54.

<u>Response</u>: Agreed, and implemented. We have added greater discussion regarding Steller sea lions in Sections 4.4 and 4.5.

17. Page 57 - The paragraph under the heading "Conditions in Queen ..." correctly characterizes the different conclusions about the role of marine conditions "outside" of Vancouver Island compared to "inside" that were drawn by the current report and the report from the PSC workshop in June of 2010.

<u>Response</u>: Thank you.

18. Page 58 - Everything from the first line "Three model sets were tested ..." to the end of this section at "... drivers examined" needs to be <u>thoroughly</u> re-written because it is very confusing, uses undefined terms such as "global model" and "model sets", and does not even mention which dependent variable the models are trying to explain! I had to re-read this page and a half several times to deduce, for example, what "model sets" meant. Here it appears that one could simply substitute the word "period" for "model sets", because the term seems to imply models that were analyzed across three time periods. However, if you make that substitution here, it will be at odds with how "model sets" are used on pages 78-79. I purposely did <u>not</u> yet read Appendices 3 and 4, so that I could comment on how understandable this section was without reading the detailed methods in those appendices. Unfortunately, this section does not work as it stands. Fortunately, the text on pages 58-59 can be helped considerably by inserting a table that indicates in words (not in equations) which independent or predictor variables are used in each model and for which time periods data on those variables were available. The text above the table should at least state whether you are using a multiple linear regression or some other form of statistical model.

<u>Response</u>: This section has been completely rewritten, and we have introduced our quantitative methods in plain language in section 3.3.6.

19. Page 60 - The exceptional case of the Harrison River sockeye should be moved from its current hidden location at the end of point 4 and put into its own point. This will enable you to emphasize the importance of the evidence that could be gleaned from studying that stock more thoroughly, given that its life history is quite different from other Fraser sockeye stocks.

<u>Response</u>: We have moved comments on the Harrison stock into their own bullet point to emphasize that stock-specific knowledge of its migration route and timing would be especially useful given its unique life history and productivity trends (i.e., the only stock with increasing productivity).

20. Page 61 - I would add a new point under "Key things we need to know better" that would specifically state the need to take the current knowledge about consumption rates of sockeye salmon and other species by marine mammals, the bioenergetics of those mammals along with their population sizes, and combine these into estimates of total consumption of sockeye salmon by populations of a given species of marine mammal. For too long now, this last step has been missing, yet it should be easy to calculate a range of estimates given a standard set of assumptions like those that Christensen and Trites apparently used for their spiny dogfish example described on page 53.

<u>Response</u>: We agree with the reviewer's comment and have added this recommendation under "Key things we need to know better". This recommendation has the advantage of being fairly specific and preliminary efforts could be initiated immediately with the information currently available.

21. In the context of the previous comment, lines 8-10 on page 62 make a statement that is inconsistent with the point made on page 53 about the total potential impact of spiny dogfish predation on salmon, despite salmon being a tiny portion of the diet of the dogfish. The offending sentence is: "On the return journey back to the Fraser, there are many marine mammals that will prey on adult salmon, but sockeye salmon do not appear to be a substantial portion of any of their diets". Surely, the authors have to be consistent in their logic and say the same thing about the marine mammals as they did for the spiny dogfish.

<u>Response</u>: We have revised this section.

22. The line in Figure 4.5-2 does not seem to be the best-fit line; visually at least, it seems like it should have a lower slope. What was the assumption about the error term in the fitting method?

<u>Response</u>: This graph was extracted as an image from the publication cited and therefore the "trend" line could not be removed. We were not able to acquire the underlying data

before submitting the draft report. We have since acquired the raw data, updated to 2010. The original did not contain any information on the nature of this trend line. We have now graphed the same data without a trend line but including labels for the axes.

23. Page 65, 7th line - This statement "no obvious connection to sockeye abundance" is not supportable. See point #21 above.

<u>Response</u>: This quote from the workshop has been removed as it is inconsistent with the information available on Steller sea lions. The available evidence does not definitively show that there is a connection between marine mammals and sockeye abundance but the data does provide some support for this idea and therefore the potential connection cannot be rejected, as in the above statement.

24. Page 77, section 4.7.1 - As noted above, I did not read Appendix 3 or 4 prior to reading this section in order to view it from the perspective of a non-technical reader. Unfortunately, this section is poorly written and suffers from similar problems to those described above for pages 58-59. For instance, there is no clear statement that identifies the dependent, let alone the independent variables, and the definition of "model set" here is different than what is implied on pp. 58-59. Again, a table like I suggested for pp. 58-59 might solve several problems here.

<u>Response</u>: This section has been rewritten and restructured. It now contains both a synthesis of our qualitative analyses of cumulative effects across all life stages, as well as a clearer summary of our quantitative analyses. Our quantitative methodology is now introduced in Section 3.3.6. to provide readers with sufficient information on the approach so they will be able to understand the results presented in this section without needing to delve into the technical details of the appendices. We have also added two tables to Section 4.7.2 that illustrate the differences between the models tested and describe which specific variables are included in each of the models discussed. We have tried to ensure (in both of the sections mentioned) that any technical terms (e.g. model set, parameters, covariates, "project-based models", "all-marine" model, etc.) are either more clearly defined or simply reworded using clearer, non-technical language.

25. Page 77, 2nd-to-last line - "If data are missing ..." Is this sentence true even if only one data point is missing in a time series for a particular variable? If so, this procedure does not seem right.

<u>Response</u>: This is not what we intended to imply in this section or later in the methods. The sentence:

> **"If data are missing for one variable in one stock, then all of the records for that stock will be excluded from the analyses."**

referred to cases where one variable of interest (e.g., contaminants) was unavailable in ANY year for a particular stock. When a single data point is missing, it is only necessary to drop that particular year x stock from the analysis. For cases where only a small number of records were missing for a particular variable, we considered using interpolation (either

based on time or other stocks) to 'fill in' the dataset and therefore reduce the number of data points that had to be dropped from the analysis. In the end this strategy was rejected because data sets with only small gaps only resulted in a small loss of data and data sets with larger gaps (often at the beginning or end of the data set) were not able to be 'filled in' with confidence. We have re-written the description of how we handled 'missing data' in 4.7 as well as in Appendix 3.

26. Page 78 - The table suggested above should define what is meant by "Three additional models were tested with the model set...", the "all marine model", and other equally vague terms.

Response: This section has been completely rewritten. Please refer to the response for #24.

27. Section 4.7.3 on pp. 79-80 - A summary table is also necessary here.

Response: This section has been completely rewritten. Please refer to the response for #24.

28. Page 81 - In the last two paragraphs prior to section 4.8, you bring in pink salmon data without describing what types of mechanisms the PSC workshop concluded were plausible. Here the reader will have no idea whether you are talking about competition or predation by pinks. The last sentence prior to section 4.8 talks only in vague terms about the mechanism; it must be more explicit.

Response: We have revised this paragraph, providing more details on the hypotheses evaluated in the PSC report.

29. Page 86 - what do you mean by "database assimilation"?

Response: We have rewritten this line to clarify the intended meaning, that collected data would be assimilated into a central, integrated database.

30. Page 87 - An intriguing, but to me, impractical suggestion is made here: "... continue existing topic-specific databases (e.g., climate data, ocean conditions, stock information, contaminants, habitat data, disease), each maintained by the entities that have collected these data, but link key fields of each one to an integrated, interdisciplinary, geo-referenced database." The footnote to this idea notes that the Trinity River Restoration Project is moving in this direction. It would be worth expanding upon that example here to demonstrate that the suggestion made by the authors in the quote above is achievable.

Response: We have expanded our description and included some discussion of the challenges involved with integrated but regionally distributed databases.

31. Page 90 - Insert "Strait of Juan de Fuca" next to the other bodies of the ocean mentioned in section 4.4 of the table because this is the strait apparently used by

juvenile Harrison River sockeye.

<u>Response</u>: Done.

32. Need to do the usual cross-checking of all references.

<u>Response</u>: We have cross-checked all references between the body of the report and the references section.

33. This report frequently uses contractions (e.g., "doesn't", "won't", etc.). These do not belong in scientific writing; spell out the full words.

<u>Response</u>: We have replaced all contractions (i.e. aren't, can't, couldn't, doesn't, don't, hasn't, wasn't, we'd, it's, that's, there's, what's, they're).

<u>Specific comments on Appendix 3</u>

34. Page 103 - Table A3.3-1 is missing some entries in the "units" column. Also, there appear to be very few cases in which the qualitative time series of data were provided. Is that correct? If so, say so in section A.3.2.2. For instance, "... only X% of the data that we analyzed were from these qualitative time series".

<u>Response</u>: The missing entries have been entered in this table. A sentence has been added to describe that qualitative time series were only received from two projects. We think that Section A3.3 ("… Data Received") is the more appropriate location for this sentence, which follows directly after the section described by the reviewer.

35. The material in section A3.5.1 (Qualitative Analyses) under the heading "Weight of evidence..." repeats what was already said earlier in section 3.3.5 of the main report. No need for both.

<u>Response</u>: We have added a footnote to explain that this section is an expanded version of Section 3.3.5 of the main report. The version in the appendix contains substantially more detail on this approach and how it has been adapted from the foundational literature. We felt that this greater depth was relevant given the multiple audiences for this report. We now explicitly note that Section 3.3.5 is therefore repeated in this section.

36. Page 137 - Delete "or not" from the last line of this page.

<u>Response</u>: Done.

37. Page 138 - You state that rather than using residuals from the underlying best-fit spawner-recruit relationship that "We used ln(R/S) for this analysis." Not only should you justify why you did that, but you should also state the potential biases that you introduce by doing so. That is, when your results are presented, you should interpret

them in terms of how changes in spawner abundance (S) alone (even with constant recruitment, R) might have affected the time trends in $\log_e(R/S)$.

Response: We used ln(R/S) so that the potential effects of density dependence (i.e. effects of changes in S on R/S) would be considered concurrently with the potential effects of other stressors. The form of multiple regression equation that we used is a Ricker spawner-recruit model with additional covariates. Since Peterman and Dorner (2011) only found evidence for delayed density dependence for the Quesnel stock, this simplification seems reasonable. The analysis could be repeated using the residuals from the best fit spawner-recruit model as the dependent variable, rather than ln(R/S).

38. Bottom of page 140 to top of 141 - I believe that you meant to say that you are plotting the "concentration profile", or cumulative probability of stock composition here. Careful with wording here; "distribution" at the top of p. 141 might mean spatial distribution to some readers.

Response: We have changed the wording to say 'concentration profile' and then defined what we mean by that term.

39. Page 142 - Insert "variable" between "dependent" and "dataset" and make dataset two words. Same with "smallest independent datasets". Also, "See Appendix 3-4 refers to the wrong appendix number (this error appears elsewhere too). Page 142 is where the "no missing data" statement comes up again, just as in the main text, yet you do not fully explain how that was interpreted. If there was even one year with missing data, did you throw out the entire time series of that particular independent variable? This does not seem reasonable, nor is it necessary. Ecological data often have missing data points, yet the remaining parts of the time series can still be very informative and can be used to fit statistical models.

Response: We have added 'variable' to independent and dependent where necessary. We have changed 'dataset' to 'data set' throughout the document. We have fixed the Appendix reference. As described above (in response to comment 25) we have clarified the text regarding how missing data were handled.

40. Page 143 - What are the D-L series? You were not even clear earlier in this paragraph whether the "A-series, B-series, and C-series of model sets" refer to the bulleted list of A, B, and C just above this paragraph. Despite the attempt by the authors to describe "model sets", I still am not sure what exactly those refer to, even by the middle of page 143. You need some concrete examples of statistical models embedded in the text to define these terms more clearly. It was not until I saw some tables in Appendix 3 that I began to understand what "model sets" meant.

Response: We now introduce what we mean by 'model sets' in the general introduction to 'multiple regression'. We have expanded the detailed 'model set' section to describe the D-L series as well as the A-C series. In addition, we have changed the bulleted list to read A-

series, B-series, etc. to clarify that these bullets are what the text is referring to. We have now embedded statistical models explicitly in the 'model structure' section.

41. Even Table A3.5-1 adds to the confusion given the (perhaps mis-formatted) heading of "Model [spaces] set" with "group" below it. That table requires a more extensive caption to explain the symbols. For instance, what is "w/in Inc-Lak" on row D? What do "yes" and "no" mean and how does the latter differ from "N/A"? The entries in this table are also formatted poorly.

Response: We have reformatted the table to avoid the awkward gaps. In addition we have replaced the short hand in the tables with expanded text. We have also updated the table caption to clarify what yes/no indicate in the table.

42. "Timeseries", "lifehistory" (and "lifestages" and "broodyears" elsewhere) should each be split into two words, and "principle components" should read "principal components". I will not mention any more of these basic spelling errors; they should all be fixed with a thorough editing.

Response: These terms have been split into two words throughout the document. The exception is cases where "BroodYear" is used to name the field in the database that contains data on the brood year. The misspelling of "principal components" has been corrected.

43. Page 146 - Was the following step applied to data sets for all predators and all alternative prey? "...we took each dataset individually and generated a new quantile based dataset..."

Response: No, it was not applied to the marine mammal data. We have added a table to Appendix 3 that describes each of the predator/alternative prey data sets we received along with: the hypothesized effect on sockeye (mechanism and life stage), and a description of the data reduction if it occurred.

44. In the "Model structure" section, you have to provide some example equations (including the assumed error structure) for technically-trained readers to clarify what exactly you are doing. This lack of information is really frustrating. The equations are not clear, contrary to what you say here: "Table A3.5-2 illustrates the process we used to document the model structure for each model set".

Response: We have added an equation to the model structure section to explicitly illustrate what models we fit. We have also expanded the heading for Table A3.5-2 to clarify how to read the candidate models from this table.

45. The second column heading in Table A3.5-2 should read "Independent variable". The caption for this table is quite inadequate. What do the 0s and 1s in the columns M1 through M10 indicate? I use mixed-effects models myself, so I would assume that they

refer to some variable being included in the particular equation for a particular row, but which variables those refer to are not shown or stated in the text -- a major oversight!

<u>Response:</u> We have substantially updated the Table A3.5-2 heading to clarify the information contained in the table. It may have been confusing because models are usually specified in rows, but we have used columns M1-M10 to represent the different models.

46. Pages 149-150 - I am not sure how useful the description of these potential future analyses will be to readers. Furthermore, the wording of some of them is confusing because it implies that the authors of this report did in fact use that method. For instance, the second sentence under the heading "Structural equation modeling (SEM)" says "In this analysis, we first specify a set of structural equations based on..." yet at the end of the paragraph it states that the authors did not use SEM. In the section on Mantel's test, why not cite the Mueter et al. paper in the normal manner?

<u>Response</u>: Yes, we agree. We have added a short summary table at the front of Appendix 3 to list the different approaches we considered and those that were ultimately recommended / completed based on expert feedback and the Nov. 30 / Dec. 1 workshop. We have kept a section on potential analyses, but limited this to approaches that were highly recommended but not completed as part of this project, as well as ideas that were raised by the peer reviewers of this project.

47. Overall, this Appendix 3 was written very poorly. It should be revised in the format of a methods section of a journal paper so that readers with statistical background can understand what the authors did and evaluate its appropriateness.

<u>Response</u>: We had very little time to complete quantitative analyses prior to submission of the draft report, and focused all of that time on the analyses themselves rather than the description of methods. Appendix 3 has now been substantially re-written to improve the overall presentation and provide sufficient detail for readers with statistical background, while still ensuring that important concepts can be understood by all readers.

<u>Specific comments on Appendix 4</u>

48. The sequential numbering for Figure A3-2 is out of order with the surrounding figures. The spelling of "E.Stewart" in the figure caption should be Early Stuart. Also, give the P value to justify "... significant decline..."

<u>Response</u>: We have corrected the figure numbering in this section and written out stock names in full where appropriate.

49. Why are these four plots the only ones shown for the slope and change-point analyses? There is no explanation.

<u>Response</u>: This is a fair question. We selected several example figures to illustrate cases when either the hockey stick model or straight line model fit better, but rather than showing the full diagnostic figures for both models and all stocks we summarized the rest of the results in a table to save space. We have decided to remove all of the diagnostic figures from Appendix 4 and simply present the table of results. We still include an example of the diagnostic figures that were generated for each stock in the methods section (Appendix 3)

50. The Tables A4-2 (there are mistakenly two of them) show the statistics and "recent trend", although the latter refers to the trend over the entire time series.

<u>Response</u>: We have corrected the table numbering in this section.

51. The two darkest colored lines in Figures A4-5 and A4-6 are not distinguishable. This should be fixed, especially in Figure A4-5 where it matters most.

<u>Response</u>: We have redrawn the figures using dashed lines for two of the time-periods to clarify the difference between lines.

52. Captions of Figures A4-7 through A4-10 should define the R/S series as black solid dots and lines.

<u>Response</u>: Corrected as suggested.

53. Page 163 - You now have yet a third Table A4-2!

<u>Response</u>: All tables have been re-numbered.

54. Page 163 - Finally, we get to see what "model set" means. However, it is still incomplete. Where does the reader find which 6 stressors were used for model M3, for example, let alone all the other models? There should be a table similar to Table A4-5 on page 168 for each model set. Also, there is no statement about why the particular model sets were chosen to be provided on pages 163 onward. Are these only examples or were they your only analyses?

<u>Response</u>: Yes, we agree. We have added tables to explicitly list the variables included in each model. The analyses presented represent all of the analyses that were completed. We have added a paragraph to the methods in Appendix 3 to describe why we selected the model sets we did.

55. Pages 163-170 are written very poorly. Results should be presented in a manner similar to that of a journal article. At present, some paragraphs describe results without referring to the supporting information in tables that I finally ran across later (parameter estimates, AIC values, etc.). At the end of the first sentence where results are reported, you should include a concise reference to the appropriate table (e.g., "Results show that

... (Table xx)". Structures of these sections also differ unnecessarily among model sets, as do headings of tables and model names.

Response: References to results have been added in the main text as recommended. We have improved the consistency of the different sections describing results.

56. Table A4-3 does not specify which variables were included in several cases, but instead uses general labels such as water quality variables, bird predators, fish predators, etc.

Response: We have generated consistent tables that explicitly describe all variables for all model sets.

57. Reduce the number of decimal places in tables. Provide standard journal-type table captions to clearly define each column heading and other symbols.

Response: We have reduced the number of decimal places used in the results tables. We have revised the table captions to clearly explain each column heading and any symbols used.

58. In Table A4-14, what does "Correction" refer to? You should be using the AIC_c formula (i.e., the one corrected for small sample size) instead of the one for AIC. The former equals the latter if sample size is large enough.

Response: We used the AICc in our model selection however, we have also reported both the raw AIC and the correction in the table (AICc=AIC+correction), this was simply to illustrate the impact of the relatively large number of parameters to observations. We have clarified this in the table captions.

59. The sentence near the top of page 167 does not appear justified: "This appears to provide some additional confirmation that organizing the qualitative synthesis and evaluation of evidence by lifestage was indeed justified." Just because results are different for the analysis organized by life stage from the one set up by Cohen Commission project does not necessarily mean that the first rank ordering of models is more valid; it only says that they are different.

Response: We have removed this sentence, both from this location and where a similar statement was made in the main body.

60. Page 167 - Here is good example of why one of my earlier comments is important. Model 8 turns out to be best (lowest AIC in Table A4-22), yet Table A4-4 does not specify which temperature measure is used in the Strait of Georgia (when and where). Several options were described previously, so the variable that was used is not obvious.

Response: Yes, we agree. We have added tables to explicitly list the variables included in

each model.

61. Add "C4a" to the sentence just after the end of Table A4-5 to read "in the previous model set (C4a), ..."

Response: Done.

62. An important new result, which should be highlighted more here and in the main text, is the one on page 168: "... they indicate that the QCS models have greater explanatory value than SoG models for Fraser River sockeye salmon productivity during 1980-2004." This result alters the conclusion from the Peterman et al. (2010) report from the June 2010 PSC workshop and is legitimate because of new data and analyses not seen at that workshop.

Response: This result has now been emphasized in both Appendix 4 and the main report (section 4.4).

63. The wordings of these sections on results of model sets really need a lot of polishing. You don't even put the tables describing models in the same order as the tables of parameter estimates and fitting statistics (e.g., C1a QCS and C1a SoG).

Response: We have ordered the results tables more carefully and embedded the tables with estimates and AIC weights in each section to make it easier to read.

64. Page 170 - Replace SST with SSS in the line: " This suggests that SST is an uninformative parameter..."

Response: This section has been rewritten.

65. Page 170 - The paragraph of results starting with "Within the SoG model set, chlorophyll does not appear to be..." does not correspond at all with results shown in Table A4-16 (Model fit information for model set C1a, Georgia Strait). Either the table is completely wrong or the text refers to another table that is not shown.

Response: This paragraph has been reorganized so that the writing and results are clearer.

Report Title: Fraser River sockeye salmon: data synthesis and cumulative impacts
Reviewer Name: Sean Cox
Date: 18 March 2011

1. Identify the strengths and weaknesses of this report.

Strengths
The database is the primary strength of this report. The project seems to have created an efficient way to organize and store a wide range of data, meta-data, and documentation. Development of such databases will undoubtedly be critical to future salmon research.

<u>Response</u>: Once data are made available from the Cohen Commission, we hope that many researchers working on salmon populations can expand and apply this database using a number of diverse analytical approaches, and have expanded section 5.2.2 to include this recommendation. We note however that there are some serious limitations to the types of indicators available for various stressors, in terms of their specificity for various stressors, as well as spatial and temporal coverage. We have also included discussion on future types of analyses that may be valuable to conduct with these data.

The report examines a wide range of potential factors that might explain changes in sockeye salmon productivity. The assemblage of data and analyses for sockeye populations spread throughout the Pacific northwest represents a meta-analytic approach that is more powerful than analyses on single stocks.

This Project 6 report is heavily based on other reports, so it is difficult to identify unique strengths.

Weaknesses
This report attempted to synthesise a vast amount of information in a short period of time. Like any report/paper that attempts a broad review and synthesis, it sometimes struggles to draw conclusions and recommendations that are unique compared to the source reports. Many of the critical comments below are probably a reflection of an outsider's view of this struggle.

The conceptual model developed in this report does not live up to its intended purpose; that is, to "organize complex relationships among factors". What is described as a conceptual model is really just a life-history sequence connected to a list of potential explanatory "factors" in a linear way. There are no feedbacks or even basic directional effects indicated (i.e., "+", "-", or "+/-") for any of the factors, possibly because all of the factors are assumed to have negative impacts only. It is common scientific knowledge that salmon recruitment is based on survival through a series of density-dependent life stages – so a negative effect in one stage can be compensated by a positive effect in a subsequent stage. Where is this basic feature represented in the conceptual model?

Response: Our conceptual model (Figure 3.3.-1) is meant to provide an overview of the potential interactions amongst purported stressors to a broad set of audiences for this report, that include (in order of priority): Judge Cohen, Commission staff, Commission participants, the public, and scientists. At the Nov. 30 to Dec. 1 workshop, a similar draft conceptual model was presented – all of the participants who provided feedback suggested that this model was already too complex for the target audiences (as noted in Appendix 6). We nevertheless decided to maintain that level of complexity in this report to illustrate the factors potentially affecting each life history stage, as discussed within the Cohen Commission technical reports. We believe that adding more complexity to Figure 3.3-1 as suggested (i.e., feedback loops, +, -, +/- along each arrow), while very helpful for building a quantitative model, would be inappropriate for the intended purposes and audience. We have however updated the caption on Figure 3.3-1, and redrafted Figure 2.3-1 to reflect the important processes you describe.

The linear, correlative approach taken in the report has failed to explain much in the way of salmon population dynamics despite decades of work. In fact, prominent scientists have doubted our ability to link recruitment to environmental factors for more than two decades. Myers (1998), for example, raised such concern based on dismal performance of correlations in his re-analysis of over 50 recruitment-environment correlations: "The utility of spending large amounts of public research funding to establish predictions of recruitment based upon environmental indices should therefore be questioned (Walters and Collie 1998; Walters 1989)". It appears that these influential works in fisheries science were not consulted at all for this report even though the core topics are the same.

Response: It isn't clear from these comments whether you are referring to our qualitative syntheses of evidence, our quantitative data analyses, or both. We'll address each in turn.

Qualitative syntheses of evidence. **Thank you for reminding us of these papers (Walters and Collie 1988, Walters 1989, Myers 1998), and the very real constraints on predicting recruitment of fish populations. These will be useful to work into the introductory paragraph to section 3.1. All three of these papers are focused on the difficulties of predicting recruitment of fish populations for the purposes of fisheries management, including the lack of persistence of environment-recruitment correlations. We agree with these authors' conclusions and indeed emphasized these very challenges in section 3.1, where we noted the inaccuracy of pre-season predictions of sockeye returns (as evaluated by English et al. 2011). However, our qualitative synthesis is not focused on predicting future recruitment; it is a *retrospective* ecological risk assessment or RERA. As we note in section 3.3.5 when describing our RERA approach: "Because this method is an inherently retrospective form of analysis, the results cannot be used to make future predictions." Our RERA approach seeks to reduce the likelihood of factors which show weak evidence of exposure, and weak / no correlations with observed patterns of changing sockeye productivity; we are not attempting to predict recruitment with those covariates which**

show stronger correlations. Hence, while the caveats you raise are important reminders (and have now been added to section 5.2.2 as well as section 3.3.5), they are not a legitimate criticism of our explicitly retrospective approach.

Quantitative analyses. **We acknowledge that there are many non-linear and other approaches which could also be applied to our database, but did not have enough time to apply them. As indicated above, both Appendix 4 and section 5.2.2 now mention alternative approaches. Our broad, multi-population analyses actually followed several of the recommendations of Myers (1998, pg. 297 "How can research be improved"), including his first recommendation:**

> **"Test general hypotheses. By examining many populations at once, it should be possible to detect general patterns. For example, the sign of the correlation between environmental factors corresponds to that predicted at the limit of the range, i.e., at the colder limit of a species range one would expect a positive relationship with temperature, and a negative one at the warmer limit of the range".**

The analysis of 64 stocks by Peterman and Dorner is consistent with this principle; we did not however have sufficient data on environmental covariates to include non-Fraser sockeye stocks in our retrospective quantitative analyses.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

It is difficult to determine the validity of the quantitative analyses because there is limited information presented on the alternative model fits. In particular, I did not find any indication of how much variation in salmon productivity is explained by the alternative models (i.e., R^2 values).

<u>Response</u>: As we were implementing the analyses we focused on reporting AIC's for the purpose of model comparison as we were only thinking about relative performance of different models rather than absolute performance of individual models. In hindsight we should have written the code to extract all of the relevant information so that we could also have reported R^2 values. Given that our analysis was retrospective and we were not trying to generate a predictive model (so the omission is less serious), as well as the limited time we had to respond to reviewers feedback we have not generated R^2 values.

As stated in the report, the multiple regression analyses are "constrained by the smallest independent datasets" because of the AIC-based hypothesis-testing approach that was taken. I'm a bit surprised that a Bayesian estimation approach was not considered – such an approach would provide the necessary "weight of evidence" in the form of a probability distribution on parameters associated with each factor rather than the AIC "in/out" result. Bayesian methods are also well-suited to dealing with multiple datasets of varying quality, as well as possible spatial and temporal autocorrelation in time-series.

Response: As discussed above, we did not have time to implement such approaches, though we have now expanded our description of alternative modelling approaches in Appendix 3. We agree with the reviewer that simple in/out selection criteria to identify the so called 'best' model is not a good approach. We used a weight of evidence or support approach to interpret the alternative candidate models rather than simply presenting the 'best' model and assuming this was correct.

Most interpretations in this report are re-statements of conclusions/observations drawn in other reports. However, here are two examples from this report of incorrect interpretations of stock dynamics that make me doubt their "best" scientific interpretations:

a. On page 39, that authors incorrectly state that cyclic variation in abundance is a condition for delayed-density-dependence. In fact, cyclic variation is one potential result of a delayed-density-dependent process, and not all delayed-density-dependent processes show cyclic variation in abundance.

Response: This is a helpful clarification. Peterman and Dorner (pers. comm.) confirm that delayed density-dependence doesn't necessarily have to lead to a cyclic dominance pattern. It all depends on whether the mechanisms involved combine with life history traits in a way that generates and maintains a persistent cycle. The absence of regular wide-ranging fluctuations makes it less likely that delayed density dependence plays a strong role, but doesn't completely preclude the possibility that it is having an impact. We have rephrased this part of our report to say:

> **Peterman et al. (2010; Section 4.7) noted that stocks outside of the Fraser Basin usually do not have such strong and regular fluctuations in abundance; they therefore concluded that delayed density dependence was not a likely mechanism for observed declines in non-Fraser sockeye stocks.**

b. Trends in stock productivity are incorrectly described in Appendix 4 figure captions. Declining ln(R/S) over time does not indicate that a "stock has been in decline" (Figure A4-3) or that there is "a non-zero trend in the L. Shuswap stock" (Figure A4-4), and so on. This is pretty basic knowledge that will confuse readers who are looking for declining trends in stock abundance – these are actually trends in indices of stock productivity. In some cases, the actual stock abundance has been increasing.

Response: The errors in the figure captions for Figures A4-3 and A4-4 were oversights, and have been corrected. However, we have decided to summarize these results in tabular format rather than figures, so the original figures have been removed.

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

As noted above, a Bayesian approach would allow most, if not all, the data to be utilized more in characterizing, and possibly explaining, the shared productivity patterns among

Fraser and non-Fraser sockeye populations. Hierarchical Bayesian methods are increasingly common in applied fisheries science, and this particular case would seem to benefit from information-sharing among multiple stocks.

Response: As discussed above, we did not have time to implement such approaches, though we have now expanded our description of alternative modelling approaches.

I expected this report on cumulative effects to provide a "systems" view of sockeye salmon dynamics. That is, factors affecting sockeye dynamics do not necessarily operate independently, unidirectionally (i.e., all arrows point to only sockeye), and linearly. Sockeye salmon populations influence, and are influenced by, many potential feedbacks within freshwater, river, and oceanic ecosystems.

Response: We agree, and our conceptual model (while not representing all interactions for reasons stated above) do show various interactions amongst factors. However, our terms of reference (Appendix 1) as well as those of the Cohen Commission (http://www.cohencommission.ca/en/TermsOfReference.php) are explicitly sockeye-centric, rather than ecosystem-centric. Therefore, we have been more focused on how various ecosystem stressors affect sockeye, rather than the reverse effects (how sockeye affect ecosystems). To provide a more "systems" view, we've added some text under the discussions of Plausible Mechanisms (e.g., in Section 4.2.1, we note that declining abundances of sockeye result in less nutrients being transferred from marine to freshwater ecosystems, with potential negative effects on both subsequent generations of sockeye and other ecosystem components). In section 4.4.1, we discuss various ecosystem processes affecting the degree of predation on sockeye in inshore areas. As discussed above, we have mentioned feedbacks in Figures 3.3.1 and 2.3.1.

This may reflect my ignorance, but has any research been done to determine whether the observed pattern in productivity is an expected result of Ricker-type stock-recruit dynamics? Are sockeye populations over-shooting some capacity limits and therefore showing natural signs of suppressed productivity? The abundances of sockeye during the 1990s and early 2000s were very high all over the northeast Pacific (including Alaska), which may have lead to covariation in ocean growth and survival over broad spatial scales. I am not aware of recent research examining among-stock density-dependence in ocean survival of sockeye, even though it might be possible. Scientists have argued for decades that massive enhancement of Japanese chum salmon suppresses growth of North American chum salmon, so I wonder why similar arguments have not been explored for sockeye.

Response: The regression models we applied included Ricker-model representations of density dependence for each stock. Ruggerone et al. (2010) have an excellent summary of trends in wild and hatchery salmon populations, and note that hatchery-raised chum form 62% of the combined total wild and hatchery salmon abundance. They also discuss the potential for a "tragedy of the commons" effect in the North Pacific. Our analyses of the effects of pink salmon abundance reflect potential competitive impacts of wild plus

hatchery pinks on sockeye. Consistent with the need to have more of a systems view, we have included a discussion of these effects in section 4.4.1.

There is practically no consideration of the uncertainty in any of the quantitative analyses. Yet, the paper makes some rather sweeping recommendations about the types of research that are needed to better understand (and manage) Fraser River sockeye. I don't see how these recommendations can be made in the absence of knowledge about the potential information/value gains from research.

Response: Model selection uncertainty has been considered. We are only looking at interpretive value retrospectively, not attempting to make predictions prospectively, so we did not focus on predictive uncertainty.

Our recommendations for research and monitoring are largely drawn from the qualitative analyses and work in Commission technical reports, rather than from our own quantitative analyses. We have listed several questions in section 5.2.2 which specifically address the potential information value gains from research, and highlight the need for further prioritization to select the most cost-effective activities.

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

The recommendations are mainly a summary of possible areas for future research that could be done, prioritized according to explanatory importance and relevance to management. It is hard to disagree with most of the recommendations because the list covers just about every aspect of sockeye life history and fisheries. Clearly, some thought needs to be put into how to further prioritize and reduce such a list.

I recommend a comprehensive assessment of what research should be done given limited resources.

Response: We agree. That is why we discussed 4 prioritization questions in section 5.2.2.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

Proposing new information to be collected does not seem to be a reasonable request at this point. I've spent two days (+) reviewing this report, whereas the authors of this and supporting reports have spent weeks assembling information on the topic. What I do suggest is a small, informal working group tasked with thinking about sockeye salmon dynamics from alternative perspectives than the default correlative viewpoint. This group might generate new insights about key processes and information needs.

Response: We agree. The reviewer's suggestion would be an excellent "next step". The data that has been collected from the Cohen Commission technical projects are now available in

a single database for other researchers and scientists to use. These data could be examined using many other analytical techniques. In Appendix 3 (summary in section 5.2.2), we have suggested some further methods that might yield interesting results. Such a working group would be able to expand that list further and decide to prioritize those expected to provide the most benefit. Furthermore, we have relied on the contractors of other projects to forward the most appropriate data sets but have not actively searched for additional data. However, this working group may also be able to improve upon the database by identifying gaps for particular stressors or life stages where some data is known to exist but was not available within the Cohen Commission technical reports.

6. Please provide any specific comments for the authors.

Overall, there needs to be a major clean up of the text to make it more readable. Please fix ambiguous references, especially beginning sentences (i.e., search for "this", "these", "It", "It's"), over-use and misuse of "it's", apparently random use of *italic* and **bold** fonts, incorrect use of "which" vs "that", useless jargon (e.g., what is a "focal" VEC?), etc.

Response: The text has been corrected as suggested.

We recognize that the draft report contained an over usage of contractions and that such language is not appropriate for scientific writing – all such words have been replaced. To the extent possible, we have examined the usage of "which" vs. "that" throughout the document and corrected it where necessary.

The second paragraph of the Executive Summary leaves the reader hanging with "This is the pattern that we seek to explain", and then no pattern is actually described. Presumably, the authors mean the patterns described in the two referenced papers and the text that follows on the next page. Please move that text to the second paragraph where it belongs.

Response: The text has been corrected as suggested.

Another sentence "Major data gaps led us to the outcome that *no conclusion was possible*". Hopefully, the authors meant to include the phrase "In some cases", just before "Major".

Response: The text has been corrected as suggested.

P2, par3: the last sentence does not seem accurate. The statement of work did not describe any intent to guide "management strategies".

Response: The text has been corrected as suggested.

Statements like: "None of the factors considered for Stage 2 are likely to have shown a sudden worsening in 2007…" should be re-worded to, e.g., "None of the factors considered for Stage 2 are likely to have been much worse in 2007…or much better in 2008…"

Response: The text has been corrected as suggested.

P6, par1: The text "…CEA should be focused on VECs rather than projects…" needs to be reworded because the meaning is not clear until the whole paragraph is finished. I think the authors mean that the VECs should be the fundamental unit of assessment rather than projects.

Response: The text has been reworded to improve clarity.

Section 3.1, par1: This paragraph is nonsense and should be deleted. It is a convenient, yet distracting story cooked up by ecologists who have never actually done rocket science…usually because that field was too hard for them to get into in the first place. Please communicate some of the very real issues of complexity (e.g., the Peterman and Dorner quote) in fisheries ecology if that is the intent.

Response: We believe that the comparison of fisheries science and rocket science is a very helpful metaphor, given the various audiences for this report. Nevertheless we have made several modifications, incorporating some of the concerns you've raised and the references that you've discussed above. The Cohen Commission defined the target audiences for the Technical Reports in this order of priority: Judge Cohen, the Cohen Commission scientific and legal staff, the Cohen Commission participants, concerned members of the public, and then fellow scientists. This paragraph is not intended to be a rigorous comparison of fisheries ecology versus rocket science, but merely an illustration of the "very real issues of complexity" the reviewer describes in a manner that is hopefully accessible to all audiences. The reviewer raises a valid point, that none of the authors (and to our knowledge none of the reviewers and likely very few other readers) have actually done rocket science – it is a fair implication that we may not fully grasp exactly how complicated real rocket science is, but we also believe that many members of our target audiences may also not fully grasp how complicated real fisheries science is. We have therefore kept the analogy but removed any claim that fisheries science is *more* difficult than rocket science.

Section 3.1, par3: the final sentence in this paragraph appears over-stated. Flowery statements like "forces that have never before been observed" and "…with cascading influences…" are more appropriate in a TV documentary rather than a serious scientific investigation. Statements like these are not consistent with the uninformative and/or weak effects generally found in this report.

Response: The text has been modified so as not to appear overstated.

P57: highlighting "very likely" implies that Peterman's notion of "very likely" is the same as qualitatively defined in this report, and I doubt that is true.

Response: We have removed the italics from the evaluations provided by both Peterman et al. (2010) and the participants of the Cohen Commission workshop so that such formatting does not imply that the ratings from those two assessments are identical to the similarly named ratings reported by us in our qualitative evaluation. We have also added a footnote to explicitly address the differences between these approaches.

P58: Why are comparisons made among models here when the actual approach is not described until p77?

Response: We have added a new section (3.3.6) that provides a high-level overview of our methodology such that readers will be introduced to the approach prior to being shown any results (i.e. in Section 4.4.5 that the reviewer identifies and in Section 4.7.2) and will not need to consult the appendices in order to understand the results presented.

The change-point analyses don't' seem particularly valuable, especially when there is no substantial synthesis of the results.

Response: We have kept these analyses and expanded upon our justification for including them and improved the discussion of their results, in both section 4.1 and Appendix 4. We wanted to explore the commonly quoted statements regarding the productivity of Fraser River sockeye stock being in decline since approximately 1990. We wanted to have an objective assessment of when and how strong trends in each of the sockeye stocks were, hypothesizing that there may be substantial differences among stocks in the timing and strength of declines in productivity. If there were groups of stocks with similar change-points, the similarities among those particular stocks might indicate important factors. These data were also available long before any of the covariate data from the other technical reports. Other methods of determining the timing of productivity changes are included in Peterman and Dorner (2011) and McKinnell et al. (2011); different analytical approaches generate somewhat different results, but the overall conclusions are similar.

P63: This report seems to overuse terms like "striking" and "dramatic".

Response: Those terms have been removed.

Figure 4.5-2 (this figure has no labels): if this is a time-series, then the points should be connected by a line. That way, inter-annual variability is easier to see.

Response: This graph was extracted as an image from the publication cited. We were not able to acquire the underlying data before submitting the draft report and therefore it was presented in its original form. We have since acquired the raw data, updated to 2010. We have now graphed the same data without a trend line but including labels for the axes. This figure is a time-series, but these data should not be connected by a line because the variable represents a discrete annual event (i.e. return migration). Representing these data with a line graph would incorrectly imply this is a continuous measure for which values between

annual data points can be interpolated.

Hasn't the total sockeye return been increasing along a similar trend to the diversion rate? Is it possible that the average diversion rate (~0.4-0.5) was actually typical back when there were a lot more sockeye around (i.e., prior to Hell's Gate slide), and so this pattern is a return to normal migration patterns?

Response: We have not attempted to provide any explanation for theses apparent changes. We simply identify diversion rate and age-type proportions as other potential response variables that appear to have also experienced changes over recent decades and suggest that work to increase our understanding of these patterns would likely be beneficial. They could be responding to the same factors that have been driving changes in productivity, or similar factors, or completely different factors. The reviewer asks an excellent question to be explored in further research – are these patterns shifting away from "normal" patterns or returning toward "normal" patterns in a long recovery following the catastrophic Hell's Gate slide in 1913? This question is worth further investigation but the time series available to us cannot offer any insights for that question.

We have not conducted any quantitative analyses for this question, but offer the following qualitative observations based only on a visual examination of the data. First, the diversion rate data appears to indicate a possible shift in the late 1970s to a state of higher diversion rates on average but with greater variability rather than a gradual increase. The "trend" line in Figure 4.5-2 was present in the original figure extracted from Levy (2006); since we only had access to this figure and did not have access to the original data, we were unable to remove this trend line (but have removed it in this final report). Second, the patterns in sockeye salmon returns (e.g. Figure 4.1-5 shows total returns by brood year cycle) do not appear (based on visual inspection) to correspond with the diversion rate pattern. Sockeye returns were increasing over the 1960s, 1970s, and 1980s (i.e. the pattern starts well before any notable changes in diversion rate) and have been decreasing since approximately 1990 (i.e. the pattern reverses with no notable change in diversion rates). However, these are only preliminary qualitative observations and this deserves further quantitative examination.

P65: it is not clear what the "definitive correlation" compares.

Response: This sentence has been rewritten to be a clearer reflection of the idea it references.

There is considerable repetition of information/review under Stages 3 and 4: can these be combined into one section?

Response: We recognize that there is some repetition between these stages. In some cases the information, analyses and knowledge presented in other technical reports did not, or was not able to, clearly distinguish between these two marine-based life stages and therefore similar evidence was available for both stages. We have tried to highlight the

evidence unique to each life stage. However, we do not feel it would be appropriate to combine these two stages into one section because there are also cases where not only is the evidence different between the two stages, but this evidence leads to different conclusions between stages regarding the likelihood of particular factors. It therefore seems prudent to maintain this distinction despite the consequence of there being some repetition.

P69: "pre-spawn mortality" is only measured for females, correct?

<u>Response</u>: Yes. From Hinch and Martins (section 2.7): "Pre-spawn mortality is defined as females that have arrived on spawning grounds but die with most of their eggs retained in their body." We have defined this term in our report.

P69: I don't see the point of comparing upriver migrating adults with downriver migrating smolts here.

<u>Response</u>: We have removed this paragraph.

P70: the report should not bring up the topic of sockeye genetic adaptation to temperature regimes over thousands of years, and then only talk about the last 60 years.

<u>Response</u>: We have removed the phrase "over thousands of years".

Does "total summer flows" mean "peak summer flows"?

<u>Response</u>: No. The source of this text was section 1.5.1 from Hinch and Martins (2011), which reads as follows:

> **"In the Fraser River, the date for ⅓ and ½ of the year cumulative flow has been occurring progressively earlier at the rate of 1.1 and 0.9 days per decade, respectively, since the 1950s (Foreman et al. 2001). Despite the shift towards an earlier onset of the spring freshet, there have been no significant changes in *total summer flows* of the Fraser River (Patterson et al. 2007a)." [italics added]**

We have clarified the wording in our report, so that it now reads as follows:

> **"While there have been no significant changes in the total cumulative flow over the summer season, more of the cumulative summer flow is arriving earlier in the year. One measure is the date at which the first half of the cumulative summer flows occurs, which is happening a day earlier per decade."**

P72: the reference to Figure 4.5-2 should point to Figure 4.6-2

<u>Response</u>: That has been corrected.

P80: remove the last two paragraphs about correlation vs causation. This seems rather pedantic.

Response: We have kept these two paragraphs. We feel that it may be valuable to some audience members. As discussed in Section 1 of this review, this report is intended for many audiences who will vary in their levels of technical proficiency. The prioritization of these audiences has also been clearly defined for us (see Section 1).

P158: why are differences in stock composition so "striking"? Isn't that just a result of the dominant four-year life history? I also don't see an actual comparison of the 2009 and 2010 returns referred to at the bottom of p158.

Response: The reviewer is correct – the differences in stock composition are a result of the dominant four-year life history. The purpose of these graphs is simply to illustrate that there are in fact substantial differences in stock composition among the cohorts. This may be a fairly obvious observation to those with a scientific background in sockeye salmon; however, based on our observations of media coverage and other public fora it appears that this difference in stock composition among cohorts is often not recognized. In the public discourse, the poor 2009 returns are often compared/contrasted with the high 2010 returns (these are the "comparisons" to which we refer), without acknowledging that the situation is actually more complicated since not only do the two years come from different generations/cycles, but the composition of each is distinctly different. These graphs show quite clearly that 2009 vs 2010 is not a simple "apples-to-apples" comparison.

The "Key things we need to know better" seem to include just about everything, and I somehow doubt that we need to know all of it.

Response: Within each life stage, we limited ourselves to 4-6 key recommendations, selected from a much longer list. We strongly agree that further prioritization is required, and as noted in section 5.2.2, have suggested some questions and procedures to help in that process.

Report Title: Data Synthesis and Cumulative Impacts
Reviewer Name: Rick Routledge
Date: March 20, 2011

1. Identify the strengths and weaknesses of this report.

- I am generally in agreement with the conclusions of this report. Subject to the limitations associated with both (i) the scope of the "Statement of Work" and (ii) weaknesses in the underlying base of knowledge and data, the team has done a solid job of the task put to them.
- I also concur with the need for substantive caveats on the conclusions that can be drawn from such a study, though I do recommend that key weaknesses in the quantitative assessments need to be highlighted more effectively. I also recommend that there be more qualitative discussion, perhaps with examples from other situations, of the inherent weaknesses in such approaches to analyzing the behaviour of complex interactions that encompass such a diverse, geographically extensive set of ecosystems.

Response: We agree with this recommendation. Section 3.2 already provides several caveats. We have added some more discussion and caveats to the Executive Summary (end of Conclusions), the start of section 3.1, Section 4, Appendix 4, and end of Section 5.1. The limitations of this method have been explicitly described in Appendix 3.

- Nonetheless, I have some concerns regarding weaknesses in technical details of the analyses to which I feel that the team ought to pay more attention – at least insofar as to give these weaknesses greater prominence in the report. Some of them are clearly far too complex and time consuming to implement in the limited time frame of this study.

Response: This feedback is further elaborated upon, and responded to, in Part 6 below.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

Please see detailed comments in the specific comments to the authors below.

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

Please see detailed comments in the specific comments to the authors below.

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

Please see detailed comments in the specific comments to the authors below.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

In addition to my comments below, I would like to emphasize my concerns over the weakness of a multiple regression-style statistical assessment of such a potentially complex phenomenon as the cumulative impact of multiple stressors. Although it can provide useful hints regarding major potential stressors, it is not an effective tool for detecting nonlinear relationships and non-additive interactions. The latter weakness seems particularly critical in an assessment of cumulative impacts.

<u>Response</u>: We agree, and have added text regarding this issue to Appendix 3.

Also, the report correctly highlighted the critical lack of information on pathogens. This strikes me as a highly important knowledge gap that warrants much immediate attention.

<u>Response</u>: This feedback is further elaborated upon, and responded to, in Part 6 below.

6. Please provide any specific comments for the authors.

I am generally in agreement with the conclusions of this report. Subject to the limitations associated with both (i) the scope of the "Statement of Work" and (ii) weaknesses in the underlying base of knowledge and data, the team has done a solid job of the task put to them.

I also concur with the need for substantive caveats on the conclusions that can be drawn from such a study, though I do recommend that key weaknesses in the quantitative assessments be highlighted more effectively. I also recommend that there be more qualitative discussion, perhaps with examples from other situations, of the inherent weaknesses in such approaches to analyzing the behaviour of complex interactions that encompass such a diverse, geographically extensive set of ecosystems.

I also have some concerns regarding weaknesses in technical details of the analyses to which I feel that the team ought to pay more attention – at least insofar as to give these weaknesses greater prominence in the report. Some of them are clearly far too complex and time consuming to be addressed in the limited time frame of this study.

Following are more specific comments.

1. The main conclusions to my mind are as follows:
    a. That the early marine environment emerges as a major potential source of the decline in productivity.
    b. That the majority of potential factors associated with the freshwater environment can be rated as unlikely to be major contributors.
    c. That pathogens emerge as the most critical knowledge gap.

    I view these conclusions as significant, valuable corroboration of widespread impressions and subjective assessments and opinions. Limitations of the multiple regression approach notwithstanding, the quantitative analysis lends valuable credence to these conclusions.

<u>Response</u>: We have further emphasized the early marine environment in our recommendations for future work, in both the Executive Summary and Section 5.2.2. We have further emphasized the importance of the knowledge gap on pathogens, especially in our recommendations. We believe that we have already placed sufficient emphasis on Point 'b', regarding the freshwater environment.

2. The following key, inherent weaknesses in the multiple regression approach need to be more solidly described and highlighted.
    a. Linearity: By necessity, most of the analyses appear to have assumed that each factor, on its own, contributes a linear effect. There was an attempt to consider the so-called hockey stick model with a linear effect kicking in after a threshold was passed, but this approach is a relatively simplistic way to address this issue. There is typically inadequate justification for assuming the presence of a sharp threshold, and data such as in Figure A3.5-3 are inadequate even for distinguishing between a hockey-stick model vs. a parabolic relationship let alone identifying the location of a threshold or the start of a downward trend[17]. Additivity: It seems to me that, when assessing cumulative impacts, the potential for nonlinear and non-additive interactions is key. The authors address a related issue in their Figure 2.3-1, but this figure seems to be focused primarily on the extent to which multiple, minor stressors might accumulate, potentially over several life stages, but in a sort of additive fashion, to produce a large impact over the entire fish life cycle. It does not address the potential for some factor, perhaps a pollutant encountered in the Salish Sea, to possibly combine with a shortage of food in Queen Charlotte Sound to produce a devastating impact on marine survival when either of these factors on its own might not present the fish with a significant challenge.
    b. Several candidate explanatory variables are in fact functions over time (e.g., sea surface salinity or river discharge). The authors sensibly attempted to use basic background information, such as the timing of the migration run, to reduce these functions to simple averages over a reasonable time window. However, in my work on Rivers Inlet sockeye salmon, I have found that there can be surprising timing anomalies whose causes are not immediately clear – sometimes even after they have come to our attention. I would recommend that this potential be highlighted as well. In addition, though there is insufficient time for the authors to develop a functional regression analysis, this technique can address these sorts of issues more definitively.[18]

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[17] Chiu, G. Lockhart, R. and Routledge, R. 2006. ***Journal*** of the ***American Statistical Association***, **101**:: 542–553.
[18] Ainsworth, L.M., Routledge, R., and Cao, J. 2011. Functional Data Analysis in Ecosystem Research: the Decline of Oweekeno Lake Sockeye Salmon and Wannock River Flow. Journal of Agricultural, Biological, and Ecological Statistics. Available online (DOI: 10.1007/s13253-010-0049-z).

c. I anticipate that a collection of factors whose impacts were felt through a combination of time lags on non-additive and nonlinear stress impacts would be very hard, if not impossible, to detect with this sort of multiple regression analysis – especially when so little is known about some key factors like pathogens.

Response: These are all excellent points. We had only limited time to conduct statistical analyses, and so we chose the simplest approaches. In Appendix 3 and a new section in the main report (3.3.6), we acknowledge the weaknesses and limitations of our approaches. We believe that the data limitations (i.e., appropriate covariates reflecting the impact pathways of concern; sufficient levels of contrast) are at least as serious a problem as the analytical problems.

To address specific components of the reviewer's comments:

a) In Section 4.7, we discuss potential cumulative effects over the entire life cycle, though we also note the difficulty of determining the form (e.g. additive or non-additive), magnitude, location and timing of such effects. We have also added further discussion on the potential for other functional forms for the candidate models (i.e. non-linear covariates, interactions) in our descriptions of the methods. The description and rationale for the approach we used with the change-point analyses has also been expanded.

b) We have discussed functional regression analysis in Appendix 3 as a potential technique to be used in the future.

c) We agree.

3. These inherent weaknesses notwithstanding, I believe that the authors used good judgment in applying these techniques. In particular, I support their use of scientific knowledge and common sense in limiting the candidate factors for the multiple regression models.

4. I would encourage the authors to provide examples of instances in which the sort of approach taken here would not have brought fundamental, underlying causes to light. For example, it seems unlikely that a multiple regression analysis without appropriate time lags could have drawn anyone's attention to the key phenomenon of bioaccumulation in the early days of research on ecological impacts of DDT.

Response: This is a good example, which we will incorporate into our discussion of the limitations of our analyses (in Appendix 3). Other mechanisms which could cause linear regressions to miss important ecosystem linkages include non-linear relationships between ecosystem productivity, sockeye abundance and predation (Christensen and Trites 2011, pgs. 13, 76), as well as non-linear threshold effects from contaminants (MacDonald et al. 2011).

5. I would also encourage the authors to address some of the concerns regarding pathogens that have emerged in recent Commission hearings. Although they did indeed identify that the information base on pathogens was too weak for their analyses, I believe that it is important that the potential for pathogens to explain much of the recent decline in productivity be highlighted. There are many examples of pathogens playing a major role in population declines – the bubonic plague being perhaps the most famous. This is an important weakness in our current knowledge base that, in my assessment, deserves a very high profile.

Response: We agree. We have emphasized this critical knowledge gap in numerous places. In our recommendations (as well as in other parts of the report), we have emphasized the need to address the lack of knowledge regarding pathogens. We have reviewed the relevant sections of the transcripts from Scott Hinch's testimony on the topic of climate change at the Cohen Commission, where he discusses the potential association between diseases and en route mortality; however, the actual topic of disease will not be heard until August.

6. It might also be useful for the report to highlight, where feasible, missing contrasts that might shed light on the causes of the productivity decline. I note, in particular, that the report pays limited attention to Harrison sockeye salmon, and does not give the determination of the early-marine migration route for this population an elevated priority in the list of recommendations. I anticipate that this population could provide an unusually valuable contrast given the divergent trend in the Harrison population vs. others. Also, basic knowledge of the migration routes and timing of other populations such as sockeye salmon that spawn on the Central Coast and on the west coast of Vancouver Island, along with selected populations of other salmon species, could play a key role in sifting through potential causes of the decline in Fraser River sockeye salmon. I would encourage the authors to give such matters a higher profile in their recommendations.

Response: This is a good point. We do discuss the Harrison stock in sections 4.3.2, 4.3.3 and 4.4.7. We agree that it makes sense to elevate the priority of understanding the migration routes of Harrison sockeye (#13 in Table 5.2-1), as contrasts in their exposure to various stressors may be most informative, given their relatively strong productivity during the last two decades.

7. Personally, I would not place as high a priority on some of the highlighted recommendations, and would add some others. Here are some detailed suggestions.
    a. **Parental spawning…:** I agree with the low rating for recommendations 1 and3, but would recommend more thorough monitoring of smaller conservation units.
    b. **Juvenile rearing…:** Although the highlighted recommendations are not

without merit, I would not give these as high a priority as other recommendations associated with what have been identified as more likely sources of problems.

c. **Downstream migration to estuary:** Given recent concerns about disease and emerging evidence of high mortality rates during the migration down the estuary and through the passage inside Vancouver Island, I would be inclined to elevate the priority for these recommendations.
d. **Inshore migration:** I would recommend a high priority for all of these recommendations, including #13 on Harrison sockeye given the key contrast that they seem capable of providing.
e. **Growth in North Pacific …:** I agree that estimates of returns, etc., continue to be important. Also, estimating abundance of arrivals at the Gulf of Alaska seems likely to me to be very challenging and expensive, and hence I agree that this should not be awarded a high priority. Assessment of ocean conditions seems to be very important though, especially in light of the circumstantial nature of the evidence associated with the potential role of the volcanic eruption in contributing to the strong 2010 returns. The uncertainty over the ecosystem consequences of the anomalously large phytoplankton production that it produced underscores in my mind the importance of improving our collective understanding of this ecosystem.
f. **Migration back to spawning:** I agree with the priority assignments to these recommendations.

<u>Responses:</u> All of our prioritization suggestions are preliminary, and will need to be reviewed by a well-informed panel of scientists and managers. Our responses to your recommendations are as follows (same lettering):

a. **We agree, and have increased the priority of recommendation 2, though as for recommendation 1 we would only do this for a strategically selected subset of smaller CUs.**
b. **We partly agree, and have reduced the priority of recommendation 5 (conditions in rearing lakes). However, we have maintained the high priority of recommendation 4 (smolt estimates) as we believe that it's essential to first determine the life history stages with higher levels of mortality, and then to seek the causes of such mortality. We recognize that for stocks with a history of fry estimates only, it will be essential to continue these time series.**
c. **For reasons mentioned under b, we have increased the priority of recommendation 7 (smolt survival rates), but left recommendation 8 (size and health of smolts) to be contingent upon the observation of poor lake to estuary smolt survival.**
d. **We agree, as mentioned above.**
e. **We believe that with the other measurements of sockeye abundance at various life stages, it should be possible to determine if there are unexpected changes in survival during the growth of adults in the Pacific. Then if such**

events occur, it should be possible through strategic alliances with other agencies (e.g., NOAA, ADFG) to collect information on potential explanatory variables. We therefore have maintained oceanographic information for the Gulf of Alaska at its current level of priority.

Report Title: 6. Data Synthesis and Cumulative Impacts
Reviewer Name: John D. Reynolds, Simon Fraser University
Date: 1 April 2011

1. Identify the strengths and weaknesses of this report.

Strengths: well-organized, clear framework, integration of information from a large number of other technical reports as well as the workshop, compilation of large database from those reports, new quantitative analyses from that database.

Thank you.

Weaknesses: apparent lack of consistency about what is meant by "productivity", need for impacts of potential stressors to be combined more clearly into a more "cumulative" synthesis.

Response: We have defined productivity in both the Executive Summary and Introduction, and have added further discussion of cumulative impacts over the life cycle in Section 4.7.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

The data interpretations seem fine, including the conclusions for impacts on each stage of the life cycle, summarized in a separate table in each section. I agree with the interpretations, and with the reasons given.

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

The basic analytical framework, based on multiple regressions and information theoretic methods, seems fine.

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

Yes, the recommendations seem fine. We could also add more, but the benefits of further research and analyses beyond those suggested would need to be weighed carefully against the costs.

Response: We have added further discussion of the criteria and process that should be used to refine and prioritize our recommendations (in Section 5.2.2).

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

I don't have anything to add beyond what has been recommended.

6. Please provide any specific comments for the authors.

I like the approach of considering the potential cumulative impacts from a life history perspective of the fish, i.e. following the fish through their life cycle and considering exposure to each potential impact along the way. It is unfortunate that the Aquaculture technical report was not available to the authors at the time of writing, and the Commission should bear that in mind when evaluating these interim conclusions.

Response: We have reiterated this point (i.e. conclusions do not include information on aquaculture) in each of the relevant sections (i.e. Executive Summary, Coastal migration life stage (4.4.4, 4.4.5 and 4.4.7), and Conclusions (5.1, 5.2)).

The authors have done a good job of summarizing the information from the other technical reports, and also compiling data from those reports so that they could do their own integrative analyses. I agree with their view that the database that they have compiled could be the first step toward an important long-term resource, and I hope the Commission will consider recommendations that could lead to further development. I have always felt that information such as this should be much more accessible, and perhaps long-term funding could be made available to the Pacific Salmon Commission or some other organization to take this on.

Response: In response to a comment by Dr. Peterman on the form of such a database, we have expanded the discussion in Section 5.2.2.

The general analytical approach, involving multiple regressions analyzed within an information-theoretic framework, seems like the right way to go. I agree with the authors' logic in using multiple partial analyses rather than attempting one grand analysis, given missing values in data sets, and the need to account for too many variables at once. The authors reduced the number of variables through common sense about which might be informative, as well as through Principal Components Analysis. They could also have considered using Variance Inflation Factors to test for multicollinearity as a basis for dropping variables, as an alternative or adjunct to the use of PCA. But as long as the PCA axes are interpretable, this approach seems fine.

Response: We have substantially improved the clarity of our description of the methods we used (in a new Section 3.3.6, as well as in Appendix 3).

The conclusion follows the structure of the rest of the report, in breaking up the analyses by life stage. But I felt that what's missing is a final section putting the life stages back together, and integrating across all of the possible or likely stressors. In other words, I would have liked to have seen a final section that fully tackles the "cumulative" in cumulative impacts. This would match the detailed section that was provided describing what cumulative impacts mean.

<u>Response</u>: We have added such a discussion to Section 4.7.

A comment on pagination – it's confusing to have each section start at page 1. Below I will refer to the page numbers within each section, followed by the pdf electronic page number.

<u>Response</u>: We have corrected this pagination issue. The Executive Summary appears first and is not paginated. The main report (including all appendices except Appendix 6) is numbered continuously. We have maintained the original page numbering for Appendix 6 (Workshop Report) for consistency since it is a stand-alone report that has also been released on its own.

P. 4 / pdf 12 of the Executive Summary brings up a question concerning the terms of reference. "While there are some survival estimates for acoustically tagged smolts, these data (which in any case only cover a few stocks) were not analyzed by any of the Cohen Commission technical studies." The published studies of acoustically tagged smolts, e.g. smolts from Cultus Lake, are very relevant, even if not analyzed by any of the technical studies. The Statement of Work in Appendix 1 of this report does clearly focus on the other reports as the basis for material, and the authors are clear about this later on (pdf p. 21). However, I think it's a shame to ignore information that has been published in peer-reviewed journals, just because it slipped through the cracks of the other technical reports (more on this later). There's an additional limitation with this approach, which the authors are too polite to say: some of the technical reports that they rely on are much weaker than others, and it's a shame to be unable to fill in the gaps left by some of them.

I'm not sure what to recommend here. The authors have followed their Statement of Work and cannot be faulted for taking a clear approach that was doable within their timeframe. But if there's room for them to fill gaps left by other reports based on published literature here and there, I hope they and the Commission will consider this possibility.

<u>Response</u>: We have indeed focused our efforts on synthesizing results from the Cohen Commission Technical Reports, according to the Statement of Work, and on results from the recent PSC workshop on Fraser River sockeye salmon. There was neither sufficient time nor resources to complete a comprehensive literature review of information beyond those sources discussed in the Technical Reports. Where reviewers have suggested other information sources that were not included in the Technical Reports, but may be very relevant (e.g. the studies of acoustically tagged smolts from Cultus Lake), we have added references to our report.

p. 5 / pdf 13. "The evidence presented suggests that sockeye salmon in the Strait of Georgia have little direct exposure to human activities and development, leading to a conclusion that it is unlikely that these factors have contributed to the decline of Fraser River sockeye salmon." I would argue that exposure to salmon farms in the upper Strait constitutes an exposure to human activities. These farms have been shown to be significant sources of sea lice (Price et al. PloS One, 2011) and they are a potential source of viral pathogens (note my emphasis on the word "potential" due to lack of clear evidence that I'm aware of). The impacts of exposure to fish farms on population trends of Fraser sockeye are not clear, but the exposure of wild out-migrating juveniles to farms is clear. Salmon farms may have been ignored here because the aquaculture report is still in progress. If the authors agree with my point, that juvenile sockeye are exposed to a significant human activity in the form of salmon farms, the wording on p. 59 should be changed too, as should the Conclusion.

Response: The reviewer is correct - salmon farms are not currently included in the present report because the aquaculture report is still in progress. When it is completed we will write an addendum to our report that qualitatively considers the evidence provided in the aquaculture report. The reviewer raises a reasonable point regarding exposure to salmon farms in the upper Strait constituting an exposure to human activities. To avoid implying that sockeye are *not* exposed to salmon farms, we have modified the text in both the Executive Summary and Section 4.5.2 to explicitly clarify that we are only referring to human activities covered by Technical Report #12 and not to salmon farms.

p. 5 / pdf 13. "It's also very likely that marine conditions during the inshore migration life stage contributed to the poor returns observed in 2009." I would add that it is also very likely that improved marine conditions (cooler temperatures and associated food webs?) contributed to the improved return in 2010.

Response: We've added a brief discussion of 2007 vs 2008 (and their implications for returns in 2009 and 2010) to section 4.4.3, based on McKinnel et al (2011).

p. 5 / pdf 13. I am confused by the paragraph called "Stage 5: Migration back to Spawn". The authors say: "…the Fraser sockeye productivity indices already account for en-route mortality (i.e., recruits = spawners + harvest + en-route mortality)." I suggest starting with a clear definition of what, exactly, is meant by "productivity", and "recruits". Productivity can defined as the number of returns per spawner, where a "return" is a fish that comes back to the coast. Further sources of mortality are not included, such as fishing and en-route mortality in the river. From parts of the rest of the report, including the use of the SFU Think Tank's figure on p. 21 (pdf 35), I THINK the authors and I agree that productivity means what I am calling "returns to the coast" per spawner. But in other places I'm not so sure. The definition the authors have used suggested to me, the first few times I read it, that they were INCLUDING survival through the fishery and en route mortality as part of the definition of "productivity". That is also implied by their analyses of Recruits/Spawner later in the report. My question is, are different metrics being used to represent "productivity"?

Response: We have now clearly and consistently defined productivity in the Executive Summary, Introduction, and Section 4.1. We have applied the term consistently throughout the report. Three metrics are explained in Section 4.1, based on Peterman and Dorner

(2011).

This confusion continues with the logic that since "…the Fraser sockeye productivity indices already account for en-route mortality (i.e., recruits = spawners + harvest + en-route mortality)", "there is no point in examining correlations between en-route mortality and life cycle or post-juvenile productivity indices within the same generation." Well, if "productivity" means "returns to the coast" per spawner, then fishing and en-route mortality are NOT already accounted for, unless the authors mean that they have calculated these losses back in. This probably just needs to be re-worded to make it more clear.

Response: We believe that the definitions mentioned above clarify this issue.

p. 5/19. "If the effects of an individual project are insignificant, it is assumed that the project's contribution to potential cumulative effects will also be insignificant and a CEA will not be required for project approval (Greig 2010b)." Well, maybe, but isn't the point of a cumulative effects consideration that insignificant effects can be added or multiplied together? Admittedly, such effects would be very difficult to detect.

Response: Yes, this is completely true – the cumulative effect of multiple forces/factors that are themselves insignificant could still be significant due to additive or multiplicative interactions. The sentence quoted above describes how the concept of "cumulative effects" is commonly implemented within current practice in the field of environmental impact assessment in Canada. The wording of this paragraph has also been modified, based on other feedback, to clarify that this perspective reflects current *practice* not current *standards*. The whole paragraph describes not what "cumulative effects" *is* or *should be*, but simply how it is frequently applied. But the subsequent paragraph describes why this definition is inadequate and falls short of what "cumulative effects" analyses *should* be considering. We felt that contrasting very different definitions of cumulative effects would be a useful way of exploring some of the important ideas underlying this complex concept. We have expanded on the point raised by the reviewer in the revised section 4.7.

p. 12 / pdf 26. The approach that's outlined for the cumulative impacts analysis (3.3.1. Overview) does not, in my opinion, fully capture the "cumulative" nature of the impacts that are being assessed. That is, the 3 components of the approach could be examined without any of the considerations that were presented earlier on how cumulative impacts analyses work – each could be assessed totally independently of the other, at least the way this is written, and the way that much of the rest of the text is presented. The summary tables of exposure and likelihood of impacts of each potential stressor consider each stressor one at a time. I don't see anything "accumulating" here.

Response: We have added discussions of potential interactions among factors to various parts of Sections 4.2-4.6, and possible interactions across life history stages to Section 4.7. We have added some discussion in Section 2.3 to explicitly describe how the cumulative effects concepts described in Section 2 are integrated into the report. Point 3 in Section

3.3.1 has been revised to say "Assess the relative likelihood of feasible explanatory factors <u>and their potential interactions</u>". We have added some discussion regarding the consideration of cumulative effects and interactions in our methodological summary (Section 3.3.6) and Appendix 3 now provides greater discussion on some of the issues with including interactions in our quantitative analyses (e.g. we cannot assess the interactions with disease because there are no data available).

p. 19 / pdf 33. I like the conceptual flow diagram.

<u>Response</u>: Thank you for the positive feedback.

p. 43 / pdf 57. 4.3.2 Exposure of Fraser River sockeye to stressors. It would be good to add a couple sentences reminding readers how the Nelitz et al. index of cumulative stress works.

<u>Response</u>: Added to Section 4.3.2.

p. 46 / pdf 60. "As discussed above, MacDonald et al. (2011) compared water contaminant concentrations during the smolt migration period with thresholds established from laboratory and field studies, and no evidence against the hypothesis that contaminants encountered by smolts contributed to declining sockeye productivity." I'm not sure what this means: did they find evidence against the hypothesis because of lack of information, or perhaps evidence for the hypothesis

<u>Response</u>: Thank you for catching this error. The phrase "against the hypothesis" should be removed.

p. 49-49 / pdf 62-63. It seems odd that sea lice are not mentioned in the section on potential pathogens. They were mentioned in several places in the Disease report, though not in much detail.

<u>Response</u>: We limited our discussion of potential pathogens to those that Kent (2011; Pathogens and Disease) evaluated as being "high risk". Kent (2011) ranked the sea lice *L. salmonis* and *C. clemensi* as "moderate risk". He reports that there are many research publications (both finding and failing to find support) on the purported link between salmon farms, sea lice and increases in mortality of wild pink and chum populations. Kent (2011) further reports that "there are reports of *L. salmonis* infections on sockeye salmon, but there is not [any] direct indication that the parasite causes significant mortality in this species". However, it is not clear whether this conclusion reflects findings based on actual data or simply reflects an overall lack of appropriate data to test for such a relationship. When the technical reports on aquaculture are available, an addendum to this report will be completed to assess the cumulative effects on sockeye including salmon farms.

p. 53 / pdf 67. "For example, if 0.1% of the diet of spiny dogfish was sockeye smolts, they would consume 14.5 million smolts within the Strait of Georgia (very significant predation)…" Well, to say that level is significant requires a back-of-the-envelope comparison with how many smolts leave the Fraser each year. Otherwise, we can't tell if this is a lot or a few in terms of potential impacts on the populations.

Response: We have modified this sentence. We have added a sentence on the average number of Chilko smolts to provide some frame of reference.

p. 60 / pdf 74. What's missing from this section on marine conditions is any mention of the high returns in 2010. It would be nice to have a discussion of whether the negative oceanic conditions that are mentioned for Queen Charlotte Sound and the Strait of Georgia were reversed for the smolts that contributed to the strong 2010 return.

Response: This is addressed above, with respect to your comment on pg. 5 / pdf 13.

p. 63 / pdf 77. Fig. 4.5-1. This figure on the proportion of Early Stuart fish returning as 5 year-olds doesn't seem to be introduced in the text, though the Fraser temperature figure is referred to in the text as having this figure number.

Response: There were three paragraphs at the beginning of Section 4.5.2 that were accidentally removed from the draft submitted, including a paragraph discussing Figure 4.5-1. This oversight has been corrected and the figure is now introduced properly. The references to the Fraser temperature figure (i.e. Figure 4.*6*-1) have been corrected.

p. 82 / pdf 96. "Food resources" are listed as a topic that was not covered by the Commission's reports. I wonder how that could have happened, and I also raised this as a concern in my review of the technical report on Lower Fraser and Strait of Georgia. The final version of that report omitted 2.5 pages of my review, which included this comment, and the authors did not answer it.

Response: We cannot offer a response to this comment. The issues raised are more appropriately directed toward the Cohen Commission and the authors of Technical Report #12, respectively. However, we have discussed some aspects of food resources in various parts of Section 4.

More generally, the Commission should consider how the items in this table (4.8-1, p. 82) will be dealt with. Perhaps examination of witnesses will suffice, but the Commission could also consider whether a short report that picks up the items that have slipped through the cracks would also be helpful, if this could be done within the tight timeline.

Response: We agree with the reviewer. We thought it was important to at least identify that there are still further hypotheses and potential factors outside of the set of topics that the technical reports were commissioned to investigate. We believe it is important for both the Commission and other audiences to recognize that the set of factors explored by the technical reports is not an exhaustive list of ALL potential factors but a set of some of the

most likely contributors to the recent patterns of change observed in Fraser River sockeye salmon. However, we also acknowledge that Table 4.8-1 is also not an exhaustive list of other factors.

Appendix 3. Data and Methods

A3.1 Appendix Outline

This appendix provides a detailed description of the data used and methods applied in the present report. The subsequent subsections explain:

1) the process of collecting data from the other technical reports, including the data template and data requirements provided to contractors submitting data;
2) the data that was ultimately received from the other technical reports;
3) the process of compiling and integrating the collected data into a central database and preparing it for analysis; and,
4) the qualitative and quantitative analysis methods applied in this report.

A3.2 Data Collection

To facilitate the acquisition of the necessary data sets and associated metadata from each scientific research project, we designed an Excel template and an accompanying set of guidelines. The Cohen Commission distributed these data templates to all appropriate scientific contractors in late September, with a deadline of November 1, 2010 for submitting the requested data, corresponding with the deadline for the submission of project progress reports. The objective of this template was to collect the necessary data in a consistent format, facilitating a range of quantitative and qualitative analyses exploring the relative and cumulative impacts of different stressors on Fraser sockeye productivity. Several project submitted data on November 1, 2010, but by the end of 2011, data had only been received four out of the seven project that would be submitting data for the cumulative impacts analysis. The outstanding data were a critical component of the cumulative impacts, representing over 70% of the final set of variables included. These data were received in mid to late January, forcing a compressed timeline for the remaining tasks associated with the organization and preparation of data (Section A3.4), the subsequent analyses of these data (Section A3.5), and the interpretation of the results (Appendix 4).

We recognized from the outset that data limitations would vary in severity by stressor and particular metric, including limited time spans of data, gaps in the time series, and only qualitative estimates for some years/metrics/stocks rather than quantitative measurements. The data template was designed with flexibility to accommodate these potential issues. The data template user guidelines are included in **Appendix 5**.

A3.2.1 Integrative quantitative metrics

Each contractor (excepting projects #6, 7, 10, and 11) was instructed to provide data for a few integrative metrics (or indices) of the stressors that his or her research group examined. Project 10 (Peterman and Dorner, 2011) was required to provide data; however, as they were providing the productivity data of each stock to be used as the response variable (i.e. not a covariate or potential stressor), the following criteria did not apply to their data submission.

It was specified that the metrics provided should adhere to the following guidelines:

- **Few**: Limit submission to 1-5 metrics per contractor. Additional metrics can be added if justified – i.e., metric represents an important but independent source of variation.
- **Integrative**: Each study will likely have a lot of data. The few integrative metrics provided to ESSA should synthesize these data. Each contractor is a discipline expert that will know which variables are most important or how best to integrate data into integrative metrics.
- **Independent**: Integrative metrics should be chosen to reflect independent sources of variation (i.e. not be highly correlated with each other).
- **Annual**: The metrics provided by each contractor need to be provided annually, for those years where data exist. Each contractor will know the most relevant approach to summarize intra-annual data into an annual metric (e.g., maximum weekly average temperature experienced during upstream migration of each stock of Fraser sockeye).
- **Stock specific**: Provide only one data point per stock per year. The same data point may apply to multiple stocks; contractors can specify which ones.

Furthermore, each reported metric should be clearly connected with a biologically-supported hypothesis that emphasizes why this metric is potentially important in explaining patterns in sockeye productivity over time and/or space. We also asked contractors to consider where their hypotheses fit within an initial conceptual model that we provided.

Finally, the original data sources and analytical methods would need to be explicitly described to communicate how each integrative metric was generated. The leaders of each project are expected to be the experts on how to best integrate stressor-specific data over space and time, but all users (intermediate and final) must be able trace the steps by which an integrative metric was generated from its primary sources. The data template therefore asked each contractor to provide metadata, describing all primary sources and assumptions used to derive the integrative metric.

A3.2.2 Qualitative assessment data sets

It was anticipated that many important metrics would have a limited data record, with gaps in both time and space. To overcome these limitations, contractors were asked to supply qualitative estimates or educated guesses for the entire time period. This would complement the quantitative data set.

Contractors were required to fill in a second data form with qualitative assessments (5 point scale) of the same integrative metrics for which they had provided quantitative data, but covering the entire time period from 1950 to now. This would be based on the expert experience of each contractor in their respective field, reflecting the contractor's best guess at the level of a particular stressor, not the actual impact of that stressor on sockeye productivity. Contractors were to provide their qualitative ratings independent of the productivity data (i.e. not assigning ratings based on looking at the productivity data, as that would make the ratings biased and unusable in the present analyses).

If not possible to distinguish among multiple quantitative metrics in making qualitative judgments for the entire period of record, contractors were given the discretion to qualitatively evaluate only a single overarching measure for their particular stressor. For example, the research group on contaminants could provide an overall estimate of the extent to which water contamination in general has changed over the past 60 years across Fraser River sockeye salmon's habitat range.

A3.3 Summary of Data Received

Table A3.3-1 shows a summary of the data variables ultimately received from each Cohen Commission scientific project and included in the cumulative impacts database, as described below. Of the six projects that submitted data sets for potential covariates, only two provided qualitative data assessments as described above in Section A3.2.2.

Table A3.3-1. A summary of data sets received from contractors and included in the cumulative impacts database The table shows the variables from each project, the location to which the data apply, the period of record (although this does not imply that the data series is complete over this time period), the number of stocks to which the data apply (less than 19 implies there are multiple stock-specific data series for the variable, whereas generally a stock count of 19 implies that there is only a single data series, which applies to all stocks), and the units of measurement.

Project Number	Project Name	Variable	Subset	Location	Min of Observation Year	Max of Observation year	Stock Count	Units
2	Contaminants	CCME Water Quality Index	Outmigration	Fraser Watershed - Migration Areas	1967	2010	17	index
2	Contaminants	CCME Water Quality Index	Rearing	Fraser Watershed - Rearing Areas	1971	2010	10	index
2	Contaminants	CCME Water Quality Index	Spawning	Fraser Watershed - Spawning Areas	1970	2010	9	index
2	Contaminants	CCME Water Quality Index	Upstream migration	Fraser Watershed - Migration Areas	1967	2010	19	index
2	Contaminants	CCME Water Quality Index - Qualitative	Outmigration	Fraser Watershed - Migration Areas	1948	2010	17	Qualitative magnitudes
2	Contaminants	CCME Water Quality Index - Qualitative	Rearing	Fraser Watershed - Rearing Areas	1948	2010	10	Qualitative magnitudes
2	Contaminants	CCME Water Quality Index - Qualitative	Spawning	Fraser Watershed - Spawning Areas	1948	2010	9	Qualitative magnitudes
2	Contaminants	CCME Water Quality Index - Qualitative	Upstream migration	Fraser Watershed - Migration Areas	1948	2010	19	Qualitative magnitudes
3	Freshwater ecology	Area forest harvested	Mainstem spawning areas	Fraser Watershed - Spawning Areas	1980	2010	12	percent
3	Freshwater ecology	Area forest harvested	Migration corridor	Fraser Watershed - Migration Areas	1980	2010	18	percent
3	Freshwater ecology	Area forest harvested	Nursery lakes	Fraser Watershed - Rearing Areas	1980	2010	16	percent
3	Freshwater ecology	Area forest harvested	Tributary spawning areas	Fraser Watershed - Spawning Areas	1980	2010	2	percent
3	Freshwater ecology	Human population density	Mainstem spawning areas	Fraser Watershed - Spawning Areas	1986	2009	12	#/km2
3	Freshwater ecology	Human population density	Migration corridor	Fraser Watershed - Migration Areas	1986	2009	18	#/km2
3	Freshwater ecology	Human population density	Nursery lakes	Fraser Watershed - Rearing Areas	1986	2009	18	#/km2
3	Freshwater ecology	Human population density	Tributary spawning areas	Fraser Watershed - Spawning Areas	1986	2009	14	#/km2
3	Freshwater ecology	Lake influence		Fraser Watershed - Spawning Areas	2009	2009	17	percent
3	Freshwater ecology	Road density	Mainstem spawning areas	Fraser Watershed - Spawning Areas	2009	2009	13	km/km2
3	Freshwater ecology	Road density	Migration corridor	Fraser Watershed - Migration Areas	2009	2009	18	km/km2
3	Freshwater ecology	Road density	Nursery lakes	Fraser Watershed - Rearing Areas	2009	2009	18	km/km2

Project Number	Project Name	Variable	Subset	Location	Min of Observation Year	Max of Observation year	Stock Count	Units
3	Freshwater ecology	Road density	Tributary spawning areas	Fraser Watershed - Spawning Areas	2009	2009	14	km/km2
3	Freshwater ecology	Spring air temperature		Fraser Watershed - Rearing Areas	1948	2009	18	Degrees Celsius
3	Freshwater ecology	Summer air temperature	CU set 1	Fraser Watershed - Migration Areas	1948	2009	18	Degrees Celsius
3	Freshwater ecology	Summer air temperature	CU set 2	Fraser Watershed - Migration Areas	1948	2009	5	Degrees Celsius
4	Marine ecology	Chlorophyll concentration	July mean	Queen Charlotte Sound	1998	2009	19	$ug.l^{-1}$
4	Marine ecology	Chlorophyll concentration	June mean	Queen Charlotte Sound	1998	2009	19	$ug.l^{-1}$
4	Marine ecology	Chlorophyll concentration	May mean	Queen Charlotte Sound	1998	2008	19	$ug.l^{-1}$
4	Marine ecology	Chlorophyll concentration	September mean	Queen Charlotte Sound	1997	2009	19	$ug.l^{-1}$
4	Marine ecology	Chlorophyll concentration	30 March - 22 April	Queen Charlotte Sound	1998	2009	19	$ug.l^{-1}$
4	Marine ecology	Chlorophyll concentration	April mean	Queen Charlotte Sound	1998	2009	19	$ug.l^{-1}$
4	Marine ecology	Chlorophyll concentration	August mean	Queen Charlotte Sound	1998	2009	19	$ug.l^{-1}$
4	Marine ecology	River discharge	Klinaklini (Knight Inlet)	Queen Charlotte Sound	1977	2008	19	m3/s
4	Marine ecology	River discharge	Wannock (Rivers Inlet)	Queen Charlotte Sound	1929	2009	19	m3/s
4	Marine ecology	Sea surface salinity	July mean	Queen Charlotte Sound	1970	2010	19	PSU
4	Marine ecology	Sea surface salinity	June mean	Queen Charlotte Sound	1970	2010	19	PSU
4	Marine ecology	Sea surface salinity	May mean	Queen Charlotte Sound	1970	2010	19	PSU
4	Marine ecology	Sea surface salinity	September mean	Queen Charlotte Sound	1970	2009	19	PSU
4	Marine ecology	Sea surface salinity	April mean	Queen Charlotte Sound	1970	2010	19	PSU
4	Marine ecology	Sea surface salinity	August mean	Queen Charlotte Sound	1970	2009	19	PSU
4	Marine ecology	Sea surface salinity	April-Aug average	Queen Charlotte Sound	1970	2010	19	PSU
4	Marine ecology	Sea surface salinity	May-Sept average	Queen Charlotte Sound	1970	2010	19	PSU
4	Marine ecology	Sea surface temperature	July mean	Queen Charlotte Sound	1982	2009	19	Degrees Celsius
4	Marine ecology	Sea surface temperature	July-June difference	Queen Charlotte Sound	1982	2009	19	Degrees Celsius

Project Number	Project Name	Variable	Subset	Location	Min of Observation Year	Max of Observation year	Stock Count	Units
4	Marine ecology	Sea surface temperature	August mean	Queen Charlotte Sound	1982	2009	19	Degrees Celsius
4	Marine ecology	Sea surface temperature	August-June difference	Queen Charlotte Sound	1982	2009	19	Degrees Celsius
4	Marine ecology	Sea surface temperature	July-Aug average	Queen Charlotte Sound	1982	2009	19	Degrees Celsius
4	Marine ecology	Summer wind regime	FACTOR	Queen Charlotte Sound	1948	2009	19	m/s
4	Marine ecology	Summer wind regime	U-direction	Queen Charlotte Sound	1948	2009	19	m/s
4	Marine ecology	Summer wind regime	V-direction	Queen Charlotte Sound	1948	2009	19	m/s
4	Marine ecology	North Pacific Index	Nov-Mar Average	Other North Pacific Ocean	1900	2010	19	Mb
4	Marine ecology	North Pacific Index	Anomalies	Other North Pacific Ocean	1900	2010	19	Mb
8	Predation (marine and freshwater)	Pinniped count	California sea lions		1971	2009	19	Count
8	Predation (marine and freshwater)	Pinniped count	Steller sea lion		1913	2010	19	Count
8	Predation (marine and freshwater)	Pinniped estimate	California sea lions		1971	2009	19	Count
8	Predation (marine and freshwater)	Pinniped estimate	Harbour seals		1913	2008	19	Count
8	Predation (marine and freshwater)	Pinniped estimate	Steller sea lion		1913	2010	19	Count
8	Predation (marine and freshwater)	Christmas Bird Count	BC Common murre		1957	2009	19	#/hour
8	Predation (marine and freshwater)	Christmas Bird Count	BC Cormorants, B+P		1957	2009	19	#/hour
8	Predation (marine and freshwater)	Christmas Bird Count	BC D-C cormorant		1957	2009	19	#/hour
8	Predation (marine and freshwater)	Christmas Bird Count	BC Gulls		1957	2009	19	#/hour
8	Predation (marine and freshwater)	Christmas Bird Count	BC Pelagic cormorant		1957	2009	19	#/hour
8	Predation (marine and freshwater)	Christmas Bird Count	BC Bald eagle		1957	2009	19	#/hour
8	Predation (marine and freshwater)	Christmas Bird Count	BC Brandts cormorant		1958	2009	19	#/hour
8	Predation (marine and freshwater)	Christmas Bird Count	BC Common merganser		1958	2009	19	#/hour
8	Predation (marine and freshwater)	Fish predators	Blue shark abundance		1980	2002	19	tons of biomass (millions)
8	Predation (marine and freshwater)	Fish predators	Arrowtooth flounder biomass		1961	2007	19	kg of biomass

Project Number	Project Name	Variable	Subset	Location	Min of Observation Year	Max of Observation year	Stock Count	Units
8	Predation (marine and freshwater)	Alternate prey	BC herring-CC	BC Central Coast	1950	2008	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	BC herring-PRD	Prince Rupert District	1950	2008	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	BC herring-QCI	Queen Charlotte Islands	1950	2008	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	BC herring-SoG	Strait of Georgia	1950	2008	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	BC herring-WCVI	West Coast Vancouver Island	1950	2008	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	California Current Pacific hake		1966	2009	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	Gulf of Alaska Pacific cod		1984	2005	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	Pacific Jack mackerel		1950	2006	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	Pacific mackerel		1929	2009	19	tons of biomass
8	Predation (marine and freshwater)	Alternate prey	Walleye pollock		1977	2007	19	tons of biomass
9	Climate change	LFR water temp for returning adults		Fraser Watershed - Migration Areas	1951	2010	19	Degrees Celsius
9	Climate change	LFR water temp for returning adults - Qualitiative		Fraser Watershed - Migration Areas	1948	2010	20	Qualitative magnitudes
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	July mean	Northern Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	July mean	Strait of Juan de Fuca	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	July mean	Central Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Northern Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Strait of Juan de Fuca	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Central Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Northern Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Strait of Juan de Fuca	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Central Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	September mean	Northern Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	September mean	Strait of Juan de Fuca	1998	2010	19	mg/m^3

Project Number	Project Name	Variable	Subset	Location	Min of Observation Year	Max of Observation year	Stock Count	Units
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	September mean	Central Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	April mean	Northern Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	April mean	Strait of Juan de Fuca	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	April mean	Central Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Northern Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Strait of Juan de Fuca	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Central Georgia Strait	1998	2010	19	mg/m^3
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge April total	Strait of Georgia	1970	2009	19	m^3/s
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge August total	Strait of Georgia	1970	2009	19	m^3/s
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge July total	Strait of Georgia	1970	2009	19	m^3/s
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge June total	Strait of Georgia	1970	2009	19	m^3/s
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge May total	Strait of Georgia	1970	2009	19	m^3/s
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge October total	Strait of Georgia	1970	2009	19	m^3/s
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge September total	Strait of Georgia	1970	2009	19	m^3/s
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	June-July average	Strait of Georgia	1970	2009	19	m^3/s
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	July mean	Strait of Georgia	1936	2008	19	PSU
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	June mean	Strait of Georgia	1936	2009	19	PSU
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	May mean	Strait of Georgia	1936	2009	19	PSU
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	September mean	Strait of Georgia	1936	2009	19	PSU
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	April mean	Strait of Georgia	1937	2009	19	PSU
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	August mean	Strait of Georgia	1936	2009	19	PSU
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	April-Aug average	Strait of Georgia	1936	2009	19	PSU
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	May-Sept average	Strait of Georgia	1936	2009	19	PSU

Project Number	Project Name	Variable	Subset	Location	Min of Observation Year	Max of Observation year	Stock Count	Units
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	July mean	Strait of Georgia	1936	2009	19	Degrees Celsius
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	June mean	Strait of Georgia	1936	2009	19	Degrees Celsius
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	May mean	Strait of Georgia	1936	2009	19	Degrees Celsius
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	September mean	Strait of Georgia	1936	2009	19	Degrees Celsius
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	April mean	Strait of Georgia	1937	2009	19	Degrees Celsius
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	August mean	Strait of Georgia	1936	2009	19	Degrees Celsius
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	April-Aug average	Strait of Georgia	1936	2009	19	Degrees Celsius
12	Lwr Fraser River and Strait of Georgia habitat inventory	Population census	Lower Fraser	Lower Fraser River	1986	2006	19	count
12	Lwr Fraser River and Strait of Georgia habitat inventory	Population census	Strait of Georgia	Strait of Georgia	1986	2006	19	count
12	Lwr Fraser River and Strait of Georgia habitat inventory	Population census	Strait of Juan de Fuca	Strait of Juan de Fuca	1986	2006	19	count
12	Lwr Fraser River and Strait of Georgia habitat inventory	Solid waste disposed	Lower Fraser	Lower Fraser River	1990	2006	19	tons/yr
12	Lwr Fraser River and Strait of Georgia habitat inventory	Solid waste disposed	Strait of Georgia	Strait of Georgia	1990	2006	19	tons/yr
12	Lwr Fraser River and Strait of Georgia habitat inventory	Solid waste disposed	Strait of Juan de Fuca	Strait of Juan de Fuca	1990	2006	19	tons/yr
12	Lwr Fraser River and Strait of Georgia habitat inventory	Liquid waste	Flow	Strait of Georgia	1997	2009	19	MLD
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total dredge volume	Lower Fraser	Lower Fraser River	1970	2006	19	m3
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total farm area	Lower Fraser	Lower Fraser River	1991	2006	19	ha
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total farm area	Strait of Georgia	Strait of Georgia	1991	2006	19	ha
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total farm area	Strait of Juan de Fuca	Strait of Juan de Fuca	1991	2006	19	ha
12	Lwr Fraser River and Strait of Georgia habitat inventory	Contaminants	Mill effluent loading	Strait of Georgia	1989	1999	19	mg/d x100
12	Lwr Fraser River and Strait of Georgia habitat inventory	Marine vessels	Gross register tonnage (domestic)	Strait of Georgia	1998	2008	19	tons
99	Pink Salmon	Pink salmon abundance	NE Pacific	Other North Pacific Ocean	1952	2005	19	millions of fish
99	Pink Salmon	Pink salmon abundance	Russia	Other North Pacific Ocean	1952	2005	19	millions of fish
99	Pink Salmon	Pink salmon abundance	ALL North Pacific	Other North Pacific Ocean	1952	2005	19	millions of fish

A3.4 Data Preparation

Contractor data was received in Excel files of various formats - very few of the data sets received used the data template that had been developed. These data were imported to an Access database to accomplish the brood year adjustments. The non-template data sets arrived in many different, non-standardized forms, adding a layer of complexity to their integration into a single database. Figure A3.4-1 shows the database diagram for that cumulative impacts database.

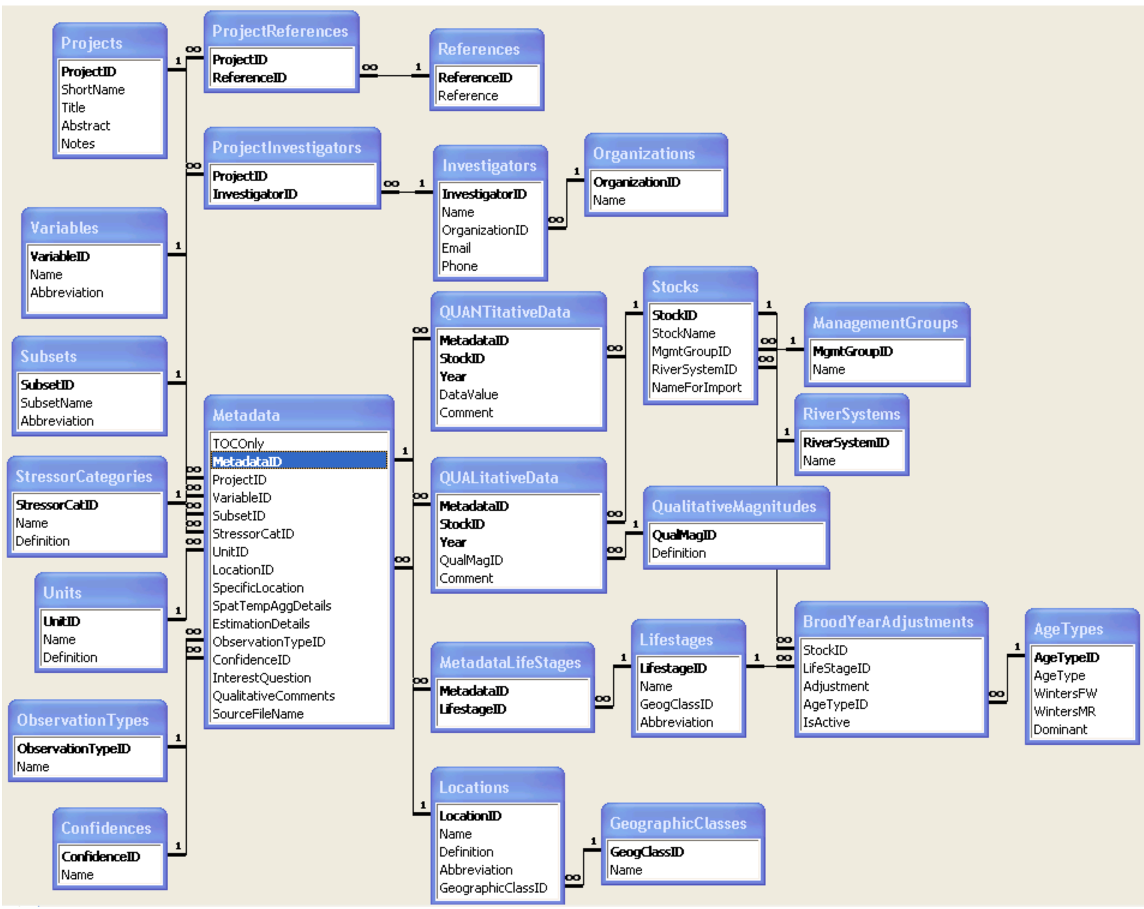


Figure A3.4-1. The Cohen Commission cumulative effects database diagram.

Each data product received from the contractors was assigned a unique identifier in the Metadata table. Each data product was assigned to a variable name and where appropriate a variable subset was specified (for example, if August mean sea surface temperature was received, the metadata record would specify “sea surface temperature” as the variable and “August mean” as the variable subset). The metadata table also specifies the location and units of the data product among other supplementary information. Table A3.4-2 shows an example entry in the Metadata table.

Table A3.4-2. An example entry in the Metadata table for Queen Charlotte Sound August mean sea surface temperature data.

TOCOnly	FALSE
MetadataID	27
ProjectID	4
VariableID	Sea surface temperature
SubsetID	August mean
StressorCatID	Marine conditions - physical
UnitID	Degrees Celsius
LocationID	Queen Charlotte Sound
SpecificLocation	
SpatTempAggDetails	QCS SST data, average values on the 3 grid points. Correlations among grid points from 1982 are ~0.995
EstimationDetails	August average. Data from: ftp://ftp.emc.ncep.noaa.gov/cmb/sst/oimonth_v2/YEARLY_FILES/
ObservationTypeID	Measured
ConfidenceID	
InterestQuestion	Were there extremes in sea surface temperature that could have been responsible for extreme mortality of Fraser River sockeye but not others (Columbia River or Barkley Sound)?
QualitativeComments	
SourceFileName	QCS_SST.xls

The actual observation data was imported to the QuantitativeData table (or the QualitativeData table where qualitative data was provided). Each entry in the QuantitativeData table is linked to a metadata record. The table MetadataLife stages associates the metadata records with the applicable life stage(s).

For example, Table A3.4-3 shows the life stage associations for the August mean sea surface temperature data (MetadataID 27).

Table A3.4-3. The MetadataLife stages table associates the Queen Charlotte Sound August mean sea surface temperature data (MetadataID 27) with two life stages.

MetadataID	Life stage Name
27	Migration to rearing areas-Marine
27	Migration to spawning area-Marine

Observation year to brood year adjustments are based on the BroodYearAdjustments table. This table contains the adjustment factor for each stock, life stage and age type. Table A3.4-4 shows the summary of the life history of Fraser River sockeye salmon that was used to determine the appropriate adjustments to make for each life stage. Table A3.4-5 shows the brood year adjustments used for the dominant age type of all stocks except Harrison, as expressed in the database.

Table A3.4-4. Summary of the life history of the Fraser River sockeye salmon. This table shows the timing of major stages and processes for the dominant age-types, including the year (relative to brood year) during which each occurs. This information was used to guide the process of aligning the observation values within each received data series with the brood year to which it would apply. BY = brood year. SoG = Strait of Georgia. LFR = Lower Fraser River. Sources: Burgner (1991); McKinnell et al. (2011)

Life history		Timing of Dominant Age-Type					
Develop-mental Stage	**Process**	**All non-Harrison Fraser River stocks (age-type 4_2)**			**Harrison stock (age-type 4_1)**		
		Season	**Year**	**Comment**	**Season**	**Year**	**Comment**
EGG	Spawning	Aug-Nov	**BY**			**BY**	
	Incubation	Winter	**BY+1**		Winter	**BY+1**	
ALEVIN	Emergence	April - early June	**BY+1**		Spring	**BY+1**	
FRY to PARR	Freshwater rearing	Summer - Winter	**BY+1**				
		Winter - Spring	**BY+2**				
SMOLT	Outmigration	April/May	**BY+2**				
	Estuary rearing		**BY+2**	minimal or n/a	Spring/ Summer	**BY+1**	up to 5 months in estuary
					by late July	**BY+1**	enter Fraser plume
POST-SMOLT	SoG passage	by late May	**BY+2**	dispersed N&W from Fraser	by Aug/Sept	**BY+1**	dispersed into SoG
	Coastal migration	by June/July	**BY+2**	most left SoG			
		by Aug/Sept	**BY+2**	spread along coast	by Autumn	**BY+1**	migration to continental shelf
ADULT	Growth and maturation in North Pacific	by late Autumn/ early Winter	**BY+2**	move offshore		**BY+1**	
			BY+3			**BY+2** **BY+3**	
	Migrate towards Fraser River	Spring	**BY+4**		Spring	**BY+4**	
		July - early Sept	**BY+4**	Passing through Strait of Georgia			
	Lower Fraser River passage	mid-June - mid-Oct	**BY+4**	Finer scale by run-timing group	mid-Aug - early Oct	**BY+4**	late run group
	Upstream migration		**BY+4**				
	Spawning	Aug-Nov	**BY+4**		Sept-Oct	**BY+4**	(based on LFR passage)

Table A3.4-5. Brood year adjustment factors for the 4_2 age type (used for all stocks except Harrison).

AgeType	Adjustment	Life stage Name
4sub2	0	Spawning-Freshwater
4sub2	-1	Incubation-Freshwater
4sub2	-1	Emergence-Freshwater
4sub2	-1	Freshwater rearing
4sub2	-2	Freshwater rearing
4sub2	-2	Smolt outmigration-Freshwater
4sub2	-2	Estuary rearing
4sub2	-2	Migration to rearing areas-Marine
4sub2	-2	Growth and maturation-Marine
4sub2	-3	Growth and maturation-Marine
4sub2	-4	Migration to spawning area-Marine
4sub2	-4	Spawning-Freshwater

The unique lifecycle of the Harrison stock is captured in the BroodYearAdjustments table under the 4_1 age type (Table A3.4-6). Although not shown here, the subdominant age type brood year adjustments are also captured in the BroodYearAdjustments table (age type 5_2 for all stocks except Harrison, age type 3_1 for Harrison). Brood year adjustments were made for the subdominant age classes however, at present, no analyses have been performed on these data.

Table A3.4-6. Brood year adjustment factors for the 4_1 age type Harrison stock.

StockName	AgeType	Adjustment	Life stage Name
Harrison	4sub1	0	Spawning-Freshwater
Harrison	4sub1	-1	Incubation-Freshwater
Harrison	4sub1	-1	Emergence-Freshwater
Harrison	4sub1	-1	Smolt outmigration-Freshwater
Harrison	4sub1	-1	Estuary rearing
Harrison	4sub1	-1	Migration to rearing areas-Marine
Harrison	4sub1	-1	Growth and maturation-Marine
Harrison	4sub1	-2	Growth and maturation-Marine
Harrison	4sub1	-3	Growth and maturation-Marine
Harrison	4sub1	-4	Migration to spawning area-Marine
Harrison	4sub1	-4	Spawning-Freshwater

A series of queries were run to format data for output and adjust the observation year data to brood year. First, data was pulled from 4 tables to format it succinctly for the brood year adjustments (Figure A3.4-2). Each observation data value was aligned with its variable, variable subset, observation year, stock, location, and life stage.

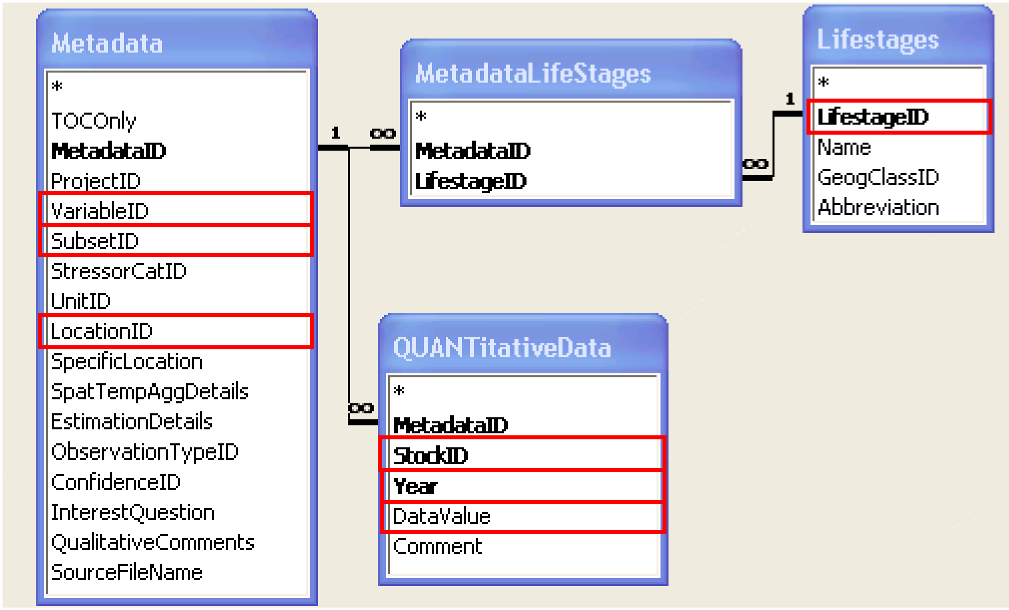


Figure A3.4-3. Querying data to prepare for brood year adjustment.

These data were stored in a temporary table called OutputQuant. The stock and life stage values were used to join the OutputQuant table to the BroodYearAdjustment table (Figure A3.4-3).

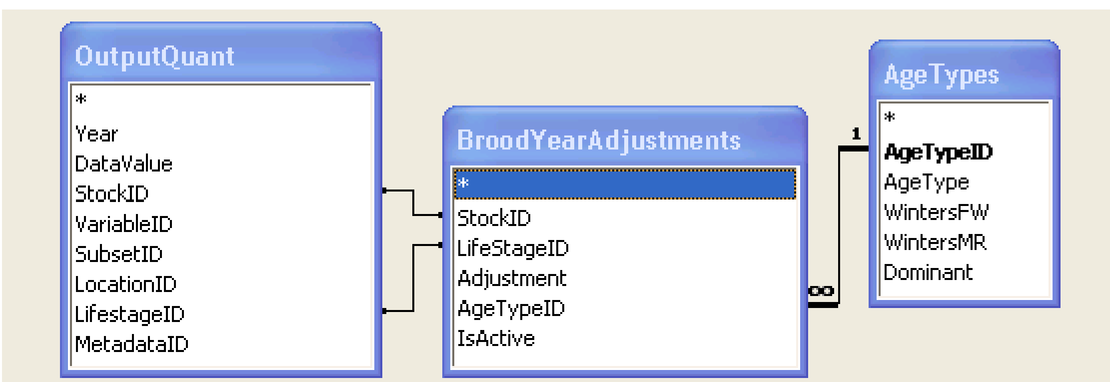


Figure A3.4-4 The query used to make the brood year adjustments.

Observation years were adjusted to brood years based on stock, life stage and age-type. An example output from the brood year adjustment process is shown in Table A.3-4. For the 4_2 age type, the sockeye salmon from brood year 1985 would have experienced the 1987 August mean sea surface temperature of 12.859 °C in Queen Charlotte Sound as they migrated along the coast to their marine rearing areas. Two years later, the same sockeye salmon (brood year 1985) would have experienced the 1989 August mean sea surface temperature in Queen Charlotte sound of 14.83 °C if they migrated back to their spawning areas via the northern diversion.

Table A3.4-7. Example output from the brood year adjustment process.

MetadataID	27	27
Variables.Name	Sea surface temperature	Sea surface temperature
SubsetName	August mean	August mean
Locations.Name	Queen Charlotte Sound	Queen Charlotte Sound
AgeType	4sub2	4sub2
StockName	E.Stuart	E.Stuart
Life stages.Name	Migration to rearing areas-Marine	Migration to spawning area-Marine
ObservationYear	1987	1989
BY Adjustment	-2	-4
BroodYear	1985	1985
DataValue	12.85	14.83

For analysis purposes, the brood year adjusted data was exported from the database to csv files. Data was reported by stock and brood year for each variable, variable subset, location, life stage and age-type combination. These unique combinations were termed "variable sets". Each variable set was assigned a unique identifier based on abbreviations for each component. Figure A3.4-5 shows the definition of an example variable set.

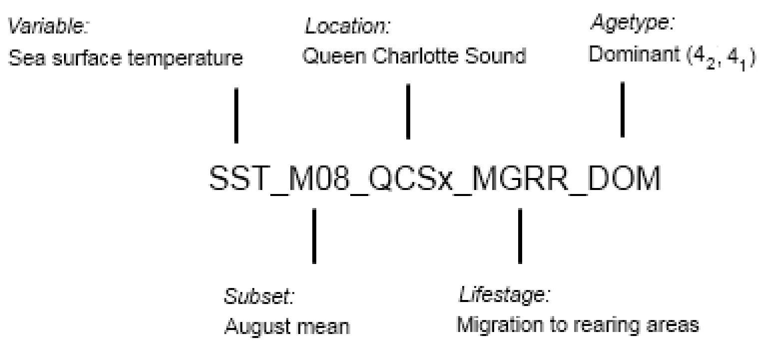


Figure A3.4-5. Variable set definition.

An example of final output data from the database is shown in Table A3.4-8.

Table A3.4-8 Example output from database, ready for analysis. This example data set contains only the mean August sea surface temperature for Queen Charlotte Sound as experienced by post-smolts passing through during their migration to their ocean rearing areas, and only for one single brood year. The data sets used in the analyses performed in the present project use many variables over many years (refer to Appendix 3.5 and Appendix 4).

Spawners	lnRS	BroodYear	StockName	RunTimingGroup	SST_M08_QCSx_MGRR_DOM
0.005758	3.754099	1985	Birkenhead	Late	12.85
0.00303	1.845149	1985	Bowron	Early Summer	12.85
0.034995	2.795625	1985	Chilko	Summer	12.85
0.000195	2.523058	1985	Cultus	Late	12.85
0.11661	2.338612	1985	E.Stuart	Early Stuart	12.85
0.000696	3.893783	1985	Fennell	Early Summer	12.85
0.002031	4.173986	1985	Gates	Early Summer	12.85
0.001825	2.070912	1985	Harrison	Late	12.6
0.000806	2.919312	1985	L.Shuswap	Late	12.85
0.159101	3.093156	1985	L.Stuart	Summer	12.85
0.007722	1.802942	1985	Nadina	Early Summer	12.85
0.002088	2.40829	1985	Pitt	Early Summer	12.85
0.00096	3.292746	1985	Portage	Late	12.85
0.694708	2.893605	1985	Quesnel	Summer	12.85
0.001922	0.858018	1985	Raft	Early Summer	12.85
0.001422	3.432398	1985	Scotch	Early Summer	12.85
0.002684	2.787198	1985	Seymour	Early Summer	12.85
0.021968	1.768224	1985	Stellako	Summer	12.85
0.022773	1.112869	1985	Weaver	Late	12.85

Table A3.4-9 shows the final set of variables available in the database as aligned with the appropriate life stages to which each data series is associated.

Table A3.4-9. The table of contents for all data sets within the cumulative impacts database, as aligned with the life history affected, by brood year. Each life history stage that a particular variable affects is treated as a separate variable in the database because it often requires the raw observation data to be adjusted by different amount in order to correctly align with the brood year that would be affected by that particular stressor in that particular life stage. This table only shows the data sets received as they line up with life stages for the 4sub2 age-types (the dominant age-type of all Fraser River sockeye salmon stocks except Harrison). In the full database, these data are also lined up with the dominant age-type for Harrison (4sub1) and the subdominant age-type for all non-Harrison stocks (5sub2) and the Harrison stock (3sub1). A "stock count" of less than 19 implies that there are multiple, stock-specific data series for that particular variables, whereas generally a stock count of 19 implies that there is only a single data series, which has been applied to all stocks.

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
2	Contaminants	CCME Water Quality Index	Outmigration	Fraser Watershed - Migration Areas	Smolt outmigration-Freshwater	4sub2	17	1965	2008
2	Contaminants	CCME Water Quality Index	Rearing	Fraser Watershed - Rearing Areas	Freshwater rearing	4sub2	10	1969	2009
2	Contaminants	CCME Water Quality Index	Spawning	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	9	1969	2009
2	Contaminants	CCME Water Quality Index	Spawning	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	9	1969	2009
2	Contaminants	CCME Water Quality Index	Spawning	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	9	1966	2006
2	Contaminants	CCME Water Quality Index	Upstream migration	Fraser Watershed - Migration Areas	Migration to spawning area-Marine	4sub2	18	1963	2006
2	Contaminants	CCME Water Quality Index - Qualitative	Outmigration	Fraser Watershed - Migration Areas	Smolt outmigration-Freshwater	4sub2	17	1946	2008
2	Contaminants	CCME Water Quality Index - Qualitative	Rearing	Fraser Watershed - Rearing Areas	Freshwater rearing	4sub2	10	1946	2009
2	Contaminants	CCME Water Quality Index - Qualitative	Spawning	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	9	1947	2009
2	Contaminants	CCME Water Quality Index - Qualitative	Spawning	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	9	1947	2009
2	Contaminants	CCME Water Quality Index - Qualitative	Spawning	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	9	1944	2006
2	Contaminants	CCME Water Quality Index - Qualitative	Upstream migration	Fraser Watershed - Migration Areas	Migration to spawning area-Marine	4sub2	18	1944	2006
3	Freshwater ecology	Area forest harvested	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	11	1979	2009
3	Freshwater ecology	Area forest harvested	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	11	1979	2009
3	Freshwater ecology	Area forest harvested	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	11	1976	2006
3	Freshwater ecology	Area forest harvested	Migration corridor	Fraser Watershed -	Migration to spawning	4sub2	17	1976	2006

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
				Migration Areas	area-Marine				
3	Freshwater ecology	Area forest harvested	Migration corridor	Fraser Watershed - Migration Areas	Smolt outmigration-Freshwater	4sub2	17	1978	2008
3	Freshwater ecology	Area forest harvested	Nursery lakes	Fraser Watershed - Rearing Areas	Freshwater rearing	4sub2	16	1978	2009
3	Freshwater ecology	Area forest harvested	Tributary spawning areas	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	2	1979	2009
3	Freshwater ecology	Area forest harvested	Tributary spawning areas	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	2	1979	2009
3	Freshwater ecology	Area forest harvested	Tributary spawning areas	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	2	1976	2006
3	Freshwater ecology	Human population density	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	11	1985	2008
3	Freshwater ecology	Human population density	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	11	1985	2008
3	Freshwater ecology	Human population density	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	11	1982	2005
3	Freshwater ecology	Human population density	Migration corridor	Fraser Watershed - Migration Areas	Migration to spawning area-Marine	4sub2	17	1982	2005
3	Freshwater ecology	Human population density	Migration corridor	Fraser Watershed - Migration Areas	Smolt outmigration-Freshwater	4sub2	17	1984	2007
3	Freshwater ecology	Human population density	Nursery lakes	Fraser Watershed - Rearing Areas	Freshwater rearing	4sub2	17	1984	2008
3	Freshwater ecology	Human population density	Tributary spawning areas	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	13	1985	2008
3	Freshwater ecology	Human population density	Tributary spawning areas	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	13	1985	2008
3	Freshwater ecology	Human population density	Tributary spawning areas	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	13	1982	2005
3	Freshwater ecology	Lake influence	NULL	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	16	2008	2008
3	Freshwater ecology	Lake influence	NULL	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	16	2008	2008
3	Freshwater ecology	Lake influence	NULL	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	16	2005	2005
3	Freshwater ecology	Road density	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	12	2008	2008
3	Freshwater ecology	Road density	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	12	2008	2008
3	Freshwater ecology	Road density	Mainstem spawning areas	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	12	2005	2005
3	Freshwater ecology	Road density	Migration corridor	Fraser Watershed -	Migration to spawning	4sub2	17	2005	2005

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
				Migration Areas	area-Marine				
3	Freshwater ecology	Road density	Migration corridor	Fraser Watershed - Migration Areas	Smolt outmigration-Freshwater	4sub2	17	2007	2007
3	Freshwater ecology	Road density	Nursery lakes	Fraser Watershed - Rearing Areas	Freshwater rearing	4sub2	17	2007	2008
3	Freshwater ecology	Road density	Tributary spawning areas	Fraser Watershed - Spawning Areas	Emergence-Freshwater	4sub2	13	2008	2008
3	Freshwater ecology	Road density	Tributary spawning areas	Fraser Watershed - Spawning Areas	Incubation-Freshwater	4sub2	13	2008	2008
3	Freshwater ecology	Road density	Tributary spawning areas	Fraser Watershed - Spawning Areas	Spawning-Freshwater	4sub2	13	2005	2005
3	Freshwater ecology	Spring air temperature	NULL	Fraser Watershed - Rearing Areas	Smolt outmigration-Freshwater	4sub2	17	1946	2007
3	Freshwater ecology	Summer air temperature	CU set 1	Fraser Watershed - Migration Areas	Migration to spawning area-Marine	4sub2	17	1944	2005
3	Freshwater ecology	Summer air temperature	CU set 2	Fraser Watershed - Migration Areas	Migration to spawning area-Marine	4sub2	5	1944	2005
4	Marine ecology	Chlorophyll concentration	30 March - 22 April	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1996	2007
4	Marine ecology	Chlorophyll concentration	April mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1996	2007
4	Marine ecology	Chlorophyll concentration	August mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1996	2007
4	Marine ecology	Chlorophyll concentration	August mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1994	2005
4	Marine ecology	Chlorophyll concentration	July mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1996	2007
4	Marine ecology	Chlorophyll concentration	July mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1994	2005
4	Marine ecology	Chlorophyll concentration	June mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1996	2007
4	Marine ecology	Chlorophyll concentration	June mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1994	2005
4	Marine ecology	Chlorophyll concentration	May mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1996	2006
4	Marine ecology	Chlorophyll concentration	May mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1994	2004
4	Marine ecology	Chlorophyll concentration	September mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1993	2005
4	Marine ecology	North Pacific Index	Anomalies	Other North Pacific Ocean	Growth and maturation-Marine	4sub2	ALL	1897	2007
4	Marine ecology	North Pacific Index	Nov-Mar Average	Other North Pacific	Growth and	4sub2	ALL	1897	2007

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
				Ocean	maturation-Marine				
4	Marine ecology	River discharge	Wannock (Rivers Inlet)	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1927	2007
4	Marine ecology	Sea surface salinity	April mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1968	2008
4	Marine ecology	Sea surface salinity	April-Aug average	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1968	2008
4	Marine ecology	Sea surface salinity	August mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1968	2007
4	Marine ecology	Sea surface salinity	August mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1966	2005
4	Marine ecology	Sea surface salinity	July mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1968	2008
4	Marine ecology	Sea surface salinity	July mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1966	2006
4	Marine ecology	Sea surface salinity	June mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1968	2008
4	Marine ecology	Sea surface salinity	June mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1966	2006
4	Marine ecology	Sea surface salinity	May mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1968	2008
4	Marine ecology	Sea surface salinity	May mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1966	2006
4	Marine ecology	Sea surface salinity	May-Sept average	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1966	2006
4	Marine ecology	Sea surface salinity	September mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1966	2005
4	Marine ecology	Sea surface temperature	August mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1980	2007
4	Marine ecology	Sea surface temperature	August mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1978	2005
4	Marine ecology	Sea surface temperature	August-June difference	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1980	2007
4	Marine ecology	Sea surface temperature	August-June difference	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1978	2005
4	Marine ecology	Sea surface temperature	July mean	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1980	2007
4	Marine ecology	Sea surface temperature	July mean	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1978	2005
4	Marine ecology	Sea surface temperature	July-Aug average	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1980	2007
4	Marine ecology	Sea surface temperature	July-Aug average	Queen Charlotte	Migration to spawning	4sub2	ALL	1978	2005

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
				Sound	area-Marine				
4	Marine ecology	Sea surface temperature	July-June difference	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1980	2007
4	Marine ecology	Sea surface temperature	July-June difference	Queen Charlotte Sound	Migration to spawning area-Marine	4sub2	ALL	1978	2005
4	Marine ecology	Summer wind regime	FACTOR	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1946	2007
4	Marine ecology	Summer wind regime	U-direction	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1946	2007
4	Marine ecology	Summer wind regime	V-direction	Queen Charlotte Sound	Migration to rearing areas-Marine	4sub2	ALL	1946	2007
8	Predation (marine and freshwater)	Alternate prey	BC herring-CC	BC Central Coast	Growth and maturation-Marine	4sub2	ALL	1947	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-CC	BC Central Coast	Migration to rearing areas-Marine	4sub2	ALL	1948	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-CC	BC Central Coast	Migration to spawning area-Marine	4sub2	ALL	1946	2004
8	Predation (marine and freshwater)	Alternate prey	BC herring-PRD	Prince Rupert District	Growth and maturation-Marine	4sub2	ALL	1947	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-PRD	Prince Rupert District	Migration to rearing areas-Marine	4sub2	ALL	1948	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-PRD	Prince Rupert District	Migration to spawning area-Marine	4sub2	ALL	1946	2004
8	Predation (marine and freshwater)	Alternate prey	BC herring-QCI	Queen Charlotte Islands	Growth and maturation-Marine	4sub2	ALL	1947	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-QCI	Queen Charlotte Islands	Migration to rearing areas-Marine	4sub2	ALL	1948	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-QCI	Queen Charlotte Islands	Migration to spawning area-Marine	4sub2	ALL	1946	2004
8	Predation (marine and freshwater)	Alternate prey	BC herring-SoG	Strait of Georgia	Growth and maturation-Marine	4sub2	ALL	1947	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-SoG	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1948	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-SoG	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1946	2004
8	Predation (marine and freshwater)	Alternate prey	BC herring-WCVI	West Coast Vancouver Island	Growth and maturation-Marine	4sub2	ALL	1947	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-WCVI	West Coast Vancouver Island	Migration to rearing areas-Marine	4sub2	ALL	1948	2006
8	Predation (marine and freshwater)	Alternate prey	BC herring-WCVI	West Coast Vancouver Island	Migration to spawning area-Marine	4sub2	ALL	1946	2004
8	Predation (marine and	Alternate prey	California Current Pacific	NULL	Growth and	4sub2	ALL	1963	2007

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
	freshwater)		hake		maturation-Marine				
8	Predation (marine and freshwater)	Alternate prey	California Current Pacific hake	NULL	Migration to rearing areas-Marine	4sub2	ALL	1964	2007
8	Predation (marine and freshwater)	Alternate prey	California Current Pacific hake	NULL	Migration to spawning area-Marine	4sub2	ALL	1962	2005
8	Predation (marine and freshwater)	Alternate prey	Gulf of Alaska Pacific cod	NULL	Growth and maturation-Marine	4sub2	ALL	1981	2003
8	Predation (marine and freshwater)	Alternate prey	Gulf of Alaska Pacific cod	NULL	Migration to rearing areas-Marine	4sub2	ALL	1982	2003
8	Predation (marine and freshwater)	Alternate prey	Gulf of Alaska Pacific cod	NULL	Migration to spawning area-Marine	4sub2	ALL	1980	2001
8	Predation (marine and freshwater)	Alternate prey	Pacific Jack mackerel	NULL	Growth and maturation-Marine	4sub2	ALL	1947	2004
8	Predation (marine and freshwater)	Alternate prey	Pacific Jack mackerel	NULL	Migration to rearing areas-Marine	4sub2	ALL	1948	2004
8	Predation (marine and freshwater)	Alternate prey	Pacific Jack mackerel	NULL	Migration to spawning area-Marine	4sub2	ALL	1946	2002
8	Predation (marine and freshwater)	Alternate prey	Pacific mackerel	NULL	Growth and maturation-Marine	4sub2	ALL	1926	2007
8	Predation (marine and freshwater)	Alternate prey	Pacific mackerel	NULL	Migration to rearing areas-Marine	4sub2	ALL	1927	2007
8	Predation (marine and freshwater)	Alternate prey	Pacific mackerel	NULL	Migration to spawning area-Marine	4sub2	ALL	1925	2005
8	Predation (marine and freshwater)	Alternate prey	Walleye pollock	NULL	Growth and maturation-Marine	4sub2	ALL	1974	2005
8	Predation (marine and freshwater)	Alternate prey	Walleye pollock	NULL	Migration to rearing areas-Marine	4sub2	ALL	1975	2005
8	Predation (marine and freshwater)	Alternate prey	Walleye pollock	NULL	Migration to spawning area-Marine	4sub2	ALL	1973	2003
8	Predation (marine and freshwater)	Alternate prey - quantile	PRY average	NULL	Growth and maturation-Marine	4sub2	ALL	1926	2007
8	Predation (marine and freshwater)	Alternate prey - quantile	PRY average	NULL	Migration to rearing areas-Marine	4sub2	ALL	1927	2007
8	Predation (marine and freshwater)	Alternate prey - quantile	PRY average	NULL	Migration to spawning area-Marine	4sub2	ALL	1925	2005
8	Predation (marine and freshwater)	Alternate prey - quantile	Walleye pollock	NULL	Growth and maturation-Marine	4sub2	ALL	1974	2005
8	Predation (marine and freshwater)	Alternate prey - quantile	Walleye pollock	NULL	Migration to rearing areas-Marine	4sub2	ALL	1975	2005
8	Predation (marine and freshwater)	Alternate prey - quantile	Walleye pollock	NULL	Migration to spawning area-Marine	4sub2	ALL	1973	2003
8	Predation (marine and	Christmas Bird Count	BC Bald eagle	NULL	Migration to spawning	4sub2	ALL	1953	2005

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
	freshwater)				area-Marine				
8	Predation (marine and freshwater)	Christmas Bird Count	BC Brandts cormorant	NULL	Migration to rearing areas-Marine	4sub2	ALL	1956	2007
8	Predation (marine and freshwater)	Christmas Bird Count	BC Common merganser	NULL	Smolt outmigration-Freshwater	4sub2	ALL	1956	2007
8	Predation (marine and freshwater)	Christmas Bird Count	BC Common murre	NULL	Migration to rearing areas-Marine	4sub2	ALL	1955	2007
8	Predation (marine and freshwater)	Christmas Bird Count	BC Cormorants, B+P	NULL	Migration to rearing areas-Marine	4sub2	ALL	1955	2007
8	Predation (marine and freshwater)	Christmas Bird Count	BC D-C cormorant	NULL	Smolt outmigration-Freshwater	4sub2	ALL	1955	2007
8	Predation (marine and freshwater)	Christmas Bird Count	BC Gulls	NULL	Migration to rearing areas-Marine	4sub2	ALL	1955	2007
8	Predation (marine and freshwater)	Christmas Bird Count	BC Pelagic cormorant	NULL	Migration to rearing areas-Marine	4sub2	ALL	1955	2007
8	Predation (marine and freshwater)	Christmas Bird Count - quantile	CBC MGRR average	NULL	Migration to rearing areas-Marine	4sub2	ALL	1955	2007
8	Predation (marine and freshwater)	Christmas Bird Count - quantile	CBC SMLT average	NULL	Smolt outmigration-Freshwater	4sub2	ALL	1955	2007
8	Predation (marine and freshwater)	Fish predators	Arrowtooth flounder biomass	NULL	Migration to rearing areas-Marine	4sub2	ALL	1959	2005
8	Predation (marine and freshwater)	Fish predators	Blue shark abundance	NULL	Growth and maturation-Marine	4sub2	ALL	1977	2000
8	Predation (marine and freshwater)	Fish predators	Blue shark abundance	NULL	Migration to spawning area-Marine	4sub2	ALL	1976	1998
8	Predation (marine and freshwater)	Pinniped count	California sea lions	NULL	Migration to rearing areas-Marine	4sub2	ALL	1969	2007
8	Predation (marine and freshwater)	Pinniped count	California sea lions	NULL	Migration to spawning area-Marine	4sub2	ALL	1967	2005
8	Predation (marine and freshwater)	Pinniped count	Steller sea lion	NULL	Migration to rearing areas-Marine	4sub2	ALL	1911	2008
8	Predation (marine and freshwater)	Pinniped count	Steller sea lion	NULL	Migration to spawning area-Marine	4sub2	ALL	1909	2006
8	Predation (marine and freshwater)	Pinniped estimate	California sea lions	NULL	Migration to rearing areas-Marine	4sub2	ALL	1969	2007
8	Predation (marine and freshwater)	Pinniped estimate	California sea lions	NULL	Migration to spawning area-Marine	4sub2	ALL	1967	2005
8	Predation (marine and freshwater)	Pinniped estimate	Harbour seals	NULL	Migration to rearing areas-Marine	4sub2	ALL	1911	2006
8	Predation (marine and freshwater)	Pinniped estimate	Harbour seals	NULL	Migration to spawning area-Marine	4sub2	ALL	1909	2004
8	Predation (marine and	Pinniped estimate	Steller sea lion	NULL	Migration to rearing	4sub2	ALL	1911	2008

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
	freshwater)				areas-Marine				
8	Predation (marine and freshwater)	Pinniped estimate	Steller sea lion	NULL	Migration to spawning area-Marine	4sub2	ALL	1909	2006
9	Climate change	LFR water temp for returning adults	NULL	Fraser Watershed - Migration Areas	Migration to spawning area-Marine	4sub2	18	1947	2006
9	Climate change	LFR water temp for returning adults - Qualitiative	NULL	Fraser Watershed - Migration Areas	Migration to spawning area-Marine	4sub2	18	1944	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	April mean	Central Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	April mean	Northern Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	April mean	Strait of Juan de Fuca	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Central Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Central Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Northern Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Northern Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Strait of Juan de Fuca	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	August mean	Strait of Juan de Fuca	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	July mean	Central Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	July mean	Central Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	July mean	Northern Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia	Chlorophyll concentration	July mean	Northern Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
	habitat inventory								
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	July mean	Strait of Juan de Fuca	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	July mean	Strait of Juan de Fuca	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Central Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Central Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Northern Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Northern Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Strait of Juan de Fuca	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	June mean	Strait of Juan de Fuca	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Central Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Central Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Northern Georgia Strait	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Northern Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Strait of Juan de Fuca	Migration to rearing areas-Marine	4sub2	ALL	1996	2008
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	May mean	Strait of Juan de Fuca	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	September mean	Central Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	September mean	Northern Georgia Strait	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Chlorophyll concentration	September mean	Strait of Juan de Fuca	Migration to spawning area-Marine	4sub2	ALL	1994	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Contaminants	Mill effluent loading	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1987	1997
12	Lwr Fraser River and Strait of Georgia habitat inventory	Contaminants	Mill effluent loading	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1985	1995
12	Lwr Fraser River and Strait of Georgia habitat inventory	Liquid waste	Flow	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1995	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Liquid waste	Flow	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1993	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Marine vessels	Gross register tonnage (domestic)	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1996	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Marine vessels	Gross register tonnage (domestic)	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1994	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Population census	Lower Fraser	Lower Fraser River	Smolt outmigration-Freshwater	4sub2	ALL	1984	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Population census	Strait of Georgia	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1984	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Population census	Strait of Georgia	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1982	2002
12	Lwr Fraser River and Strait of Georgia habitat inventory	Population census	Strait of Juan de Fuca	Strait of Juan de Fuca	Migration to rearing areas-Marine	4sub2	ALL	1984	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Population census	Strait of Juan de Fuca	Strait of Juan de Fuca	Migration to spawning area-Marine	4sub2	ALL	1982	2002
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge April total	Strait of Georgia	Smolt outmigration-Freshwater	4sub2	ALL	1968	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge July total	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1968	2007
12	Lwr Fraser River and Strait of Georgia	River discharge	Fraser discharge June total	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1968	2007

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
	habitat inventory								
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge May total	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1968	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge May total	Strait of Georgia	Smolt outmigration-Freshwater	4sub2	ALL	1968	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	June-July average	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1968	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	April mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1935	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	April-Aug average	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	April-Aug average	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	August mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	August mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	July mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2006
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	July mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	June mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	June mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	May mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	May mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	May-Sept average	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	September mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	April mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1935	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	April-Aug average	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	August mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	August mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	July mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	July mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	June mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	June mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	May mean	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1934	2007
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	May mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	September mean	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1932	2005
12	Lwr Fraser River and Strait of Georgia habitat inventory	Solid waste disposed	Lower Fraser	Lower Fraser River	Smolt outmigration-Freshwater	4sub2	ALL	1988	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Solid waste disposed	Strait of Georgia	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1988	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Solid waste disposed	Strait of Georgia	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1986	2002
12	Lwr Fraser River and Strait of Georgia	Solid waste disposed	Strait of Juan de Fuca	Strait of Juan de Fuca	Migration to rearing areas-Marine	4sub2	ALL	1988	2004

Project Number	Project	Variable	Subset	Location	Life stage	Age Type	Stock Count	Min of Brood Year	Max of Brood Year
	habitat inventory								
12	Lwr Fraser River and Strait of Georgia habitat inventory	Solid waste disposed	Strait of Juan de Fuca	Strait of Juan de Fuca	Migration to spawning area-Marine	4sub2	ALL	1986	2002
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total dredge volume	Lower Fraser	Lower Fraser River	Smolt outmigration-Freshwater	4sub2	ALL	1968	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total farm area	Lower Fraser	Lower Fraser River	Smolt outmigration-Freshwater	4sub2	ALL	1989	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total farm area	Strait of Georgia	Strait of Georgia	Migration to rearing areas-Marine	4sub2	ALL	1989	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total farm area	Strait of Georgia	Strait of Georgia	Migration to spawning area-Marine	4sub2	ALL	1987	2002
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total farm area	Strait of Juan de Fuca	Strait of Juan de Fuca	Migration to rearing areas-Marine	4sub2	ALL	1989	2004
12	Lwr Fraser River and Strait of Georgia habitat inventory	Total farm area	Strait of Juan de Fuca	Strait of Juan de Fuca	Migration to spawning area-Marine	4sub2	ALL	1987	2002
99	Pink Salmon	Pink salmon abundance	ALL North Pacific	Other North Pacific Ocean	Migration to spawning area-Marine	4sub2	ALL	1948	2001
99	Pink Salmon	Pink salmon abundance	NE Pacific	Other North Pacific Ocean	Migration to spawning area-Marine	4sub2	ALL	1948	2001
99	Pink Salmon	Pink salmon abundance	Russia	Other North Pacific Ocean	Migration to spawning area-Marine	4sub2	ALL	1948	2001

A3.5 Data Analysis

A3.5.1 Qualitative analyses

We have employed a series of integrative frameworks to illustrate potential cumulative impacts of multiple stressors on Fraser River sockeye salmon over time and space. Where appropriate we have taken a life history approach to cumulative impact analysis. The frameworks utilized are:

a) a weight of evidence framework for retrospective ecological risk assessment
b) a conceptual model comprising a life history diagram with the pathways of different stressors (including both direct and delayed effects);
c) a spatial life history diagram illustrating the spatial scale of the sockeye's life cycle and the location of different stressors (as data permits); and
d) an expert-driven evaluation of the relative likelihood of each given hypothesis, building on the Expert Panel Report to the Pacific Salmon Commission on the Decline of Fraser Sockeye (Peterman et al. 2010)

<u>A weight of evidence approach to retrospective ecological risk assessment[19]</u>

Weight of Evidence

In the present project we apply a weight of evidence (WOE) approach to synthesize evidence presented across the scientific and technical projects, incorporate new evidence generated by the statistical analyses for select data put forth by the contractors for each project, and assess the overall likelihood. Weed (2005) conducted a review of the concept of WOE and its associated methods. He concluded that although the term is used throughout the scientific literature, it may be used to represent many different types of methodologies from established formal methods to informal metaphorical perspectives and that no common definition exists. Weed (2005) emphasizes that given the variation in the use of the term, it is critical to define what "WOE" means in the context of any given research project.

The two key objectives defining our WOE approach are:

1. Use the full breadth of evidence presented within the Cohen Commission projects.
2. Synthesize and evaluate the evidence within a logical and systematic framework.

[19] This section represents an expanded description of the Weight of Evidence Approach to Retrospective Ecological Risk Assessment already presented in Section 3.3.5 of the main body of the report. The present section expands upon Section 3.3.5, providing a much more thorough explanation of the approach, especially with regards to the foundational literature upon which our approach is based. Consequently, the material in Section 3.3.5 is repeated here.

The objective of our approach is to use, wherever possible, all the major sources of evidence brought forth by the investigations and analyses presented in the other Cohen Commission technical projects. Whereas it is not realistic to use every single piece of evidence presented in this body of scientific work, the intent is to incorporate the *breadth* of evidence presented, recognizing that the weight of evidence synthesis cannot possibly capture the *depth* of evidence presented within each project. However, this approach still requires the compilation and synthesis of many different types of both qualitative and quantitative evidence (as described above), available over varying timeframes. All of these lines of evidence are then examined and presented within a logical and systematic framework. The structure of this framework is based on the work of Forbes and Callow (2002) and Burkhardt-Holm and Scheurer (2007) on Retrospective Ecological Risk Assessment (RERA) but further modified where necessary to function within the constraints of the present project.

Retrospective Ecological Risk Assessment

One of the obvious but crucial attributes of RERA is that it is applied retrospectively to examine adverse ecological impacts that have already occurred. RERA is intended for situations where the evidence for ecological impairment already exists and a number of factors have already been identified as possible causal agents. The objective of RERA is thus to evaluate how likely it is that each of those potential causal factors may have contributed to the adverse ecological impacts observed. However, there are usually many constraints and limitations on the quantity and quality of evidence available to evaluate such ecological impairments. For ecological problems the available evidence is often very limited and predominantly qualitative (Forbes and Callow, 2002). Quantitative data is usually short, incomplete, sparse, or simply non-existent, and where limited quantitative data does actually exist, it is likely to be complex, variable, ambiguous, and/or noisy, often making rigorous statistical analysis almost impossible (Forbes and Callow, 2002; Burkhardt-Holm and Scheurer, 2007). The available evidence is often correlative at best, and further complicated by the interaction of multiple co-existing hypotheses and confounding factors that are uncontrollable, or even unknown (Forbes and Callow, 2002; Burkhardt-Holm and Scheurer, 2007). Given this context, the objective of incorporating WOE into RERA is therefore to provide a framework in which to synthesize and evaluate the evidence that is available in a manner that is transparent, systematic, logical, and less subjective (Forbes and Callow, 2002; Burkhardt-Holm and Scheurer, 2007). The WOE RERA approach outlined by Forbes and Callow (2002), which was subsequently adapted by Burkhardt-Holm and Scheurer (2007), therefore appears to be an extremely suitable basis for the present work due to the following criteria being well met:

1. The adverse ecological impact has already occurred.

    The focus of the Cohen Commission technical research projects is inherently retrospective – Fraser River sockeye salmon productivity <u>has been</u> declining over recent decades and the 2009 returns <u>were</u> exceptionally poor.

2. The evidence for this impairment already exists.

    Data on the abundance Fraser River sockeye salmon recruits and spawners confirms the declines in both returns and productivity.

3. Factors that could potentially be causal agents of this impairment have been identified.

    The Cohen Commission identified a selection of broad factors that could feasibly have contributed to the decline of Fraser River sockeye salmon, and within each of the contracted scientific and technical projects a range of specific potential stressors are identified.

4. The evidence available to evaluate the likelihood of each possible factor is limited.

    *Collectively, the evidence available with which to evaluate all of the factors that may potentially have contributed to the decline of Fraser River sockeye salmon reflect virtually **<u>all</u>** of the constraints and limitations described above.*

A Method for Incorporating WOE Concepts into RERA

Forbes and Callow (2002) state that "the primary challenge in retrospective risk assessment is to make best use of the available evidence to develop rational management strategies and/or guide additional analyses to gain further evidence about likely agents as causes of observed harm", which precisely describes the challenge of the present project as well.

To address this challenge, Forbes and Callow (2002) present a framework to incorporate WOE concepts into a RERA, based on earlier methodological linkages that had been developed between human epidemiology studies and ecological studies. Their framework uses seven sequential questions to systematically assess the available evidence on each potential causative agent. These questions are situated within a flow diagram such that the answers can be used to systematically assign a categorical likelihood (i.e. unlikely, possible, likely, or very likely) to each potential factor. The overall approach is thus to: 1) formulate the problem, 2) screen potential agents, and 3) focus future work. Forbes and Callow (2002) demonstrate their approach using case studies of several distinctively different ecological problems. Burkhardt-Holm and Scheurer (2007) use this method to assess the decline of brown trout in Swiss rivers over the past several decades, but reconfigure the sequence of questions to better reflect the situation of fish declines in Switzerland. They describe this approach as "semi-quantitative method for identifying causal factors are likely to explain adverse effects occurring in investigated ecosystems" (Burkhardt-Holm and Scheurer, 2007). This method both integrates the available data and facilitates the summary and communication of results.

The WOE approach outlined by Burkhardt-Holm and Scheurer (2007) challenges the available evidence for each potential factor with the following sequential questions. The answers to some of these questions are necessarily site-specific, whereas others may be derived from a broader range of similar case studies.

1. Plausible mechanism:
   "Does the proposed causal relationship make sense logically and scientifically?"
2. Exposure:
   "Is there evidence that fish population is, or has been, exposed to be causal factor?
   - However, presence of a causal factor alone does not indicate exposure
   - Exposure might not be proven but only suspected
   - Exposure may be historical as well as current
3. Correlation/Consistency:
   "Is there evidence for association between adverse effects in the population in the presence of the causal factor, either in time or space?"
   - Any type of formal relationship may be taken as evidence but statistical correlation is preferable
   - Recognize that correlation does not imply causation
   - Acknowledge potential scale issues between potential stressors and ecological responses
4. Thresholds:
   "Do the measured or predicted exposure levels exceed quality criteria or biologically meaningful thresholds?"
   - Both current and historical exceedances of thresholds are relevant
5. Specificity:
   "Is there an effect in the population gnome to be specifically caused by exposure to the stressor?"
   - Absence of a specific response does not prove a lack of exposure or impact
   - Presence of a specific response is stronger evidence than absence
6. Experiments:
   "Have the results from controlled experiments in the field or laboratory lead to similar effects?"
   - Results from controlled experiments are stronger evidence than observational studies

7. Removal:
   "Has the removal of the stressor led to an amelioration of the effects in the population?"
   - Response to a removal may be delayed rather than immediate
   - Lack of improvement does not disprove the importance of a causal factor
   - Affirmative results are stronger evidence than negative results

Adaptation of the Methodology to the Present Project

We have adapted this methodology as necessary in current circumstances. One of the important limitations to our ability to apply this methodology in full is that we are applying this approach retrospectively to a series of projects that themselves did not utilize such a framework. Therefore it is not possible to satisfactorily answer all of the WOE questions within this framework because it is not possible to answer questions that were not asked in the projects themselves. Consequently, we have modified the structure by grouping questions 4-7 into a single question covering all other evidence beyond question 1-3, as shown in Figure A3.5-1.

Within each life stage we examine the major potential causative agents identified within the other Cohen commission technical research projects. For each stressor, we synthesize: 1) the plausibility of each mechanism, 2) the evidence that Fraser River sockeye salmon have been exposed to the stressor, 3) the evidence for any spatial or temporal correlation between the stressor and the observed patterns in the Fraser River sockeye salmon and, where possible, the observed patterns in non-Fraser River sockeye salmon, and 4) other evidence regarding the potential impact of the stressor on Fraser River sockeye salmon (especially including any information on question 4-7 above). Within each step of this evaluation, we emphasize both what is known and what is not known, and within each life stage we identify the key things that need to be known better. Based on the evidence available, a relative likelihood is assigned to each broad category of stressor (e.g., contaminants, predators, etc.) at each life stage, according to the framework shown in Figure A3.5-1. The conclusions from each life stage apply to the contribution of each broad impact factor to the overall in the observed Fraser River sockeye salmon. There may be cases in which the relative likelihoods of particular stressors do not all align perfectly with the relative likelihood assigned to the parent stressor category. For example, the evaluation of the overall impact of predators may not match the evaluation of particular predators. There may also be cases in which the results from this evaluation framework might be different for individual stocks. However, the focus of the present project is to evaluate the likelihood that each broad factor has made a significant contribution to the overall observed decline in the Fraser River sockeye salmon stock complex.

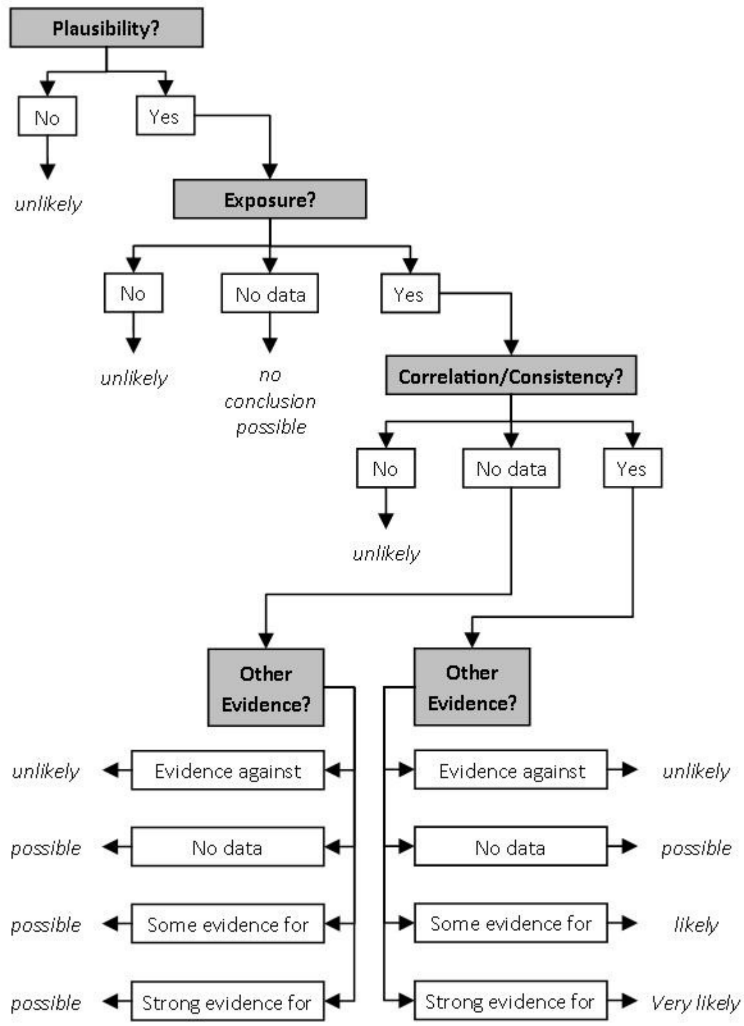


Figure A3.5-1. Flow diagram used to assign the relative likelihood that a particular factor has made a substantial contribution to the decline of Fraser River sockeye salmon, based on the answers to the questions used to challenge the available evidence. This structure is adapted from Burkhardt-Holm and Scheurer (2007, Figure 1).

Because this method is an inherently retrospective form of analysis, the results cannot be used to predict the impacts that these factors may have in the future. Both Forbes and Callow (2002) and Burkhardt-Holm and Scheurer (2007) emphasize that it is unrealistic to expect these methods to be definitive in terms of ascribing causation. While such an approach may be able to explain retrospectively which factors most likely contributed to past patterns of change in productivity, the importance of particular factors may be more or less important in the future and will vary within any given year in both magnitude and relative importance. Even if we had complete data on all of the factors potentially affecting sockeye over the entire period of record for the stock productivity data, we would not be able to predict in advance how these factors will combine in the future to affect productivity.

Conceptual model

In the U.S. Council on Environmental Quality's handbook *Considering Cumulative Effects Under the National Environmental Policy Act* (1997), it is suggested that conceptual models such as network diagrams are "often analysts' best method for identifying the cause-and-effect relationships that result in cumulative effects." Within such diagrams or models it is possible to illustrate all relevant components and the linkages among them, with the further flexibility of representing feedback loops where these relationships are known. Lorne Greig and Peter Duinker, who have written extensively about cumulative effects assessment in Canada, stress that an appropriate model is an absolutely key component of cumulative effects analysis and any models utilized need to be represented explicitly (Greig and Duinker 2008).

This project uses a detailed conceptual model as a central framework to which subsequent quantitative analyses and alternative qualitative methods can be connected. This provides a common structure that can facilitate explicit linkages among a variety of analysis approaches. The conceptual model is used to organize the complex relationships among factors and sockeye salmon such that the quantitative analyses performed in this project and the synthesis and discussion of evidence presented in other projects could be integrated into a singular life history approach.

The conceptual model presented in the PSC Report was taken as a starting point (Peterman et al. 2010). This base model was then further modified based on expert feedback elicited from the participants of the science workshop, data submissions from contractors and the technical reports from each of the other projects. The final conceptual model is shown in Figure 3.3-1. Alternate representations of this conceptual model were explored to improve clarity to a variety of audiences.

Spatial life history diagram

One such permutation of the core conceptual model is a projection of the life history model onto the Fraser River sockeye salmon's geographic habitat range where particular stressors can be represented at the scale at which they potentially affect Fraser River sockeye salmon (Figure 3.3-2). This is a communication tool for illustrating the spatial scale of sockeye salmon's life cycle as well as critical geographic constraints to non-technical audiences.

The two approaches above represent a "bottom-up" perspective for exploring potential cumulative impacts, detailing where different particular stressors impact sockeye in space and time. These representations may show where or when sockeye may be exposed to single or multiple stresses simultaneously. These frameworks are also useful for representing potential interactions or feedback loops among stressors.

Relative likelihood of given hypotheses

An alternative “top-down” approach is to rely on expert assessment of the overall likelihood that a particular factor has made a significant contribution to the decline in productivity of Fraser River sockeye. This approach (building on many sources of evidence) was used by the expert panel who wrote the PSC report mentioned above (Peterman et al. 2010). At the first workshop for the Cohen Commission technical research projects, the scientific experts working on each projects will examine the judgements made in the PSC report and (if warranted by new evidence not considered by the PSC panel) make appropriate modifications. Further details of this approach will be described in the report on the first workshop (Appendix 6).

A3.5.2 Quantitative methods

Solicitation of expert feedback

In early September we organized a meeting with Dr. Randall Peterman and Dr. Carl Schwarz of Simon Fraser University to solicit their expert advice on potential analytical methods. The two objectives of this meeting were to: 1) clarify questions regarding the evaluation of cumulative and relative impacts; and 2) propose alternative methods for both evaluations, given the types of data that we could expect to receive from each research project. The second objective was approached via three distinct steps. Step 1 was to identify a broad selection of potential analyses for further evaluation. Step 2 was to anticipate the types, quality and extent of data sets that might be available from each research project in order to prospectively identify potential data limitations. Step 3 was to critically evaluate each proposed method with respect to project goals and anticipated data limitations. This evaluation process considered the data input needs, the types of output results, the process feasibility, and the overall usefulness of each potential analytical method. We then presented a draft analytical plan for review by rest of the Cohen Contractors at the November 30-December 1 Technical and Scientific Research Projects Workshop. The outcomes of these meetings shaped our analysis framework (Table A3.5-1) and the data collection process Appendix 5.

Table A3.5-1. Complete summary of analytical approaches considered, recommended priorities, and current status. For approaches applied in this project, detailed methods are provided in this section.

Approach	Reasoning	Priority/Timing	Status
Conceptual Model	Provides a central framework to link both the qualitative summary and quantitative analyses.	High/Early	Complete
Change-point analyses	Provides an objective stock specific assessment of changes in trends over time (assuming the model is appropriate). May be able to identify stock groupings with similar patterns of change. This analysis was completed early in the project as these data were available early.	High/Early	Complete
Correlation analyses / Principal components analysis (PCA)	These methods inform data reduction strategies that should be completed prior to the multiple regression analysis. In addition, they may provide insights into relationships among independent variables.	High/requires all contractor data	Complete
Multiple Regression	Multiple regression is the best tool we have for addressing the primary objective of this analysis (i.e., understanding the cumulative and relative impact of all of the stressors).	High/ requires all contractor data	Initial analyses complete, Much more could be done
Bayesian Belief Networks	A BBN could be developed from the conceptual model (Figure 3.3-1) to improve our understanding of the cumulative impacts, interactions, and relative effects of stressors across all projects.	Recommended	Beyond scope of this project
Cluster analysis	Each of these approaches was evaluated and rejected for at least one of the evaluation criteria identified above.	Not recommended at this time	Not Applicable
Discriminant analysis or logistic regression			
Mantel's i test			
Attenuation analyses			
Randomization tests			
Path analyses			
Structural Equation Modeling			

Change point analysis of productivity data

During the initial phases of this project, it was frequently stated that there had been declines in productivity of Fraser River sockeye since the early 1990's. Peterman and Dorner (2011) explored the patterns of productivity in far more detail and now suggest there were in fact 3 periods of change. In parallel, we decided it was important to have an objective assessment of when and how strong trends in each of the sockeye stocks were; hypothesizing that there may be substantial differences among stocks in the timing and strength of declines in productivity. If there were groups of stocks with similar behaviour over time, the similarities among those particular stocks might suggest important factors. We completed these analyses very early in the project as these data were available long before any of the covariate data from the other technical reports.

Where time-series data are available, a regression model between time and the data set of interest can be fit to assess whether or not there is a trend over time and to describe the nature of the trend. Straight line models are easy to interpret as a trend can be estimated by the slope of the straight line fit to the data (Equation A3.5-1). We fit a straight line model to the $\log_e$ transformed data for: a) the entire time series or b) segments of the time-series. A $\log_e$ transformation is often used to linearize exponential growth or stabilize variance typical of population data (Dixon & Pechmann 2005). In many cases it may not be appropriate to fit a single trend line across the entire time-series. There may be periods of either increasing or decreasing trend that do not extend throughout the data set. In particular, it is of interest to understand what the current trend is and when that trend began. Where a single trend line is not appropriate we try fitting a piece-wise regression model where two lines are joined at a single sharp change point (Equation A3.5-2) (Toms & Lesperance 2003). All possible change points are evaluated and the most likely one (i.e., minimizing the sums of squares (SS) of the residuals) based on the data is selected. More complex models are possible (e.g., more than two lines, curved segments rather than straight lines), but are beyond the scope possible for this project given the time and budget. More complex time-series methods that incorporate temporal autocorrelation are also beyond the scope of this project.

Straight line model: $y_t = \beta_0 + \beta_1 x_t + \varepsilon_t$ (Equation A3.5-1)

This model fits a single straight line of best fit through the entire time series of data.

- β_1 represents the slope of the line of best fit

Piece-wise $y_t = \begin{cases} \beta_0 + \beta_1 x_t + \varepsilon_t & \text{for } x_t \le \alpha \end{cases}$

regression model: $\beta_0 + \beta_1 x_t + \beta_2(x_t - \alpha) + \varepsilon_t$ for $x_t > \alpha$ (Equation A3.5-2)

- β_1 represents the slope of the line of best fit for the years prior to the break point (α)
- $(\beta_1 + \beta_2)$ represents the slope of the line of best fit for the years after the break point (α)

For each stock we fit both a straight-line model across the entire time series and a piece-wise regression model. In both cases, usual model diagnostics were used to assess the fit of the model (Draper and Smith 1998; Devore 1995). Examples of the figures we used to assess the model fit are provided in Figure A3.5-1 (straight-line model) and Figure A3.5-2 (corresponding piece-wise regression model). If the diagnostics confirm the model is of an appropriate form, then we can test the hypothesis that the slope of the line(s) is zero (no trend) or not.

These analyses provide information about trends and important 'change points' in time that can be compared across stocks and stressors. We used ln(R/S)[20] to provide a simple easy to understand interpretation. This does not account for density dependence so density dependence is one possible factor in explaining any patterns observed. Alternatively we could use the residuals from the best fit model, which incorporates density dependence, and have also been provided by Peterman and Dorner (2011).

[20] R = Recruits (returning spawners that reached the spawning ground + harvested adult fish + returning spawners that died between the Mission counting station and the spawning ground). S = Effective Female Spawners in the parent generation that produced the returning spawners (generally four years previous). ln = natural logarithm (base *e*).

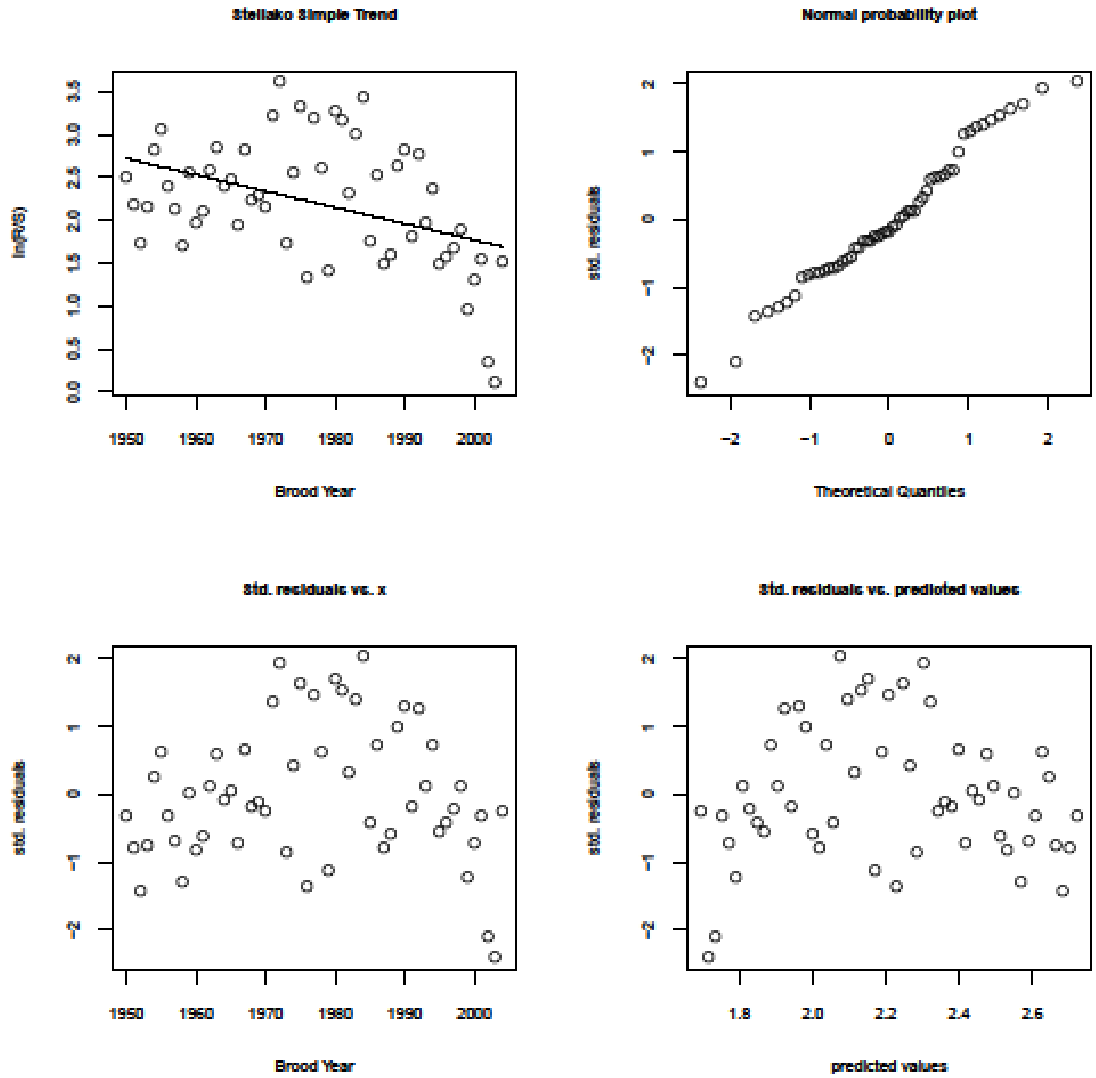


Figure A3.5-1. This is an example of residual diagnostic plots used to assess the fit of a single straight line trend in time across the full data set for Stellako productivity (i.e., ln(R/S)). Notice the remaining pattern in residuals when plotted against time (lower left panel); the later brood years are much more negative and there appears to be a parabolic shape to the residuals suggesting a single trend line doesn't adequately fit the data.

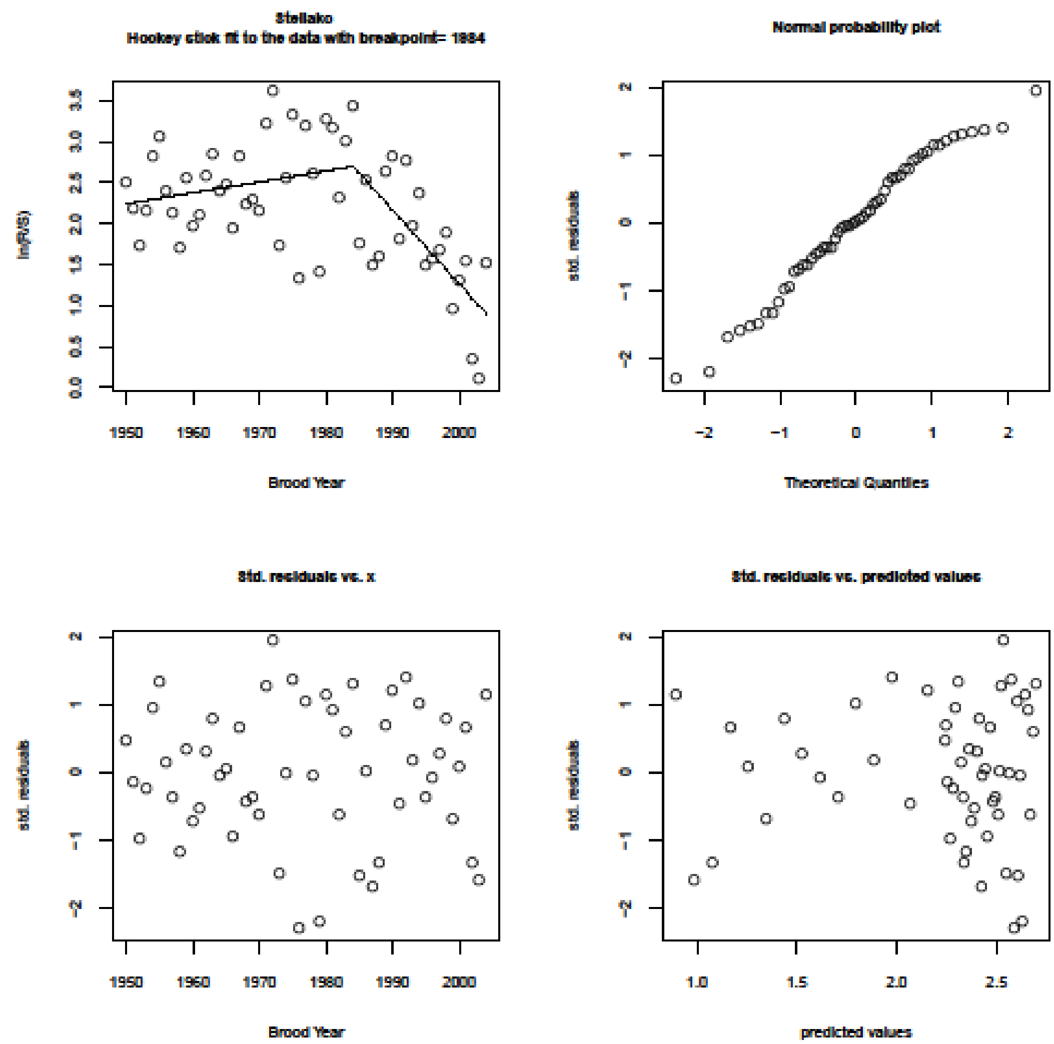


Figure A3.5-2. This is an example of residual diagnostic plots used to assess the fit of a piece-wise regression model with two straight lines for Stellako productivity (i.e., ln(R/S)). The most likely model suggests a change point in 1985 (brood year).

Stock portfolio summaries

Schindler et al. (2010) found that stock composition plays an important role in the overall variability of a regional stock complex (in their case Bristol Bay sockeye). In particular they found that having a portfolio of many stocks results in less variability across the whole regional stock complex, than if the portfolio was represented by only a few individual stocks. The Fraser River Sockeye regional stock complex consists of 36 Conservation Units (CUs) (refer to the Freshwater Technical Report (# 3) for CU status assessments). We were interested in finding out, for the 19 stocks where we have data, how balanced the portfolio of Fraser River sockeye stocks is. Additionally, we were interested to see whether that balance has changed over time. We used recruits for this analysis as we wanted to remove the harvest effect. First we plotted the most recent complete data set for recruits (i.e., 2006) to see the current concentration profile (i.e., the proportion of the total number of recruits by stock). Second we grouped the stocks into 5 time periods (12 years / 3 brood cycles each) to see if the stock composition had shifted over time. Stocks were averaged across the time period and then a cumulative sum of recruits by stock was plotted for each time period. Two figures were generated: one with the y axis scaled to 1 and the second with the y axis on the raw recruit scale. This approach clearly illustrates the number of stocks that account for the majority of the recruits, but it does not inform us about which stocks dominate or whether they have changed over time. Based on the knowledge that at least some of the stocks (i.e., Lower Shuswap) have cohorts with very different sizes, we split the data set by cohort to assess how the stock portfolios differed by cohort. We selected the eight most dominant stocks across all cohorts and plotted these annually in a stacked bar graph, while the remaining stocks were aggregated.

Multiple regression

Regression analysis was the primary focus of our quantitative analyses and the most complex approach applied. This section begins with a high level summary of regression intended to inform all readers (regardless of background) about the general approach and the limitations of the analysis. We then provide detailed descriptions of our approach to: data reduction, creation of model sets, candidate models, model structure, and model selection.

General approach

Multiple regression can be used to determine the relative importance of each covariate for explaining the variability in sockeye productivity. Non-linear relationships between covariates and sockeye productivity can be explored. Covariates that are hypothesized to have an additive cumulative impact on sockeye productivity (i.e., each factor on its own may have an insignificant biological impact but when encountered together the sum of the effects may be biologically important) can be analyzed in groups rather than one at a time. Regression can also be used to test hypothesized interactions between covariates (i.e., multiplicative cumulative impacts). Multiple regression is valuable tool for addressing the primary objective of this analysis (i.e., understanding the cumulative and relative impact of all of the stressors).

Regression analysis is used to understand how different variables relate to one another. Typically there is one response variable (i.e., dependent variable) of interest and one or more predictor variables (i.e., independent variables or covariates). In this case the dependent variable is an annual stock specific index of productivity. The independent variables are all factors identified as likely to be important by each of the other Cohen Commission Technical Reports (e.g., sea surface temperature). Regression analysis entails specifying a mathematical model that describes the functional form of the relationship between the covariates and the response variable and using the observed data to estimate the parameters in the model.

Many different models are possible. For example, models may include different covariates, linear and non-linear covariates, and/or interactions among different covariates. As long as there are sufficient data, parameters for any model can be estimated but just because parameters can be estimated does not mean the model is sensible. Not surprisingly there is a vast amount of literature dedicated to the subject of model selection and comparison. We use the Burnham and Anderson (1998) hypothesis-driven approach to model selection and inference. In hypothesis-driven analyses, the only factors that would be allowed to enter the analyses would be those that are connected to a logical, and in this case, biologically justified hypothesis. This reduces the potential that some variables will emerge as significant simply by chance and not as a result of any underlying mechanism, which is quite likely to happen in a project where there are large numbers of covariates and hence potential models. Standard practice is to select multiple feasible candidate models, fit each model (i.e., estimate the parameters), and then compare the performance of each model. There are many approaches for comparing among models; we used the small sample size corrected Akaike's information criterion (AIC_c) (Burnham and Anderson, 1998).

This project is unusual in its scope. While the response variable, ln(R/S) is available for 19 stocks across B.C. and approximately 50 years of data are available for each stock, the number of potential covariates is very large. A total of 126 quantitative and 5 qualitative data sets were provided to us from the other technical reports (Table A3.4-9). We then calculated an additional 32 data sets from the originals. It is possible for a single data set to be linked to (i.e., hypothesized to impact) multiple life stages of Fraser River sockeye. In addition, there are up to 4 different age types (i.e., 4sub2, 5sub2, 4sub1, and 3sub1). These links are described in Table A3.4-5 through Table A3.4-9 and result in a total of 1058 possible covariates to include in the analysis. However, not all covariates are available for all years and stocks. Models can only be compared using AICs when the models are fit using the same data. The implication of this is that we cannot compare all models of interest on the full data set but instead must identify time periods with complete data for different subsets of the covariates. For example, there is a small subset of the covariates (e.g., sea surface salinity for the Strait of Georgia) that have data extending back to 1950, but there are other covariates that only have data starting in 1996 (e.g., chlorophyll a). If we wish to compare models with these two covariates (i.e. salinity and chlorophyll), we would have to either reduce the data set to those years with data for both covariates (i.e. limit the model to 1996-present and sacrifice the earlier data for salinity), or exclude covariates with limited years of data (i.e. limit the model to only salinity and sacrifice the extra covariate, but extend it back to 1950). Choosing any particular set of covariates forces you to truncate longer time series to the length of the shortest data set. Choosing any particular time period forces you to limit your analyses to those covariates with period of record that is sufficiently long. We chose to evaluate different time-periods independently because each time period presents a different trade-off between the length of the data and the number of covariates that can be included. Within each time-period we generated different model sets. A model set represents a set of covariates that have complete data over a specified period of time. Within each model set, different models (i.e. combinations of variables) can be tested to determine their ability to explain the observed variability in the dependent variable, sockeye productivity in this case. Expressed another way, a 'model set' is simply a suite of candidate models within a given time-period that are organized to address a particular question. For example, one question of interest is whether factors affecting a particular life stage are more important than others. Most projects or papers only consider a single 'model set' by this definition. However, the large but incomplete data set combined with the range of questions this project attempts to address required this additional layer.

Key points:

- Models may differ in the number and type of covariates, linear vs. non-linear terms, and the presence of interaction terms.
- Many models are possible, but we should only test models that have biologically justified hypotheses.
- In order to compare the relative performance of different models using Akaike's Information Criterion (AIC_c), models should be fit using the same data.
- Comparison of AIC_c scores does not tell us the *best model possible*, but rather helps us to understand the relative support for *models we have estimated*.
- You need more data (n) than parameters (k) in order to be able to estimate the parameters. In addition, if the ratio $(n/k) < 40$, small sample size corrections should be employed in the assessment of model fit (Burnham and Anderson (p76), 1998).

Data reduction

We had hoped there would not be substantial correlation among metrics from a single contractor – one of the criteria specified was that the data metrics submitted should be independent. However, we found that in many cases we received several correlated data sets (e.g., sea surface salinities for 5 months). We first dropped any variable by life stage combinations where there was not a reasonable hypothesis of a potential impact (e.g., we know that smolts are not in the ocean during a particular month). Where our knowledge of the biological relationships could not reduce the number of variables we used a combination of correlation analysis and principal components analysis to try to reduce the number of variables. We generated correlation matrices and scatterplots for the longest time series of data sets where we expected correlation (e.g., multiple months of data for the same metric). Data reduction and interpretability are the primary goals of a PCA. The idea is to try to determine which components explain the majority of the total system variability. Although you may need many variables to describe all of the variability, it is often the case that only a few are needed to account for most of the variability in the system (Johnson and Wichern 2002). The outcome of PCA is an ordered set of components (usually a small number explain most of the variability). Each component is a linear combination of all of the variables. In most cases the loadings were spread pretty evenly among all months of data and we simply chose to average across the plausible months. In a few cases, one or two months of data were included separately.

Chlorophyll a

There were insufficient years of data to interpret correlations among chlorophyll monthly data sets. Instead we decided to simply use both the April and May monthly means and ignored the June-Sept values based on our understanding of the hypothesized relationship between chlorophyll and ocean productivity during the period when smolts are leaving the Fraser river. For Strait of Georgia we were provided with two different locations of data (Central and North) but upon closer evaluation found that the Northern data set was far more variable (Figure A3.5-3) and so selected the Northern data set anticipating that it would be a more useful predictor. We recognize that this was an arbitrary decision but given the severe data restrictions and lack of solid scientific basis for selecting one particular region or averaging the two regions, we decided to use this approach for now.

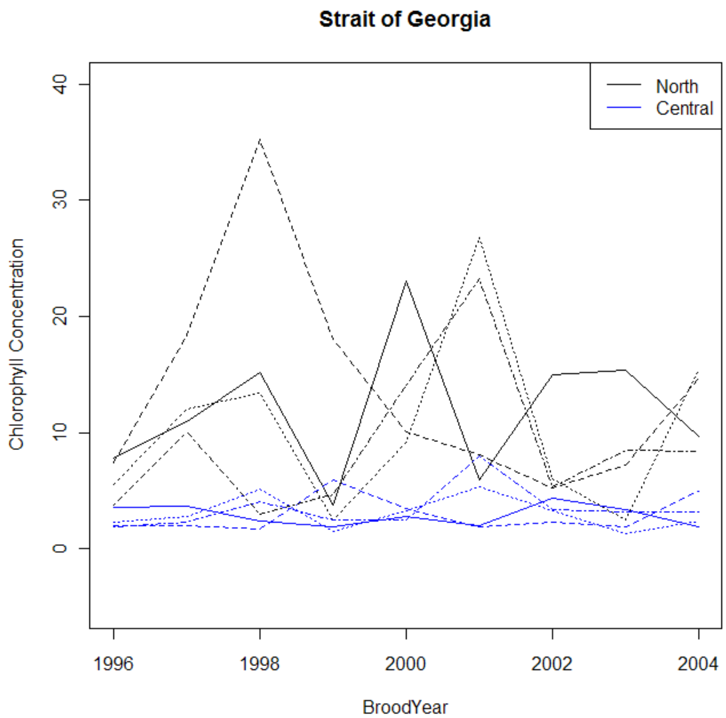


Figure A3.5-3. Average chlorophyll concentration measured at two different locations in the Straight of Georgia. Each line represents a monthly mean for a given location. April – July means are shown for the Northern location in black, and for the Central location in blue.

Sea surface salinity

We found several extreme outliers in the Queen Charlotte Sound sea surface salinity data set (values exceeding 90) when the rest of the data set was around 30. We removed these values assuming they were a data entry mistake as such values are completely unrealistic (Parsons et al.1977).

Predator and alternate prey data

The technical report on predators (Christensen and Trites, 2011) provided a total of 21 data sets, including: 7 bird data sets, 3 pinniped data sets, 2 fish predator data sets, and 9 fish alternative prey data sets. The three species of marine mammal (all pinnipeds) for which data were provided were used directly. However, it was less clear how to best incorporate the bird and fish data. These data sets were selected by the authors of the predators technical report as being the most relevant available data, but recognising they were not collected specifically for these purposes and that other species may also be important (Christensen and Trites, 2011). In order to reduce the number of variables in the model and yet still incorporate these variables we took each data set individually and generated a new quantile based data set where the lowest 25 % of observations were given a value of 1, the highest 25 % of observations were given a value of 3 and the middle 50% of observations were given a value of 2. We then averaged these standardized data sets across groups of similar species, hoping that we could identify years where there were *more than usual* or *less than usual* abundance of a particular type of predator (i.e. fish or bird) or alternative prey for a given life stage. Aggregate indices were only generated for species that were hypothesized to impact the same life history stage (Table A3.5-2).

Table A3.5-2. Summary of the predator/alternative prey data provided and the reduced data sets actually used in the regression analysis.

Hypothesized mechanism	Hypothesized life stage(s)	Data provided	Reduced data set
Predation	Smolt outmigration	Double Crested Cormorant	Quantile based aggregate index (2 species)
Predation	Smolt outmigration	Common Merganser	
Predation	Coastal migration	Common Murre	Quantile based aggregate index (4 data sets)
Predation	Coastal migration	Pelagic Cormorant	
Predation	Coastal migration	Brandt's Cormorant	
Predation	Coastal migration	Gulls	
Predation	Upstream migration	Bald Eagle	Quantile based index
Predation	Migration to rearing areas- Marine Migration to spawning area- Marine	California sea lions	No change, used raw abundance data
Predation	Migration to rearing areas- Marine Migration to spawning area -Marine	Stellar sea lions	No change, used raw abundance data
Predation	Migration to rearing areas- Marine Migration to spawning area- Marine	Harbour seals	No change, used raw abundance data
Predation	Growth and maturation – Marine Migration to spawning area- Marine	Blue shark abundance	No change, used raw abundance data
Predation	Migration to rearing areas- Marine	Arrowtooth flounder biomass	No change, used raw abundance data
Alternate prey	All three marine life stages: • Migration to rearing areas • Growth and maturation • Migration to spawning area	Herring (Central Coast)	Quantile based aggregate index (8 data sets)
Alternate prey	Same as above	Herring (Prince Rupert District)	
Alternate prey	Same as above	Herring (Queen Charlotte Islands)	
Alternate prey	Same as above	Herring (Straight of Georgia)	
Alternate prey	Same as above	Herring (West Coast Vancouver Island)	
Alternate prey	Same as above	California Pacific Hake	
Alternate prey	Same as above	Gulf of Alaska Pacific cod	
Alternate prey	Same as above	Pacific Jack mackerel	
Alternate prey	Same as above	Walleye pollock	Was not available until later than the other alternative prey species and so not relevant to the model sets we considered.

Status only data sets
In many cases the data for particular stressor only included an estimate of the current status. We could not incorporate these data into the regression analysis. It is not possible evaluate the effect of a particular stressor on sockeye productivity over time if there is no information on how that stressor has been changing over the time period in which sockeye productivity has been changing. With status only data sets, it is not even known whether the stressor has been increasing or decreasing.

Model sets

Candidate model sets were built around the conceptual model (Figure 3.3-1). We considered multiple sets of hypotheses, each set designed to answer particular questions. Each of these "series" (arbitrarily ordered and named) and its relevant question(s) of interested are described below and listed in Table A3.5-3

A-series) Life history bottlenecks: identify all stressors that are hypothesized to affect a particular life history stage and add and remove these together

Question: *Which life history stages have the greatest effect on productivity over the whole sockeye life cycle?*

B-series) Stressor category: add and remove suites of similar stressors

Question: *Which categories of stressors (organized by the same categories as the Cohen Commission Technical Reports) have the greatest effect on productivity over the whole sockeye life cycle?*

C-series) Geographical regions: identify all stressors that are hypothesized to occur in a particular geographic location and add and remove these together. Only one particular case was explored.

Question: *Which is the more important factor in explaining the observed variability in sockeye productivity: marine conditions in the Strait of Georgia or marine conditions in Queen Charlotte Sound*[21]*?*

D-series – L-series) Each of these model sets considers factors within a particular life history stage or combination of life stages (e.g. marine life history stages).

Question: *Within a particular life history stage, which stressors have the greatest effect on productivity over the whole sockeye life cycle?*

[21] The rationale for this question is thoroughly described in Section 4.4.5.

Table A3.5-3. Summary of appropriate timeframes for model sets within each group. The entries of "Yes" and "No" represent the evaluation of whether or not that particular series would be worthwhile to evaluate at over particular time frame ("default time frames"). Moving to a shorter time period represents a trade-off between adding more covariates and decreasing the overall length of the resultant data set that can be analyzed. If moving to a shorter time period does not add any new variables, it is not worthwhile to analyze. If only one variable is added it may be dependent on the particular variable and how many years are removed. In some of the cases presented, it is noted that there may be an appropriate time frame for analysis that is similar but not identical to the default periods.

	Model Set Group	Very Long	Long	Medium (longer)	Medium (shorter)	Short
	DEFAULT TIMEFRAMES	1950-2004	1969-2004	1980-2004	1985-2004	1996-2004
A	Comparison by *life stage*	Yes	Yes	Yes	Yes	Yes
B	Comparison by *project*	Yes	Yes	Yes	Yes	Yes
C	Comparison between *QCS and SoG* factors	No	Yes (could start in 1968)	Yes	No	Yes
D	Comparison within *incubation-lake rearing*	Qualitative contaminants only	No variables added	Only forestry added (1979)	Yes	No variables added
E	Comparison within *smolt outmigration*	Qualitative contaminants and air temp only	Yes	Only forestry added (1978)	Yes	Only solid waste added (99-04)
F	Comparison within *coastal migration*	Yes	Yes	Yes	Only adds 1 alternate prey	Yes
G	Comparison within *ocean rearing*	No	1958-2004	Excludes 1 alternate prey	1981-2004	No
H	Comparison within *return to the Fraser River*	Yes	Yes	Yes	No	No
I	Comparison within *upstream migration*	Yes	1953-2004 Only bald eagle added (1953)	Only forestry added (1976)	1982-2004 Adds population	No
J	Comparison within *spawning*	Only qualitative contaminants	Only adds quantitative contaminants (1 stock complete)	Only forestry added (1976)	1982-2004 Adds population	No
K	Comparison among all *freshwater life stages*	Yes	Yes	No	Yes	No
L	Comparison among all *marine life stages*	Yes	Yes	No	1981-2004	Yes

The A-series of model sets based on life history were our primary focus and complement the qualitative and weight of evidence approach used throughout this project. The B-series of model sets was completed to address the original scope of work for this project but was not considered the most appropriate approach. The C-series of model sets had fewer data limitations because of the reduced scope, in terms of potential variables to consider, and as a result probably provide the best opportunity for meaningful results. D-L series of model sets designed to focus within a particular category of stressor. For example, a model set might be designed to ask the question, "within the category of contaminants, which measure has the greatest effect on productivity over the whole sockeye life cycle?" Such model sets were not considered since they reflect a similar scale of stressor-centric investigation as had already been tasked to each of the other technical reports. Within each series of model sets, we evaluated the available data for different time-periods. We began with one of the simpler series of model sets (i.e., the C-series evaluating the difference between QCS and SoG). This question was selected first as the hypotheses were more focused (i.e., just marine conditions during coastal migration) and so required fewer covariates. Then we went to the most complex model sets (A-series and B-series) and started with the longest time periods but found there were insufficient covariates available back to 1950 to perform meaningful analyses. The second longest time period (starting in 1969) had quite a few covariates available and so the A-series and B-series model sets over the 1969-2004 time period were the next set of models we evaluated. When moving to the period beginning in 1980, quite a few more covariates were available and we attempted to run the A-series and B-series model sets over the more recent time period. At this point we encountered data limitations as the number of covariates increased substantially but the number of dependent observations was reduced as a result of the shortened time series. There should be sufficient data to work with this time period given further investigation of the covariates and data reduction. Many of the smaller models in this time period could run, but there were a few covariates that were still too strongly correlated to run the larger models. The data reduction and candidate model selection (i.e., which covariates to include) would benefit from additional input from the authors of the other Cohen Commission Technical Reports. Table A5.3-4 lists all model sets for which we present results in this report.

Table A3.5-4. Description of the 6 model sets that were examined as part of this project.

Model Set name	Description	Time period (by Brood year)
A4c	Comparison across life stages	1969-2001
A4b	Comparison across life stages, with pink salmon included	1969-2001
B4c	Comparison across stressor categories	1969-2001
B4b	Comparison across stressor categories with pink salmon included	1969-2001
C4a	Comparison of all available marine data between SoG and QCS. No data for QCS SST.	1969-2004
C3a	Comparison of all available marine data between SoG and QCS. Including QCS SST.	1980-2004
C1a	Comparison of all available marine data including chlorophyll for SoG and QCS separately.	1996-2004

Candidate models

Candidate models refer to the list of alternative models compared within each model set. Each of the candidate models is fit using the same data set. Recall that models may differ in terms of the combination of stressor covariates and the functional form of the model. Covariates could enter the model in some non-linear way or interactions among covariates could be specified. However, all candidate models should be based on biological hypotheses. We did not feel we had sufficient knowledge regarding the expected functional form of the relationship between the vast number of covariates and the response variable to assume anything beyond the simplest linear relationship. Possible interactions were also considered based on the information provided by the Cohen Commission Technical Reports and our own qualitative synthesis. The only interactions that were explicitly discussed in our report were:

- Disease/Pathogens & temperature
- Disease/Pathogens & pollutants
- Disease/Pathogens & land use practices
- Sea surface salinity & sea surface temperature

The first three interactions were impossible to explore given the lack of disease/pathogen data. Interactions among marine factors during coastal migration could be explored with existing data but were not considered at this time. With more time and input from subject experts (e.g., authors of the other Cohen Commission Technical Reports) the hypothesized links between covariates and productivity (Section A3.2-A3.4) could be refined and added to. Our approach with this report given the vast scope and volume of data was to start with the simplest non-trivial case, providing useful initial results and setting the stage for future analyses. Therefore, for this project the difference between candidate models within a given model set was simply the combination of stressor covariates included. We did not test every possible combination of covariates. Different combinations of covariates were laid out to specifically address one the question of interest for the given model set as described above. For example, for the A-series of model sets we were interested in determining which life stage might be most important in explaining the variability in productivity. An example of a candidate model from the A-series model set is a model where all covariates that are hypothesized to impact sockeye productivity during a particular life stage are included.

Final data processing

We extracted the data set for each model set (i.e., series and time period) separately. We then deleted all records associated with the Pitt stock based on the recommendation of Randall Peterman (pers. comm.) that this stock is too heavily hatchery influenced to be relevant to the other wild stocks. Finally we evaluated the remaining missing data to see if it was sensible to use interpolation (either across time or across space) to fill in any gaps or whether rows with missing data should simply be dropped. In the end we simply dropped rows with missing data as the gaps were often too big to justify interpolation or else occurred at the beginning or end of the data set making interpolation impossible. In the few occasions where the data gaps were relatively small gaps, this approach resulted in minimal data loss and we concluded that it was not worth the effort to interpolate the missing values. This does not mean that an entire covariate was removed if there was a single missing value. It means that that particular year by stock combination was removed, for example if there was no contaminant data for 1999 in the Quesnel stock, then the 1999 Quesnel productivity and all associated 1999 Quesnel covariates (i.e., one row) were removed. If a covariate had extensive missing data and could not be ‘filled in’ in some way then we would not include it in that particular model set. Another strategy we used for sparse data sets was to use the qualitative data sets we requested from each contractor. Only two contractors provided us with qualitative data sets, but in the case of contaminants this enabled us to include contaminants in analyses they would otherwise have been excluded from. Each model set had its own complete data set saved for use in the analyses to ensure comparisons within a model set were always on the same data set.

Model structure

All models consist of three components: 1) the assumed stock-recruitment relationship, 2) the suite of covariates, and 3) the error. Peterman and Dorner (2011) examined the available Fraser sockeye productivity data and found that in most cases the Ricker stock-recruitment model

(Equation A3.5-3) provided a better fit than the Larkin model, which allows for density dependence among cohorts of the same stock and requires 3 extra parameters for each stock (Equation A3.5-4). Based on their findings and in order to minimize the number of parameters in the model we assumed a Ricker stock recruitment model structure for all models in our analysis. All models used a stock specific *b* term (representing the within stock density-dependence) based on the wide range of estimates observed for different stocks (Peterman and Dorner, 2011). Stock is represented by the subscript *i* in the following equations and year is represented by the subscript *t*.

$$\ln(R_{i,t} / S_{i,t}) = a + b_i S_{i,t} \quad \text{(Equation A3.5-3)}$$

$$\ln(R_{i,t} / S_{i,t}) = a + b_i S_{i,t} + b_{1i} S_{i,t-1} + b_{2,i} S_{i,t-2} + b_{3,i} S_{i,t-3} \quad \text{(Equation A3.5-4)}$$

Two types of covariate variables were included: r*andom effects* and *fixed effects*. Year and stock were incorporated as random effects as we are not interested in predicting the results for a given year or stock but rather in understanding the variability among stocks or years. All models include year and stock as crossed random effects (i.e., each year has multiple stocks, and each stock has multiple years so they are crossed rather than nested random effects (Bates, 2010). A single parameter is used to represent the variability among years, $R_{1,t} \sim N(0,\sigma_{years})$, and stocks, $R_{2,i} \sim N(0,\sigma_{stocks})$. Models differ only in the number and composition of stressor variables. These are always incorporated into the model as fixed effects: $F_{1,t,i} \ldots F_{N-1,t,i}$. The final component is the error term $\varepsilon_{t,i} \sim N(0, \sigma_\varepsilon)$, which represents the remaining error that is unexplained by the model.

$$\ln\left(R_{t,i} \big/ S_{t,i} \right) = \beta_0 + \beta_{1,i} S_{t,i} + \beta_2 F_{1,t,i} + \ldots + \beta_N F_{N-1,t,i} + R_{1,t} + R_{2,i} + \varepsilon_{t,i} \qquad \text{(Equation A3.5-5)}$$

All analyses were completed using the statistical software package, R (R Development Core Team, 2010). Table A3.5-2 illustrates the process we used to document the model structure for each model set. We then used a custom-built function in R to read the data provided in Table A3.5-5 and write the necessary R code to run the analyses and summarize all results. The actual regression analysis was completed using the lme4 package in R. While restricted maximum likelihood (REML) estimates are generally preferred to Maximum likelihood estimates (MLE), we used the MLE approach as it is recommended for the purpose of comparing among models (Bates 2010, p. 8). We then extracted the AICs and calculated the AICc (small sample size corrected AIC) and the AIC weights for all models within a model set, as per Burnham and Anderson (1998). These along with the estimates for all fixed effects in each model were compiled and are reported in Appendix 4.

Table A3.5-5. Example of the model specification document created for each model set. Each row describes a possible independent variable, including the project it came from, the location, the life stage it is hypothesized to effect (it is possible to effect more than one life stage), the unit of measurement, dates available, and unique database name. Effect type indicates if the independent variable is to be included as a fixed effect or a random effect. Columns M1-M10 each represent a particular candidate model. The models differ in terms of which independent variables are included, as indicated by a 1 (include) or 0 (exclude).

Project	Independent Variable	Subset Name	Location	Life stage	Units	Start Year	End Year	VariableSetID	Effect Type	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Marine ecology	River discharge	Wannock (Rivers Inlet)	Queen Charlotte Sound	Migration to rearing areas-Marine	m3/s	1980	2004	DIS_x69_QCSx_MGRR_DOM	Fixed	1	1	0	1	0	0	0	0	0	0
Marine ecology	Sea surface salinity	April-Aug average	Queen Charlotte Sound	Migration to rearing areas-Marine	PSU	1980	2004	SSS_A48_QCSx_MGRR_DOM	Fixed	1	1	0	1	1	0	1	0	0	0
Marine ecology	Sea surface temperature	July-Aug average	Queen Charlotte Sound	Migration to rearing areas-Marine	Degrees Celsius	1980	2004	SST_A78_QCSx_MGRR_DOM	Fixed	1	1	0	1	1	0	0	0	1	0
Marine ecology	Summer wind regime	FACTOR	Queen Charlotte Sound	Migration to rearing areas-Marine		1980	2004	WND_x28_QCSx_MGRR_DOM	Fixed	1	1	0	0	0	0	0	0	0	0
Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	Fraser discharge May total	Strait of Georgia	Migration to rearing areas-Marine	m3/s	1980	2004	DIS_T05_SoGx_MGRR_DOM	Fixed	1	0	1	0	0	0	0	0	0	0
Lwr Fraser River and Strait of Georgia habitat inventory	River discharge	June-July average	Strait of Georgia	Migration to rearing areas-Marine	m3/s	1980	2004	DIS_A67_SoGx_MGRR_DOM	Fixed	1	0	1	0	0	0	0	0	0	0
Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface salinity	April-Aug average	Strait of Georgia	Migration to rearing areas-Marine	PSU	1980	2004	SSS_A48_SoGx_MGRR_DOM	Fixed	1	0	1	0	0	1	0	1	0	0
Lwr Fraser River and Strait of Georgia habitat inventory	Sea surface temperature	April-Aug average	Strait of Georgia	Migration to rearing areas-Marine	Degrees Celsius	1980	2004	SST_A48_SoGx_MGRR_DOM	Fixed	1	0	1	0	0	1	0	0	0	1
								BroodYear	Random	1	1	1	1	1	1	1	1	1	1
								StockName	Random	1	1	1	1	1	1	1	1	1	1

Model selection

We use the Burnham and Anderson (1998) approach to model selection and inference. First we create a list of candidate models based on biological hypotheses. Then we use Akaike's Information Criteria (AIC) statistic to assess the relative importance of the different candidate models. Burnham and Anderson (1998) promote a hypothesis-driven approach to analysis. In hypothesis-driven analyses, the only factors that would be allowed to enter the analyses would be those that are connected to a logical, and in this case, biologically justified hypothesis. They recommend substantial effort be expended up front to generate a small number of sensible *a priori* hypotheses to then test with the observed data. On the other hand, in exploratory analyses many different variables that are not necessarily justified by a hypothesis are added and removed in order to explore different relationships that might exist and develop ideas for hypotheses to be examined in a more rigorous manner. The concern with this approach is that some variables will be correlated simply by chance and not as a result of any underlying mechanism and often these results are used without further testing.

The analysis methods we have used are intended to apply this criterion and exclude any variables that are not connected to a hypothesis. Although we have attempted to structure our analyses within the hypothesis-driven perspective, our final approach has been somewhere between these contrasting approaches for two reasons. First, we aligned observational data series with particular life stages based on hypotheses wherever possible, but in many cases the details of the underlying hypothesis were not known or not specified. For example, the inclusion of predators could likely be improved by making clearer distinctions among fish predators and alternate prey that apply to coastal migration along the continental shelf versus those that apply to the Gulf of Alaska. Second, our original task was to perform analyses across all factors wherever the data are actually available.

Models should only be compared using AICs if the same data set was used to fit both models. This means that we need a complete data set to allow comparisons among models. Not surprisingly data availability limited the extent of the analyses we were able to complete. While we have a substantial dependent variable data set (recruits per spawner indices from 19 Fraser stocks from ~1950-2004, Peterman & Dorner Project #10), we were constrained by the smallest independent variable data sets. Instead of one 'grand' analysis we had to complete the regression analysis on smaller subsets of stressors for which data were available. The expectation that many data sets would be incomplete led to the request of an expert opinion based data set as well. It is important to recognize that each analysis can only be used to make statements about data sets that are included within the analysis. If data from only 3 stressor categories (i.e. projects) are used, then the analysis can only tell us about the relative and cumulative impact of these 3 categories of stressors. We cannot evaluate or make conclusions about how they relate to other categories of stressor not included in that particular analysis.

Summary of approach

The basic steps we used to complete this analysis were:

1. Generate model sets
    - Generate hypotheses linking all data we received to the appropriate life stage (Appendix 3.4-3-3.4-9)
    - Summarize the available data by time period and type (Table A3.5-1)
    - Select windows of time where different covariates could be compared. For example, we identified which covariates were available for a ‘Very Long’ time (i.e., 54 years).
    - Identify questions/hypotheses that could be tested within each model set. For example, the ‘Very Long’ time period would not enable us to compare models with sea surface temperature and chlorophyll, but the ‘Short’ time period would.

2. Generate candidate models
    - Identify logical groupings of covariates that can be included or excluded to test specific questions/hypotheses (e.g., which life stage is limiting sockeye productivity?)
    - Consider whether or not to include any non-linear terms
    - Consider whether or not to include any interaction terms

3. Data Reduction
    - Reduce the number of variables based on our best understanding of the biological hypotheses, correlation analysis, and principal components analysis
    - Extract the data for a given model set and time period

4. Final processing and analysis
    - Process the data to produce a complete data set for each model set (i.e., remove any rows with missing data for any of the covariates within the model set and time period)
    - Fit each model (i.e., estimate the parameters) in the model set and generate a table of AICc values to compare the relative fit of each model.

Limitations

- We only considered the most basic candidate models. We did not incorporate any non-linear or interaction terms. Even if we had incorporated these, it is doubtful that we would be able to correctly identify the functional form of the relationships given the complexity of the underlying system. Regression would not be expected to detect relationships that are not explicitly incorporated into the candidate models and therefore regression is not the correct approach for identifying complex relationships (e.g, involving interactions among more than 2 factors, time lags etc.) that have not previously been hypothesized.
- Many of the life stages or stressor categories had very sparse data and so conclusions regarding the importance of a given life stage or project are limited to the covariates that were available.
- There were no data available for the disease/pathogen stressor category and so no statements can be made about the relative likelihood of disease/pathogens based on the quantitative analysis, although there is belief among many experts that this may be an important factor.
- There were no data available for the incubation-rearing life stage and so no statements can be made about the relative likelihood of the incubation-rearing life stage being limiting based on the quantitative analysis.
- Due to the large number of covariates we were asked to consider simultaneously we had to assume the same relationship between covariates and all stocks. We couldn't estimate a separate parameter for every stock, because it would increase the number of parameters 18 fold. For example, we use a single parameter to represent the relationship between productivity and sea surface temperature for all stocks. If we believed the relationship was different for every stock and wanted to estimate this relationship separately we would need to include a unique parameter for all 18 stocks. The only stock specific parameter we estimated was the density dependence relationship (Ricker b term) as it was shown to vary substantially among stocks (Peterman and Dorner, 2011).
- Some of the aggregate indices we generated to reduce the number of parameters (e.g., April-Aug mean sea surface salinity) may actually mask true underlying relationships. Determining appropriate ways to generate annual estimates of the physical covariates to relate to the annual biological response (sockeye productivity) was a major difficulty encountered during this project. Functional data analysis may be a better approach for addressing this challenge (Ainsworth and Routledge, 2011), but will also be limited by the sheer volume of data sets, potential hypotheses, and limited expert knowledge about the underlying system.

- In some cases it may be the timing rather than the size of a variable that is driving sockeye productivity. It would be a good idea to consider generating indices that reflect this hypothesis or to evaluate timing through functional data analysis. For example, perhaps it is the timing of the plankton bloom rather than the magnitude of it that is most important.

Additional approaches / next steps

Bayesian analytical approach

Parameter estimation, as described earlier, involves finding the parameter values for a given model that best fit the observed data. Bayesian approaches allow the parameters to be described with a distribution rather than assuming they have a single true underlying value, which is the classical or frequentist approach. These methods directly quantify uncertainty and are able to handle very complex problems (Gelman et al. 2004) making them a natural next step to the traditional regression analyses presented here. Hilborne and Walters (1992) specifically recommend Bayesian methods for fisheries data as a strategy for coping with heterogeneous data (i.e., data from different sources and potentially differing quality). While we have explicitly considered model uncertainty (i.e., we have not assumed that one 'true' underlying model and set of parameter estimates exists) by looking at the relative weights of different candidate models, the Bayesian approach would extend that concept even further.

Functional data analysis

Functional regression analysis differs from classical regression (used in this report) in that the regression coefficient is actually a function. In classical regression the covariates and the response variable have the same dimension. That is, if there is one productivity measure per year, then we need a corresponding data point for each covariate of interest. In reality many physical covariates such as: sea surface temperature or river discharge, are measured on a much finer temporal scale. Functional data analysis (FDA) enables the covariate to be incorporated at a finer scale by letting the parameter (i.e., regression coefficient) be a function rather than a fixed value.

This approach may enable us to improve the 'data reduction' step described above as it will help us to understand the behaviour of the covariate over time and hopefully better capture the underlying behaviour that relates to the response variable. Ainsworth and Routledge (2011) describe how FDA may be applied for this specific purpose. However, they point out that expert biological/system knowledge was still critical to the application.

Bayesian belief networks (BBN)

BBNs are models that graphically and probabilistically represent correlative and causative relationships among variables (Cain 2001). A particular BBN defines various events, the dependencies between them, and the conditional probabilities involved in those dependencies. This is represented as a probabilistic graphical model that represents a set of variables and their probabilistic independencies. BBNs lend themselves well to representing the variability of natural systems and uncertainty of understanding, and the implications of this to management decisions (Kuikka et al. 1999). A BBN could be developed from the conceptual model (Figure 3.3-1) to improve our understanding of the cumulative impacts, interactions, and relative effects of stressors across all projects.

Control charts

This is a concept taken from statistical process control theory usually applied to a manufacturing process. Control charts are used on an ongoing basis to monitor whether or not the system is 'in control'. Both the actual value and the variability are monitored. Early detection of systematic changes resulting in either a change to the value or increase in variability (or both) is critical, presumably the same concepts could be useful for informing managers of a natural system. It may be useful to assess whether or not the productivity data has been stable or increasing in terms of variability. During the course of this project, we identified two other sockeye related data sets where there appeared to be increasing variability over time: 1) age of return (Figure 4.5-1) and the 2) returning spawner migration route (Figure 4.5-2). It would be useful to quantify this observation and if valid determine if there is some way to assess the cause.

Appendix 4. Quantitative Results

A4.1 Trend and Change Point Analysis of Productivity by Stock

Trend analyses of sockeye productivity (i.e., ln(R/S)) over time found that 6 of the 19 Fraser stocks were better fit by the piece-wise regression model (allowing for 2 different trends over the time-series) than a single straight line regression over time (Table A4.1-1). The recent trends for 5 of these stocks (excluding Pitt) ranged from: -0.050 to -0.141, which is equivalent to annual declines on the R/S scale of: ~5% (Early Stuart) to 13%[22](Quesnel). The earliest change-point occurred in 1965 (Early Stuart) and the latest occurred in 1988 (Chilko). Pitt is reported separately as we are not sure how reflective this stock is of other wild Fraser stocks due to its high hatchery influence. The recent trend in Pitt was -0.466, which corresponds to an average annual decline of ~35% since 1999. Despite having only 5 years of data to estimate the post 1999 trend, the p-value was <0.001. Each of the other 5 stocks that were fit with the change-point model had p-values of <0.001 indicating that the recent trends are significantly decreasing.

Table A4.1-1. Summary of stocks where a piece-wise regression model was more appropriate than a simple straight-line fit. The estimated slope of both lines and associated test statistics and p-values are shown.

Stock	Change point	B1 (slope of first line)			B3 (slope of second line)			Recent Trend
		estimate	test stat	p-value	estimate	test stat	p-value	
Birkenhead	1983	0.004	0.305	0.762	-0.112	-4.706	< 0.001	↓
Chilko	1988	0.003	0.278	0.782	-0.113	-4.313	< 0.001	↓
E.Stuart	1965	0.069	3.027	0.004	-0.050	-6.818	< 0.001	↓
Pitt	1999	-0.008	-1.083	0.284	-0.466	-3.845	< 0.001	↓
Quesnel	1983	0.022	1.867	0.068	-0.141	-6.932	< 0.001	↓
Stellako	1984	0.013	1.635	0.108	-0.090	-5.874	< 0.001	↓

The change-point model did not improve the fit for the remaining 13 stocks (based on examination of residuals) and so we report the simple straight-line model fit across the entire time-series (Table A4.1-2). As described in Appendix 3.5.2, many other more complex models are possible and in some cases these may be superior to the simple models shown here. 7 of the 13 stocks fit with a single trend line found that ln(R/S) has been significantly ($p<0.05$) declining since the beginning of the time-series (i.e., 1950 in most cases). 2 of the 13 stocks show weak evidence of a declining trend in ln(R/S) (Nadina, p=0.074 and Portage, p=0.059). Only 4 of the 13 stocks show no evidence of a non-zero trend in ln(R/S): Harrison, Late Shuswap, Raft, and Weaver. The significantly declining long term trends ranged from: -0.017 (Bowron) to -0.067

[22] Each year the R/S is roughly the previous year's value multiplied by exp(slope), for example: $e^{(0.050)} \approx 0.95$.

(Fennell), which is equivalent to annual declines on the R/S scale of: ~1.7% to 6.5% since ~1950.

Table A4.1-2. Summary of stocks where a single trend line was more appropriate. The estimated slope of the line is shown along with the associated test statistic and p-value (significant p-values are indicated by a *). Arrows indicate the direction of the trend.

Stock	Slope (b1)	Test statistic for b1	p-value[23]	Trend over entire time-series
Birkenhead	-0.035	-4.059	< 0.001*	↓
Bowron	-0.017	-2.520	0.015*	↓
Fennell	-0.067	-5.374	< 0.001*	↓
Gates	-0.050	-4.071	< 0.001*	↓
Harrison	0.012	0.978	0.332	↔
L.Shuswap	-0.007	-0.889	0.378	↔
L.Stuart	-0.027	-2.464	0.017*	↓
Nadina	-0.028	-1.849	0.074	↓ (weak evidence)
Portage	-0.021	-1.935	0.059	↓(weak evidence)
Raft	-0.005	-0.690	0.493	↔
Scotch	-0.048	-3.346	0.002*	↓
Seymour	-0.023	-3.073	0.003*	↓
Weaver	-0.004	-0.294	0.770	↔

A4.2 Analyses of Stock Composition

Three time periods follow a very similar pattern both in terms of the shape of the concentration profile and the average number of recruits (between 4 & 6 million), these include the two earliest time periods: 1948-1959, 1960-1971, and the most recent one: 1996-2006 (Figure A4.2-1). The other two time periods have a similar shape but the average number of recruits was substantially higher: 1972-1983 (~8 million) and 1984-1995 (~11 million). When the y-axis was scaled to 1 to represent the cumulative proportion of total recruits, we see that the shape of the curves are very similar across all time periods with 80% of the total recruits composed of only 4-6 stocks out of the 19 evaluated (Figure A4.2-2). The primary reason for plotting these figures was to determine if the portfolio balance had changed over time and if that might be a potential explanation for the long-term decline in Fraser River sockeye productivity. While the total number of recruits has varied substantially over time, the shape of the concentration profile has not. Contrary to our expectation, there has not been a substantial change in the "portfolio

[23] P-value is associated with the null hypothesis that the slope (b1) = 0. A small p-value (i.e., <0.05) indicates that there is significant evidence to reject the null hypothesis and that the slope is non-zero.

balance" over time and so this it is unlikely that the observed portfolio imbalance is responsible for the declines in productivity.

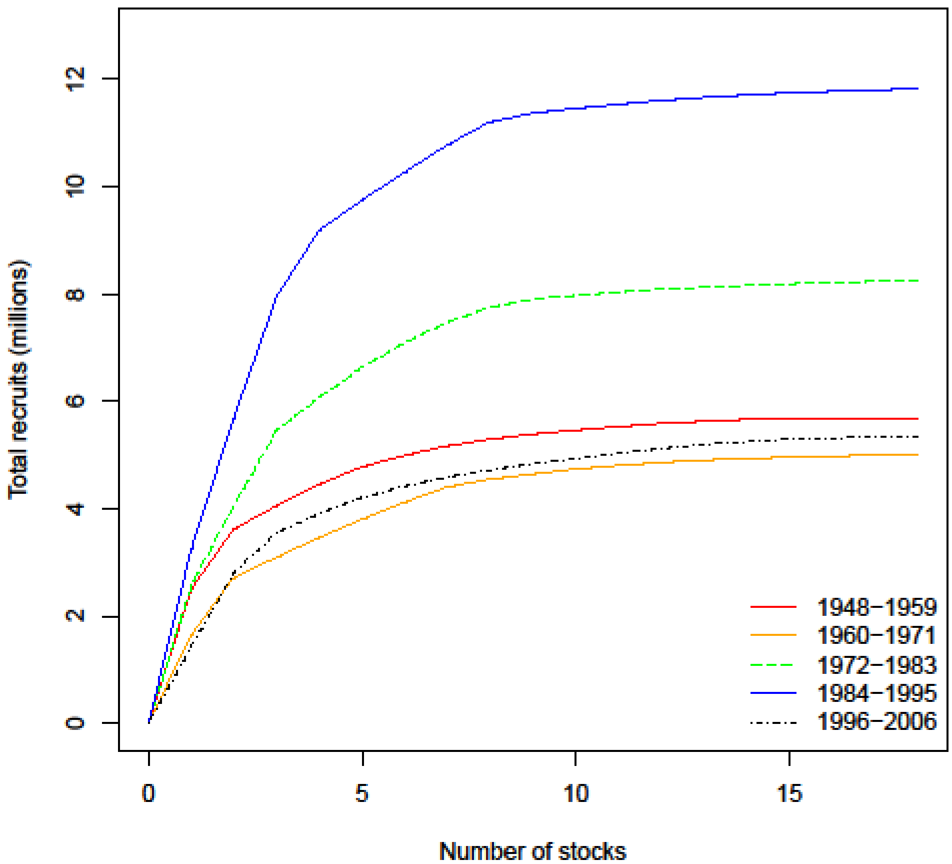


Figure A4.2-1. Figure illustrating how the composition of the stock portfolio is dominated by only a handful of stocks as well as illustrating how the total number of recruits has varied across time.

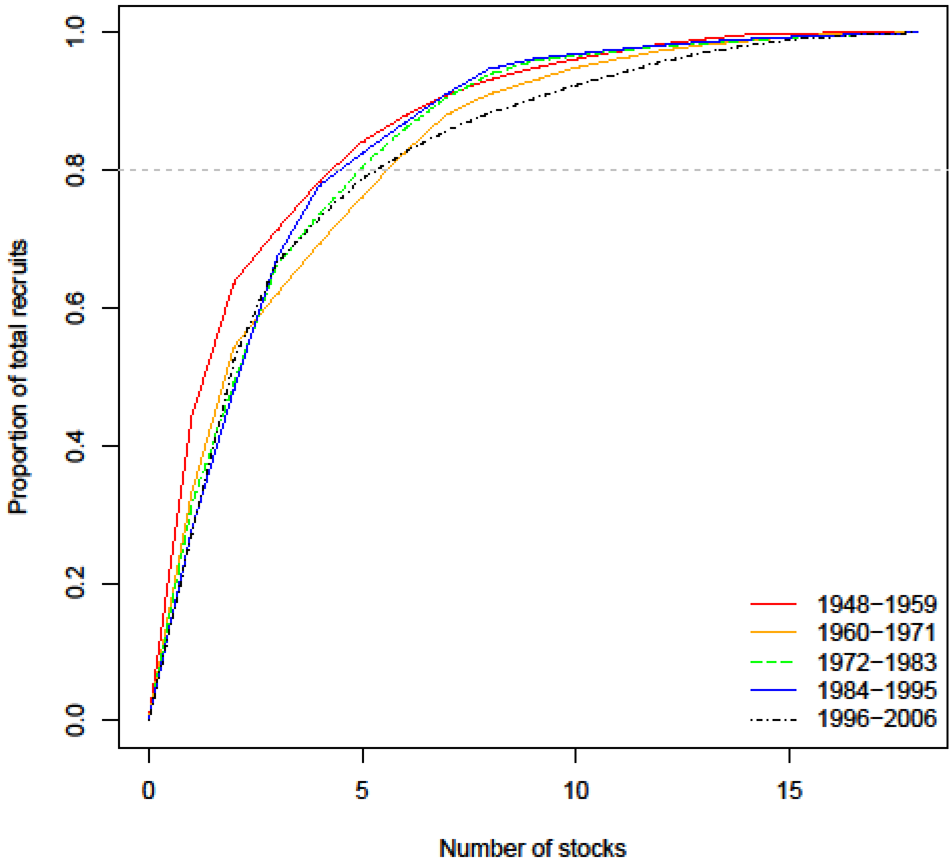


Figure A4.2-2. Stock composition, scaled to a common axis for 5 different time periods. All five time periods in this figure reach 80% of the total recruits with only about 4 to 6 stocks.

Decomposition of the dominant Fraser River sockeye stocks with data available illustrates the sizeable contrasts among cohorts resulting from the dominant four-year life history. The purpose of these graphs (Figure A4.2-3, A4.2-4, A4.2-5, A4.2-6) is simply to illustrate that there are in fact substantial differences in stock composition among the cohorts. This may be a fairly obvious observation to those with a scientific background in sockeye salmon; however, based on our observations of media coverage and other public fora it appears that this difference in stock composition among cohorts is often not recognized. In the public discourse, the poor 2009 returns are often compared/contrasted with the high 2010 returns (these are the "comparisons" to which we refer), without acknowledging that the situation is actually more complicated since not only do the two years come from different generations/cycles, but the composition of each is distinctly different. These graphs show quite clearly that 2009 versus 2010 is not a simple "apples-to-apples" comparison.

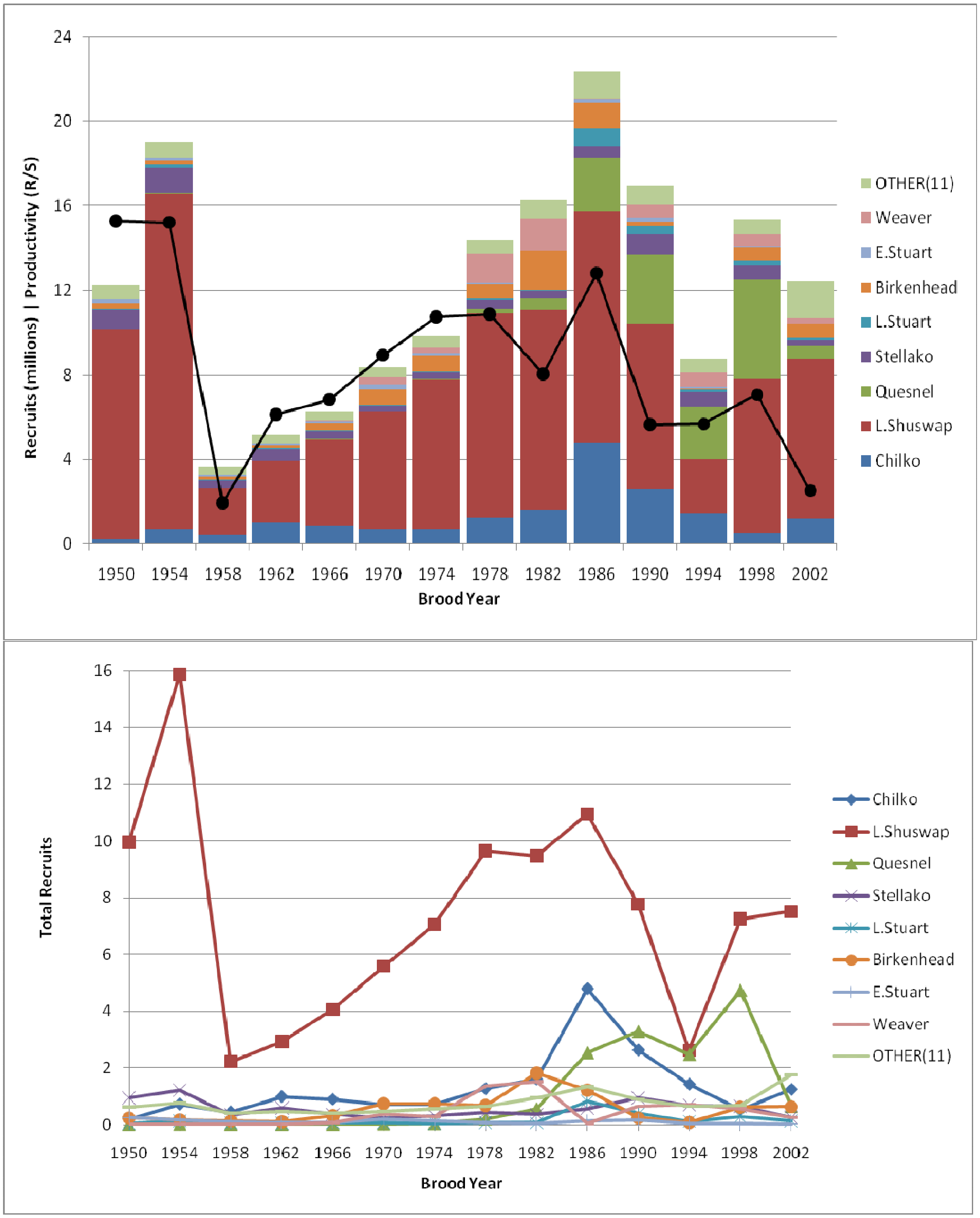


Figure A4.2-3. Stock composition for the 1950 brood year cohort. The sockeye salmon that returned in 2010 belong to this brood year cohort. The top graph shows the total recruits by stock (stacked bar chart) and productivity (R/S, black solid dots with connecting lines). The bottom graph shows the total recruits (in millions) of each stock wihtin this cohort over time. Only the eight most dominant stocks (over all cohorts, over 1950-2004) are shown individually.

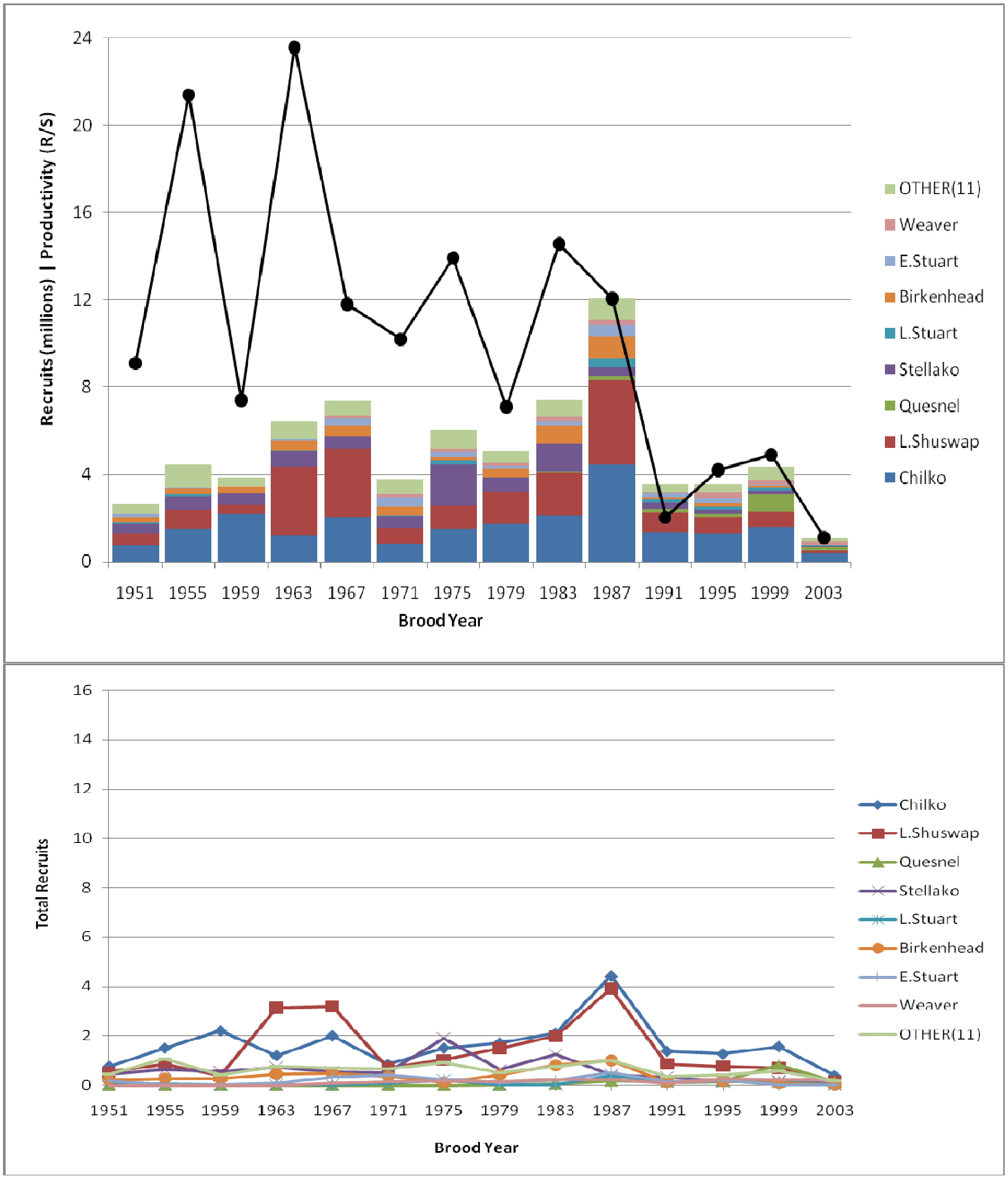
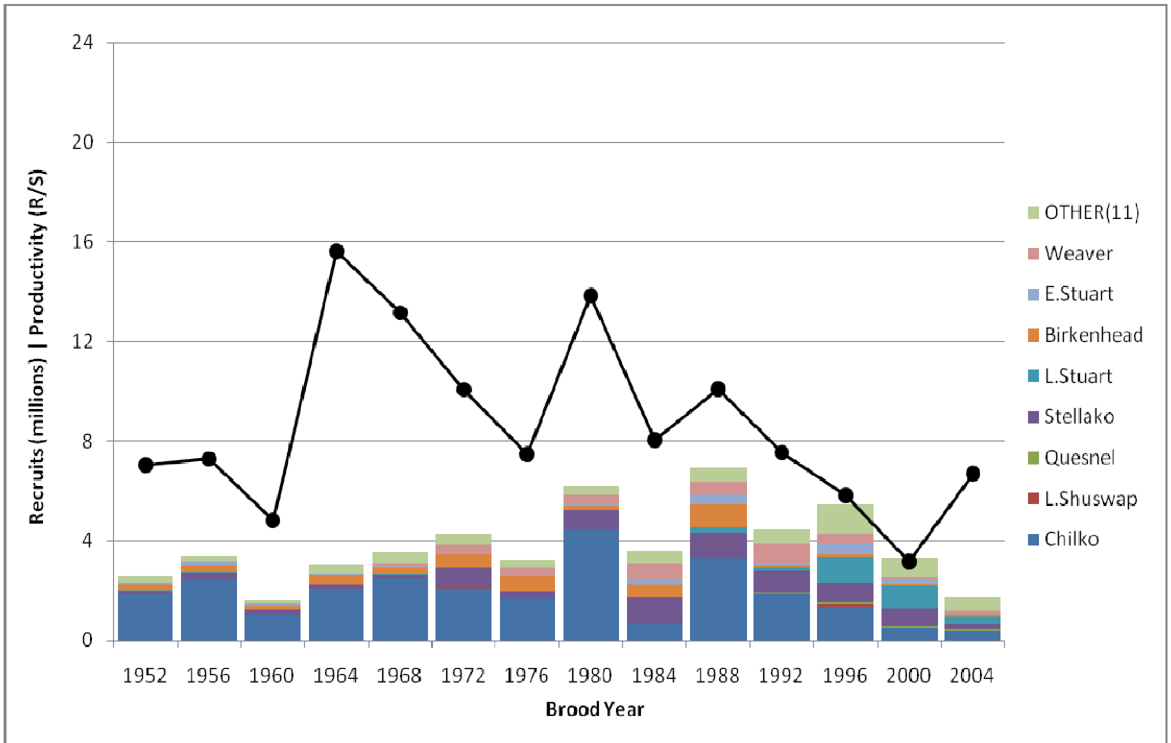


Figure A4.2-4. Stock composition for the 1951 brood year cohort. The top graph shows the total recruits by stock (stacked bar chart) and productivity (R/S, black solid dots with connecting lines). The bottom graph shows the total recruits (in millions) of each stock wihtin this cohort over time. Only the eight most dominant stocks (over all cohorts, over 1950-2004) are shown individually.



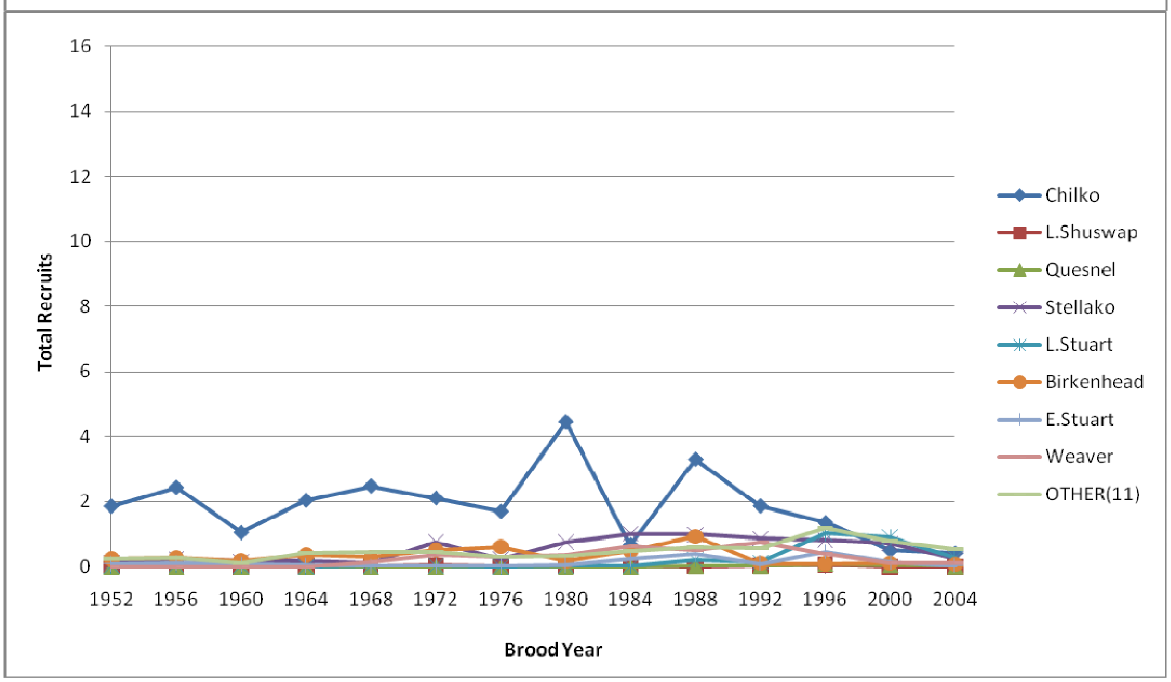


Figure A4.2-5. Stock composition for the 1952 brood year cohort. The top graph shows the total recruits by stock (stacked bar chart) and productivity (R/S, black solid dots with connecting lines). The bottom graph shows the total recruits (in millions) of each stock wihtin this cohort over time. Only the eight most dominant stocks (over all cohorts, over 1950-2004) are shown individually.

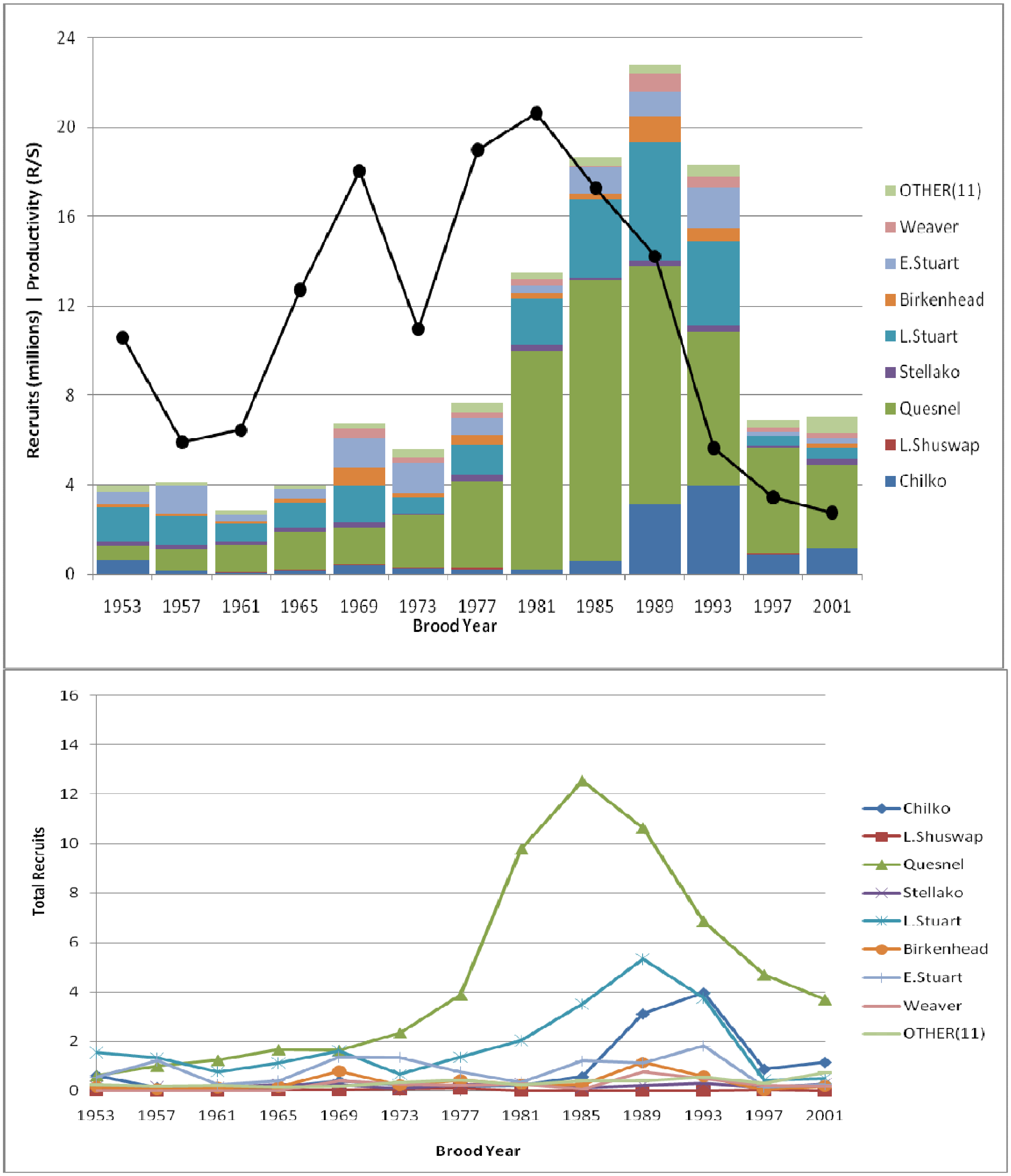


Figure A4.2-6. Stock composition for the 1953 brood year cohort. The sockeye salmon that returned in 2009 belonged to this brood year cohort. The top graph shows the total recruits by stock (stacked bar chart) and productivity (R/S, black solid dots with connecting lines). The bottom graph shows the total recruits (in millions) of each stock wihtin this cohort over time. Only the eight most dominant stocks (over all cohorts, over 1950-2004) are shown individually.

A4.3 Multiple Regression Results

A4.3.1 Summary of analyses

This section describes the results of the regression analysis for each of the 6 model sets that were examined as part of this project (Table A4.3-1). Detailed descriptions of covariates included in at least one of these 6 model sets are provided in Table A4.3-2.

Table A4.3 -1. Description of the 6 model sets that were examined as part of this project.

Model Set name	Description	Time period (by Brood year)
A4c	Comparison across life stages	1969-2001
A4b	Comparison across life stages, with pink salmon included	1969-2001
B4c	Comparison across stressor categories	1969-2001
B4b	Comparison across stressor categories with pink salmon included	1969-2001
C4a	Comparison of all available marine data between SoG and QCS. No data for QCS SST.	1969-2004
C3a	Comparison of all available marine data between SoG and QCS. Including QCS SST.	1980-2004
C1a	Comparison of all available marine data including chlorophyll for SoG and QCS separately.	1996-2004

Table A4.3-2. Description of the actual covariates used in various model sets. Each covariate is linked to a particular life stage and stressor category[24]. The database variable name is provided to assist with interpreting the model outputs. Other covariates were available for other time-periods but were not examined during this project.

Life stage	Stressor category	Variable Description	Database Variable Name	Dates[25]
Coastal migration	Habitat conditions in Lower Fraser & SoG	Chlorophyll, Northern SoG, April average.	CHL_M04_NSoG_MGRR_DOM	1998-
Coastal migration	Habitat conditions in Lower Fraser & SoG	Chlorophyll, Northern SoG, May average.	CHL_M05_NSoG_MGRR_DOM	1998-
Coastal migration	Habitat conditions in Lower Fraser & SoG	SoG discharge , June-July average	DIS_A67_SoGx_MGRR_DOM	1970-
Coastal migration	Habitat conditions in Lower Fraser & SoG	SoG discharge, May average	DIS_T05_SoGx_MGRR_DOM	1970-
Coastal migration	Habitat conditions in Lower Fraser & SoG	Sea surface salinity. SoG, April-Aug average.	SSS_A48_SoGx_MGRR_DOM	1950-
Coastal migration	Habitat conditions in Lower Fraser & SoG	Sea surface temperature. SoG, April-Aug average.	SST_A48_SoGx_MGRR_DOM	1950-
Coastal migration	Marine conditions	Chlorophyll, QCS, April average.	CHL_M04_QCSx_MGRR_DOM	1998-
Coastal migration	Marine conditions	Chlorophyll, QCS, May average.	CHL_M05_QCSx_MGRR_DOM	1998-
Coastal migration	Marine conditions	QCS discharge, June-Sept average (Wannock)	DIS_x69_QCSx_MGRR_DOM	1969-
Coastal migration	Marine conditions	Sea surface salinity. QCS, April-Aug average.	SSS_A48_QCSx_MGRR_DOM	1970-
Coastal migration	Marine conditions	Sea surface temperature, QCS, July-Aug average	SST_A78_QCSx_MGRR_DOM	1982-
Coastal migration	Marine conditions	Summer wind regime. QCS.	WND_x28_QCSx_MGRR_DOM	1948-
Coastal migration	Predator/Alternative Prey	5 marine bird species: Quantile based aggregate estimate	CBQ_108_NULL_MGRR_DOM	1958-
Coastal migration	Predator/Alternative Prey	Arrowtooth flounder biomass	FPR_x87_NULL_MGRR_DOM	1961-
Coastal migration	Predator/Alternative Prey	California sea lion estimate	PNE_x25_NULL_MGRR_DOM	1971-
Coastal migration	Predator/Alternative Prey	Harbour seal estimate	PNE_x39_NULL_MGRR_DOM	1913-
Coastal migration	Predator/Alternative Prey	Stellar sea lion	PNE_x61_NULL_MGRR_DOM	1913-
Coastal migration	Predator/Alternative Prey	Alternative prey quantile based aggregate estimate of 8 species/locations.	PRQ_110_NULL_MGRR_DOM	1950-
Growth in North Pacific	Marine conditions	North Pacific Index, Nov-Mar average	NPI_x51_NPOx_GROW_DOM	1900-

24 Each stressor category corresponds to a particular Cohen Technical project.
25 Dates in this table refer to the earliest date a measurement is available. The date is the actual date the metric was measured not the brood year.

Life stage	Stressor category	Variable Description	Database Variable Name	Dates[25]
Growth in North Pacific	Predator/Alternative Prey	Alternative prey quantile based aggregate estimate of 8 species/locations.	PRQ_110_NULL_GROW_DOM	1950-
Return to Fraser	Competition with pinks	Pink salmon abundance (NE Pacific)	PNK_x50_NPOx_MGRS_DOM	1952-
Return to Fraser	Competition with pinks	Pink salmon abundance (Russia)	PNK_x58_NPOx_MGRS_DOM	1952-
Return to Fraser	Habitat conditions in Lower Fraser & SoG	Sea surface salinity. SoG, May-Sept average.	SSS_A59_SoGx_MGRS_DOM	1950-
Return to Fraser	Habitat conditions in Lower Fraser & SoG	Sea surface temperature. SoG, Sept average.	SST_M09_SoGx_MGRS_DOM	1950-
Return to Fraser	Marine conditions	Sea surface salinity. QCS, May-Sept average.	SSS_A59_QCSx_MGRS_DOM	1970-
Return to Fraser	Predator/Alternative Prey	California sea lion estimate	PNE_x25_NULL_MGRS_DOM	1971-
Return to Fraser	Predator/Alternative Prey	Harbour seal estimate	PNE_x39_NULL_MGRS_DOM	1913-
Return to Fraser	Predator/Alternative Prey	Stellar sea lion	PNE_x61_NULL_MGRS_DOM	1913-
Return to Fraser	Predator/Alternative Prey	Alternative prey quantile based aggregate estimate of 8 species/locations.	PRQ_110_NULL_MGRS_DOM	1950-
Smolt outmigration	Contaminants	Qualitative water quality index. Stock specific.	WQQ_x53_FWMx_SMLT_DOM	1948-
Smolt outmigration	Freshwater	Spring air temperature CU specific	SPT_x82_FWRx_SMLT_DOM	1948-
Smolt outmigration	Habitat conditions in Lower Fraser & SoG	Discharge, SoG, April total	DIS_T04_SoGx_SMLT_DOM	1969-
Smolt outmigration	Habitat conditions in Lower Fraser & SoG	Discharge SoG, May total	DIS_T05_SoGx_SMLT_DOM	1969-
Smolt outmigration	Habitat conditions in Lower Fraser & SoG	Lower Fraser total dredge volume	DRG_x45_LFRx_SMLT_DOM	1970-
Smolt outmigration	Predator/Alternative Prey	Double Crested Cormorant and Common Merganser: Quantile based aggregate estimate	CBQ_107_NULL_SMLT_DOM	1958-
Upstream migration	Climate change	Lower Fraser water temperature for returning adults.	WTT_x82_FWMx_MGRS_DOM	1951-
Upstream migration	Contaminants	Qualitative water quality index. Stock specific.	WQQ_x66_FWMx_MGRS_DOM	1948-
Upstream migration	Freshwater	Summer air temperature. CU specific.	SUT_x26_FWMx_MGRS_DOM	1948-
Upstream migration	Predator/Alternative Prey	Bald Eagle abundance.	CBQ_x91_NULL_MGRS_DOM	1957-

A4.3.2 Analyses by life stage

Model: A4c
Brood years: 1969-2001

A model set was tested with the available data for brood years 1969-2001. The list of potential variables provided by the Cohen Contractors is not exhaustive (i.e., other important variables may exist, or data may not have been available). However, for this time period there are at least a few variables for all but two life stages: incubation-rearing and spawning. There are a total of 33 potential stressor variables. While there are 611 records in this time period, there are only 463 observations of ln(R/S) with complete data. Two stocks: Harrison and Cultus, have no data for one stressor variable (Water Quality during outmigration) in this time period and are not included in this analysis. Each stressor was linked to a particular life stage as described in Appendix A3-4 Data Preparation). In some cases the same data may be linked to several life stages (e.g., predators could potentially impact sockeye during their inshore migration or during their return migration to spawn). Table A4.3-3 describes the ten different models in this model set, Table A4.3-4 shows the relative fit of each model, and Table A4.3-5 provides the estimates for each parameter and model.

Table A4.3-3. Model descriptions for model set A4c (comparison among life stages for brood years 1969-2001).

Model Name	Model description	Number of stressors	Total number of parameters
M1	Global model: contains variables associated with all life stages.	31	50
M2	Life stage 1: Incubation-rearing.	0	19
M3	Life stage 2: Smolt Outmigration	6	25
M4	Life stage 3: Inshore Migration and Migration to Rearing Areas	13	32
M5	Life stage 4a: Growth in North Pacific	2	21
M6	Life stage 4b: Return to Fraser	8	26
M7	Life stage 5a: Return to spawn (upstream migration)[26]	4	23
M8	Life stage 5b: Spawning	0	19
M9	All freshwater life stages: 1, 2, 5a, and 5b	7	26
M10	All marine life stages: 3, 4a, and 4b	23	41

[26] Note: the response variable used in the analysis, ln(R/S) already incorporates en-route mortality and so this hypothesis refers to any delayed effect on productivity (e.g., spawners may not produce as many offspring if they are stressed) resulting from the upstream migration.

The results show strong support for M10 (all marine life stages), with weak support for M4 (Inshore Migration) and M6 (Return to the Fraser). Despite the large number of parameters (41) M10 had the lowest AICc providing strong support for this model. The next two models had substantially fewer parameters but their AICc scores were 5-7 units higher than that of M10 indicating some information loss as a result of the reduced number of parameters. Overall these results indicate that the marine component of the life stage is more important in explaining the overall productivity than the freshwater component. However, it must be noted that there were limited stressor data available for the freshwater component and those data available may not have been the most appropriate data. The true interpretation of this result is that the marine data available do a better job of explaining the overall productivity of Fraser sockeye, than the freshwater data available over this time period. Estimates of effect sizes are presented in Table A4.3-5 for all models. Interpretation of the actual estimates, their magnitude and sign is difficult particularly for very complex models with many covariates. As described in the previous section (Interpretation of results) models with only a few stressors are easier to interpret. If interested in digging into the estimates in detail, one should also obtain the estimates of variability for each of these parameters. These are available, but not provided in this document in the interest of space.

Table A4.3-4. A4c candidate models ordered by AICc from best (lowest) to worst (biggest). M.ID=model identification, M.AIC=the estimated AIC for the model, num.obs=the total number of observations (i.e., complete rows in the data set), num.par=the total number of fixed effects + random effects, Correction= the difference between the AICc (corrected for small sample size compared to number of parameters) and the AIC, M.AICC= the AICc for the model, min.AICC = the smallest AICc observed within the model set, delta= the difference between the min.AICC and each M.AICC, and AICC_wts= the Akaike weight (i.e., support) for each model.

M.ID	M.AIC	num.obs	num.par	Correction	M.AICC	min.AICC	delta	AICC_wts
M10	1127.51	463	41	8.18	1135.69	1135.69	0	88.43
M4	1135.78	463	32	4.91	1140.69	1135.69	5.00	7.25
M6	1139.55	463	26	3.22	1142.77	1135.69	7.08	2.56
M1	1131.35	463	50	12.38	1143.73	1135.69	8.04	1.59
M5	1146.65	463	21	2.10	1148.75	1135.69	13.06	0.13
M8	1151.31	463	19	1.72	1153.02	1135.69	17.33	0.02
M2	1151.31	463	19	1.72	1153.02	1135.69	17.33	0.02
M7	1152.93	463	23	2.51	1155.44	1135.69	19.75	0.0045
M3	1155.74	463	25	2.97	1158.71	1135.69	23.02	0.00089
M9	1156.46	463	26	3.22	1159.68	1135.69	23.99	0.00055

Table A4.3-5. Estimates for all fixed effects parameters included in each model, for model set A4c. Fixed effect parameters (i.e., covariates) are listed in the rows. The estimates for each model are provided in the columns. A value of 'NA' indicates that that particular model did not include the covariate in the corresponding row.

ModelSet_A4c_VarName	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
(Intercept)	47.74	2.55	2.12	-9.77	1.04	1.86	4.63	2.55	2.06	-4.46
CBQ_107_NULL_SMLT_DOM	0.19	NA	-0.05	NA	NA	NA	NA	NA	-0.10	NA
CBQ_108_NULL_MGRR_DOM	0.86	NA	NA	-0.06	NA	NA	NA	NA	NA	-0.03
CBQ_x91_NULL_MGRS_DOM	-0.46	NA	NA	NA	NA	NA	-0.27	NA	NA	NA
DIS_A67_SoGx_MGRR_DOM	-1.5E-06	NA	NA	2.3E-06	NA	NA	NA	NA	NA	6.4E-06
DIS_T04_SoGx_SMLT_DOM	1.4E-06	NA	-8.5E-06	NA	NA	NA	NA	NA	-8.5E-06	NA
DIS_T05_SoGx_MGRR_DOM	-2.1E-06	NA	NA	3.6E-06	NA	NA	NA	NA	NA	3.8E-06
DIS_x69_QCSx_MGRR_DOM	0.0012	NA	NA	1.8E-05	NA	NA	NA	NA	NA	-0.0018
DRG_x45_LFRx_SMLT_DOM	-1.4E-07	NA	4.4E-08	NA	NA	NA	NA	NA	5.4E-08	NA
FPR_x87_NULL_MGRR_DOM	-8.9E-06	NA	NA	-2.3E-06	NA	NA	NA	NA	NA	-3.9E-06
NPI_x51_NPOx_GROW_DOM	-0.07	NA	NA	NA	-0.007	NA	NA	NA	NA	-0.05
PNE_x25_NULL_MGRR_DOM	-0.0006	NA	NA	6.4E-05	NA	NA	NA	NA	NA	5.7E-05
PNE_x25_NULL_MGRS_DOM	0.0016	NA	NA	NA	NA	-6.9E-05	NA	NA	NA	6.6E-05
PNE_x39_NULL_MGRR_DOM	-0.0003	NA	NA	1.2E-05	NA	NA	NA	NA	NA	-5.2E-05
PNE_x39_NULL_MGRS_DOM	0.0004	NA	NA	NA	NA	-8.9E-06	NA	NA	NA	7.5E-05
PNE_x61_NULL_MGRR_DOM	-0.0006	NA	NA	0.0001	NA	NA	NA	NA	NA	-3.6E-06
PNE_x61_NULL_MGRS_DOM	0.0004	NA	NA	NA	NA	4.5E-05	NA	NA	NA	0.0001
PRQ_110_NULL_GROW_DOM	-7.36	NA	NA	NA	0.73	NA	NA	NA	NA	-3.01
PRQ_110_NULL_MGRR_DOM	3.61	NA	NA	1.17	NA	NA	NA	NA	NA	3.24
PRQ_110_NULL_MGRS_DOM	-0.56	NA	NA	NA	NA	0.38	NA	NA	NA	0.39
SPT_x82_FWRx_SMLT_DOM	0.04	NA	0.02	NA	NA	NA	NA	NA	0.02	NA
SSS_A48_QCSx_MGRR_DOM	-0.89	NA	NA	0.13	NA	NA	NA	NA	NA	-0.11
SSS_A48_SoGx_MGRR_DOM	0.23	NA	NA	0.07	NA	NA	NA	NA	NA	0.24
SSS_A59_QCSx_MGRS_DOM	-0.97	NA	NA	NA	NA	0.09	NA	NA	NA	0.02
SSS_A59_SoGx_MGRS_DOM	0.30	NA	NA	NA	NA	-0.15	NA	NA	NA	-0.11
SST_A48_SoGx_MGRR_DOM	0.37	NA	NA	0.28	NA	NA	NA	NA	NA	0.51
SST_M09_SoGx_MGRS_DOM	0.09	NA	NA	NA	NA	0.08	NA	NA	NA	-0.07
StockNameBirkenhead:Spawners	-8.63	-9.30	-9.02	-8.71	-9.24	-9.52	-9.25	-9.30	-8.88	-9.64
StockNameBowron:Spawners	-83.92	-98.08	-96.23	-104.29	-98.88	-95.50	-98.32	-98.08	-96.49	-103.13
StockNameChilko:Spawners	-1.91	-2.40	-2.33	-2.13	-2.32	-2.28	-2.45	-2.40	-2.30	-2.17

ModelSet_A4c_VarName	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
StockNameE.Stuart:Spawners	-1.79	-1.88	-1.98	-1.59	-1.78	-1.67	-1.85	-1.88	-1.88	-1.98
StockNameFennell:Spawners	-142.96	-159.24	-155.87	-154.13	-159.78	-149.78	-158.11	-159.24	-156.68	-154.76
StockNameGates:Spawners	-26.47	-31.14	-28.33	-26.20	-31.27	-22.02	-29.26	-31.14	-26.01	-28.31
StockNameL.Shuswap:Spawners	-0.57	-0.54	-0.51	-0.54	-0.56	-0.61	-0.52	-0.54	-0.49	-0.57
StockNameL.Stuart:Spawners	-1.20	-1.36	-1.38	-1.08	-1.28	-1.22	-1.30	-1.36	-1.34	-1.35
StockNameNadina:Spawners	-10.00	-13.02	-14.95	-13.94	-12.19	-11.76	-13.59	-13.02	-14.53	-10.67
StockNamePortage:Spawners	-99.35	-99.97	-96.11	-90.92	-101.93	-100.43	-97.79	-99.97	-93.30	-105.65
StockNameQuesnel:Spawners	-0.53	-0.61	-0.59	-0.49	-0.58	-0.56	-0.61	-0.61	-0.59	-0.58
StockNameRaft:Spawners	-26.08	-21.71	-23.93	-18.53	-18.72	-16.13	-22.58	-21.71	-24.36	-16.83
StockNameScotch:Spawners	-2.75	-5.22	-1.52	-0.36	-4.08	-5.15	-3.99	-5.22	-3.12	-0.54
StockNameSeymour:Spawners	-7.41	-8.81	-8.33	-7.47	-8.91	-9.22	-7.99	-8.81	-8.65	-7.85
StockNameStellako:Spawners	-4.08	-5.03	-5.33	-4.97	-4.90	-4.39	-5.15	-5.03	-5.17	-4.59
StockNameWeaver:Spawners	-4.14	-6.35	-5.72	-4.90	-7.05	-6.58	-7.45	-6.35	-5.45	-6.11
SUT_x26_FWMx_MGRS_DOM	0.23	NA	NA	NA	NA	NA	-0.06	NA	NA	NA
WND_x28_QCSx_MGRR_DOM	-0.15	NA	NA	-0.22	NA	NA	NA	NA	NA	-0.22
WQQ_x53_FWMx_SMLT_DOM	-0.12	NA	-0.03	NA	NA	NA	NA	NA	-0.03	NA
WQQ_x66_FWMx_MGRS_DOM	-0.01	NA	NA	NA	NA	NA	0.03	NA	0.06	NA
WTT_x82_FWMx_MGRS_DOM	0.002	NA	NA	NA	NA	NA	-0.03	NA	NA	NA
DIS_T05_SoGx_SMLT_DOM	NA	NA	5.6E-06	NA	NA	NA	NA	NA	5.1E-06	NA

Model: A4b
Brood years: 1969-2001

A second set of analyses were performed on a modified version of this model set, in which data on the abundance of pink salmon in the Northeast Pacific and from Russia were added. The analysis was extended to include pink salmon because: 1) the hypothesis that competition with odd-year pink salmon is a factor that has potentially contributing to the decline of Fraser River sockeye salmon productivity was included in the Expert Panel's Report to the Pacific Salmon Commission (Peterman et al., 2010), though not included among the Cohen commission Technical Reports; and 2) the data were made readily available to us from an early date. As identified in Appendix 4-3 Data preparation pink salmon are hypothesized to compete with sockeye during their forth year (i.e., second ocean year). For the purpose of this analysis they were lined up with life stage 4b, Return to the Fraser and included in Model 6. The results for this analysis were similar to the previous analysis with M10 achieving the lowest AICc, but now M4 (Inshore Migration) receives strong support as well.

Table A4.3-6. A4b candidate models ordered by AICc from best (lowest) to worst (biggest). M.ID=model identification, M.AIC=the estimated AIC for the model, num.obs=the total number of observations (i.e., complete rows in the data set), num.par=the total number of fixed effects + random effects, Correction= the difference between the AICc (corrected for small sample size compared to number of parameters) and the AIC, M.AICC= the AICc for the model, min.AICC = the smallest AICc observed within the model set, delta= the difference between the min.AICC and each M.AICC, and AICC_wts= the Akaike weight (i.e., support) for each model.

M.ID	M.AIC	num.obs	num.par	Correction	M.AICC	min.AICC	delta	AICC_wts
M10	1130.72	463	43	9.03	1139.75	1139.75	0	58.75
M4	1135.78	463	32	4.91	1140.69	1139.75	0.94	36.66
M6	1142.88	463	28	3.74	1146.62	1139.75	6.87	1.89
M1	1133.22	463	52	13.44	1146.66	1139.75	6.91	1.85
M5	1146.65	463	21	2.10	1148.75	1139.75	9.00	0.65
M8	1151.31	463	19	1.72	1153.02	1139.75	13.27	0.08
M2	1151.31	463	19	1.72	1153.02	1139.75	13.27	0.08
M7	1152.93	463	23	2.51	1155.44	1139.75	15.69	0.02
M3	1155.74	463	25	2.97	1158.71	1139.75	18.96	0.0045
M9	1156.46	463	26	3.22	1159.68	1139.75	19.93	0.0028

Table A4.3-7. Estimates for all fixed effects parameters included in each model, for model set A4b. Fixed effect parameters (i.e., covariates) are listed in the rows. The estimates for each model are provided in the columns. A value of 'NA' indicates that that particular model did not include the covariate in the corresponding row.

ModelSet_A4b_VarName	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
(Intercept)	-1.53	2.55	2.12	-9.77	1.04	2.01	4.63	2.55	2.06	-7.86
CBQ_107_NULL_SMLT_DOM	0.41	NA	-0.05	NA	NA	NA	NA	NA	-0.10	NA
CBQ_108_NULL_MGRR_DOM	-0.21	NA	NA	-0.06	NA	NA	NA	NA	NA	-0.06
CBQ_x91_NULL_MGRS_DOM	-0.34	NA	NA	NA	NA	NA	-0.27	NA	NA	NA
DIS_A67_SoGx_MGRR_DOM	1.6E-05	NA	NA	2.3E-06	NA	NA	NA	NA	NA	9.1E-06
DIS_T04_SoGx_SMLT_DOM	4.9E-07	NA	-8.5E-06	NA	NA	NA	NA	NA	-8.5E-06	NA
DIS_T05_SoGx_MGRR_DOM	6.1E-06	NA	NA	3.6E-06	NA	NA	NA	NA	NA	5.1E-06
DIS_x69_QCSx_MGRR_DOM	-0.005	NA	NA	1.8E-05	NA	NA	NA	NA	NA	-0.0026
DRG_x45_LFRx_SMLT_DOM	3.2E-08	NA	4.4E-08	NA	NA	NA	NA	NA	5.4E-08	NA
FPR_x87_NULL_MGRR_DOM	-6.0E-06	NA	NA	-2.3E-06	NA	NA	NA	NA	NA	-4.1E-06
NPI_x51_NPOx_GROW_DOM	-0.06	NA	NA	NA	-0.01	NA	NA	NA	NA	-0.06
PNE_x25_NULL_MGRR_DOM	5.6E-05	NA	NA	6.4E-05	NA	NA	NA	NA	NA	2.8E-05
PNE_x25_NULL_MGRS_DOM	-0.0002	NA	NA	NA	NA	-7.4E-05	NA	NA	NA	-4.2E-06
PNE_x39_NULL_MGRR_DOM	1.8E-05	NA	NA	1.2E-05	NA	NA	NA	NA	NA	-3.5E-05
PNE_x39_NULL_MGRS_DOM	4.1E-05	NA	NA	NA	NA	-9.1E-06	NA	NA	NA	6.0E-05
PNE_x61_NULL_MGRR_DOM	-1.0E-05	NA	NA	0.0001	NA	NA	NA	NA	NA	9.1E-06
PNE_x61_NULL_MGRS_DOM	2.4E-05	NA	NA	NA	NA	4.1E-05	NA	NA	NA	0.0001
PNK_x50_NPOx_MGRS_DOM	0.008	NA	NA	NA	NA	0.0007	NA	NA	NA	0.0023
PNK_x58_NPOx_MGRS_DOM	7.2E-05	NA	NA	NA	NA	-0.0009	NA	NA	NA	-0.0001
PRQ_110_NULL_GROW_DOM	-5.27	NA	NA	NA	0.73	NA	NA	NA	NA	-3.17
PRQ_110_NULL_MGRR_DOM	6.07	NA	NA	1.17	NA	NA	NA	NA	NA	3.66
PRQ_110_NULL_MGRS_DOM	0.74	NA	NA	NA	NA	0.30	NA	NA	NA	0.51
SPT_x82_FWRx_SMLT_DOM	0.04	NA	0.02	NA	NA	NA	NA	NA	0.02	NA
SSS_A48_QCSx_MGRR_DOM	-0.38	NA	NA	0.13	NA	NA	NA	NA	NA	-0.12
SSS_A48_SoGx_MGRR_DOM	0.46	NA	NA	0.07	NA	NA	NA	NA	NA	0.30
SSS_A59_QCSx_MGRS_DOM	-0.09	NA	NA	NA	NA	0.09	NA	NA	NA	0.08
SSS_A59_SoGx_MGRS_DOM	-0.13	NA	NA	NA	NA	-0.15	NA	NA	NA	-0.13
SST_A48_SoGx_MGRR_DOM	0.59	NA	NA	0.28	NA	NA	NA	NA	NA	0.52
SST_M09_SoGx_MGRS_DOM	-0.13	NA	NA	NA	NA	0.08	NA	NA	NA	-0.08
StockNameBirkenhead:Spawners	-8.33	-9.30	-9.02	-8.71	-9.24	-9.56	-9.25	-9.30	-8.88	-9.56

ModelSet_A4b_VarName	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
StockNameBowron:Spawners	-82.33	-98.08	-96.23	-104.29	-98.88	-93.14	-98.32	-98.08	-96.49	-101.91
StockNameChilko:Spawners	-1.91	-2.40	-2.33	-2.13	-2.32	-2.27	-2.45	-2.40	-2.30	-2.15
StockNameE.Stuart:Spawners	-1.80	-1.88	-1.98	-1.59	-1.78	-1.60	-1.85	-1.88	-1.88	-1.87
StockNameFennell:Spawners	-138.47	-159.24	-155.87	-154.13	-159.78	-149.25	-158.11	-159.24	-156.68	-152.96
StockNameGates:Spawners	-21.96	-31.14	-28.33	-26.20	-31.27	-22.28	-29.26	-31.14	-26.01	-26.03
StockNameL.Shuswap:Spawners	-0.58	-0.54	-0.51	-0.54	-0.56	-0.62	-0.52	-0.54	-0.49	-0.57
StockNameL.Stuart:Spawners	-1.14	-1.36	-1.38	-1.08	-1.28	-1.19	-1.30	-1.36	-1.34	-1.29
StockNameNadina:Spawners	-10.68	-13.02	-14.95	-13.94	-12.19	-11.55	-13.59	-13.02	-14.53	-9.81
StockNamePortage:Spawners	-93.86	-99.97	-96.11	-90.92	-101.93	-101.18	-97.79	-99.97	-93.30	-104.64
StockNameQuesnel:Spawners	-0.51	-0.61	-0.59	-0.49	-0.58	-0.56	-0.61	-0.61	-0.59	-0.59
StockNameRaft:Spawners	-25.00	-21.71	-23.93	-18.53	-18.72	-16.21	-22.58	-21.71	-24.36	-15.23
StockNameScotch:Spawners	-2.48	-5.22	-1.52	-0.36	-4.08	-4.65	-3.99	-5.22	-3.12	-1.11
StockNameSeymour:Spawners	-7.51	-8.81	-8.33	-7.47	-8.91	-9.17	-7.99	-8.81	-8.65	-7.74
StockNameStellako:Spawners	-4.15	-5.03	-5.33	-4.97	-4.90	-4.34	-5.15	-5.03	-5.17	-4.40
StockNameWeaver:Spawners	-4.23	-6.35	-5.72	-4.90	-7.05	-6.71	-7.45	-6.35	-5.45	-6.12
SUT_x26_FWMx_MGRS_DOM	0.18	NA	NA	NA	NA	NA	-0.06	NA	NA	NA
WND_x28_QCSx_MGRR_DOM	0.04	NA	NA	-0.22	NA	NA	NA	NA	NA	-0.17
WQQ_x53_FWMx_SMLT_DOM	-0.12	NA	-0.03	NA	NA	NA	NA	NA	-0.03	NA
WQQ_x66_FWMx_MGRS_DOM	-0.0086	NA	NA	NA	NA	NA	0.03	NA	0.06	NA
WTT_x82_FWMx_MGRS_DOM	-0.0012	NA	NA	NA	NA	NA	-0.03	NA	NA	NA
DIS_T05_SoGx_SMLT_DOM	NA	NA	5.6E-06	NA	NA	NA	NA	NA	5.1E-06	NA

A4.3.3 Analyses by stressor category

Model Set: B4c
Brood years: 1969-2001

A second model set was developed using the same data set as in the previous section (i.e. all available data across all projects and life stages for brood years 1969-2001). Within this model set, multiple models were tested, each of which contained all the available variables associated with a particular broad stressor category, as represented by the Cohen Commission Technical Reports: contaminants, freshwater habitat factors, marine conditions, predators, climate change, and habitat conditions in the lower Fraser River and the Strait of Georgia. An additional global model with all available variables for this timeframe was also tested. These models were then evaluated using the same dataset to determine which models have the greatest amount of support.

The goal of this approach was to evaluate the relative importance of different categories of stressors in explaining variability in productivity. However, several categories of stressor (i.e., Cohen Commission projects) have limited or no data available over this time period and even where data are available it may not adequately represent the category of stressor as a whole. For example, "climate change" is only represented by a single variable – delayed effect of lower Fraser River water temperature for returning adults – which does not fully capture the potential impacts of climate change on sockeye salmon over their entire life. A second example is the impact of pathogens and disease, which are simply not represented at all within any of these models because of the lack of data. Therefore it is not possible to make any conclusions, even weak ones, about the relative importance of pathogens and disease compared to other projects. Table A4.3-8 describes the eight different models in this model set, Table A4.3-9 shows the relative fit of each model, and Table A4.3-10 provides the estimates for each parameter and model.

Table A4.3-8. Model descriptions for model set B4c (comparison among stressor categories for brood years 1969-2001).

Model Name	Model description (i.e., stressor categories included)	Number of stressors	Total number of parameters
M1	Global model: contains all available data from all stressor categories	31	50
M2	Contaminants	2	21
M3	Freshwater	2	21
M4	Marine conditions	5	24
M5	Predator/Alternate prey	13	32
M6	Climate change	1	20
M7	Habitat conditions in Lower Fraser and Georgia Strait	8	27

M8	No stressor variables added.	0	19

The results show that the global model (M1) had the greatest level of support. Like in the previous analysis, the fact that this model has the lowest AICc even with 18 more parameters than the next model indicates that the variables associated with only a single stressor category are not sufficient to explain the pattern in productivity. When comparing the relative performance of models representing individual projects the predators/alternate prey model (M5) has the greatest level of support followed closely by the lower Fraser/Strait of Georgia project (M7). It is important to remember that the predator/alternate prey model reflects two possible mechanisms for impacting Fraser sockeye: direct predation as well as alternate prey availability. It may be more sensible to test these separately in the future.

Table A4.3-9. B4c candidate models ordered by AICc from best (lowest) to worst (biggest). M.ID=model identification, M.AIC=the estimated AIC for the model, num.obs=the total number of observations (i.e., complete rows in the data set), num.par=the total number of fixed effects + random effects, Correction= the difference between the AICc (corrected for small sample size compared to number of parameters) and the AIC, M.AICC= the AICc for the model, min.AICC = the smallest AICc observed within the model set, delta= the difference between the min.AICC and each M.AICC, and AICC_wts= the Akaike weight (i.e., support) for each model.

M.ID	M.AIC	num.obs	num.par	Correction	M.AICC	min.AICC	delta	AICC_wts
M1	1131.35	463	50	12.38	1143.73	1143.73	0	82.16
M5	1142.77	463	32	4.91	1147.68	1143.73	3.95	11.38
M7	1146.23	463	27	3.48	1149.70	1143.73	5.97	4.15
M8	1151.31	463	19	1.72	1153.02	1143.73	9.29	0.79
M6	1151.37	463	20	1.90	1153.27	1143.73	9.54	0.70
M4	1151.12	463	24	2.74	1153.86	1143.73	10.13	0.52
M2	1154.06	463	21	2.10	1156.15	1143.73	12.42	0.16
M3	1154.22	463	21	2.10	1156.32	1143.73	12.59	0.15

Table A4.3-10. Estimates for all fixed effects parameters included in each model, for model set B4c. Fixed effect parameters (i.e., covariates) are listed in the rows. The estimates for each model are provided in the columns. A value of 'NA' indicates that that particular model did not include the covariate in the corresponding row.

ModelSet_B4c_VarName	M1	M2	M3	M4	M5	M6	M7	M8
(Intercept)	47.74	2.48	3.68	1.09	2.39	3.19	8.07	2.55
CBQ_107_NULL_SMLT_DOM	0.19	NA	NA	NA	0.20	NA	NA	NA
CBQ_108_NULL_MGRR_DOM	0.86	NA	NA	NA	0.04	NA	NA	NA
CBQ_x91_NULL_MGRS_DOM	-0.46	NA	NA	NA	-0.17	NA	NA	NA
DIS_A67_SoGx_MGRR_DOM	-1.5E-06	NA	NA	NA	NA	NA	4.2E-07	NA
DIS_T04_SoGx_SMLT_DOM	1.4E-06	NA	NA	NA	NA	NA	-2.4E-06	NA
DIS_T05_SoGx_MGRR_DOM	-2.1E-06	NA	NA	NA	NA	NA	1.9E-06	NA
DIS_x69_QCSx_MGRR_DOM	0.0012	NA	NA	0.0016	NA	NA	NA	NA
DRG_x45_LFRx_SMLT_DOM	-1.4E-07	NA	NA	NA	NA	NA	4.5E-08	NA
FPR_x87_NULL_MGRR_DOM	-8.9E-06	NA	NA	NA	-1.7E-06	NA	NA	NA
NPI_x51_NPOx_GROW_DOM	-0.07	NA	NA	-0.01	NA	NA	NA	NA
PNE_x25_NULL_MGRR_DOM	-0.0006	NA	NA	NA	0.0002	NA	NA	NA
PNE_x25_NULL_MGRS_DOM	0.0016	NA	NA	NA	-0.0001	NA	NA	NA
PNE_x39_NULL_MGRR_DOM	-0.0003	NA	NA	NA	-2.7E-05	NA	NA	NA
PNE_x39_NULL_MGRS_DOM	0.0004	NA	NA	NA	3.9E-05	NA	NA	NA
PNE_x61_NULL_MGRR_DOM	-0.0006	NA	NA	NA	-4.9E-05	NA	NA	NA
PNE_x61_NULL_MGRS_DOM	0.0004	NA	NA	NA	8.0E-05	NA	NA	NA
PRQ_110_NULL_GROW_DOM	-7.36	NA	NA	NA	-1.49	NA	NA	NA
PRQ_110_NULL_MGRR_DOM	3.61	NA	NA	NA	1.79	NA	NA	NA
PRQ_110_NULL_MGRS_DOM	-0.56	NA	NA	NA	0.10	NA	NA	NA
SPT_x82_FWRx_SMLT_DOM	0.04	NA	0.0099	NA	NA	NA	NA	NA
SSS_A48_QCSx_MGRR_DOM	-0.89	NA	NA	0.03	NA	NA	NA	NA
SSS_A48_SoGx_MGRR_DOM	0.23	NA	NA	NA	NA	NA	0.02	NA
SSS_A59_QCSx_MGRS_DOM	-0.97	NA	NA	-0.01	NA	NA	NA	NA
SSS_A59_SoGx_MGRS_DOM	0.30	NA	NA	NA	NA	NA	-0.16	NA
SST_A48_SoGx_MGRR_DOM	0.37	NA	NA	NA	NA	NA	-0.23	NA
SST_M09_SoGx_MGRS_DOM	0.09	NA	NA	NA	NA	NA	0.06	NA

ModelSet_B4c_VarName	M1	M2	M3	M4	M5	M6	M7	M8
StockNameBirkenhead:Spawners	-8.63	-9.21	-9.18	-9.22	-8.91	-9.60	-9.65	-9.30
StockNameBowron:Spawners	-83.92	-98.51	-99.81	-95.23	-96.07	-95.73	-94.29	-98.08
StockNameChilko:Spawners	-1.91	-2.39	-2.44	-2.30	-2.18	-2.43	-2.34	-2.40
StockNameE.Stuart:Spawners	-1.79	-1.86	-1.91	-1.93	-1.75	-2.02	-1.89	-1.88
StockNameFennell:Spawners	-142.96	-157.00	-158.56	-152.27	-152.56	-158.78	-151.79	-159.24
StockNameGates:Spawners	-26.47	-29.74	-29.66	-28.39	-25.64	-30.37	-25.41	-31.14
StockNameL.Shuswap:Spawners	-0.57	-0.53	-0.50	-0.55	-0.53	-0.60	-0.59	-0.54
StockNameL.Stuart:Spawners	-1.20	-1.33	-1.41	-1.40	-1.13	-1.36	-1.37	-1.36
StockNameNadina:Spawners	-10.00	-12.61	-13.81	-13.51	-12.46	-12.98	-13.17	-13.02
StockNamePortage:Spawners	-99.35	-96.63	-98.81	-98.15	-90.88	-105.14	-101.96	-99.97
StockNameQuesnel:Spawners	-0.53	-0.60	-0.63	-0.62	-0.50	-0.61	-0.59	-0.61
StockNameRaft:Spawners	-26.08	-22.01	-20.64	-21.92	-17.67	-22.24	-18.43	-21.71
StockNameScotch:Spawners	-2.75	-6.53	-3.58	-3.90	-0.06	-4.68	-4.43	-5.22
StockNameSeymour:Spawners	-7.41	-8.73	-8.30	-8.07	-7.73	-8.73	-9.13	-8.81
StockNameStellako:Spawners	-4.08	-4.88	-5.33	-4.76	-4.57	-5.00	-4.56	-5.03
StockNameWeaver:Spawners	-4.14	-5.94	-6.56	-5.71	-5.99	-8.23	-6.41	-6.35
SUT_x26_FWMx_MGRS_DOM	0.23	NA	-0.07	NA	NA	NA	NA	NA
WND_x28_QCSx_MGRR_DOM	-0.15	NA	NA	-0.19	NA	NA	NA	NA
WQQ_x53_FWMx_SMLT_DOM	-0.12	-0.03	NA	NA	NA	NA	NA	NA
WQQ_x66_FWMx_MGRS_DOM	-0.0111	0.05	NA	NA	NA	NA	NA	NA
WTT_x82_FWMx_MGRS_DOM	0.0019	NA	NA	NA	NA	-0.04	NA	NA

Model: B4b
Brood years: 1969-2001

We repeated the comparison by stressor category with abundance of pinks included as an additional stressor. The same stressor category models were tested with the addition of pink salmon as its own stressor category model. The results from this set of analyses show that the pink salmon model (M8) and the global model (M1) appear as the strongest two models. They have similar AICc's (ΔAICc of 2.8) and because they are substantially different models (21 versus 52 parameters), the interpretation is that they provide legitimately competing models to explain the patterns observed in Fraser River sockeye salmon. The predators/alternate prey model (M5) also receives some support while the lower Fraser /Strait of Georgia stressors (M7) rank forth. The fact that the pink salmon model does well is in some ways not surprising: there is a scientifically supported hypothesis, with good data for the attribute that the hypothesis relates to, and the connection is specific to a life-history stage, whereas many of the project groupings do not have the most appropriate data. Given the discussion above about whether or not particular data are representative of the factors of interest, and the idea that it may be more justified to organize data around life-history stages with biologically based boundaries rather than projects with sometimes arbitrary boundaries, it makes sense that the pink salmon model would do well compared to other project-based models where those considerations are not as clearly met.

Overall, we do not believe that organizing the data by project is as useful of an approach as is organizing the data by life-history stage. The boundaries are arbitrary and many of the categories are lacking in data. In this model set, none of the models had definitively higher support than the global model which included all available variables. By contrast, when the exact same data were organized by life-history stage, several of the models achieved a higher level of support than the global model.

Table A4.3-11. B4b candidate models ordered by AICc from best (lowest) to worst (biggest). M.ID=model identification, M.AIC=the estimated AIC for the model, num.obs=the total number of observations (i.e., complete rows in the data set), num.par=the total number of fixed effects + random effects, Correction= the difference between the AICc (corrected for small sample size compared to number of parameters) and the AIC, M.AICC= the AICc for the model, min.AICC = the smallest AICc observed within the model set, delta= the difference between the min.AICC and each M.AICC, and AICC_wts= the Akaike weight (i.e., support) for each model.

M.ID	M.AIC	num.obs	num.par	Correction	M.AICC	min.AICC	delta	AICC_wts
M8	1141.75	463	21	2.10	1143.84	1143.84	0	68.30
M1	1133.22	463	52	13.44	1146.66	1143.84	2.82	16.68
M5	1142.77	463	32	4.91	1147.68	1143.84	3.84	10.02
M7	1146.23	463	27	3.48	1149.70	1143.84	5.86	3.65
M6	1151.37	463	20	1.90	1153.27	1143.84	9.43	0.61
M4	1151.12	463	24	2.74	1153.86	1143.84	10.02	0.46
M2	1154.06	463	21	2.10	1156.15	1143.84	12.31	0.15
M3	1154.22	463	21	2.10	1156.32	1143.84	12.47	0.13

Table A4.3-12. Estimates for all fixed effects parameters included in each model, for model set B4b. Fixed effect parameters (i.e., covariates) are listed in the rows. The estimates for each model are provided in the columns. A value of 'NA' indicates that that particular model did not include the covariate in the corresponding row.

ModelSet_B4b_VarName	M1	M2	M3	M4	M5	M6	M7	M8
(Intercept)	-1.53	2.48	3.68	1.09	2.39	3.19	8.07	3.31
CBQ_107_NULL_SMLT_DOM	0.41	NA	NA	NA	0.20	NA	NA	NA
CBQ_108_NULL_MGRR_DOM	-0.21	NA	NA	NA	0.04	NA	NA	NA
CBQ_x91_NULL_MGRS_DOM	-0.34	NA	NA	NA	-0.17	NA	NA	NA
DIS_A67_SoGx_MGRR_DOM	1.6E-05	NA	NA	NA	NA	NA	4.2E-07	NA
DIS_T04_SoGx_SMLT_DOM	4.9E-07	NA	NA	NA	NA	NA	-2.4E-06	NA
DIS_T05_SoGx_MGRR_DOM	6.1E-06	NA	NA	NA	NA	NA	1.9E-06	NA
DIS_x69_QCSx_MGRR_DOM	-0.005	NA	NA	0.0016	NA	NA	NA	NA
DRG_x45_LFRx_SMLT_DOM	3.2E-08	NA	NA	NA	NA	NA	4.5E-08	NA
FPR_x87_NULL_MGRR_DOM	-6.0E-06	NA	NA	NA	-1.7E-06	NA	NA	NA
NPI_x51_NPOx_GROW_DOM	-0.06	NA	NA	-0.01	NA	NA	NA	NA
PNE_x25_NULL_MGRR_DOM	5.6E-05	NA	NA	NA	0.0002	NA	NA	NA
PNE_x25_NULL_MGRS_DOM	-0.0002	NA	NA	NA	-0.0001	NA	NA	NA
PNE_x39_NULL_MGRR_DOM	1.8E-05	NA	NA	NA	-2.7E-05	NA	NA	NA
PNE_x39_NULL_MGRS_DOM	4.1E-05	NA	NA	NA	3.9E-05	NA	NA	NA
PNE_x61_NULL_MGRR_DOM	-1.0E-05	NA	NA	NA	-4.9E-05	NA	NA	NA
PNE_x61_NULL_MGRS_DOM	2.4E-05	NA	NA	NA	8.0E-05	NA	NA	NA
PNK_x50_NPOx_MGRS_DOM	0.0080	NA	NA	NA	NA	NA	NA	-0.0043
PNK_x58_NPOx_MGRS_DOM	7.2E-05	NA	NA	NA	NA	NA	NA	-0.0015
PRQ_110_NULL_GROW_DOM	-5.27	NA	NA	NA	-1.49	NA	NA	NA
PRQ_110_NULL_MGRR_DOM	6.07	NA	NA	NA	1.79	NA	NA	NA
PRQ_110_NULL_MGRS_DOM	0.74	NA	NA	NA	0.10	NA	NA	NA
SPT_x82_FWRx_SMLT_DOM	0.04	NA	0.01	NA	NA	NA	NA	NA
SSS_A48_QCSx_MGRR_DOM	-0.38	NA	NA	0.03	NA	NA	NA	NA
SSS_A48_SoGx_MGRR_DOM	0.46	NA	NA	NA	NA	NA	0.02	NA
SSS_A59_QCSx_MGRS_DOM	-0.09	NA	NA	-0.01	NA	NA	NA	NA
SSS_A59_SoGx_MGRS_DOM	-0.13	NA	NA	NA	NA	NA	-0.16	NA
SST_A48_SoGx_MGRR_DOM	0.59	NA	NA	NA	NA	NA	-0.23	NA
SST_M09_SoGx_MGRS_DOM	-0.13	NA	NA	NA	NA	NA	0.06	NA
StockNameBirkenhead:Spawners	-8.33	-9.21	-9.18	-9.22	-8.91	-9.60	-9.65	-9.30

ModelSet_B4b_VarName	M1	M2	M3	M4	M5	M6	M7	M8
StockNameBowron:Spawners	-82.33	-98.51	-99.81	-95.23	-96.07	-95.73	-94.29	-97.60
StockNameChilko:Spawners	-1.91	-2.39	-2.44	-2.30	-2.18	-2.43	-2.34	-2.39
StockNameE.Stuart:Spawners	-1.80	-1.86	-1.91	-1.93	-1.75	-2.02	-1.89	-1.70
StockNameFennell:Spawners	-138.47	-157.00	-158.56	-152.27	-152.56	-158.78	-151.79	-158.17
StockNameGates:Spawners	-21.96	-29.74	-29.66	-28.39	-25.64	-30.37	-25.41	-32.18
StockNameL.Shuswap:Spawners	-0.58	-0.53	-0.50	-0.55	-0.53	-0.60	-0.59	-0.57
StockNameL.Stuart:Spawners	-1.14	-1.33	-1.41	-1.40	-1.13	-1.36	-1.37	-1.25
StockNameNadina:Spawners	-10.68	-12.61	-13.81	-13.51	-12.46	-12.98	-13.17	-13.12
StockNamePortage:Spawners	-93.86	-96.63	-98.81	-98.15	-90.88	-105.14	-101.96	-99.35
StockNameQuesnel:Spawners	-0.51	-0.60	-0.63	-0.62	-0.50	-0.61	-0.59	-0.55
StockNameRaft:Spawners	-25.00	-22.01	-20.64	-21.92	-17.67	-22.24	-18.43	-22.03
StockNameScotch:Spawners	-2.48	-6.53	-3.58	-3.90	-0.06	-4.68	-4.43	-3.27
StockNameSeymour:Spawners	-7.51	-8.73	-8.30	-8.07	-7.73	-8.73	-9.13	-8.40
StockNameStellako:Spawners	-4.15	-4.88	-5.33	-4.76	-4.57	-5.00	-4.56	-5.07
StockNameWeaver:Spawners	-4.23	-5.94	-6.56	-5.71	-5.99	-8.23	-6.41	-6.30
SUT_x26_FWMx_MGRS_DOM	0.18	NA	-0.07	NA	NA	NA	NA	NA
WND_x28_QCSx_MGRR_DOM	0.04	NA	NA	-0.19	NA	NA	NA	NA
WQQ_x53_FWMx_SMLT_DOM	-0.12	-0.03	NA	NA	NA	NA	NA	NA
WQQ_x66_FWMx_MGRS_DOM	-0.0086	0.05	NA	NA	NA	NA	NA	NA
WTT_x82_FWMx_MGRS_DOM	-0.0012	NA	NA	NA	NA	-0.04	NA	NA

A4.3.4 Analysis by region

Model: C4a
1969-2004

A model set was tested with the available data for brood years 1969-2004, which included variables for sea surface salinity (SSS), discharge and wind for QCS, and sea surface temperature (SST), SSS and discharge for SoG. While temperature is known to be important (e.g. Hinch and artins, 2011; McKinnell et al., 2011), however, this model set was performed despite not having SST for QCS because it represents the longest time period available with a selection of variables for both regions. The individual models run within the model set are specified in Table A4.3-13.

Table A4.3-13. Model specifications for the 1969-2004 (brood years) model set. This table shows the variables included in each of the 8 models tested (i.e., M1 to M8) within this model set. Table 4.4-1 explains which specific data sets were used for each of these variables. “Rank of model” reflects the AIC_c score showing level of support (#1 ranked model had the highest level of support and lowest AIC_c score).

Region	Variable	M1	M2	M3	M4	M5	M6	M7	M8
QCS	Salinity	X	X		X		X		
QCS	Discharge	X	X		X				
QCS	Wind	X	X						
SoG	Temperature	X		X					X
SoG	Salinity	X		X		X		X	
SoG	Discharge	X		X		X			
Rank of model		**3**	**4**	**5**	**2**	**7**	**8**	**6**	**1**

The results show that the models with the most support are M8, M4, M1, then M2, with strong support for models M8 (SoG SST) and M4 (QCS SSS and discharge) in particular (Table A4.3-14 and Table A4.3-15). However, the AICc scores indicate that there is little difference in degree of support among these four models (ΔAICc = 2.28). For SoG during this period, temperature (M8) is more valuable for explaining the observed variability in Fraser River sockeye salmon productivity than salinity (M7). Overall, the analysis of this time period shows that there is support for both QCS and SoG models – the top ranked model was for SoG, the second for QCS, and the third was the global model, including both regions. These results show that for these particular variables, over this particular time period, there is no clear evidence of any difference between the explanatory value of the two regions; however, the absence of temperature data for QCS is a substantial shortcoming of this model set, and chlorophyll is not included in any model.

Table A4.3-14. C4a candidate models ordered by AICc from best (lowest) to worst (biggest). M.ID=model identification, M.AIC=the estimated AIC for the model, num.obs=the total number of observations (i.e., complete rows in the data set), num.par=the total number of fixed effects + random effects, Correction= the difference between the AICc (corrected for small sample size compared to number of parameters) and the AIC, M.AICC= the AICc for the model, min.AICC = the smallest AICc observed within the model set, delta= the difference between the min.AICC and each M.AICC, and AICC_wts= the Akaike weight (i.e., support) for each model.

M.ID	M.AIC	num.obs	num.par	Correction	M.AICC	min.AICC	delta	AICC_wts
M8	1613.65	614	22	1.71	1615.36	1615.36	0	40.18
M4	1614.87	614	23	1.87	1616.74	1615.36	1.38	20.15
M1	1614.25	614	28	2.78	1617.02	1615.36	1.66	17.51
M2	1615.61	614	24	2.04	1617.64	1615.36	2.28	12.82
M3	1616.73	614	25	2.21	1618.95	1615.36	3.59	6.69
M7	1619.46	614	22	1.71	1621.17	1615.36	5.81	2.20
M5	1622.68	614	24	2.04	1624.72	1615.36	9.36	0.37
M6	1626.11	614	22	1.71	1627.82	1615.36	12.46	0.08

Table A4.3-15. Estimates for all fixed effects parameters included in each model, for model set C4a. Fixed effect parameters (i.e., covariates) are listed in the rows. The estimates for each model are provided in the columns. A value of 'NA' indicates that that particular model did not include the covariate in the corresponding row.

ModelSet_C4a_VarName	M1	M2	M3	M4	M5	M6	M7	M8
(Intercept)	0.98	-6.78	6.66	-5.41	4.76	-1.15	7.48	7.31
DIS_A67_SoGx_MGRR_DOM	-1.5E-06	NA	1.2E-06	NA	2.2E-06	NA	NA	NA
DIS_T05_SoGx_MGRR_DOM	5.7E-08	NA	2.1E-06	NA	1.1E-06	NA	NA	NA
DIS_x69_QCSx_MGRR_DOM	0.0017	0.0030	NA	0.0029	NA	NA	NA	NA
SSS_A48_QCSx_MGRR_DOM	0.26	0.25	NA	0.21	NA	0.12	NA	NA
SSS_A48_SoGx_MGRR_DOM	-0.15	NA	-0.02	NA	-0.11	NA	-0.19	NA
SST_A48_SoGx_MGRR_DOM	-0.23	NA	-0.29	NA	NA	NA	NA	-0.34
StockNameBirkenhead:Spawners	-9.83	-9.92	-9.84	-9.90	-9.96	-10.10	-10.00	-9.89
StockNameBowron:Spawners	-103.73	-103.22	-104.61	-102.60	-105.33	-106.07	-105.18	-104.21
StockNameChilko:Spawners	-2.24	-2.28	-2.20	-2.30	-2.27	-2.34	-2.27	-2.21
StockNameCultus:Spawners	-51.24	-49.82	-53.54	-49.69	-51.90	-51.82	-51.76	-53.74
StockNameE.Stuart:Spawners	-2.01	-2.21	-1.83	-2.19	-1.86	-2.10	-1.83	-1.87
StockNameFennell:Spawners	-145.83	-147.64	-142.98	-148.57	-147.91	-151.17	-147.89	-142.38
StockNameGates:Spawners	-33.61	-35.98	-30.70	-36.81	-34.82	-35.47	-34.14	-29.31
StockNameHarrison:Spawners	-65.85	-71.29	-63.09	-69.79	-60.98	-68.46	-58.75	-66.28
StockNameL.Shuswap:Spawners	-0.32	-0.33	-0.34	-0.33	-0.36	-0.36	-0.36	-0.34
StockNameL.Stuart:Spawners	-1.38	-1.51	-1.29	-1.51	-1.33	-1.44	-1.30	-1.31
StockNameNadina:Spawners	-10.55	-11.37	-10.71	-11.31	-10.96	-11.34	-10.60	-10.49
StockNamePortage:Spawners	-95.71	-98.07	-95.69	-98.20	-98.19	-100.73	-98.46	-96.69
StockNameQuesnel:Spawners	-0.86	-0.92	-0.86	-0.92	-0.89	-0.93	-0.89	-0.87
StockNameRaft:Spawners	-21.24	-24.46	-20.73	-25.23	-23.43	-24.31	-22.89	-20.30
StockNameScotch:Spawners	5.81	4.57	5.00	4.29	3.44	2.86	3.20	4.76
StockNameSeymour:Spawners	-6.86	-7.01	-7.24	-7.10	-7.68	-8.04	-7.81	-7.32
StockNameStellako:Spawners	-5.25	-5.50	-5.20	-5.59	-5.54	-5.70	-5.51	-5.17
StockNameWeaver:Spawners	-10.54	-10.24	-10.47	-10.36	-10.62	-10.59	-10.76	-10.68
WND_x28_QCSx_MGRR_DOM	-0.0089	-0.09	NA	NA	NA	NA	NA	NA

Model: C3a
1980-2004

A model set was tested with the available data for brood years 1980-2004, which included the same variables as described above, albeit for a shorter time period, but with the addition of SST for QCS. The individual models run within the model set are specified in Table A4.3-16.

Table A4.3-16. Model specifications for the 1980-2004 (brood years) model set. This table shows the variables included in each of the 10 models tested (i.e. M1 to M10) within this model set. Table 4.4-1 explains which specific data sets were used for each of these variables. "Rank of model" reflects the AIC_c score showing level of support (#1 ranked model had the highest level of support and lowest AIC_c score).

Region	**Variable**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**
QCS	Temperature	X	X		X	X				X	
QCS	Salinity	X	X		X	X		X			
QCS	Discharge	X	X		X						
QCS	Wind	X	X								
SoG	Temperature	X		X			X				X
SoG	Salinity	X		X			X		X		
SoG	Discharge	X		X							
Rank of model		**6**	**3**	**10**	**1**	**2**	**8**	**4**	**9**	**5**	**7**

The three models with the lowest AICc scores were M4 (QCS SST, SSS and discharge), M5 (QCS SST and SSS), and M2 (QCS SST, SSS, discharge, and wind) (Table A4.3-17). Together they indicate that the QCS models have greater explanatory value than SoG models for Fraser River sockeye salmon productivity during 1980-2004. This conclusion is supported further by the fact that the models with the next two lowest AICc scores are M7 (QCS SSS) and M9 (QCS SST). This finding is an important new result because it is alters the conclusion of Peterman et al. (2010) based on new data and analyses that were not available at the PSC workshop.

The results also highlight the importance of not being able to include for QCS SST in the previous model set, because within this model set all of the models that include QCS SST have a much higher level of support than any of the models that include SoG SST.

Within both of the model sets discussed above (i.e. 1969-2004 and 1980-2004), and across all models for both QCS and SoG, SST demonstrated an negative or inverse relationship with the productivity of Fraser River sockeye salmon (Table A4.3-18). This is an unsurprising result in that it simply agrees with a well-established literature on the subject. SSS also had a consistent relationship across all models within both of the model sets discussed above; however, the direction of the relationship is in the opposite direction for the two regions, positive for QCS, and negative for SoG. We cannot offer a definitive explanation for why this might be the case or suggest any underlying mechanism, but it does provide an excellent opportunity to emphasize some of the potential limitations of this analysis and considerations that need to be kept in mind. First, it is possible due to strong regional differences, that the mechanisms that might connect SSS with sockeye salmon productivity are in fact different in the two regions. An exploration of some of the oceanographic and climatic variables over time shows that there are many ways in which the two regions appear quite distinct from each other. Second, correlational analyses find relationships among data, but correlation does not imply causation – just because there is a negative correlation over time between SSS in SoG and productivity of sockeye salmon does not mean that there is a direct mechanism relating the two. The fact that the direction of the relationship with SSS is opposite as for QCS could imply that there is another factor that is unique to SoG, for which we do not have data in the model, that confounds the expected relationship between SSS and sockeye productivity. Third, it is important to consider the scale of the underlying measurements. In this case, the SSS data come from point measurements at two particular lighthouses. These data sources were chosen by Cohen Commission contractors as being the most representative of the two regions but it is possible that there is fine scale variation that is lost when using a point measure as a regional index. For example, SSS measured at one lighthouse in SoG may not always reflect conditions experienced along the migration paths of sockeye salmon or the depth at which they travel.

Table A4.3-17. C3a candidate models ordered by AICc from best (lowest) to worst (biggest). M.ID=model identification, M.AIC=the estimated AIC for the model, num.obs=the total number of observations (i.e., complete rows in the data set), num.par=the total number of fixed effects + random effects, Correction= the difference between the AICc (corrected for small sample size compared to number of parameters) and the AIC, M.AICC= the AICc for the model, min.AICC = the smallest AICc observed within the model set, delta= the difference between the min.AICC and each M.AICC, and AICC_wts= the Akaike weight (i.e., support) for each model.

M.ID	M.AIC	num.obs	num.par	Correction	M.AICC	min.AICC	delta	AICC_wts
M4	1136.05	423	24	3.02	1139.06	1139.06	0	45.62
M5	1136.89	423	23	2.77	1139.66	1139.06	0.60	33.87
M2	1137.88	423	25	3.27	1141.15	1139.06	2.09	16.04
M7	1142.86	423	22	2.53	1145.39	1139.06	6.33	1.93
M9	1143.81	423	22	2.53	1146.34	1139.06	7.28	1.20
M1	1142.84	423	29	4.43	1147.27	1139.06	8.21	0.75
M10	1146.07	423	22	2.53	1148.60	1139.06	9.54	0.39
M6	1148.06	423	23	2.77	1150.83	1139.06	11.77	0.13
M8	1149.92	423	22	2.53	1152.45	1139.06	13.39	0.056
M3	1151.84	423	25	3.27	1155.11	1139.06	16.05	0.015

Table A4.3-18. Estimates for all fixed effects parameters included in each model, for model set C3a. Fixed effect parameters (i.e., covariates) are listed in the rows. The estimates for each model are provided in the columns. A value of 'NA' indicates that that particular model did not include the covariate in the corresponding row.

ModelSet_C3a_VarName	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
(Intercept)	-3.47	-4.50	7.65	-4.89	-3.34	6.81	-7.26	3.41	5.76	6.63
DIS_A67_SoGx_MGRR_DOM	-1.4E-06	NA	-1.1E-06	NA	NA	NA	NA	NA	NA	NA
DIS_T05_SoGx_MGRR_DOM	-4.0E-06	NA	1.0E-06	NA	NA	NA	NA	NA	NA	NA
DIS_x69_QCSx_MGRR_DOM	0.0026	0.0021	NA	0.0022	NA	NA	NA	NA	NA	NA
SSS_A48_QCSx_MGRR_DOM	0.37	0.29	NA	0.30	0.31	NA	0.32	NA	NA	NA
SSS_A48_SoGx_MGRR_DOM	-0.19	NA	-0.02	NA	NA	-0.01	NA	-0.04	NA	NA
SST_A48_SoGx_MGRR_DOM	0.25	NA	-0.32	NA	NA	-0.29	NA	NA	NA	-0.29
SST_A78_QCSx_MGRR_DOM	-0.34	-0.22	NA	-0.22	-0.26	NA	NA	NA	-0.25	NA
StockNameBirkenhead:Spawners	-8.84	-8.78	-8.71	-8.78	-8.89	-8.71	-8.90	-8.71	-8.67	-8.71
StockNameBowron:Spawners	-144.67	-144.51	-141.58	-144.73	-142.39	-142.17	-148.01	-145.06	-139.23	-141.98
StockNameChilko:Spawners	-2.32	-2.29	-2.15	-2.29	-2.28	-2.16	-2.29	-2.17	-2.14	-2.16
StockNameCultus:Spawners	-87.72	-91.09	-96.10	-91.17	-94.71	-95.77	-95.40	-95.50	-95.17	-95.84
StockNameE.Stuart:Spawners	-2.98	-3.08	-3.06	-3.08	-3.05	-3.04	-3.26	-3.16	-3.00	-3.05
StockNameFennell:Spawners	-103.02	-101.63	-97.20	-101.10	-101.65	-97.28	-104.85	-99.52	-95.83	-97.21
StockNameGates:Spawners	-15.72	-14.71	-9.79	-14.38	-12.37	-10.10	-14.32	-11.78	-9.54	-10.03
StockNameHarrison:Spawners	-10.01	-8.55	6.80	-9.27	-5.98	3.90	-5.16	5.50	2.71	3.77
StockNameL.Shuswap:Spawners	-0.31	-0.30	-0.33	-0.29	-0.31	-0.34	-0.32	-0.35	-0.35	-0.34
StockNameL.Stuart:Spawners	-1.70	-1.71	-1.54	-1.71	-1.64	-1.55	-1.69	-1.58	-1.53	-1.55
StockNameNadina:Spawners	-11.32	-11.81	-10.74	-11.78	-11.67	-10.78	-11.65	-11.19	-11.14	-10.79
StockNamePortage:Spawners	-42.25	-40.91	-38.14	-40.88	-40.83	-38.58	-41.67	-37.88	-36.86	-38.58
StockNameQuesnel:Spawners	-0.74	-0.74	-0.74	-0.74	-0.73	-0.74	-0.77	-0.77	-0.75	-0.74
StockNameRaft:Spawners	-27.64	-26.85	-23.10	-26.47	-24.94	-23.52	-26.05	-25.49	-24.67	-23.53
StockNameScotch:Spawners	7.97	8.71	7.56	8.87	8.40	7.48	7.29	6.32	6.98	7.48
StockNameSeymour:Spawners	-6.37	-6.32	-6.94	-6.27	-6.89	-6.87	-7.07	-7.27	-7.15	-6.88
StockNameStellako:Spawners	-5.28	-5.18	-4.88	-5.14	-5.08	-4.93	-5.33	-5.15	-4.93	-4.93
StockNameWeaver:Spawners	-5.35	-4.65	-4.14	-4.65	-4.52	-4.27	-4.26	-3.96	-4.11	-4.25
WND_x28_QCSx_MGRR_DOM	0.02	0.04	NA	NA	NA	NA	NA	NA	NA	NA

Model: C1a
1996-2004

For 1996-2004, it was not possible to test a model set with both QCS and SoG because the time period was too short for the number of variables to be included for the two regions. The alternative approach was to develop two model sets, one for each region, to test the importance of chlorophyll against the other variables independently within each region (Tables A4.3-19 and A4.3-22). Even though this is an extremely short time period, it reflects the earliest data available for chlorophyll, which is known to be an important factor (McKinnell et al., 2011)and thus it seemed important to test this model set.

Table A4.3-19. Model specifications for the 1996-2004 (brood years) model set for Queen Charolotte Sound. This table shows the variables included in each of the 9 models tested (i.e. M1 to M9) within this model set. Table 4.4-1 explains which specific data sets were used for each of these variables. "Rank of model" reflects the AIC_c score showing level of support (#1 ranked model had the highest level of support and lowest AIC_c score).

Region	**Variable**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
QCS	Chlorophyll	X	X	X	X	X				X
QCS	Temperature	X	X	X	X		X		X	
QCS	Salinity	X	X	X		X	X	X		
QCS	Discharge	X	X							
QCS	Wind	X								
Rank of model		**9**	**6**	**4**	**2**	**3**	**8**	**5**	**7**	**1**

Within the QCS model set, the four models with the lowest AICc scores are M9 (chlorophyll), M4 (chlorophyll and SST), M5 (chlorophyll and SSS), and M3 (chlorophyll, SST and SSS), respectively (Table A4.3-20 and Table A4.3-21). The values reported suggest there is not a substantial difference among these four models in terms of their level of support (ΔAICc=2.33), and because each of these model only vary by one parameter, they would not be considered to be legitimately competing models (Arnold 2010). This result suggests that chlorophyll may be an important metric in explaining the variation in sockeye salmon productivity over the period of 1996-2004.

Table A4.3-20. QCS C1a candidate models ordered by AICc from best (lowest) to worst (biggest). M.ID=model identification, M.AIC=the estimated AIC for the model, num.obs=the total number of observations (i.e., complete rows in the data set), num.par=the total number of fixed effects + random effects, Correction= the difference between the AICc (corrected for small sample size compared to number of parameters) and the AIC, M.AICC= the AICc for the model, min.AICC = the smallest AICc observed within the model set, delta= the difference between the min.AICC and each M.AICC, and AICC_wts= the Akaike weight (i.e., support) for each model.

M.ID	M.AIC	num.obs	num.par	Correction	M.AICC	min.AICC	delta	AICC_wts
M9	374.45	135	23	9.95	384.40	384.4	0	34.88
M4	374.61	135	24	10.91	385.52	384.4	1.13	19.85
M5	375.26	135	24	10.91	386.16	384.4	1.77	14.40
M3	374.80	135	25	11.93	386.73	384.4	2.33	10.88
M7	378.72	135	22	9.04	387.75	384.4	3.36	6.51
M2	374.88	135	26	13.00	387.88	384.4	3.49	6.10
M8	380.29	135	22	9.04	389.32	384.4	4.93	2.97
M6	379.41	135	23	9.95	389.35	384.4	4.96	2.92
M1	376.57	135	27	14.13	390.70	384.4	6.31	1.49

Table A4.3-21. Estimates for all fixed effects parameters included in each model, for model set C1a, QCS. Fixed effect parameters (i.e., covariates) are listed in the rows. The estimates for each model are provided in the columns. A value of 'NA' indicates that that particular model did not include the covariate in the corresponding row.

ModelSet_C1a_QCS_VarName	M1	M2	M3	M4	M5	M6	M7	M8	M9
(Intercept)	1.93	-25.73	-20.97	-9.64	-7.13	-15.97	-6.57	-6.26	0.02
CHL_M04_QCSx_MGRR_DOM	0.42	0.19	0.36	0.43	0.37	NA	NA	NA	0.43
CHL_M05_QCSx_MGRR_DOM	0.75	-0.24	0.28	0.25	0.20	NA	NA	NA	0.18
DIS_x69_QCSx_MGRR_DOM	-0.03	0.02	NA	NA	NA	NA	NA	NA	NA
SSS_A48_QCSx_MGRR_DOM	0.60	-0.11	0.35	NA	0.25	0.35	0.29	NA	NA
SST_A78_QCSx_MGRR_DOM	-0.54	1.30	0.72	0.65	NA	0.53	NA	0.57	NA
StockNameBirkenhead:Spawners	-8.91	-9.46	-9.69	-9.58	-9.77	-10.05	-9.30	-9.93	-9.68
StockNameBowron:Spawners	-220.31	-161.60	-169.13	-164.84	-169.48	-167.13	-188.50	-165.03	-165.60
StockNameChilko:Spawners	-3.46	-2.81	-2.88	-2.83	-2.89	-2.92	-3.24	-2.87	-2.85
StockNameCultus:Spawners	-995.51	-929.65	-957.51	-936.40	-974.92	-970.81	-1005.56	-929.08	-952.29
StockNameE.Stuart:Spawners	-9.01	-13.55	-14.24	-13.87	-13.73	-14.62	-9.21	-14.52	-13.50
StockNameFennell:Spawners	-153.76	-98.27	-102.31	-99.54	-102.33	-103.16	-135.99	-100.65	-99.95
StockNameGates:Spawners	-30.63	-9.06	-12.16	-10.05	-12.15	-11.00	-19.23	-10.16	-10.18
StockNameHarrison:Spawners	-17.80	106.15	78.10	101.56	77.36	57.45	7.87	74.79	94.75
StockNameL.Shuswap:Spawners	-0.23	-0.29	-0.31	-0.31	-0.30	-0.29	-0.22	-0.30	-0.31
StockNameL.Stuart:Spawners	-5.38	-4.61	-4.83	-4.72	-4.73	-4.81	-4.90	-4.83	-4.63
StockNameNadina:Spawners	-9.00	-8.41	-9.25	-8.71	-9.07	-8.34	-6.60	-8.40	-8.56
StockNamePortage:Spawners	-123.52	-76.18	-79.88	-78.44	-78.45	-80.33	-114.96	-78.76	-77.66
StockNameQuesnel:Spawners	-0.76	-1.13	-1.16	-1.16	-1.14	-1.18	-0.82	-1.19	-1.14
StockNameRaft:Spawners	-43.22	-23.99	-25.88	-24.63	-25.29	-25.12	-34.20	-24.71	-24.24
StockNameScotch:Spawners	17.45	14.77	13.85	13.96	14.23	14.84	18.31	14.63	14.12
StockNameSeymour:Spawners	3.01	0.22	-0.82	-0.52	-0.83	-0.35	3.96	-0.36	-0.66
StockNameStellako:Spawners	-6.29	-6.19	-6.43	-6.31	-6.40	-6.28	-5.67	-6.24	-6.30
StockNameWeaver:Spawners	3.64	25.55	24.30	24.76	24.17	23.72	9.21	24.09	24.50
WND_x28_QCSx_MGRR_DOM	0.50	NA	NA	NA	NA	NA	NA	NA	NA

Table A4.3-22. Model specifications for the 1996-2004 (brood years) model set for the Strait of Georgia. This table shows the variables included in each of the 8 models tested (i.e. M1 to M8) within this model set. Table 4.4-1 explains which specific data sets were used for each of these variables. “Rank of model” reflects the AIC_c score showing level of support (#1 ranked model had the highest level of support and lowest AIC_c score).

Region	**Variable**	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**
SoG	Chlorophyll	X	X	X	X				X	
SoG	Temperature	X	X	X		X		X		
SoG	Salinity	X	X		X	X	X			
SoG	Discharge	X								X
Rank of model		**3**	**9**	**8**	**6**	**2**	**1**	**5**	**4**	**7**

Within the SoG model set, Models M6 (SSS) and M5 (SSS and SST) have the strongest support within the group (Table A4.3-23 and Table A4.3-24). M6 and M5 have very similar AICc scores (ΔAICc = 1.53) and only differ by one parameter, this implies that SST is an uninformative parameter relative to SSS (Arnold 2010). However, the ΔAICc show that there is also relatively little difference in support from the M1 global model (ΔAICc = 2.59 and M6) despite the addition of 5 extra parameters and therefore M1 is a legitimately competing model for SoG. Chlorophyll in SoG on its own does not appear to be an important explanatory variable for Fraser River sockeye salmon productivity, at least over the period of 1996-2004.

In summary, while the results show that QCS chlorophyll may be an important metric in explaining the variation in sockeye salmon productivity over the period of 1996-2004, whereas QCS temperature and salinity are relatively uninformative parameters. To the contrary, within SoG during this timeframe, salinity has strong support and the remaining parameters are found to be uninformative, except when they are all included together in the global model. One should be very cautious about drawing conclusions from patterns observed over such a very short period of time, but these results do at least indicate that there may be strong regional differences in the importance of the potential drivers examined. During the data processing steps of this project, it was noted that the variance in chlorophyll measured in the Northern SoG was substantially greater than that measured in the Central SoG across all months where data were provided (Figure A3.5-3). It may be worth examining these regional differences more closely.

Table A4.3-23. SoG C1a candidate models ordered by AICc from best (lowest) to worst (biggest). M.ID=model identification, M.AIC=the estimated AIC for the model, num.obs=the total number of observations (i.e., complete rows in the data set), num.par=the total number of fixed effects + random effects, Correction= the difference between the AICc (corrected for small sample size compared to number of parameters) and the AIC, M.AICC= the AICc for the model, min.AICC = the smallest AICc observed within the model set, delta= the difference between the min.AICC and each M.AICC, and AICC_wts= the Akaike weight (i.e., support) for each model.

M.ID	M.AIC	num.obs	num.par	Correction	M.AICC	min.AICC	delta	AICC_wts
M6	377.49	135	22	9.04	386.53	386.53	0	42.80
M5	378.11	135	23	9.95	388.06	386.53	1.53	19.92
M1	374.99	135	27	14.13	389.12	386.53	2.59	11.70
M8	379.94	135	23	9.95	389.89	386.53	3.36	7.97
M7	381.42	135	22	9.04	390.46	386.53	3.93	6.00
M4	379.97	135	24	10.91	390.88	386.53	4.35	4.86
M9	382.05	135	23	9.95	392.00	386.53	5.47	2.78
M3	381.70	135	24	10.91	392.61	386.53	6.09	2.04
M2	380.79	135	25	11.93	392.72	386.53	6.19	1.93

Table A4.3-24. Estimates for all fixed effects parameters included in each model, for model set C1a, SoG. Fixed effect parameters (i.e., covariates) are listed in the rows. The estimates for each model are provided in the columns. A value of 'NA' indicates that that particular model did not include the covariate in the corresponding row.

ModelSet_C1a_GS_VarName	M1	M2	M3	M4	M5	M6	M7	M8	M9
(Intercept)	186.87	35.27	-1.17	36.03	13.47	19.28	-2.89	2.01	0.68
CHL_M04_NSoG_MGRR_DOM	-0.20	-0.07	0.04	-0.05	NA	NA	NA	0.04	NA
CHL_M05_NSoG_MGRR_DOM	-0.09	-0.005	-0.02	-0.02	NA	NA	NA	-0.03	NA
DIS_A67_SoGx_MGRR_DOM	5.4E-06	NA	NA	NA	NA	NA	NA	NA	-2.0E-06
DIS_T05_SoGx_MGRR_DOM	-9.3E-05	NA	NA	NA	NA	NA	NA	NA	1.2E-05
SSS_A48_SoGx_MGRR_DOM	-6.37	-1.50	NA	-1.24	-0.68	-0.65	NA	NA	NA
SST_A48_SoGx_MGRR_DOM	0.07	0.50	0.20	NA	0.44	NA	0.32	NA	NA
StockNameBirkenhead:Spawners	-9.48	-9.82	-8.86	-9.89	-9.91	-9.99	-9.96	-8.85	-9.97
StockNameBowron:Spawners	-160.20	-168.06	-198.56	-168.28	-170.75	-169.29	-167.72	-199.44	-167.69
StockNameChilko:Spawners	-2.79	-2.87	-3.20	-2.88	-2.89	-2.89	-2.89	-3.22	-2.89
StockNameCultus:Spawners	-921.45	-919.45	-954.35	-931.09	-917.22	-928.36	-926.55	-958.79	-929.32
StockNameE.Stuart:Spawners	-13.37	-14.14	-9.32	-13.87	-14.31	-13.89	-14.58	-8.90	-14.01
StockNameFennell:Spawners	-96.81	-101.79	-137.66	-101.89	-102.20	-101.71	-101.33	-139.05	-101.81
StockNameGates:Spawners	-7.56	-12.86	-23.53	-12.84	-13.87	-13.13	-11.81	-23.61	-12.75
StockNameHarrison:Spawners	105.53	86.42	31.09	80.78	79.90	73.29	71.10	26.94	73.76
StockNameL.Shuswap:Spawners	-0.30	-0.29	-0.25	-0.29	-0.30	-0.29	-0.29	-0.24	-0.29
StockNameL.Stuart:Spawners	-4.55	-4.85	-5.23	-4.79	-4.96	-4.86	-4.92	-5.18	-4.82
StockNameNadina:Spawners	-8.06	-9.36	-8.38	-9.23	-9.81	-9.41	-9.00	-8.17	-9.12
StockNamePortage:Spawners	-76.78	-76.85	-115.25	-76.22	-78.46	-78.05	-77.94	-116.41	-76.17
StockNameQuesnel:Spawners	-1.14	-1.15	-0.82	-1.13	-1.16	-1.14	-1.18	-0.80	-1.14
StockNameRaft:Spawners	-23.36	-25.76	-37.81	-25.42	-26.37	-25.54	-25.40	-37.86	-25.24
StockNameScotch:Spawners	14.55	14.76	17.01	15.02	14.31	14.65	14.76	17.30	15.24
StockNameSeymour:Spawners	0.18	-0.41	3.09	-0.40	-0.84	-0.65	-0.51	3.29	-0.29
StockNameStellako:Spawners	-6.13	-6.35	-6.03	-6.33	-6.43	-6.36	-6.31	-5.97	-6.30
StockNameWeaver:Spawners	25.79	24.44	8.57	24.33	24.09	24.07	23.94	7.81	24.10

Appendix 5. Data Template User Guidelines

User Guidelines and Template Instructions

General

Please carefully read through the entire guidelines before beginning to import data into the template.

This document has three sections:

A. Overall Objective

Providing data and metadata to support data syntheses and analyses of cumulative impacts across all of the factors being investigated by Cohen Commission contractors

B. Overview of Input Data

High-level guidelines for required data inputs, including important concepts and considerations

C. Template Instructions

Mechanical details on how to actually bring these data into the template

Overall Objective

The overall objective of this template is to collect the necessary data for ESSA to complete a range of quantitative and qualitative analyses under the Cohen Commission contract dealing with Data Synthesis and Cumulative Effects. ESSA will be using the collected data to conduct *quantitative* analyses exploring the relative and cumulative impacts of different stressors on Fraser sockeye productivity.

ESSA will also use the data collected in *qualitative* analyses of potential cumulative effects and interactions over space, over time and over life-stages. ESSA will generate methods of communicating the results to the diverse audiences of the Cohen Commission.

It is anticipated that there will be various data limitations that will vary by stressor and particular metric, including limited time spans of data, gaps in the time series, and only qualitative estimates for some years/metrics rather than quantitative measurements. The data template has been designed with flexibility to accommodate these potential issues.

Overview of Required Input Data

Integrative Quantitative Metrics

Each contractor (excepting #7 and 11) should provide preliminary data for a few integrative metrics (or indices) of the stressors that he or she is examining. Key characteristics include:

Few: Limit submission to 1-5 metrics per contractor. Additional metrics can be added if justified – i.e., metric represents an important but independent source of variation.

Integrative: Each study will likely have a lot of data. The few integrative metrics provided to ESSA should synthesize these data. Each contractor is a discipline expert that will know which variables are most important or how best to integrate data into integrative metrics.

Independent: Integrative metrics should be chosen to reflect independent sources of variation (i.e. not be highly correlated with each other).

Annual: The metrics provided by each contractor need to be provided annually, for those years where data exist. Each contractor will know the most relevant approach to summarize intra-annual data into an annual metric (e.g., maximum weekly average temperature experienced during upstream migration of each stock of Fraser sockeye).

Stock specific: Provide only one data point per stock per year. The same data point may apply to multiple stocks; contractors can specify which ones.

- ❖ *Do not submit many data series. For example, there may be data on 100s of individual contaminants or 100s of temperature buoys. Choose the most critical data series or decide how to integrate similar series into an index.*

- ❖ *If temperature data are hourly or daily, decide how best to integrate into an annual metric. An average over a particular season may make more sense than an annual average.*

- ❖ *Some freshwater variables may contain more than one data point for a single stock in a single year (i.e. multiple nursery lakes for one stock). Decide how best to integrate these values into a single value for the stock.*

Ultimately, each metric will provide a **SINGLE VALUE PER YEAR PER STOCK**, though many metrics may apply to all stocks equally.

Metric Connected to Biologically-supported Hypothesis

Each reported metric should be clearly connected with a biologically-supported hypothesis that emphasizes WHY this metric is potentially important in explaining patterns in sockeye productivity over time and/or space. Consider where these hypotheses fit within the initial conceptual model provided in the template. As stated in David Levy's letter of Sept 8, hypotheses should be expressed in the form of questions.

- *A temperature index may be developed that only integrates temperature data from one season because that is when sockeye would be most affected by temperature or pass by that region.*

- *If a statistical method such as multiple regression or PCA is used to determine that January temperatures are most significant but this is not biologically supportable (e.g., sockeye are not in the area in January), then that would be a poor index.*

Metadata – Sources and Methods

The original data sources and analytical methods need to be explicitly described to communicate HOW this integrative metric was generated. The leaders of each project are expected to be the experts on how to best integrate stressor-specific data over space and time, but all users (intermediate and final) must be able trace the analysis pathway of a particular metric from its sources to its final form. Key metadata components are included in the template (specific details below).

Qualitative Evaluation

It is anticipated that many important metrics will have a limited data record. To overcome this limitation and to facilitate additional analyses over the entire time period of data on Fraser River sockeye stock productivity, we would like to have Contractors supply a qualitative data which provides estimates/ educated guesses for the entire time period. This would complement the quantitative data set.

Contractors will be required to fill in a second, complete data set with qualitative assessments (5 point scale) of the same integrative metrics over time. This is based on the expert experience of each contractor in their respective field. This qualitative assessment will also be collected based on each contractor's expert knowledge of their particular stressor outside of the Fraser system as well.

This assessment should be the contractor's best guess at the LEVEL of a particular stressor, not the actual IMPACT of that stressor on sockeye productivity. Contractors should provide their qualitative ratings **independent** of the productivity data (i.e. do not assign ratings based on looking at the productivity data, as that would make the ratings biased and unusable in ESSA's analyses).

- *Stock X may have been subject to a low level of pollution prior to 1985, but increased to a high level of pollution when a pulp mill was built. Similar changes may have occurred at other times for other stocks.*
- *The "level" of salmon farms might reflect the total number or the total production capacity over time and apply to all stocks migrating past each set of farms.*
- *Some metrics may have remained at relatively constant levels over the timeframe indicated.*

If it is not possible to distinguish among multiple quantitative metrics in making qualitative judgments for the entire period of record, contractors may choose to qualitatively evaluate only a single overarching measure for their particular stressor.

Template Instructions

General

- Examples are included. Overwrite these with your own input.
- Many cells contain comments with additional guidance. Look for cells with red triangles and hold your cursor over such a cell to read the comment.
- Much of the template is protected. You should not need to edit protected cells. Opportunities for including descriptive comments are included throughout the template.
- Many of the drop-down menus provide flexibility to add additional items as necessary. Additional items can be added by finding the relevant list on the "Lists" worksheet and entering new values.
- IMPORTANT: "Year" refers to the **year of data measurement**, NOT the brood year potentially affected. Data will be adjusted later as necessary based on its associated life history stage. Do not adjust metrics for brood year.

Initial Conceptual Model (Worksheet: Initial Conceptual Model)

This model originated from the work of the Pacific Salmon Commission workshop in June 2010. It is intended to be a DRAFT STARTING POINT. Please comment on missing components, mechanisms, or processes, while recognizing that this is meant to be a high level model of the entire system (but feel free to also provide more detailed conceptual models of the stressors and sub-systems you are investigating). Please refer to this initial model when describing the spatial/temporal questions that each metric is intended to address.

Project-level Information (Worksheet: Project Info)

This worksheet contains information applicable to entire submission and should be self-explanatory.

Integrative Metric (Worksheet: Metric1)

Each metric will have its own worksheet. However, the quantitative data and qualitative evaluation of a particular metric are entered on the same worksheet.
Each worksheet has a detailed metric-specific metadata section, a section for entering quantitative data for the metric, then a section for entering the qualitatively determined data for the metric. Each section is explained below and there are examples in the actual template.

Quantitative Metric

Metadata

Stressor name The name of the particular index or variable.

Stressor category Associated Cohen Commission project.

Units The units that apply to the reported values.

General location Identify the general region with which this metric is associated.

Specific locations used Provide details on spatial locations of underlying data from which the metric is derived.

Spatial and temporal aggregation details
If necessary, how were data from different spatial locations aggregated into a single metric? How were annual values determined? How were sub-annual data aggregated?

Estimation details	What additional methods were used (after spatial and temporal aggregation) to derive this metric from the original data sources?
Observation type	What type of observation does this metric represent? i.e., measured, expert estimate, etc.
Confidence	What is the overall level of confidence in these data in terms of its ability to potentially provide answers to the spatial and temporal questions posed below? This wraps together concepts of both measurement error and sampling error.
Spatial question	What is the spatial question that these data are intended to address? (e.g., Do Fraser sockeye stocks with a greater level of exposure to salmon farms have the same productivity trends as those which have less exposure to salmon farms?)
Temporal question	What is the temporal question that these data are intended to address? (e.g., Are time trends in Fraser sockeye productivity negatively correlated with time trends in salmon farm production?)
Life history stage association	Indicate the life history stages with which this metric is associated (e.g., estuary rearing, marine migration to rearing areas, marine growth and maturation).

Values

Enter index/metric values by year by stock, as available. Represent MISSING VALUES AS BLANKS.

Year	Years are provided from 1948 to 2010. Enter values only for years where data are available. Enter values for the **year of data measurement**, NOT the brood year affected.
Stocks Affected	For each year values can be entered by the stock they would have affected, if known. If the same value is known to apply to all stocks or the metric cannot be distinguished between stocks, enter the value under ALL. If a value is entered under ALL, the stock-specific cells will be greyed out for that year only. If the value under ALL is deleted, the stock-specific cells will

	open again. It is acceptable to enter values for different groups of stocks each year.
Comments	Additional comments on the record for a particular year.

Qualitative Metric

Comments specific to qualitative assessment below

Comments on how the qualitative evaluation values were generated. Were they the expert opinion of one person or many? What sorts of factors were considered or excluded?

<u>Values</u>

Years	Provide qualitative estimate of metric (1-5 scale, refer to below) for EVERY year in the template.
Stocks	If a qualitative estimate of the metric can be provided by stock, enter values by stock for each year, otherwise enter values under the ALL column. To the extent possible, provide a qualitative estimate of the metric as it would have applied to other non-Fraser sockeye stocks within BC.
Value/Rating	The qualitative rating should be a qualitative assessment based on your expert knowledge. You should be rating the LEVEL of the particular metric, not the impact it may have had on productivity (the latter will emerge from multivariate analyses). Ratings are on a 1-5 scale as follows: 1 = very low, lowest 20% of the observed values 2 = low, second quintile (21^{st} to 40^{th} percentiles of the distribution of values) 3 = moderate level, third quintile (41^{st} to 60^{th} percentiles) 4 = high level, fourth quintile (61^{st} to 80^{th} percentiles) 5 = very high level, fifth quintile (81^{st} to maximum value)

Given the above definitions, you should use all rating levels from 1 to 5. In practice, the distribution among these 5 values may not be completely even, due to occasional large changes (e.g., a new pulp mill constructed that substantially changes the level of pollution). The most important thing is to assign 1s to the best years, 5s to the worst years and scale the values in between. The distribution among quintiles may only be approximate, but ensure that the full range of values is used. If you can only evaluate years as 1, 3, or 5, that is acceptable too.

Proceed to Next Metric

Once you have finished adding the data for one metric, begin with the next metric in the subsequent worksheet.

End of Guidelines

Appendix 6. Workshop Report 1 (Nov. 30-Dec. 1, 2010)

Technical and Scientific Research Projects' Workshop
November 30 - December 1, 2010.

Workshop Summary

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Background

In response to the declines of Fraser River Sockeye Salmon since the late 1980s, as well as the low abundance and productivity of 2009, Prime Minister Stephen Harper appointed a commission, headed by BC Supreme Court Justice Bruce Cohen, to investigate the decline of sockeye salmon in the Fraser River (termed the *Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River* or the *Cohen Commission*). The Commission has identified a range of fish biology and ecosystem issues that may be relevant to the recent sockeye salmon decline and their future sustainability (Cohen Commission 2010). These issues cover the range of natural conditions and human stressors that influence the productivity, survival, and diversity of Fraser sockeye in freshwater and marine environments. The Commission then grouped these issues into twelve complementary statements of work for evaluation by selected experts.

The Cohen Commission held a workshop, November 30 – December 1, 2010, in which each of the twelve scientific contractors presented their technical and scientific findings. In addition to presentations, the workshop included plenary discussions of findings, subgroup discussions of alternative hypotheses within particular thematic areas, and research and monitoring recommendations. Participants included Scientific Contractors, Peer Reviewers, and Cohen Commission Science Staff. The main objectives of the workshop were to understand the patterns of changes in Fraser sockeye, communicate and integrate scientific findings among researchers, identify potential linkages and interactions among possible causes, identify knowledge gaps and recommend future research and monitoring. Appendix C contains detailed notes on the meeting.

The workshop included presentations on the following topics:

1) Productivity dynamics of sockeye salmon: patterns that need to be explained
2) Conservation Unit Status Assessment
3) Fisheries & Fisheries Management (Fraser & Bristol Bay)
4) Status of DFO Management and Science
5) Diseases and Parasites
6) Contaminants
7) Freshwater Factors
8) Marine Ecology
9) Marine mammal, fish and bird predation
10) Lower Fraser Habitat Analysis
11) Climate Change
12) Data synthesis and cumulative effects

Presentations

Productivity Dynamics of Sockeye Salmon: Patterns that Need to be Explained

Randall Peterman & Brigitte Dorner

The return of 1.5 million Fraser sockeye salmon in 2009, the lowest since 1947, is part of a continued, long-term trend of decline in abundance and productivity across several decades. The main objective of this study is to evaluate the long-term spatial and temporal patterns in productivity for 19 Fraser sockeye stocks and 45 non-Fraser sockeye stocks (from other parts of BC, Washington and Alaska). This study estimated a number of sockeye productivity indices, including: the number of returning adult salmon (recruits) produced per spawner, juveniles / spawner, and recruits / juvenile. Standard methods were used for productivity estimation, including the application of two different stock-recruitment models[1] to remove the effects of spawner density on estimates of productivity. A Kalman filter method was used to extract underlying trends from year to year variation.

Declines in the overall productivity of Fraser sockeye stocks (recruits / spawner) were more strongly associated with declines in post-juvenile productivity (juveniles to adults) than with pre-juvenile productivity (spawners to juveniles). There has been no reduction over time in freshwater productivity (spawners to juveniles). These findings are similar to the results from the Pacific Salmon Commission (PSC) workshop in June 2010 (Peterman et al. 2010). Peterman and Dorner identified three periods of extended declines: the 1970s, the mid-1980s and the late 1990s to early 2000s. Importantly, other non-Fraser BC stocks showed similarly large and rapid decreases in productivity starting in the late 1990s. This result, not available from the PSC workshop, reveals that conditions outside the Strait of Georgia, contributed to the shared patterns of decline in productivity. Two individual stocks, Harrison and Pitt, do not follow the same decline.The widespread and shared trends of many sockeye stocks (including Fraser stocks, Barkley Sound, Puget Sound, the BC Central Coast, the BC North Coast, and SE Alaska) are most likely due to large-scale forces in the ocean affecting survival. There may also be some common forcing factors in fresh water, after juvenile densities are estimated (e.g., during the downstream migration to the ocean), though lack of data makes it impossible to assess this hypothesis.

Some of the key issues raised by workshop participants concerned the methods of estimating productivity and the resulting trends. Questions concerned the results from smoothed data versus

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[1] The Ricker stock-recruitment model estimates recruits per spawner as a function of the stock's carrying capacity and the density of spawners in the brood year. The Larkin model is similar, but in addition to the carrying capacity and density of spawners in the brood year, it also considers the densities of spawners in the three years prior to the brood year, to account for possible positive or negative effects from past escapements on future productivity.

raw data, the range of error around the estimates and methodological differences in estimates of recruits prior to the mid-1990s. Responses to issues raised by participants can be found in Appendix C.

Conservation Unit Status Assessment

Katherine Wieckowski, ESSA

One of the tasks of this research is to evaluate the methodology that Fisheries and Oceans Canada (DFO) has developed to assess the population and habitat status of 36 Fraser River sockeye Conservation Units (CUs) (Holt et al. 2009). Two alternative methodologies for assessing population status were compared to the DFO method – one that has been developed specifically for Fraser sockeye (Pestal and Cass 2009) and another that is not species-specific (Faber-Langendoen et al. 2009). Four criteria were used to evaluate each approach: 1) ecological relevance, 2) method for setting benchmarks, 3) data requirements and availability, and 4) feasibility of implementation.

The inherent vulnerability of CU habitats to various stressors was assessed using landscape-level indicators of migratory, spawning and rearing habitats, including: total spawning extent, ratio of lake influence to total spawning; nursery lake area, and nursery lake productivity. Indicators were based on mapped habitat features from provincial GIS datasets and DFO lake productivity estimates. There was little correlation among the three landscape-level indicators, or between these indicators and CU population status.

Workshop participants explored potential errors in assessing conservation status, especially when data are lacking or poor. Pestal and Cass (2009) explicitly considered the uncertainty in available data, and only made status determinations for 25 of the 36 CUs in the Fraser Basin.

Fisheries & Fisheries Management (Fraser & Bristol Bay)

Karl English, LGL

The overarching goal of the study is to examine the Fraser sockeye salmon and Bristol Bay fisheries according to three key metrics: accuracy, precision and reliability. Factors examined included catch monitoring programs, pre-season forecasting methods, in-season abundance estimates, and escapement goals. Preliminary results showed that in both the Fraser and Bristol Bay, catch and escapement estimates are sufficiently reliable to manage fisheries and track trends for major stock groups, but that pre-season forecasts are not reliable. In the Fraser, harvest rates were high in the 1980s and early 1990s (70-90%), but much lower from 1995-2009 (18-41%); overharvesting is not a concern now.

In-season assessments are timely and reliable for achieving escapement goals in both fisheries. In the Fraser Basin (though not in Bristol Bay) there is considerable debate about escapement goals, and scope for improvement, particularly for cyclic stocks. The biggest data gap identified was a lack of reliable annual estimates of en route loss. The Bristol Bay fishery is different than the Fraser fishery in many ways (e.g., fewer fisheries, gear types and sectors; more terminal fisheries; fewer mixed stock challenges; unambiguous management control over fishery openings and closings). It is therefore difficult to compare to the Fraser River and Bristol Bay sockeye fisheries.

A key issue raised by workshop participants is the importance of distinguishing between the unknown (no one has done the work) and the unknowable (data are impossible to acquire). Further, it is important to consider how the information will be used: pre-season forecasts are used to modify expectations but in-season information is used to manage stocks.

Status of DFO Management and Science

Edwin Blewett, Counterpoint

The three core tasks of this project were to: 1) evaluate DFO management against stated objectives, 2) detail DFO Science and Research expenditures on Fraser River sockeye salmon, and 3) assess DFO's ability to carry out applied sockeye salmon research. For the first two tasks, researchers conducted an extensive review of documents and interviewed key contacts to identify and evaluate relevant objectives. Fourteen objectives were identified for inclusion in the report based on their focus on stock management, relevance to Fraser River sockeye, level of specificity, ends (as opposed to means), and largest effects and impacts. Last, they defined the required human and financial resources to compare/contrast with the actual programs and activities implemented by DFO. Major information gaps included evaluation data for post-season spawning escapement targets, expenditure data prior to 2005, and funding for 2009 PSF, FRP and SF research projects. Very little information was available in electronic format or updated databases. Preliminary results show a decline in the proportion of total spending allocated to research in recent years, across all of DFO's Pacific Region.

Key issues raised by participants included: how to account for university research that results from DFO funded research, how to account for NSERC-funded sockeye research, how well DFO research is informing management (i.e. what is needed to make management decisions), and how to avoid short-sightedness, considering the need for fundamental science that provides long-term insights.

Diseases & Parasites

Michael Kent, Oregon State University

The focus of the study was to review infectious diseases in sockeye salmon in BC and assess their role in mortality. The information for this study was obtained from peer-reviewed literature, government documents and interviews with DFO fish health specialists. Results found few documented outbreaks of disease in BC sockeye salmon. Limited survey data do not suggest recent increases in infectious disease.

Most research has been performed on hatchery fish. For wild fish, some research has been performed in freshwater but there is minimal information on marine stages. In agreement with the PSC findings, it was noted that some pathogens picked up in freshwater may not cause mortality until they reach the marine stage (Peterman et al. 2010). Most of the results agree with the list of high risk (possible) infections reported by the PSC workshop. However, IHN was found in freshwater (fry), a finding different from the PSC report (Peterman et al. 2010). Information gaps occur where diseases affect different life history stages, but most studies have only focused on one stage. Factors that may cause potential interactions and cumulative effects include: temperature, intermediate hosts, pollutants and land use practices.

A key participant question was how to design a rigorous survey program for examining pathogens. Other questions pertained to sea lice and the role of fish farms, temperature and pathogen thresholds, and availability of pathogen data at different life stages of the salmon.

Potential Effects of Contaminants

Don MacDonald, MacDonald Environmental Sciences, Ltd.

The objective of this research is to evaluate the effects of potential contaminants on Fraser River sockeye salmon. The scope of work includes an inventory of aquatic contaminants in the Fraser River Basin in relation to sockeye CUs, a comparison of water quality conditions in the Fraser River Basin to toxicity data for sockeye salmon, an assessment of contaminants encountered by juvenile and adult sockeye salmon and an evaluation of the extent to which reductions in sockeye productivity are related to contaminant conditions. The inventory confirmed that a wide variety of contaminants have been released into the Fraser River Basin. Elevated levels of conventional pollutants, nutrients and metals were observed during key life history stages. However, pre-1990 and post-1990 comparisons suggest that water quality may be improving in certain areas of the Fraser River, particularly the lower Fraser.

Data gaps included limited or no data on water chemistry, endocrine disruptors, sediment, and few fish tissues. Based on the spatial and temporal patterns of both contaminants and sockeye productivity, the researchers concluded that existing data do not support the hypothesis that water quality and contaminants have contributed to the decline of Fraser River sockeye salmon. However, due to the large data gaps, evidence is insufficient to exclude *some* effects on sockeye health and survival. The PSC report had similar conclusions (Peterman et al. 2010).

Workshop participants pointed out that Harrison sockeye are interesting – given that they linger in the estuary for much longer; they should be getting the highest levels of contaminant exposure, but yet have done the best. Other issues raised included 2007 (did levels of contamination or water quality change?) and pulp mill effluents (before-after effects of reductions in pollutants during the 1990's).

Freshwater Factors

Marc Porter, ESSA Technologies

The focus of this study is to evaluate the impacts of local human activities on Fraser River sockeye spawning habitats, rearing / nursery lakes, and migratory corridors for smolt outmigration / adult migration. The focal human activities (potential stressors) included forestry, hydroelectricity, urbanization, agriculture, mining and water use. GIS was used to assess interactions between stressors and sockeye habitats across CUs. At the time of the meeting, initial quantitative / qualitative assessments were completed for only a few of the stressors.

Run-of-river Independent Power Producers (IPPs) are located in the upper, fishless reaches of streams, which makes it very unlikely that they would have any serious direct impacts on sockeye rearing, spawning or migratory habitats. In addition, there are very few IPPs in the Fraser Basin. Thus it seems highly unlikely that IPPs have had any significant role in recent sockeye declines. Log storage and associated handling activities can have potentially serious impacts to local habitats in the Fraser Estuary. However, as the magnitude or timing of log storage activities in the Estuary appear generally unchanged over the past decade, there is no evidence that increasing log storage has played a significant role in recent sockeye declines. No large hydro projects exist in the Fraser River itself and only a limited number of large projects exist in large Fraser tributaries. Potential impacts on survival of migrating sockeye smolts and adults at these facilities are well known and have apparently been successfully mitigated to a large extent. As it appears that mitigation targets have been sufficient to consistently minimize sockeye losses at the projects, there is no evidence that large hydro projects have played a significant role in recent sockeye declines. Mining activities are widespread in the Fraser Basin and have the potential to cause local impacts to sockeye spawning and migratory corridors. However, mines in the Fraser are generally not located close to areas that support the majority of sockeye spawning. While there may be significant localized effects on fish habitat, the impacts of mining on sockeye population densities are likely to be small and difficult to detect. A major data gap is the general lack of time-series data for most stressors that could allow researchers to relate changing stressor intensity to changes in fish population or fish habitat status.

Key issues raised by workshop participants were: 1) the importance of scaling the indicators to a more directly interpretable measure, relative to the stress on sockeye, 2) lack of high quality data for all CUs should not rule out using existing data, but with caveats, and 3) caution that impacts may be local and subtle.

PICES Advisory Report on the Decline of Fraser River Sockeye Salmon in Relation to Marine Ecology

Skip McKinnell, PICES

The main objective is to assemble a comprehensive summary of what is known about Fraser River sockeye salmon in the ocean. Much of the study involved reviewing data/ technical reports and peer-reviewed literature, although some original data were re-analyzed. To explain the long-term decline in sockeye salmon, McKinnel presented evidence that there was an abrupt "shift" to lower productivity in 1992 rather than a "trend" of a gradual decline in productivity. The low returns of 2009 are associated with the 2007 (2nd lowest) ocean entry year (OEY) for sockeye salmon. The 2006/7 el Niño created extremes in discharges (runoff) on the central coast of BC that may have affected the salmon by altering surface salinity. Furthermore, there were unusually strong southeasterly winds in the summer of 2007 (the most extreme since 1948), which kept freshwater entrained in Queen Charlotte Sound (QCS). This raised the sea level and maintained a low salinity, freshwater "lens" in QCS, all of which delayed the spring bloom of algae (the latest since records began to be collected in 1998). Additional evidence for ocean forcing were warm surface sea temperatures (SSTs) in QCS in 2007.

Data which extend the PSC report include: 1) the 2006 Harrison River brood year returns, 2) 2004 Chilko Lake sockeye marine survival, and 3) 2007 weather, climate, oceanography and phenology of Queen Charlotte Sound/Strait. The most important unknowns for sockeye salmon in the ocean are the numbers of smolts entering the sea, by stock. There have been no studies documenting where and when sockeye salmon die in the ocean.

This presentation stimulated many questions from workshop participants including:

- What's the relative likelihood of different mechanisms that are not mutually exclusive?
- Chums did poorly in 2010 and sockeye well, but both entered ocean in 2007 - why?
- Why were conditions more extreme in QCS during 2007 than in Georgia Strait?
- Could there have been harmful algae blooms in QCS as suggested in the PSC report?
- Why didn't Mackas or Peterson indices predict the low 2009 return?
- Did you compare median recruits per spawner against Mackas red and blue years?
- PSC report suggested that zooplankton production in 2007 was not anomalous
- Can one really determine whether it's a gradual or step change in productivity?
- Can you explain other stock patterns (e.g., West Coast Vancouver Island, Fraser pinks)?

- Can you find the same shared trend in productivity for stocks outside the Fraser?[2]

Marine Mammal, Fish and Bird Predation

Andrew Trites, UBC
Villy Christensen, UBC

The overall objective of this study is to evaluate the effects of predators on Fraser River sockeye salmon, with an extensive review of primary literature. Dr. Trites reported that in general sockeye salmon is not an important part of marine mammal diets. Among those mammals that eat salmon, sockeye is not a preferred prey species. There is no evidence of significant predation on smolts, only adult sockeye. Data were too sparse to assess the predator impacts on different sockeye stocks. Evidence agrees with the PSC report on several points including the increase in Steller sea lions since protection 40 years ago, especially in recent years (Peterman et al. 2010). Likewise, sightings of Pacific white-sided dolphins have increased, harbour seal populations have recovered to historical levels in the Strait of Georgia and humpback whale populations are growing in BC and Alaska. Unlike the PSC report findings, the researchers concluded that total food consumption by mammals is not large enough to affect sockeye. While the timing of sockeye declines coincides with increases in Stellar sea lions, sockeye form only a small fraction of their diet (about 2-3%). Information gaps include outdated and seasonally limited data for harbour seals (only available for summer), DNA analysis of prey remains would determine species of salmon consumed by predators.

Dr. Christensen reported on fish and bird predation in the Georgia Strait, Queen Charlotte Sound and Northeast Pacific Ocean (not addressed in the PSC report). Based on the available data, freshwater predators are not likely to have caused declines in sockeye salmon. Similarly, predation by marine birds does not seem to be a likely contributor to Fraser sockeye declines. Recent declines in other fish species could increase sockeye's relative importance as prey for ocean predators. Specifically, salmon sharks and daggertooth should be considered for further studies.

The most important unknown is monitoring the changing abundances of key predators in freshwater and marine ecosystems. In order to explain what happens in these ecosystems, we need to understand changes in productivity, fisheries and food webs. Information is poor for the open ocean and in freshwater. DFO's attempts to implement integrated management have been very limited.

[2] This question was addressed by Peterman and Dorner's presentation. In general, stocks outside the Fraser do show the same shared trend in productivity.

Key issues raised by workshop participants included: 1) the availability of other salmon species as alternate prey to predators; 2) a very small percentage of predator diet consisting of sockeye is not enough to reject a potential predator as influential, without more data such as DNA or bio-energetic analyses; and 3) it is important to examine the overlap of predators and smolts in both space and time.

Fraser Sockeye Salmon Habitat Analysis: Lower Fraser River & Strait of Georgia

Mark Johannes, Golder Associates

The objectives of this study are to identify and evaluate key sockeye habitats and habitat use in the Lower Fraser, Fraser Estuary and Strait of Georgia. Key indicators include anthropogenic changes and biophysical characteristics in the Strait of Georgia, focusing on the period from 1990 to 2010. Researchers used spatial and temporal overlays of the indicators with the degradation of key sockeye habitat to determine potential interactions. Comparisons to the PSC report were preliminary, but so far showed agreement (Peterman et al. 2010). A major data gap is the lack of clear indicators on human development. Consistent indicators of biophysical conditions in Strait of Georgia and biological observations of sockeye habitat use are also limited. There is a general lack of time series data.

A key issue raised by workshop participants is the broad scope of the research topic. One suggestion was to focus on locations and times that sockeye are in specific areas. Other suggestions included consideration of river discharge (temperature effects), light pollution in Georgia Strait, and the relative importance of Lower Fraser habitats versus larger scale factors.

Climate & Climate Change Effects on Fraser Sockeye

Scott Hinch, UBC
Eduardo Martins, UBC

The overarching theme of this research is to review the occurrence and effects of climate change on Fraser River sockeye and their relative importance to their long-term decline. The first part of this study examined en route mortality, pre-spawn mortality and intergenerational effects. The second study component assessed the relationships between climate and climate-affected variables (temperature, precipitation, river flow, salinity) and sockeye salmon survival and productivity. Hinch showed that en route loss can be large relative to harvest and spawning escapement, and has become really important in recent years; nine out of 12 stocks had high mortality in more than 50% of recent years. Contrast among non-Fraser stocks showed the opposite effects of temperatures between southern and northern stocks (e.g, warmer years are generally better for Alaska sockeye marine survival and worse for Fraser sockeye marine survival) and inter-stock variability in other river systems.

Hinch hypothesized that thermal (and related) issues play a large role in among and within-stock variation in en-route and pre-spawn mortality. En route loss observations, lab experiments, and field telemetry studies showed stock-specific differences in how fish deal with acute and chronic thermal stressors. Most stocks experience substantially elevated mortality rates when migration temperatures exceed 18 C˚. The preliminary results and conclusions of the study agree with the PSC findings that en route mortality does not contribute directly to the decline in productivity, defined as recruits per spawner, since en route mortality is already included in the calculation of recruits. However, en route mortality clearly reduces the density of spawners, and therefore can have substantial long term effects on the sockeye fishery. Although there was no overall trend in pre-spawn mortality across all Fraser stocks, Hinch found a trend of increasing pre-spawn mortality in late runs since early migration began in 1995. Migration mortality is likely a greater contributor to declining trends in spawning abundance for early and late runs, or stocks that do not cope well with high temperatures. Similar to the PSC findings, pre-spawn mortality was found to reduce the number of effective female spawners, which could play a role in reduced productivity for late run stocks. Intergenerational effects are plausible, but the supporting evidence is weak. Overall, climate change is a possible contributor to recent declines in average Fraser River sockeye productivity, given inter-annual and inter-stock variability.

There are data gaps that could be improved through future studies (i.e. unknown information that is "knowable"). There are no direct measures of migration survival, no data on the effects of fisheries bycatch on migration mortality, and sparse research on the intergenerational effects.

Workshop participants were interested in the earlier timing of the freshet in recent years. There is evidence that zooplankton blooms occur 30 days earlier and for a shorter period. High Fraser discharge and wind patterns could be linked to the timing of blooms.

Data Synthesis and Cumulative Effects

Alex Hall & Darcy Pickard, ESSA Technologies

This study seeks to understand the mechanisms by which stressors across all projects interact or combine. The timeline for this study extends beyond that of the other reports, because it relies on data from each of the other studies. Using qualitative and quantitative approaches, researchers will illustrate the potential cumulative impacts of multiple types of stressors through a series of integrative frameworks. Qualitative analysis will use a life-history approach with a conceptual model of the pathways of different stressors, a spatial life-history diagram illustrating the spatial scale of the sockeye's life cycle, and an expert evaluation of the relative likelihood of evidence. The latter exercise will build upon findings in the PSC report (Peterman et al. 2010).

Quantitative analysis will use integrative metrics to synthesize the data from each research group. These data should be independent, annual and stock-specific. It will be very difficult to do one single integrative analysis that incorporates all variables into a single framework, especially due to data limitations, including gaps within the data, limited length of record, data only for current status rather than over time, and the complete lack of any data on some components. Instead, multiple models will be tested using straightforward statistical approaches.

During the workshop, participants were given a draft conceptual model and asked to contribute their ideas. One of the key recommendations was to simplify the model.

Key issues raised by workshop participants:

- Using longer time series with only fair quality data may be more informative than using shorter time series with more complete data
- Using expert opinion ratings to fill data gaps is a good idea
- This task seems very complex – there is little evidence for cumulative interactions, but perhaps more for the relative importance of different factors
- Remember that it’s okay to say “we don’t know the answer”

Relative Likelihood of Alternative Hypotheses

Workshop participants were asked to examine the PSC Report *Probability of, or relative likelihood of, alternative hypotheses* (i.e. Table E-1, Peterman et al. 2010). Working in subgroups, they were asked to compare the PSC conclusions to participants' own research and the findings presented during the workshop. When participants were in disagreement with the PSC report, they were asked to give a new rating to each of the hypotheses. Since the nine alternative hypotheses from the PSC report did not exactly correspond to the twelve areas of research presented here, participants also added new hypotheses and ratings when appropriate.

Given the available evidence, participants judged the relative likelihood that a given hypothesis contributed to both the poor returns in 2009 and the long-term decline in productivity of Fraser River sockeye salmon. Participants used qualitative terms (*very likely, likely, possible, unlikely*, or *very unlikely*) to rate the hypotheses. The colour of shading reflects the degree of importance associated with each factor (dark=major contributing factor, light=contributing, but not major factor). After some discussion about how to interpret Table E-1, participants clarified that this table only considered whether or not the alternative hypotheses were likely to be contributing factors (i.e., multiple factors are likely to be involved in the observed declines). For summary purposes and simplification of results, the entire range of values given by participants are indicated in the updated table, whether or not there was a consensus. There are three important caveats regarding this exercise:

- the PSC Panel had several days to carefully review and debate evidence which led to greater convergence on ratings
- participants at the Cohen Commission workshop had only 1.5 hours for this exercise, with each subgroup doing their ratings independently, leading to a greater variation in judgments; and
- only a few participants attended both the PSC and Cohen Commission workshop, and were able to weigh both sets of presented evidence.

There was some variation in support of hypotheses, which is reflected in the updated table (Appendix D). Overall, there was a greater range of variation in ratings within each hypothesis: 14 of 22 hypothesis/timeframe combinations were given relative likelihoods that spanned 3 or more rankings. Of all the rankings assigned by workshop participants, 21 hypothesis/likelihood ratings were in agreement with the conclusions of the PSC panel and 28 ratings were in disagreement.

The main conclusions and differences about the relative likelihoods of each hypothesis are as follows:

- Changes inside Strait of Georgia were rated as less likely than in the PSC findings, and were not seen as major factor for the low returns of sockeye in 2009.
- Factors outside Strait of Georgia (especially in Queen Charlotte Sound, as opposed to the open ocean) are more likely to have contributed to declines in sockeye, and were seen as a major factor for the low returns in 2009.
- Wider ranges of likelihood were expressed for contaminants, freshwater factors, marine influences, mammal predation, and delayed density dependent mortality.
- Diseases were considered to be less important by workshop participants, excluding any influence of salmon farms / sea lice (which was not evaluated at this workshop).
- Better evidence was provided for contaminants, whose overall importance was thought to be less than reported by PSC.
- Climate change, which was not in the PSC report, was thought to be *possible* or *likely* for the overall declines, and *unlikely* to *likely* for the low returns in 2009.
- Fish/bird predation (not in PSC) was *possible* overall and *possible* to *very unlikely* for the low returns in 2009.
- En route mortality was considered to be important for spawner abundance but cannot be evaluated against the productivity measure of recruits per spawner.

Although many of the hypotheses were thought to possibly contribute to the decline, none of the available evidence points toward a single hypothesis as the only contributing factor in the decline of sockeye salmon from the Fraser River.

Research and Monitoring Recommendations

Participants were asked to examine the PSC Report *Priorities for Monitoring and Research* (and Table E-3)(Peterman et al. 2010) as a starting point for a plenary discussion. Given that twelve projects presented their research and contain recommendations within each of their respective reports, the purpose of this exercise was to broadly address priorities for monitoring and research beyond project boundaries.

The participants agreed with the PSC outcome that a co-ordinated, multi-disciplinary program should be implemented. There was consensus among the group that a focused oceanographic and fisheries research program targeting the Georgia Strait, Queen Charlotte Sound and extending along the continental shelf to the Alaska border would considerably advance our knowledge of current and future Fraser River sockeye populations. The program should focus on three core areas: 1) data collection, 2) database assimilation and integrated analysis, and 3) dissemination of information.

There was widespread agreement with the PSC report that the 2009 and long-term declines in sockeye productivity were likely due to the effects of multiple stressors and factors. Future efforts should focus not only on increasing our basic biological knowledge of sockeye salmon, but should also use information gained from the cumulative effects assessment to determine priority research areas. Certain monitoring needs (research questions) can be answered with a single (one-time, annual) study; however, others require long-term effort and monitoring. A strong emphasis should be placed on studying the entire life cycle of sockeye salmon along with their potential stressors. It was noted that in some cases, additional sample collection would be straightforward to implement by simply augmenting current data collection efforts. Data collection and monitoring efforts could be extended to other salmon species as well, increasing the potential for comparative research. Unlike the PSC report, participants felt that research efforts should be expanded outside the Strait of Georgia as a priority area, as well as increasing efforts inside the Strait.

One of the resounding issues throughout the workshop was researchers' difficulty in obtaining and understanding data from the existing databases. Considerable effort should be spent building and maintaining an integrated database, with focused research and monitoring goals in mind. The database should include the historical sockeye data with clear metadata as well as data from current and future monitoring. In order for the database to be useful to scientists, it would need to be regularly updated and maintained. As mentioned in the PSC report, it would be critical to create a framework that would allow simultaneous coordination of research across disciplines, allow for recognition of the potential for cost-effective joint sampling programs, and promote identification of synergistic effects and interactions.

The decline of sockeye salmon in the Fraser River is an issue that has captivated the province of British Columbia. Participants felt that the proposed increase in data collection and monitoring should be followed by transparent dissemination of information to scientists and non-scientists on a regular basis. Given the potential funding of new initiatives and future findings, an annual report on the State of the Salmon should be compiled and made publicly available.

More specifically, the extended research program should be co-ordinated with a U.S. program covering those areas of the Alaskan continental shelf containing high sockeye densities. Since much of the research will augment existing research programs, funding of current programs should be maintained. Further, recommendations for research should be directly compared to current monitoring and research to determine expenditures and assess their relative merits. As emphasized in the PSC Report, new data collection and analysis techniques exist that would facilitate research efforts and increase efficiency in effort and cost. An extended research effort would require that Canada acquire a new oceanographic/fisheries research vessel.

References

Faber-Langendoen, D., L. Master, J. Nichols, K. Snow, A. Tomaino, R. Bittman, G. Hammerson, B. Heidel, L. Ramsay, and B. Young. 2009. NatureServe Conservation Status Assessments: Methodology for Assigning Ranks. NatureServe, Arlington, VA.

Holt, C., Cass, A., Holtby, B., and Riddell, B. 2009. Indicators of status and benchmarks for conservation units in Canada's Wild Salmon Policy. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/058. viii + 74 p.

Peterman R.M., D. Marmorek, B. Beckman, M. Bradford, N. Mantua, B.E. Riddell, M. Scheuerell, M. Staley, K. Wieckowski, J.R. Winton, C.C. Wood. 2010. Synthesis of evidence from a workshop on the decline of Fraser River sockeye. June 15-17, 2010. A Report to the Pacific Salmon Commission, Vancouver, B.C., 123 pp. + 35 pp. of appendices.

Pestal, G. and A. Cass. 2009. Using Qualitative Risk Evaluations to Prioritize Resource Assessment Activities for Fraser River Sockeye. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/071. 89 p.

Appendix A: **List of Projects and Investigators**

Cohen Commission Science Contractors and Projects

Topic	Investigators	Agency
Climate Change	Scott Hinch, Eduardo Martins	University of British Columbia (UBC)
Cumulative Effects, Workshop Facilitation	Dave Marmorek, Darcy Pickard, Alex Hall, Liz Martell	ESSA Technologies, Ltd.
Diseases and Parasites	Michael Kent	Oregon State University
Fisheries Harvesting and Management	Mike Staley Karl English, Bob Bocking	IAS Ltd LGL
Freshwater Ecology, CU Status	Dave Marmorek, Marc Porter, Marc Nelitz, Katherine Wieckowski, Alex Hall, Katy Bryan, Eric Parkinson (independent), Carl Schwarz (SFU)	ESSA Technologies, Ltd.
Habitat analysis, Lower Fraser River and Strait of Georgia	Mark Johannes	Golder Associates
Marine Ecology	Skip McKinnell Howard Freedland Enrique Curchitser Masahide Kaeriyama Mike LaPointe Kees Groot UW High Seas Program	North Pacific Marine Science Organization (PICES)
Predators	Andrew Trites – Mammals Villy Christensen-Fish & Birds	University of British Columbia (UBC)
Production Dynamics	Randall Peterman, Brigitte Dorner	Simon Fraser University (SFU)
Status of DFO Science and Management	Edwin Blewett Bert Ionson Mike Staley	Counterpoint
Water Pollution	Don MacDonald	MacDonald Environmental Sciences, Ltd.

Appendix B**: Workshop Agenda**

Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River

Commission d'enquête sur le déclin des populations de saumon rouge du fleuve Fraser

COHEN COMMISSION
COMMISSION COHEN

Technical and Scientific Research Projects' Workshop

Morris J. Wosk Centre for Dialogue, Room 320
580 West Hastings Street, Vancouver, BC

November 30 – December 1, 2010

Workshop Objectives

1. Understanding the pattern of changes in Fraser sockeye (and other stocks) that we seek to explain
2. Communicate scientific findings among Cohen Commission researchers
3. Identify linkages among Cohen Commission research projects
4. Explore and evaluate the relative merits of the identified possible causes for the decline in Fraser River sockeye stocks
5. Explore potential interactions among possible causes
6. Identify critical knowledge gaps and recommendations for research and monitoring
7. Integrate scientific findings to date

Participant Roles

ESSA: Organize and facilitate workshop; synthesize workshop findings.

Scientific Contractors: Present technical and scientific findings within each respective research project to the collective group of researchers and peer reviewers. Apply knowledge of Fraser River sockeye, ecosystem processes, and other factors affecting survival of salmon that may have contributed to the observed decline; synthesise information for each possible cause and systematically evaluate its relative plausibility and reasons therefore; and identify information gaps. Provide constructive feedback on the findings of other research projects. Apply knowledge to integrative discussions of linkages and interactions among all projects.

Peer Reviewers: Provide constructive feedback on the findings of research projects, based on knowledge of Fraser River sockeye, ecosystem processes and other factors affecting survival of salmon that may have contributed to the observed decline. Suggest linkages and interactions among research projects.

Cohen Commission Science Staff: Listen to presentations and ask clarification questions. Provide updates on recent progress of the Commission.

Cohen Commission Participants: Not in attendance.

Public: Not in attendance.

Workshop Agenda

November 30th, 2010 (Day 1)

8:00 am Workshop start [coffee and pastries provided]

Welcome and Overview [1.5 hours]

8:15 am Introduction of participants; review of workshop objectives, agenda, principles, code of conduct, roles, and task processes. [David Marmorek; 30 min]

8:45 am Cohen Commission welcome and introduction [David Levy; 15 min]

- Welcome from Cohen Commission Science Staff
- Update on Cohen Commission progress

9:00 am Challenges and Opportunities [David Marmorek; 30 min]

- building on past work (e.g. PSC Panel)
- key ideas and questions
- cumulative effects concepts

Cohen Commission Science Research Program Presentations

9:30 am Productivity Dynamics [20 min presentation, 20 min discussion]
Randall Peterman, Brigitte Dorner

10:15 am **Break [15 minutes]**

10:30 am Conservation Unit Status [15 min presentation, 15 min discussion]
ESSA Technologies

11:00 am Fisheries [20 min presentation, 20 min discussion]
LGL

11:45 pm DFO Science & Management [20 min presentation, 20 min discussion]
Counterpoint

12:30 pm **Lunch [1 hour] – lunch provided**

1:30 pm Diseases and Parasites [20 min presentation, 20 min discussion]
Michael Kent

2:15 pm Contaminants [20 min presentation, 20 min discussion]

MacDonald Environmental Sciences Ltd.

3:00 pm **Break [15 minutes]**

3:15 pm Freshwater Factors [20 min presentation, 20 min discussion]
ESSA Technologies

4:00 pm Marine Ecology [20 min presentation, 20 min discussion]
PICES

4:45 pm Wrap-up [15 minutes]

5:00 pm **End of Day 1**

December 1st, 2010 (Day 2)

8:00 am Workshop start [coffee and pastries provided]

8:15 am Introductory remarks and plan for Day 2 [David Marmorek; 15 min]

8:30 am Predators [2 x 20 min presentation, 20 min discussion]
Mammal predation – *Andrew Trites*
Fish predation – *Villy Christensen*

9:30 am Lower Fraser Habitat Analysis [20 min presentation, 20 min discussion]
Mark Johannes

10:15 am **Break [15 minutes]**

10:30 am Climate Change [2 x 20 min presentation, 20 min discussion]
En route mortality – *Scott Hinch*
Climate Change – *Eduardo Martins*

11:30 am Cumulative Effects [1 hour]

- Examples of intended analyses
  - Qualitative
  - Quantitative (including looking at data template)
- Exploring conceptual models
  - Interactive/collaborative discussion

12:30 pm **Lunch [1 hour] – lunch provided**

1:30 pm Integrative Workshop Task [1.5 hours]
Relative Likelihood of Alternative Hypotheses
Individual review of relevant PSC outputs & subgroup discussion

- Examine relevant parts of PSC report (Peterman et al. 2010)) as a straw starting point [20 min]
    - *Probability of, or relative likelihood of, alternative hypotheses*
    - *Table E-1*
- Discuss in 2-3 inter-disciplinary sub-groups [40 min]
    - Compare PSC conclusions to participants' own research
    - Agreement/disagreement? Missing lines of evidence?
    - Are there any concerns based on what you know so far?
- Report back to group in plenary [30 min]

3:00 pm **Break [15 minutes]**

3:15 pm Integrative Workshop Task [1.5 hours]

Research and Monitoring Recommendations

Individual review of relevant PSC outputs & plenary discussion

- Examine relevant parts of PSC Report (Peterman et al. 2010) as a straw starting point [20 min]
    - *Priorities for Monitoring and Research*
    - *Table E-3*
- Discuss in plenary [70 min]
    - Go through recommendations by life-history stage
    - Consider workshop presentations
    - Agreement/disagreement with PSC recommendations?
    - Additional items needed? If so, what management decisions would they inform?

4:45 pm Wrap-up and closing remarks [15 minutes]

5:00 pm **End of Day 2**

Appendix C: Workshop Minutes

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Welcome and overview

Dave Marmorek, ESSA

Following introductions, Marmorek reviewed the workshop objectives, which included understanding patterns of change in Fraser sockeye populations, communicating research findings and identifying linkages among projects. Participants would also be asked to weigh the evidence presented to assess the relative likelihood of different factors causing the declines in Fraser sockeye. The Day 2 exercises would look at potential interactions between factors, identify critical knowledge gaps (especially those relevant to management) and integrate the scientific findings so far.

Marmorek reviewed the agenda, noting that after some initial overview presentations, presenters would take turns reporting on their findings to date, with a discussion of cumulative effects to follow. Participants would be asked to assess the relative likelihood of various hypotheses, to evaluate the conclusions of the PSC panel on the relative likelihood of various factors and to comment on priorities for further research and monitoring.

The roles of different participants – scientific contractors, peer reviewers and Cohen Commission staff were outlined. Public participants would be invited to the second science workshop in February, so it would be important for those discussions to be framed in more user-friendly language.

Cohen Commission welcome and introduction

Dave Levy, Cohen Commission

Levy welcomed researchers, stressing the importance of this workshop, which brings the researchers together to address the causes of the decline in Fraser sockeye and provide an overview of scientific research activities to date.

Explaining the Commission's terms of reference, Levy noted it has 21 participants with standing, each of which is legally recognized as part of the commission and eligible for funding. This is the largest number in Canadian history – many more applied initially for standing and they were encouraged to form groups. The Commission has been directed to conduct the enquiry without finding fault. This includes investigating policies and practices at DFO, which has disclosed over 300,000 documents to date. The Commissioner has been directed to make findings of fact, based on scientific and legal evidence, and to develop recommendations.

The Commission's interim report, which is now out, reviewed 20 past reviews and over 700 recommendations that arose from them, although it is clear that very few of the past recommendations were ever implemented. Commissioner Cohen's objective is to make this the last Fraser sockeye enquiry. In addition to the formal hearings now underway, the Commission has hosted public forums and conducted site visits along Fraser sockeye migratory routes, with visits to communities such as Kamloops, Campbell River, Chilliwack, and Victoria to hear directly from the public. The final report is due in 2011.

The Commission's science agenda has tried to build substantively on previous activities relating to Fraser sockeye, such as the Simon Fraser University (SFU) / Pacific Fisheries Resource Conservation Council (PFRCC) Think Tank last December, the March 2010 SFU Speaking for the Salmon forum and the Pacific Salmon Commission (PSC) workshop in June. The spectacular 2010 return is also very much within the Commission's area of interest as it relates to the issue of variability.

Twelve science projects have been commissioned to address risk factors that may be affecting Fraser sockeye populations. The draft marine ecology report was provided to the Commission on November 15 but the report investigating the possible impact of salmon fish farms won't start until early in 2011. Draft final reports for all other projects are due on December 15. This deadline is strict as the Commission's legal hearings depend on the science work being done in time. The peer reviewers, who will do their reviews from December 15 to January 15[3], are participating in this workshop as equal participants. Final reports are due January 31, and will be distributed via the official website.

An expanded executive summary is required for each report to accelerate the federal French translation requirements, permitting executive summaries to be posted on the website in advance of the complete reports. The plan is to create a standardized technical report series that facilitates citation, so the Commission will provide all contractors with the basic document template. A public science workshop is planned for February 23 – 25. That will cover four projects per day, allowing time for questions for clarification.

This scientific work will be integrated with the formal Commission hearings process and researchers can expect to be called as witnesses by any of the Commission participants.

[3] Peer-review comments on the marine ecology paper were due by December 1.

Levy urged researchers to bear in mind as they write their reports that the primary audience is Commissioner Cohen, followed by the 21 participants and then the general scientific audience. Each project will have three reviews, to be completed by January 15. Reviewer comments will be added as appendices, and report authors can add their own further comments if they disagree.

Levy provided a table listing the reviewers and their assignments. Every effort was made to line up reviewers' expertise with the content of assigned projects. In some cases the content is outside the primary experience of the reviewer, though this does offer the benefit of a fresh eye.

Confidentiality is important. Many of the scientists have already generated important new findings. The Commission has a carefully-planned process for releasing all the findings publicly in February, so no findings should be released until then. If there are leaks and scientists are contacted for comment by the media, they should refer all such requests to the Commission's Communications Director, Carla Shore

Discussion

Shore: Reiterated the importance of confidentiality requirements, noting that she was also available to provide advice and media coaching around the planned February release.

Peterman: Several of us will be at the SFU Think Tank on Friday.

Shore: Until the reports are published, scientists are not at liberty to discuss their research for the Cohen Commission.

McKinnell: There was extensive review of my report within my organization, so it has been viewed by multiple reviewers from many countries.

Shore: There may be leaks and we will deal with those, but researchers are not in a position to comment until the work is published. What you understand from your research and its broader implications will be different from how it will be publicly perceived, so we want to make sure it's all put out in the proper context.

Levy: We will encourage you to discuss your work publicly, but only after all the reports are written and properly reviewed.

Q/A: Reviewer comments on the draft reports will be included as appendices.

Marmorek: What if the reports are changed or the authors disagree?

Levy: A response can be added noting changes and where the authors reject the reviewers' findings.

Discussion: Should you list each comment and response individually or as summaries?

ACTION: Levy to advise whether reviewer comments and responses should be reported individually or as summary reviews and summary responses.

Levy: The intent of this workshop is to get everyone on the same page, to develop the cumulative effects analysis and to expose reviewers to the other research underway. Proceedings will be provided by December 15.

ACTION: Scientific contractors requested to keep Excel and Access files handy to facilitate translation of all figures in their reports (tables should be okay).

Challenges and Opportunities

Dave Marmorek, ESSA

It's useful to think of all the science contractors as one science panel probing the evidence. This work seeks to build on the most recent PSC report, regarding the evidence for and against different factors. Contractors should build on that report, but not be constrained by it. If those of you who attended the PSC workshop reached different conclusions (say you found better indicators), provide evidence for changing your conclusions. Understand the pattern and then seek the causes. Look at patterns over space and time and between stocks to say which suspects or combination of suspects are most likely.

The cumulative effects project, which will be discussed further on Day 2, is looking at the relative importance of different factors and which are most relevant, and also at combined effects or causal mechanisms that may be inter-related (e.g. various impacts stemming from climate change).

If the workshop produces a long list of priorities, that is not useful. Think about what decisions are affected by the information (e.g. If I knew X what would I do differently) and whether there is a role for real management experiments and if so on what scale.

There are different forms of indirect evidence that we can think about. Even if there is imperfect evidence, can we still see contrast across different stocks or across time or space?

Research program presentations

Productivity dynamics of sockeye salmon: patterns that need to be explained

Randall Peterman & Brigitte Dorner

This presentation covered data and methods, spatial and temporal patterns in productivity for Fraser and non-Fraser sockeye stocks, stocks with similar patterns, and conclusions and an emergent hypothesis.

Background: The disastrous 2009 Fraser sockeye return (1.5 million adults, the lowest since 1947) was just the latest in a decades-long decline in abundance and productivity (returning adults per spawner) for Fraser sockeye. The Fraser saw peak runs of up to 40 million sockeye every fourth year until the 1913 Hells Gate slide. Following that event, decades of slow rebuilding continued through the 1980s and then changed to a decline. The 4-year moving average for adult returns per spawner hovered around 5 or 6 adult returns per spawner from the late 1960s until the early 1990s, then declined steadily to less than 1 in 2009, before returning to about 6 in 2010. (This was the overall pattern across all Fraser sockeye stocks – trends differed among individual stocks.)

The study looked at 52 sockeye stocks with decent time series of spawners and the resulting adult recruits, covering an area extending from Lake Washington in Seattle to Alaska (19 of these stocks were from the Fraser River). It looked at standard productivity indices (recruits per spawner; plus for the Fraser only, there were data for effective female spawners, which is a better measure). The stationary Ricker model (it assumes a and b are stationary) was used to calculate annual residuals. The Larkin model was included as an alternative to the Ricker model to investigate possible delayed-density dependence. Both the Ricker and Larkin models remove within-population, within-brood-year density-dependent effects to show what other variations (non-density-dependent effects) there are in survival rates. In addition, the Larkin model removes within-population density-dependent effects that occur among successive brood lines (across up to three successive brood years).

We know the ocean environment is not stable and we're interested in long-term signals, but those signals are clouded by observation error and natural variability, both of which are high-frequency patterns compared to the long term trends. Kalman filter estimation, a standard method used in engineering to extract high-frequency noise from noisy data, was applied to the Ricker model to separate the long-term, low-frequency signal from the noise.

To test this method, the study built on previous work that simulated performance of parameter estimation procedures for both the standard Ricker model and the Kalman filter version of it. The Ricker model over-estimated productivity during low productivity periods (and under-estimated productivity when it was high), whereas the Kalman filter results provided a better fit with the actual data. In effect, this work showed that the Kalman filter was good at tracking changes in productivity over time.

The study applied the Kalman filter estimation method to both the Ricker and Larkin models, fitting a time-varying assumption for the *a* parameter (productivity) in both models. Examples of data processed with these various methods were then compared and the time trends in productivity were much clearer when the high-frequency annual variability was removed.

In addition to looking at trends for specific stocks, they looked for shared trends (or how individual stock trends deviated from the overall trend). Early Stuart showed a long downward trend starting in the 1960s. Most of the individual Early Summer stocks showed downward trends. An exception is the Pitt River stock, which increased. Most Fraser Summers showed an upward trend until the early 1990s, followed by a downward trend. Harrison sockeye also showed increasing productivity since the early 1980s. Quesnel showed a different pattern (little decline since 1990). (The graphs all reflect standard deviation units so that the stocks could be compared).

Lake Washington stocks showed a dramatic decrease in productivity starting in the late 1990s, a pattern shared by Barkley sockeye stocks. Sampling has shown that juveniles of the Lake Washington stock migrate outside Vancouver Island, not through Johnstone Strait.

Sockeye stocks from the BC Central Coast, the Skeena and the Nass all show similar decreases in productivity from the late 1990s. Some of the declines started earlier (e.g. Rivers and Smith Inlets), and some of them had a temporary increase in productivity prior to decreasing sharply in the early 2000s.

Further analysis of the Fraser sockeye trends showed that one principal component of the pattern (a long downward trend since the mid-1980s) accounts for 65% of the variation, while a second component (increasing trend in productivity until around 1990, then decreasing) explains 23%. Together these account for 88% of the changes over time, so they represent strong signals.

These trends, as measured in standard deviation units and based on the smoothed Kalman filter, were also presented visually to demonstrate shifts in productivity over time for other BC, Washington and Fraser stocks. For the Fraser, this analysis showed declining productivity for all stocks since around 1990, except for the Harrison and Pitt river stocks, which showed increasing productivity.

Conclusion #1: Most other BC and Lake Washington sockeye stocks show a similar pattern of declining productivity to that of most Fraser River sockeye stocks, especially since the late 1990s.

For 8 Fraser stocks that have juvenile data available, a similar analysis of spawner-to-juvenile and juvenile-to-recruit data showed very high correlation between juvenile-to-recruit and spawner-to-recruit trends, suggesting that most mortality associated with these productivity shifts over the whole life span is occurring in the late juvenile to adult life phase (although it could possibly represent delayed mortality from a freshwater agent to which they were exposed earlier).

An analysis of data for Tahltan age 1+ and age 2+ smolts compared survival rates for those that have the same brood year but different ocean-entry year and found a correlation of r = 0.24. But when data for smolts with the same ocean-entry year were compared instead, the correlation jumped to 0.56. The latter, higher correlation when juveniles have a shared ocean-entry year vs. the same brood year indicates that shared marine or late freshwater conditions dominate changes in productivity of these sockeye stocks.

Conclusion #2: Most of the temporal changes in recruits/spawner arise in the marine and or freshwater post-juvenile estimation stages. The Tahltan analysis indicates this is unlikely due to delayed mortality from a freshwater agent. Furthermore, the similarity of the productivity decline throughout Washington and BC sockeye stocks, especially after around the year 2000, suggests poor ocean conditions outside of Georgia Strait. This conclusion differs from the PSC workshop in June, because they have these new data now.

Harrison sockeye, which have shown an opposite trend in productivity, enter the sea as fry (not smolts) and are believed to migrate out through Juan de Fuca Strait, not Johnstone Strait.

These results of a shared time trend in productivity of B.C. stocks, but the opposite trend for Alaskan stocks, would be consistent with a paper by Mueter et al. (2002, Can. J. Fish. Aquatic Sci. 59:456), which linked productivity declines in BC to increases in stock-specific locations for summer sea surface temperature (SST) when juveniles enter the ocean. Specifically, changes in individual sockeye stock productivity ($\log_e$(recruits per spawner)) per degree Centigrade increase in summer SST (SST coefficient) were graphed for stocks ranging from Washington and BC north to Alaska. The resulting graph showed a clear pattern of increasing productivity for Alaska stocks with increasing SST, and decreasing productivity for BC and Washington stocks with increasing SST. Potential causes of this BC trend include a zooplankton-poor or predator-rich environment when waters are relatively warm off the coast of BC.

Brigitte Dorner

Further analysis of sockeye productivity trends in relation to changes in summer sea surface temperature looked at the bigger picture coast-wide.

Two types of animated graphs were shown. First was an animated map of the time-trend in individual stock productivities for BC, with one map per year starting in 1950. During certain periods, geographical clusters of Fraser River stocks (based on their spawning-ground location) appeared to change in similar ways. The other animated diagram showed stock-specific productivities since 1950 (as derived from the Kalman filter analyses), illustrating in yet another way that when productivity for Fraser River and Washington stocks were generally declining, those in Bristol Bay were increasing over the same period.

To address potential skepticism over the Kalman filter and Ricker Larkin models, other data were also analyzed. Raw data for $\log_e$(recruits per spawner) show the same pattern as Kalman filter analyses, with southern and Fraser sockeye stocks (except Pitt and Harrison) decreasing over time, and Alaska stocks increasing. The pattern for BC non-Fraser stocks was similar to that for the Fraser, but additional patterns at smaller geographical scales indicate there may also be some underlying freshwater patterns too.

Conclusion #3: Alaskan productivity patterns are the opposite of those for the Fraser and other southern stocks. This is likely due to a shared large-scale driver within each region, possibly relating to climate.

Overall Conclusions: There were three periods of extended decreases in productivity: One starting in the mid-1960s affected Early Stuart and Early Summer stocks like Bowron, Fennell, Nadina, Pitt, Seymour. A second from the late 1980s to around 1990 affected the Summers (Chilko, Late Stuart, Stellako), Birkenhead, and the Barkley Sound, Central Coast, Skeena and Nass stocks. A third period starting in the late 1990s affected most BC and Lake Washington stocks except the Harrison and Pitt stocks, which have been increasing. This has happened at the same time as higher SST.

The emergent hypothesis is that widespread shared trends since the 1990s and 2000s are likely due to large-scale forcing in the ocean, plus possibly some shared forcing in freshwater but in the post-juvenile estimation stage.

Discussion

Routledge: Regarding the high proportion of the change explained by the principal components – perhaps this is because it was smoothed data. If you used the raw data, would that be lower?

Peterman: Yes.

McKinnell: This relies on two different time series – one based on observations of spawners and one on observed returns. It's not clear how the signal and noise relating to the observation of spawners is captured in the model.

Peterman: There is some overlap since recruits consist of spawners plus catch. To get total returns you have to use expansion factors. I'm not sure it would have a huge influence but we are sensitive to the issue. Recruits per spawner show the same pattern but the Kalman filter turned out to provide the best method for tracking it. This is not how nature works – all models are wrong of course – but they are useful nonetheless.

Cox: What is the error range around the estimates?

Peterman: The trends are still prominent.

Routledge: I understand the concern but it's an over-simplification. This is about smoothing the rough points, not an issue of trying to capture true biological processes.

Peterman: The raw data show a very similar pattern – with shared spatial variation – it's all in the report's appendices.

Cox: Did you try instead letting *b* be free instead of maintaining a fixed *b* value?

Peterman: That was done and it does not explain the variation in the data as well as the *a* parameter. You can't estimate simultaneously both the *a* and *b* parameters in a Kalman filter version of either the Ricker or Larkin models.

Staley: Did you consider the shift in estimating recruitment for Fraser sockeye since the mid-1990s? Prior to that, apparently there was no en-route loss. Since then, recruitment is estimated as catch plus the Mission escapement estimate. How did you deal with that shift in accounting for the trends?

Peterman: It would only be relevant if en-route losses were occurring at a rate that would throw the trend off.

Marmorek: If they hadn't added the en-route losses back into the estimates of recruitment, the trend would have been worse before the mid-1990s.

Q/A: The first record of pre-spawning (en-route?) mortality was the 1992 return year.

Marmorek: Did you see any pattern consistent with the Pacific Decadal Oscillation?

Peterman: We did not look at that.

Routledge: It seems the important conclusion was that the problem is in the ocean. I'm inclined to agree but I'm not sure how strong the evidence is. Tahltan was only one stock, which makes me uneasy.

Peterman: There were others that were not shown due to limited time.

Routledge: That eases my concern.

Peterman: There are not a lot of stocks that line up such that it allows you to do that analysis.

Reynolds: Was Dorner's work indicating more of a leaning towards freshwater?

Dorner: There are also some patterns in freshwater, just from looking at it spatially, but I'm not saying there is not also the large-scale ocean pattern. The freshwater pattern varies across watersheds, in some cases covering stocks that don't have the same ocean migration routes.

Peterman: These are not inconsistent messages. There are certain years where the interior BC and far northwest stocks are all red together (decreasing productivity) for a few years. They share the geographical area but we don't have all the data. Brigitte Dorner also did standard cluster analyses and you get different groupings of stocks, depending on which clustering methods were used. Nothing produced a different picture than what you saw in the animations.

Cox: Harrison sockeye go out as fry. Do Pitt sockeye do the same?

Johannes: They go out as smolts.

Cox: Is there anything similar about their out-migration timing?

Peterman: I unfortunately have no information on Pitt sockeye. There is some evidence for Harrison migration patterns, though. Beamish's sampling studies found Harrison juveniles in northern Georgia Strait later in the season than other Fraser sockeye. They also go to sea as fry rather than as smolts, and rear more in the Fraser River estuary instead of migrating directly out into the Strait, though we don't know very much about them.

Pickard: When we do the cumulative effects project and we use your data, there is concern that the findings will be out of whack if we use Kalman filter data for when the impacts are actually happening.

Peterman: You shouldn't just use one data series; instead, examine different assumptions (i.e. use multiple dependent variables and compare results).

Dorner: If the series changes slowly, probably the lag doesn't matter as much.

Staley: Re the little evidence for delayed density-dependent effects question, using cyclic vs. not cyclic models will make a significant difference – there will be a debate on this.

Peterman: The difference in data from using Ricker vs. Larkin can be substantial (Larkin delayed density dependent effect across brood years). The productivity parameter stayed high in recent years for Quesnel with Larkin, but with Ricker it went down. We found there was quite a difference between the models, but in this analysis it was only important for Quesnel. Larkin seems better for Quesnel only. Carl Walters appears to have backed off on his previous conclusions about the prevalence of the advantage of the Larkin over the Ricker model and he agrees that Quesnel is about the only stock where delayed density dependence makes a difference. We have to do sensitivity analysis for everything we do because we don't know what the true underlying dynamics are. So we use raw and processed data and if they are different, we examine why.

Conservation Unit Status Assessment

Katherine Wieckowski, ESSA

This analysis reviewed several methods for assessing conservation status, using the 36 Fraser sockeye Conservation Units (CUs) proposed by Holtby et al (DFO is still considering reducing these.)

The approaches reviewed included the DFO paper on indicators of status and benchmarks for CUs. This was developed by Carrie Holt et al, and elements of it are included in the paper by Sue Grant. The second approach was Pestal and Cass's paper on the use of qualitative risk evaluations to prioritize assessment activities for Fraser sockeye. The third approach was the more generic NatureServe paper by Feber-Langendoen et al, which was eliminated as not viable/ideal.

Recognizing that all methods have strengths and weaknesses, four evaluation criteria were used for the analysis: ecological relevance (to life history, habitat usage, etc.; the method for setting benchmarks; the data needs for that method and how available is the data required for all CUs; and feasibility of implementation (how realistic is it for DFO to implement).

Ecological relevance: Holt et al and Pestal/Cass both address abundance, trends in spawners, distribution and fishing mortality. Holt does not address genetic diversity, only life history diversity. This raises the question of indirect methods and whether it is okay to have proxy indicators, and with limited resources, this should be considered. Pestal included habitat condition but didn't specify what the habitat condition indicator was. Holt did not address habitat, which is covered under Strategy 2 of the WSP.

Data needs, uncertainty and availability: The availability of data required for Holt et al and Pestal/Cass was summarized in a table, which indicated more gaps for the former approach. Both approaches make noteworthy attempts to account for uncertainty.

Benchmark setting: Holt takes into account uncertainty in the data in setting benchmarks. The advantages include that the benchmark is more reflective of that CU and takes into account uncertainty. But you need a lot more data to develop these benchmarks vs. Pestal/Cass, which takes a more qualitative approach to develop benchmarks. Both have clear consistent rules to avoid comparing apples and oranges, so both are defensible. The Holt et al approach didn't reach consensus on metrics to use for distribution and also presented several possible benchmarks for fishing mortality.

Feasibility: Holt is very technical, so it requires a lot of effort to roll out in order to determine status, raising the question of whether it is reasonable to expect DFO to implement a method that is so rigorous and data intensive across all CUs, given limited resources, data and funding. Grant et al applied a modified version, using only abundance and trends in abundance, and weren't able to determine status for 15 CUs. Pestal/Cass applied their method to all CUs and were unable to assess 11 CUs, as they had a broader array of indicators and could thus better deal with the ones that are data-poor.

Considerations moving forward include ease of dissemination and transparency, as there needs to be trust that CU status has credence. Other issues include data gaps, resources for monitoring and analysis and indicator roll-up (weighting).

Pestal and Cass plotted out an assessment that combined status and uncertainty for each CU. Status for the 36 CUs was also mapped geographically.

Habitat status:

Population status is a function of survival, which is a function of habitat condition. Habitat condition in turn relies on a number of freshwater factors. One thing that has not been fully developed is how to assess habitat and incorporate the results in an assessment of stock status.

Landscape-level indicators were used to assess the quality and quantity of migratory, spawning and rearing habitats. These indicators are based on mapped habitat features extracted or derived from provincial GIS data sets and DFO lake productivity estimates.

Migratory habitat: Factors examined included CU migration route/distance, thermal profile of adult migration routes and historical spring air temperatures at nursery lakes.

Spawning habitat: Factors included the extent of sockeye spawning reaches for each CU, whether it was lake outlet (buffered) or tributary/inlet, and the ratio of each spawning category relative to total spawning extent in the CU.

Rearing habitat: Factors included combined surface area of nursey lakes for each CU and average juvenile productivity in smolts per hectare.

The results for each type of habitat for each CU were presented in a dashboard summary that shows how results for the CU line up with all other Fraser sockeye CUs. Three indicators were taken from each of the three categories (migration distance, ratio of lake buffered spawning and lake area). Instead of trying to roll them up into one composite index, the approach was to try to show where a CU lay with respect to all three dimensions. Migration distance was strongly correlated with air temperature with both upstream and downstream migrations, so was considered a good surrogate of temperature issues. Nursery lake area strongly correlated with total juvenile production.

The idea was to see if it was possible to link those CUs that were doing well with a habitat index. However, the results showed no consistent pattern in how the CUs were doing from a conservation perspective and how they were doing from a habitat perspective.

Discussion

Peterman: Were the terms of reference for this project to assess the status of Fraser stocks?

Wieckowski: Initially, but it was not possible to do that in the permitted time frame, so we reviewed others' assessments. The Grant paper was just out, so we looked at whether we agreed with their assessment. From a preliminary walk-through, Grant agrees fairly well with Pestal.

Routledge: Nothing stands out in terms of mistakes in conservation status?

Wieckowski: One of the things in benchmark setting is to decide whether it is conservation- or management-oriented, and then to consider how to weight the criteria accordingly. If you're doing precautionary management, the trend in abundance would be weighted more heavily than simple abundance because you don't have full time series (i.e. the data peak may not be the real historical peak). DFO is still deliberating over benchmarks and metrics, so it's hard to say. The method is very scientifically robust, but they haven't rolled it out completely, so it's hard to say right now where they're at.

Hinch: The habitat indicators suggest the stocks with shorter migration routes should be doing well, but that's not happening – and many are in fact doing worse. It's not so much distance but migration timing that seems to be important.

Wieckowski: Yes, we can look at that, though I'm not sure how available those data are.

McKinnell: Why is Chilko experiencing such high lake productivity?

Peterman: It's been suggested that this is linked to changes in the lake due to lower outflows of glacial till into the lake, thereby clearing it up and allowing more light in for primary productivity.

Staley: I have trouble seeing the relevance of these indicators, since you can't move a lake, for example. The Grant paper…? set up abundance trends, fishing mortality and distribution. ?…ruling out where the stocks have no data. The distribution one…? still alive, especially for the bigger CUs.

Wieckowski: I agree on the distribution question. The concern with Grant/Holt is what happens where there is no data. Pestal can come up with a better uncertainty score with less data, if distribution is important for assessing status

Martin: You could also look at fishing mortality as a surrogate productivity indicator over time.

Fisheries & Fisheries Management (Fraser & Bristol Bay)

Karl English, LGL

To assess whether or not the Fraser sockeye management framework was solid, a number of factors were examined, including catch monitoring, pre-season forecasting, in-season abundance estimates, escapement enumeration, escapement targets, over-harvesting and Cultus recovery efforts. For Bristol Bay, pre-season and in-season forecasting, escapement and goals were reviewed.

Key metrics: For each of the above elements, it was necessary to define what was meant by accuracy (were estimates biased and were they based on modeling or known values), precision (what were the quantitative bounds) and reliability (level of confidence in estimates, quality and quantity of data).

Quality of catch estimates: A table summarized the assessed accuracy, precision and reliability of catch estimates for all Canadian fisheries from 2001 to 2009, along with the relative proportion of Canadian TAC (Total Allowable Catch) taken by each fishery. Many of the values for precision were unknown. There was good accuracy for both First Nations fisheries. A closer look at commercial fisheries showed inconsistent quality across gear types (e.g. sales slip in net fisheries not representing total catch).

Pre-season forecasts: A summary of forecast error (mean absolute percent error) for the 19 Fraser sockeye stocks from 1990 – 2009 showed similar error rates for most stocks except for those in the Late Summer group, most of which were much higher. Error rates for each run-timing group and for total Fraser sockeye stocks (40%) were also provided.

A second table summarizing the proportion of the return variation for each stock that was explained by forecasts from 1980 to 2009 (i.e. prediction ability of forecasts) showed significant differences between stocks. Forecasts for Late Shuswap (a strong cyclic stock) had the strongest predictive relationship. The relationship was better for the run-timing groups and for the Fraser overall, but not so much for individual stocks.

In-season run-size forecasts: Median percent error (accuracy - 1997-2009): In-season estimates for Early Stuart started high but correct rapidly by mid-July. (Does this allow enough time to plan the fishery?) For Early Summers, estimates have been under-estimating abundance early in the season. By the time they correct, it is too late for a fishery. Summers start with a large over-estimation and significant correction in late July to mid-August. There is lots of opportunity to harvest from there on. For lates, there was a lot more variability. Estimates start off close and then tend to go down.

Measures of precision for the four run-timing groups, (median absolute percent error, 1997-2009) show that in-season forecasts can be off by 20 to 50% for most of the season, including the critical period when the bulk of fishing must take place in marine areas. Reliability of in-season forecasts also improves for all run-timing groups towards the end of the season.

Basis for recent escapement goals: Goals for Fraser sockeye low escapement benchmarks and fixed escapement targets are set by the FRSSI (Fraser Sockeye Spawning Initiative) model.

Summaries were presented showing the four-year moving average escapement for each of the four run-timing groups from 1960 to 2008, relative to the interim limit and target reference points for escapement. In recent years, only Early Stuart escapement has fallen below the limit reference point, although the Early Summers are getting close.

Run size and exploitation rates: Comparison of run size and exploitation for each of the four groups show that over-harvesting may have been an issue in the 1960s, but not recently.

Bristol Bay review: There are substantial differences between the Fraser and Bristol Bay fisheries. The latter has fewer fisheries, gear types and sectors, less mixed-stock fishing issues, very small sport and First Nations subsistence harvests and few in-river fisheries. Area managers have very timely and accurate data on catch and escapement, clearly-defined escapement goals that vary little between years and unambiguous authority to open and close fisheries.

Their pre-season forecasts in some cases are not as good but they rely mostly on in-season management. Their performance in meeting escapement targets has been pretty good in terms of staying above minimum escapement levels and usually in the range close to the upper target.

Information/evidence gaps: These include uncertainties around en route losses. Given the potential scale of the latter (greater than total escapement or total catch in some years), this is probably much more of an issue than the amount that they are off with the estimates of catch and escapement, which are not perfectly monitored but pretty reliable estimates. The numbers for en route losses are best guess based on very limited and questionable data.

Discussion

Staley: Where the quality of data is unknown, it may be unknowable or simply unknown because no one has done the work. You should distinguish between the two.

English: For commercial fisheries, there are aerial surveys and reported catch rates. You can get reasonable estimates of effort for some gear types and catch rates. There is no estimate of precision and no verification but a good proportion of the fleet is reporting. We could try to verify the data but the challenge is getting the information from FOS (DFO's Fisheries Information System) in time for this project.

Staley: Re the pre-season forecasts, it's surprising that the performance of the forecast for total Fraser sockeye run size is not significantly better than that for individual stocks.

English: The median absolute percent error was lowest for the overall Fraser run.

Peterman: The r-squared values in the bar graph "significance of forecast vs. return relationship" seem high.

English: The data were from a document that shows pre-season and post-season numbers.

Peterman: The pre-season data may actually be in-season estimates, so check that those are actually the pre-season forecast numbers because I've never seen a correlation that high for forecasting on the Fraser.

That could also be that it's based on data going back to the 1950s, not just the last 30 years.

Cox: How are en route losses calculated?

English: For some, it's based on Mission counts against spawning ground counts minus catch. For some recent years, estimates are based on telemetry data.

Cox: How does that figure in calculating recruits per spawner?

English: Total returns are based on catch, escapement and en route mortality.

McKinnell: Highly cyclic stocks have high r-squared because of the contrast between very high and very low years.

English: That's certainly the case for Shuswap. There is more detail in the report, which definitely shows that Shuswap has the biggest error and the highest r-squared.

McKinnell: Few or none of the pre-season forecast methods consider ocean conditions.

English: They are based on stock recruit relationships, though there is some additional consideration. 2006 was a good example: the models suggested a good return for Quesnel but there was concern over the small size of outgoing smolts and the return was indeed dismal. But basically one of several stock recruit models are used. Managers don't pay much attention to the forecasts – they rely on in-season estimates to manage fisheries.

Marmorek: It's important to think about how the information will be used: pre-season forecasts are used to modify expectations but in-season information is used to manage harvest.

Status of DFO Management and Science

Edwin Blewett, Counterpoint

This presentation covers three projects that focused on the period from 1985 to 2009. The first evaluated DFO management of Fraser sockeye against stated objectives; the second detailed science and research expenditures on Fraser sockeye (not an evaluation); and the third assessed DFO's ability to carry out applied sockeye research.

1. Evaluate DFO management of Fraser sockeye against stated objectives

This study evaluated management against stated objectives, with a focus on objectives relating to stock management. PSC objectives were interpreted as DFO objectives and expenditures of other organizations like NSERC were included but not evaluated.

Method: The approach was to identify stated management objectives, define evaluation indicators and the data required to inform them, then submit information requests (those started in July and significant data gaps remain, but we are proceeding with what we have). Further steps included organizing the data, evaluating it, interviewing key contacts (time will not likely allow for this step) and writing up the results.

DFO's stated objectives were sourced from key agreements and policy documents, plus annual salmon IFMPs (Integrated Fisheries Management Plans), and grouped under nine headings: conservation, international, First Nations, stock management, fleet management, economic, allocation, process and programs. Not all objectives were included in the evaluation: the focus was on retaining those objectives: most useful to the Commissioner, focused on stock management, specific to Fraser sockeye, on "ends" vs. "means" objectives, on specific (vs. general) objectives and on the biggest impacts and effects.

Information requirements: A contract was issued to an Ottawa consultancy, BMB Data Consulting Services, for the massive job of extracting Fraser sockeye expenditures from overall management expenditures from 2005/06 – 2009/10 for these projects. The information available doesn't include FTEs, but it does include salaries.

2. Fraser sockeye science/ research expenditures

This study details but does not evaluate expenditures by DFO and other agencies on Fraser sockeye science and research by program and activity, with much of the information derived from the earlier-noted contract. The BMB data are for a much shorter period than ours. No expenditure data other than the BMB was available, however.

Method: The approach included formulating information requests, categorizing expenditures by program and activity, assessing changes and trends over time and writing up the results.

3. Assess DFO ability to carry out applied management and science/research

This project sought to determine DFO's ability to carry out applied sockeye science/research, given the financial and human resources allocated to the task. It is a forward-looking assessment, whereas the previous two were retrospective.

Method: The intended approach included formulating information requests (there was very little information on human resources) then defining the programs and activities required to manage Fraser sockeye, what resources were needed to do this well and to compare this to what DFO was actually doing (gold standard approach). But it was decided that with the data available, it was more realistic to take a "marginal" approach focused on identifying shortfalls or gaps and areas where programs and resources could or should be adjusted.

Information requirements included human resources, salaries, Fraser sockeye science/research activities and budgets.

Preliminary graphs were presented summarizing total annual Fraser sockeye expenditures from 2005 to 2009 by organization and by activity (managements science, habitat, enhancement and administration).

Preliminary results were presented for several of the performance indicators, including actual escapement relative to the final in-season target for the four run-timing groups, a comparison of US target vs. actual harvest share, total science spending as a percentage of total spending for the Region (some decline in recent years), Fraser sockeye science as a percentage of total science expenditures, and total expenditures on Fraser sockeye as a percentage of total Region expenditure.

Information gaps include gaps in evaluation data (e.g. post-season spawning escapement targets); expenditures prior to 2005 and very little information available in electronic format or updated databases.

Key research/ monitoring needs: If evaluation is valuable, a good evaluation framework is required that covers criteria, indicators and what data need to be collected to inform evaluation. A single, regularly-updated evaluation database is needed.

Discussion

McKinnell: Did you consider looking at the number of primary publications by DFO authors? You will likely find that the amount of science done as a proportion of the actual work they do has been shrinking over time. It would be useful to see a graph on the number of published articles on Fraser sockeye where DFO scientists were the senior authors.

Peterman: One of our recommendations was that all agencies, including DFO, the PSC, Alaska, and Washington State, need to get all their data together in one database, standardized (e.g. column headings). There were many errors in the data and because there are large-scale processes involved, we need to get the information in cross-jurisdictional databases.

Blewett: These questions require ongoing evaluation, not one-off studies.

Christensen: We keep hearing about over-escapement and that stocks are doing well when there is lower escapement. What are the economic consequences of over-escapement is a reasonable question to ask

Blewett: We would need to do that analysis: in years when there is very high escapement and foregone harvests, is that as serious as not meeting escapement targets.

Hinch: How do you get NSERC information specific to Fraser sockeye?

Blewett: We asked NSERC but have not received an answer.

Hinch: Other groups are picking up the ball that DFO is dropping, with significant costs for university research. How do you bring that into the picture?

Routledge: Maybe instead of looking at costs or just tracking published DFO papers, you can also compare that to how many other papers are published.

Peterman: What is the purpose of this part of the assessment? Collectively we aren't spending enough on Fraser sockeye – is that the purpose?

Blewett: In part. It's to describe the state of science and research – is there enough of it.

Peterman: You also need to ask the managers. It's one thing to do a lot of research and another to see if it's informing management. The number of studies won't measure the latter. We need that input as well or it's missing the point.

Blewett: The evaluation is focused on management, not science. The third project gets at research capacity.

Peterman: That's a different question than what is needed to make management decisions. The benefits of that research can't be measured by dollars spent.

Blewett: That's a massive piece of work.

Staley: The bulk of expenditures are on management (e.g. spawning ground enumerations). Most are directly management-related.

English: Our report may help a bit. We will document what information there is to support escapement monitoring, in-season abundance estimates and catch monitoring. You will see clearly that the amount of documentation supporting each of these components is strikingly little. Most recent effort has been focused on defining the CUs and now the benchmarks. The other piece done regularly is the pre-season forecast. Outside of that there are not many documents that describe other efforts. The PSC is now drafting a document that describes the in-season assessment systems. The fact that was not documented before is a concern.

Marmorek: Given the difference in performance for Bristol Bay, it would be interesting to look at how much they spend on science as a reference point.

Wieckowski: Beyond how much is spent in the US, there is a structural difference regarding US managers and their powers, so just looking at spending doesn't do it justice.

Blewett: We are looking at the East Coast and what is comparable.

Cox: The Columbia River would be comparable

McKinnell: The difference between Canadian and US research expenditure is in orders of magnitude.

Staley: Our project needs to compare expenditures in the Canadian context.

Routledge: A concern about a focus on science that informs managers in terms of short-term decisions is that you lose the ability to do fundamental science that provides important long-term insights that filter down to the management level. It should not be too short-sighted.

Peterman: You can focus on what is relevant to management but look at what this means over the long term

Peterman: The important issue is how this informs Cohen's decisions. Bristol Bay stocks have a much stronger pattern over time, so they are easier to forecast and manage from this and other respects logistically. So we need to be really careful to not compare apples and oranges.

English: Our report will highlight how different they are and how complex the Fraser is in terms of the people involved. Alaska managers have full control and simple targets. They spend a tiny fraction of the value of the fishery on management and the environmental, social economic and other issues are all very different.

Diseases & parasites

Michael Kent, Oregon State University

The task was to report on infectious diseases in general and those affecting Fraser sockeye in particular and assessing the role of infectious diseases in mortality, especially in wild fish.

The approach included a review of peer-reviewed literature, government documents and PBS case reports and interviews with DFO fish health specialists.

The study reviewed each pathogen by taxonomic units, including arbitrary (low, medium, high) potential risk assessment for each. It is rare to have a quantitative risk assessment, so it's a very subjective approach. Much of the report consists of a summary for each pathogen, plus the risk assessment. It also includes a review of approaches used to document pathogen-associated mortality in wild fish, a review of environmental associations with these pathogens, conclusions and recommendations

Key metrics: These include whether the pathogen is virulent to Pacific salmon and to sockeye in particular; occurrence and prevalence in wild salmon and in the Fraser; how was this determined (literature reviews and interviews); and how these metrics are connected to biologically-justified hypotheses.

The list of pathogens includes a number of viruses, bacteria, fungi, protozoa, myxozoa, worms and arthropods. Documented or suspected freshwater outbreaks include IHN virus in fry. In the ocean, *Parvicapsula* is worth looking at (about 15 years ago, there was a report documenting mortality in Barkley Sound pre-spawners – returning fish were trapped and suffered heavy infection) and sea lice (Barkley Sound prespawners). There are very few documented reports of mortality specifically caused by parasites or other pathogens in BC, except when you look at pre-spawning mortality. Work in Oregon on returning fish shows a long list of pathogens associated with pre-spawning mortality, with losses of over 50% in some cases.

High risk diseases: There are few pathogens documented or suspected of killing Fraser sockeye (ones that are recognized as killing sockeye and suspected of occurring in the Fraser). These include IHN (freshwater virus); Bacterial kidney disease (freshwater and ocean), Furunculosis (freshwater and ocean) and Vibriosis (marine). There is very little data on how the latter impacts wild salmonids, but it is highly lethal for farm salmon if they are not vaccinated. Parasites include *Parvicapsula* (freshwater, marine), Ich (freshwater), PKX (found previously in kokanee; freshwater and marine) and sea lice. Not a lot of effort was devoted to sea lice because it is expected to be dealt with in-depth in the fish farm paper. It is very controversial there is no information specific to sockeye salmon.

Assessing impacts of chronic infections (e.g. parasites): Criteria for investigations include having adequate data on prevalence and abundance; infections that are easy to identify and evaluate and which persist; and temporal studies, which can be difficult to do with salmonids, since you need to look at what is happening over time.

Parasite distribution issues include abundance vs. prevalence. Normal is not normal for parasites (negative binomial distribution) and having many animals with no or light infections, but few with heavy infections. A 1971 Crofton paper compares predicted and observed frequency of the parasite, based on data from lightly-infected animals, to provide parasite-associated mortality.

Impacts of highly-virulent pathogens: Virulence is documented in lab studies and prevalence needs to be considered at various life stages. Environmental influences include temperature (most pathogens increase with temperature, as do hosts vectors, while temperature influences the immune status of fish). Pollution and contaminants may also play a role. Organic eutrophication can increase intermediate hosts and opportunistic fungi and bacteria. Toxicants can impair fish immune systems but may also kill invertebrate hosts. Land use practices are a key consideration, as temperature and organic loads influence prevalence and abundance of pathogens, directly and indirectly. Land use practices have also been strongly linked to these changes in other systems.

Conclusions: Most research on disease has focused on hatchery fish and there is minimal data on the marine phase. There have been few documented outbreaks for BC sockeye and limited survey data do not point to increases. Many potential pathogens could cause wild mortality and Kent agrees for the most part with the PSC's potential list.

Recommendations include more research, especially in the marine phase; continued surveillance of farmed fish; surveys and data collection so that established methods can be applied; collaborative research with ecologists, oceanographers and epidemiologists to investigate links of prevalence and abundance with environmental factors and land use practices.

Discussion

Reynolds: How specific are these pathogens to specific species of salmon? And is it a good idea to restrict the scope to known cases involving sockeye?

Kent: I don't exclude any from the list. Where sockeye are less susceptible to disease, I would put it as a moderate risk assessment.

Reynolds: Is that a good criterion to use? If studies show sea lice can infect other species of salmon, it might be useful to tackle it head-on, to take sea lice out of the picture.

Kent: There are some studies, with pretty empirical data. Others just reported it in pinks. It would be good to separate whether the studies document that sockeye are not susceptible or whether it was just not seen.

Q: Will the fish farm study go ahead?

Levy: It will go ahead in January. It will be timed to be ready for the aquaculture part of the hearings. The implications for us are that we will have to re-open the cumulative effects analysis.

Routledge: It's correct that there is no evidence re sea lice and Fraser sockeye but there are studies on impacts in Atlantic salmon, which are relatively large, and they can cause mortality, so I wouldn't want to discount it.

Routledge: Is there any evidence of vectors for disease to consider?

Kent: You can show in lab studies that *Lep* can jump from adult fish. Some pathogens for example are transmitted via leeches but can also transfer through the water. Could sea lice be transmitting disease? In freshwater, there have been increases in snail-borne disease due to increasing numbers of snails. There is the whirling disease story in the US Rockies, linked to land use and eutrophication. Arthropods as vectors is also worthy of addressing.

Reynolds: A recent paper showed sea lice do jump from host to host in the wild. Male *Lep* jumped from pink to coho smolts.

Peterman: Re recommendations 3 and 4, a problem with pathogens is the need for a rigorous survey program over a long period to see something interesting. It would be useful for the Commission to know how you would recommend dealing with this given limited dollars.

Kent: One concern is epizootics and outbreaks of new pathogens. The other one (work was done with coho parasite impacts on over-winter survival – see the Crofton slide) that can have a significant impact on populations is that at a certain level you get a dramatic increase in pathogen-associated mortality. So it doesn't have to be a brand new or highly-lethal pathogen. It could be a shift in the severity of the pathogen level. So if you are collecting fish samples anyway, why not collect disease information as well so that you have information over time. You can do more sophisticated models that also look at things like the relationship between parasite burden and size.

Peterman: To get the data for that graph, you need a well-designed consistent program. These programs may be opportunistic, which may not be good enough.

English: Juveniles can pick up *Parvicapsula* in freshwater, then migrate out to the ocean. It is reasonable to assume that the *Parvicapsula* is continuing to impact and potentially killing them or attacking them as returning adults.

Kent: *Parvicapsula* is similar to another estuarine parasite in a US river that infected fish going out and in. There is the question of whether there is a heavier load, so it's not just a question of whether they are present or absent. Abundance is driven by temperature and most fish leave before temperatures are high enough, but it could be a shift where they are now out of whack.

Martin: Given temperature and geographic changes in survival for a large number of stocks, does that eliminate or point to some of the parasites listed today?

Kent: There is the example of *Parvicapsula* (but I'm not saying parasites are a major driver of mortality).

Martin: It could be one contributing factor.

Kent: (…?) parasite mortality in coho that spans many rivers. Of all the pathogens, *Parvicapsula* seems the one to look at in the interim. It is a widespread pathogen and there is normally a low intensity of infection, unless something has shifted. Temperature really drives these, so just a few degrees change in ocean temperature can change these to pathogenic.

Marmorek: It would be interesting to take McKinnell's ocean temperature data and compare it to the thresholds for these parasites.

Kent: There are high levels of parasites in freshwater and the fish are leaving with those so they could theoretically die in sea water. For *Parvicapsula*, one study found a high level in freshwater and then they didn't see it in the marine environment, but it needs more study

Hinch: We've done a lot of work on *Parvicapsula*. We don't see it in the kidneys in adults. It's either turned on or re-acquired. Some years we see strong disease and temperature correlations, including *Parvicapsula*. We should also distinguish between en route and pre-spawning mortality, which are treated distinctly in Canadian management.

Ashley: Was whirling disease introduced or did eutrophication amplify existing levels.

Kent: This is an endemic pathogen, so land use activities on the Klamath River intensified an endemic disease. Snails are also vectors for human disease so there has been lots of work on the effects of land use practices on snails and parasites.

Ashley: The message to Cohen regarding watershed management is that these are principles you should do anyway, but they have been ignored by agriculture.

Kent: It was very difficult to tie land use practices to pathogen burdens as you need to show it across multiple rivers. There are two mechanisms: directly increasing temperature and increasing invertebrate hosts important for disease transmission.

Staley: How will you deal with Kristi Miller's work?

Kent: I'm meeting her next week. We looked and didn't see brain lesions. We don't think the evidence is as strong of a pathogenic virus that killed the fish. Can I quote her with her permission in my report?

Levy: Yes.

Hinch: Miller has a paper on this about to be published in a journal.

Potential effects of contaminants

Don MacDonald

This project included preparing an inventory of aquatic contaminants in the Fraser River in relation to the distribution of sockeye CUs, comparing water quality in the Fraser to toxicity data for Fraser sockeye, assessing the contaminants and natural substances encountered by juvenile and adult sockeye, and evaluating the extent to which reductions in sockeye abundance are associated with contaminant conditions in the river.

Approach: An ecological risk-based approach was used to identify where and when sockeye are exposed to contaminants, which ones they could be exposed to in their life cycle and a preliminary assessment of potential effects (exposure levels and potential adverse effects) to identify contaminants of concern to guide a more detailed assessment.

It was understood in advance that it would be difficult to address potential effects of emerging contaminants like endocrine disruptors, so the study used qualitative evaluation to take a focused look at these substances. The study also set out to identify uncertainties and key data gaps, before presenting conclusions and recommendations.

Fifteen areas of potential exposure within the Fraser watershed were identified by mapping the spawning, rearing and migration habitats of Fraser sockeye CUs. It was also necessary to identify key exposure times during spawning and incubation, juvenile rearing, outmigration and adult upstream migration. Given the variable timing among different stocks, the analysis was simplified by using average timing for each of these four life stages, based on information from the literature.

Aquatic contaminants inventory: Information from published sources and GIS databases were used to identify land and water uses (e.g. pulp mills) with the potential to affect water quality and the intensity of each activity in each of the 15 areas of interest. Contaminants associated with each activity were derived from the literature and this information was then integrated to identify contaminants that might be present for each watershed. This resulted in a lengthy list (29 groups of contaminants) though only a few of these have usable data.

The preliminary assessment of effects involved compiling and evaluating exposure data (the provincial environmental review process has now been merged with Environment Canada – there is other data, but it probably won't be available in time). Next steps include selecting toxicity screening values, calculating hazard quotients, and then identifying contaminants of concern.

A map of the Fraser basin showed the limited areas for which routine water quality data is available. There is no data for many streams and rearing lakes. When this information is overlaid with the locations where sockeye could potentially encounter contaminants within the Fraser basin, it shows that there is no data for most of the 29 contaminant groups that could be encountered in the four freshwater life stages.

Toxicity screening and threshold values were established to identify which of the contaminants in the inventory were preliminary contaminants of concern that could be expected to have adverse effects on Fraser sockeye.

The evaluation of hazards relied primarily on water quality data, along with sediment quality conditions and tissue residues where such data was available. These data were separated into two periods (pre- and post-1990), marking overall positive and negative productivity for most Fraser sockeye stocks. Analysis of maximum hazard quotients for the preliminary list of contaminants of concern, broken down by stock and life history phase, showed that many either declined or changed very little in the post-1990 period. A water quality index that combines the frequency of events exceeding water quality guidelines, along with magnitude and other factors, shows no clear pattern for the pre- and post-1990 period for the spawning or rearing phases, though there were possibly some increases for the in and out migration phases.

Overall, it's hard to see a strong pattern suggesting water quality has degraded. Further analysis of productivity vs. water quality index revealed no relationship between the two, where data, for any of the four freshwater life history phases. This analysis was done for Fraser sockeye overall and for several specific stocks.

A detailed hazard evaluation, which involves a more realistic estimate of exposure and effects, is still pending. Results are also pending for the focused qualitative evaluation of endocrine disruptors and other emerging contaminants.

Data gaps: Few water chemistry data are available for spawning and incubation areas or juvenile rearing areas. There are no data on dissolved metal concentrations, herbicides and pesticides, wood preservatives, fire retardants, most endocrine disruptors and few sediment chemistry data except for the Lower Fraser. Fish tissue chemistry data are limited to very few studies there is no data for the Harrison (the study had hoped to contrast their potential exposure against that for other stocks).

Conclusions: The inventory confirms that a wide variety of contaminants has been released into aquatic habitats within the Fraser basin. Existing data don't support that contamination has contributed to declining sockeye productivity since 1990 or to the low returns in 2009, but it can't be concluded that contamination is not a factor, due to data limitations.

Discussion

Peterman: The PSC report came to the same conclusion: there is a lack of information, but contaminants are probably unlikely causes of the decline in Fraser sockeye.

Q/A: The "00" in Table 7 = No Data

Marmorek: Harrison juveniles spend a lot of time in the estuary and Greater Vancouver probably has higher levels of contaminants than other areas. If they're doing well it suggests contaminants are not a smoking gun.

MacDonald: Agreed: they should be getting the highest exposure

Routledge: Did you find any contaminants were increasing in concentration?

MacDonald: Many of those associated with municipal waste water would be increasing as population increases. Those include new contaminants such as those from personal care products like anti-microbials or fire retardants.

Q/A: Contaminants in Georgia Strait were not examined.

Levy: Johannes' and MacDonald's studies overlap, so that needs to be discussed.

Ashley: Given the significant improvements in effluent discharge quality that resulted from the Federal EEM program for pulp and paper mills (Environment Effects Monitoring), did you pick up any changes pre- and post 1990?

MacDonald: You don't see it in the routine monitoring data but you see it in the five- year reports. You do see improvement in mill discharges, but the caution is that some of the new products may have a stronger endocrine disrupting signal.

McKinnell: Did any of the contaminants you have listed, for which there are no data, have the capacity to kill a lot of out-migrating sockeye in the river in 2007?

MacDonald: An excellent question relating to mass loading. We haven't completed those calculations yet.

Ashley: If there was a major event like the Cheakamus spill in the Fraser, we should have heard of it.

MacDonald: We're waiting for all the data to confirm that.

McKinnell: Unless it was something relating to the 2007 flooding.

Rosenau: Conversely, is it possible that there was an event in 2008 that ameliorated contaminations (e.g. all mills shut down due to a strike)?

MacDonald: There are no data to suggest that there was something in 2007 that didn't happen in 2008 – no evidence of "taps turned off" somewhere.

Marmorek: With acid rain, there was a major debate between the US and Canada over Inco's contribution, until there was a strike that showed the impact was more than Canada claimed.

Freshwater factors

Marc Porter, ESSA

Freshwater stressors examined in this study include activities like logging and agriculture, urbanization upstream of Hope, water use and hydro, as well as factors like temperature and contaminants. These stressors can affect the quality or quantity of spawning habitat, the productivity of rearing lakes or migration conditions.

To assess stressor impacts on sockeye, GIS was used to create spatial layers to define consistent "zones of influence" for these three types of habitat and for stressor indicators. These two layers are then overlaid to examine interactions between stressors and sockeye habitats.

The presentation described how the study spatially bounded summaries of freshwater stressors on CU habitat and then listed the indicators selected for each of the seven key stressors (urbanization, logging, roads, agriculture, water use, hydro and mining).

Data sources included provincial agencies, the Canadian Forest Service, BC Hydro and Google maps. Data analysis is now underway for some of the stressors.

Forestry: the analysis addresses harvest levels (stable since early 1970s, but with increased density of road/stream crossings); Mountain Pine Beetle (largest outbreak in history, with different impacts from normal logging, but greatly accelerated logging in some Fraser watersheds); and log storage (log storage agreements in the Fraser estuary cover 862 hectares currently. There is minimal data, so a comparison of aerial photos from 2001 and 2009 was done).

Mining: Analysis focused on effects on spawning habitats, looking at different mine types, density of mines and claims across CUs. Shuswap CUs are most heavily impacted by mining but most of the activity is in the upper river, not geographically linked to major spawning areas.

Hydro: The focus was on large-scale projects – two of these (Bridge/Seton and Kemano) with the greatest potential effect on sockeye were evaluated. At Bridge/Seton, there were effects on smolts and adults, though smolt mortality was significantly reduced by mitigation. Further work is needed to assess the extent of adults affected. At Kemano, impacts included low flows in the Nechako, which were mitigated by a water flow model, so minimal impacts are assumed. Another consideration is the impact of IPP (Independent Power Production) hydro projects. These are generally located in fish-less reaches and short stream channels but have potential impacts on gravel and water temperature downstream. There is only one IPP in a Fraser sockeye watershed, so we can't see explanatory value in the sockeye declines.

Urbanization upstream of Hope since the 1980s has been highly variable. The study is using municipal boundaries, urban road density, domestic water licences, census boundaries and human population trends as indicators.

Agriculture: Crop production and grazing can increase sedimentation, destabilize banks, reduce flows, increase temperature and impair water quality. The Fraser supports 53% of the province's farmland, but this data is still being analyzed.

Water use: Excessive human water use can result in altered or reduced flows and high temperatures. The study is intersecting the locations of water licences and allocations with CU habitat types.

The study results will be presented in a "CU Dashboard" format that visually graphs a portfolio of the relative intensity of stressors in each of the above categories for each CU.

Interpretations: Initial qualitative and quantitative assessments have been completed for a few of these freshwater stressors, but the integrative analysis across the full set of quantitative indicators still has to be done. Next steps include completing the portfolio of relative stressor assessments across CUs and seeing if a relationship emerges between the relative intensity of stressors and recent population patterns.

No recommendations or data gaps have yet been identified. In most cases, we lack the full time series. Data collection is not repeated on a very frequent basis, so that will be a key recommendation: more frequent updates of changes in watershed stressors over time.

Discussion

Wieckowski: Dorner's earlier presentation showed Fraser sockeye stocks in some geographic areas doing well concurrently and then switching. Is there any idea yet why this may be happening?

Porter: Not yet. The PSC report did not find any relationship but we have more detailed data on localized impacts.

Peterman: How will the study look for correlations?

Porter: We are still working out how to distinguish the scope of this project from the cumulative effects project.

Peterman: Has any thought been given as to how you might scale some of these indicators to address what levels might represent a stress?

Q/A: Groundwater removal is not part of the assessment, nor does it directly quantify flow changes over time.

Reynolds: There are bits and pieces of flow information available.

Porter: We looked at water restrictions for an indication of some places that might have problems.

Rosenau: There are good data sets available via the Water Survey of Canada, including data sets for the whole year or broken down by the time of year, going back to 1913. They have sampling stations all over the Fraser watershed and have integrated everything, including extractions, in one package. Elevation and discharge levels are available all over the Fraser, including Shuswap and North Thompson. Some of the data go back 100 years, some just 10 years. The Coldwater has two gauges, for example, so it's on a pretty fine scale.

Hinch: The Fraser River Environmental Watch program also has a large monitoring program independent of that one. It generally operates from spring to fall, with data up the Fraser mainstem and in many of the tributaries since the mid/ late 1990s. Dave Patterson can provide more information.

Routledge: It seems almost like an impossible task. You get all this data and look for patterns but I suspect that if there are impacts, they will be local and subtle, such as warm water during the return migration on the Horsefly.

Peterman: You won't have ideal data sets for all CUs but you may have very useful data just for some, so you should not rule it out if you don't have data for all.

Marmorek: We can look at stressor vs. productivity to see if there is a positive, negative or neutral correlation, for example if there is any difference in productivity in areas that have been most or least impacted by the Mountain Pine Beetle.

Martin: Re cumulative effects and the graph that says the portfolio stays fairly constant over time, one way of looking at that is that despite the variation in individual stocks, the Fraser is very resilient because of those different stocks. That you have the same portfolio over 60 years highlights the resilience.

Pickard: The reality might be multiple stressors.

Routledge: It's upsetting to see the decline in the number of people who are actually out looking at what's happening in the Horsefly, for example. We're sitting here looking at data sets instead of talking to people who actually see things happening and that poses the risk of missing something.

PICES advisory report on the decline of Fraser River Sockeye salmon in relation to marine ecology

Skip McKinnell, PICES

The presentation opened with a quote from a 1909 media report describing the "discovery" by a pre-eminent ichthyologist that the marine refuge for Fraser salmon between the time they leave the river and the time they return to spawn is located 10 miles off Vancouver Island. The following slide showed Fraser River sockeye tagging locations spanning the entire Northeast Pacific. This, McKinnell noted, highlights the difference between what we profess without adequate observations and what we know when there is relevant data.

This project looked at marine factors that might be linked to the low sockeye returns in 2009 as well as the gradual decline in productivity.

It turns out that Fraser River sockeye smolts that went to sea in 2005 had the lowest survival on record (many scientists anticipated that). Those that went to sea in 2007 had the second lowest survival overall, except for Harrison sockeye, which had the highest total survival on record.

The winter of 2006/2007 was an "official" El Nino. Each El Nino is different but several characteristics are fairly common, including lower than average sea level pressure in the Gulf of Alaska, an eastward shift in storm tracks and intensification of storms. Wind patterns tend to follow the pressure contours, which in the winter of 2007 were blowing towards the BC central coast. That winter featured wetter snow and the highest snowpack since records began in 1953. A cool spring delayed the melt and allowed more snow to accumulate. Then came hot weather in late May and a widespread rain-bearing storm in early June that affected the Bulkley, Skeena and nearby central coast basins, leading to extreme river discharge from the north coast and central coast mountains. There was also high discharge from the Fraser (though not extreme). Record discharge led to record low salinity in Queen Charlotte Strait/Sound in 2007 – essentially there was a surface layer of much fresher water covering Queen Charlotte Sound. Mark Trudel happened to be doing his annual survey early in the melt period (June 28/29) and he recorded the most extreme low salinity since sampling began in 1998, extending to a depth of eight metres. The consequence was an unusually stable water column.

In a separate analysis of sea surface temperatures, we had found that the only location of extreme SSTs anywhere in the Gulf of Alaska in any month in 2007 occurred right in Queen Charlotte Sound. This led to the idea that this heat may have been caused by the freshwater anomalies, not ocean circulation from the south. Adding to this theory was our observation that the large-scale wind patterns in Queen Charlotte Sound that summer were extreme. The typical summer pattern is for northwesterly winds in June/July, but the average for June/July 2007 had the most extreme easterly wind anomaly since 1948 when these wind records began (it was essentially a winter wind pattern). There is typically a net flow of surface water out of the Sound in summer but the prevailing winds that year did the opposite, keeping the freshwater layer backed up in Queen Charlotte Sound. The Fraser sockeye smolts were obligated to migrate through this region on their way out to the open ocean.

Further insight was provided by Jim Irvine's observation that marine survival of Chilko sockeye is correlated with April chlorophyll concentrations in Queen Charlotte Sound/Strait. Low chlorophyll indicates a late spring bloom in Queen Charlotte Sound. The 2007 bloom was the latest in the satellite chlorophyll record going back to 1998. So the smolts would have encountered extreme salinity, wind, temperature anomalies in addition to a delayed bloom. Other studies in the region, of seabirds at Triangle Is. for example, have shown that survival of upper trophic level animals is sensitive to bloom timing.

In summary, our study looked at bottom-up effects to see if we could find conditions that were potentially lethal to sockeye. We know there is correlation between SST and survival but we don't know much more.

Productivity declines: shift or trend?

Median values of log (recruits per effective female spawner) were calculated for smolts that spend one summer rearing in lakes, using data from 1950 to the present for 16 Fraser sockeye stocks with lengthy time series (excluding Harrison). The resulting graph indicated that the pattern of decline was a step shift that occurred in 1992, rather than a gradual decline. Examining each of the 16 stocks individually suggested a shift was the better model than a trend for most, so the idea of a shift is worth paying attention to. There is evidence for a 1992 shift in some other stocks, including Long Lake, Rivers Inlet, Barkley Sound and the Columbia River (but not Sakinaw).

Peterson Index: A group of oceanographers, biologists and climate researchers have been meeting annually for over a decade to look at what happens in the ocean each year and to discuss what we think it means for salmon. Bill Peterson (U.S. National Marine Fisheries Service, Oregon) built an index that combines large-scale ocean variables and also local oceanographic and biological variables. The combined rank for all variables in each year showed 2008 as the best year in terms of marine conditions for salmon and 2005 was the worst year. Since 1998, the aggregate index is significantly correlated with Chinook and Coho returns to Bonneville Dam.

Mackas Ecosystem Productivity Index: Dave Mackas (DFO) has also developed an ecosystem productivity index for SW Vancouver Island. His index showed a period of warm, unproductive conditions starting in 1992. The summer of 1992 was noteworthy for the return of sardines to BC after a 47 year absence. The warm and unproductive period continued through the 1997/98 El Nino. A few years around 2000 were better for coho survival on the west coast but not for Fraser sockeye. Indeed, the 2007 ocean entry year tended to cold and productive rather than warm and unproductive. The mismatch between the MEPI and Fraser R. sockeye salmon survival from 1999-2002 may have arisen from differing locations of MEPI data and sockeye migration routes. As with Peterson's index from the coast of Oregon, the MEPI shows that 2008 was the most extreme of the years of cold and productive.

Fulton and LeBrasseur's work in the 1980s indicated that the BC coast is in a transition between two major marine zones. In El Nino years, the west coast of Vancouver Island is dominated by southern/offshore subtropical copepods instead of the lipid-rich subarctic zooplankton that form the basis of an enriched food web where salmon seem to prosper. And since 1992, there have been far more unproductive than productive years.

In defining the nature of the decline in Fraser River sockeye salmon productivity, it's important to get the pattern right because you would look for different causes if you think it's a shift vs. a trend.

Discussion

Reynolds: Neither Mackas or Peterson predicted the bad 2009 return.

McKinnell: The factors that appear to have affected the 2009 return involved climate, ocean and terrestrial interactions focused on Queen Charlotte Sound – both the Mackas and Peterson indices are based on West Coast indicators. I think the difference is largely because a result of where the data for the indicators are derived.

Reynolds: It would be useful if there was independent data to actually show that the correlation broke down that one year.

McKinnell: It would be interesting plot MEPI vs. the salinity

Peterman: The PSC report suggested that zooplankton production in Queen Charlotte Sound/Strait 2007 was not anomalous.

McKinnell: Recall that the spring bloom in Queen Charlotte Sound/Strait was the latest in 2007 since records began in 1998. There is also a need to consider where the zooplankton biomass records came from. Those near Triangle Is. may have been rather normal, but those in eastern Queen Charlotte Sound may have been quite different.

Peterman: Rick Thompson pointed out there was much stronger downwelling along the coast, which would lead to a consistent effect.

McKinnell: There have been significant reorganizations of North Pacific climate system along the West coast. There was definitely one around 1977 and the next significant change was in 1989, but there was no productivity decline that year. The more obvious decline in productivity in B.C. occurred in 1992.

Routledge: You could find a better fit, such as quadratic, for the pattern than a step. I don't think you can settle whether it's a step or a shift from that graph.

McKinnell: The point is that a shift in productivity has been not considered, yet it occurred in Rivers Inlet and Long Lake, so you can't rule it out.

Q/A: The graph was based on median values for the 16 time series

Peterman: This is intervention analysis. You need to take into account the autocorrelations in the time series if you do formal hypothesis tests in the future. When you go to a shift vs. a trend, it's formal intervention analysis.

Rosenau: We had the most massive Harrison return in 2010 from the same 2007 sea entry. Fraser chum that went to sea in 2007 were down. So these are two stocks with almost the same life history, but one is up and one almost collapsed.

Groot: It's probably ocean distribution.

Rosenau: Once they get out of Georgia Strait, maybe there is a difference depending on where they go.

Groot: Fraser chum go north through Johnstone Strait, Harrison River sockeye don't.

Rosenau: These two stocks provide almost a controlled experiment. They spawn in the same gravel and both went out to the ocean the same year at the same time.

Q/A: By August, the anomaly would have subsided. Harrison smolts go out through Juan de Fuca. Beamish found them in Georgia Strait in September 2007. They were found on the West coast of Vancouver Is. the following March.

Groot: The similarity with chum is the difference in timing. Most sockeye go right out but not chum. Harrison sockeye also stay around. Probably it was a mismatch for sockeye.

McKinnell: There are a number of these observations from 2007 that need to fall in line. The survival for age-2.x Chilko Lake sockeye salmon smolts that went out in 2007 was about 4% vs. 0.3% for the age-1.x. So how did smolts from the same lake, passing through the Strait of Georgia at the same time have such a different survivals? Perhaps it's because the age-2.x smolts are larger and maybe they have more energy to get through bad times.

Marmorek: Did you try to compare median recruits per spawner against the Mackas red and blue years?

McKinnell: The basic pattern holds, though there are some outliers for the ocean entry years 1999-2002.

Peterman: Fraser pinks that went to sea in 2008 also came back in 2009 in large numbers. Can you do something similar for WCVI to explain the pattern for other stocks?

McKinnell: In 2005, the whole Gulf of Alaska lit up, with positive extreme SSTs everywhere. It was followed by a general cooling trend everywhere. The major exception was from northern Vancouver Island to SE Alaska in the summer of 2007. For northern Vancouver Island, there was a blip of warm water beginning in July. We think that, because salinities were higher, that a different process was responsible for the warmer temperatures. Notably, it doesn't seem to have affected the West coast sockeye salmon stocks that, presumably, were migrating along the West coast that year.

English: The PSC report discussed harmful algae blooms. Could you have had that in Queen Charlotte Sound?

McKinnell: Or parasites. There were very high temperatures, but there is no algae bloom monitoring. *Heterosigma* has appeared in Georgia Strait in years of higher river discharge. There was a persistent *Heterosigma* bloom in Georgia Strait in July and August that year.

English: I saw an extensive bloom of some kind in Queen Charlotte Strait while sailing through the area that year.

Marmorek: Page 74 of the PSC report talks about the Georgia Strait and Queen Charlotte Sound algae bloom.

McKinnell: We looked at bottom-up effects of phytoplankton/chlorophyll, not harmful blooms. I can imagine that there could have been a combination of undesirable trophic conditions, plus a bloom. But I keep coming back to why the survival of 2-year old Chilko smolts was so much higher than that of the 1-year olds if they both encountered a *Heterosigma* bloom.

English: It could be timing.

Christensen: It's a compelling story, but if this was a prosecutor, his case would be breaking down and we are still trying to find proof of guilt.

McKinnell: No one found dead sockeye at sea to provide firm proof. But we have observed an extreme effect in biology and we are looking to see whether there are equivalent extremes in oceanography. We find that those are far more evident in Queen Charlotte Sound/Strait rather than Georgia Strait.

Marmorek: The prosecutor may not be the best analogy for what we're doing. We're looking at what is the relative likelihood of different theories, which may not be mutually exclusive and may be collaborating. For example, contaminants don't seem likely. Which factor or combination of factors explains the pattern that Peterman and Dorner outlined? Did the PSC get it right or does new evidence point elsewhere. We're looking at conceptual models and how factors may be interacting. The idea of an attack from the land is a new idea.

Peterman: Did you find the same pattern as we did in terms of a shared trend for stocks outside the Fraser?

McKinnell: Yes, the spatial scale of the effect is bigger than Georgia Strait.

Day 2

Introductory remarks, plan for Day 2

Dave Marmorek, ESSA

Marmorek welcomed everyone and reviewed the day's agenda.

Research program presentations (continued)

Predators

Marine mammal predation

Andrew Trites, UBC
The presentation covers which marine mammals eat sockeye, marine mammal population levels and how much they eat. The assessment was based on peer-reviewed literature, government reports and unpublished data. Key metrics include numbers of marine mammals, population trends, diet composition and estimated consumption.

Changes over time are linked to the history of hunts, culls, protection, recovery, stabilization and/or increases (e.g. Stellar sea lions). There are temporal patterns, but no obvious connection to sockeye abundance. Data is too sparse to say whether there is a difference in distribution that may relate to sockeye. Marine mammals move around – they are not sedentary. On whether any one life stage appears to be impacted, there is no evidence of significant predation on smolts; predation is limited to adults and sockeye does not appear to be an important part of their diets.

Predation by marine mammals has undoubtedly helped to shape the life history and physiology of sockeye, including potential traits such as run timing, density of schools and swimming performance, all factors which would enhance their ability to escape being eaten.

Evidence for stressor: Many species of marine mammals have been observed eating sockeye – people fishing notice the mammals taking sockeye off their lines. Many populations have also recovered to historic highs. And the Strait of Georgia has the highest density of harbor seals in the world; and also because highest density of harbour seals in the world (are they eating sockeye or something else?).

However, sockeye is not a preferred prey species among those marine mammals that eat salmon. The seal population in Georgia Strait stabilized in the 1990s, before Fraser sockeye declined. Predation by marine mammals should also be equal across all Fraser River salmon stocks, and should not just be affecting Fraser stocks since most marine mammals are not concentrated in the Strait of Georgia.

The evidence supports some but not all of the conclusions in the PSC report. It is agreed that populations of several species are back up, including Stellar sea lions, Pacific white-sided dolphins, harbor seals and humpback whales. However the evidence disagrees that total food consumption by marine mammals is large enough to affect sockeye populations. This would only be true if they only ate sockeye but the evidence suggests that sockeye account for less than 1% of their diet, not over 20% of the summer and fall diet of Stellar sea lions, as the PSC report suggested.

Information gaps include outdated diet data for harbour seals, limited diet data for porpoises and dolphins, data for other seasons besides the summer months and more DNA studies to determine the species of salmon consumed (DNA has been used successfully in the last 5 year).

Salmon-eating marine mammals in BC:

Stellar sea lions: Populations declined from the late 1950s due to culls, then saw a rapid rise from the late 1990s and are still growing. Populations are still at all-time lows in Alaska.

Seasonal population distribution patterns show highest concentrations at the northern tip of Vancouver Island in summer. The much larger males eat 15 – 35 kg per day and salmon represents 17% of their diet (third highest contributor). Their major food source is forage fish (sandlance, herring and sardines are believed to be driving the population increases). Most salmon are found in their diet in the fall and those are mostly adults. There are different proportions of salmon in summer diets by region (North Danger Rocks has the highest proportion of salmon at over 35%). Overall, for Southern BC and Washington State (Cape Caution to the Columbia River), salmon comprised 10% of their overall diet. They primarily prey on adult-size salmon from all 5 species of salmon and steelhead, but mostly focus on pink and chum. Sockeye comprises the smallest proportion of all salmon species eaten. A 2009 study covering BC and the Eastern Aleutians found sockeye represented 9% of total salmon in the diet of Stellar sea lions. Unpublished data from Olesiuk et al for Southern BC and Washington confirmed sockeye was the prey in just 5% of all salmon DNA diet samples.

Harbour seals: Historical populations are thought to have been in the range of 80,000 to 100,000. Hunting and culling significantly reduced those numbers, but a steady increase has brought those numbers back to historical levels. Distribution patterns show they stay close to home, all around the BC coast, and they eat around 1.9 kg per day. Scat studies in the 1980s show salmon was only 4% of their diets. The species of salmon eaten is unknown but DNA testing could reveal that if the samples are still there. Populations tend to be largest in estuaries with large chum and coho runs. They appear to eat mostly adult salmon, although two areas (Comox Harbour and Port Moody) reported high numbers of chum and coho juveniles in scats.

California sea lions: The big males come north in the fall, and some move into Georgia Strait in winter with the herring. But only about 3,000 of the total 240,000 California sea lion population reaches BC waters. Their BC diet is unknown, but likely similar to that of Stellar sea lions. They are also not present in the summer.

Northern fur seals: Stomach samples in the 1950s and 1970s indicated a diverse diet but did not find any sockeye.

Killer whales: A 2006 study observed 423 salmon kills occurring between May and December, but they seem to specialize in Chinook. Only one of the salmon killed was a sockeye.

Other species: There is no significant evidence of sockeye predation among other marine mammals such as minke and humpback whales, elephant seals, porpoises and dolphins.

Why killer whales don't eat more sockeye is unknown. Perhaps it relates to quality, swimming speed, inconsistent returns, or return timing coinciding with other options during a limited window.

Fish & bird predation on Fraser sockeye

Villy Christensen, UBC

This report addresses fish and bird predation (neither were addressed in the PSC report) in the freshwater and estuarine environment, Georgia Strait, Queen Charlotte Sound/BC and the Northeast Pacific Ocean. There is no doubt that sockeye are eaten in large numbers out in the ocean, but there has been very little study of what's eating them out there.

A few hundred previous studies were looked at, but very few relate to sockeye predation mortality at different life stages. Key metrics include diets (most diet studies are only qualitative), abundance of potential predators, trends, predation mortalities (rare) and time scales. A few long time series exist, mainly for commercial species, but for most potential fish predators, there is next to no information available.

Freshwater predators: A table was presented summarizing potential freshwater fish predators, including other salmon species. Availability of information on abundance estimates, trends and monitoring was indicated by shaded blocks. Very little information is available on these potential predators, except for abundance estimates for coho and Chinook salmon. For potential bird predators in freshwater, abundance and trend data were available for most species. Many salmon tags have been found in bird colonies in the Columbia but there were no major shifts in bird abundance trends (except for bald eagles, but those populations are not large enough to have a big impact). So there were no likely suspects found in freshwater.

Ocean predators: A similar table presented for potential ocean predators indicated more data available, especially for commercial species. Humboldt squid are not likely the culprit, though they may have some impact. Lamprey took a significant number of smolts but their abundance and trends are not known. Spiny dogfish could prey on sockeye but stomach samples did not find any evidence for this. It should be noted that there could be some impact even if sockeye are a very small proportion of the diet of highly abundant species, but you would need to look at stomach samples at the right time (when sockeye are present) and you might need to look at thousands of samples to detect it.

Daggertooth is an obscure deepwater fish. There is much evidence of Daggertooth wounds on returning sockeye but no information on abundance or trends (efforts are being made to get some information from Japan). There is also evidence that sablefish go after smolts and they could have some impact but their numbers have not been increasing in the last 20 years. Blue shark populations have been increasing in the ocean, but salmon represent a small proportion of their diet. Salmon sharks and Daggertooth are more likely suspects, but there is no data on either one. Similarly, there is no “smoking gun” to be found among marine birds that could prey on Fraser sockeye.

An evidence levels matrix listed the most likely fish and bird predators, summarizing the level of knowledge in each case about diet, abundance, overlap and population increases or decreases.

Potential interactions: Can sockeye research be isolated from what happens in the ocean? In order to explain what happen in the ecosystem, we need to understand changes in productivity as well as fisheries and food webs. Most salmon are eaten. More fry means more competition, which means smaller smolts and higher predation. Decreased environmental production also means slower growth and higher predation.

If there is a decline in alternate prey, could predators switch to feeding on sockeye? Pacific hake has declined in Georgia Strait. Herring adults are also down in BC. In the NE Pacific Ocean, Pacific jack mackerel and Pacific mackerel are both down. In the Gulf of Alaska, Walleye Pollock is way down. They don’t eat sockeye but are potential prey for predators like salmon sharks. Major shifts have occurred with several fish species in the NE Pacific and the Gulf of Alaska in recent decades. Arrowtooth flounder populations are way up and they can eat smolts. Pacific cod is also down. When a predator species like Arrowtooth flounder has grown to a total biomass of over 2 million tons at the same time that a prey species like Pacific mackerel declined sharply from 1.4 billion metric tonnes, it represents a big gap. Salmon biologists are not looking at total biomass.

Information gaps: The most important unknown is ecosystem monitoring for key predators. Information is poor for the open ocean and in freshwater. DFO's attempts to implement integrated management have been very limited and the recent ecosystem initiative was so poorly funded as to be meaningless. Key research needs include learning more about the abundance of non-commercial species and what's happening in the open ocean.

Discussion

Peterman: You have made an important point that sockeye could represent only 0.1% of the diet of dogfish and still suffer significant impact, given the abundance of the latter. We need to do the rest of these calculations. We haven't got the total salmon biomass that could be eaten by marine mammals.

Christensen: We can say let's have an experimental fishery. Stomach samples reveal the average diet. With DNA, you can identify prey that comprises only a very small proportion of the diet.

Trites: It's very simple to do the next step of putting a number on it. We need to do it for the fish as well because the fish eat far more. A big part of the diet of harbour seals was hake. What are those hake eating? So the seals could also be controlling other salmon predators, thus having a positive as well as a negative impact. You can't just put one number out without context – ecosystem models are important.

Christensen: It's very clear from this that we can't point to one single species so we are probably looking at cumulative effects.

McKinnell: We also have to consider the behaviour of these species. Which predators have a behaviour that could put them in contact with high densities of outgoing sockeye smolts (e.g. which ones operate in the top 10 metres of water)?

Christensen: This highlights the point in the quote about the salmon ocean refuge being 10 miles offshore. About 15% of recent sockeye samples had daggertooth wounds.

McKinnell: Regarding the diet of salmon sharks, it's important to ensure that the target species for the fishery where they are caught for stomach analysis was for salmon sharks. They will eat whatever else is in the net, so if they are caught in a salmon fishery, that will create bias.

Routledge: Do Pacific mackerel only come north when the ocean is warmer?

Christensen: That was not a major part of the argument. What is important is the big changes happening in the Gulf of Alaska.

Routledge: It has been hypothesized that mackerel are a major predator during El Nino events.

Christensen: I don't know.

Martin: There has been a large change in the biomass of pilchards and mackerel over time.

Christensen: There are now studies showing how much individual salmon sharks move around but little is known about overall populations.

Trites: Stellar sea lions are probably the ones that have been best studied, and pilchards show up in their diets when there are big changes.

Dorner: The likely suspects are in the Gulf of Alaska, but Alaska stocks have not been affected.

Christensen: Bristol Bay stocks are distributed further to the west. These changes are more in the Gulf of Alaska.

McKinnell: Those predators live largely on the ocean shelf and sockeye are mostly distributed off the shelf.

Christensen: That is true after they leave the coast but smolts have to pass through the shelf as well.

McKinnell: So do the Bristol Bay fish.

Peterman: This provides a good summary of a lot of things that were not in the PSC report. Important issues include alternate prey and what is happening with other salmon species (e.g. very high Fraser pink abundance) and the study that showed total salmon abundance in the North Pacific is at an all-time high.

Christensen: Plus the issue of very high pink and chum hatchery releases.

Peterman: Sometimes diet indicates different distribution. Conversely finding few sockeye in the diet can reflect low sockeye abundance.

Trites: But there was evidence with the killer whale study where the sockeye were there and they were not selecting them.

English: Re Beamish’s juvenile salmon abundance surveys in Georgia Strait, was information requested on the other species caught?

Christensen: We requested but did not receive information from DFO. There are indications that they caught quite a few potential predators in those surveys.

English: Especially important is evidence of trends in abundance for alternate prey. Sandlance, anchovies, etc are said to be down but that should show up in Beamish’s surveys.

Christensen: Hake is another interesting one but information on hake in Georgia Strait is very poor.

English: There were studies on early marine survival in the 1980s. Much of the focus was on interactions with Chinook but there were also data on Barkley Sound sockeye. Is there any information on increasing humpback whale populations in the Gulf of Alaska and any potential for a shift to preying on salmon smolts?

Trites: There are observations around Langara but we don’t see the same bubblehead feeding behaviour. That’s the group most likely to be getting smolts and we need to do more work but we don’t see the same feeding behaviour. We do know that they are taking a lot of pilchards off Vancouver Island.

Hinch: We shouldn’t lose sight of what happens in freshwater. There was a tagging study of 200 smolts last year and half had disappeared by the mouth of the Fraser. We saw predation occur early in the migration.

Christensen: Agreed. I’m surprised that isn’t known.

Trites: I’m looking for feedback or insights as to possible reasons or behaviour that might explain why we are not finding sockeye taken by killer whales.

Fraser sockeye salmon habitat analysis: Lower Fraser River & Strait of Georgia

Mark Johannes, Golder Associates

The study objectives included developing an inventory of sockeye habitats in the Lower Fraser and Georgia Strait; identifying potential human factors affecting habitat and potential links or overlaps between human development and key sockeye habitats/habitat use; summarizing the biophysical and water quality characteristics in Georgia Strait that relate to sockeye habitat use; identifying habitat protection approaches; and reporting on linkages between Fraser sockeye and human development activities.

The approach included identifying key sockeye habitats in the Lower Fraser, the estuary and Georgia Strait, along with indicators of anthropogenic change and of biophysical characteristics and change in the Strait of Georgia over the study period (1990-2010). A key metric was the loss or degradation of key sockeye habitats.

Inventory of key sockeye habitats: This was based on Fraser sockeye habitat use at different life history stages. During their out-migration, most sockeye smolts move very quickly through the Lower Fraser. Some use very specific habitats, such as the brackish areas just below Hope instead of the real estuary, where they develop energy stores before they head out. They use the shelf areas of Georgia Strait and travel around both sides of Texada. They also use the 10 – 15 metres of water.

Human development: GVRD is growing the fastest of all the urban centres – and population growth can affect habitat quality. Data was also examined for other indicators, including the number and location of large projects over time, agricultural land use, changes in forest harvesting, Lower Fraser dredging and shipping (the only increase is cruise ships) – no evident links.

Strait of Georgia biophysical and water quality indicators included SST, suspended solids and chlorophyll, with the information compiled in a database that breaks the data down by time period over the summer. Information on invasive species and harmful algae blooms like *Heterosigma* was also compiled. Sampling for *Heterosigma* is principally associated with aquaculture so there is a need to investigate whether the location of blooms overlaps with sockeye habitat areas.

Management: Habitat and management practices are improving but there is a higher volume of effluent discharges simply due to the magnitude of population growth. So this needs to be pulled out.

So far, initial findings appears consistent with the PSC paper, though more work still needs to be done. It’s unlikely however that freshwater habitat conditions in the Lower Fraser River have changed enough during the study period to affect sockeye.

Evidence gaps: There are few if any consistent time series for indicators, no clear indicators of human development and limited consistent indicators of biophysical conditions in the Strait of Georgia. The hope is to develop a better information base so that we are not just making circumstantial arguments about associations. We’re still quoting good work that was done 2 – 3 decades ago. We haven’t yet seen Beamish’s trawl survey data. The hope is to get the characteristics of good sockeye habitat so that we’re not looking all over the place.

Comments are welcomed on the indicators and their potential influence on sockeye habitat use and potential risk of loss or degradation of key sockeye habitats from 1990 to 2010.

Discussion

McKinnell: When was Roberts Bank built?

Johannes: In the 1980s? It's important mostly for sediment as you don't catch sockeye smolts there, only pink and chum.

McKinnell: I wonder if increased light pollution in Georgia Strait makes sockeye smolts more vulnerable to predation?

Johannes: We don't know. The Fraser plume is dynamic and while there is only one study on this, I can't imagine sockeye not using the plume wherever possible. They use favourable currents in Georgia Strait to move quickly. If they are in good condition, they will stop to feed, but if conditions are bad they will move fast. Re light pollution, they will shy away pretty quickly.

Dorner: Are there any thoughts on cruise ship discharges and *Heterosigma* blooms?

Johannes: We only have Port of Vancouver data for ballast discharge. I suspect the amounts pales compared to resident discharges. *Heterosigma* may be part of a "death by a thousand knives" pattern.

Ashley: Transport Canada regulations specify conditions for ship discharges. I will send you a report that collected data on cruise ships.

English: This is a very broad topic. I would encourage you to focus on the specific locations and times when sockeye are in specific areas. For example, what are the river discharges like at the time when juvenile sockeye are migrating out. There is limited data, but there is some from recent tagging and also smolt timing at the Chilko fence, and then compare that to algae blooms, river flow, temperature, etc.

Johannes: I've taken every observation I can find and put it in the database so we will have time-place association. There is anecdotal information but not good data on when the bulk of sockeye smolts are moving through the Lower Fraser. But we will try to do the association with algae blooms, etc.

Rosenau: Do you have enough data to say where sockeye are distributed in Georgia Strait. Is it just the shorelines?

Johannes: They use the (upper limnetic?) habitats, not the littoral zone and they use the shelf rather that the deep troughs. I will try to catalogue whatever information exists on which environment sockeye are using, but the issue is that it can change from year to year.

Rosenau: Where are boundaries of the study? Do you go up to Campbell River or does it stop earlier. It's very different from Campbell River to northern Vancouver Island, and this relates to fish farms and massive anthropogenic effects. This may be covered by other groups but we should look at habitat for the greater Georgia basin

Johannes: I can comment in my report but I understand that other groups are investigating it. The northern boundary is Quadra/Cortes and I will use whatever information I have. Sockeye move around a lot and how do these changes affect survival. The best data I have are herring survey data, but they were looking for herring, not sockeye. There is disparate information but we can put it on a map to show how they use the environment and how that changes and overlay it with other information and see what associations there are.

Routledge: Michael Price's sampling information may be useful.

Marmorek: On Day One, the Kalman filter analysis showed the pattern was at a larger geographic scale, so how likely is it that Lower Fraser habitats are what's driving the long-term decline?

Johannes: I don't know. The data don't show how they stop and start. Some years they barrel through and other years they dally around Malaspina and Texada. We couldn't pull apart the characteristics by stock but there may be a tie in between what they hit in Queen Charlotte Sound – if they find unfavourable conditions there. In other circumstances, they split along the two sides of Georgia Strait and slow down.

Pickard: What data indicate the speed at which they travel in Georgia Strait.

Johannes: Seine catches (1960s to 2003 catch data), June sampling data for herring and some POST tagging studies.

Pickard: Regarding the northern boundaries, it would seem sensible to include the area with the fish farms.

Johannes: I will make clear what information exists and doesn't exist on habitat use and how it changes annually.

Marmorek: How does this study relate to the fish farm chapter?

Levy: This project needs to be clearly separated from #5.

Adult river migration and spawning success

En route mortality, pre-spawn mortality and intergenerational effects

Scott Hinch

Factors examined for this study were among-year and among-stock patterns and their relationship with spawner abundance and spawning success.

Definitions: En route loss is defined as the difference between Mission and spawning ground escapement estimates, after accounting for in-river harvest (it includes unreported catch). Pre-spawn mortality is the percent unsuccessful egg deposition by female spawners.

En route loss can be large relative to harvest and escapement and has been very important in recent years. Prior to 1992 it was rarely shown, which was partly due to the way the data were collected. It has been very high in recent years for Early Stuart. Early Summers show the same pattern of increasing en route losses, though the proportions are lower. Late runs show very large en route losses, starting suddenly after the mid-1990s.

DNA analysis can now be used to assign in-river migration mortalities to specific stocks. Nine of 12 Fraser sockeye stocks had high en route mortality (over 50%) in most recent years, with the early and late stocks suffering the worst impacts.

Key metrics: The most important metric is temperature. The key metrics examined changes over time and found clear temporal patterns. The pattern varies among Fraser sockeye stocks and are likely to be similar for non-Fraser sockeye stocks such as those in the Columbia River.

Biological hypothesis: Thermal and related issues play a large role in among- and within-stock variations in en-route and pre-spawn mortality. Differences in migration distance and entry timing among stocks directly affects their thermal migratory experience (those that enter early and travel long distances accumulate more hot days and hotter days). The Early Summer and Summer stocks encounter the highest Fraser temperatures.

Thermal changes: Since the 1950s, there has been an increase of about 2 degrees Centigrade in summer Fraser water temperature, and an increase of around 1 degree C in the last 20 years. Discharge patterns are changing and many recent years have had extreme high summer temperatures. Since 1996, late-run sockeye have been entering the river 4 – 6 weeks earlier than normal, instead of holding as in the past at the mouth of the river, and thus encounter temperatures up to 5 degrees C warmer than usual. River temperatures of more than 18 degrees C are now routinely experienced during return migrations.

High temperature can kill salmon in different ways. Even when temperatures are sub-lethal, they can still cause mortality before the salmon reach their spawning grounds. It is not known whether these effects have intergenerational consequences.

Evidence: Lab studies of swimming and cardiac performance under different temperature and flow conditions simulated in swim tunnels show that optimum and lethal high temperature thresholds vary among stocks. The results show that stocks are thermally adapted to their migration timing, in some cases with a small window between the optimal and critical high temperature thresholds. For example, Early Stuart is adapted to river temperatures between 14 and 16 degrees C. The Late runs that are now migrating earlier face much warmer temperatures than in the past.

When adult late-run sockeye are held in water warmed to 20 degrees C in the lab, they all die, even if the water is subsequently cooled to 18 degrees. Mortality is only slightly abated if the water is cooled to around 10 degrees (which speaks to the value of thermal refuges in lakes).

Potential interactions among the examined factors and other stressors include pathogens and disease and rate of senescence. Most such interactions are negative or neutral, dependent on migration timing.

For example, *Parvicapsula* is picked up by all returning Fraser sockeye in the Lower Fraser. Experiments showed that kidney infections in lab-held sockeye increased rapidly when individual fish had accumulated around 370 degree days. There is a correlation between the level of disease and mortality and many diseases are thermally mediated, so the more hot days, the more rapidly the disease agents will act. Field studies show that differences between the Mission and spawning ground estimates (i.e. en route mortality) are related to exposures to high river temperatures and flows. Survival estimates from telemetry studies also show stock-specific relationships between river survival and temperature. For Chilko, higher temperatures did not seem to matter, but other stocks, like Quesnel, seem highly affected. For most stocks, 18 degrees C seems to be a tipping point, with 40% or more of the run lost at 20 degrees C.

In 2002, a major research program was launched to investigate the early migration of returning Late-run sockeye. Studies showed much higher mortality in recent years with early migration. It was also shown that tagged fish returned to the river suffered much higher mortality if they had been kept in warmer water. It's still not understood why the fish are migrating earlier but they are returning in poor physiological condition and then they encounter much higher river temperatures.

Pre-spawn mortality: There is a long history of information showing that this affects all stocks, with mortality of up to 90%. Occurrences are variable and episodic among years and may be higher and more variable in recent years. There does not appear to be an overall trend for Fraser sockeye but it does appear to be higher and more variable in Late-run stocks.

There are many causes of PSM, including disease, stress and time spent on spawning grounds. There is evidence that it is simply a continuation of the processes that are killing fish during their return migration.

Conclusions: Migration mortality is substantial in many stocks across all run-timing groups in recent years, particularly when river migration temperatures exceed 18 degrees C. Lab and field studies show there are stock-specific differences in how fish deal with acute and chronic high temperatures. Migration mortality is likely a contributing factor in declining trends in spawning abundance for stocks that don't cope well with high temperatures (early and late runs). Pre-spawn mortality reduces the number of effective female spawners and could be a factor in declining productivity for some late-run stocks.

DFO and others are starting to do studies on possible inter-generational effects, but results to date are limited and equivocal.

This study agrees with the three conclusions from the PSC report regarding en-route mortality, pre-spawn mortality and intergenerational effects.

Information gaps: These include intergenerational effects, direct measures of migration survival, and effects of bycatch/discard releases on survival. All three of these information needs are knowable.

Climate & climate change effects on Fraser sockeye: literature review

Eduardo Martins

The study objectives were to review the literature on documented effects of climate on sockeye and to make a qualitative assessment of the role of recent climate change on the decline in Fraser sockeye productivity.

The presentation discusses how the literature was compiled, climate change and its effects on Fraser sockeye habitats, the likelihood of climate change effects on survival, survival by life-stage and the likelihood of changes.

A search was undertaken of primary and grey literature specific to sockeye. Most of the papers focused on freshwater, though there have been more papers on the marine in the past 2 - 3 years.

Climate change and Fraser sockeye habitats: Summer temperatures in the Fraser River have warmed by 2 degrees C since the 1950s, and 13 of the last 20 summers have been the warmest on record. There have also been substantial changes in precipitation (an average increase of 22% per century but highly variable across BC). Fraser River flows show no trend, though the freshet is slightly earlier. For Georgia Strait and the Gulf of Alaska, temperatures have warmed by 0.25

degrees C per decade, but that trend is confounded by large trends like the ENSO and PDO, with a warming trend attributed to the 1977-97 PDO.

Likelihood of climate change effects: Climate changes could affect phenology, growth and survival, thought this study only examined direct (observations and tagging) and indirect (productivity) evidence of changes in survival. Criteria were defined for ratings of Unlikely, Possible, Likely and Very likely.

Egg and alevin survival: One study showed survival decreased when there were increased flows during incubation. Another showed productivity increased in years with more rainfall, which may mean more spawning area. So the two factors may offset each other. The rating was therefore that survival possibly decreased. Additional comments are that there may be inter-stock variability, with coastal (Weaver) doing better than interior (Adams) stocks.

Fry survival: Evidence from lab and field studies suggests that higher temperature possibly decreased fry survival. Temperature may not affect fry survival directly but it may lead to increased predation rates on fry (one study suggested that coho predation on sockeye increased with temperature). A study in the Columbia showed small-mouth bass and walleye increased predation on sockeye fry by 25% to 35%.

Smolt and post-smolt survival: There is no lab but much field data indicating that temperatures in the ocean and estuary area decreased survival, so this was rated as likely decreased. Additional comments are that opposite effects were seen in Alaska stocks. Temperature might be a proxy for changes in food abundance, quality and/or increased predation, but we don’t know.

Immature sockeye survival: There are no lab and just one field study suggesting that temperature decreased survival. This was rated as possibly decreased, but there is very little data

Adult survival: There is much lab and field work showing that temperature reduces survival, and some field study showing that high flow decreases survival, so this was rated as very likely decreased. Studies show low survival across many sockeye stocks at 18 – 20 degrees C, with inter-stock variability. Mechanisms for this are relatively well known and there is recent evidence that female survival and spawning success is exacerbated by warmer temperatures. Possible intergenerational effects need to be considered.

Concluding remarks: More data is needed: different stocks have different life histories so they experience effects differently and this could provide valuable clues. More studies of mechanisms are also needed.

Cumulative effects: Climate itself could be a significant factor generating a number of cumulative effects. If sockeye adults return smaller and with less energy, they will be more susceptible to stressors during the return migration. Impacts may also be nested: there may be effects across all life stages and there may also be intergenerational effects with climate playing a role.

Conclusion: Climate change is a possible contributor to recent declines in Fraser sockeye productivity on average, with inter-annual and inter-stock variability.

Discussion

Woodruff: Is there any information for 2010 on holding patterns for Late-run sockeye in Georgia Strait?

English: There was extensive holding among a dominant group.

Hinch: Some early fish were also coming in.

Woodruff: Pre-spawn mortality for Cultus is quite high. Do we know why? Is it hatchery-related?

Hinch: They allow some fish to try to spawn naturally though there has been a lot of pre-spawn mortality in recent years. But there have been problems with Cultus for quite a while related to lake spawning conditions.

Staley: One of the challenges is you can't find the carcasses because they are lake spawners.

Peterman: We have heard of temporal changes in major indices where the focus was either on marine or freshwater in each case, but it is likely both, since both are linked. Regarding the earlier timing of the freshet in recent years, are there any data on this relevant to the bloom-timing mismatch hypothesis?

Martins: There are some data on zooplankton blooms occurring 30 days earlier and for a shorter period. If the Fraser discharge is very high, it may affect this as well.

McKinnell: Wind patterns have a big effect on the BC coast. Mean wind patterns for April show that starting in 1989, there was a persistence of typical winter wind patterns (average wind speeds and direction) into April. Prior to that, the summer northwest wind pattern used to set up about a month earlier. With the southeast winds, you get a combination of warmer winds plus a push of water from south to north. Both Mackas and the Peterson index show that temperature is a reflection of variable patterns in the entire ecosystem.

Routledge: There is a one- to two-month time lag from the bloom to the emergence of the plankton that sockeye want to eat, so the timing is about right that it would affect them. We saw a dramatic change in 2007, as McKinnell described.

Data synthesis and cumulative effects

Alex Hall & Darcy Pickard, ESSA

This project involves data synthesis and integration; workshop organization, facilitation and reporting; the cumulative impact analysis, quantitative analyses across projects; and communicating to the Cohen Commission on the complexity of potential interactions. The timeline includes a December 15 final deadline to collect data from projects, with the final report due February 21, in time for the public workshop.

Cumulative effects can involve a single type of effect repeated over time or space, multiple effects that occur at one point in time and space, multiple effects that occur over time and space, or multiple effects that occur at different times and places.

It is important to distinguish between relative impacts (relative magnitude of each stressor – i.e. which effects have greater relative importance relative to others) and cumulative impacts (which involve mechanisms whereby different stressors combine). This project looks at both, using data from the research projects, along with both qualitative and quantitative data and analyses. Limitations include data gaps and complexity.

The presentation reviewed examples of different morbidity-mortality patterns resulting from the combination of different stressors: a low-level accumulation across the life span that leaves the subject less fit to deal with major stresses late in the life cycle; a rapid accumulation in the early stages that causes an extended sub-lethal level (i.e. leaving the subject vulnerable to any small additional impact); or a steady, even accumulation of stressors over the entire life span (stepped pattern – death by a thousand cuts). If the situation with Fraser sockeye resembles the last pattern, it would be very hard to prove that.

Weight of evidence approach: A key challenge is how to use imperfect evidence – complex evidence, with confounding factors and data gaps – to gain as much insight as possible to guide rational decisions. This requires looking for plausible mechanisms, evidence of exposure and adverse effects, including the specificity and timing of effects (i.e. ensure there is a match in space and time). Additional questions to be asked include whether the exposure level exceeds thresholds, whether the effect can be experimentally confirmed and whether removal of the stressor reduces the effect.

Qualitative approaches: Key elements of the proposed approach for this project include a conceptual model of stressors over the life history, showing pathways and interactions, a spatial life history diagram that gives a better idea of the scale and spatial overlap of stressors and an expert evaluation of relative likelihood that integrates multiple sources of evidence.

Quantitative approaches: The presentation also reviewed data availability and limitations, noting that data was expected from all of the projects except the diseases and parasites project (lack of data), the aquaculture contract (uncertainty re timing), and the fisheries and science/ management projects (not applicable). The extent of data available and the ability to correlate potential stressors to Fraser sockeye both temporally and spatially over their life history varies dramatically between projects. Limitations include missing data for some stocks and some years, having nothing more than snapshot data in some cases, the large number of parameters, data that is sometimes only available at a different spatial scales for some stocks and gaps in terms of being able to verify data quality, which raises the question of how to weight it (e.g. data collected for other species and purposes that is mined after that fact).

Potential analyses: The data can be organized by life history stage or habitat type, by location or by project. The proposed approach is to look for evidence through any of these lenses (e.g. evidence from several projects that relates to stressors occurring a particular life-history stage or geographic location).

Univariate analyses: Peterman's productivity data were used to do trend analyses and stock profile summaries (e.g. are fewer stocks making the system less resilient?). Also being considered are control charts to see if there is any evidence of variability that is abnormal for the system. A lot can also be done also to assess patterns for stressors in time and space. The individual projects are covering this so this project will mainly focus on presenting those results simultaneously (e.g. likelihood table).

An example was presented of the trend analysis for one stock, Early Stuart, showing 1965 as the breakpoint in an up/down productivity trend since 1950. The intent is to get an idea of the recent productivity trend so as to focus in on that and also to see if it's possible to determine whether all stocks started to decline at once or if certain groups of stocks showed similar patterns. The Kalman filter is another way of doing this. For Early Stuart, the best-fit model was that a change in productivity happened in 1965. Other stocks show a straight line pattern, which suggests that it may be more complicated than something that affected all stocks at the same time. A comparison of stock composition for the total Fraser sockeye run over different (12-year) time periods showed that 4 to 6 stocks (of the 19 that have data) consistently made up about 80% of the run for each time period.

Cross project analysis: The project also involves correlation analyses to assess correlation among variables across projects and also comparisons among groups (run timing, year types, Fraser vs. non-Fraser, climate periods, migration routes or timing.

Multivariate analyses: These include discriminant analysis or logistic regression to determine which stressors are best able to "discriminate" among groups of stocks with similar productivity patterns (don't have covariates beyond the Fraser to follow that through). Principal component analysis (data reduction and interpretability among predictor variables) may provide (?a better idea of the uncertainty around relationships?).

Multiple regression can assess the relative importance of each stressor as well as hypothesized interactions and is probably the best tool to address the question of relative and cumulative effects. The intent is to use an information theoretic approach: to develop candidate models, to fit models and compute AICs, and to assess relative weight for each model.

Caveats are that while this quantitative analysis is important, it also has important limitations (e.g. stocks with no data don't even enter into the comparisons). There is a tendency to think that the numbers trump everything else in terms of validity, but these should be seen as just one piece to add to the overall weight of evidence and every effort will be made to communicate that very clearly.

Questions: These include how to deal with missing data: Is interpolation possible or will it be necessary to drop incomplete rows? Is it better to use a reduced set of years with data from more stressors or to look at a reduced set of stressors (or both)? Should the project try to come up with a status-only dataset across all stressors? For the productivity metric, which is the right response variable: current slope, CU status or trends? Knowing that there will be many gaps, it is proposed to use expert opinion to develop a complete data set: Is that a viable approach?

Feedback was sought on redundancies and gaps (vs. what other projects were doing), priority analyses and additional suggestions.

Discussion

Johannes: In looking at habitat loss and degradation, is 1990 to 2010 an appropriate time period? I have an accumulation of individual data sets and I don't know how to address them, but the conceptual model starts to address the question of how to look at them.

Pickard: Where is the overlap between stressors in space and time? In a more complex model, we use that with the life history model to (…?). If we have data – how to use the conceptual models to drive (…?) to be able to look at the relative importance of different models to explain the productivity data. I'm not confident that it's going to work, so we'll take the univariate analysis and the trends where we do have data. It won't be conclusive but we will have all the evidence summarized as best we can.

Christensen: I like the idea of expert opinion data sets. Without complete time series, if you restrict it to years with data it would put more weight on those that have the long time series.

Hall: We have limited data on stressors for that time period, so that is future work.

Peterman: Before you conclude from your concentration profile analysis that there has not been much change in the overall stock/life history composition of Fraser sockeye, you should look at how that profile compares with one for Bristol Bay sockeye. With cumulative probability plots like your concentration profile, you can have large changes that don't show up clearly on the graphs.

Hall: Agreed. This was a very quick look at it.

Routledge: Blow up the scale to see how the weak stocks are doing. But really, you could throw up your hands in despair at this task. The fundamental purpose is to understand the cumulative impacts of multiple stressors that could impact Fraser sockeye in multiple ways. I don't think there is much hope of answering that in a couple months. The other idea that looks more positive is the notion of trying to tease out effects of different stressors – additive impacts. That looks achievable. The other one is important too but I don't know what we can do, so I encourage you to keep open the option of saying that we don't really know.

Hall: It's important to take care to avoid mis-communicating the findings or over-stating the case.

Marmorek: If this big circle is the story, the portion told by quantitative data is a very small portion. Most of it will be qualitative or expert judgment.

Exploring conceptual models

Darcy Pickard, ESSA

The draft conceptual model and spatial life history diagrams were based on information from the PSC report, plus the progress reports received to date, so they are not exhaustive. Participants were invited to study the diagrams and to add comments regarding missing pieces or elements to subtract. The intent is to use these diagrams to present all the information from the research reports in one integrative way, with a focus on the factors that have the greatest explanatory power in the productivity declines. This will be used to select model sets to test, so having every fact at every life stage would not be useful.

- Blewett: Suggest using four colour bands to more clearly show the four key geographic spaces in which these things occur.

Integrative workshop tasks

PSC report on relative likelihood of hypotheses

Marmorek explained the intent of the breakout exercise, stressing the importance of looking at the big picture. The task was to review the conclusions of the PSC report, as summarized in Table E-1, and to consider whether or not participants agreed with their conclusions and why.

Participants broke up into three groups, and their discussions were summarized on flipchart notes).

Recommended monitoring and research priorities:

Participants were asked to take a few moments to individually review and comment on whether or not they agreed with the monitoring and research priorities outlined in Table E-3.

Q/A: Researchers should also feel free to make recommendations on research priorities in their reports.

Discussion

Participants were asked to share their most important change to the identified priorities, and reported as follows:

Peterman: A major effort to construct and maintain databases with appropriate QA/ QC procedures, so that we can answer questions quickly and with some credibility. In addition to salmon data, such databases should include data related to mechanisms and ecosystems.

Routledge: Include condition and length in the recommended juvenile assessments.

Christensen: The table has a very low emphasis on ocean research: we're "looking under the streetlight." Relevance to management actions is important and we should do fishery experiments all the time if it's important. Also research on the abundance of predators.

Trites: Predator diet studies (fish and mammals) using DNA to see which salmon species they are eating.

Dorner: Studies of outside migration routes are just as important as inside studies.

Staley: I agree with the database suggestion. Also ensuring that we maintain capacity to manage the fishery. We should not lose sight of this in looking for interesting information about the fish.

Blewett: I also agree with Peterman. Take these recommendations and combine them with a similar description of the monitoring that's being done now, put them together and put cost data against each one so that you can make good decisions about how to optimize investments in research programs.

Rosenau: Georgia Strait is the term used here. It should be clarified that we need to look at migration and survival routes from Campbell River north to the tip of Vancouver Island and south via the Strait of Juan de Fuca. We need discrete macro units assessed for juvenile migration patterns and survival rates.

Martin: Focus on productivity and changes in rearing lakes: limnology, smolt and fall fry studies.

Ashley: A user-friendly annual report on the state of the salmon. Start with sockeye but ultimately cover all species.

Johannes: Redefine the rows in this table and link Rows 2, 3 and 4 as a single program. Successfully-funded programs are life-history specific. POST is one mechanism for studying it but we no longer have sampling programs that look at the distribution of smolts. We have no index for smolts. We don't need fences, do net catches. There is also nothing on the timing of the freshet.

English: Too much energy is going into improving forecasting instead of into doing proper in-season monitoring. We need inside Georgia Strait studies. A first priority should be an initial scoping of data – it's unlikely to be done in the next two weeks – on things like harmful algae and contaminants. Some things could be done via existing data and it could guide a future program. Also what's happening with fish going through Georgia Strait. If the action is outside Georgia Strait we will need major dollars to study it.

McKinnell: There are no marine survival indices – the fences are all up in the rivers so there is no starting point from which to generate abundance information. So monitoring needs to estimate post-smolt emigration from river by stock. We should expend some effort to try to find dead sockeye smolts. Find a way to see how sockeye are dying. We can't use recruits per spawner or smolt survival – we need a census of population as they enter the sea. Ideally, you could sample them at a "fence" in Johnston Strait to say what is coming out of Georgia Strait.

Q/A: The difficulty with POST is that it is labour-intensive. Alternatives include sonar.

Martins: My concern is that parental spawning success and incubation is a low priority. This is important to management. I agree with Martin's suggestion about lake studies. Also predation.

Hinch: I agree with Johannes, McKinnell and English. We need direct assessment of survival in the juvenile and post-juvenile stages. We can make statements with the adults because we measure those but we do very little with juveniles. It transcends several of these categories – we need a way to assess relative abundance as they're migrating out. Whether we use POST or another technology that's not as expensive, we can link that with oceanography or coastal research.

Marmorek: The first step is to find where and when the victim died.

Kent: My comment is about the near-shore research for pathogens. I think it's important, though others don't think pathogens are important. If you do it, you need to look at pre-smolt fish as pathogen research requires you to look at the host through different life stages.

Porter: Methods to address broad changes in the quality of spawning habitat. Assessment across a CU's spawning reaches and showing annual changes. There is no method in place to do that. This includes water quality.

Wieckowski: Looking at whether there are any inter-generational impacts from adults coming in really stressed, if this could be more common in the future.

MacDonald: A general comment is that I like a lot of it but that there is opportunity to sharpen up a lot of these recommendations to more specifically address what we're looking at. Priorities include temperature effects and en route losses and interactive effects of temperature and contaminants in en route losses.

Groot: What is obvious is our lack of biological information on what they do in the open ocean. We are way behind the oceanographers. We now have lighthouses, Argus floats and monitoring stations, so use the technology that we have (we use tags for birds, even butterflies, so use them for salmon too). With changing climate there will be more fluctuations, so we need to get out and observer instead of continually rehashing the old data.

Peterman: We were discussing the same thing. Astronomers and oceanographers get big, expensive projects approved.

Martin: We need a sockeye research collaborative – not just for BC but international – that looks at the flow through the whole life history – a big picture approach.

Peterman: We're lacking the big picture because we're not thinking big enough. The proposal for a fully-integrated Strait of Georgia study is not thinking big enough - everyone is studying small pieces.

McKinnell: I think there is an opportunity. The coastal salmon ecology group is meeting annually and has had some success with regard to ocean survival of salmon in the early life stages. We are trying to find an umbrella to share observations from California to Alaska. Take a network of people who are working under the radar and formalize it as an organization, an international cooperative that has the same research objectives.

Levy: With this Commission we have a unique opportunity to advance some of these concepts so there is no problem thinking big. The government of Canada will be listening.

McKinnell: Even something like the old Fisheries Research Board model. Look at what is failing and where advances could be made in a way that is cost effective and that provides new insights.

Peterman: Not just for Fraser sockeye: we need something to compare Fraser sockeye with for the whole life history, with well-focused questions.

Kent: I'm involved in three Oregon studies that were part of a bigger program. It was very rewarding because the work was so well integrated with toxicology and fishery biology.

Christensen: Is this what DFO has in the 5-year plan? It's worth looking at the ecosystem research initiative and how effective it has been. They are chopping the funding into such small pieces.

Marmorek: There is a report that deals with DFO management and science so that seems like the logical place to address it.

Johannes: It would be useful to have a group of authors write a white paper on this.

Levy: ESSA's cumulative effects paper would be a good place to do it.

ACTION: Email any further comments on conceptual models to ESSA (Darcy)

Closing comments

Levy thanked everyone for an enlightening discussion, noting the brain power in the room had been effectively harnessed in the agenda, that he was very pleased with the progress heard and that he looked forward to continuing to work with the researchers.

- Q/A: The report deadline is fixed, and further changes after the deadline would not be encouraged.

Levy closed by thanking ESSA for a great job organizing and facilitating the workshop.

Adjourned: 4:45

List of Participants

Dave Marmorek, ESSA (Facilitator)
Darcy Pickard, ESSA
Alex Hall, ESSA
Marc Porter, ESSA
Katherine Wieckowski, ESSA
Liz Martell, ESSA
Dave Levy, Cohen Commission
Patricia Woodruff, Cohen Commission
Carla Shore, Cohen Commission
Don MacDonald, MESL
Michael Kent, Oregon State University
Mark Johannes, Golder Associates
Kees Groot, DFO retired
Marc Labelle, L4 Biotech
Al Martin, MoE retired
Ken Ashley, BCIT
Edwin Blewett, Counterpoint
Mike Staley, Counterpoint
Bert Ionson, Counterpoint
Brigitte Dorner, SFU/Driftwood Designs
Andrew Trites, UBC
Villy Christensen, UBC
Randall Peterman, SFU
Sean Cox, SFU
Marvin Rosenau, BCIT
Karl English, LGL
Skip McKinnell, PICES
Eduardo Martins, UBC
Scott Hinch, UBC
Rick Routledge, SFU
John Reynolds, SFU

Dawn Steele (note-taker)

Summary of action items

- Levy to advise whether reviewer comments and responses should be reported individually or as summary reviews and summary responses.
- Scientific contractors requested to keep Excel and Access files handy to facilitate translation of all figures in their reports (tables should be okay).
- Email any further comments on conceptual models to ESSA (Darcy)

Appendix D: **Table of likelihood/ hypotheses**

Workshop participants were asked to examine the PSC Report *Probability of, or relative likelihood of, alternative hypotheses* (i.e. Table E-1, Peterman et al. 2010) and compare the results to the workshop findings. Participants judged the relative likelihood that a given hypothesis contributed to both the poor returns in 2009 and the long-term decline in productivity of Fraser River sockeye salmon. Ratings are shown for both the PSC Panel ("PSC", grey - contributing factor; black - major factor) and the participants at the Cohen Commission workshop ("workshop", orange – contributing; red - major). Participants used qualitative terms (*very likely*, *likely*, *possible*, *unlikely*, or *very unlikely*) to rate the hypotheses. Strength of evidence was only recorded at the workshop where participants felt there was a need to qualify their judgments.

Cohen Commission Project	Time Period	Strength of evidence	Source of Ratings	Relative likelihood that each hypothesis *contributed significantly to* observed changes in productivity: Very Likely	Likely	Possible	Unlikely	Very Unlikely
1 – Diseases & Parasites	overall	Fair	PSC	grey	grey	grey		
			Workshop		orange	orange	orange	
	2009	Fair	PSC	grey	grey	grey		
			Workshop		orange	orange	orange	
2 – Contaminants	overall	Poor	PSC			grey		
		Good	Workshop			orange	orange	orange
	2009	Poor	PSC				grey	grey
		Good	Workshop				orange	orange
3 – Freshwater Factors	overall	Fair	PSC				grey	grey
		ND[4]	Workshop			orange	orange	orange
	2009	Fair	PSC					grey
		ND	Workshop				orange	orange
4 – Marine Ecology (*inside* Georgia Strait)	overall	Fair	PSC		black			
			Workshop		orange	orange		
	2009	Good	PSC	black				
			Workshop		orange	orange		
4 – Marine Ecology (*outside* Georgia Strait)[5]	overall	Fair	PSC			grey		
			Workshop	orange	orange	orange		
	2009	Fair	PSC			grey		
		Good	Workshop	red	orange			
8 – Predators 1 (Mammals)	overall	Fair	PSC			grey		
			Workshop			orange	orange	orange
	2009	Fair	PSC					grey
			Workshop				orange	orange
8 – Predators 2 (Fish & Birds)	overall		PSC	*not evaluated by PSC*				
		few data	Workshop			orange		
	2009		PSC	*not evaluated by PSC*				
		few data	Workshop			orange	orange	orange
9 – Climate	overall	Good	PSC					grey

[4] ND = no data presented at workshop; only qualitative judgments
[5] evaluation of this factor at the workshop focused on Queen Charlotte Sound

Cohen Commission Project	Time Period	Strength of evidence	Source of Ratings	Relative likelihood that each hypothesis *contributed significantly to* observed changes in productivity: Very Likely	Likely	Possible	Unlikely	Very Unlikely
Change 1 (en route mortality)			Workshop			*for S*[6]		
	2009	Good	PSC					
			Workshop					
9 – Climate Change 2 (effects of en route mortality on next generation)	overall	Poor	PSC					
		ND	Workshop	*for S*				*for R/S*
	2009	Poor	PSC					
		ND	Workshop	*for S*				*for R/S*
9 – Climate Change 3 (overall effects)	overall		PSC			*not evaluated by PSC*		
		Good	Workshop					
	2009		PSC			*not evaluated by PSC*		
		Good	Workshop					
10 – Delayed Density Dependence	overall	Fair	PSC					
			Workshop					
	2009	Fair	PSC					
			Workshop					

[6] S = returns of spawners; R/S = recruits / spawner (en route mortality already included in R, together with returning spawners and harvest)