Synthesis of Evidence from a Workshop on the Decline of Fraser River Sockeye

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Executive Summary

Background

Fraser River sockeye salmon (*Oncorhynchus nerka*) have faced many challenges, especially beginning in the 1990s. These difficulties include unfavourable ocean conditions, increasing Fraser River temperatures, and unusually early upstream migration of some populations. The latter two factors have caused high mortality rates of adult salmon during their in-river migration to spawning areas. More recently, there have been several years of extremely limited fishing opportunities for Fraser River sockeye. In addition, concerns have been raised about infections by sea lice, predation by increasing populations of marine mammals, contaminants in rivers and the Strait of Georgia, and ocean conditions possibly associated with climate change. Some British Columbia sockeye populations, including Cultus Lake sockeye within the Fraser, have reached precariously low abundance levels. The combination of increasing challenges for Fraser River sockeye, as well as increasing awareness of problems facing salmon more generally, have heightened concerns about the long-term viability of this valuable resource. In 2009, these concerns were reinforced when only 1.5 million Fraser River adult sockeye returned -- the lowest number since 1947 and only 14% of the pre-season forecast of 10.5 million fish.

As serious as it was, this 2009 event was only the latest in a series of indications that Fraser River sockeye populations were facing serious widespread problems. The most important indicator of those problems is the decrease in **productivity over the total life cycle** (adult recruits produced per spawner) that 16 out of the 18 Fraser River sockeye populations considered here have shown since the late 1980s or early 1990s. Eight stocks with additional data on juvenile abundance (fry or smolts), have shown no reductions in **freshwater productivity** (i.e., from spawners to juveniles), but have shown reductions in **post-juvenile productivity** (i.e., from juveniles to returning adult recruits). This observation indicates either that the primary mortality agents on sockeye occurred in the post-juvenile stage, or that certain stressors that were non-lethal in freshwater caused mortality later in the sockeye's life history. Section 3 of this report describes details of these circumstances, which we refer to collectively as the "Fraser sockeye situation".

The Pacific Salmon Commission (PSC) is an institution established under the Pacific Salmon Treaty to jointly manage U.S. and Canadian fisheries directed at Fraser River sockeye in the Fraser Panel area, as well as other species. Out of concern for recent declines in abundance and productivity of Fraser River sockeye salmon, the PSC arranged a workshop on 15-17 June 2010 in Nanaimo to evaluate evidence for and against possible causes of these declines. This workshop was viewed as a first step toward evaluating and synthesizing evidence on alternative explanations for the Fraser sockeye situation. An Expert Advisory Panel was created, composed of 11 experienced researchers from Washington and British Columbia who are the authors of this report. As well, about 25 other experts were invited to attend the workshop to make presentations and to critically evaluate data and hypotheses about causes of the decline. Many observers also attended, so that a total of 68 participants were at the meeting.

The workshop included presentations on the Fraser sockeye situation and alternative hypotheses to explain recent declines in abundance and productivity of Fraser River sockeye salmon. Data were also presented on non-Fraser sockeye salmon populations, as well as chinook (*O. tshawytscha)* and coho (*O. kisutch*) populations, which overlapped with Fraser

sockeye in space and time to various extents, ranging from none to partial. Such data created comparisons with Fraser sockeye that might provide clues about important factors affecting the latter. In addition to presentations, the workshop included plenary discussions of evidence, subgroup discussions of hypotheses within particular thematic areas, and survey forms to provide the Expert Advisory Panel with participants' summaries and appraisals of the evidence for different hypotheses.

Hypotheses Considered

The committee organizing the workshop endeavoured to ensure that all possible hypotheses were considered. At the workshop, scientists gave 16 presentations on various possible explanations for the Fraser sockeye situation. These scientists, and the many co-authors who contributed to their presentations, were instructed to dispassionately evaluate the evidence for and against their assigned hypothesis. Subsequent to the workshop, the Panel grouped the possible explanations into the following nine categories:

(1) Predation by marine mammals and/or unreported fishing in the ocean
(2) Marine and freshwater pathogens, including parasites, bacteria and/or viruses
(3) Oceanographic conditions (physical and biological) inside and/or outside Georgia Strait
(4) Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca
(5) Contaminants in the Fraser River and/or Strait of Georgia
(6) Freshwater habitat conditions in the Fraser River watershed
(7) Delayed density-dependent mortality
(8) En-route mortality during upstream migration, plus its effects on fitness of the next generation
(9) Competitive interactions with wild and hatchery pink salmon (*O. gorbuscha)*

Each of these hypotheses is described and evaluated in Section 4 of this report. In four cases (numbers 1, 3, 8 and 9), sub-hypotheses are considered separately.

Probability of, or relative likelihood of, alternative hypotheses

Based on all of the evidence presented at the workshop and summarized in this report, the Panel rated each of the nine alternative hypotheses as shown in Table E-1 in terms of the relative probability or likelihood that a given hypothesis could explain the Fraser sockeye situation. These ratings were made separately for explaining the overall decline or the 2009 returns. When Panel members concluded that the available evidence was consistent with a factor contributing to Fraser sockeye stock declines during the period of interest (i.e., either the overall period or 2009 returns), they rated that hypothesis as *likely* or *very likely*. Conversely, if they concluded that the available evidence was inconsistent with a factor contributing to Fraser sockeye declines, they rated the factor as *unlikely* or *very unlikely*. An intermediate level of support received the rating *possible*. The Panel did not attempt to force a consensus on their ratings. Although there was some variation in support for a few hypotheses, Panel members generally had similar ratings for most hypotheses.

The Panel agreed that multiple hypothesized causal mechanisms are very likely to be operating simultaneously and their effects may be additive, multiplicative (i.e., synergistic), or may tend to offset one another's effects (e.g., mortality earlier in the life history can create less density dependence and higher survival later in the salmon's life cycle).

The Panel concluded that the available evidence for and against each of the nine hypotheses does **_not_** point to a single cause of either the poor adult returns of Fraser River sockeye in 2009 or the long-term decrease in returns per spawner. Instead, the evidence suggests that multiple causal mechanisms very likely operate simultaneously and that their effects may be additive, multiplicative (i.e., synergistic), or may tend to offset one another's effects. An example of the latter would arise if mortality early in the life history leads to less density-dependent competition and higher survival late in the salmon's life cycle). Furthermore, the most probable mechanisms largely affect juvenile sockeye migrants and fish in their early marine life stages.

The main conclusions about the alternative hypothesized causes of the Fraser sockeye situation are as follows.

Main conclusions about mechanisms

The Panel's judgments, summarized in Table E-1, are that physical and biological conditions inside the Strait of Georgia during the juvenile life stage are *very likely the major cause* of poor survival of the cohort that returned in 2009. Those conditions in the Strait are also *likely the major cause* of the long-term decrease in productivity of most Fraser sockeye stocks that has occurred since the late 1980s or early 1990s. Similar physical and biological conditions were judged to affect survival of Fraser sockeye outside the Strait of Georgia, but to a lesser degree. The Panel lacked certain types of information needed to identify the mechanisms more specifically (as described in Section 4) and has recommended future research that may lead to such detailed conclusions (see Section 5).

From the available evidence, the Panel also deduced that freshwater and marine pathogens (that is, viruses, bacteria, and/or parasites) are an important contributor to both the poor returns in 2009 and the long-term decrease in productivity, but again, data did not permit distinguishing further among those factors. It is conceivable that pathogens picked up in fresh water did not cause mortality until the ocean life stage. The Panel members' views on pathogens ranged from a *very likely contributor* to a *possible contributor* to the Fraser sockeye situation (Table E-1). Panel members believe that diseases caused by these pathogens are likely made worse by natural and anthropogenic stressors.

Only three other hypothesized mechanisms received ratings as high as *likely contributing* factors. First, a bloom of harmful algae in southern Georgia Strait in 2007 was a *possible* explanation of the poor returns in 2009, and a *possible to unlikely* explanation of the long-term decline in productivity of Fraser sockeye. Second, Panelists expressed conclusions ranging from *likely* to *unlikely* for the hypothesis that delayed density-dependent mortality contributed to the long-term decrease in productivity. The delayed mechanism is indirect because increased mortality on a given cohort of juvenile sockeye is attributed to excessive abundances of spawners in previous years that lead to reduced food supply, increased predation, and/or an increased incidence of pathogens. Finally, competitive interactions between pink salmon and Fraser River sockeye were rated as either a *likely contributor* or a *possible contributor* to the long-term downward trend in Fraser sockeye productivity.

Hypotheses that are rated as only *possible* or *unlikely* are also shown in Table E-1.

Summary of Evidence

Table E-2 concisely summarizes the evidence **for** and *against* each of the nine hypotheses that was discussed in detail in Section 4 of this report. That evidence formed the basis for the Panel's judgments about likelihoods for those hypotheses, which are presented in Table E-1. We have separated the summary of evidence concerning the overall decline since the late 1980s/early 1990s from the summary of evidence relating to the low 2009 returns. We also summarize the possible mechanisms associated with each hypothesis, as well as evidence for and against those mechanisms. The Glossary (Section 6) defines technical terms.

Priorities for Monitoring and Research

Table E-3 lists monitoring and research activities recommended by the Expert Panel based on their expertise and on evidence from participants at the workshop. The recommendations (1) are consistent with the Panel's conclusions about potential causes of the "Fraser sockeye situation" (decreasing adult returns per spawner, i.e., productivity) as identified in Table E-1, (2) considered the strength of evidence noted for each hypothesized cause, and (3) considered the potential consequences of not addressing these issues. ***The recommendations address only the problems specific to Fraser River sockeye salmon***. Recommendations are stated broadly; a more comprehensive work plan that identifies specific monitoring and research topics would follow from this report.

Given that the workshop considered 12 primary and secondary hypotheses (nine main ones plus sub-hypotheses) and advice provided by over 35 technical experts, the list of possible recommendations for monitoring and research could be extensive. To focus this advice on high-priority issues, potential monitoring and research activities were organized by life history stage and related to the hypotheses assessed in Table E-1. The importance of these activities was rated as High, Medium, and Low in Table E-3 after considering both the relative likelihood that all of the factors operating within a given life stage contributed to the sockeye declines (i.e., a synthesis across all of the hypotheses affecting each life stage), and the degree to which information generated through the monitoring or research activity could improve the management and sustainability of Fraser sockeye and their habitats.

The recommended monitoring and research activities are expected to considerably advance knowledge concerning the state of Fraser sockeye productivity and the management actions needed to sustain Fraser sockeye populations. However, there was broad agreement among the Panel members that both the longer-term trend in productivity of Fraser River sockeye stocks, as well as the 2009 decline, were likely due to a complex suite of factors or interactions of several of the hypothesized mechanisms considered during the meeting. Thus, each recommendation should be seen as a component of a fully integrated, multi-disciplinary research program for Fraser sockeye salmon. Such an integrated approach is strongly recommended because multiple inter-dependent factors influence Fraser sockeye survival, and their cumulative effects ultimately determine the abundance of adult sockeye returning to spawn.

This integrated research plan can have two phases. The first phase can start immediately by having appropriate experts collaborating to identify the key individuals to be involved and to more fully exploit the rich dataset on Fraser River sockeye and pink salmon provided by the Pacific Salmon Commission and DFO.

The second phase of this plan involves development of the integrated freshwater, marine, and analytical programs required to implement the recommendations presented here. Many of the scientific staff involved in the workshop could immediately begin to coordinate their work more closely, but new programs will need to be developed and funded. As a conceptual framework for integrating future research and monitoring activities, the Panel members supported developing an overall model of the components of mortality of Fraser sockeye salmon. The goal of this model would be to better understand the individual factors that contribute to mortality at differing life stages and, perhaps more importantly, how these factors interact and are modulated by various environmental conditions. The development of such a model would be unique. Because estimates of natural mortality typically contain a large degree of uncertainty, a better understanding of interactions among these factors could substantially improve the accuracy of models used to forecast run strength for Fraser River sockeye.

To accomplish this overall goal, research could be focused around providing input to a geographic information system (GIS) that would allow spatially referencing activities and building multiple data layers of information about hypotheses. Such a framework would recognize the need for simultaneous coordination of research across multiple disciplines. This tool for coordination would avoid the all-too-common situation of scientists who are working on one component of a program not being fully integrated with scientists conducting sampling on other components, thereby missing opportunities for cost-effective joint sampling programs and also failing to identify synergistic effects of one factor on another. The latter situation has created cases in which causal mechanisms of observed changes are difficult to understand.

The Panel suggests that a co-ordinated, multi-disciplinary two-phase research program be seriously considered in the immediate future. The Panel particularly notes seven recommended monitoring and research topics that were assessed as being very important for the future sustainability of Fraser River sockeye salmon (**the seven are noted in bold in Table E-3**). It is worth emphasizing that there are new technologies in genomics, molecular genetics, tagging, remote sensing and monitoring, and data visualization that can now greatly facilitate information gained from these research efforts.

While we propose that our new initiatives focus on studies within the Strait of Georgia, there are existing short-term commitments to surveys in a number of offshore locations. Even modest augmentation of these existing programs in the form of support for sample collection and analysis, stock identification, and other biological information would improve our knowledge of Fraser sockeye abundance and distribution in offshore areas.

In weighing the evidence for alternative factors potentially affecting Fraser sockeye, the Panel found it enormously helpful to have data for sockeye populations outside of the Fraser Basin, as well as for other salmon species within and outside the Fraser Basin (i.e., Chinook, coho, chum, pink). These data provided the Panel with very helpful comparisons in terms of life histories, migratory pathways, and the magnitude and timing of hypothesized stressors, which helped to elucidate which mechanisms likely were or were not affecting Fraser sockeye productivity in a given year. Consistent with the above-described intent of developing a well-focused, integrated monitoring program, the Panel recommends including other salmon species in the selected set of well-monitored indicator populations and streams, both within and outside the Fraser Basin. This recommendation is consistent with The Wild Salmon Policy, which requires DFO to monitor each Conservation Unit, and would provide valuable information for managing other salmon species. Once a sampling platform is established for monitoring one salmon species, there is a relatively low incremental cost for monitoring others.

Scope for reducing stressors on Fraser Sockeye through management actions

Table E-4 summarizes the Panel's recommendations for potential management actions to improve the sustainability of Fraser sockeye in the future. These actions follow from those that were recommended in Table E-3 and in many cases require collection of new information. It is important to note that **these management actions should be taken <u>in addition to</u> current management actions**. Certain stressors (e.g., changes in ocean conditions) are not immediately within management control, but others could be acted upon soon after greater efforts are made to acquire background information. The importance placed on each recommended management action (and the associated sockeye life stages) reflect the views of the Panel about the Strength of Evidence in Table E-1, the potential impacts of not taking these actions, and the ease and costs associated of each management action if it were implemented.

The first five actions listed in Table E-4 (related to contaminants, pathogens, harmful algal blooms, marine mammals, and the delayed density-dependent hypothesis) would in total greatly increase the understanding of determinants of sockeye productivity and the early-marine survival of these fishes. Monitoring the survival of Fraser sockeye through the Strait of Georgia could provide an important advance in predicting the subsequent return of adult sockeye and could be assessed two years before their return. Without these efforts and with the expected continuing environmental changes, our understanding of sockeye productivity and appropriate management actions are not likely to improve.

Given the level of uncertainty about the multiplicity of potential causes of the long-term decline in productivity of Fraser River sockeye, as well as the unexpectedly poor returns in 2009, the Panel was not able to recommend other high-priority actions beyond those listed in Table E-4 that could be considered prudent measures to take in the present circumstances. However, there is one management concept that would be prudent to follow, and that is to continue to manage Fraser River sockeye salmon in a biologically cautious manner. This approach is also consistent with the recent certification conditions placed on Fraser sockeye salmon by the Marine Stewardship Council.

A cautionary note: Additional information is required to resolve the uncertainties surrounding Fraser sockeye productivity and future fishing opportunities. Some recommended studies will be of limited duration but other actions will require annual monitoring and evaluation. Thus, the Panel recognizes that these recommended monitoring, research, and management actions will require new financial resources. However, since our proposed research program builds on some existing programs, it is important that funding of these programs be maintained, and not reduced to fund these new initiatives.

Table E-1. The Expert Advisory Panel's judgment of the relative likelihood that a given hypothesis was either a major factor in, or merely contributed to, the observed spatial and temporal patterns in productivity of Fraser River sockeye populations. These likelihoods are based on evidence presented at the workshop, during subgroup discussions, and Panelists' background knowledge. The top row for each hypothesis reflects conclusions with respect to overall productivity patterns (i.e., over the long term). Shading of multiple cells reflects a range of opinions among Panel members. The second row considers just the 2009 *return year*. The colour of shading reflects the Panel's conclusion about the degree of importance: **black** = major factor; **grey** = contributing factor. The strength-of-evidence column reflects the quantity and quality of data available to evaluate each hypothesis/stressor. Panel members made their best judgments of the relative likelihood of each hypothesis, given the available evidence.

Hypothesis	Time Period	Strength of evidence	Relative likelihood that each hypothesis caused observed changes in productivity during the indicated time period				
			Very Likely	Likely	Possible	Unlikely	Very Unlikely
1a. Predation by marine mammals is an important contributor to the Fraser sockeye situation (Section 4.1).	overall	Fair			grey		
	2009	Fair					grey
1b. Unreported catch in the ocean outside of the Pacific Salmon Treaty area is an important contributor to the Fraser sockeye situation (Section 4.1).	overall	Good				grey	
	2009	Good					grey
2. Marine and freshwater pathogens (bacteria, parasites, and/or viruses), are important contributors to the Fraser sockeye situation (Section 4.2).	overall	Fair	grey	grey	grey		
	2009	Fair	grey	grey	grey		
3a. Ocean conditions (physical and biological) <u>inside</u> Georgia Strait are important indicators of contributors to the Fraser sockeye situation (Section 4.3).	overall	Fair		black			
	2009	Good	black				
3b. Ocean conditions (physical and biological) <u>outside</u> Georgia Strait are important indicators of contributors to the Fraser sockeye situation (Section 4.3).	overall	Fair			grey		
	2009	Fair			grey		
4. Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation (Sec 4.4).	overall	Fair			grey	grey	
	2009	Fair			grey		
5. Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation (Section 4.5).	overall	Poor			grey		
	2009	Poor				grey	grey
6. Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation (Section 4.6).	overall	Fair				grey	grey
	2009	Fair					grey

Hypothesis	Time Period	Strength of evidence	Relative likelihood that each hypothesis caused observed changes in productivity during the indicated time period				
			Very Likely	Likely	Possible	Unlikely	Very Unlikely
7. Delayed density dependent mortality is an important contributor to the Fraser sockeye situation (Section 4.7).	overall	Fair		■	■	■	
	2009	Fair					■
8a. En-route mortality during upstream migration is an important contributor to the Fraser sockeye situation (Section 4.8). En-route mortality is already considered in estimates of total recruits, so while potentially strongly affecting *spawner abundance*, this hypothesis cannot explain declines in *recruits per spawner*.	overall	Good					■
	2009	Good					■
8b. The effects of en-route mortality on fitness of the next generation is an important contributor to the Fraser sockeye situation (Section 4.8).	overall	Poor					■
	2009	Poor					■
9. Competitive interactions with pink salmon are important contributors to the Fraser sockeye situation (Section 4.9).	overall	Fair		■	■		
	2009	Fair			■	■	■

Table E-2. A summary of evidence that is given in detail in Section 4 of this report for and against each hypothesis. For the sake of discussion, each hypothesis is stated as if true, but evidence in the table either supports that statement or does not. Evidence in favour is shown in blue normal font, evidence against is in *red italics*, and other notes (e.g. elaborations, data gaps) are in **black boldface font**. Abbreviations: AK=Alaska; HABs = Harmful Algal Blooms; QCS = Queen Charlotte Sound; R/EFS = adult recruits per effective female spawner; SEAK= Southeast Alaska; SK=sockeye; SoG=Strait of Georgia; PST=Pacific Salmon Treaty; WCVI = West Coast Vancouver Island. See Glossary for explanations of terms.

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
1. (a) Predation by marine mammals, and (b) unreported catch in the ocean by humans, are important contributors to the Fraser sockeye situation (Section 4.1).	Overall (late 1980s - now)	▪ Steller sea lions were severely depleted by hunting until protected 40 years ago. They have increased 3-fold since 1970, and are increasing at 5%/yr. ▪ Sightings of Pacific white-sided dolphin have increased since late 1980s. ▪ *Harbour seals were severely depleted by hunting until protected 40 years ago but have since recovered to historical levels. The population in SoG stabilized in the 1990s before the Fraser sockeye decline.* ▪ Humpback whale populations are growing in B.C. and Alaska. ▪ *There's no evidence of significant harvest of Fraser SK in non-Pacific Salmon Treaty (PST) fisheries in high seas or Alaska (AK)* ▪ *Harrison sockeye should be exposed to approximately the same predation rates, yet they have not declined.*	▪ *Since marine mammals are mainly distributed outside the Strait of Georgia, non-Fraser sockeye stocks should in theory be at least as vulnerable to marine mammal predation as Fraser sockeye. Columbia and Barkley Sound sockeye stocks have recently had much better post-juvenile survival rates than Fraser sockeye. This is evidence against the hypothesis that marine mammal predation was an important contributor to overall Fraser sockeye declines.*	▪ Total food consumption by mammals is potentially large enough to affect SK, but quantitative estimates are poor ▪ There are 60,000 Steller sea lions in B.C. SK are > 20% of their diet in summer & fall (better diet data expected in Nov 2010), so significant effects on SK are plausible. ▪ There are 25,000 Pacific white-sided dolphin in B.C., **but the % of sockeye in their diet is unknown.** ▪ There are 100,000 harbour seals in B.C. (40,000 in SoG), *but there has been little change since the 1990s. Sockeye were less than 5% of diet in a 1980s study,* but no recent diet data are available. ▪ Humpback whales have been observed feeding on salmon smolts in SEAK; large size and appetite, quick ability to learn new foraging; no recent diet data ▪ *Documented harvest in B.C. and SEAK (under the PST) is already accounted for in estimates of productivity (R/EFS)*
	2009 returns	▪ *The percent of prey eaten is higher when prey are scarce, so record high Chilko smolt output in 2007 should have led to a low predation rate.* ▪ *There were no sudden increases in either fisheries or mammals in 2007-2009* ▪ *Unreported marine catch is very unlikely to explain low sockeye returns in 2009*	▪ *See comment above; it also is evidence against the hypothesis that marine mammal predation was an important contributor to low returns in 2009.*	

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
2. Marine and freshwater pathogens (e.g., bacteria, parasites, and/or viruses), are important contributors to the Fraser sockeye situation (Section 4.2).	Overall (late 1980s - now)	▪ Fish farms and hatcheries (possible sources of novel pathogens) have increased in the Strait of Georgia, but data on fish farm diseases and salmon production are not publicly available. ▪ Some fraction of the Harrison sockeye juveniles are suspected to migrate later and via the Strait of Juan de Fuca, avoiding transit past fish farms and avoiding co-mingling with large numbers of infected adults.	▪ The relationship with returns of non-Fraser stocks was not examined. ▪ Since the 1980s, similar effects have been apparent in Yukon River Chinook (higher temperatures, fungal-like disease from parasite *Ichthyophonus*). ▪ Coastal steelhead in Oregon are much more sensitive to the parasite *Ceratomyxa Shasta* than interior steelhead, which have evolved resistance (parasite endemic).	▪ It is plausible that declines could have been caused by synergistic effects of changes in the ocean, including increased temperatures and changes in food quantity and/or quality, which also increased disease impacts (especially bacteria & parasites). ▪ Strong genomic evidence for presence of a disease condition, possibly viral (Miller), but its nature, source, date of introduction, current host, and range are unknown. ▪ The expansion of salmon farms provides a mechanism for amplifying endemic pathogens (Morton). ▪ Sea lice (either wild or farmed origin) are increasing in abundance, leading to increased disease (Jones). ▪ This mechanism is likely operating synergistically with other factors (e.g., higher water temperatures due to global warming), but is not solely responsible for declines.
	2009 returns	▪ There is no direct evidence of unusual diseases affecting 2009 returns, other than normal senescence on the spawning grounds. ▪ The extremely large abundance of Chilko smolts (nearly double the previous 50-year maximum) coupled with extremely low marine survival of Chilko sockeye (one-quarter of 50-year minimum) is consistent with a potential disease effect.	▪ The relationship with 2009 returns of non-Fraser stocks was not examined	▪ Pathogens were likely operating synergistically with other factors (e.g., starvation), as a contributing factor, but were not solely responsible for the poor 2009 returns.

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
3. Ocean conditions (physical and biological) **inside and/or outside** Georgia Strait are important indicators of contributors to the Fraser sockeye situation (Section 4.3).	Overall (late 1980s - now)	▪ The shared downward trends in total and post-juvenile productivity indicate that the mortality causing declines occurred in habitats shared by stocks. ▪ The total productivity (R/EFS) for most Fraser SK is much more highly correlated with post-juvenile productivity (R/juvenile) than with juvenile productivity (juveniles / female). ▪ There's a very strong correlation (r^2=0.87) between algal biomass (Mar 30-Apr 22 avg. Chlorophyll *a*) in QCS and Chilko SK marine survival (1998-2007). **However, the mechanisms are not understood. There are no long-term data on zooplankton abundance in the Strait of Georgia.** ▪ There's some correspondence between periods of intensified winter/spring downwelling on the B.C. coast and the declining productivity of Fraser SK ▪ There's a positive correlation between the abundance of juvenile sockeye (catch per unit effort) in the Strait of Georgia and $\log_e$(total Fraser SK production) two years later over 1998-2007 (r^2=0.35 with all of the data).	▪ There was also a downward trend in the productivity of Central Coast (Skeena River) and WCVI sockeye, during ~2000-2004. ▪ Fraser R. and Central Coast sockeye productivity trends did not correlate with trends from the Columbia Basin or Barkley Sound during 1990-present, suggesting that the causes are limited to inshore waters where juvenile sockeye migrate early in their marine life, a conclusion that is consistent with many past studies. ▪ The productivity of other species (chinook, coho) that share the Strait of Georgia show similar, but not completely consistent, decreasing patterns compared to productivity of Fraser sockeye.	▪ Climate-driven changes in nutrients & food production can reduce smolt growth after they enter the ocean environment, leading to more size-selective predation (stage 1), and reduced winter survival after the first summer at sea due to lower fat reserves (stage 2). ▪ There's evidence for these mechanisms from SEAK pink salmon, Columbia R. spring chinook and steelhead, Bristol Bay SK, Puget Sound Chinook and coho, Washington, Oregon, & SoG coho. ▪ DFO salmon surveys (Puget Sound, SoG, WCVI, QCS) show large yearly variation in ocean conditions, food, and sockeye abundance, growth, diet, and energetics. ▪ **Lack of detailed knowledge about spatial / temporal patterns of marine migration of juvenile sockeye, phytoplankton and zooplankton abundance, and salmon mortality make it hard to distinguish between early mortality in SoG and later mortality further north.** ▪ Ocean conditions may operate synergistically with pathogens, parasites, HABs & contaminants in freshwater and estuary, **but it is impossible to attribute a % mortality to each factor**
	2009 returns	▪ There were poor ocean (shallow mixing zone) and food conditions in the Strait of Georgia in 2007. ▪ *Conditions outside the SoG are not consistent with the hypothesis (average zooplankton in QCS, good fledgling success of planktivorous birds at Triangle Island)*, though algal biomass (April chl_a) was very low in QCS	▪ There was average zooplankton production in QCS in summer 2007, but apparently poor zooplankton production in the Strait of Georgia.	

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		▪ Fraser SK caught in QCS and Hecate Strait in 2007 were the smallest on record (1999-2009), yet Chilko smolts leaving the lake were large sized. This could be due to poor food in the Strait of Georgia in 2007. ▪ *There's no direct evidence for why Harrison SK would have a different productivity pattern than other Fraser SK*		
4. Harmful algal blooms (HABs) in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation (Sec 4.4).	Overall (late 1980s - now)	▪ Since 1989, large-scale blooms have caused severe mortality of farm fish and some observed wild fish mortality in Puget Sound. ▪ Since 1989, the marine survival of Chilko SK is 2.7% in years when their entry into SoG coincided with major HABs, and 10.9% in years with no bloom or only minor blooms. ▪ Before 2002, Heterosigma blooms began in late June or later. Since 2002, blooms have occurred as early as late May or early June, more coincident with the timing of juvenile SK entry into Southern SoG. ▪ May-June blooms appear to be correlated with larger / earlier Fraser River discharges. ▪ *There was improved survival of juvenile SK in the Strait of Georgia in the spring of 2008 despite HABs in June,* which may reflect variation in migration timing, routes and exposure to HABs. ▪ *Harrison SK are apparently not affected by HABs,* but may miss HABs due to different juvenile migration timing. ▪ Lack of HAB data during the 1980s (and gaps in 2000, 2004, 2005) weaken the ability to compare long term trends in HABs with long-term trends in Fraser SK productivity.	▪ There was a strong correlation between the total survey weight of young-of-year Pacific Herring in the SoG and the smolt-to-adult survival rate of Chilko SK for ocean-entry years 1997-2007 *(though not for years before then),* suggesting that common factors affect both species in the SoG (not necessarily harmful algal blooms; it could be any of several different mechanisms) ▪ The relationship with returns of non-Fraser stocks was not examined.	▪ HABs (especially Heterosigma) can kill fish via gill damage and respiratory failure, and harm their prey, though the response of SK to HABs is unknown. ▪ It's credible that HABs could cause acute or chronic toxicity and/or food web or prey impoverishment. ▪ The spatial location of the largest HABs in the southern SoG appears to generally overlap with the migratory route of Fraser SK. ▪ The timing of the largest HABs is generally consistent with SK migration timing in 2006-08, but there were no HAB data in southern SoG in 2000, 2004 and 2005.

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
	2009 returns	▪ The location and timing of HABs in 2007 are consistent with hypothesis that HABs may have contributed to low 2009 returns.	▪ The main occurrence of HABs in southern SoG may partly explain why other stocks (e.g. Barkley Sound, Columbia River, central B.C. Coast) showed less reduction in productivity of 2009 returns, *though HABs did occur in Broughton and QCS in 2007*	
5. Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation (Section 4.5).	Overall (late 1980s - now)	▪ Contaminant effects (e.g., concentrations in water or fish tissues) could not be correlated with productivity indicators for Fraser SK due to lack of data on both environmental loadings and body burdens. ▪ *No contaminants were identified as a probable cause for recent declines in Fraser SK* ▪ Some contaminants have increased over the period of interest. (e.g., pesticides, flame retardants, pharmaceuticals and personal care products) *while others have decreased (e.g., persistent, bioaccumulative and toxic (PBT) contaminants).*	▪ *Columbia Basin SK recently showed improved productivity despite considerable contamination.* ▪ *SK productivity has been poor in Smiths and Rivers Inlet (Owikeno) since mid-1990s, even though there is very little industrial development in these regions* ▪ *Harrison River juveniles are resident in the lower Fraser River and would be exposed to water-borne pollution in the lower river and estuary for a few months, yet this sockeye stock has shown increasing productivity over time.*	▪ Contaminants are known to have many lethal and sublethal effects on fish; both types of effects may increase when fish are challenged by other factors such as high temperatures or nutritional stress. ▪ *It's highly unlikely that there were direct fish kills from toxic chemicals on Fraser SK,* though sublethal effects are possible, and may be a secondary factor contributing to reduced productivity. ▪ Persistent, Bioaccumulative, and Toxic contaminants (PBTs) in adult SK fat tissues could affect reproduction, growth and development, and can be detected in fatty tissues. ▪ Non-persistent contaminants could affect hatching, rearing or migration **but do not provide any chemical fingerprint.**
	2009 returns	▪ *Despite the lack of quantitative data on contaminants, there's no reason to believe that there was a sudden increase in the contamination of SoG or the Fraser Estuary in 2007, the ocean-entry year for Fraser sockeye returning in 2009.*	▪ The relationship of this hypothesis with 2009 returns of non-Fraser stocks was not examined.	

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
6. Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation (Section 4.6).	Overall (late 1980s - now)	▪ *Total productivity (R / EFS) for most Fraser SK stocks is much more highly correlated with post-juvenile productivity (R / juvenile) than with juvenile productivity (Juveniles / female spawner), suggesting that variation is driven by changes in juvenile-to-adult portion of the life cycle, rather than in the egg-to-juvenile portion.* ▪ *Covariates related to human disturbance (i.e., road density, recent logging, stream crossings, human land use) are not correlated with Fraser sockeye productivity trends.* ▪ *The only significant covariates negatively correlated with Fraser SK productivity trends were those related to watershed location (i.e., distance from ocean, latitude, nursery lake elevation),* which is consistent with the potential for increased mortality during longer downstream (or upstream) migrations ▪ *Primary productivity in Chilko and Quesnel lakes is not correlated with trends in Fraser SK productivity.* ▪ Though there are many gaps in the time series, *recent lake productivities for Fraser stocks appear as high as (or higher than) in late 1980s / early 1990s.* ▪ There's evidence for density-dependent survival and growth of lake-rearing juveniles, *but there are no meaningful trends over time in Shuswap, Quesnel, and Chilko lakes, and no consistent trends across nursery lakes* ▪ *There are no systematic shifts in the median migration date of smolts measured at Chilko Lake or Mission.* ▪ There are no reliable survival estimates for Fraser SK during their outmigration except for the 2010 Chilko Lake study.	▪ Studies of other SK stocks on the west coast of N. America suggest that freshwater spawning and rearing environments may be important for stock productivity and abundance.	▪ There are many potential mechanisms by which logging, agriculture, roads, urbanization, industrial development and warming climate could affect SK habitats and survival rates (Table 4.6.1). ▪ More than 50% of the total life-cycle mortality occurs in natal spawning and rearing areas ▪ *Sockeye should be less sensitive to freshwater conditions than other species of Pacific salmon (e.g., coho) because they rear in lakes rather than streams* ▪ *Compensatory mortality in lakes may buffer populations against habitat impacts on the spawning grounds (i.e., if egg-fry survival is lower in streams, fry-smolt survival may be higher in downstream lakes due to less competition).*

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		▪ Cultus Lake smolts migrate 13 days later than they did 80 years ago, but Cultus is not one of the 18 Fraser stocks examined		
	2009 returns	▪ *No major changes in freshwater habitat conditions are known to have occurred during 2005-2006, or in downstream migratory conditions during 2007* (other than earlier and larger flows). *Major changes would be required if freshwater habitat were to have significantly contributed to the poor 2009 returns.*	▪ *Despite having similar freshwater spawning and rearing habitats to Fraser SK (dry interior watersheds), Columbia River SK returned in record numbers in 2008 & 2009.*	
7. Delayed density dependent mortality is an important contributor to the Fraser sockeye situation (Section 4.7).	Overall (late 1980s - now)	▪ For several major stocks that account for most of the Fraser SK production (i.e., Early Stuart, Late Stuart, Stellako, Quesnel, Chilko, Seymour and Late Shuswap), the variation in R / EFS since the late 1980s is better explained by including lagged density dependent effects of past spawner abundance (Larkin model) than by standard Ricker models. This suggests that large spawning returns may have had negative effects on subsequent brood years in some stocks and years. ▪ When data from abundant years (more precise data) are given more weight, the Larkin model fits the historical pattern better. ▪ The Larkin model can explain most of 1990-2002 recruitment decline in the above listed stocks, *but not after that, nor does it explain that decline in smaller Fraser SK stocks, which might not have sufficient abundance for delayed density-dependent effects.* ▪ *The Larkin model still has large deviation for the 2003 and 2005 brood years,* though smaller than those for the Ricker model.	▪ In the Fraser, 4-year-old fish dominate and cycles occur regularly. In AK some SK systems are dominated by 5-year-old fish and cycles are regularly observed. ▪ The effects of delayed density dependence may not occur in most non-Fraser stocks where there are mixtures of ages; few of those stocks show cyclic dominance. ▪ Most other sockeye systems in British Columbia have mixed ages of returns (3, 4 and 5 years old), and the cycles are not observed in those cases.	▪ Delayed density dependence could be caused by predators, parasites, disease and/or reduced zooplankton production. Predation effects are theoretically possible (have been modeled for Late Shuswap). **There are insufficient data to test whether any of these mechanisms are actually operating.** ▪ *There was no evidence of zooplankton food limitation in Quesnel Lake following record escapements of 2001 & 2002 (section 4.6), so some other mechanism (e.g. disease, predators) would need to be responsible for delayed density dependence there.* ▪ Density-dependent mechanisms may have operated prior to industrial fisheries; (1) large abundances may have masked periods of low productivity, (2) abundances may have been highly variable due to lagged interaction with predators and disease, (3) there were periods of low returns and famine, as recorded in First Nations' oral history; and 4) traps and weirs resulted in high exploitation rates on some stocks.

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
	2009 returns	▪ *This hypothesis does not explain the 2009 return year: 77 million unusually large Chilko smolts went to sea in 2007, yet poor returns were observed in 2009. If freshwater density-dependent mechanisms were driving poor returns, then fewer smolts should have gone to sea.* One alternative explanation is that smolts were diseased or in poor condition when they left freshwater, but did not die until after they left the lake. There is little evidence for or against this hypothesis except that Chilko smolts were large in body size, which is not consistent with suffering from a disease.	▪ The relationship of this hypothesis with 2009 returns of non-Fraser stocks was not examined.	
8. (a) En-route mortality during upstream migration, and (b) effects on fitness of the next generation, are important contributors to Fraser sockeye situation (Section 4.8).	Overall (late 1980s - now)	▪ *En-route mortality does not contribute to declines in <u>productivity</u> (R/EFS) of Fraser SK because the losses are already factored into the calculation of recruitment (R in R / EFS).* ▪ En-route mortality does reduce spawner abundance unless compensated for by lower harvest rates. Managers have attempted to reduce the impacts of en-route mortality on spawner abundance by reducing harvest rates (and catches) in recent years, partly in response to predictions of high rates of en-route mortality. ▪ *The absence of declining trends in freshwater survival in populations that have suffered en-route mortality (e.g., Early Stuart fry/EFS, Weaver fry/EFS) does not support the hypothesis that intergenerational effects are a major contributor to the decline.*	▪ The results obtained for en-route mortality of Fraser River sockeye salmon are generally consistent with those for Columbia River populations in that exposure to temperature stress outside of the normal or historic range can contribute to mortality. *However, this does not help to explain declines in Fraser sockeye productivity.*	▪ *En-route mortality does not contribute to the decline in productivity in R/EFS since R is defined as the abundance of fish that arrive at the coastal fishing areas. Thus, estimates of R already include estimated en-route losses.* However, en-route mortality will tend to reduce spawner abundance and population viability. ▪ There is abundant field and experimental evidence that populations are stressed by temperatures > 18°C, leading to direct mortality, exhaustion, or disease, with females more vulnerable than males. ▪ Intergenerational effects refer to impacts of parental condition on fitness of offspring (e.g., reduction in fry quality or survival caused by nutritional or disease status of the parents). Significant intergenerational effects could cause changes in R/EFS, but there isn't yet any evidence of such effects. *Again,*

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		▪ Intergenerational effects are not yet documented. *One study shows that incubated eggs from dying or recently dead females show no effect on viability of their eggs or juveniles.*		*incubated eggs from dying or recently dead females show no effect on viability of the eggs or juveniles.* ▪ A delayed intergenerational effect on smolts is possible (and consistent with survival data), but a mechanism (e.g., disease) has yet to be identified.
	2009 returns	▪ *En-route mortality cannot account for poor returns in 2009, because estimates of those returns are made at entry to freshwater, before en-route mortality takes place.*		
9. Competitive interactions with pink salmon are important contributors to the Fraser sockeye situation (Section 4.9).	Overall (late 1980s - now)	▪ There are 3 different mechanisms by which this hypothesis may be operating (see right-most column). ▪ The overall productivity of Fraser SK over the past 45 years is inversely correlated with the aggregate abundance of adult pink salmon returning to the Fraser, SEAK, and Prince William Sound in the year that age-4 Fraser SK return. These results are consistent with version 2 *but not version 1 of the hypothesis.* ▪ The mean normalized length of age 1.2 Fraser sockeye is larger in even years than odd years, consistent with a competition mechanism (i.e., version 2 of the hypothesis) *but not with a mechanism in which maturing Fraser pinks eat seaward migrating juvenile Fraser SK (i.e., version 3).* ▪ The two largest negative anomalies in Fraser sockeye returns, as well as in returns per spawner were both in odd years (brood years 2003 and 2005). *However, pink salmon abundance in the North Pacific Ocean did not increase dramatically in those years (i.e. not consistent with a larger than normal competitive effect under version 2 of the hypothesis)*	▪ Fraser SK populations and SK populations outside of SoG should experience similar competitive interactions with pink salmon in North Pacific, to the extent that their migratory routes overlap. ▪ *Increasing or stable trends in productivity of non-Fraser sockeye populations (e.g., those in northern B.C., Barkley Sound, and Columbia River) require postulating different migratory patterns that affect the degree of interaction with pink salmon, so the hypothesis cannot be considered complete or parsimonious.*	▪ Competition for food between pink salmon and SK has potential to cause density-dependent reduction in growth and/or survival of Fraser sockeye, through two possible mechanisms: 1. Odd-year Fraser pink fry may compete with even-year Fraser SK smolts migrating into SoG in spring and summer of same year. If so, <u>even-yr</u> Fraser SK should show poorer growth and survival than odd-yr SK *(not supported by evidence).* 2. Abundant odd-yr pink salmon from AK and Russia may compete with Fraser SK on high seas. If so, <u>odd-yr</u> Fraser SK should show poorer growth & survival than even-yr SK (<u>is</u> supported by evidence). 3. A third possible mechanism is predation by returning Fraser adult pink salmon on Fraser SK smolts that are migrating seaward during early summer. This would affect odd-yr Fraser SK more *(**not** sup-*

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		▪ The hypothesis is inadequate as a sole explanation, but may have contributed to the longer term decline in productivity of Fraser SK. ▪ Sea-type SK in the Fraser River (Harrison River and Widgeon Slough) migrate to sea a year earlier than lake-type sockeye and could interact with pink salmon in different years or in different geographical areas. Consequently, opposite trends in abundance and/or productivity observed for these populations do not disprove the hypothesis, **although there was no analysis of Harrison or Widgeon stocks in this regard.**		*ported by evidence). Such predation has not been documented and seems unlikely because it would be restricted to a short period of overlap of smolts and adults in early summer. Also, productivity of Fraser sockeye was not significantly inversely correlated with numbers of adult pink salmon that returned in the year that the SK smolts migrated.* ▪ Competitive interactions more plausible because diets and distributions of immature pink and SK salmon are known to overlap. Competitive interactions could also decrease overall productivity of Fraser SK by reducing adult size and fecundity, with or without direct effects on SK survival. Version **2** is more consistent with evidence than versions **1** or **3**.
	2009 returns	▪ The evidence is consistent with pink salmon being a contributing cause to the low returns in 2009, but not the sole cause. ▪ The lowest-ever average weight of adult Fraser River pink salmon in 2009 suggests that poor food may have affected both pink and sockeye salmon that returned that year, and that competition between pinks and sockeye may have occurred in the N. Pacific.		

Table E-3. The Panel's recommended research and monitoring priorities listed by sockeye life stage, indicating relevant hypotheses from Table E-1. 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 hypotheses affecting that life stage), and (2) "Relevance to Management Actions", i.e., the value that such knowledge has for informing potential management actions. The Panel categorized that relevance as High, Medium, or Low. 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 Panel's highest priority research and monitoring topics.

Life stage for Fraser River sockeye salmon	Relevant hypotheses (Table E-1)	Explanatory Importance	Relevance to Management Actions	Comments and issues for recommended research and monitoring activities
Parental spawning success and incubation	2, 6, 8b	Low	Low	Unlikely an explanation for the "Fraser sockeye situation" (particularly given rating of Hypothesis 8b), but may possibly be related to disease concerns. The latter could become a stronger priority in the future given climate change.
Juvenile rearing, production capacity, and smolt production	2, 6, 7	Medium	High	Although freshwater habitat was rated as a very unlikely explanation for the "Fraser sockeye situation", quantitative assessment of smolt production is essential to separately estimate survival rates in pre- and post-juvenile life stages. Such estimates will help focus management responses. However, direct estimation of abundance of seaward-migrating smolts is currently limited to only Chilko and Cultus lakes. Furthermore, ecosystem dynamics within Fraser watershed lakes are poorly monitored. **The Panel strongly recommends increased numbers of quantitative juvenile assessments and studies of in-lake responses, especially as the latter relate to hypothesis 7 (delayed-density dependent mortality).**
Downstream migration to estuary	2, 5, 6, 7	Medium	High	In addition to the point above about life-stage-specific productivity estimates, the survival rate of sockeye juveniles <u>during their migration</u> 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.
Estuary and near-shore (<u>inside</u> Strait of Georgia and migration channels)	1a, 2, 3a, 4, 5, 7, 9	High	High	The life stage <u>inside</u> the Strait of Georgia received the strongest agreement as the most likely period for explaining both the poor 2009 returns as well as the long-term decrease in productivity of Fraser sockeye. Better understanding of this life stage may therefore improve future forecasting models. **At least four research and monitoring programs are recommended**:

Life stage for Fraser River sockeye salmon	Relevant hypotheses (Table E-1)	Explanatory Importance	Relevance to Management Actions	Comments and issues for recommended research and monitoring activities
				(1) A fully integrated oceanographic and ecological investigation of the Strait of Georgia would involve both monitoring and research covering several disciplines simultaneously, including establishment of comprehensive sampling for zooplankton, harmful algal blooms, estimates of predation by marine mammals, etc. Such an integrated, coordinated research effort would help partition sources of mortality of Fraser sockeye salmon. (2) Studies of residency and migration paths of Fraser sockeye are needed in the Strait of Georgia. (3) Attention should be given to pathogens and contaminants in sockeye and how they may be expressed under different marine conditions (includes concerns for transmission of pathogens due to salmon farming). (4) Studies are needed to estimate the annual relative survival of Fraser sockeye over the period of residency in the Strait of Georgia. Studies of Fraser sockeye growth and survival are considered essential within the Strait of Georgia before these fish leave this semi-enclosed system and enter the North Pacific Ocean ecosystem. Estimates of relative survival over time can be used to guide the focus of future research and monitoring efforts, which could expand to more offshore areas if appropriate. For example, if future survival estimates indicate that most of the yearly variation in mortality occurs within the Strait of Georgia, the research and monitoring focus would remain there. On the other hand, if survival estimates were to indicate that more of the variation in mortality is occurring outside rather than inside the Strait of Georgia, then more effort would need to be allocated outside the Strait.
Migration to offshore areas (coastal but <u>outside</u> of Strait of Georgia)	1a, 2, 3b, 4, 7, 9	Medium	Medium	The Panel only rated hypothesized mechanisms occurring <u>outside</u> the Strait as "possible" explanations for both the Fraser sockeye situation over the long term and in 2009, which is a lower rating than mechanisms <u>inside</u> the Strait. Research outside of the Strait should be increased if the integrated research program suggested above for <u>inside</u> the Strait fails to be informative. If such research outside of the Strait is expanded, it should conform to the same fully integrated oceanographic and ecological model mentioned above, which includes several disciplines. Critical challenges for this element of the research program are its potentially high cost and mixtures of different stocks, which require genetic stock identification. Coastal surveys via remote sensing may also provide broader spatial information on ocean environmental conditions. Research and monitoring in this region should build on ongoing work, including DFO surveys for juvenile salmon in Queen Charlotte Strait, Queen Charlotte Sound and Dixon Entrance, and NOAA surveys of larval fish in the Gulf of Alaska, which also catch juvenile salmon.

Life stage for Fraser River sockeye salmon	Relevant hypotheses (Table E-1)	Explanatory Importance	Relevance to Management Actions	Comments and issues for recommended research and monitoring activities
Open-ocean rearing	1a, 3b, 9	Medium	Low	Open-ocean research may be important for understanding competition between salmon species (e.g., pink-sockeye salmon, hypothesis 9), determination of growth and maturity, and over-wintering survival. The information is unlikely to be focused only on Fraser sockeye salmon, but as the Panel has found, informative data on non-Fraser populations has been useful in helping to narrow down the processes affecting Fraser sockeye. However, information with the resolution required to be useful for management of Fraser sockeye is unlikely here without great expense.
On-shore migration (includes periods in which marine fishing occurs)	1a, 1b, 2	Low	High	Because marine fishing mortality is not considered an explanation for the "Fraser sockeye situation" or the 2009 return, the importance for "explanation" is clearly low. However, continued assessments of return abundances are very important to future management decisions and sustainability of Fraser sockeye. The issues of appropriate harvest rates and catch allocation are more related to policy decisions than to research and monitoring.
Up-stream migration: (In-river fishing, migration rates/timing, survival rate accuracy of data)	2, 8a	Low	High	In the absence of any evidence of inter-generational effects (hypothesis 8b), this life stage receives a low rating for "explanation"; however, it merits a higher importance rating when future environmental conditions and allowable harvest rates are considered. With expectations for increased uncertainty and changes in environments in the presence of climate change, **the Panel recommends continued evaluation of the accuracy of in-river sockeye assessments and improvements in those assessments, as well as research and monitoring of in-river mortality of sockeye salmon. This recommendation should be extended to adult pink salmon** as well because there is currently no assessment of spawning escapement for Fraser pink salmon.

Table E-4. The Panel's recommendations for management actions to reduce impacts on Fraser sockeye salmon, as suggested by the ratings and evidence for potential causes of the Fraser sockeye situation given in Tables E-1 and E-2, as well as the monitoring and research recommended in Table E-3. Also shown are risks associated with <u>not</u> taking the recommended actions. Each action listed below is given a High importance rating.

Potential Action	Life stage(s)	Risks associated with <u>NOT</u> implementing these actions.
<u>Contaminants</u>: Acquire data to construct chemical budgets within the Fraser watershed, improve accountability for their use, and assess impacts of contaminants in freshwater and marine environments.	Juvenile, smolts, and early marine rearing	The issue of contaminants is recognized as an unknown risk at this time and their usage is poorly documented. Current usage may be having direct lethal effects or more likely chronic sub-lethal effects that act synergistically with other stressors, in particular pathogens or increasing temperatures. These could be controllable impacts that are not currently being assessed.
<u>Pathogens (bacteria, parasites, and/or viruses)</u>: Create an on-going evaluation of pathogens in Fraser sockeye, and incorporate potential impacts from net-pen salmon farming. Ensure that new Aquaculture Regulations being developed by DFO include full reporting of fish health issues and production levels on farms.	Early marine rearing and the period during migration from in-shore to off-shore	Although pathogens were rated as possible to very likely contributors to the Fraser situation, direct evidence of this is limited (as seen by the variation of opinions). It is expected though, that in the future, with continued environmental change, pathogens could be a significant cause of reduction in sockeye productivity and sustainability. All sources of potential effects of pathogens must be assessed and opportunities for mitigation/control should be considered, including actions on fish farms and their processing plants.
<u>Harmful algal blooms</u>: Annually monitor and assess the frequency and intensity of blooms in the Strait of Georgia.	Early marine rearing	Management of some algal blooms has been undertaken using clay solutions to neutralize a bloom. These blooms are known to cause mortality of salmonids. Failure to acknowledge and assess this risk could cause direct mortalities in Fraser sockeye.
<u>Marine mammals</u>: If marine mammals prove to be a significant source of mortality to Fraser sockeye, then controls could be implemented.	Downstream migrants and early marine rearing	Production of yearling sockeye could be reduced and the sustainability of smaller sockeye populations could be put at risk. Predation poses a higher risk to smaller populations because typically a higher percentage of prey are killed as prey become less abundant (i.e., mortality is depensatory). Controls could be difficult to implement but may be limited to critical locations and periods.
<u>Delayed-density Hypothesis</u>: If the statistical evidence of this hypothesis is confirmed, then the current management policy for Fraser sockeye escapement goals should be re-examined. Wild Salmon Policy benchmarks also need to consider the effect of this hypothesis.	Returning adults and up-stream migrants	Interactions between brood years would reduce the productivity of some Fraser sockeye populations and reduce possible fishing opportunities (depending on the mechanism of interaction). Future environmental change could exacerbate these effects if not addressed.
<u>En-route mortality losses</u>: Continue monitoring and assessment of environmental conditions in-river and making the resulting adjustments to allowable harvest rates. Modify in-river fishing to minimize fishing-associated mortalities, and examine environmental mitigation where possible.	Adult up-stream migrants	Sockeye spawning escapement will be lower than desired and may threaten future sustainability of Fraser sockeye salmon.

Potential Action	Life stage(s)	Risks associated with <u>NOT</u> implementing these actions.
<u>Incorporate pink salmon into ecological research and fishing decisions:</u> If evidence of competition between sockeye and pink salmon continues to accumulate, take action to optimize production of both species, possibly through limiting natural and hatchery production of pink salmon.	Early marine rearing and adult returns	An increasing abundance of pink salmon could depress sockeye productivity, and potentially undermine efforts to restore sockeye production. However, the importance of pink salmon to other species must be balanced with any efforts solely directed to sockeye salmon issues.

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1.0 Introduction

To many people in the Pacific Northwest, Fraser River sockeye salmon (*Oncorhynchus nerka*) are an icon. These populations have historically supported substantial First Nations, commercial, and recreational fisheries, as well as nature-based tourism. However, Fraser sockeye have faced several challenges beginning in the 1990s. These include unfavourable ocean conditions, increasing Fraser River temperatures, and unusually early migration of some populations. The latter two factors have caused high mortality rates of adult salmon during their in-river migration to spawning areas. These impacts and other factors have resulted in several major public inquiries into reasons for either (1) unusually low total abundances of returning adults, or (2) substantial numbers of so-called "missing fish", which refers to the difference between spawning ground estimates and lower-Fraser-River estimates of abundance of returning sockeye salmon, after accounting for in-river harvests. More recently, there have been several years of extremely limited fishing opportunities for Fraser River sockeye.

In the last 10 years, other issues have emerged about salmon on the West Coast. Concerns have been raised about infections by sea lice, predation by increasing populations of marine mammals, contaminants in rivers and the Strait of Georgia, and ocean conditions possibly associated with climate change. Additionally, some British Columbia sockeye populations, including Cultus Lake sockeye within the Fraser, as well as other salmon species in nearby in Washington and Oregon, have reached precariously low abundance levels. The combination of increasing challenges for Fraser River sockeye, as well as increasing awareness of problems facing salmon more generally, have heightened concerns about the long-term viability of this valuable resource.

In 2009, these concerns were reinforced when only 1.5 million Fraser River adult sockeye returned -- the lowest number since 1947 and only 14% of the pre-season forecast of 10.5 million fish. As serious as it was, this 2009 event was only the latest in a series of indications that Fraser River sockeye populations were facing serious widespread problems. Specifically, the largest returns of these fish in 80 years occurred in the early 1990s (over 20 million sockeye in 1990 and 1993), but this situation quickly changed to having the lowest returns since the 1920s in 2007, 2008, and 2009 (less than 2 million per year) (slides 9 and 10 of Mike Lapointe's introductory talk at the workshop, Appendix C). An important observation is that this decrease in returns occurred despite a sharp <u>reduction</u> in harvest rates starting in the mid-1990s (top-right panel of Lapointe slide 10, Appendix C) and a substantial <u>increase</u> in spawner abundance since the 1980s for most stocks relative to their previous values (bottom-left panel of Lapointe slide 10, Appendix C).

Because returns decreased despite increases in spawner abundances for most Fraser River sockeye populations, the key problem of low total returns of adults appears to be decreasing productivity, i.e., survival rate from eggs to adults (Lapointe slide 11, Appendix C). Salmon biologists calculate productivity as the number of mature adults produced per spawner, where those adult abundances are estimated as the number of fish returning to the coast *before* the onset of fishing. This definition of productivity is directly analogous to the definition of productivity of workers in a factory, e.g., the output produced per worker per week. The *total production* by the factory per week is the number of workers times their *productivity.* Similarly, the total abundance of returning adult Fraser sockeye salmon is a product of the number of spawners times their productivity (where productivity is the number of mature adult fish produced per spawner). If spawner abundance has generally increased and total adult returns

prior to the start of fishing have decreased, then the main cause must be decreased *productivity*.

The Panel for this workshop therefore focused on gaining an understanding of causes for changes in productivity in Fraser River sockeye, rather than changes in abundance of adult recruits (although the latter is clearly ultimately affected by the former). It is important to note that because abundance of adult recruits is estimated as the population before fishing starts, and the problem is actually due to low adult recruits produced per spawner, the effect of harvesting is <u>not</u> among the hypotheses dealt with by the Panel.

The key problem that the Panel addressed is as follows. As is described in detail in Section 3, 16 of the 18 major Fraser River sockeye salmon populations have shown a decrease in *productivity* over time, which started in either the late 1980s or early 1990s, depending on the population. These decreasing trends, along with the unusually low returns of adults in 2009, are henceforth collectively referred to in this report as "the Fraser sockeye situation".

The intricacies of interactions among processes that affect salmon create challenges in understanding causes of change in both adult returns per spawner and total adult returns of Fraser River sockeye salmon. For this reason, the Pacific Salmon Commission (PSC), an institution established under the Pacific Salmon Treaty (PST) to jointly manage the Fraser River sockeye as well as other species, created an Expert Advisory Panel. The PSC arranged a workshop on 15-17 June 2010 in Nanaimo to evaluate evidence for and against possible causes of the declines in Fraser River sockeye salmon. This workshop was viewed as a first step toward synthesizing information on possible causes. The Expert Advisory Panel was composed of 11 experienced researchers from Washington and British Columbia who are the authors of this report. As well, about 25 other experts were invited to attend the workshop to make presentations and to critically evaluate data and hypotheses about causes of the decline. Many observers also attended.

1.1   Hypotheses considered

Causes of the observed patterns in Fraser sockeye that the workshop considered ranged across many hypotheses associated with:

(1) Predation by marine mammals and/or unreported fishing in the ocean.
(2) Marine and freshwater pathogens, including parasites, bacteria and/or viruses.
(3) Oceanographic conditions (physical and biological) inside and/or outside Georgia Strait.
(4) Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca.
(5) Contaminants in the Fraser River and/or Strait of Georgia.
(6) Freshwater habitat conditions in the Fraser River watershed.
(7) Delayed density-dependent mortality.
(8) En-route mortality during upstream migration, plus its effects on fitness of the next generation.
(9) Competitive interactions with wild and hatchery pink salmon.

1.2   Workshop objectives

The workshop had three specific objectives:
   (1) Explore and evaluate the relative merits of multiple potential causes for the decline in Fraser River sockeye stocks and determine the relative likelihood of each hypothesized cause being correct.
   (2) Identify next steps of investigation or analysis that may be required to determine the relative importance of those hypothesized causes and distinguish among their effects.
   (3) Provide a summary of scientific evaluations to the Commission.

In this report, the Panel also addresses a fourth objective:
   (4) Describe management actions that can be taken to reduce the effect of any given hypothesized cause.

1.3   Structure of this report

This report was written by the Expert Advisory Panel, with the assistance of ESSA Technologies Ltd. in Vancouver, B.C. It contains four sections in addition to this Introduction. Section 2, the Methods, provides details of the workshop's logistics and participants. Section 3 describes the spatial and temporal patterns in Fraser sockeye data that the various hypothesized mechanisms are attempting to explain. As well, Section 3 describes data for non-Fraser salmonids to help determine whether the Fraser sockeye trends are unique or are shared by other populations. The extent of such sharing provides clues about the plausibility of different hypotheses. Section 4 of this report describes and evaluates those hypotheses in detail. From the background information in Section 3, as well as input from invited experts and other participants at the workshop, the Panel drew various conclusions about evidence for and against the hypotheses, as described in Section 4. This evidence is then condensed into a concise Table 5-1 in Section 5, and Table 5-2 indicates the Panel's final conclusions about the probability, or relative likelihood, that each of the 9 sets of hypotheses caused observed changes in productivity. These hypotheses were assessed in terms of explanations of (1) the long-term decline in Fraser sockeye adults produced per spawner, and (2) the unusually low abundance of total returns in 2009. The appendices to this report include: an outline of the assignments given to speakers (Appendix A); the workshop agenda (Appendix B); slides for two introductory talks (one on Fraser sockeye and the other on non-Fraser salmon), plus short documents written by presenters of hypotheses (Appendix C); graphs from the data set provided by the PSC (Appendix D); and a summary of observers' comments on the workshop (Appendix E).

There are four critical caveats about this report:
   (1) The report is not intended to be an authoritative review of the scientific literature and knowledge on each of the diverse hypotheses. That was impractical in the short time available.
   (2) Instead, the report summarizes what the Expert Advisory Panel heard at the two-day workshop and read in documents provided by speakers, integrated with what the Panel already knew about topics related to the hypotheses.
   (3) The Panel recognizes that there may be other evidence relevant to the Fraser sockeye situation that was not presented at the workshop.
   (4) The Panel also knows that there are many ways to analyze and interpret evidence. We therefore encourage others to do further analyses and syntheses to improve understanding of key factors affecting Fraser River sockeye salmon.

1.4   Realistic expectations

Before proceeding, it is important for readers to have realistic expectations about the ability of the Panel, or any other scientists, to unequivocally identify the causes of the decline in productivity of Fraser River sockeye. The dynamics of any ecosystem, including the freshwater and marine ecosystems traversed by Fraser River sockeye, are affected by multiple simultaneously operating natural and human sources of variability. It is therefore very unlikely that there has been a single cause of the long-term decrease in productivity of Fraser sockeye, or that there was a single cause behind the extremely low returns in 2009. Such reductions can arise from several mechanisms that occur in one or more places in the salmon life cycle, ranging from poor viability of eggs to reduced survival rates of juveniles, and mortality of fish while at sea. It is also clear from previous research on salmon, as well as many other species of animals, that changes in one mortality agent can interact with other mortality factors to produce complicated net effects. For instance, poor food supply for fry causes slower growth, which makes them more vulnerable to being eaten by predators while migrating seaward as smolts or while rearing in the ocean. Also, unfavourable environmental conditions such as water temperature may trigger disease outbreaks that would not occur without those environmental conditions. Such synergistic effects are common in ecological systems.

Further complicating our understanding of the number of adults produced per spawner are interactions in which increased mortality rate at one life stage tends to affect mortality rate at subsequent life stages. For instance, by thinning out a cohort of fish, mortality at one life stage will reduce competition for food but make each fish more vulnerable to predation. The net effect of such interactions is therefore difficult to predict.

Because of these complications, it is unlikely that definitive evidence of causes of changes in productivity of Fraser sockeye will emerge from non-experimental, observational monitoring programs, which most scientists have been forced to use. Instead, definitive evidence will require direct, human-controlled, manipulative experiments. Obviously, such experiments are generally not feasible for wild Pacific salmon, and the next-best approach, to couple monitoring with directed studies on particular mortality processes, is either currently under way or is recommended later in this report. Thus, expectations about the Panel's ability to draw conclusions about mechanisms affecting Fraser sockeye salmon should be adjusted accordingly.

To add to the body of evidence about causal mechanisms, the Panel has also used comparisons among populations (even of other species) that are likely to be exposed to either similar or different processes than Fraser sockeye because of their respective spatial locations and/or timing of movement of fish through the environment. This approach is outlined in Sections 3 and 4.

2.0 Methods

This section summarizes the structure of the workshop and the methods used to solicit information from participants.

2.1 <u>Workshop roles</u>

Individuals attending the workshop were assigned one of the following five roles/designations:

(1) <u>Canada-U.S. organizing committee</u>: The committee was composed of individuals from the Pacific Salmon Commission (PSC), Fisheries and Oceans Canada, Simon Fraser University, and ESSA Technologies. The committee developed the workshop's objectives and hypotheses, selected the expert panel and presenters, prepared workshop materials, and facilitated the workshop.

(2) <u>Expert Advisory Panel (Panel)</u>: The Panel was composed of leading scientists in each of a number of thematic areas. The Panel drew on its members' collective expertise and knowledge of Fraser sockeye to synthesize the material presented, evaluate the plausibility of each hypothesis, identify information gaps, suggest priorities for monitoring, research, and management responses, and contribute to one or more thematic sections of the report.

(3) <u>Presenters</u>: Each presenter was assigned a hypothesis and asked to present evidence for and against that hypothesis at the workshop both verbally and in short written documents for the Panel (Appendix C). Presenters were also asked to identify information gaps and possible management actions to take if their hypothesis were true, and assess the plausibility of hypotheses in their thematic area, as well as other hypotheses discussed at the meeting.

(4) <u>Independent scientists</u>: Scientists with expertise in each of the thematic areas were asked to evaluate hypotheses under that theme based on the information presented, and to identify information gaps that could be filled with research and/or monitoring. Feedback from the independent scientists was used by the Panel to inform their discussions and conclusions.

(5) <u>Observers</u>: Individuals who were not part of the four groups above attended the workshop as silent observers. They listened to presentations, plenary discussions, and subgroup discussions. Direct feedback from observers was limited to completion of a survey, which the Panel took into account (results in Appendix E).

2.2 <u>Hypotheses</u>

The organizing committee carefully selected sixteen hypotheses to evaluate initially at the workshop (Table 2-1). Hypotheses were categorised into five major thematic areas: (1) predators, parasites, and disease; (2) toxic algae and pollutants; (3) physical oceanographic conditions; (4) freshwater conditions; and (5) other factors affecting Fraser River sockeye. Note that these hypotheses are not mutually exclusive. Several may have acted together to cause the observed declines in Fraser sockeye. The organising committee selected well-respected scientists actively involved in related research to present the body of evidence for and against a given hypothesis. Scientist were selected based on their knowledge of material relevant to the hypothesis and not on their personal opinions regarding a particular hypothesis. Scientists, and the many co-authors who contributed to their presentations, were instructed by the organising committee to dispassionately evaluate the evidence for and against their assigned hypothesis. The individuals tasked with presenting the evidence are listed in Table 2-1.

Table 2-1. Hypotheses evaluated at the PSC workshop and associated presenters. For consistency, these hypotheses are stated as if true, but evidence for and against each hypothesis was evaluated by the Panel. The phrase "Fraser sockeye situation" is described in Section 3 of this report and refers generally to the reduced productivity of these stocks.

Session A - Predators, parasites, and disease	Presenter
Predation by marine mammals is an important contributor to the Fraser sockeye situation	John Ford, DFO
Sea lice, either naturally occurring or passed from fish farms, are an important contributor to the Fraser sockeye situation	Simon Jones, DFO
Pathogens, including sea lice and diseases such as bacteria and/or viruses, either naturally occurring or passed from fish farms, are an important contributor to the Fraser sockeye situation.	Alexandra Morton, Raincoast Research Society
Genomic studies suggest that some disease has infected sockeye and has become an important contributor to the Fraser River sockeye situation.	Kristi Miller, DFO
Diseases in freshwater and marine systems are an important contributor to the Fraser sockeye situation.	Kyle Garver, DFO
Session B - Toxic algae and pollutants	
Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation.	Jack Rensel, Rensel Associates
Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation.	Robie Macdonald, DFO
Session C - Physical oceanographic conditions	
Physical oceanographic conditions **inside and/or outside** Georgia Strait are important indicators of contributors to the Fraser sockeye situation.	Rick Thomson, DFO
Outside of Georgia Strait, oceanographic conditions, food, and/or predators (including squid) are important contributors to the Fraser sockeye situation.	Marc Trudel, DFO
Inside Georgia Strait, oceanographic conditions, food, and/or predators are important contributors to the Fraser sockeye situation.	Dick Beamish, DFO
Physiological and growth conditions affect marine survival of sockeye smolts in Alaska.	Ed Farley, NOAA
Session D - Freshwater conditions	
Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation.	Daniel Selbie, DFO
Predation, food supply, overescapement, disease, and parasites are important contributors to the Fraser sockeye situation.	Carl Walters, UBC
En-route mortality during upstream migration, plus effects on fitness of the next generation, are important contributors to the Fraser sockeye situation.	Scott Hinch, UBC
Session E - Other factors affecting Fraser sockeye	
Unreported catch in the ocean outside of the Pacific Salmon Treaty area is an important contributor to the Fraser sockeye situation.	Phil Mundy, NOAA
Competitive interactions among wild and hatchery fish (potentially all salmon species) are important contributors to the Fraser sockeye situation.	Greg Ruggerone, Natural Resources Consultants Inc.

The life cycle of sockeye salmon is illustrated in Figure 2-1 and is described in more detail in Section 3. Some of the hypotheses above are unique to one particular stage of the sockeye's life cycle, whereas other hypotheses may affect multiple stages, as summarized in Table 2-2. The numbering of hypotheses in Table 2-2 does not represent either their relative importance (i.e., explanatory power) or the Panel's level of confidence in those hypotheses. Instead, the numbering in that table, and the way that the initial 16 hypotheses were grouped by the Panel, is an artefact of the order in which hypotheses were presented during the June workshop, as well as the need to facilitate sub-group discussions during the workshop.
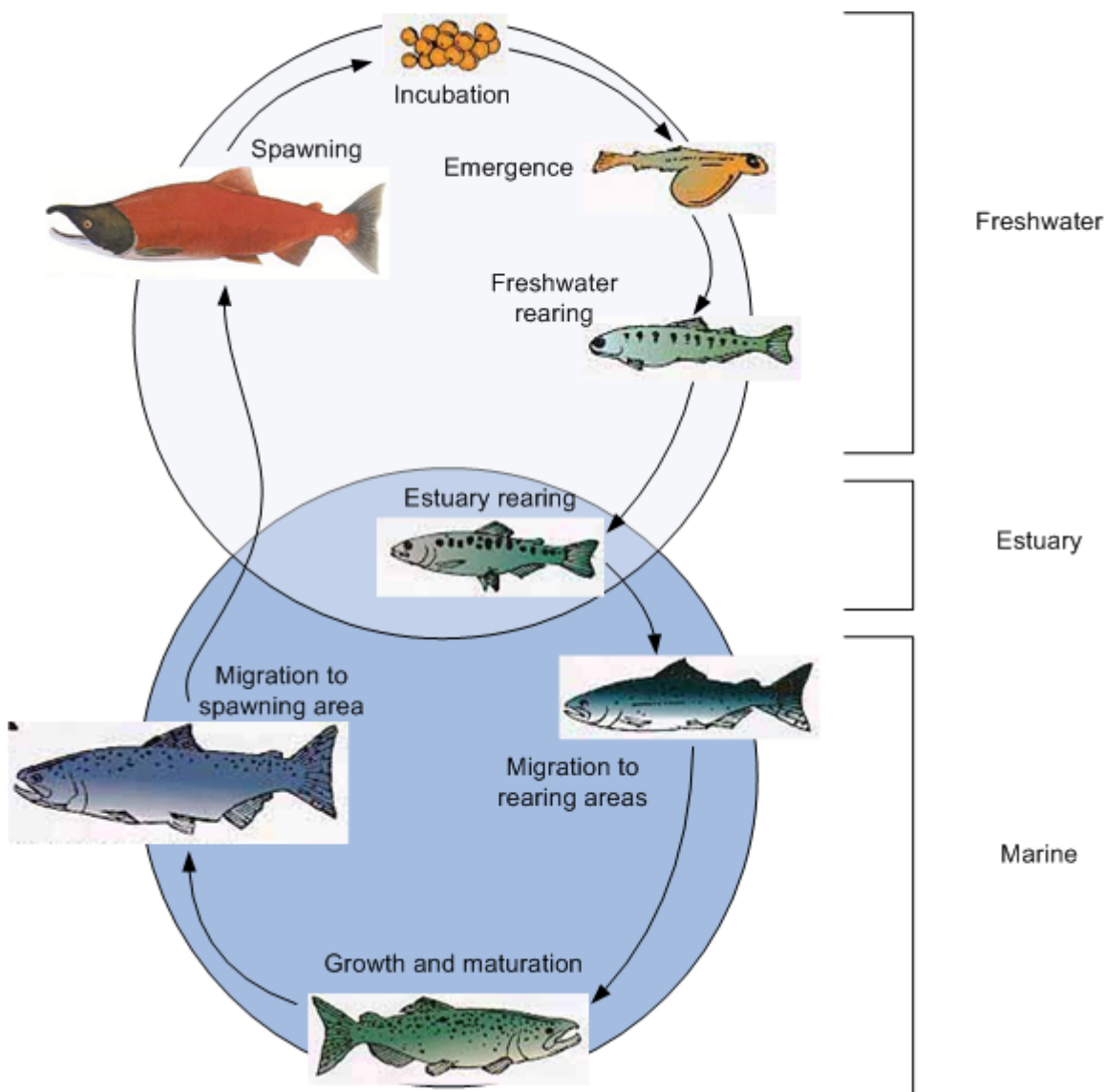
Figure 2-1. Life cycle of sockeye salmon. Most sockeye stocks in the Fraser River spawn in lake-fed streams or rivers in the late summer or fall, with their eggs incubating over winter and hatching the following spring as alevins. They quickly grow into fry and then spend the next year (sometimes 2 years) rearing and growing in a lake before heading to the Fraser estuary as smolts. Once in the ocean, they migrate north to rearing areas (as far west as the International Date Line and as far north as the Gulf of Alaska, where they spend 2 years (sometimes 3 years) growing and maturing. They then return to the Fraser estuary over the summer and fall, return upstream to their natal spawning grounds to repeat the cycle, with adults dying after spawning. Harrison River sockeye have a different life history from the rest of Fraser River sockeye populations. They enter the ocean as fry (sometimes called underyearling smolts) the year after spawning occurs, rather than rearing for a year in a lake before smolting. Sources include: http://www.pac.dfo-mpo.gc.ca/fm-gp/species-especes/salmon-saumon/facts-infos/sockeye-rouge-eng.htm

Table 2-2.   Life history stages affected by each hypothesis.

Hypothesis	FRESHWATER		ESTUARY	MARINE			FRESHWATER
	Incubation & emergence	Freshwater rearing	Estuarine migration	Migration in inshore waters	Growth in the North Pacific	Migration back to spawn	Spawning
1. Predation by marine mammals and/or unreported harvest in the ocean are important contributors to the Fraser sockeye situation (Section 4.1).			■	■	■	■	
2. Marine and freshwater pathogens (e.g., bacteria, parasites, and/or viruses), are important contributors to the Fraser sockeye situation (Section 4.2).	■	■	■	■			■
3. Ocean conditions (physical and biological) inside and/or outside Georgia Strait are important indicators of contributors to the Fraser sockeye situation (Section 4.3).			■	■	■	■	
4. Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation (Sec 4.4).			■	■			
5. Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation (Section 4.5).			■	■			
6. Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation (Section 4.6).	■	■					■
7. Delayed density dependent mortality is an important contributor to the Fraser sockeye situation (Section 4.7).	■	■	■	■			■
8. (1) En-route mortality during upstream migration, and (2) effects on fitness of the next generation, are important contributors to Fraser sockeye situation (Section 4.8).	Sub-hypoth. 2					Sub-hypoth. 1	Sub-hypoth. 1
9. Competitive interactions with pink salmon are important contributors to the Fraser sockeye situation (Section 4.9).			■	■	■	■	

2.3   Organization and presentation of evidence for each hypothesis

Presenters were tasked with preparing a 15-minute presentation accompanied by a more detailed 2-to-5 page summary for their respective hypotheses. To ensure that the Panel received all pertinent information for a given hypothesis and that evidence could be compared across hypotheses, presenters were asked to focus directly on four questions. In brief, the four questions looked at: (1) spatial and temporal trends across the stocks; (2) direct and indirect evidence in support (or not in support) of the hypothesis; (3) research needs; and (4) management needs. The specific questions to presenters are provided in Appendix A. The 2-to-5 page summaries prepared by the presenters are in Appendix C.

Prior to the workshop, presenters received time series data on **total life-cycle productivity** (spawner-to-recruits) for 18 Fraser sockeye stocks, as well as **juvenile productivity** (spawners-to-juveniles) and **post-juvenile productivity** (juveniles-to-recruits) for 8 stocks. They also received data on run timing and smolt size for the few stocks where this type of information is collected. These data and analyses were provided courtesy of the PSC and were used by the speakers to inform their analyses of specific hypotheses.

In addition to the presentation and summary, presenters were asked to complete a handout (in Appendix A) asking them to evaluate how indices related to the stressor hypothesis that they were investigating (e.g., ocean temperatures, contaminant levels) correlated with two key indicators of sockeye productivity:

> **Productivity Indicator 1 (total life-cycle productivity)**: Residuals from a Ricker model fit to $\log_e$(adult recruits **per effective female spawner** as a function of effective female spawner abundance). Graphs of these residuals over time are shown in Appendix D, Figures D-T1 through D-T6, as provided by the PSC. These graphs (available for all 18 stocks) show changes in productivity over the entire life cycle, relative to the expected amount of recruits per effective female spawner for a given number of those spawners.

> **Productivity Indicator 2 (post-juvenile productivity):** Residuals from a Ricker model fit to $\log_e$(adult recruits **per juvenile** as a function of juvenile abundance). Graphs of these residuals over time are shown in Appendix D, Figures D-P1 through D-P3 for the 8 of the 18 stocks for which time series of juvenile abundances were available. These graphs show changes in productivity over the post-juvenile portion of the life cycle, relative to the expected amount of recruits per juvenile for a given number of juveniles.

2.4   Workshop agenda

The workshop took place over the course of three days and involved a combination of presentations, surveys, and subgroup discussion. The first two days of the workshop included the Panel, presenters, independent scientists, and observers; the third day involved only the Panel. Hypotheses and relevant evidence were given by presenters on days 1 and 2. On the afternoon of the second day, presenters and independent scientists were divided into five subgroups, each corresponding to one of the five session themes (Table 2-1). Observers were permitted to listen (but not contribute) to subgroup discussions. Each subgroup examined the hypotheses that fell under their assigned theme and weighed the associated evidence. Each subgroup reported back to the Panel during a plenary session at the end of day 2. On day 3 of the workshop, the Panel came together to discuss the information presented over the previous

two days, and to draw conclusions regarding the probability, or relative likelihood, that a given hypothesis contributed to the Fraser sockeye situation. The 16 hypotheses discussed at the workshop were grouped into nine subsections for this report. One member of the Panel was assigned to write each subsection, summarizing the information presented and discussed at the workshop and stating the Panel's conclusion about the likelihood for the hypotheses considered within that section. Each section ended with priorities for future research as well as management options that could reduce the effect of the hypothesized mechanism.

During the workshop, independent scientists and presenters were asked to complete two surveys (see Appendix B for copies of the surveys). Survey 1 was designed to collect detailed information on a single hypothesis, while Survey 2 asked presenters and independent scientists to record their conclusions about the relative importance of each hypothesis in contributing to the observed spatial and temporal patterns in Fraser River sockeye. Given their ranking of hypotheses, they were asked to identify research priorities and management actions. Observers were invited to complete a third survey (their responses to categorical questions are summarized in Appendix E).

The information collected from the surveys was carefully reviewed by the Panel and was used to inform their evaluation of hypotheses, research priorities, and possible management actions (summarized in Section 5). Based on all of the evidence presented at the workshop and summarized in this report, Panel members rated their likelihood for each of the nine alternative hypotheses, separately considering how well a given hypothesis explained (1) the long-term overall decline in productivity of Fraser sockeye, and (2) the extremely low 2009 returns. When Panel members concluded that the available evidence was consistent with a factor contributing to Fraser sockeye stock declines during the period of interest (i.e., either the overall period or 2009 returns), they rated that hypothesis as *likely* or *very likely*. Conversely, if they concluded that the available evidence was inconsistent with a factor contributing to Fraser sockeye declines, they rated the factor as *unlikely* or *very unlikely*. An intermediate level of support received the rating *possible*. The Panel did not attempt to force a consensus on their ratings. Although there was some variation in support for a few hypotheses, Panel members generally had similar ratings for most hypotheses.

For each hypothesis, Section 4 lists research and monitoring priorities. In section 5, the Panel integrated and prioritized these suggestions across all hypotheses and life history stages, taking into account both the probability, or likelihood, that the factor or mechanism was responsible for sockeye declines, and the ability of the information generated by the proposed monitoring or research activity to improve management of sockeye and their habitats. Hence, the recommendations in Section 5 regarding research and monitoring reflect a higher level of synthesis than in Section 4.

3.0 Patterns that We Seek to Explain

3.1   Changes in Fraser River Sockeye Salmon

As mentioned in the Introduction, the extremely low return of 1.5 million adult sockeye to the Fraser River in 2009 was only the latest and most extreme sign of a longer-term problem. Specifically, productivity over the entire life span (adult recruits per spawner) has been on a downward trend for most Fraser sockeye populations since the late 1980s or early 1990s. These trends have not been straight lines, but rather have been mixed with occasional years with above-average survival rates. The overall downward trend is shown most dramatically by the 4-year moving average of total adult sockeye recruits per spawner for all Fraser sockeye stocks combined (Figure 3-1). In the absence of fishing, populations will decline when the ratio of recruits per spawner is less than 1.0, but to sustain fishing, the ratio must exceed 1.0 over the long term. Because the ratio in Figure 3-1 was calculated from summing all returns across all stocks and dividing by all spawners summed across stocks, the graph mainly reflects time trends of the most abundant stocks. Nonetheless, most stock-specific time trends in this measure of productivity show similar decreasing values, even for small populations, with the majority of them experiencing below-average productivities in the 1990s and 2000s. For brevity, we subsequently use the term *"Fraser sockeye situation"* to refer to these collective observations about decreasing stock-specific and overall trends in productivity. A more extensive graphical overview of data for Fraser River sockeye is given in Mike Lapointe's slides at the start of Appendix C and in Appendix D.
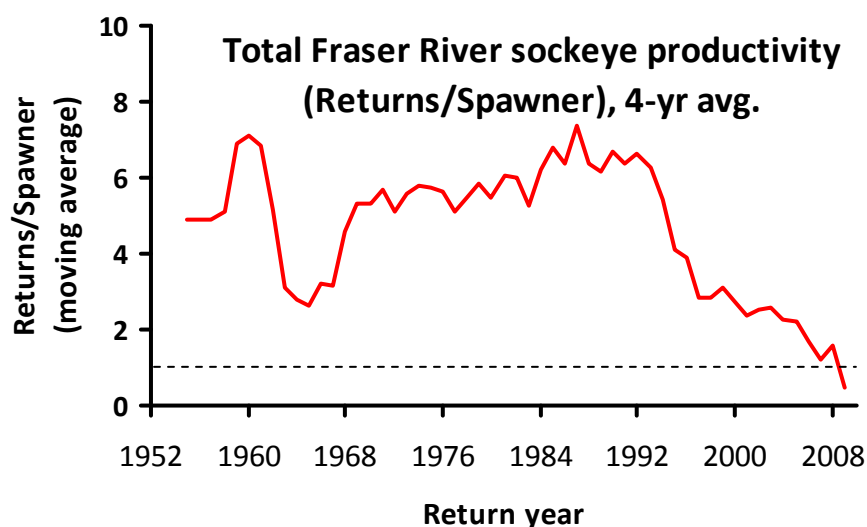
Figure 3-1.   Four-year moving average of total adult returns per spawner across all Fraser River sockeye stocks (not including the minor jacks component) divided by total spawners 4 years before. Return year is the last year of the four used to produce the moving average. The horizontal dashed line indicates the productivity at which the population can replace itself, i.e., returns/spawner = 1. Pacific Salmon Commission data from Michael Lapointe's slide 11, Appendix C.

Speakers at the workshop were asked to present evidence for a wide range of hypotheses to explain this Fraser sockeye situation, as well as other more detailed data. The Panel then separately evaluated each hypothesis in terms of its ability to explain two observations: (1) the

long-term decrease in productivity; and/or (2) very low returns and low productivity of the 2005 brood year, which returned primarily in 2009. Hypotheses that might explain the poor 2009 return may or may not be equally important for the long-term trend, and vice versa.

Section 3.1.1 below describes in detail the data and indicators developed by the PSC to describe the Fraser sockeye situation. While this background is essential for technical scientists who wish to understand the quantitative measures of productivity, other readers more interested in results of the Panel's analysis may wish to skip to Section 3.1.2, "Differences in productivity trends among life stages".

3.1.1   Three types of indicators of productivity

3.1.1.1   Standard productivity indicators

Before proceeding, it is important to understand the nature of the indices that the various hypothesized mechanisms are attempting to explain. The PSC compiled background data on Fraser River sockeye and sent them to all presenters of hypotheses on 23 April 2010 so that they could incorporate those data into their evaluations. The data set included information for 18 main component stocks of Fraser River sockeye salmon. In most cases, data started with the 1952 brood year (year of spawning). Variables provided by the PSC were by brood year and included:

- **Abundance of effective female spawners** (EFS), which adjusts the initial estimate of female spawner abundance for the proportion of eggs that was *not* spawned, based on spawning-ground sampling.

- **Abundance of juveniles** resulting from those EFS. Only one stock, Chilko Lake, has long-term estimates of smolt abundance useful for this workshop's objectives, and only seven other stocks have estimates of fry (pre-smolt) abundance. The latter are estimated either in the spring after emergence (Early Stuart, Gates, Nadina, Weaver, Stellako), during migration to lakes, or in the subsequent fall prior to smolting and migrating to the ocean (Quesnel, Shuswap). Cultus Lake also has smolt estimates, but PSC staff have pointed out that interpreting them in terms of productivity is problematic because, for several recent years, adults have been removed for hatchery brood stock, and hatchery juveniles have been released to boost productivity of this stock. For this reason, Cultus Lake data were omitted from the data set provided to speakers, although these data can still provide insights on post-juvenile survival, as we describe later.

- **Age-specific and total adult returns (recruits)** from brood-year EFS. These returns are estimates of abundance *prior to* the onset of fishing.

From these three initial variables, productivity indices were calculated to reflect survival rates across different life stages and to account for density-dependent factors and observation error. The latter is caused by the inevitable uncertainty that arises from sampling a population rather than completely enumerating it. The main productivity indices were as follows.

(1) **Freshwater productivity** was calculated annually as juvenile abundance (J) per effective female spawner (J/EFS). As noted above, juvenile abundances were fry except for Chilko, which has smolt abundance estimates.

(2) **Post-juvenile productivity** was calculated annually as adult recruits per juvenile (R/J). For Chilko sockeye, this ratio is usually referred to as "marine survival rate", but strictly speaking, mortality of some unknown amount occurs after smolts are estimated and as they migrate downstream before entering the ocean. Post-juvenile productivity is therefore a more correct term. Marine survival rate was used for brevity by some presenters.

(3) **Productivity across the entire life span** ("total life-cycle productivity") was calculated annually as adult recruits per effective female spawner (R/EFS). This ratio summarizes the net effect of the sequence of mortality processes that occur in fresh and salt water across the entire life cycle, starting with eggs and continuing up until mature adults return to the coast prior to the start of fishing.

3.1.1.2   Residuals of productivity indicators to account for density dependence

In any salmon population, the average ratio of recruits to spawners must eventually decrease as the abundance of parental spawners increases. This reduction is due to a variety of factors affecting either spawners (e.g., competition for spawning sites) or the next generation (e.g., predation rates, disease, or increased competition for food). Such factors (density-dependent processes) have been known since the 1950s, so PSC staff calculated indices of productivity that removed this density-dependent effect in order to enable researchers to more easily identify factors in addition to spawner abundance that affect productivity. To do this, PSC staff fit a standard Ricker stock-recruitment equation to each stock's data for each life stage and then calculated the annual residuals from the best-fit function for that stock. For instance, they fit a linearized version of the Ricker model using $\log_e(J/EFS)$ as the Y variable and EFS as the X variable. Each brood year's residual thus reflected variation over time in factors _other than_ those directly indexed by the variable in the denominator, effective female spawners in this example. This standard fitting procedure removed the potentially confounding interpretation caused by the portion of variation over time in $\log_e(J/EFS)$ that arises from variation in EFS alone. That is, the procedure removed density-dependent effects, making it easier to discern the effect of other factors affecting survival rates. This procedure for calculating residuals was repeated for the productivity indices for adult recruits per juvenile (R/J) and adult recruits per effective female spawner (R/EFS). The resulting data file was then provided to presenters about 6 weeks prior to the workshop to represent freshwater productivity (residuals in units of $\log_e(J/EFS)$), post-juvenile productivity (residuals in units of $\log_e(R/J)$), and total life-cycle productivity (in residual units of $\log_e(R/EFS)$).

For most Fraser sockeye stocks, though, these density-dependent effects within a generation are weak. This conclusion is reflected by the fact that the _residual_ measures of productivity described above, which remove those density-dependent effects, are generally highly positively correlated with their respective standard _non-residual counterparts_ that do not remove density dependence, $\log_e(J/EFS)$, $\log_e(R/J)$, and $\log_e(R/EFS)$. In fact, for the 18 stocks in the PSC data file, the median correlation between the time series of $\log_e(R/EFS)$ and _residuals_ of $\log_e(R/EFS)$ from the best-fit stock-specific function is 0.89 (ranging from 0.61 to 0.99). Such correlations were also high for the other life stages for the seven stocks with juvenile abundance data: a median correlation of 0.79 (range of 0.66 to 0.97) for $\log_e(\text{juveniles}/EFS)$ and a median of 0.96 (range of 0.85 to 0.99) for $\log_e(R/J)$. These high correlations of the two types of indicators reflect the weak density dependence that exists in most of these populations over the range of densities examined. Stocks with the lowest correlation between the residual indicator of productivity and the standard non-residual indicator tended to be those in which spawner abundance had increased dramatically in the last 20 years or so (e.g., Quesnel, Stellako, and

Pitt). For these stocks, density dependence may have become important (discussed in more detail in Section 4.7).

3.1.1.3   Time-varying estimates of productivity (Ricker a_t values)

Past research shows that adult recruits per spawner for many Pacific salmon species and stocks have been greatly affected by changing oceanographic regimes, as well as reductions in the quantity or quality of freshwater habitats (the latter effect most notably applies to stocks in the conterminous United States). As a result, the recruits-per-spawner productivity index for North American pink and sockeye salmon increased by about 50% in the mid-1970s when the North Pacific became more favorable for salmon, but became less so starting in 1989. Clearly, time trends in salmon productivity can have important implications for development of management strategies, which normally assume a constant underlying productivity of fish. It is not a simple matter to detect such time trends in salmon productivity, though, because observation error and natural year-to-year variability in survival rates tend to obscure underlying longer-term trends in recruits per spawner.

A Kalman filter estimation procedure for fitting a Ricker spawner-recruit model has previously been shown through simulation testing to effectively describe such underlying trends in the presence of observation error (e.g., errors in abundance estimates) and large natural variation in year-to-year survival. Technical details of the Kalman filter method are beyond the scope of this report, but they can be found in (Peterman et al. 2000). Briefly, the Kalman filter estimation method used for some graphs in this report assumed that the Ricker a parameter was not necessarily constant, but could change from year to year (hence denoted as a_t). This Ricker a_t parameter represents the average $\log_e$(recruits/spawner) at extremely low abundance of spawners, i.e., where there is no density-dependent effect of spawner abundance on recruits/spawner. In other words, it represents the maximum rate of increase that the population could have with no fishing and low spawner abundance (also more generally called r_{max} or the 'intrinsic productivity' by ecologists). The Kalman filter estimation method assumes that changes over time in estimated a_t could arise from observation error as well as natural variation in year-to-year survival. This method attributes a portion of variation in the observed data to observation error and the rest to systematic process variation (slowly changing trends or a rapid change to a new persistent average productivity). Hence, it produces a "cleaner" data series than the original recruits/spawner data. As well, a Kalman filter fixed-interval smoother produces the maximum likelihood estimates of the annual productivity parameter, a_t (Harvey 1989). PSC staff used spawner and recruit data with the computer code from Dorner et al. (2008) to estimate such time series of smoothed a_t values to reflect time-varying total-life-cycle productivity of salmon.

3.1.2   Differences in productivity trends among life stages of Fraser sockeye

An important feature of the Fraser sockeye data is the marked difference among productivity time trends for the three life stages: juvenile, post-juvenile, and total life-cycle productivity. Most of the eight Fraser sockeye populations for which there are estimates of juveniles do not show any time trend in freshwater productivity (residuals for $\log_e$(juveniles/EFS)) (Figures D-J1 to D-J3, Appendix D). In fact, the only exceptions show freshwater productivity _increasing_ (for Chilko starting with the 2005 brood year) or being above average (Weaver since the late 1980s brood years). In contrast, both post-juvenile (Figures D-P1 to D-P3, Appendix D) and total life-cycle productivity residuals (Figures D-T1 to D-T6, Appendix D) for most stocks tend to decrease, starting either in the late 1980s or early 1990s.

On the surface, it would therefore appear logical to conclude that the total life-cycle productivity residuals reflect events in the post-juvenile stage more than in the freshwater juvenile stage. This conclusion is backed up by a simple statistical analysis. The median of the 8 stock-specific correlations between *freshwater* productivity residuals and *total life-cycle* residuals is 0.29, but the median jumps to 0.83 for correlations between *post-juvenile* residuals and *total life-cycle* residuals (Table 3-1). Similar results emerge when the *non-residual* indices of productivity are used, that is, $\log_e(J/EFS)$, $\log_e(R/J)$, and $\log_e(R/EFS)$. There, the median correlation is 0.43 between freshwater and total life-cycle measures, and 0.81 between post-juvenile and total life-cycle measures (Table 3-1). Note that the above analysis does not separate the relative contribution to those correlations of shared time-trends in productivity, as opposed to shared year-to-year fluctuations in productivity.

Table 3-1. Pairwise correlations of time series of indices of productivity for populations for which time series of juvenile abundance estimates are available (all cases are fry except for Chilko, which uses smolt abundance data).

Population	Using <u>residuals</u> from best-fit productivity function		<u>Not using residuals</u>	
	Freshwater productivity vs. total-life-cycle productivity (residuals of J/EFS vs. residuals of R/EFS)	Post-juvenile productivity vs. total-life-cycle productivity (residuals of R/J vs. residuals of R/EFS)	Freshwater productivity vs. total-life-cycle productivity (J/EFS vs. R/EFS)	Post-juvenile productivity vs. total-life-cycle productivity (R/J vs. R/EFS)
Early Stuart	0.29	0.73	0.28	0.82
Stellako	0.19	0.83	0.45	0.72
Quesnel	0.11	0.76	0.30	0.67
Chilko	0.23	0.95	0.69	0.83
Late Shuswap	0.54	0.64	0.54	0.62
Weaver	0.30	0.96	0.49	0.90
Gates	0.30	0.93	0.34	0.92
Nadina	0.34	0.83	0.40	0.80
Median:	**0.29**	**0.83**	**0.43**	**0.81**

Although post-juvenile productivity indices are clearly most highly correlated with total life-cycle productivity, we should <u>not necessarily</u> jump to the conclusion that the causal factors behind the decline in total life-cycle productivity mainly occur in the post-juvenile stage (i.e., after fry are estimated, or after smolts are estimated for Chilko sockeye). The reason for caution in making this jump is that there may be processes operating in fresh water that do not cause substantial mortality of fish until after juvenile abundances are estimated. For instance, bacteria, viruses, or parasites that are picked up in fresh water may not cause mortality until the marine life phase. Similarly, poor growth in fresh water or other aspects of habitat quality may produce juveniles that are in poor condition and are more vulnerable to predators later. In most cases, simple abundance estimates of juveniles will not indicate the condition of fish or their potential fate.

However, the correlation pattern of Table 3-1 suggests that the hypothesis of predation on sockeye juveniles in nursery lakes is not likely an important contributor to the long-term decline in total productivity, unless it primarily acts in an indirect manner on juveniles. That is, rather than predation being a cause of large direct mortality, if it caused reduced growth among juvenile sockeye by restricting their access to food to avoid predation, then the resulting smaller

juveniles might be more likely to die later. Size-dependent mortality at sea has been documented repeatedly by researchers.

3.1.3   Differences in time trends of productivity among Fraser River sockeye stocks

The trend in total Fraser River sockeye productivity (Figure 3-1) can be decomposed into trends for each of the 18 component populations. Figures D-T1 to D-T6, Appendix D show *total life-cycle* productivity residuals from spawners to recruits for each population. By the way they are calculated, the stock-specific residuals in these figures have a mean of zero; values below zero indicate below-average productivity residuals. Note that in most of these populations, except Harrison River, these total life-cycle productivities are consistently below average in the 1990s and/or show a notable downward trend in the 2000s. Prime examples are Early and Late Stuart, Stellako, Bowron, Quesnel, Chilko, Birkenhead, Portage, Weaver, and Nadina. The exception, Harrison River, has had mostly above-average total life-cycle productivity since 1997. We will return to this exceptional case later, because it may provide important clues about sources of downward trends in other Fraser sockeye stocks.

As expected from the correlations shown in Table 3-1, the *post-juvenile* residual productivity indices also show similar trends to total life-cycle productivity (Figures D-P1 to D-P3, Appendix D). Stellako, Quesnel, Chilko, Weaver, and Nadina show particularly low values later in their series, especially in the 2000s. Even Cultus Lake sockeye, despite some confounding caused by stocking the lake with hatchery-reared fry and removing freshwater predators (northern pikeminnow), show the same decreasing trend in adults per smolt as Chilko Lake sockeye (Grant et al. 2010, Figure 4B). In contrast, *spawner-to-juvenile* productivity residuals (Figures D-J1 to D-J3, Appendix D) show no downward time trend consistent with temporal patterns in post-juvenile or total life-cycle productivities.

Therefore, any mechanisms that are causing the reduction in total life-cycle productivity observed in Fraser River stocks must be causing most fish to die *after juvenile abundance is enumerated*. As mentioned above, this statement does *not* preclude factors from starting their effect in the egg-to-juvenile stage, *as long as the resulting lower survival occurs after that stage*. Speakers at the workshop described several such potentially relevant processes, but unfortunately, data were lacking on most of them to determine when mortality occurred. Those potentially important processes include, among others, freshwater pathogens, contaminants, temperature and nutrient conditions in nursery lakes that affect available food for salmon, and effects of predators in freshwater that reduce growth rates of sockeye juveniles and make them more vulnerable to mortality agents later in life. These and other hypotheses are evaluated in detail in Section 4.

We now return to the Harrison River sockeye stock, which shows quite a different time trend from other Fraser River sockeye. From 1997 onward, it has had mostly above-average total life-cycle productivity (Figure D-T6, Appendix D), as opposed to below-average for other Fraser sockeye. Significantly, Harrison River sockeye have a different freshwater life history from the rest of Fraser River sockeye populations. They enter the ocean as fry (sometimes called underyearling smolts) the year after spawning occurs, rather than rearing for a year in a lake before smolting. Thus, ocean-entry year for Harrison sockeye is one year after spawning, instead of two years after for other Fraser sockeye populations. Harrison juveniles appear to spend a few to several months rearing in sloughs of the Fraser River estuary and are somewhat smaller when they enter Georgia Strait later than smolts from lake-rearing stocks. By September though, Harrison juveniles appear to be almost as large as those smolts. Additionally, data from juvenile salmon surveys conducted in Georgia Strait have documented that Harrison sockeye

juveniles are in Georgia Strait in September, while most other Fraser sockeye populations migrate quickly through Georgia Strait in late spring and summer. Some limited evidence suggests another important difference -- Harrison juveniles *may* migrate out to sea mainly via Juan de Fuca Strait at the south end of Vancouver Island, rather than through Johnstone Strait at the north end. These differences in location, juvenile body size at sea entry, and the route and timing of seaward migration prompted explanations such as Harrison juveniles encountering oceanographic conditions, predators, competitors, food supply, or parasites and other pathogens that are different from those encountered by other Fraser River sockeye.

The final indicator of productivity is the time-varying Ricker a_t parameter, as estimated by smoothed Kalman filter results. Recall that this parameter represents a population's maximum rate of increase. As factors affecting productivity change, this Ricker a_t parameter will change. As noted above, these Ricker a_t values reflect an underlying change in productivity better than the other productivity indicators used here because the Kalman filter removes some of the observation error or other variation not associated with systematic change in productivity. Time trends in smoothed Kalman filter a_t values are shown for all stocks in standard deviation units, i.e., the a_t value in a given year minus the mean stock-specific a_t, all divided by the standard deviation of that a_t time series. This unit allows easy comparison of time trends across stocks.

The result is a remarkably clear pattern of decreasing total life-cycle productivity in 16 of the 18 Fraser sockeye stocks (Figure 3-2). Increasingly large light orange dots to the right in this figure reflect Ricker a_t values dropping further below average since the 1990s for most stocks, and since the 1980s for Pitt and Raft. Note that these 16 populations vary considerably in the location of spawning grounds, distance from the ocean for juveniles to migrate, timing of that migration, and other factors, yet these patterns are shared strongly among stocks. Standard line plots of these smoothed Kalman filter Ricker a_t trends are provided in Figures 3A-3R of Grant et al. (2010).

Figure 3-2 shows the _smoothed_ Kalman filter estimates of time-varying Ricker a_t values, which, as noted above, are the maximum likelihood estimates, i.e., the most probable values. For comparison, Figure 3-3 shows the _unsmoothed_ estimates, i.e., the filtered values prior to smoothing. The patterns of decreasing productivity over time described for smoothed values in Figure 3-2 still clearly appear in unsmoothed values in Figure 3-3; the smoothing merely dampens year-to-year variation in estimated productivity.

Two notable exceptions to the trends of decreasing productivity in Figures 3-2 and 3-3 are Harrison and Late Shuswap (the famed Adams River sockeye run). Harrison sockeye have above-average and increasing productivity in the last decade, and Late Shuswap has shown no discernable time trend (Figure 3-2). Recall that Harrison fish exhibit quite a different life history from other Fraser sockeye, going to sea as fry, rearing in Fraser River sloughs and the estuary, returning as mature adults mostly as 3- and 4-year olds after two or three years at sea, and possibly migrating out mostly through the southern route, Juan de Fuca Strait. Whatever conditions they encounter have permitted their survival rates to go up rather than down. Late Shuswap exhibits a strong cyclic dominance pattern (Lapointe's talk slide 15, Appendix C) and has historically contributed the largest portion of sockeye to the Fraser River system in dominant-cycle years. This stock has been close to average productivity, or slightly below it, since the mid-1990s (Figure D-T3, Appendix D) but it shows no time trend in Ricker a_t values.
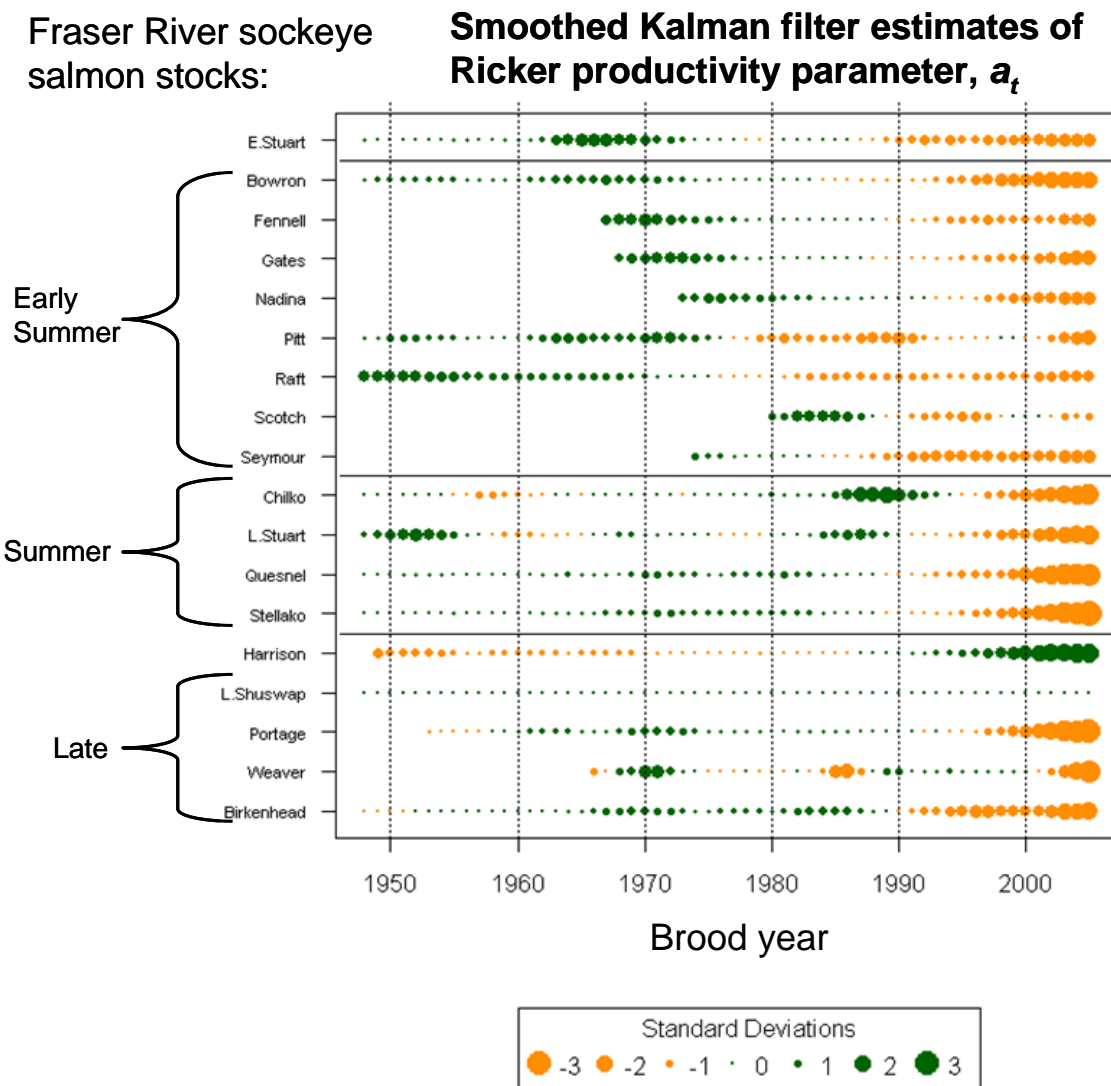
Figure 3-2. Time-varying Ricker a_t parameter values of **total life-cycle productivity** (i.e., from spawners to recruits), as measured by **smoothed** Kalman filter estimates, shown for each Fraser sockeye stock. Ricker a_t parameters for all stocks are in the same units, i.e., standard deviation units, or deviations above or below the stock-specific long-term mean. Brood year is year of spawning. Sizes of dots represent how many standard deviations above (dark green dots) or below (light orange dots) the mean the Ricker a_t values are. Constant dot size (Late Shuswap) indicates no time trend. Note that because values are plotted relative to each stock's mean and standard deviation, differences in sizes of circles between stocks do not imply differences in relative productivity of different stocks. From Michael Lapointe's slide 25, Appendix C.

Fraser River sockeye salmon stocks: **Unsmoothed Kalman filter estimates of Ricker productivity parameter, a_t**
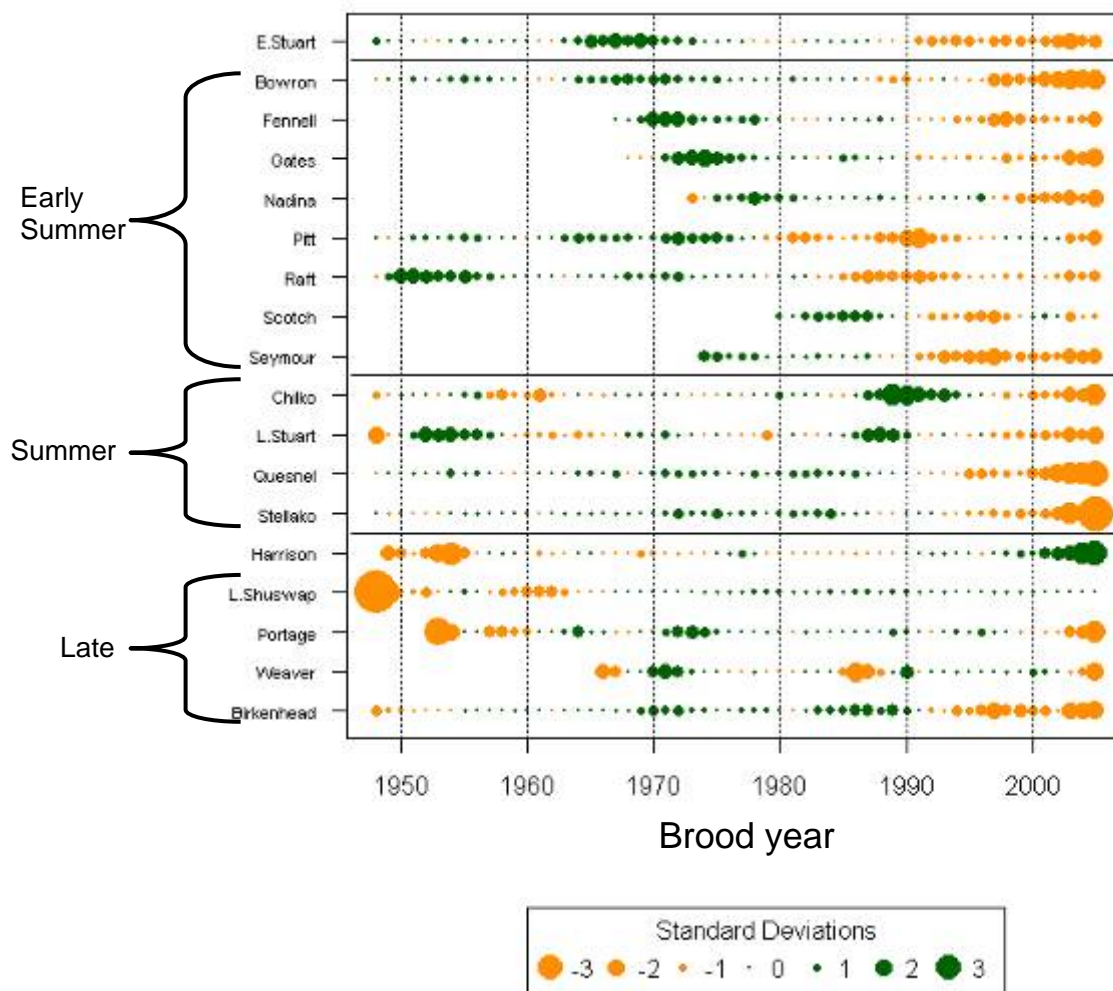
Figure 3-3. Same as Figure 3-2, except these are **<u>unsmoothed</u>** Kalman filter estimates of Ricker a_t parameters for **total life-cycle productivity** (i.e., from spawners to recruits). Ricker a_t parameters for all stocks are in the same units, i.e., standard deviation units, or deviations above or below the stock-specific long-term mean. Note that because values are plotted relative to each stock's mean and standard deviation, differences in sizes of circles between stocks do not imply differences in relative productivity of different stocks.

However, closer inspection of Late Shuswap data suggests a different interpretation. Spawning abundances for this stock and a number of other sockeye populations have, within a given 4-year period, one very abundant population of a few million adults (i.e., dominant cycle line), a somewhat less abundant population (sub-dominant cycle line), and two much-less-abundant populations as low as a few hundred fish (off-cycle lines). Consequently, biologists often use only data from the two high-abundance years when estimating productivity relationships because very low abundances in the two off-cycle years can lead to substantial errors in stock identification and proportionally large errors in abundance estimates for Late Shuswap fish. When Ricker a_t values were re-estimated separately from Late Shuswap data for the distinct cycle lines, rather than combining all four of them, a decreasing productivity trend emerged for

the analyses that used (a) only sub-dominant cycle-line data, and (b) only dominant plus sub-dominant cycle-line data (Figure 3-4). However, there was no time trend using only dominant cycle-line data (Figure 3-4). These divergent results for different data groupings suggest that decreased productivity since the 1990s in the combined sub-dominant plus dominant data set may be due to interactions between cycle lines. For instance, depletion of food in a nursery lake in one year can reduce food supply for juveniles the next year, or predator or pathogen populations can build up in high-abundance years but also carry over their effects into subsequent years. This possibility is explored further in Section 4.7.

Figure 3-4. Time-varying Ricker a_t parameter values of **total life-cycle productivity** (i.e., from spawners to recruits), as measured by smoothed Kalman filter estimates, shown for the Late Shuswap stock only using five different groupings of data: (1) all data (top row), (2) only dominant cycle-line data, i.e., every 4th year in 1954-2006, (3) sub-dominant cycle-line data, i.e., every 4th year in 1953-2005, (4) dominant and sub-dominant cycle-line data combined, and (5) off-cycle lines. Ricker a_t parameters for all cases are in the same units, i.e., standard deviation units, or deviations above or below the long-term mean. Brood year is year of spawning. Sizes of dots represent how many standard deviations above (dark green dots) or below (light orange dots) the mean the Ricker a_t values are. Constant dot size indicates no time trend. From Michael Lapointe's slide 26, Appendix C.

Clearly though, it is not sufficient to merely describe changes in indicators of productivity of Fraser sockeye salmon and attempt to attribute those changes to a cause by merely describing plausible-sounding hypothesized mechanisms. As noted in this report's Introduction, statistical analysis of data gathered from carefully designed manipulative experiments is the best way to understand causal mechanisms in ecological systems, but in the case of Fraser River sockeye, such experiments are not practical, except perhaps with changing spawner abundance through altered harvest rates. Therefore, indirect comparisons of the type described above are required

among life-history stages, populations, and spatial locations to gain insight into causes of changes in Fraser sockeye. Such comparisons must be made not only among Fraser sockeye stocks, but also between those stocks and other sockeye outside of the Fraser system, as well as other salmon species inside and outside of the Fraser River. For example, if several Fraser sockeye salmon populations show similar time-trends in productivity to non-Fraser stocks, they may be sharing similar drivers of change in productivity. Such a finding would discount hypotheses that are solely related to spawning sites, which are obviously unique to each population. Therefore, the next section describes population dynamics of sockeye outside of the Fraser system, as well as both Fraser and non-Fraser chinook (*Oncorhynchus tshawytscha)* and coho (*O. kisutch*) salmon stocks. In Section 4, each hypothesis will be evaluated in terms of how well it explains not only the majority of cases of Fraser sockeye that have had decreasing productivity, but also the increase in Harrison River productivity and any other divergent trends for non-Fraser River sockeye or other species.

3.2 Recent Changes in B.C., Washington and Alaskan Salmon other than Fraser River Sockeye

This section summarizes data presented by Arlene Tompkins (for Timber Whitehouse, DFO) on other salmon populations to compare with Fraser sockeye. Those cases included Fraser Chinook, Fraser coho, as well as some non-Fraser North American sockeye, Chinook, and coho populations. We also consider additional information on post-juvenile-to-adult survival of non-Fraser sockeye populations that became available from DFO staff after the workshop.

The first comparisons are with non-Fraser-River sockeye populations in B.C. Based on the same method used to estimate time-varying Ricker a_t values for Fraser River sockeye, all seven B.C. sockeye populations show the same reduced productivity in the 2000s as the Fraser sockeye, with reductions starting in the 1990s for Skeena, Smith Inlet, and Owikeno, except the latter showed a slight but brief increase in productivity in the late 1990s (Figure 3-5). Thus, the time patterns in productivity for these B.C. sockeye stocks are very similar to the patterns of decreasing productivities for most Fraser sockeye populations (Figure 3-2). This similarity exists despite substantial differences in geographical locations of spawning grounds, nursery lakes, freshwater migration corridors, and early ocean life, as well as differences in timing of ocean entry and migratory routes in the ocean. However, as described in the next few paragraphs, it seems likely that this similarity of decreasing trends over time among Fraser and other B.C. sockeye populations is merely coincidental, and that different causal mechanisms operated on different groups of stocks.

The best evidence that the decreasing trends in the most recent years resulted from different causes in Fraser sockeye than in other B.C. sockeye populations comes from comparisons of post-juvenile productivity in a subset of indicator populations for which estimates of pre-smolt or smolt abundance are available. Estimated spawner-to-juvenile and post-juvenile productivity (i.e., residuals from best fitting recruitment curves) are shown separately in Appendix D for six Fraser River sockeye populations for which there are data up through sea-entry year 2007 (Early Stuart, Quesnel, Chilko, Weaver, Gates, and Nadina). Post-juvenile productivity has been declining in five of these six populations, whereas juvenile productivity has been stable in five populations and increasing in Chilko. ***For sea entry year 2007, residuals are consistently negative (in fact, strongly negative in four of the six populations) for post-juvenile productivity but positive or near-zero for spawner-to-juvenile productivity***. Hatchery smolt-to-adult survival data are also available for two other (endangered) populations of sockeye that enter the Strait of Georgia – Cultus Lake in the lower Fraser River and Sakinaw Lake just 80 km

northwest of the Fraser River. In both cases, smolt-to-adult survival has been at or near record-low levels in the most recent sea-entry years (2005, 2006 and 2007) (Bradford et al. in press; Wood et al. in press). The strong similarity in these trends suggests that conditions had become increasingly unfavourable for Fraser sockeye smolts *after they left the nursery lake*, especially in 2007.

There are contrasting results for other cases in which smolt or pre-smolt abundances have also been monitored for a number of B.C. sockeye populations that enter the ocean outside the Strait of Georgia (Osoyoos and Skaha lakes in the Columbia River; Great Central and Sproat lakes in Barkley Sound on the west coast of Vancouver Island; Smith Inlet on the central BC coast; and Tahltan and Tuya lakes in the Stikine River on the northern BC coast). Although post-juvenile survival rate in these populations was consistently poor in sea-entry year 2005 (a year with significantly delayed onset of spring/summer upwelling in the California Current System), it improved significantly in 2006 and 2007 (Kim Hyatt, unpublished manuscript, DFO, Nanaimo, for southern populations; Peter Etherton, personal communication, DFO, Whitehorse, Yukon, for Stikine River populations). Most interestingly, post-juvenile survival for sea-entry year 2007 was actually above the long-term average in Barkley Sound and Columbia River populations, and just below the long-term average in Smith Inlet and Stikine River populations.

It is also worth considering adult sockeye returns to Heydon Lake situated in Johnstone Strait immediately north of the Strait of Georgia. The Heydon sockeye population is the only sockeye population in Johnstone Strait for which reliable adult abundance (fence counts) and age composition data are available to allow inferences about productivity. Adult returns to Heydon Lake in 2009 were considerably larger than the parent escapement, indicating above-average total survival (i.e., freshwater and marine phases combined) for smolts migrating seaward in 2007 (Pieter van Will, personal communication, DFO, Port Hardy). This favorable survival suggests that the unfavourable conditions affecting seaward migration of Fraser sockeye smolts in 2007 existed south of Johnstone Strait.

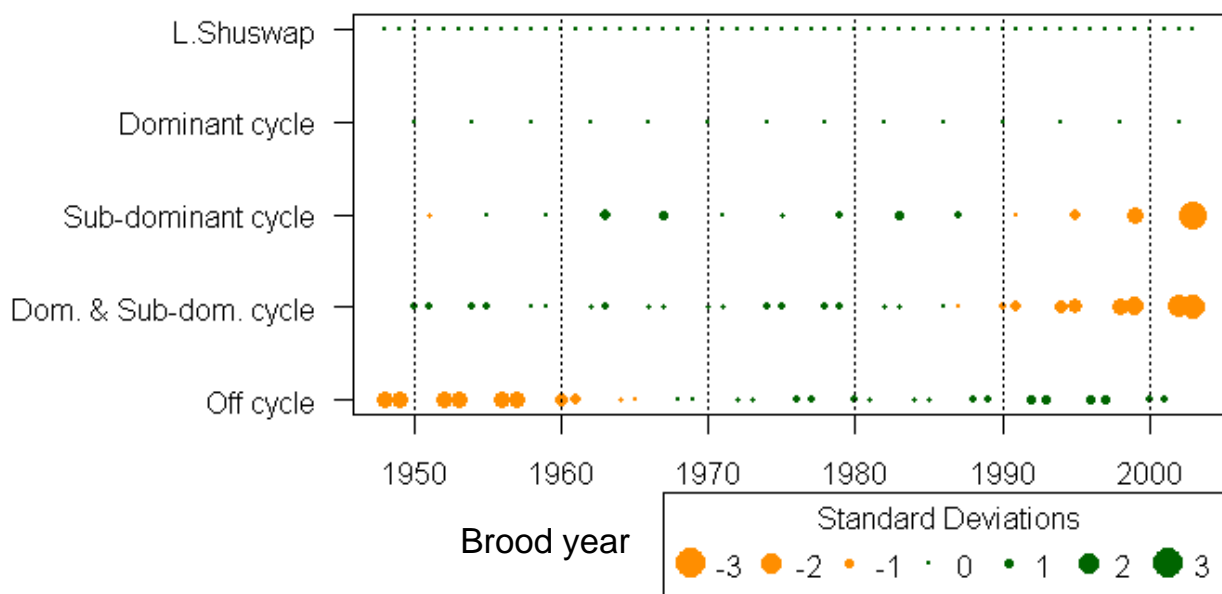**Kalman Filtered a[t] values for Sockeye**

Figure 3-5. Time-varying Ricker a_t parameter values of **total life-cycle productivity** (i.e., from spawners to recruits), as measured by smoothed Kalman filter estimates, shown for some **sockeye** stocks in British Columbia other than Fraser River sockeye, as well as Alaska. Ricker a_t parameters for all stocks are in the same units, i.e., standard deviation units, or deviations above or below the stock-specific long-term mean. The top seven stocks are from Bristol Bay, Alaska, and the next seven are from B.C. Brood year is year of spawning. Sizes of dots represent how many standard deviations above (dark green dots) or below (light orange dots) the mean the Ricker a_t values are. Note that because values are plotted relative to each stock's mean and standard deviation, differences in sizes of circles between stocks do not imply differences in relative productivity of different stocks. This is an updated version, provided by Arlene Tompkins, of her slide 11, Appendix C.

Productivity trends for Alaskan sockeye are also informative. Most Bristol Bay sockeye populations have had above-average productivities in the 1990-2005 period when B.C. sockeye productivities were decreasing (Figure 3-5). The major exception is the Kvichak River stock, which used to be the world's most abundant sockeye population, but which has suffered a considerable decrease in productivity since the early 1990s. These patterns of opposite productivities, as well as negative correlations between most Alaskan and B.C. sockeye abundances, have been well-known for many years (Peterman and Wong 1984; Mantua et al.

1997). The dominant explanation of these opposite patterns is that in early phases of ocean life, juvenile salmon from these two regions encounter different predator and prey conditions as a result of distinct oceanographic conditions in their respective areas of ocean entry (Mantua et al. 1997; Mueter et al. 2002).

Chinook stocks are studied extensively through the PSC's Chinook Technical Committee (CTC), and their data, largely based on coded-wire tag studies, are informative as well. Chinook salmon have two distinct life histories; juveniles of fall (or "ocean-type") Chinook migrate to sea in early summer as "underyearlings" after only a few months rearing in fresh water, whereas juvenile spring (or "stream-type") Chinook rear in streams until the following spring and go to sea as "yearlings" at a correspondingly larger size. These two life-history types can therefore encounter different predator and prey conditions and can provide useful contrasts with Fraser sockeye salmon, which enter the sea as large yearling smolts (except for the Harrison River sockeye stock, which is like ocean-type Chinook in that they enter salt water as smaller underyearling smolts, i.e., seaward migrating fry). Large numbers of tagged juveniles from hatcheries and wild stocks, along with an extensive tag recovery program, permit estimating post-juvenile productivities for numerous Chinook populations.

The resulting data series of productivities for Chinook start in the late 1970s. The CTC traditionally aggregates similar stocks, so abundance or productivity trends for an aggregate may mask individual stock trends. Furthermore, wild aggregates may include some enhancement, and in some cases, the indicator for wild stocks is a hatchery population (for details, see http://www.psc.org/publications_tech_techcommitteereport.htm#TCCHINOOK). However, Chinook trends are generally similar within an aggregate, with exceptions noted below.

Based on these Chinook data, Ricker a_t parameters were estimated with a Kalman filter in the same way as for sockeye stocks described above. **Results clearly show a period of low productivity for Chinook populations in the 1990s throughout the entire West Coast (Figure 3-6), which is similar to the pattern observed for most Fraser River sockeye. However, unlike the Fraser sockeye, only some of those Chinook populations suffered continued decreases in productivity throughout the 1990s and into the 2000s. It is noteworthy, though, that six out of the eight cases for British Columbia Chinook population aggregates did show below-average productivity in the 2000s (Figure 3-6).** For instance, the productivity trend for *late* Fraser Chinook aggregate is more similar to Fraser sockeye than the early Fraser Chinook run. However, the latter aggregate is composed of the increasingly productive Lower Shuswap/South Thompson Chinook, and the unproductive Nicola and Dome Chinook populations that are stocks of concern. West Coast Vancouver Island (WCVI) Chinook have below-average productivity, as do Lower Georgia Strait Chinook, despite occupying geographically separate habitats in early ocean life. To the extent that these fish occupy similar habitats from Queen Charlotte Sound and northward, this may indicate that they share similar mortality factors. We emphasize that Figure 3-6 describes trends in productivity (recruits/juvenile) and thus does not necessarily reflect changes in relative abundance, which may be increasing or decreasing as a result of changes in spawner abundance and or numbers of hatchery releases.

Finally, both wild and hatchery coho salmon in southern B.C. show decreasing post-juvenile productivity since the 1970s or 1980s, depending on the stock aggregate (Figure 3-7). Survival rates began to decrease for Fraser River and Georgia Strait coho in 1988 (data not provided before then), closely paralleling the downward trend in survival rate of Chilko Lake sockeye smolts.
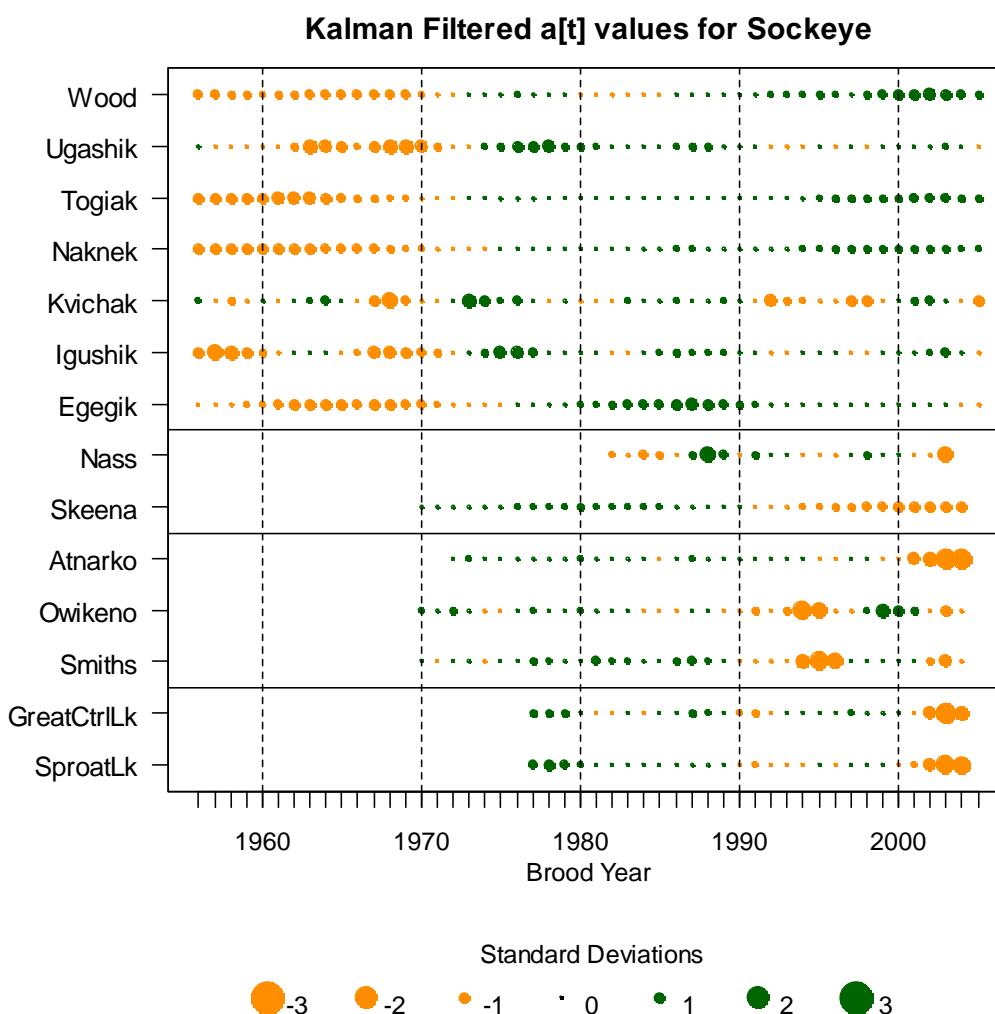
Kalman Filtered a[t] values for Chinook
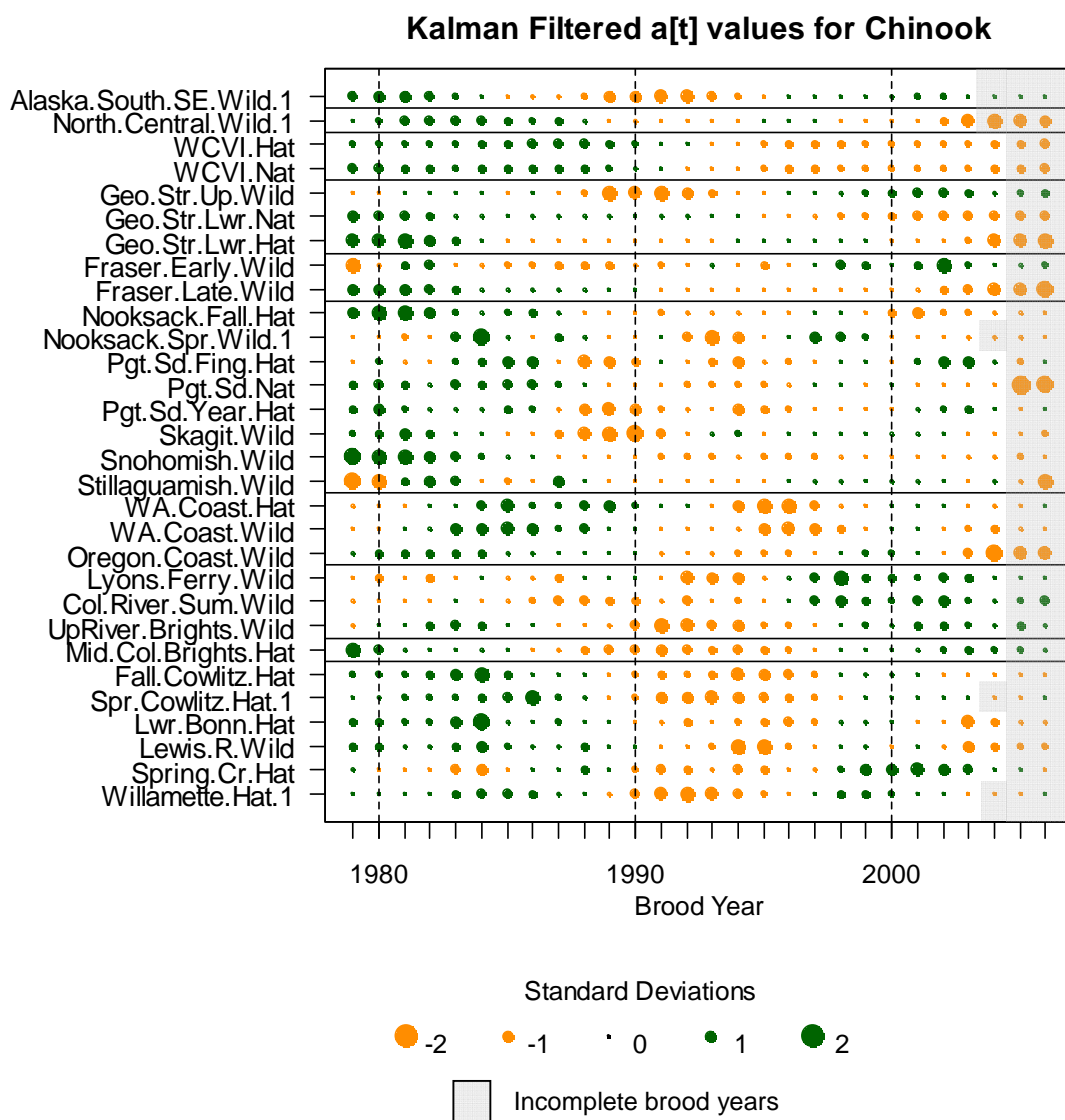
Figure 3-6. Time-varying Ricker a_t parameter values of **post-juvenile productivity** (i.e., from juveniles to recruits), as measured by smoothed Kalman filter estimates, shown for **Chinook** salmon stocks in southeast Alaska, British Columbia, Washington, and Oregon. All stocks are fall Chinook except those with labels ending in "1", which are spring stocks. Ricker a_t parameters for all stocks are in the same units, i.e., standard deviation units, or deviations above or below the long-term mean. Brood year is year of spawning. In shaded years only, results were estimated partly from projections of future returns for particular stocks.[1] Sizes of dots represent how many standard deviations above (dark green dots) or below (light orange dots) the mean the Ricker a_t values are. Note that because values are plotted relative to each stock's mean and standard deviation, differences in sizes of circles between stocks do <u>not</u> imply differences in relative productivity of different stocks. This is an updated version, provided by Arlene Tompkins, of her slide 12, Appendix C.

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[1] For brood years 2005 onward (gray blocks), results are projections rather than actual data because returns are incomplete. That is, the oldest-aged Chinook adults either have not yet returned or those data are not yet available. For 5 of the stocks, this is also the case for the 2004 brood year (Alaska South, North/Central, Nooksack spring, Spring Cowlitz, and Willamette.

Southern BC Coho Average

Strait of Georgia Coho
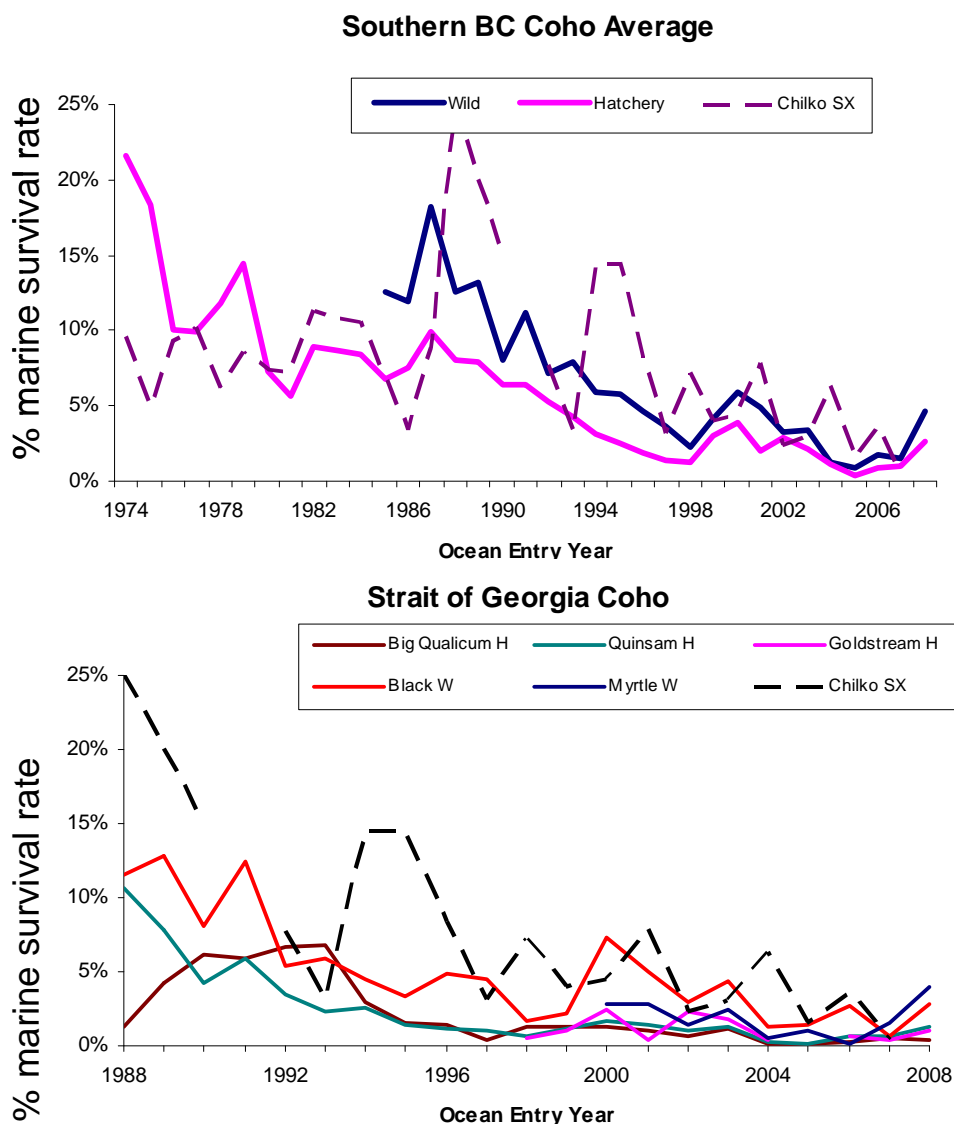
Figure 3-7. Estimated **post-juvenile** ("marine") survival rates **by ocean-entry year** for **coho** salmon stocks in southern British Columbia (i.e., average of Fraser River and Strait of Georgia (top) and Strait of Georgia alone (bottom). Adapted from Arlene Tompkins' slide 15, Appendix C.

In contrast to Fraser sockeye salmon, Fraser pink and Fraser chum (*O. keta)* salmon have not shown a trend of decreasing productivity. In fact, the fry-to-adult productivity of Fraser pink salmon (which exist only as odd-year spawning populations) has varied around a constant mean, or even increased slightly, since the 1960s, and the 2007 brood year, which produced the large run of Fraser pink salmon in 2009, only had a slightly above-average fry-to-adult survival rate (Bruce White, personal communication, records at the Pacific Salmon Commission, Vancouver, B.C.). Interestingly, these Fraser pink and chum salmon leave fresh water early in the spring and migrate to sea as very small fry, i.e., underyearling smolts (much like Harrison River sockeye). They likely rear in brackish water in the estuary until they become large enough to osmoregulate in full-strength sea water.

4.0 Description and Evaluation of Alternative Hypotheses

Before reading this section, remember that each hypothesis is stated as if it were true merely for the sake of discussion. The evidence presented for and against each hypothesis then led the Panel to various conclusions about the validity of the hypotheses.

4.1 Predation by marine mammals and/or unreported fishing in the ocean are important contributors to the Fraser sockeye situation.

4.1.1 Description of the hypotheses

This section covers two hypotheses about losses of Fraser River sockeye salmon -- one related to predation by marine mammals and the other about unreported fishing in the ocean. Salmon are eaten by a variety of mammalian predators, including humans. The first hypothesis is that total food consumption by marine mammals was large enough to account for declines in Fraser River sockeye. The second hypothesis is that unreported fishing in the ocean might have removed enough salmon to account for the observed declines in Fraser River sockeye.

The second hypothesis requires further explanation. The total catch of Fraser River sockeye in marine fisheries in British Columbia and Southeast Alaska that are subject to the Pacific Salmon Treaty (PST) is monitored closely and reported in estimates of adult returns; therefore, as noted in Section 3, this source of mortality is not considered here. However, unreported catches of Fraser sockeye could occur on the high seas and in non-PST fisheries in central or western Alaska. These fisheries are monitored to various degrees and have the potential to remove Fraser sockeye without detection. We therefore discuss such fisheries in non-PST areas below, based on the presentation by Phil Mundy (see his paper in Appendix C).

The presentation by John Ford on predation by marine mammals suggested that consumption of sockeye was negligible for most marine mammals species, based on existing knowledge of their diet, abundance, and/or distribution. For example, recent studies have confirmed that killer whales have the potential to affect trends in abundance for Chinook, but not sockeye salmon because killer whales eat primarily Chinook (70% of salmonids killed) and chum (25%) but relatively few sockeye salmon (1%). However, four other predators - the Steller sea lion, Pacific white-sided dolphin, harbour seal, and humpback whale - were considered to have the greatest potential for contributing to declines of Fraser sockeye, but hard data on consumption rates are not yet available to estimate the potential numbers of salmon that they eat. Although salmon are not the dominant item in diets of those four predator species, the life stages of salmon affected varies among predators. Steller sea lions and harbour seals eat primarily adult salmon, whereas humpback whales eat primarily juvenile salmon, and Pacific white-sided dolphins likely eat both.

The Steller sea lion population in B.C. was severely depleted by pelt and bounty hunting in the last century, but it has increased three-fold since a prohibition on hunting in 1970. The present population is estimated at 60,000, and is increasing at 5% per year. Pacific salmonids (all species) account for a significant portion of the diet of Steller sea lions, exceeding 20% of their diet in summer and fall. Steller sea lion consumption of salmon has very likely increased over the last 20 years. However, in the summer, two-thirds of Steller sea lions in B.C. breed on a small number of rookeries between northern Vancouver Island and Haida Gwaii. During the breeding period, their access to Fraser sockeye would be restricted to areas within 50 km of the

rookeries (P. Olesiuk, pers. comm.). According to John Ford, an important update to estimates of predation on sockeye salmon by Steller sea lions is due to be available in November 2010. That research is being conducted by P. Olesiuk of DFO.

The Pacific white-sided dolphin is widely distributed in the North Pacific Ocean, with an estimated 25,000 occurring in B.C. The extent of their predation on Pacific salmon is unknown, but juvenile and adult salmonids, including sockeye, have been identified in their diet. Sightings of Pacific white-sided dolphin have become increasingly numerous since the late 1980s in the nearshore waters of B.C.'s central and north coast. For this reason, further consideration of their potential role in the decline of Fraser sockeye is warranted.

The harbour seal population was also severely depleted by pelt and bounty hunting until 1970, but has subsequently recovered to and stabilized at historic levels (just over 100,000 animals in B.C). The population recovered most quickly (at 11.5% per year) in Georgia Strait until it stabilized at about 40,000 animals in the mid-1990s. Extensive studies in the 1980s indicated that salmonids accounted for a small (<5%) part of their diet, although harbour seal predation on both salmon smolts and adults can be significant in particular (artificial) situations like the Puntledge River. The low occurrence of salmonids in the diet of harbour seals, and their stable abundance over the last decade, suggest that harbour seals are unlikely to have contributed to the recent decline in Fraser sockeye. However, harbour seals are very abundant and their total consumption of fish is large. Their diet has not been monitored or studied in recent years, so it remains possible (but unlikely) that their predation of Fraser sockeye has increased to a significant level.

The humpback whale population in B.C. and Alaska is also recovering following the cessation of whaling in the 1960s. Humpback whales have been observed learning to feed on salmon smolts near hatcheries in Southeast Alaska. Further consideration of their potential role in the decline of Fraser sockeye is warranted given the continuing increase in their abundance, their large size and appetite, and their ability to learn new foraging habits.

4.1.2   Consistency with spatial and temporal trends in productivity of <u>Fraser</u> sockeye

We will first discuss the low 2009 Fraser sockeye returns, and then the long-term situation. Unreported catch in the ocean by humans and predation by other mammals cannot alone explain the very low Fraser sockeye return in 2009. Monitoring that aims to detect vessels that are fishing illegally, as well as the distribution and abundance of marine mammals, appear to have been sufficient to rule out any anomalies of this magnitude. Moreover, predation by natural predators is typically depensatory such that the percentage mortality rate decreases as prey abundance increases. Given the above-average forecast for Fraser sockeye returning in 2009 (based in part on the observed record-high abundance of Chilko smolts), but depending on where most mortality of that cohort occurred, aggregate mortality from predation might be expected to be relatively low for that return year, unless there was an unusual shift in predator abundance, distribution, or diet. Regulated harvesting by humans on Fraser sockeye has not been depensatory in recent years because the exploitation rate has decreased with reduced abundance as fisheries managers responded to growing conservation concerns.

On the other hand, the situation over the long term is different. The abundance of several marine mammal species has increased significantly as their populations continue to recover from severe depletion in the last century. Marine mammal predation of Fraser sockeye salmon has probably also increased over the last few decades, contributing in some part to the decreased productivity (i.e., increased natural mortality) of Fraser sockeye in that period.

Unfortunately, the magnitude of this contribution has not been estimated, but Peter Olesiuk's imminent report on Steller sea lions should contain relevant information. Note that if the contribution were large, the increasing time trend in productivity of Harrison River, in contrast to the decreasing trend in other Fraser stocks, would have to be attributed to some undocumented difference in vulnerability of this "outlier" stock to predation by marine mammals and/or unreported catch in the ocean.

Based on a wide variety of data sources, Phil Mundy's review of the extent of monitoring for illegal fishing showed no evidence to suggest that significant numbers of Fraser sockeye are killed in non-PST fisheries on the high seas or in Alaska (Mundy's paper in Appendix C). The high seas drift net fishery is monitored and is declining. No coded-wire tags in sockeye from the Fraser River have ever been recovered in these fisheries (although some are caught in PST fisheries). For similar reasons, no evidence exists to suggest an increasing trend in the number of sockeye killed in non-PST fisheries. Thus, it seems unlikely that unreported catches in the ocean have contributed to the declining trend in productivity of Fraser sockeye.

4.1.3   Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

Because non-PST fisheries, and most marine mammals, are distributed outside of Georgia Strait, a similar impact might be expected on all populations that migrate to the Gulf of Alaska. Consequently, the discrepancy between (a) the stable or increasing trends over time in abundance and productivity of Columbia and Barkley Sound sockeye populations, and (b) the decreasing trend in most Fraser River lake-type populations, is inconsistent with the hypothesis. In particular, for sockeye smolts migrating seaward in 2007, post-juvenile survival was extremely low in all populations entering the Strait of Georgia (Chilko, Cultus, and Sakinaw), but was above the long-term average for all sockeye populations to the south in the Columbia River (Osoyoos, Skaha, and Redfish Lake populations) and on the west coast of Vancouver Island (Great Central and Sproat lake populations). For the central coast of B.C. (the Long Lake population in Smith Inlet), post-juvenile survival was just below the long-term average, but was significantly higher than any other sea-entry year more recent than 1991. The hypothesis can be saved only by postulating different migratory patterns that alter their vulnerability to the fisheries and predators considered in this hypothesis. Although migratory patterns likely do vary among populations, no evidence exists currently to explain the opposing patterns, and the hypothesis cannot be considered adequate or parsimonious in its present form.

4.1.4 Plausibility and realism of proposed mechanism

Unreported fishing in the ocean and predation by marine mammals is known to occur. Although unreported fishing in the marine environment is not <u>consistently</u> monitored, evidence from enforcement work suggests that such total unreported catches of sockeye are not increasing. Interception of Fraser sockeye in unreported catches in the ocean has not been observed and cannot be common (based on absence of coded-wire tag recoveries from southern populations), but it is plausible that interceptions of Fraser sockeye would increase if global warming shifts migration routes northward. Similarly, predation by marine mammals is likely increasing as marine mammal populations continue to recover from depletion last century.

4.1.5   Conclusions about the likelihood that the hypothesis is correct

Unreported catch in the ocean and predation by marine mammals are both considered **very unlikely** as explanations for the low abundance of Fraser sockeye in 2009.

Unreported catch in the ocean is also considered **unlikely** as an explanation for the long-term decline in productivity of Fraser sockeye.

Marine mammal predation is considered **possible** as an explanation for the long-term decline in productivity of Fraser sockeye.

4.1.6   Proposed Research

(1) Continued monitoring and enforcement of non-PST fisheries is required to maintain confidence that unreported catches in the ocean do not include intercepted Fraser sockeye.
(2) Further research on these non-PST fisheries is considered much less important than other research activities from the present perspective (to gain understanding of the Fraser sockeye situation), but additional stock identification studies are warranted for other reasons (i.e., to investigate the extent of interception of Fraser sockeye and other Canadian salmon populations).
(3) Further research on the diet, distribution and abundance of marine mammals is considered somewhat higher priority.
(4) Research on abundance, distribution and diet is already well under way for Steller sea lions, but has scarcely begun for Pacific white-sided dolphins.
(5) The distribution and abundance of harbour seals and humpback whales are currently being monitored, but further studies of diet and foraging behaviour are warranted.
(6) Tracking studies of Fraser sockeye (e.g., with acoustic tags) are important to determine when and where prey and predator distributions overlap, and more generally, when and where Fraser sockeye become vulnerable to other stressors considered at the workshop.

4.1.7   Management Actions

(1) Unreported catches in the ocean can be managed by monitoring and enforcement.
(2) Mammal predation can sometimes be reduced by the use of deterrent devices, although these devices have often proven ineffective for seals and sea lions.
(3) In the past, marine mammals have been killed to reduce their competition with human fisheries. However, such predator control programs to increase economic benefits to humans cannot be justified on ethical grounds, and would likely be seen as unacceptable by many Canadians. As well, many predator control programs, both terrestrial and aquatic, have failed to achieve long-term objectives because the population dynamics of the target species often necessitates a multi-year predator control program.
(4) Predation poses a greater threat to the recovery of small populations than to large populations because, typically, a smaller *proportion* of prey are killed as prey become more abundant (i.e., the mortality is depensatory). This effect occurs through the "safety in numbers" mechanism, which is a combination of the limited consumption capacity of predators and the reduced probability that any individual prey item will be consumed when there are many prey. The same depensatory mortality effect could arise from fishing on small populations of Fraser River sockeye unless managers choose appropriately strict regulations.

4.2 Marine and freshwater pathogens, including parasites, bacteria and/or viruses, are important contributors to the Fraser sockeye situation.

4.2.1 Description of the hypothesis

Endemic pathogens are a component of all ecosystems. Features of the host, pathogen, and environment can affect the ecology of a given disease. Large effects from disease are generally related to one of two mechanisms: (1) introduction of a new pathogen into a naïve population having little innate resistance to the resulting disease, or (2) changes that significantly alter the ecology of a disease, typically through genetic changes in the pathogen or, especially for fish, changes in the environment that produce stressful conditions that lead to suppression of the immune response in these sensitive animals.

Presentations were given at the meeting to indicate that both of these mechanisms may be important components in the long-term declines of Fraser River sockeye, as well as the failure of the 2009 adult returns. In support of a novel, or at least currently unknown, pathogen was the presentation by Kristi Miller, who used genomic technologies to offer strong support for the presence of a disease condition, possibly of viral origin, that was responsible for losses among both pre-spawning adult sockeye and out-migrating smolts in the Fraser system. However, the nature, source, date of introduction, current host and geographic range of the pathogen are yet to be identified. Three presentations were given to support the second mechanism, which argues that critical changes have occurred in factors that affect the distribution and severity of fish diseases. Alexandra Morton presented evidence in support of the argument that the introduction of salmon farms into the region may amplify various endemic pathogens resulting in greater infection pressure on wild adult or juvenile salmon migrating through the area. Simon Jones presented data that sea lice of either wild or farmed origin are increasing in abundance due to an unknown mechanism, leading to increased disease among wild fish. Kyle Garver reviewed a range of other diseases that are increasing in severity or impact due to environmental factors yet to be determined.

From a disease perspective, the 2009 Fraser sockeye situation can be viewed as an extreme event within a longer-term trend. The disease hypothesis argues that a variety of infectious diseases of both local and perhaps exotic origin are increasing in frequency or severity in response to a suite of environmental and human-induced changes that are altering the historic host-pathogen relationship in favour of greater disease. With the possible exception of novel or currently uncharacterized pathogens, the hypothesis argues that disease is not operating in isolation as a driver of either the longer-term decline in sockeye productivity or the extremely low 2009 returns of Fraser sockeye. Instead, it is important to view this hypothesis as operating synergistically with other factors identified at this workshop.

4.2.2 Consistency with spatial and temporal trends in productivity of Fraser sockeye

No direct comparisons were provided between specific disease indices and productivity trends in Fraser sockeye. However, because fish diseases can operate at a variety of spatial and temporal scales, it is relatively easy to imagine that both spatial and temporal trends in productivity of Fraser sockeye may, at least in part, be the result of a changing suite of diseases that can differ in severity by year, stock, or location. These trends will be driven by both the nature of the agent, the susceptibility of the specific stock or life stage, and the temporal or local environmental conditions that can increase or decrease the impact of disease. For example, the

longer-term trends, especially since the 1990s, show declines in abundance and productivity of most Fraser sockeye stocks. These trends may be a response to longer-term changes in the physical environment (e.g., decadal-scale changes in upwelling that alters temperature and productivity in coastal regions, ocean acidification that affects critical components of the food chain, as well as regional warming that has led to higher water temperatures and greater disease impacts, especially those due to bacteria and parasites). Differences in the exposure of some stocks (e.g., Harrison) to certain of these factors would explain why there appear to be exceptions to the longer-term trend. For example, the migratory route for Harrison juveniles is suspected (based on some limited evidence) to be both later and more southerly through the Strait of Juan de Fuca rather than Johnstone Strait, thereby avoiding exposure to sources of certain pathogens (e.g., transit past fish farms, co-mingling with large numbers of infected adults or juveniles in the Strait of Georgia) or encountering less stressful conditions that enhanced resistance to disease (e.g. better environmental conditions, lower competition, improved nutritional status).

With respect to the 2009 return, the unexpectedly high mortality that occurred among many stocks of Fraser sockeye that entered the ocean as smolts in 2007 represents an unfortunate nexus (or "Perfect Storm") of particularly adverse conditions. These events may have contributed directly to excess mortality (e.g., starvation) or to greater stress that significantly increased the impact of diseases in the specific stocks most affected by these stressors. For example, the post-juvenile productivity of Chilko sockeye that went to sea in 2007 was approximately 25% of the previous 50-year minimum. While direct evidence of starvation and/or disease is lacking, similar short-term declines are known to occur in other fish stocks (e.g., a very large-scale mortality event that occurred in the 1990s among Pacific sardines near Port Hardy on Vancouver Island due to viral hemorrhagic septicaemia when the fish encountered unusually cold water).

4.2.3   Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

As illustrated in the information presented by Arlene Tompkins (Appendix C and summarized in Section 3.2) similar decadal-scale trends can be observed among certain stocks of sockeye and other species of Pacific salmon outside the Fraser System. As well, since the 1980s, Chinook salmon in the Yukon River have been suffering from an increase in a fungal-like disease caused by the protistan parasite, *Ichthyophonus*. Decadal-scale increases in Yukon River water temperatures during the salmon migration (from an average of 15-16°C in the 1970s to as high as 20°C in recent years) appear to be responsible for greater disease severity with a resulting increase in pre-spawning mortality. While the broad declines in many stocks of sockeye and other species of Pacific salmon are suggestive of certain large-scale drivers, some stocks and species show a differing trend indicative of local effects.

In this regard, it is well known that disease outbreaks in fish can vary greatly in spatial or temporal scales in response to local environmental conditions that affect the distribution or abundance of the pathogen or host. In addition, significant differences in innate susceptibility to disease have also been reported for various species and stocks of Pacific salmon. For example, stocks of coastal steelhead trout in Oregon were shown to be very much more susceptible to a parasite, *Ceratomyxa shasta*, than stocks from the interior where the parasite was endemic and where local stocks had evolved to become highly resistant.

4.2.4   Plausibility and realism of proposed mechanism

Globally, long-term changes are occurring in biological factors that can affect severity of disease over time (novel strains of pathogens potentially introduced by increasing numbers of fish farms or hatcheries, changes or reductions in trophic food webs that reduce resistance of fish to infections, and changes in species composition and migration routes that affect the transmission of pathogens). In addition, other human-induced changes since the 1990s may be operating to increase the frequency or intensity of disease in a wide range of Pacific salmon including Fraser sockeye (e.g., development of large-scale fish farming, changes in levels and types of contaminants released from municipal and industrial sources, and intensive high-seas fisheries that target important forage species or alter marine food webs).

The Panel has a high degree of confidence that this hypothesis is a plausible mechanism contributing to both the long-term declines as well as the 2009 outcome. However, we were not confident that infectious disease, either in isolation or in specific cases, was likely to be the sole mechanism operating to cause the longer-term declines or the 2009 loss. There was broad support for the concept that synergistic effects between infectious diseases and other physical and biological hypotheses were a more plausible compound mechanism to account for both the longer-term declines and the 2009 Fraser situation.

4.2.5   Conclusions about the likelihood that the hypothesis is correct

Most Panelists, and, almost without exception, respondents to the workshop surveys, rated this hypothesis either **very likely** or **likely** to be an important factor in the declines of Fraser sockeye. While some Panelists and speakers indicated there is a current lack of evidence for a specific infectious agent or disease mechanism (e.g. introduction of a novel pathogen, amplification of an existing pathogen by fish farms) to be a major component of causes of decline, there was strong support for the concept that diseases caused by parasites, bacteria, or viruses were likely increasing due to human-caused changes and were an important component in both the longer-term and 2009 declines.

4.2.6   Proposed Research

The research needs listed below will provide information that can be used to test the disease hypothesis. Like most semelparous salmonids, all adult Fraser River sockeye eventually die from a variety of diseases on the spawning grounds. The impact of these diseases on productivity is accounted for in estimates of pre-spawn mortality used to calculate the number of effective female spawners. Thus, in order to improve our understanding of disease effects on productivity, we emphasize that the recommended research listed below should be focused on juveniles or sub-adults prior to their reaching their natal spawning areas. Research topics are listed in an approximate order that would allow results to build upon earlier work.

(1) Continue long-term surveillance in the marine environment for pathogens and parasites affecting sockeye and other species within the Fraser system. Include stock-specific surveys.

(2) Conduct research on factors affecting the host-pathogen relationship for pathogens of Fraser River sockeye, including gene expression studies, to determine differences in disease prevalence or innate resistance among stocks and features of the disease process including infectious dose, shedding rate, and formation of a carrier state for important pathogens. This will assist in the design of models for disease ecology.

(3) Develop tools to identify and characterize novel pathogens (especially pathogens that may be responsible for an "unhealthy" genomic signature). Include studies of fish from wild and farmed sources.

(4) Use seawater challenge tests to investigate factors affecting levels of delayed mortality from infections acquired in freshwater or seawater habitats.

(5) Examine synergistic effects of environmental factors on susceptibility or mortality to diseases (temperature, nutritional state, contaminants, density, inter-specific interactions, immune status, etc.).

(6) We need to model spatial and temporal distributions of pathogens, including point sources from salmon farms (similar to sea lice models).

4.2.7 Management Actions

(1) Scientists need a database for pathogens of wild fish at all life stages that can integrate with other management and environmental data to help build models of the disease component of natural mortality. Developing a pathogens database for sockeye could be an overarching goal to knit the various research activities together and would enable scientists to provide better advice to managers.

(2) Scientists, managers, and the public need better access to information about health of salmon in fish farms.

(3) Efforts should be increased to reduce/eliminate sources of pathogens from fish farms and processing plants.

(4) Adaptive management of net-pen salmon farms could be valuable for learning about the possible influence of fish farms on sockeye.

4.3 Oceanographic conditions (physical and biological) inside and/or outside Georgia Strait are important contributors to the Fraser sockeye situation.

4.3.1 Description of the hypotheses

Variation in juvenile survival rates during early marine life stages is an important component of the total life-cycle productivity of salmon populations. Ocean conditions can influence sockeye productivity through impacts on food availability and quality, which affect sockeye growth and survival by changing susceptibility to predation and other mortality agents. Winds, currents, upwelling and other oceanographic processes affect food availability by altering the timing and distribution of food production relative to timing of juvenile salmon migration (e.g., match/mismatch hypothesis). These mechanisms are often referenced in descriptions of the "critical period, critical size" hypotheses for marine fish. Spatial distribution of predators is also affected by physical oceanographic conditions. Because sockeye salmon survival rates likely depend upon the physiological condition of the juvenile salmon, there are links among the effects of ocean conditions and other factors (e.g., pathogens, parasites, contaminants, etc.) that affect both the marine and earlier phases of the sockeye life cycle. Thus, hypotheses involving ocean conditions cannot be viewed as isolated from other hypothesized mechanisms.

Subsets of the ocean conditions hypothesis were addressed in four presentations covering overlapping regions of the migratory routes used by juvenile sockeye during their early marine life.

The four sub-hypotheses evaluated in the ocean conditions thematic session were:

Sub-hypothesis 1: Physical oceanographic conditions inside and/or outside Georgia Strait are important contributors to the Fraser sockeye situation (Rick Thomson)

Sub-hypothesis 2: Outside of Georgia Strait, oceanographic conditions, food, and/or predators (including squid) are important contributors to the Fraser sockeye situation (Marc Trudel).

Sub-hypothesis 3: Inside Georgia Strait, oceanographic conditions, food, and/or predators are important contributors to the Fraser sockeye situation (Dick Beamish).

Sub-hypothesis 4: Physical and growth conditions affect marine survival of Bristol Bay sockeye smolts in Alaska (Ed Farley).

Evaluations of each sub-hypothesis were based on a variety of data sources. Researchers examined physical measurements such as winds, sea surface temperature, and salinity. Georgia Strait trawl surveys collected data on juvenile salmon abundance, diet, body size, and stock composition. Trawl surveys conducted off of the west coast of Vancouver Island, to the north in Queen Charlotte Sound, and in more seaward areas provided information on the stock composition, body size and seasonal migration patterns. Other biological data examined included chlorophyll concentration levels, zooplankton biomass estimates, and juvenile herring abundance estimates. The reproductive success of planktivorous birds that breed on Triangle Island in Queen Charlotte Sound was also considered. Additionally, information was presented about interannual variation of the abundance and distribution of Humboldt squid and sardines in relation to salmon survival.

Last, there were several presentations outside of the ocean-conditions thematic session that covered ocean-related factors. These included evaluation of marine mammal predation (Section 4.1), competitive interactions with pink salmon (Section 4.9), impacts of pathogens (in freshwater, estuary, and marine environments; Section 4.2), and harmful algal blooms in the Salish Sea (Georgia Strait/Puget Sound/Strait of Juan de Fuca; Section 4.4). As noted above, ocean conditions interact with these other factors.

4.3.2   Consistency with spatial and temporal trends in productivity of <u>Fraser</u> sockeye

Few direct comparisons between ocean indices and Fraser sockeye productivity were presented at the workshop, and there are apparent inconsistencies in the fisheries oceanographic evidence with respect to the relative importance of factors *inside* versus *outside* Georgia Strait. Below we summarize some patterns that emerged, starting with the long-term declining trend in productivity since the early 1990s, and then specifically for the 2009 return year.

Long-term trend

The following observations support the hypothesis that oceanographic factors *outside* of Georgia Strait are important contributors to the long-term declines in productivity observed in Fraser River sockeye since the late 1980s and early 1990s.

- The downward trend in total life-cycle productivity and post-juvenile productivity found in most Fraser sockeye populations suggests that the mechanisms causing productivity changes are occurring in habitats shared by those stocks. The similar downward trends in productivity since the early 2000s for Central Coast B.C. sockeye populations, and

poor productivity for Skeena River and West Coast Vancouver Island sockeye from brood years ~2000-2004, also support the potential for important causal factors influencing Fraser sockeye outside Georgia Strait during these years. However, differences between Fraser and non-Fraser stocks in the years when declines began and the short-period variations in productivity between the early 1990s and present can also be seen as evidence against changes outside the Georgia Strait as a common cause for declines in productivity of Fraser as well as other B.C. sockeye stocks.

- There is a very strong correlation (r^2=0.87) between April chlorophyll concentrations (which reflect phytoplankton densities) in Queen Charlotte Sound and Chilko sockeye marine survival (1998-2007).

- There is some correspondence between an observed period of intensified winter/spring downwelling along the B.C. coast and the time period of declining productivity of most Fraser River sockeye populations.

- Marine survival of acoustically tagged Cultus Lake sockeye salmon smolts estimated from the Fraser River mouth to Queen Charlotte Sound was not unusually low in either 2005 or 2007 (years of extremely low Fraser sockeye productivity) compared to 2004 and 2006 (years of much higher productivity). However, these tagged smolts were reared in a hatchery to much larger size than typical Fraser sockeye smolts and may therefore not reflect the survival rates of wild fish.

- Predation by Humboldt squid (distributed primarily outside Georgia Strait) on either adults or juveniles was rejected as a likely cause of longer term changes in productivity because their appearance on the coast of Canada in significant abundance levels is a relatively recent phenomenon (2004) compared to when productivity of Fraser sockeye began its downward trend.

- Similarly, competition with Pacific sardine, which have increased in abundance since the mid-1990s, was rejected as a cause of the long term trend because several time series of marine survival estimates for Chinook and coho were positively correlated with estimated sardine biomass.

In contrast to the points above supporting the hypothesis of the importance of oceanographic conditions **outside** the Strait of Georgia, the following information supports the hypothesis that oceanographic conditions **inside** of Strait of Georgia are important contributors to the long-term declines in productivity observed in Fraser River sockeye since the late 1980s and early 1990s.

- There is a positive correlation between juvenile sockeye catch per unit effort (CPUE) in Strait of Georgia July surveys and total Fraser River sockeye abundance 2 years later (r^2=0.35) for ocean-entry years 1998-2007.

- Observed long-term productivity trends for Fraser River do not covary with those from sockeye salmon populations from Central Coast B.C. or Bristol Bay, and sockeye run-sizes in the Columbia Basin have increased dramatically in the past few years while productivity has declined sharply in the Fraser Basin. These observations suggest that the Fraser sockeye situation is not shared beyond its unique early-ocean environment.

- A close correspondence was found between abundance of underyearling herring and smolt-to-adult survival rate of Chilko Lake sockeye, which supports the interpretation that year-class survival is mainly determined within the Strait of Georgia. However, this analysis remains preliminary because pre-1997 data for this herring-sockeye comparison do not show any association and data are missing for some years (see Section 4.4 and Figure 3 of Rensel et al. in Appendix C).

- Mechanisms supporting some of the statistical relationships (e.g., between chlorophyll in Queen Charlotte Sound and Chilko marine survival), though plausible, are not well understood and in some years are contradicted by more direct measurements of proposed underlying causal factors (e.g., zooplankton in 2007, see below). Unfortunately, there is no long-term data set for zooplankton in the Strait of Georgia.

- Harrison River sockeye have shown *increasing* productivity during the period when the productivity of most Fraser River sockeye has *declined*. Strait of Georgia trawl surveys suggest that, in contrast to juveniles of other Fraser sockeye, Harrison sockeye juveniles may reside in the Strait longer (dominant proportion in samples from September surveys) and may tend to migrate mostly through the Strait of Juan de Fuca. A positive correlation was found between the sockeye CPUE in September surveys and Harrison total abundance 2 years later (r^2=0.32).

2009 sockeye return

- Several sockeye populations for which juveniles do not enter the Strait of Georgia had post-juvenile survival rates for sea-entry year 2007 that were above the stock-specific long-term average (Barkley Sound on the west coast of Vancouver Island and Columbia River populations), and just below the long-term average in Smith Inlet and Stikine River populations.

- Many, but not all factors point to anomalous unfavourable ocean conditions ***inside*** Georgia Strait in 2007, when the sockeye returns of 2009 entered the ocean, whereas more seaward indicators (***outside*** Georgia Strait) are less consistent. Juvenile coho and Chinook salmon in Georgia Strait had the smallest body size and highest percentage of empty stomachs since Dick Beamish's sampling started in 1998, but juvenile sockeye there in 2007 were not especially small, nor was the percentage of empty sockeye stomachs unusual, unlike the Chinook and coho (Dick Beamish, personal communication). Queen Charlotte Sound chlorophyll concentrations in April 2007 were anomalously low, but Queen Charlotte Sound zooplankton abundances were not lower than the average (except for 1 euphausiid species), and the breeding success of planktivorous birds was also not anomalous. Thus, direct measures of food availability for juvenile sockeye do not support a negative impact on the food supply expected from low chlorophyll concentrations in Queen Charlotte Sound.

- Juvenile Fraser sockeye caught in juvenile surveys in Queen Charlotte Sound and Hecate Strait during June/July had the smallest average length on record in 2007 (1999-2009), but this poor growth does not appear to be consistent with either the apparently average feeding conditions in 2007 in Queen Charlotte Sound or the large body size of 2007 sea-entry Chilko smolts, and thus could reflect earlier poor feeding and growth in Georgia Strait.

- Productivity of 2009 return to Shuswap Lake populations (Early and Late Shuswap stocks) was higher than that of most other Fraser sockeye populations (except Harrison). However, no direct evidence from either inside or outside Georgia Strait was provided to explain why Shuswap sockeye would have had higher productivity.

4.3.3   Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

The mostly coinciding downward trends in productivity of Central Coast B.C. sockeye populations, and poor productivity for Skeena River and West Coast Vancouver Island sockeye from brood years ~2000-2004, support the potential for causal factors outside Georgia Strait during these years. However, differences between Fraser and non-Fraser stocks in the years

when productivity declines began and in the pattern of shorter-term productivity variations can also be seen as evidence against changes <u>outside</u> Georgia Strait as a common cause for declines in B.C. sockeye productivity. Observed productivity trends for Fraser River and Central Coast B.C. sockeye salmon populations do not covary with those from Bristol Bay, and sockeye run-sizes in the Columbia Basin have increased dramatically in the past few years while they declined sharply in the Fraser Basin. These observations all indicate that the Fraser sockeye situation is not shared with sockeye populations beyond the B.C. coast.

The pattern of productivity of other species in the early 1990s (Chinook productivity, coho marine survival, and age-0 herring recruitment) that share Georgia Strait entry with Fraser sockeye is somewhat, but not completely, consistent with the Fraser sockeye pattern (exceptions include increasing productivity for some early timed and Shuswap Chinook stocks). It is not clear from available data, but plausible, that the inconsistent patterns of some other stocks could be explained by differences in temporal and/or spatial distribution within Georgia Strait, but data are not available to determine if these differences exist. Furthermore, whereas the Georgia Strait mechanisms are not clearly understood, there is compelling evidence from many studies that early marine conditions (growth) for salmon play an important role in determining brood-year strength. Thus, the inconsistency of productivity patterns between Fraser sockeye and Chinook and coho stocks that also use Georgia Strait does not rule out the importance of Georgia Strait conditions as a cause of the Fraser sockeye situation.

4.3.4   Plausibility and realism of proposed mechanism

There is a growing body of evidence supporting a critical-size critical-period mechanism linking variability in ocean conditions to variations in marine survival and brood year strength for salmon (Farley et al. 2007a). Relevant studies supporting these linkages have been reported for SE Alaska pink salmon (Moss et al. 2005), Columbia River spring/summer Chinook and steelhead (Scheuerell et al. 2009), Bristol Bay sockeye salmon (Farley et al. 2007b), British Columbia and Alaskan sockeye (Peterman et al. 1998, Mueter et al. 2002), Puget Sound Chinook salmon (Duffy, 2009), Puget Sound and Washington coast coho salmon (Beetz, 2009), Oregon Production Area coho (Pearcy 1992; and many others), and Georgia Strait coho (Beamish et al 2004). DFO's surveys in the Salish Sea (Puget Sound and Georgia Strait), west coast of Vancouver Island, and Queen Charlotte Sound have all documented large variations in the biophysical state of marine habitat and the abundance, growth, diet, and energetics of Fraser River (and other stocks of) sockeye salmon.

Furthermore, total productivity (recruits per effective female spawner) for most Fraser River sockeye is much more highly correlated with post-juvenile productivity (recruits/per juvenile) than with juvenile productivity (juvenile per female) for the eight stock aggregates for which matching data are available. This suggests that survival during the post-juvenile life phase is the most important determinant of total productivity. However, as noted in Section 3, such mortality that occurs during ocean life could be delayed mortality resulting from some condition or process encountered by juveniles in fresh water.

These findings should not be surprising because: (1) ocean conditions vary across a broad spectrum of spatial and temporal scales; (2) marine food-webs (e.g., nutrients, phytoplankton and zooplankton) vary in response to changing ocean conditions; and (3) variation in food supply causes variations in salmon growth and survival.

4.3.5   Conclusions about the likelihood that the hypothesis is correct

There is a wealth of evidence indicating that ocean conditions are important to salmon productivity. However, documenting specific mechanisms directly linking ocean conditions to the declines in Fraser sockeye productivity that have been observed since the 1990s is difficult due to the lack of data. These data gaps include: (1) few times series of post-juvenile productivity for Fraser River salmon; (2) minimal knowledge about marine migration patterns; (3) lack of a long-term (multi-year to multi-decade) time series for key aspects of the phytoplankton and zooplankton abundance and species composition in marine waters; and (4) minimal knowledge about when, where, or how juvenile salmon mortality occurs in the marine environment. Such information is necessary in order to attribute portions of the total mortality to different potential causal agents (e.g., pathogens, food-limitation, harmful algal blooms, or marine predators).

Despite these data deficiencies, we concluded that ocean conditions *inside* the Strait of Georgia were **likely** a major causal factor in the long-term declines in Fraser sockeye productivity and **very likely** to be a major factor in the extremely low productivity associated with the 2009 return.

In contrast, ocean conditions *outside* the Strait of Georgia were rated as less likely (i.e., just **possible**), for explaining either the long-term decrease in productivity or the poor 2009 return.

4.3.6   Proposed Research

(1) Reducing the knowledge gaps in the marine ecology of Fraser river sockeye identified above requires a sustained commitment to a multidisciplinary ocean monitoring program that covers periods and regions that are most important to Fraser River sockeye marine survival.

(2) The Bering Sea sampling program that was reviewed by a speaker, Ed Farley, under sub-hypothesis 4 demonstrates what is possible with integrated ecosystem observations sustained over enough years to capture a range of conditions important for salmon productivity. That ongoing 8-year program in Alaska provides clear evidence of the value of documenting physical and biological shifts in the food web that are important for sockeye salmon growth and survival. Similar, fully integrated ecosystem research initiatives in the Strait of Georgia could provide the same kind of information, if they can be sustained for multiple years into the future. Therefore, a high priority option would be to continue a program like DFO's Ecosystem Research Initiative **but with modifications to focus on issues important to Fraser sockeye marine survival and the factors identified in this report.**

(3) Whatever research program is conducted to learn more about what is causing the decrease in productivity of Fraser sockeye salmon, it should be integrated. That is, scientists from the different disciplines reflected by the hypotheses in this report should coordinate their field sampling and databases to focus on information from the same times and places. Key elements of such a multidisciplinary program that would shed important light on the role of ocean conditions on Fraser River sockeye productivity include:

- Integrated ecosystem monitoring of:
  - o phytoplankton, zooplankton, small fish and harmful algae
  - o biological/physiological condition of sockeye other salmon, and fish (including genomic and/or other disease assessments)
  - o other relevant biophysical variables (e.g., salinity, sea surface temperatures, mixed layer depths, etc.)

- o the relative abundance of juvenile sockeye and other salmon species along key migration routes including the Fraser River mouth, Johnstone and Juan de Fuca Straits
- The above monitoring program should be designed to support:
  - o development and testing of specific hypotheses linking physical oceanography and climate to biological productivity in the Salish Sea (Georgia Strait/Puget Sound/Juan de Fuca Strait)
  - o development of time series of Georgia Strait ecosystem indicators similar to those used by the National Oceanic and Atmospheric Administration (NOAA) for tracking ocean conditions that are important for many coastal Washington and Oregon salmon stocks

(4) Juvenile sockeye encounter at least three distinct marine ecosystems in their first summer at sea: first the Georgia Strait, then Queen Charlotte Sound, and then the Gulf of Alaska. It may be necessary to monitor all three in order to better understand the influence of ocean conditions on Fraser sockeye productivity trends and variations. Such a program could be very expensive. Therefore, we recommend exploring acoustic tagging of sockeye and other salmon species with the new smaller tags to identify survival bottlenecks, migration rates and routes. Such information could help focus monitoring effort on areas and times that are most important to salmon survival.

(5) While the focus of this workshop was Fraser River sockeye, we re-emphasize the benefits and efficiencies associated with collecting data on other salmon species in this proposed monitoring effort. For example, because salmon integrate the effects of ocean conditions and other factors across their life history, improved and expanded monitoring of the marine survival of other salmon species, such as coho populations that enter Georgia Strait at a similar size as Fraser sockeye, but mature 1 year earlier, may provide opportunities for advanced warning of significant recruitment failures (see McKinnell 2007). This type of monitoring is particularly important for Fraser sockeye, because decreases in the abundance of jack sockeye have limited the usefulness of sibling relationships that have been used previously to improve pre-season forecasts in other salmon populations.

4.3.7 Management Actions

(1) There should be little doubt that ocean conditions will continue to vary across a continuum of time scales, including within-year variations like the failed springtime upwelling of 2005, year-to-year variations associated with tropical ENSO variations, and longer term oscillations associated with large-scale climate processes like the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO). Those and other kinds of variability will continue to unfold in the presence of even longer-term anthropogenic climate change and ocean acidification that are expected to become dominant factors in changing ocean conditions later in the 21st century. With essentially no capacity for controlling ocean conditions, sustained real-time monitoring offers an avenue for greatly reducing the risks associated with being surprised by significant changes in the marine portion of the Fraser sockeye life cycle.

(2) Increasing trends in productivity of Harrison sockeye during this period of declining productivity in most other Fraser sockeye populations provides an example of the potential value of maintaining biodiversity. Thus, in the absence of the ability to control environmental conditions, management actions that preserve and/or enhance the capacity for adaptation to climate change should improve the resilience of Fraser sockeye populations to future trends and variations in ocean conditions (Mantua and Francis 2004).

(3) Other possible actions might include adaptive management measures aimed at large-scale experimentation within the Georgia Strait:

- One experiment might involve altering the production and release times for coho hatchery smolts; if there is evidence for significant competitive interactions between Fraser sockeye and such hatchery produced salmon, changes in hatchery salmon production may be warranted.

4.4 Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation.

4.4.1 Description of the hypothesis

Harmful algal blooms (HAB) are known to kill fish, and the most significant species in coastal waters of the Pacific Northwest, i.e., B.C. and Washington State, is the golden brown alga *Heterosigma akashiwo*. Observations of dead salmon in shallow inlets of South Puget Sound or along beaches of North Puget Sound have occurred with every major *Heterosigma* bloom since 1989. *Heterosigma* has been termed both the most versatile and harmful algal bloom species due to its lethality to organisms ranging from bacteria to fish and its ability to rapidly migrate vertically. Mortality of fishes from *Heterosigma* exposure is thought to involve gill damage and respiratory failure. While mortalities of sockeye salmon have not been directly attributed to *Heterosigma*, there are no reasons to preclude them from this possibility.

B.C. researchers (reported in 1993) noted that *Heterosigma* cells have regularly appeared in late spring in English Bay, Vancouver, B.C. since 1967 when phytoplankton surveys were first initiated. A few large and persistent blooms were documented in Departure Bay and the Strait of Georgia in the 1990s and their effects on aquaculture then became a research priority at the Pacific Biological Station. Routine recording of cell density throughout B.C. waters began in 1999 with the initiation of the Harmful Algae Monitoring Program. Fraser River sockeye salmon abundance began to decline in the late 1980s, roughly coinciding with commencement of substantial *Heterosigma* blooms in the Strait of Georgia. Note, however, that the monitoring program for such blooms is limited in spatial coverage and only considers surface waters.

4.4.2 Consistency with spatial and temporal trends in productivity of Fraser sockeye

The alga *Heterosigma* has bloomed for several decades in British Columbia, but since 1989 large-scale blooms have caused severe mortality of farmed fish and some observed wild fish mortality in the region. Jack Rensel and his co-authors compared the percent smolt-to-adult survival rate (which Rensel refers to as marine survival) of Chilko Lake sockeye to the occurrence of observed blooms of *Heterosigma* within the Strait of Georgia (see Figure 3 of Rensel et al. in Appendix C). Since 1989, Chilko sockeye salmon survival averaged 2.7% in years when their seawater entry and migration coincided with major blooms compared to 10.9% in years when no bloom or only minor-blooms occurred (see Rensel et al. in Appendix C for data and methods). While the data series for comparisons is relatively short and data are missing for some years, the difference in survival rates for Chilko Lake sockeye does indicate reason for concern. Chilko Lake sockeye represents only one of many sockeye populations in the Fraser system, but it is the only population with a continuous estimate of adult returns per smolt.

The coincidence of relatively poor Chilko post-juvenile productivity during years with significant blooms certainly suggests that *Heterosigma* is at least partially responsible for: (1) acute or chronic (i.e., a stressor) toxicity of sockeye salmon; (2) food web and prey impoverishment; or (3) some combination of these factors.

Since 2002, *Heterosigma* blooms that previously began in late June or later have occurred earlier, as early as late May or early June, overlapping more with the migration timing distribution of juvenile sockeye salmon entering the southern Strait of Georgia. To evaluate possible effects of varying Fraser River discharge volume and timing on *Heterosigma* blooms during the juvenile sockeye salmon migration period, Fraser River discharge from years of known major blooms was compared with years with no bloom or minor blooms in southern Strait of Georgia for the 1989 through 2009 period. A plot of Fraser River discharge against juvenile migration timing (Figure 4 from Rensel et al. in Appendix C) indicates that average daily discharge (flow volume) has been substantially greater in the May-June period of major *Heterosigma* bloom years when compared to flows in other years. These data suggest a linkage between *Heterosigma* blooms in May-June and larger/earlier Fraser River discharge.

To support the hypothesis of the potentially harmful effect of *Heterosigma* within the Strait of Georgia, the authors presented a comparison of Chilko Lake sockeye survival rate with an index of young-of-the-year Herring (Figure 3 of Rensel et al. in Appendix C). The herring data were provided by Herring Assessment staff within DFO who annually conduct an assessment of underyearling Herring catch in September within the Strait (Schweigert et al. 2009). Close correspondence of the survival patterns for herring and Chilko Lake sockeye supports the interpretation that year-class survival is mainly determined within the Strait of Georgia. As herring and sockeye grow and migrate, they then no longer share a common environment. However, this analysis remains preliminary for two reasons. First, pre-1997 data for this herring-sockeye comparison do not show any association and data are missing for some years. Second, other mechanisms shared in the Strait of Georgia besides harmful algal blooms could be driving the herring-sockeye association.

Questions were raised about the inconsistency between the prediction of this hypothesis about harmful algal blooms and the increasing returns of Harrison River sockeye salmon. Given the large amount of harmful algae in 2008 (Table 1 of Rensel et al. in Appendix C), this hypothesis also does not explain the apparent improved survival of juveniles within the Strait in the spring 2008. Since we know that migration timing of juveniles differs between stocks, the most parsimonious explanation is simply that the juveniles were not exposed to HABs. Algae blooms will differ over area, season, and years so there are likely to be differences among stocks in the impact of such blooms. The observations of improved survival of juveniles in 2008 likely reflect variation in migration timing, routes, and exposure to HABs but this topic was not discussed during the workshop.

4.4.3   Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

The authors did not extend this analysis to other non-Fraser sockeye stocks. However, their evidence for determination of survival within the Strait of Georgia (comparisons among harmful algal blooms, Chilko post-juvenile productivity, and variation in young-of-year herring in the Strait of Georgia) would be consistent with observed survival patterns in other major sockeye systems from different regions of the Pacific coast that do <u>not</u> reflect the Fraser sockeye patterns (e.g., Barkley Sound, Columbia River, central and northern B.C.).

HABs may, however, still contribute to differences among stocks by acting differently in local areas or times, yet broad ocean conditions could produce the similarities between years. HABs did occur in the Broughton Archipelago and Queen Charlotte Sound in 2007, as well as in Georgia Strait. Such explanations, however, do not explain trends in the survival rate of other salmon species, particularly the recent increase in productivity of Fraser River pink salmon.

4.4.4   Plausibility and realism of proposed mechanism

The correspondence of blooms (intensities, seasonality, locations), known toxicity of *Heterosigma* to other salmonids, and correlations with Chilko Lake sockeye survival suggest this hypothesis is certainly plausible. A weakness in the discussion to date would be that responses of sockeye to such blooms are unknown. However, given the ability of the *Heterosigma* to vertically migrate, it is very possible that this alga could be distributed throughout the early marine habitats utilized by sockeye salmon in the Strait of Georgia.

There was discussion on the consistency of impact on multiple Fraser populations within one year. *Heterosigma* blooms do vary through time and space within a year and could certainly have different impacts on sockeye populations depending on their migration timing and distribution within the Strait.

4.4.5   Conclusions about the likelihood that the hypothesis is correct

Support for the hypothesis differed for explaining the 2009 return compared to explaining the longer-term decline in productivity of Fraser sockeye. As a contributing factor to the 2009 return, the hypothesis is a **possible** factor. This conclusion is based on the coherence of time and intensity of the blooms in spring/early summer 2007 in the Strait of Georgia and Queen Charlotte Sound, and the longer-term association between harmful algal blooms and survival rate of Chilko Lake sockeye.

As a contributing factor to the longer-term decline in Fraser sockeye productivity, the hypothesis was assessed as an **unlikely** contributor. The primary reason for this rating was the apparent lack of consistency of the declining trend in productivity compared to the uncertainty in spatial and temporal variability in intensity of *Heterosigma* blooms and variation between years through the 1990s. However, if information on Pacific Herring year-class strength is included, this hypothesis may merit a rating as a **possible** contributing factor. Regardless, the associations demonstrated by these authors clearly merit increased monitoring and research in the future.

4.4.6   Proposed Research

(1) Compared to the other hypotheses presented, research on this hypothesis was considered to be of average to slightly above-average importance. Given the notable increase in the frequency of blooms in recent years, and threats to future years based on certain climate-change scenarios, there was strong agreement to continuously monitor the occurrence/intensity of these blooms in the Strait of Georgia and Puget Sound. This monitoring should be associated with environmental monitoring to determine triggers of this harmful algal bloom. For example, monitoring for harmful algal blooms could be a required component of any oceanographic surveys within the Strait and its approach waters. Monitoring via remote sensing methods could be important in assessing consistency of point sources of the blooms, rapidity of growth and distribution, and duration.

(2) Studies of mortality-inducing processes from these algae were not strongly supported but there was significant interest in the potential to mitigate the occurrence of these blooms. Research on effects on sockeye salmon, if conducted, should be laboratory-based (e.g., biological response as a function of dose and time exposure) because observational studies within the marine environment would seem impractical unless the sockeye were confined (introducing added uncertainty to any study due to its relevance to the field situation).

(3) There are currently three separate research teams in Washington State focused on modes of toxicity, effects on zooplankton, and genetic differentiation of *Heterosigma* ecotypes. Means to further investigate, mitigate and reduce blooms of *Heterosigma,* and a literature review of modes of toxicity, vertical distribution of the fish and the alga and related topics are addressed by Rensel et al. (Appendix C).

4.4.7   Management Actions

(1) Jack Rensel noted that mitigation actions are possible to control the intensity and duration of blooms using clays in solution to kill algal cells in source areas, but discussion was limited on this topic. Mitigation of blooms has been used in Korea and along the eastern U.S. coasts for several years.

(2) Other possible actions might include adaptive management measures aimed at large-scale experimentation within the Georgia Strait:
- If harmful blooms of *Heterosigma* spp. prove to be negatively affecting Fraser sockeye, this would warrant active monitoring and mitigation measures to limit these harmful algal blooms during the period of juvenile sockeye migration through Georgia Strait.

4.5   Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation.

4.5.1   Description of the hypothesis

Robie Macdonald presented information on how contaminants are known to have several different effects on fish, including lethal ones. Toxic chemicals can induce a wide range of sub-lethal effects as well (Table 1 of Macdonald et al. in Appendix C). Both lethal and sub-lethal effects can be enhanced when fish are challenged by other environmental factors such as high temperatures or nutritional stress.

Broadly speaking, two classes of contaminants are: (1) *persistent, bioaccumulative* and *toxic (PBT)*; and (2) toxins that tend to be soluble and less persistent than PBTs. This distinction is important in the context of sockeye salmon because these two categories behave differently in the environment and exert their effects in different ways.

Persistent, bioaccumulative and toxic (PBT) contaminants

These contaminants include many well-known chemicals such as PCBs, DDT, and dioxins. These are subject to global transport and now pervade soil, vegetation, and water. They are also highly persistent and continue to cycle in the environment decades after their peak use (1960s-1970s), despite regulations at the national and international level. PBTs are fat-soluble, meaning that they seek to escape from water and attach to lipids or organic materials. In this way, PBTs readily accumulate in aquatic food chains, and can reach relatively high

concentrations in fishes. Fish such as sockeye salmon do not easily metabolize these contaminants, and they *carry the risk* from these contaminants with them through their entire life cycle (Figure 1 of Macdonald et al. in Appendix C). As sockeye migrate home from the sea, they use their fat reserves, so these PBT chemicals are transferred to their reproductive tissues.

Non-persistent contaminants

The second class of contaminants tends not to be carried by the fish because they are either less persistent, less fat-soluble, or do not move readily through the environment. These contaminants may be fairly localized with usage or discharge and can affect fish during sensitive developmental stages. As sockeye transit from lake to river to estuarine to marine environments, they run the gauntlet associated with multiple human-associated releases of such contaminants (Figure 2 of Macdonald et al. in Appendix C). Fish can therefore be affected by these sorts of contaminants during hatching, rearing or migration phases of their life.

Emerging contaminant concerns in British Columbia

During the past decade, there have been increasing concentrations of a variety of chemicals in British Columbia waters, including current use pesticides, flame retardants, pharmaceuticals and personal care products. This increase has especially occurred in the Lower Fraser River and Strait of Georgia. These chemicals, together with legacy PBTs and other system changes (climate, habitat conditions, etc.), provide ample room for contributing to changes in sockeye productivity. It is worth noting that information is lacking on the quantities and types of pesticides used in British Columbia agricultural and forestry sectors, as well as their carrier compounds, making it difficult to characterize risks to salmon.

Summary on Contaminants

While no single contaminant can be identified as a probable cause for the recent declines in Fraser River sockeye salmon, the many contaminants entering sockeye habitats underscore the real-world implications of risks associated with current human practices. Persistent, bioaccumulative and toxic (PBT) contaminants could predispose salmon to mortality through a range of sublethal effects on eggs, fry, smolts and/or adults. The non-persistent contaminants, *including the 286 pesticides registered for use in Canada*, are likely an increasing threat in our environment. The monitoring of non-persistent contaminants can be difficult and is poor, but these toxins may render sockeye unfit for survival and do not have a chemical fingerprint. Aquatic birds and mammals often leave a visible and well-documented legacy of contaminant effects; unfortunately, fish frequently do not leave observable mortalities for evaluation.

The number of chemicals and chemical classes has increased over the past decade, and merits further scrutiny in the context of sockeye salmon populations. Leading among these are fire retardants, pharmaceuticals, natural hormones, currently used pesticides, and surfactants (e.g. PFOS) associated primarily with municipal outfalls.

Reduced reporting requirements for pesticide use in B.C. constrains any ability to study/assess the possible impact of such contaminants in affecting Fraser sockeye productivity or explain the 2009 sockeye return. Chemicals are likely to fall into the category of *stressors that we can control*.

4.5.2 Consistency with spatial and temporal trends in productivity of <u>Fraser</u> sockeye

No contaminants were identified as a probable cause for the recent declines in Fraser River sockeye salmon. Limited site-specific data on contaminants and the often complex nature of environmental toxicological processes make any conclusion about the role of contaminants highly uncertain, but some effect cannot be ruled out. While it is difficult to generalize their effects, these chemicals generally alter normal growth and development. Limited measurement of contaminants in fish and their environment constrains any further conclusion.

Most legacy pollutants (such as PBTs) have declined during the period of declining Fraser sockeye production. However, several other chemicals have increased in sales, use, and/or release, including endocrine-disrupting chemicals, pesticides used in forestry and agriculture, and a variety of pharmaceuticals released primarily from urban sewage effluents. It is also worth emphasizing that most modes of action of these chemicals can be exacerbated by additional stresses, such as pathogens, temperature change, or nutritional stress. We also note that Harrison River sockeye should also have been exposed to contaminants during their several-month residence in the lower river and estuary, yet they have had increased productivity, compared with decreasing productivity for the other Fraser sockeye populations.

4.5.3 Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

Discussion of contaminants did not extend to non-Fraser stocks, but it is reasonable to expect greater potential impacts on Fraser River salmonids compared to those in other locations, given the extent of development and human population within the Fraser basin. However, contrary evidence does exist both north and south of the Fraser basin. The Columbia River basin is certainly an extensively altered environment with development similar to the Fraser basin, yet sockeye production in the Columbia River has been improving in recent years. It is noteworthy that the Columbia River estuary is much less disturbed than in the Fraser River. However, on the central coast of B.C., where there is little development, sockeye production in Smiths and Rivers Inlet has been very depressed since the mid-1990s. As noted above though, limited site-specific data on contaminants and the often complex nature of environmental interactions means more specific assessments would be required to explain each of these non-Fraser observations.

4.5.4 Plausibility and realism of proposed mechanism

A role for contaminants as a secondary contributor to reduced productivity of Fraser sockeye salmon is certainly plausible, but direct evidence is lacking. Furthermore, the monitoring or assessment studies to assess any impact are also lacking.

4.5.5 Conclusions about the likelihood that the hypothesis is correct

Although there have historically been clear examples of fish kills caused by contaminants, including in B.C., the problem of the low 2009 sockeye return is unlikely to involve such a direct mechanism. The Panel acknowledges that there is insufficient information upon which to judge the degree of concern, but there is <u>no</u> reason to believe that there was a sudden increase in contamination of the Strait or the Fraser estuary in 2007, the year of ocean entry for the 2009 returns. As well, appropriate data are lacking for the relationship between the long-term decline in sockeye productivity and contaminants, but they are a possible contributing factor in that decline. We conclude that contaminants are at best an **unlikely** explanation for the 2009 return but acknowledge contaminants as a **possible** contributing factor for the longer term.

4.5.6 Proposed Research

(1) Due to the number of contaminants and their wide distribution in the environment, the research proposed by Macdonald et al. and the Panel focused on *direct measurement and assessment of impacts.* For example, monitoring should be done on concentrations in *effluent* (need to know total loadings of contaminants), presence and concentration in *water*, and impacts of *body exposure* (since pharmaceuticals and many others do not bio-accumulate). Laboratory studies using Fraser River water and bioassay organisms (potentially using model species) are preferred to see biological response and to screen for harmful effects of chemicals.

(2) Natural effects on salmon populations could be assessed using experimental streams in habitats with differing chemical exposures during their life history. It is difficult to attribute causes to observed effects in such indirect assessments but, coupled with laboratory studies and/or genomics, indirect assessment may be the only means to actually assess the impacts of contaminants in total (because there is unlikely to be only one chemical in the environment). Researchers could employ prediction of effects to test their understanding and estimate risks to sockeye salmon.

Workshop participants were aware of a relatively new monitoring buoy in the lower Fraser mainstem, but were uncertain about which chemicals and environmental parameters are being assessed (www.waterquality.ec.ca/waterqualityweb/realtimeindex.aspx).

4.5.7 Management Actions

(1) An immediate management action is to get usage data to construct chemical budgets within Fraser watersheds and to assess regions of potential contaminant risks.

(2) In general there is a need for improved coordination of data between provincial (B.C. Ministry of Environment), federal (Environment Canada, DFO), municipal, and industrial entities.

(3) *The primary management actions required must be control of use and accountability.*

4.6   Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation.

4.6.1 Description of the hypothesis

Sockeye salmon from the Fraser River spend approximately one-half of their life in freshwater habitats. This freshwater period includes upstream migration by adults en route to their spawning grounds, egg incubation in streams, rearing of fry and parr in streams and lakes, and downstream migration by smolts. Thus, it is conceivable that alterations to freshwater environments could have adverse impacts on a large portion of the Fraser sockeye life cycle (Table 4-1), with subsequent declines in overall stock abundance and/or productivity.

Table 4-1. Watershed and climatic disturbance factors affecting freshwater life stages of sockeye salmon. Table from Selbie et al. in Appendix C.

Disturbance	Stressor	Effects on habitat	Population impact
Logging, agriculture and road construction (includes salvage logging of Mountain Pine Beetle stands)	Chronic and acute sediment generation	Fine sediment infiltration of spawning gravels	Reduced egg-to-fry survival
	Reduced riparian shade increases water temperatures	Higher temperatures during spawning	Higher pre-spawn mortality
		Higher temperatures during egg incubation	Advanced fry development and emergence timing
	Changes in watershed hydrology	Earlier freshet and higher scouring flows in spawning beds	Reduced egg-to-fry survival
		Increased bank erosion and bedload movement	Reduced egg-to-fry survival
Warming climate	Higher migration and spawning water temperatures	Higher energy costs and pathogen susceptibility during migration and spawning	Higher en-route and pre-spawn mortality
	Higher rearing lake surface temperatures	Reduced access by fry to epilimnetic zooplankton	Reduced in-lake growth and survival of fry; smaller smolts
Reduced salmon escapements	Reduced spawner carcass nutrient inputs	Reduced rearing-lake productive capacity	Reduced in-lake growth and survival of fry; smaller smolts
	Reduced rearing-lake fry populations	Higher proportional predation mortality	Reduced in-lake survival of fry
Urban, agriculture and industrial development in rearing lake watershed	Increased nutrient and contaminant loads to rearing lakes	Changes in productive capacity, food web structure and lake water quality	Changes in in-lake growth and survival of fry
Urban, agriculture and industrial development along adult and smolt migration routes	Increased exposure of adults to pollutants during spawning migration	Toxicological impairment	Higher en-route and pre-spawn mortality
	Increased exposure of smolts to pollutants during outmigration	Toxicological impairment	Reduced smolt survival

The presenter at the workshop, Daniel Selbie, and his colleagues focused solely on life stages ranging from adults already on the spawning grounds through to smolt outmigration (i.e., habitat conditions for upstream migrating adults were not considered here, but are covered in Section 4.8.). Selbie and colleagues divided their analyses of the freshwater life stages into two sub-hypotheses that addressed: (1) the natal and nursery environments; and (2) the smolt outmigration environment. The authors note that the availability of habitat and fisheries data varies considerably in both quantity and quality, which consequently influenced the degree to which their hypotheses could be addressed.

4.6.2 Consistency with spatial and temporal trends in productivity of <u>Fraser</u> sockeye

Sub-hypothesis 1: Variation in rates of decline in Ricker residuals (total and juvenile productivity) among Fraser River populations is related to differences in habitat conditions in natal spawning and rearing environments.

Basin-scale analyses. Selbie and colleagues developed a list of watershed characteristics with which they could look for an effect on stock productivity. These included factors associated with landscape position of a watershed (e.g., latitude/longitude, distance from ocean) as well as those related to spawning and nursery environments (e.g., lake productivity, road density, logging intensity). For these purposes, their response variable was the slope of the regression of Ricker residuals on brood year (simply referred to as "trend" in this Section 4.6) calculated for each of the 18 populations identified by the PSC. They found significant, negative correlations between the trend for each population and 3 covarying measures of the position of the natal watershed within the landscape (i.e., distance from the ocean, latitude, and lake elevation). They could not detect any other correlations between trend and the other habitat variables considered, but it is conceivable that nonlinear relationships could exist (e.g., upper vs. lower in the basin).

The lack of other identifiable relationships between trend and land-use characteristics was not much of a surprise. That is, sockeye salmon should be less sensitive than other species of Pacific salmon (e.g., coho) because they rear in lakes, which may buffer them against landscape effects due to the relatively large size of lakes compared to streams. Additionally, compensatory mortality during their lake residence may buffer them against adverse effects encountered on the spawning grounds. That is, if an unusually high mortality occurs in the egg-to-fry stage, that brood may have lower-than-usual mortality at the fry-to-smolt stage because the abundance of competing fry has been reduced.

Nursery lake conditions. Lake-rearing environments vary spatially and temporally in their ability to support juvenile sockeye salmon. For the Fraser system, data on lake primary and secondary productivity are limited largely to the ice-free season within any given year, and exist only for limited years and lakes. Available data on primary productivity for Chilko and Quesnel lakes showed no obvious relationship with trends in stock productivity. Furthermore, the one datum for 2009 in Chilko Lake suggests lake productivity is as high as it was during the late 1980s and early 1990s when the lake underwent fertilization. Similarly, primary productivity in Quesnel Lake from 2003-2007 was equal to or greater than estimates from the late 1980s.

Fall zooplankton biomass may indicate the degree of planktivory by lake-rearing juveniles during the summer, and offers insight into whether secondary production is sufficient to support juvenile growth adequate to maintain them through the winter. Following record escapements to Quesnel Lake in 2001 and 2002, fall zooplankton biomass in 2003 was lower, as expected. However, the lower biomass estimate for 2003, particularly for the preferred prey *Daphnia*, was not significantly lower than previous or subsequent years, suggesting that lake-rearing juveniles were likely getting sufficient food.

Juvenile productivity and growth. Juvenile sockeye residing in Shuswap, Quesnel, and Chilko lakes demonstrated density-dependent survival based on nonlinear relationships between indices of juvenile abundance and effective female spawners (EFS). Examination of the residuals from those model fits indicated below-expected survival of juveniles in Shuswap Lake in 7 of 8 years for which there are data since 1990. Conversely, recent data for Chilko Lake suggests above-average juvenile survival in that system.

Juvenile sockeye salmon from Shuswap, Quesnel, and Chilko lakes also showed density-dependent growth as evidenced by a negative relationship between counts of otolith circuli during freshwater residency (an index of growth) and EFS. On the other hand, there was no apparent correlation between EFS and fall fry weight in Quesnel Lake, or smolt weight in Chilko Lake. It is also worth noting, however, that the mean body size of smolts leaving Chilko Lake in

2007 (and returning as adults in 2009) was one of the largest sizes on record, suggesting that there was no shortage of food for that cohort of juveniles.

Despite evidence for density-dependent survival and growth of lake-rearing juveniles, there have been no meaningful trends over time in Shuswap, Quesnel, and Chilko lakes, and no consistent trends across nursery lakes.

Additional analyses of residuals from best-fit functions presented by Mike Lapointe, which are also summarized in Table 3-1 of this report, showed much higher correlations between total life-cycle productivity (adult recruits per EFS) and recruits per juvenile than between that same total life-cycle productivity and juveniles per EFS. This suggests that observed declines are occurring somewhere in the juvenile-to-adult portion of the life cycle. However, again, as noted in Section 3.1, it is also conceivable that some factors in the spawning-to-juvenile life stage do not cause mortality until after juveniles are enumerated.

Sub-hypothesis 2: Variation in trends in Ricker residuals for Fraser River populations is a function of differences in conditions during smolt outmigration among those populations.

Timing of smolt outmigration. Data on the timing of smolt outmigrations in the Fraser River are restricted to Chilko and Cultus lakes, and from fish intercepted at the Mission smolt trap located in the lower river. On average, smolts from Chilko Lake migrate from the lake later than those from Cultus Lake. At Mission, the smolt migration occurs from roughly mid-April through the end of May, but the migration timing of individual populations remains unknown. Although large inter-annual variability exists in both the median date and total duration of the smolt outmigration, no systematic shifts have occurred in the median migration date measured at Chilko Lake or Mission. In Cultus Lake, however, the median date of outmigration has shifted later by about 13 days over the past 80 years.

Unfortunately, no survival estimates exist for Fraser River sockeye smolts during the period of their outmigration, with the exception of a recent study of acoustically tagged hatchery smolts from Cultus Lake (a study at Chilko Lake was just initiated in 2010). As mentioned previously, there is a negative relationship between productivity trend (time trend in residuals from the best-fit Ricker model) for a given stock and distance to the ocean, indicating the potential for increased mortality during longer downstream migrations. It should be noted, however, that the pattern only applies to the recent past (1984-2004 brood years). If that spatial relationship had applied to all years, in theory there would be no way for those stocks located furthest from the ocean to persist over long periods because consistent, below-average productivity would drive them toward extinction.

4.6.3   Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

Analyses of other sockeye salmon stocks from the west coast of North America also suggest that the freshwater spawning and rearing environments may be important for overall stock productivity and abundance. Density-dependent growth and survival have been observed elsewhere to varying degrees. Recent research on sockeye and other species has also highlighted important effects of anthropogenic changes to freshwater habitat, which may become exacerbated in coming years under expected climate change. It should be noted here that sockeye salmon from the Columbia River returned in record numbers in 2008 and 2009. Although they enter the ocean in a very different place than fish from the Fraser River, the freshwater spawning and rearing habitats for sockeye in the Columbia occur in an ecoregion similar to that in the Fraser (dry interior watersheds), suggesting that large-scale climatic factors

should not have caused disproportionate changes to freshwater habitats within the Fraser relative to those in the Columbia.

4.6.4   Plausibility and realism of proposed mechanism

As already mentioned, sockeye salmon from the Fraser River basin spend approximately one-half of their life in freshwater. An earlier meta-analysis across many stocks suggested that >50% of the total life-cycle mortality occurs in the natal spawning and rearing areas; fish incur additional mortality during their downstream migration from natal lakes to the ocean. Additionally, recent studies have highlighted the importance of "biocomplexity" (e.g., variance in age structure, spawning habitats, run timing) among sockeye salmon populations in maintaining overall sustainability of stock complexes (e.g., Bristol Bay, Schindler et al. 2010). Despite this information, however, scientists and policy makers often discount the freshwater portion of the life cycle as a contributor to declines in salmon stocks. However, regional climate trends and decadal-scale variations are agents of change that contribute spatial and temporal autocorrelation to freshwater habitats and productivity variations, which could cause populations to fluctuate synchronously at a regional scale. Furthermore, based on experiences elsewhere (e.g., continental U.S.), human-induced alteration, destruction, and limitation of freshwater habitats can have significant effects on salmon productivity and abundance. Moreover, some research suggests possible latent effects of poor freshwater experiences on salmon (e.g., stress, disease, poor feeding conditions) that do not manifest themselves until after the fish enter the ocean. Thus, although the plausibility of the proposed freshwater mechanisms is inherently high, no good evidence exists *at this time* to suggest they are a major contributing factor in the recent decline of Fraser River sockeye salmon. Processes that occur in the juvenile-to-adult stage are therefore more likely candidates for explanatory mechanisms than those occurring in fresh water.

4.6.5   Conclusions about the likelihood that the hypothesis is correct

Based on the evidence at hand, little support exists for the hypothesis that changes in freshwater habitat conditions in natal and nursery environments are responsible for the observed declines in abundance or productivity of Fraser River sockeye salmon, either over the long term or the 2009 returns from the 2005 spawners. Differences in land-use and landscape features across the basin did not show any relationships to trends in productivity, with the exception of lake position within the basin. Estimates of lake productivity, juvenile survival, and juvenile size for three major rearing lakes did not reveal any meaningful changes that would explain recent declines in stock productivity. No sudden changes in freshwater habitat conditions are known to have occurred during 2005-2006, or in downstream migratory conditions during 2007, which would be required if freshwater habitat were to have significantly contributed to the poor 2009 returns. Therefore, Panel members concluded that freshwater effects on sockeye are **very unlikely** to have contributed to the poor 2009 returns and at best are **unlikely** to have contributed to the long-term decline in Fraser sockeye productivity.

4.6.6   Proposed Research

Critical knowledge gaps in freshwater environments:
> (1)   Population-specific estimates of the timing, condition (including disease status), and behaviour of sockeye smolts during their outmigration from natal lakes to Georgia Strait, including the Fraser River estuary.
> (2)   Watershed-based estimates of the degree of land-use, especially near spawning streams, and historical trends in those changes.

(3) Long-term monitoring of significant lakes in the watershed with which to evaluate temporal trends in human- and naturally-induced changes that may affect sockeye production.

Critical monitoring

(1) Expanded monitoring of smolt outmigration from the rearing lakes across populations (to include smolt size, timing of outmigration, and smolt-to-adult survival estimates).
(2) Maintain time series of freshwater productivity, nursery ecosystem (food web) structure and fry enumeration across nursery lakes, with expansion to other key populations.
(3) Maintain monitoring program for Fraser River environmental conditions with additional focus on time periods relevant for smolt outmigration.

Critical research

(1) Use experimental and tagging data to better understand mechanisms for, and the magnitude of, mortality of freshwater-outmigrating sockeye smolts. Possibilities include expanding the gear and time period for sampling at Mission for a better assessment of yearling migrations (may also assist with Chinook and coho assessments), and the use of genetic stock identification and physiological sampling to better identify stock-specific factors that may affect late freshwater, estuary, and early marine survival.
(2) Compile information on temporal changes in land-use (e.g., agriculture, forestry) and relate to changes in freshwater productivity across a range of populations (a model might be the Stuart Declines Southern Endowment Fund Final Report submitted to the PSC).
(3) Merge disparate data sources available regarding environmental conditions in the spawning, incubation, and rearing environments and relate to changes in indices of freshwater productivity, fish condition, fish behaviour.
(4) Improve our understanding of interactions between juvenile sockeye and other fish species present in rearing lakes (i.e., competition and predation) as well as other food web components (prey). These studies could be expanded to include stream habitats as well.
(5) Develop an understanding of biocomplexity among the 18 populations of sockeye within the Fraser River, and how it relates to differences in freshwater habitat.

4.6.7 Management Actions

The Panel has concluded that freshwater effects on the sockeye life cycle are unlikely to have caused the Fraser sockeye situation. Thus, no immediate management actions are warranted because they are not likely to reverse the situation. That said, however:

(1) management should continue to protect freshwater spawning, rearing, and migration habitats wherever possible; and
(2) further consideration should be given to actions that could mitigate the anticipated regional effects of global change (e.g., increased temperatures, changes in precipitation patterns, altered snowmelt runoff patterns, introduction of non-native species).

4.7 Delayed density-dependent mortality is an important contributor to the Fraser sockeye situation.

4.7.1 Description of the hypothesis

The hypothesis states that, for total life-cycle productivity (adult recruits per spawner) of a given brood year of sockeye salmon, there is some effect (usually negative) of the number of sockeye salmon spawners in previous years (i.e., with a 1-, 2-, or 3-year lag). This hypothesis is based on the assumption that a large number of spawners in one year will produce large numbers of eggs and fry that may subsequently reduce food supply for juvenile salmon in the rearing lake, increase incidence of diseases on salmon, and/or lead to an increase in predators and/or predation rate on juvenile salmon in the rearing lake or elsewhere in the life cycle. All three of these density-dependent processes may potentially reduce survival rates of cohorts of juvenile salmon in the next or other years subsequent to a large spawner abundance. Hence, this hypothesis is termed delayed density-dependent productivity.

The productivity (adult recruits per spawner) of most Fraser stock complexes has been declining since the late 1980s or early 1990s, depending on the stock. Fry-to-adult or smolt-to-adult survival estimates for most of these stocks have declined in recent years, especially since 2000, and particularly for the 2003 and 2005 brood years. Carl Walters' analysis of the delayed density-dependent hypothesis, described below, suggests that most of the earlier decline (prior to 2000) was due to reduced spawning and freshwater rearing survival that is statistically associated with increasing spawning abundance.

4.7.2 Consistency with spatial and temporal trends in productivity of <u>Fraser</u> sockeye

In Walters' analysis provided in Appendix C, data from the mid-1980s showed variation over time in recruits per spawner for some stocks that were better explained statistically by including lagged density-dependent effects of past spawner abundance using the Larkin (1971) model[2] than by using the standard Ricker[3] model. Lagged or delayed density-dependent effects can create 4-year periods in time series data with a large abundance of recruits in one year, a moderately high abundance in another, and two very low-abundance ("off-cycle") years. This pattern is often referred to as cyclic dominance[4], which is a common pattern for many Fraser sockeye stocks (Walters and Staley 1987). More recent analyses (Martell et al 2008; Pestal et al. 2010 presentation at the CSAP [Centre for Science Advice - Pacific] meeting on the Fraser River Sockeye Spawning Initiative) have resulted in much stronger statistical evidence for such delayed effects, with the Larkin model outperforming the Ricker model (using AIC[5] comparisons) for the major stocks that account for the majority of sockeye production from the Fraser River: Early Stuart, Late Stuart, Stellako, Quesnel, Chilko, Seymour and Late Shuswap.

In past analyses, the effect of delayed density dependence may have been masked by the standard statistical fitting criterion. The standard model-fitting procedure for Ricker and Larkin models involves assuming a log-normal distribution of errors around the fitted line. This approach is consistent with both theoretical and empirical analyses of frequency distributions of

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[2] The Larkin model relates $\log_e$(recruits per spawner) to the number of spawners in the brood year, as well as spawners in each of the preceding 3 years.

[3] The Ricker model relates $\log_e$(recruits per spawner) to the number of spawners only in the brood year.

[4] A large number of spawners in one year can lead to depressed productivity in subsequent years, thereby creating strong and weak cycle lines.

[5] Akaike information criterion (AIC) is a measure of the goodness of fit of an estimated statistical model.

historical adult recruitment. However, this procedure gives relatively large weight to low-recruit-abundance years, where estimates of spawners and stock-specific recruits are less reliable, compared with high-abundance years. Walters therefore also used a non-standard fitting criterion that minimized the squared difference between predicted and observed total recruitments, which increased the importance of high-abundance years.

Walters found with this new fitting criterion that the delayed density-dependent Larkin model explains the recruitment decline from 1990 to 2002 better than the Ricker model with that same fitting criterion (Figure 1 of Walters in Appendix C). Particularly notable is that, prior to 2000, there were two years (1958 and 1971) with large negative recruitment anomalies (poor recruitment in relation to predictions based on spawner abundance). Both occurrences were associated with depressed productivity two to four years after recruitment peaks. The delayed density-dependent process may have influenced a number of stocks in the way that would be expected if high spawner abundance had led to some widespread problem like a systemic disease outbreak.

Thus, the delayed density-dependent aspects of the Larkin model, together with the alternate fitting criterion, reproduce the temporal trends in productivity for the major Fraser sockeye stocks better than the standard Ricker model. Delayed density dependence does not appear as significant in the smaller stocks, though.

While the Larkin model does a better job of predicting recent recruitment for the major stocks than the Ricker model, it still has a large deviation for the 2003 and 2005 brood years (Figure 1 of Walters in Appendix C). These deviations are large but smaller than those for the Ricker model. This hypothesis does not fully explain the poor 2009 return year, in particular because Chilko smolts that contributed to that return were the most abundant on record and yet were one of the largest sizes on record (Section 4.6.2). If they had been diseased in a way that caused delayed mortality to occur after leaving the lake, it is not likely that they would also have encountered such favorable conditions to be such a large body size when leaving the lake.

There is evidence that Fraser River sockeye showed large differences among years in spawner abundance prior to the onset of industrial-scale fisheries. The oral history of aboriginal people in this region indicates that their populations were substantial and highly dependent on salmon, and that there were periods of famine due to poor returns of salmon. Written records of the Hudson Bay Company also show high variability in salmon abundance. Some harvesting methods, such as traps and weirs, were very effective, resulting in high exploitation rates on some stocks. This evidence does not point directly to cyclic dominance in every four years, though, which would be required to support the argument for delayed density-dependence existing prior to industrial-scale fishing.

4.7.3   Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

Evidence presented at the workshop by Arlene Tompkins showed that most other major sockeye salmon populations in B.C. have had below-average total life-cycle productivity (adult recruits per spawner) since the early 1990s, and strongly decreasing productivities in the early 2000s (Section 3.2). To our knowledge, though, no one has comprehensively fit the Larkin model of delayed density dependence to these non-Fraser sockeye stocks. Nevertheless, as explained below, we might expect a priori that such a model would not explain temporal variation in productivity of these non-Fraser stocks because they do not show the strong cyclic-dominant pattern of abundances exhibited by Fraser sockeye.

The effects of delayed density dependence on changes in productivity will be most evident in stocks with a large range of abundance of spawners over years. A narrow age-frequency distribution contributes to large variations in recruits and spawner abundance. For instance, in most Fraser sockeye stocks, over 90% of adult recruits are 4-year-olds and 4-year cycles in adult abundance occur regularly. In Alaska some sockeye systems are dominated by 5-year-old fish and cycles also regularly occur. In contrast to the Fraser, most other sockeye systems in British Columbia have a substantial portion of different-aged returns (3-, 4- and 5-year-olds), and cyclic dominant patterns are not observed in these stocks.

Most non-Fraser B.C. sockeye do <u>not</u> have the regular wide-ranging fluctuations in abundance that are required for delayed density-dependent processes to clearly manifest themselves. This mechanism of delayed density dependence would therefore <u>not</u> explain the decrease over time in productivity of non-Fraser sockeye. Of course, this does not imply anything against this hypothesis for Fraser sockeye, which <u>do</u> show cyclic dominance patterns in abundance.

4.7.4   Plausibility and realism of proposed mechanism

There are several plausible mechanisms that may both cause and maintain cycles in sockeye populations. First, populations of resident salmonids that prey on eggs and juvenile sockeye may have increased productivity in years when there are large numbers of prey. Models of such predator-prey interactions show that they could produce cyclic dominance in sockeye. However, there are limited data on population dynamics of most of these potential predator species. There are also disease and parasite dynamics that may be consistent with this hypothesis. However, the lack of key information on diseases also makes it difficult to link diseases and parasites to the dynamics of Fraser sockeye populations.

4.7.5   Conclusions about the likelihood that the hypothesis is correct

Many biologists who worked on the management of Fraser sockeye through the middle and latter part of last century believed that "cyclic dominance" meant that spawning targets and exploitation rates should differ across cycle lines. That is, higher percentage harvest rates in low-abundance years (off-cycle lines) would keep them low to mitigate the delayed effects on productivity of one cycle line on another. The "experiment" of the last 20 years was to see if the "off-cycles" could be built up to the levels of the strong cycles. Whether the experiment has been informative is not yet clear; Carl Walters expressed a need to confirm that his model-fitting results were "real" and not an artefact of the statistical procedures.

If the evidence is as conclusive as Walters suggests, then the experiment has been a success in that it has provided valuable information. However, the attempt to increase abundance of off-cycle years may have been a failure at producing more fish, or even the same amount of fish for harvest than would otherwise have been the case.

The Panel's opinions about the effect of delayed density dependence on the long-term decline in Fraser sockeye productivity ranged from **likely** to **possible** to **unlikely** as a contributing factor. Panel members agreed, however, that delayed density dependence is **very unlikely** to have played a role in the 2009 event.

4.7.6   Proposed Research

(1) The Fraser River Sockeye Spawning Initiative group should attempt to replicate Carl Walters' results for fitting the Larkin and Ricker models.

(2) Better (more accurate and precise) measurement of abundance at different life stages (fry, smolt, marine migrant) are needed.

(3) We need to better understand food supply dynamics.

(4) Other research needs to be conducted into mechanisms such as predators, disease and food supply so as to try to detect the density effect.

(5) Contrasting management strategies should be applied to different stocks over enough time to observe a response.

4.7.7 Management Actions

(1) Except for the Chilko Lake population, a Larkin model predicts much lower optimum spawning escapement and a substantially higher optimum exploitation rate than the Ricker model. Thus, if the evidence of delayed density dependence is confirmed as a statistical "reality" as opposed to an artefact or "anomaly", then the current approach to Fraser Sockeye stock management should be re-examined. The Fraser River Sockeye Spawning Initiative (FRSSI) model, which is currently used to explore and set harvesting rules, uses the Larkin population dynamics model. However, the fitting criterion may need to be re-assessed.

(2) The Total Allowable Mortality (TAM) rules that result from FRSSI are abundance-based but not cyclic. Policy analysis of abundance-cyclic based TAM rules that include the pattern of abundances of previous years' spawners (delayed effects – multidimensional control rule) need to be explored.

(3) Wild Salmon Policy benchmarks may need to account for and reflect the cyclic nature of some Fraser sockeye Conservation Units (CUs).

(4) If the mechanisms for the delayed response can be determined, then mitigation of those factors may be possible.

4.8 En-route mortality during upstream migration, plus effects on fitness of the next generation, are important contributors to the Fraser sockeye situation.

4.8.1 Description of the hypotheses

Scott Hinch presented two hypotheses related to stresses that affect adult Fraser River sockeye that are migrating upstream.

Sub-hypothesis #1: "En-route" mortality is defined as the loss of adult migrants between their entry to the Fraser River and arrival at spawning areas. That mortality is estimated as the abundance of fish at the Mission hydroacoustic facility in the lower river less the sum of freshwater catch and spawning escapement. En-route mortality estimates likely contain significant but unknown measurement error, unreported catch in the Fraser River, and delayed mortality associated with encounters with fishing gear.

En-route mortality does not contribute directly to the decline in productivity as defined here (recruits/spawner) because recruitment is defined as the abundance of fish that arrive at the coastal fishing areas. The estimates of recruitment thus include a component which is subsequent en-route losses. However, en-route mortality reduces the number of adults that reach the natal streams to spawn, and unless compensated for by reduced harvesting, will lead to lower-than-desired spawner abundance.

Sub-hypothesis #2: Another possible cause of decreasing productivity of Fraser sockeye stocks may be indirect between-generation, or intergenerational, effects of stresses created during upstream migration of adults, particularly females. These effects refer to the impacts that phenotypic (i.e., non-genetic) characteristics of the parents may have on fitness of their offspring. An example is a reduction in fry quality or survival caused by the nutritional or disease status of the mother. Significant intergenerational effects will cause changes in recruits/spawner ratios and thus could contribute to population declines.

4.8.2   Consistency with spatial and temporal trends in productivity of <u>Fraser</u> sockeye

En-route loss does not contribute to the declines in *productivity* in Fraser River sockeye because, as noted above, the losses are factored into the calculation of recruitment. En-route mortality also cannot account for the poor returns in 2009, because estimates of those returns are also made at entry to freshwater, before en-route mortality takes place.

Estimates of en-route loss are made for each of the major stock groups and those results indicate that en-route losses have been a significant component of recruitment in the past 15 years. Populations that migrate early in the summer (the Early Stuart and early Summer runs) and the Late Run group have been most affected, with losses being more limited for the Summer run group. Those losses have ranged from 0 to over 90% in extreme years, and for early and late runs, losses of over 50% have occurred in more than half of the past 12 years. Although en-route losses tend to be higher for earlier migrants in the Late Run stock group, it is not known whether en-route loss is a selective agent that targets specific components or phenotypes of each population.

In-season empirical models based on Fraser River discharge and water temperature are used to predict en-route losses for each stock group. Fisheries managers use these predictions to adjust harvest plans to achieve escapement goals. Thus, the impacts of en-route mortality on trends in spawner abundance have been partly mitigated by management actions because harvest rates (and catches) have decreased in recent years partly in response to predictions of high rates of en-route mortality.

Intergenerational effects could cause spatial and temporal trends in productivity, but it is difficult to evaluate this hypothesis with current levels of data and understanding. For example, it might be hypothesized that negative intergenerational effects would be greatest for broods for which the parents are under stress, as indicated by exposure to difficult migratory conditions (and suffering en-route mortality), or are suffering high rates of prespawning mortality. It is also reasonable to hypothesize that those effects would manifest themselves early in the juvenile life history and would be best tested with relationships between the stress/en-route mortality of parents and the egg-to-fry or egg-smolt survival rates of their offspring. This analysis has not been conducted, but the overall absence of declining trends in freshwater survival in populations that have suffered en-route mortality (e.g., Early Stuart fry, Weaver fry in Figures D-J1 and D-J2 of Appendix D) does <u>not</u> support the hypothesis that intergenerational effects are a major contributor to the decline. However, a delayed intergenerational impact that affects smolts or occurs in the marine phase is possible, and is consistent with the survival data, but a mechanism needs to elaborated for this hypothesis to be considered plausible. One possible mechanism would be a gradual reduction in the diversity of life history characteristics and/or run timing of stocks that are subjected to large en-route mortality. Such changes would make those stocks more vulnerable to extremes in freshwater and marine conditions. Recent work

(Schindler et al. 2010) has quantified the benefits of population and life history diversity in Bristol Bay sockeye.

4.8.3   Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

In the Columbia River, sockeye salmon enter the river in June during a period of rising water temperatures. Telemetry studies have found increasing mortality rates in later migrants, presumably the consequence of exposure to higher water temperatures. Thus, results obtained for en-route mortality of Fraser River sockeye salmon are generally consistent with those for Columbia River populations in that exposure to temperature stress outside of the normal or historic range can contribute to mortality. However, the situation in the Fraser River is more complex because of the wider range of migration timing; some populations migrate during rising temperatures, some during the peak temperatures, and some migrate later in the year as the river is cooling. Thus, the effect of increasing water temperatures and altered migration timing on en-route mortality is population-specific.

4.8.4   Plausibility and realism of proposed mechanism

Although en-route mortality is not a plausible mechanism for the decline in productivity, based on how the latter has been calculated (related to adult recruits produced per spawner), en-route mortality is a significant factor that reduces the <u>number of effective female spawners</u>, and thus may pose a threat to the long-term viability of the populations that are particularly affected.

The magnitude of en-route loss at the population level is based on estimates with likely high levels of uncertainty, however, the plausibility of the mechanism is supported by over 10 years of research effort on this issue. The population-level estimates are corroborated by tagging and telemetry studies that document mortality among upstream migrating adults. Extensive field and experimental studies have shown that populations are being stressed by exposure to river water temperatures that are above their physiological optima. For the early Fraser sockeye runs, those increased temperatures are the result of a long-term increasing trend in Fraser River water temperature that now routinely expose early run-timing groups of Fraser sockeye to temperatures >18 °C, a critical temperature for successful migration. Between 1996 and 2009, the timing of river entry of the Late runs has occasionally advanced by nearly 6 weeks and as a consequence, those populations were exposed to much higher temperatures and have had to survive a much longer period in fresh water prior to spawning than in the past. These stressors can either lead to direct mortality or predispose migrants to disease or death by exhaustion. Of particular concern is the observation that female migrants appear to be more vulnerable to these stressors than males. En-route loss can be expected to increase in severity in the future if predictions are correct that water temperature in the Fraser River will increase due to anthropogenic climate change. It is unknown whether the timing of migration or the effect of temperature on performance can evolve to allow adaptation to the changing environment.

Intergenerational effects are certainly plausible, but the supporting evidence is weak. Experimental studies that incubated eggs from dying or recently dead females have found no effect of the health of the mother on viability of the eggs or juveniles. Egg size commonly varies with female body size, such that recent trends to smaller spawners may reduce the fitness of eggs and fry. It is also plausible that contaminants or pathogens transferred from the mother to her eggs could reduce survival, although evidence is currently lacking.

4.8.5   Conclusions about the likelihood that the hypothesis is correct

It is very likely that en-route mortality is a significant factor affecting both harvest (because of restrictions imposed by anticipated losses) and the magnitude of spawning escapement. However, en-route mortality is **not relevant** to explaining the decrease in productivity indices that were used in the workshop (i.e., adult recruits produced per spawner, or residuals in those from the best-fit Ricker model). This statement is also true for both explaining the long-term trend and the 2009 event.

Intergenerational effects that cause the fitness of offspring to be affected by some aspect of the parent's condition are currently not supported by either the empirical analysis of population data or the few experimental studies that are available. Such effects might best be considered a potential contributing factor in need of observational data to identify specific mechanisms that would lead to the hypothesized population-level effects. At present, though, the Panel rated these intergenerational effects as **very unlikely** to have contributed to the long-term downward trend in productivity of Fraser sockeye and the low 2009 returns from the 2005 brood.

4.8.6   Proposed Research

(1) There is ongoing work on refining the predictive models for en-route mortality that are used for in-season management of the sockeye fishery (DFO).
(2) Climate change modeling is also underway to evaluate the long-term changes in en-route mortality under scenarios of warming. These studies will be a key component of long-term planning for Fraser sockeye. These analyses could also include assessment of the impacts of the two major diversion dams on Bridge and Nechako Rivers on migration conditions.
(3) New research projects on the impacts of non-retention by fishing gear have started. The interaction of freshwater fisheries and stressful environmental conditions is not well understood and has the potential to be a contributor to en-route loss.
(4) There is no systematic monitoring of disease (coupled with physiological and environmental studies) in adult sockeye. Sampling is restricted to either outbreaks, or enhancement facilities. An understanding of the interaction between fish condition, environmental factors and disease would likely allow for improvement of predictive models, but this is a long-term research program because large en-route losses can be episodic.
(5) Further studies of intergenerational effects are needed to identify mechanisms that might cause these effects. Sampling for contaminants or diseases could be extended to include both parents and offspring. This should be coupled with gene expression studies.

4.8.7   Management Actions

(1) There is currently a management procedure to incorporate predictions of en-route losses into fishery management planning; this procedure should be continued.
(2) Actions to alleviate stressors to migrating salmon, where possible, may reduce the severity of en-route losses. These include maintaining passage in the migration corridors, including existing fishways and fish ladders, and ensuring that there are no other barriers to migration resulting from development activities.
(3) Land-use practices in temperature-sensitive streams (riparian protection, ground and surface water use) need to be carefully evaluated to ensure that suitable flow and temperature conditions are maintained for migrating salmon.

(4) Continued participation in discussions over modification to the Kenney Dam on the Nechako River will be important to ensure those changes do not impair temperature regimes in the Nechako and Stuart Rivers.

4.9 Competitive interactions with pink salmon (both wild and hatchery fish) are important contributors to the Fraser sockeye situation.

4.9.1 Description of the hypothesis

Greg Ruggerone showed data related to a hypothesis about pink salmon competing with Fraser River sockeye. Pink salmon, both wild and artificially propagated, currently account for about 75% of total salmon abundance in the North Pacific, and their abundance has been increasing. Because their diet in the open ocean overlaps considerably with that of sockeye, competition for food between pink salmon and sockeye salmon has the potential to have caused a density-dependent reduction in growth and/or survival of Fraser sockeye. Pink salmon exist independently as even- and odd-year populations because of their obligate 2-year life history. Large differences in abundance of even- and odd-year populations in some regions provides an opportunity for comparison, i.e., a "natural experiment" to gauge the extent of competition between pink and sockeye salmon populations.

Interactions between pink and sockeye salmon populations might occur in at least three different ways, each of which has unique implications for trends in growth and abundance of Fraser sockeye (Table 4-2).

Table 4-2. Illustration of potential physical and temporal overlaps and interactions between pink salmon and sockeye salmon: ==interaction 1==; ==interaction 2==; ==interaction 3==

Stock	Year					
	0	1	2	3	4	5
Odd-yr pinks	enter ocean	return & spawn	enter ocean	return & spawn	enter ocean	return & spawn
Even-yr pinks	return & spawn	enter ocean	return & spawn	enter ocean	spawn	enter ocean
Odd-yr sockeye	in ocean	return & spawn	in lake	enter ocean	in ocean	return & spawn
Even-yr sockeye	return & spawn	in lake	enter ocean	in ocean	return & spawn	in lake

Interaction 1: Fraser pink fry may compete with Fraser sockeye smolts migrating into Georgia Strait in spring and summer of the same year (mentioned by Dick Beamish). This version of the hypothesis (yellow highlighted areas in Table 4-2) implies that odd-year pink runs compete with even-year sockeye runs because the Fraser River supports only odd-year pink populations, and pink fry migrate to sea as underyearlings (the year following spawning), whereas most lake-type sockeye (except sea-type sockeye like the Harrison River and Widgeon Slough populations) migrate to sea as yearling smolts (two years after spawning). Negative effects of such competition would be evident in a reduction of growth and/or survival of Fraser sockeye that spawn in even years relative to those that spawn in odd years.

Interaction 2: Immature pink salmon from non-Fraser regions may compete with Fraser sockeye on the high seas (Ruggerone paper in Appendix C) (green highlighted areas in Table 4-2). Very large and artificially propagated populations of pink salmon from Southeast Alaska,

Prince William Sound, and Russia may be involved in these interactions, depending upon where the overlap with Fraser sockeye distribution occurs. Evidence from scale patterns indicates that competition between Bristol Bay sockeye and Russian/Alaskan pink salmon is greatest in the summer and fall of the year of return. Because Alaskan and Russian pink populations are more abundant in odd years, the negative effects of such competition would be evident as a greater reduction of growth and/or survival in Fraser sockeye that spawn in odd years.

Interaction 3: Adult pink salmon returning to the Fraser River may eat small Fraser sockeye smolts that are migrating seaward during the early summer (purple highlighted areas in Table 4-2). Because adult Fraser pink salmon are abundant only in odd years, negative effects of such predation would be evident in a greater reduction of survival of Fraser sockeye migrating to sea in odd years (at age 2), and returning to spawn in odd years (at age 4).

The contrasting predictions between version 1 and versions 2 or 3 of the hypothesis imply that it should be possible to reject them independently given sufficient data.

4.9.2   Consistency with spatial and temporal trends in productivity of <u>Fraser</u> sockeye

After first-differencing the time series of residuals from the best-fitting recruitment model to produce a stationary time series for analysis without autocorrelation, the productivity of most Fraser sockeye populations (13 of 17 examined, but not Harrison River, Late Shuswap, Chilko, or Quesnel) has been generally greater in even years than odd years (details in Ruggerone paper in Appendix C). The overall productivity of Fraser sockeye (averaged across Fraser populations) has been inversely correlated over the past 45 years with the aggregate abundance of adult pink salmon returning to the Fraser, southeast Alaska, and Prince William Sound in the year that age 4 Fraser sockeye returned. These results are consistent with version 2 but not version 1 of the hypothesis.

After first-differencing, the mean normalized body length of age 1.2 (4-year-old) adult Fraser sockeye was larger in even brood years than odd years, consistent with competition rather than predation (i.e., version 2 of the hypothesis rather than version 3). The proportion of sockeye maturing late (at age 5 rather than age 4) for brood year t was positively correlated with the aggregate abundance of adult pink salmon returning to the Fraser, southeast Alaska, and Prince William Sound in year t+4 (i.e., the year that sibling age 4 Fraser sockeye returned). These results suggest that competition with pink salmon on the high seas tends to reduce growth and delay maturation of Fraser sockeye, as expected in Interaction 2 of the hypothesis.

The two largest negative anomalies in Fraser sockeye returns, as well as in returns per spawner, were both in odd years (brood years 2003 and 2005) (see Figure 2B in Ruggerone's paper in Appendix C). Pink salmon abundance did not increase exceptionally over this period, either in the Fraser River or in the north Pacific Ocean, so the hypothesis is insufficient as a sole explanation for the 2009 anomalies in Fraser sockeye abundance and productivity. However, interactions with pink salmon might have contributed to these anomalies and to the longer term decline in productivity of Fraser sockeye. Indeed, the lowest average weight of adult Fraser River pink salmon on record in 2009 suggests that food supply may have limited growth in both pink and sockeye salmon that went to sea in 2007.

Sea-type sockeye populations in the Fraser River (Harrison River and Widgeon Slough) migrate to sea as underyearlings a year earlier than lake-type sockeye, and could interact with pink salmon in different years or in different geographical areas. Consequently, the discrepancy between the increasing time trend in abundance and/or productivity of sea-type populations and

the decreasing trend in most other Fraser lake-type populations does not disprove the hypothesis.

4.9.3   Consistency with spatial and temporal trends of <u>non-Fraser</u> stocks

Fraser sockeye populations as well as sockeye populations outside of Georgia Strait would be expected to experience similar competitive interactions with pink salmon in the North Pacific to the extent that their migratory routes overlap in space and time on the high seas. The stable or increasing time trends in smolt-to-adult survival for Columbia and Barkley Sound sockeye populations and the decreasing trends for most Fraser sockeye populations could be explained in two ways. First, if interactions between pinks and sockeye are mostly among populations from the same river system, then the lack of large pink runs on the Columbia and Barkley systems would be sufficient to explain the difference from Fraser sockeye. Second, if instead, the most important interactions between pink and sockeye are in the Gulf of Alaska, then this would require postulating different migratory patterns for the Fraser sockeye from the non-Fraser stocks in ways that affect the degree of interaction with pink salmon. Migratory patterns likely do vary among sockeye populations, but no empirical evidence currently exists for high-seas distributions for these populations, so the hypothesis cannot be considered complete or parsimonious.

4.9.4   Plausibility and realism of proposed mechanism

Predation of seaward-migrating Fraser sockeye smolts by returning adult pink salmon has not been documented and seems unlikely because it would be restricted to a short period of overlap in early summer. Moreover, productivity of Fraser sockeye was not significantly correlated with the number of adult pink salmon that returned to the Fraser River in the year that the sockeye smolts migrated seaward (Greg Ruggerone paper in Appendix C).

Competitive interactions are more plausible because the diets and distributions of immature pink and immature sockeye salmon are known to overlap. Competition for food could also decrease overall productivity of Fraser sockeye by reducing adult body size and fecundity, with or without direct effects on sockeye survival. Statistically significant density-dependent effects on growth and survival have been demonstrated both within species (pink salmon density affecting pink salmon growth, sockeye density affecting sockeye growth), and between the two species (pink salmon density affecting sockeye growth) in a number of populations in Bristol Bay (which also suffer lower survival rate when pink abundances were high) and the Fraser River. However, the magnitude of impact on the productivity of Fraser sockeye populations appears to be small, such that interactions with pink salmon cannot be the sole or primary explanation for the Fraser sockeye situation. Interaction 2 of the hypothesis therefore appears to be more plausible and more consistent with existing evidence than Interactions 1 and 3.

4.9.5   Conclusions about the likelihood that the hypothesis is correct

Negative interactions between pink and sockeye salmon are considered to be a **possible or even likely** contributor to the long-term decrease in productivity of Fraser sockeye, but are rated less likely as a contributing factor for the poor 2009 returns, with Panelists' ratings ranging from **very unlikely** to **possible**.

4.9.6 Proposed Research

(1) Further research to refine knowledge of the nature and extent of negative interactions between pink and sockeye salmon was considered important in view of its feasibility and the potential to produce results with practical application for management.
(2) Scale pattern analysis to investigate seasonal and annual growth of Fraser sockeye could shed light on the period of their interaction with pink salmon. Further statistical analyses to explore contrasting patterns of productivity in odd and even years could also be worthwhile.
(3) Additional surveys and tracking studies could be useful to determine when and where Fraser sockeye share the ocean with high densities of pink salmon.

4.9.7 Management Actions

(1) Pink salmon abundance has increased greatly by natural and artificial propagation, primarily in Alaska and Asia. International regulation to limit pink salmon production from hatcheries might be appropriate if large adverse impacts on sockeye productivity can be demonstrated.
(2) Co-management of pink and sockeye fisheries and production may require special consideration. Specifically, efforts to rebuild sockeye populations by reducing exploitation rates in fisheries that catch sockeye as well as catch co-mingling pink salmon could increase pink salmon abundance in the next generation; an increase in pink salmon abundance could depress sockeye productivity, and potentially reduce the effectiveness of efforts to rebuild sockeye populations.

5.0 Overall Conclusions and Recommendations

All of the material in this section is also contained in the Executive Summary. The only difference here is that in this section we first present the summary of evidence for each hypothesis (Table 5-1) and then give our overall conclusions on the relative likelihood of those hypotheses (Table 5-2), whereas in the Executive Summary we present our conclusions first.

5.1   Summary of Evidence

Table 5-1 concisely summarizes the evidence **for** and *against* each of the nine hypotheses that was discussed in detail in Section 4 of this report. That evidence formed the basis for the Panel's judgments about likelihoods for those hypotheses, which are presented in Table 5-2. We have separated the summary of evidence concerning the overall decline since the late 1980s/early 1990s from the summary of evidence relating to the low 2009 returns. We also summarize the possible mechanisms associated with each hypothesis, as well as evidence for and against those mechanisms. The Glossary (Section 6) defines technical terms.

Table 5-1. A summary of evidence that is given in detail in Section 4 of this report for and against each hypothesis. For the sake of discussion, each hypothesis is stated as if true, but evidence in the table either supports that statement or does not. Evidence in favour is shown in blue normal font, evidence against is in *red italics*, and other notes (e.g. elaborations, data gaps) are in **black boldface font**. Abbreviations: AK=Alaska; HABs = Harmful Algal Blooms; QCS = Queen Charlotte Sound; R/EFS = adult recruits per effective female spawner; SEAK= Southeast Alaska; SK=sockeye; SoG=Strait of Georgia; PST=Pacific Salmon Treaty; WCVI = West Coast Vancouver Island. See Glossary for explanations of terms.

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
1. (a) Predation by marine mammals, and (b) unreported catch in the ocean by humans, are important contributors to the Fraser sockeye situation (Section 4.1).	Overall (late 1980s - now)	• Steller sea lions were severely depleted by hunting until protected 40 years ago. They have increased 3-fold since 1970, and are increasing at 5%/yr. • Sightings of Pacific white-sided dolphin have increased since late 1980s. • *Harbour seals were severely depleted by hunting until protected 40 years ago but have since recovered to historical levels. The population in SoG stabilized in the 1990s before the Fraser sockeye decline.* • Humpback whale populations are growing in B.C. and Alaska. • *There's no evidence of significant harvest of Fraser SK in non-Pacific Salmon Treaty (PST) fisheries in high seas or Alaska (AK)* • *Harrison sockeye should be exposed to approximately the same predation rates, yet they have <u>not</u> declined.*	• *Since marine mammals are mainly distributed outside the Strait of Georgia, non-Fraser sockeye stocks should in theory be at least as vulnerable to marine mammal predation as Fraser sockeye. Columbia and Barkley Sound sockeye stocks have recently had much better post-juvenile survival rates than Fraser sockeye. This is evidence against the hypothesis that marine mammal predation was an important contributor to overall Fraser sockeye declines.*	• Total food consumption by mammals is potentially large enough to affect SK, but quantitative estimates are poor • There are 60,000 Steller sea lions in B.C. SK are > 20% of their diet in summer & fall (better diet data expected in Nov 2010), so significant effects on SK are plausible. • There are 25,000 Pacific white-sided dolphin in B.C., **but the % of sockeye in their diet is unknown.** • There are 100,000 harbour seals in B.C. (40,000 in SoG), *but there has been little change since the 1990s. Sockeye were less than 5% of diet in a 1980s study,* **but no recent diet data are available.** • Humpback whales have been observed feeding on salmon smolts in SEAK; large size and appetite, quick ability to learn new foraging; **no recent diet data** • *Documented harvest in B.C. and SEAK (under the PST) is already accounted for in estimates of productivity (R/EFS)*
	2009 returns	• *The percent of prey eaten is higher when prey are scarce, so record high Chilko smolt output in 2007 should have led to a low predation rate.* • *There were no sudden increases in either fisheries or mammals in 2007-2009*	• *See comment above; it also is evidence against the hypothesis that marine mammal predation was an important contributor to low returns in 2009.*	

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		■ *Unreported marine catch is very unlikely to explain low sockeye returns in 2009*		
2. Marine and freshwater pathogens (e.g., bacteria, parasites, and/or viruses), are important contributors to the Fraser sockeye situation (Section 4.2).	Overall (late 1980s - now)	■ Fish farms and hatcheries (possible sources of novel pathogens) have increased in the Strait of Georgia, but data on fish farm diseases and salmon production are not publicly available. ■ Some fraction of the Harrison sockeye juveniles are suspected to migrate later and via the Strait of Juan de Fuca, avoiding transit past fish farms and avoiding co-mingling with large numbers of infected adults.	■ The relationship with returns of non-Fraser stocks was not examined. ■ Since the 1980s, similar effects have been apparent in Yukon River Chinook (higher temperatures, fungal-like disease from parasite *Ichthyophonus*). ■ Coastal steelhead in Oregon are much more sensitive to the parasite *Ceratomyxa Shasta* than interior steelhead, which have evolved resistance (parasite endemic).	■ It is plausible that declines could have been caused by synergistic effects of changes in the ocean, including increased temperatures and changes in food quantity and/or quality, which also increased disease impacts (especially bacteria & parasites). ■ Strong genomic evidence for presence of a disease condition, possibly viral (Miller), but its nature, source, date of introduction, current host, and range are unknown. ■ The expansion of salmon farms provides a mechanism for amplifying endemic pathogens (Morton). ■ Sea lice (either wild or farmed origin) are increasing in abundance, leading to increased disease (Jones). ■ This mechanism is likely operating synergistically with other factors (e.g., higher water temperatures due to global warming), but is not solely responsible for declines.
	2009 returns	■ There is no direct evidence of unusual diseases affecting 2009 returns, other than normal senescence on the spawning grounds. ■ The extremely large abundance of Chilko smolts (nearly double the previous 50-year maximum) coupled with extremely low marine survival of Chilko sockeye (one-quarter of 50-year minimum) is consistent with a potential disease effect	■ The relationship with 2009 returns of non-Fraser stocks was not examined	■ Pathogens were likely operating synergistically with other factors (e.g., starvation), as a contributing factor, but were not solely responsible for the poor 2009 returns.

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
3. Ocean conditions (physical and biological) **inside and/or outside** Georgia Strait are important indicators of contributors to the Fraser sockeye situation (Section 4.3).	Overall (late 1980s - now)	■ The shared downward trends in total and post-juvenile productivity indicate that the mortality causing declines occurred in habitats shared by stocks. ■ The total productivity (R/EFS) for most Fraser SK is much more highly correlated with post-juvenile productivity (R/juvenile) than with juvenile productivity (juveniles / female). ■ There's a very strong correlation (r^2=0.87) between algal biomass (Mar 30-Apr 22 avg. Chlorophyll a) in QCS and Chilko SK marine survival (1998-2007). **However, the mechanisms are not understood. There are no long-term data on zooplankton abundance in the Strait of Georgia.** ■ There's some correspondence between periods of intensified winter/spring downwelling on the B.C. coast and the declining productivity of Fraser SK ■ There's a positive correlation between the abundance of juvenile sockeye (catch per unit effort) in the Strait of Georgia and $\log_e$(total Fraser SK production) two years later over 1998-2007 (r^2=0.35 with all of the data).	■ There was also a downward trend in the productivity of Central Coast (Skeena River) and WCVI sockeye, during ~2000-2004. ■ Fraser R. and Central Coast sockeye productivity trends did not correlate with trends from the Columbia Basin or Barkley Sound during 1990-present, suggesting that the causes are limited to inshore waters where juvenile sockeye migrate early in their marine life, a conclusion that is consistent with many past studies. ■ The productivity of other species (chinook, coho) that share the Strait of Georgia show similar, but not completely consistent, decreasing patterns compared to productivity of Fraser sockeye.	■ Climate-driven changes in nutrients & food production can reduce smolt growth after they enter the ocean environment, leading to more size-selective predation (stage 1), and reduced winter survival after the first summer at sea due to lower fat reserves (stage 2). ■ There's evidence for these mechanisms from SEAK pink salmon, Columbia R. spring chinook and steelhead, Bristol Bay SK, Puget Sound Chinook and coho, Washington, Oregon, & SoG coho. ■ DFO salmon surveys (Puget Sound, SoG, WCVI, QCS) show large yearly variation in ocean conditions, food, and sockeye abundance, growth, diet, and energetics. ■ **Lack of detailed knowledge about spatial / temporal patterns of marine migration of juvenile sockeye, phytoplankton and zooplankton abundance, and salmon mortality make it hard to distinguish between early mortality in SoG and later mortality further north.** ■ Ocean conditions may operate synergistically with pathogens, parasites, HABs & contaminants in freshwater and estuary, **but it is impossible to attribute a % mortality to each factor**
	2009 returns	■ There were poor ocean (shallow mixing zone) and food conditions in the Strait of Georgia in 2007. ■ *Conditions outside the SoG are not consistent with the hypothesis (average zooplankton in QCS, good fledgling success of planktivorous birds at Triangle Island),*	■ There was average zooplankton production in QCS in summer 2007, but apparently poor zooplankton production in the Strait of Georgia.	

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		though algal biomass (April chl_a) was very low in QCS ■ Fraser SK caught in QCS and Hecate Strait in 2007 were the smallest on record (1999-2009), yet Chilko smolts leaving the lake were large sized. This could be due to poor food in the Strait of Georgia in 2007. ■ *There's no direct evidence for why Harrison SK would have a different productivity pattern than other Fraser SK*		
4. Harmful algal blooms (HABs) in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation (Sec 4.4).	Overall (late 1980s - now)	■ Since 1989, large-scale blooms have caused severe mortality of farm fish and some observed wild fish mortality in Puget Sound. ■ Since 1989, the marine survival of Chilko SK is 2.7% in years when their entry into SoG coincided with major HABs, and 10.9% in years with no bloom or only minor blooms. ■ Before 2002, Heterosigma blooms began in late June or later. Since 2002, blooms have occurred as early as late May or early June, more coincident with the timing of juvenile SK entry into Southern SoG. ■ May-June blooms appear to be correlated with larger / earlier Fraser River discharges. ■ *There was improved survival of juvenile SK in the Strait of Georgia in the spring of 2008 despite HABs in June,* which may reflect variation in migration timing, routes and exposure to HABs. ■ *Harrison SK are apparently not affected by HABs,* but may miss HABs due to different juvenile migration timing.	■ There was a strong correlation between the total survey weight of young-of-year Pacific Herring in the SoG and the smolt-to-adult survival rate of Chilko SK for ocean-entry years 1997-2007 *(though not for years before then)*, suggesting that common factors affect both species in the SoG (not necessarily harmful algal blooms; it could be any of several different mechanisms) ■ The relationship with returns of non-Fraser stocks was not examined.	■ HABs (especially Heterosigma) can kill fish via gill damage and respiratory failure, and harm their prey, **though the response of SK to HABs is unknown.** ■ It's credible that HABs could cause acute or chronic toxicity and/or food web or prey impoverishment. ■ The spatial location of the largest HABs in the southern SoG appears to generally overlap with the migratory route of Fraser SK. ■ The timing of the largest HABs is generally consistent with SK migration timing in 2006-08, **but there were no HAB data in southern SoG in 2000, 2004 and 2005.**

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		▪ Lack of HAB data during the 1980s (and gaps in 2000, 2004, 2005) weaken the ability to compare long term trends in HABs with long-term trends in Fraser SK productivity.		
	2009 returns	▪ The location and timing of HABs in 2007 are consistent with hypothesis that HABs may have contributed to low 2009 returns.	▪ The main occurrence of HABs in southern SoG may partly explain why other stocks (e.g. Barkley Sound, Columbia River, central B.C. Coast) showed less reduction in productivity of 2009 returns, *though HABs did occur in Broughton and QCS in 2007*	
5. Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation (Section 4.5).	Overall (late 1980s - now)	▪ Contaminant effects (e.g., concentrations in water or fish tissues) could not be correlated with productivity indicators for Fraser SK due to lack of data on both environmental loadings and body burdens. ▪ *No contaminants were identified as a probable cause for recent declines in Fraser SK* ▪ Some contaminants have increased over the period of interest. (e.g., pesticides, flame retardants, pharmaceuticals and personal care products) *while others have decreased (e.g., persistent, bioaccumulative and toxic (PBT) contaminants).*	▪ *Columbia Basin SK recently showed improved productivity despite considerable contamination.* ▪ *SK productivity has been poor in Smiths and Rivers Inlet (Owikeno) since mid-1990s, even though there is very little industrial development in these regions* ▪ *Harrison River juveniles are resident in the lower Fraser River and would be exposed to water-borne pollution in the lower river and estuary for a few months, yet this sockeye stock has shown increasing productivity over time.*	▪ Contaminants are known to have many lethal and sublethal effects on fish; both types of effects may increase when fish are challenged by other factors such as high temperatures or nutritional stress. ▪ *It's highly unlikely that there were direct fish kills from toxic chemicals on Fraser SK,* though sublethal effects are possible, and may be a secondary factor contributing to reduced productivity. ▪ Persistent, Bioaccumulative, and Toxic contaminants (PBTs) in adult SK fat tissues could affect reproduction, growth and development, and can be detected in fatty tissues. ▪ Non-persistent contaminants could affect hatching, rearing or migration **but do not provide any chemical fingerprint.**
	2009 returns	▪ *Despite the lack of quantitative data on contaminants, there's no reason to believe that there was a sudden increase in the contamination of SoG or the Fraser Estuary in 2007, the ocean-entry year for Fraser sockeye returning in 2009.*	▪ The relationship of this hypothesis with 2009 returns of non-Fraser stocks was not examined.	

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
6. Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation (Section 4.6).	Overall (late 1980s - now)	▪ *Total productivity (R / EFS) for most Fraser SK stocks is much more highly correlated with post-juvenile productivity (R / juvenile) than with juvenile productivity (Juveniles / female spawner), suggesting that variation is driven by changes in juvenile-to-adult portion of the life cycle, rather than in the egg-to-juvenile portion.* ▪ *Covariates related to human disturbance (i.e., road density, recent logging, stream crossings, human land use) are not correlated with Fraser sockeye productivity trends.* ▪ The only significant covariates negatively correlated with Fraser SK productivity trends were those related to watershed location *(i.e., distance from ocean, latitude, nursery lake elevation),* which is consistent with the potential for increased mortality during longer downstream (or upstream) migrations ▪ *Primary productivity in Chilko and Quesnel lakes is not correlated with trends in Fraser SK productivity.* ▪ Though there are many gaps in the time series, *recent lake productivities for Fraser stocks appear as high as (or higher than) in late 1980s / early 1990s.* ▪ There's evidence for density-dependent survival and growth of lake-rearing juveniles, *but there are no meaningful trends over time in Shuswap, Quesnel, and Chilko lakes, and no consistent trends across nursery lakes* ▪ *There are no systematic shifts in the median migration date of smolts measured at Chilko Lake or Mission.*	▪ Studies of other SK stocks on the west coast of N. America suggest that freshwater spawning and rearing environments may be important for stock productivity and abundance.	▪ There are many potential mechanisms by which logging, agriculture, roads, urbanization, industrial development and warming climate could affect SK habitats and survival rates (Table 4.6.1). ▪ More than 50% of the total life-cycle mortality occurs in natal spawning and rearing areas ▪ *Sockeye should be less sensitive to freshwater conditions than other species of Pacific salmon (e.g., coho) because they rear in lakes rather than streams* ▪ *Compensatory mortality in lakes may buffer populations against habitat impacts on the spawning grounds (i.e., if egg-fry survival is lower in streams, fry-smolt survival may be higher in downstream lakes due to less competition).*

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		▪ There are no reliable survival estimates for Fraser SK during their outmigration except for the 2010 Chilko Lake study. ▪ Cultus Lake smolts migrate 13 days later than they did 80 years ago, **but Cultus is not one of the 18 Fraser stocks examined**		
	2009 returns	▪ *No major changes in freshwater habitat conditions are known to have occurred during 2005-2006, or in downstream migratory conditions during 2007 (other than earlier and larger flows). Major changes would be required if freshwater habitat were to have significantly contributed to the poor 2009 returns.*	▪ *Despite having similar freshwater spawning and rearing habitats to Fraser SK (dry interior watersheds), Columbia River SK returned in record numbers in 2008 & 2009.*	
7. Delayed density dependent mortality is an important contributor to the Fraser sockeye situation (Section 4.7).	Overall (late 1980s - now)	▪ For several major stocks that account for most of the Fraser SK production (i.e., Early Stuart, Late Stuart, Stellako, Quesnel, Chilko, Seymour and Late Shuswap), the variation in R / EFS since the late 1980s is better explained by including lagged density dependent effects of past spawner abundance (Larkin model) than by standard Ricker models. This suggests that large spawning returns may have had negative effects on subsequent brood years in some stocks and years. ▪ When data from abundant years (more precise data) are given more weight, the Larkin model fits the historical pattern better. ▪ The Larkin model can explain most of 1990-2002 recruitment decline in the above listed stocks, *but not after that, nor does it explain that decline in smaller Fraser SK stocks, which might not have sufficient abundance for delayed density-dependent effects.*	▪ In the Fraser, 4-year-old fish dominate and cycles occur regularly. In AK some SK systems are dominated by 5-year-old fish and cycles are regularly observed. ▪ The effects of delayed density dependence may not occur in most non-Fraser stocks where there are mixtures of ages; few of those stocks show cyclic dominance. ▪ Most other sockeye systems in British Columbia have mixed ages of returns (3, 4 and 5 years old), and the cycles are not observed in those cases.	▪ Delayed density dependence could be caused by predators, parasites, disease and/or reduced zooplankton production. Predation effects are theoretically possible (have been modeled for Late Shuswap). **There are insufficient data to test whether any of these mechanisms are actually operating.** ▪ *There was no evidence of zooplankton food limitation in Quesnel Lake following record escapements of 2001 & 2002 (section 4.6), so some other mechanism (e.g. disease, predators) would need to be responsible for delayed density dependence there.* ▪ Density-dependent mechanisms may have operated prior to industrial fisheries; (1) large abundances may have masked periods of low productivity, (2) abundances may have been highly variable due to lagged interaction with predators and disease, (3) there were

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		▪ *The Larkin model still has large deviation for the 2003 and 2005 brood years,* though smaller than those for the Ricker model.		periods of low returns and famine, as recorded in First Nations' oral history; and 4) traps and weirs resulted in high exploitation rates on some stocks.
	2009 returns	▪ *This hypothesis does not explain the 2009 return year: 77 million unusually large Chilko smolts went to sea in 2007, yet poor returns were observed in 2009. If freshwater density-dependent mechanisms were driving poor returns, then fewer smolts should have gone to sea.* One alternative explanation is that smolts were diseased or in poor condition when they left freshwater, but did not die until after they left the lake. There is little evidence for or against this hypothesis except that Chilko smolts were large in body size, which is not consistent with suffering from a disease.	▪ The relationship of this hypothesis with 2009 returns of non-Fraser stocks was not examined.	
8. (a) En-route mortality during upstream migration, and (b) effects on fitness of the next generation, are important contributors to Fraser sockeye situation (Section 4.8).	Overall (late 1980s - now)	▪ *En-route mortality does not contribute to declines in <u>productivity</u> (R/EFS) of Fraser SK because the losses are already factored into the calculation of recruitment (R in R / EFS).* ▪ En-route mortality does reduce spawner abundance unless compensated for by lower harvest rates. Managers have attempted to reduce the impacts of en-route mortality on spawner abundance by reducing harvest rates (and catches) in recent years, partly in response to predictions of high rates of en-route mortality.	▪ The results obtained for en-route mortality of Fraser River sockeye salmon are generally consistent with those for Columbia River populations in that exposure to temperature stress outside of the normal or historic range can contribute to mortality. *However, this does not help to explain declines in Fraser sockeye productivity.*	▪ *En-route mortality does not contribute to the decline in productivity in R/EFS since R is defined as the abundance of fish that arrive at the coastal fishing areas. Thus, estimates of R already include estimated en-route losses.* However, en-route mortality will tend to reduce spawner abundance and population viability. ▪ There is abundant field and experimental evidence that populations are stressed by temperatures > 18°C, leading to direct mortality, exhaustion, or disease, with females more vulnerable than males. ▪ Intergenerational effects refer to impacts of parental condition on fitness of offspring (e.g., reduction in fry quality or survival caused by

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		▪ *The absence of declining trends in freshwater survival in populations that have suffered en-route mortality (e.g., Early Stuart fry/EFS, Weaver fry/EFS) does not support the hypothesis that intergenerational effects are a major contributor to the decline.* ▪ Intergenerational effects are not yet documented. *One study shows that incubated eggs from dying or recently dead females show no effect on viability of their eggs or juveniles.*		nutritional or disease status of the parents). Significant intergenerational effects could cause changes in R/EFS, but there isn't yet any evidence of such effects. *Again, incubated eggs from dying or recently dead females show no effect on viability of the eggs or juveniles.* ▪ A delayed intergenerational effect on smolts is possible (and consistent with survival data), but a mechanism (e.g., disease) has yet to be identified.
	2009 returns	▪ *En-route mortality cannot account for poor returns in 2009, because estimates of those returns are made at entry to freshwater, before en-route mortality takes place.*		
9. Competitive interactions with pink salmon are important contributors to the Fraser sockeye situation (Section 4.9).	Overall (late 1980s - now)	▪ There are 3 different mechanisms by which this hypothesis may be operating (see right-most column). ▪ The overall productivity of Fraser SK over the past 45 years is inversely correlated with the aggregate abundance of adult pink salmon returning to the Fraser, SEAK, and Prince William Sound in the year that age-4 Fraser SK return. These results are consistent with version 2 *but not version 1 of the hypothesis.* ▪ The mean normalized length of age 1.2 Fraser sockeye is larger in even years than odd years, consistent with a competition mechanism (i.e., version 2 of the hypothesis) *but not with a mechanism in which maturing Fraser pinks eat seaward migrating juvenile Fraser SK (i.e., version 3).*	▪ Fraser SK populations and SK populations outside of SoG should experience similar competitive interactions with pink salmon in North Pacific, to the extent that their migratory routes overlap. ▪ *Increasing or stable trends in productivity of non-Fraser sockeye populations (e.g., those in northern B.C., Barkley Sound, and Columbia River) require postulating different migratory patterns that affect the degree of interaction with pink salmon, so the hypothesis cannot be considered complete or parsimonious.*	▪ Competition for food between pink salmon and SK has potential to cause density-dependent reduction in growth and/or survival of Fraser sockeye, through two possible mechanisms: 1. Odd-year Fraser pink fry may compete with even-year Fraser SK smolts migrating into SoG in spring and summer of same year. If so, <u>even-yr</u> Fraser SK should show poorer growth and survival than odd-yr SK *(not supported by evidence).* 2. Abundant odd-yr pink salmon from AK and Russia may compete with Fraser SK on high seas. If so, <u>odd-yr</u> Fraser SK should show poorer growth & survival than even-yr SK (is supported by evidence).

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
		■ The two largest negative anomalies in Fraser sockeye returns, as well as in returns per spawner were both in odd years (brood years 2003 and 2005). *However, pink salmon abundance in the North Pacific Ocean did not increase dramatically in those years (i.e. not consistent with a larger than normal competitive effect under version 2 of the hypothesis),* ■ The hypothesis is inadequate as a sole explanation , but may have contributed to the longer term decline in productivity of Fraser SK. ■ Sea-type SK in the Fraser River (Harrison River and Widgeon Slough) migrate to sea a year earlier than lake-type sockeye and could interact with pink salmon in different years or in different geographical areas. Consequently, opposite trends in abundance and/or productivity observed for these populations do not disprove the hypothesis, **although there was no analysis of Harrison or Widgeon stocks in this regard.**		3. **A third possible mechanism is predation by returning Fraser adult pink salmon on Fraser SK smolts that are migrating seaward during** early summer. This would affect odd-yr Fraser SK more *(<u>not</u> supported by evidence). Such predation has not been documented and seems unlikely because it would be restricted to a short period of overlap of smolts and adults in early summer. Also, productivity of Fraser sockeye was not significantly inversely correlated with numbers of adult pink salmon that returned in the year that the SK smolts migrated.* ■ Competitive interactions more plausible because diets and distributions of immature pink and SK salmon are known to overlap. Competitive interactions could also decrease overall productivity of Fraser SK by reducing adult size and fecundity, with or without direct effects on SK survival. Version **2** is more consistent with evidence than versions **1** or **3**.

Hypothesis	Time Period	Consistency with Productivity in Fraser Stocks (section 3.1)	Consistency with Productivity in non-Fraser Salmon (section 3.2)	Plausibility and Realism of Proposed Mechanism
	2009 returns	▪ The evidence is consistent with pink salmon being a contributing cause to the low returns in 2009, but not the sole cause. ▪ The lowest-ever average weight of adult Fraser River pink salmon in 2009 suggests poor food may have affected both pink and sockeye salmon that returned that year, and that competition between pinks and sockeye may have occurred in the N. Pacific.		

5.2   Probability of, or relative likelihood of, alternative hypotheses

Based on all of the evidence presented at the workshop and summarized in this report, the Panel rated each of the nine alternative hypotheses as shown in Table 5-2 in terms of the relative probability, or likelihood, that a given hypothesis could explain the Fraser sockeye situation. These ratings were made separately for explaining the overall decline or the 2009 returns. When Panel members concluded that the available evidence was consistent with a factor contributing to Fraser sockeye stock declines during the period of interest (i.e., either the overall period or 2009 returns), they rated that hypothesis as *likely* or *very likely*. Conversely, if they concluded that the available evidence was inconsistent with a factor contributing to Fraser sockeye declines, they rated the factor as *unlikely* or *very unlikely*. An intermediate level of support received the rating *possible*. The Panel did not attempt to force a consensus on their ratings. Although there was some variation in support for a few hypotheses, Panel members generally had similar ratings for most hypotheses.

The Panel agreed that multiple hypothesized causal mechanisms are very likely to be operating simultaneously and their effects may be additive, multiplicative (i.e., synergistic), or may tend to offset one another's effects (e.g., mortality earlier in the life history can create less density dependence and higher survival later in the salmon's life cycle).

The Panel concluded that the available evidence for and against each of the nine hypotheses does ***not*** point to a single cause of either the poor adult returns of Fraser River sockeye in 2009 or the long-term decrease in returns per spawner. Instead, the evidence suggests that multiple causal mechanisms very likely operate simultaneously and that their effects may be additive, multiplicative (i.e., synergistic), or may tend to offset one another's effects. An example of the latter would arise if mortality early in the life history leads to less density-dependent competition and higher survival late in the salmon's life cycle). Furthermore, the most probable mechanisms largely affect juvenile sockeye migrants and fish in their early marine life stages.

The main conclusions about the alternative hypothesized causes of the Fraser sockeye situation are as follows.

Main conclusions about mechanisms
The Panel's judgments, summarized in Table 5-2, are that physical and biological conditions inside the Strait of Georgia during the juvenile life stage are *very likely the major cause* of poor survival of the cohort that returned in 2009. Those conditions in the Strait are also *likely the major cause* of the long-term decrease in productivity of most Fraser sockeye stocks that has occurred since the late 1980s or early 1990s. Similar physical and biological conditions were judged to affect survival of Fraser sockeye outside the Strait of Georgia, but to a lesser degree. The Panel lacked certain types of information needed to identify the mechanisms more specifically (as described in Section 4) and has recommended future research that may lead to such detailed conclusions (see Section 5).

From the available evidence, the Panel also deduced that freshwater and marine pathogens (that is, viruses, bacteria, and/or parasites) are an important contributor to both the poor returns in 2009 and the long-term decrease in productivity, but again, data did not permit distinguishing further among those factors. It is conceivable that pathogens picked up in fresh water did not cause mortality until the ocean life stage. The Panel members' views on pathogens ranged from a *very likely contributor* to a *possible contributor* to the Fraser sockeye situation (Table 5-2).

Panel members believe that diseases caused by these pathogens are likely made worse by natural and anthropogenic stressors.

Only three other hypothesized mechanisms received ratings as high as *likely contributing* factors in Table 5-2. First, a bloom of harmful algae in southern Georgia Strait in 2007 was a *possible* explanation of the poor returns in 2009, and a *possible to unlikely* explanation of the long-term decline in productivity of Fraser sockeye. Second, Panelists expressed conclusions ranging from *likely* to *unlikely* for the hypothesis that delayed density-dependent mortality contributed to the long-term decrease in productivity. The delayed mechanism is indirect because increased mortality on a given cohort of juvenile sockeye is attributed to excessive abundances of spawners in previous years that lead to reduced food supply, increased predation, and/or an increased incidence of pathogens. Finally, competitive interactions between pink salmon and Fraser River sockeye were rated as either a *likely contributor* or a *possible contributor* to the long-term downward trend in Fraser sockeye productivity.

Hypotheses that are rated as only *possible* or *unlikely* are also shown in Table 5-2.

Table 5-2. The Expert Advisory Panel's judgment of the relative likelihood that a given hypothesis was either a major factor in, or merely contributed to, the observed spatial and temporal patterns in productivity of Fraser River sockeye populations. These likelihoods are based on evidence presented at the workshop, during subgroup discussions, and Panelists' background knowledge. The top row for each hypothesis reflects conclusions with respect to overall productivity patterns (i.e., over the long term). Shading of multiple cells reflects a range of opinions among Panel members. The second row considers just the 2009 *return year*. The colour of shading reflects the Panel's conclusion about the degree of importance: **black** = major factor; **grey** = contributing factor. The strength-of-evidence column reflects the quantity and quality of data available to evaluate each hypothesis/stressor. Panel members made their best judgments of the relative likelihood of each hypothesis, given the available evidence.

Hypothesis	Time Period	Strength of evidence	Relative likelihood that each hypothesis caused observed changes in productivity during the indicated time period				
			Very Likely	Likely	Possible	Unlikely	Very Unlikely
1a. Predation by marine mammals is an important contributor to the Fraser sockeye situation (Section 4.1).	overall	Fair			grey		
	2009	Fair					grey
1b. Unreported catch in the ocean outside of the Pacific Salmon Treaty area is an important contributor to the Fraser sockeye situation (Section 4.1).	overall	Good				grey	
	2009	Good					grey
2. Marine and freshwater pathogens (bacteria, parasites, and/or viruses), are important contributors to the Fraser sockeye situation (Section 4.2).	overall	Fair	grey	grey	grey		
	2009	Fair	grey	grey	grey		
3a. Ocean conditions (physical and biological) <u>inside</u> Georgia Strait are important indicators of contributors to the Fraser sockeye situation (Section 4.3).	overall	Fair		black			
	2009	Good	black				
3b. Ocean conditions (physical and biological) <u>outside</u> Georgia Strait are important indicators of contributors to the Fraser sockeye situation (Section 4.3).	overall	Fair			grey		
	2009	Fair			grey		
4. Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation (Sec 4.4).	overall	Fair			grey	grey	
	2009	Fair			grey		
5. Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation (Section 4.5).	overall	Poor			grey		
	2009	Poor				grey	grey
6. Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation (Section 4.6).	overall	Fair				grey	grey
	2009	Fair					grey

Hypothesis	Time Period	Strength of evidence	Relative likelihood that each hypothesis caused observed changes in productivity during the indicated time period				
			Very Likely	Likely	Possible	Unlikely	Very Unlikely
7. Delayed density dependent mortality is an important contributor to the Fraser sockeye situation (Section 4.7).	overall	Fair		▓	▓	▓	
	2009	Fair					▓
8a. En-route mortality during upstream migration is an important contributor to the Fraser sockeye situation (Section 4.8). En-route mortality is already considered in estimates of total recruits, so while potentially strongly affecting *spawner abundance*, this hypothesis cannot explain declines in *recruits per spawner*.	overall	Good					▓
	2009	Good					▓
8b. The effects of en-route mortality on fitness of the next generation is an important contributor to the Fraser sockeye situation (Section 4.8).	overall	Poor					▓
	2009	Poor					▓
9. Competitive interactions with pink salmon are important contributors to the Fraser sockeye situation (Section 4.9).	overall	Fair		▓	▓		
	2009	Fair			▓	▓	▓

5.3 Priorities for Monitoring and Research

Table 5-3 lists monitoring and research activities recommended by the Expert Panel based on their expertise and on evidence from participants at the workshop. The recommendations (1) are consistent with the Panel's conclusions about potential causes of the "Fraser sockeye situation" (decreasing adult returns per spawner, i.e., productivity) as identified in Table 5-2, (2) considered the strength of evidence noted for each hypothesized cause, and (3) considered the potential consequences of not addressing these issues. ***The recommendations address only the problems specific to Fraser River sockeye salmon***. Recommendations are stated broadly; a more comprehensive work plan that identifies specific monitoring and research topics would follow from this report.

Given that the workshop considered 12 primary and secondary hypotheses (nine main ones plus sub-hypotheses) and advice provided by over 35 technical experts, the list of possible recommendations for monitoring and research could be extensive. To focus this advice on high-priority issues, potential monitoring and research activities were organized by life history stage and related to the hypotheses assessed in Table 5-2. The importance of these activities was rated as High, Medium, and Low in Table 5-3 after considering both the relative likelihood that all of the factors operating within a given life stage contributed to the sockeye declines (i.e., a synthesis across all of the hypotheses affecting each life stage), and the degree to which information generated through the monitoring or research activity could improve the management and sustainability of Fraser sockeye and their habitats.

The recommended monitoring and research activities are expected to considerably advance knowledge concerning the state of Fraser sockeye productivity and the management actions needed to sustain Fraser sockeye populations. However, there was broad agreement among the Panel members that both the longer-term trend in productivity of Fraser River sockeye stocks, as well as the 2009 decline, were likely due to a complex suite of factors or interactions of several of the hypothesized mechanisms considered during the meeting. Thus, each recommendation should be seen as a component of a fully integrated, multi-disciplinary research program for Fraser sockeye salmon. Such an integrated approach is strongly recommended because multiple inter-dependent factors influence Fraser sockeye survival, and their cumulative effects ultimately determine the abundance of adult sockeye returning to spawn.

This integrated research plan can have two phases. The first phase can start immediately by having appropriate experts collaborating to identify the key individuals to be involved and to more fully exploit the rich dataset on Fraser River sockeye and pink salmon provided by the Pacific Salmon Commission and DFO.

The second phase of this plan involves development of the integrated freshwater, marine, and analytical programs required to implement the recommendations presented here. Many of the scientific staff involved in the workshop could immediately begin to coordinate their work more closely, but new programs will need to be developed and funded. As a conceptual framework for integrating future research and monitoring activities, the Panel members supported developing an overall model of the components of mortality of Fraser sockeye salmon. The goal of this model would be to better understand the individual factors that contribute to mortality at differing life stages and, perhaps more importantly, how these factors interact and are modulated by

various environmental conditions. The development of such a model would be unique. Because estimates of natural mortality typically contain a large degree of uncertainty, a better understanding of interactions among these factors could substantially improve the accuracy of models used to forecast run strength for Fraser River sockeye.

To accomplish this overall goal, research could be focused around providing input to a geographic information system (GIS) that would allow spatially referencing activities and building multiple data layers of information about hypotheses. Such a framework would recognize the need for simultaneous coordination of research across multiple disciplines. This tool for coordination would avoid the all-too-common situation of scientists who are working on one component of a program not being fully integrated with scientists conducting sampling on other components, thereby missing opportunities for cost-effective joint sampling programs and also failing to identify synergistic effects of one factor on another. The latter situation has created cases in which causal mechanisms of observed changes are difficult to understand.

The Panel suggests that a co-ordinated, multi-disciplinary two-phase research program be seriously considered in the immediate future. The Panel particularly notes seven recommended monitoring and research topics that were assessed as being very important for the future sustainability of Fraser River sockeye salmon (**the seven are noted in bold in Table 5-3**). It is worth emphasizing that there are new technologies in genomics, molecular genetics, tagging, remote sensing and monitoring, and data visualization that can now greatly facilitate information gained from these research efforts.

While we propose that our new initiatives focus on studies within the Strait of Georgia, there are existing short-term commitments to surveys in a number of offshore locations. Even modest augmentation of these existing programs in the form of support for sample collection and analysis, stock identification, and other biological information would improve our knowledge of Fraser sockeye abundance and distribution in offshore areas.

In weighing the evidence for alternative factors potentially affecting Fraser sockeye, the Panel found it enormously helpful to have data for sockeye populations outside of the Fraser Basin, as well as for other salmon species within and outside the Fraser Basin (i.e., Chinook, coho, chum, pink). These data provided the Panel with very helpful comparisons in terms of life histories, migratory pathways, and the magnitude and timing of hypothesized stressors, which helped to elucidate which mechanisms likely were or were not affecting Fraser sockeye productivity in a given year. Consistent with the above-described intent of developing a well-focused, integrated monitoring program, the Panel recommends including other salmon species in the selected set of well-monitored indicator populations and streams, both within and outside the Fraser Basin. This recommendation is consistent with The Wild Salmon Policy, which requires DFO to monitor each Conservation Unit, and would provide valuable information for managing other salmon species. Once a sampling platform is established for monitoring one salmon species, there is a relatively low incremental cost for monitoring others.

Table 5-3. The Panel's recommended research and monitoring priorities listed by sockeye life stage, indicating relevant hypotheses from Table 5-2. 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 hypotheses affecting that life stage), and (2) "Relevance to Management Actions", i.e., the value that such knowledge has for informing potential management actions. The Panel categorized that relevance as High, Medium, or Low. 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 Panel's highest priority research and monitoring topics.

Life stage for Fraser River sockeye salmon	Relevant hypotheses (Table 5-2)	Explanatory Importance	Relevance to Management Actions	Comments and issues for recommended research and monitoring activities
Parental spawning success and incubation	2, 6, 8b	Low	Low	Unlikely an explanation for the "Fraser sockeye situation" (particularly given rating of Hypothesis 8b), but may possibly be related to disease concerns. The latter could become a stronger priority in the future given climate change.
Juvenile rearing, production capacity, and smolt production	2, 6, 7	Medium	High	Although freshwater habitat was rated as a very unlikely explanation for the "Fraser sockeye situation", quantitative assessment of smolt production is essential to separately estimate survival rates in pre- and post-juvenile life stages. Such estimates will help focus management responses. However, direct estimation of abundance of seaward-migrating smolts is currently limited to only Chilko and Cultus lakes. Furthermore, ecosystem dynamics within Fraser watershed lakes are poorly monitored. **The Panel strongly recommends increased numbers of quantitative juvenile assessments and studies of in-lake responses, especially as the latter relate to hypothesis 7 (delayed-density dependent mortality).**
Downstream migration to estuary	2, 5, 6, 7	Medium	High	In addition to the point above about life-stage-specific productivity estimates, the survival rate of sockeye juveniles <u>during their migration</u> 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.
Estuary and near-shore (<u>inside</u> Strait of Georgia and migration channels)	1a, 2, 3a, 4, 5, 7, 9	High	High	The life stage <u>inside</u> the Strait of Georgia received the strongest agreement as the most likely period for explaining both the poor 2009 returns as well as the long-term decrease in productivity of Fraser sockeye. Better understanding of this life stage may therefore improve future forecasting models. **At least four research and monitoring programs are recommended**:

Life stage for Fraser River sockeye salmon	Relevant hypotheses (Table 5-2)	Explanatory Importance	Relevance to Management Actions	Comments and issues for recommended research and monitoring activities
				(1) A fully integrated oceanographic and ecological investigation of the Strait of Georgia would involve both monitoring and research covering several disciplines simultaneously, including establishment of comprehensive sampling for zooplankton, harmful algal blooms, estimates of predation by marine mammals, etc. Such an integrated, coordinated research effort would help partition sources of mortality of Fraser sockeye salmon. (2) Studies of residency and migration paths of Fraser sockeye are needed in the Strait of Georgia. (3) Attention should be given to pathogens and contaminants in sockeye and how they may be expressed under different marine conditions (includes concerns for transmission of pathogens due to salmon farming). (4) Studies are needed to estimate the annual relative survival of Fraser sockeye over the period of residency in the Strait of Georgia. Studies of Fraser sockeye growth and survival are considered essential within the Strait of Georgia before these fish leave this semi-enclosed system and enter the North Pacific Ocean ecosystem. Estimates of relative survival over time can be used to guide the focus of future research and monitoring efforts, which could expand to more offshore areas if appropriate. For example, if future survival estimates indicate that most of the yearly variation in mortality occurs within the Strait of Georgia, the research and monitoring focus would remain there. On the other hand, if survival estimates were to indicate that more of the variation in mortality is occurring outside rather than inside the Strait of Georgia, then more effort would need to be allocated outside the Strait .
Migration to offshore areas (coastal but <u>outside</u> of Strait of Georgia)	1a, 2, 3b, 4, 7, 9	Medium	Medium	The Panel only rated hypothesized mechanisms occurring <u>outside</u> the Strait as "possible" explanations for both the Fraser sockeye situation over the long term and in 2009, which is a lower rating than mechanisms <u>inside</u> the Strait. Research outside of the Strait should be increased if the integrated research program suggested above for <u>inside</u> the Strait fails to be informative. If such research outside of the Strait is expanded, it should conform to the same fully integrated oceanographic and ecological model mentioned above, which includes several disciplines. Critical challenges for this element of the research program are its potentially high cost and mixtures of different stocks, which require genetic stock identification. Coastal surveys via remote sensing may also provide broader spatial information on ocean environmental conditions. Research and monitoring in this region should build on ongoing work, including DFO surveys for juvenile salmon in Queen Charlotte Strait, Queen Charlotte Sound and Dixon Entrance, and NOAA surveys of larval fish in the Gulf of Alaska, which also catch juvenile salmon.

Life stage for Fraser River sockeye salmon	Relevant hypotheses (Table 5-2)	Explanatory Importance	Relevance to Management Actions	Comments and issues for recommended research and monitoring activities
Open-ocean rearing	1a, 3b, 9	Medium	Low	Open-ocean research may be important for understanding competition between salmon species (e.g., pink-sockeye salmon, hypothesis 9), determination of growth and maturity, and over-wintering survival. The information is unlikely to be focused only on Fraser sockeye salmon, but as the Panel has found, informative data on non-Fraser populations has been useful in helping to narrow down the processes affecting Fraser sockeye. However, information with the resolution required to be useful for management of Fraser sockeye is unlikely here without great expense.
On-shore migration (includes periods in which marine fishing occurs)	1a, 1b, 2	Low	High	Because marine fishing mortality is not considered an explanation for the "Fraser sockeye situation" or the 2009 return, the importance for "explanation" is clearly low. However, continued assessments of return abundances are very important to future management decisions and sustainability of Fraser sockeye. The issues of appropriate harvest rates and catch allocation are more related to policy decisions than to research and monitoring.
Up-stream migration: (In-river fishing, migration rates/timing, survival rate accuracy of data)	2, 8a	Low	High	In the absence of any evidence of inter-generational effects (hypothesis 8b), this life stage receives a low rating for "explanation"; however, it merits a higher importance rating when future environmental conditions and allowable harvest rates are considered. With expectations for increased uncertainty and changes in environments in the presence of climate change, **the Panel recommends continued evaluation of the accuracy of in-river sockeye assessments and improvements in those assessments, as well as research and monitoring of in-river mortality of sockeye salmon. This recommendation should be extended to adult pink salmon** as well because there is currently no assessment of spawning escapement for Fraser pink salmon.

5.4 Scope for reducing stressors on Fraser Sockeye through management actions

Table 5-4 summarizes the Panel's recommendations for potential management actions to improve the sustainability of Fraser sockeye in the future. These actions follow from those that were recommended in Table 5-3 and in many cases require collection of new information. It is important to note that **these management actions should be taken <u>in addition to</u> current management actions**. Certain stressors (e.g., changes in ocean conditions) are not immediately within management control, but others could be acted upon soon after greater efforts are made to acquire background information. The importance placed on each recommended management action (and the associated sockeye life stages) reflect the views of the Panel about the Strength of Evidence in Table 5-2, the potential impacts of not taking these actions, and the ease and costs associated of each management action if it were implemented.

The first five actions listed in Table 5-4 (related to contaminants, pathogens, harmful algal blooms, marine mammals, and the delayed density-dependent hypothesis) would in total greatly increase the understanding of determinants of sockeye productivity and the early-marine survival of these fishes. Monitoring the survival of Fraser sockeye through the Strait of Georgia could provide an important advance in predicting the subsequent return of adult sockeye and could be assessed two years before their return. Without these efforts and with the expected continuing environmental changes, our understanding of sockeye productivity and appropriate management actions are not likely to improve.

Given the level of uncertainty about the multiplicity of potential causes of the long-term decline in productivity of Fraser River sockeye, as well as the unexpectedly poor returns in 2009, the Panel was not able to recommend other high-priority actions beyond those listed in Table 5-4 that could be considered prudent measures to take in the present circumstances. However, there is one management concept that would be prudent to follow, and that is to continue to manage Fraser River sockeye salmon in a biologically cautious manner. This approach is also consistent with the recent certification conditions placed on Fraser sockeye salmon by the Marine Stewardship Council.

A cautionary note: Additional information is required to resolve the uncertainties surrounding Fraser sockeye productivity and future fishing opportunities. Some recommended studies will be of limited duration but other actions will require annual monitoring and evaluation. Thus, the Panel recognizes that these recommended monitoring, research, and management actions will require new financial resources. However, since our proposed research program builds on some existing programs, it is important that funding of these programs be maintained, and not reduced to fund these new initiatives.

Table 5-4. The Panel's recommendations for management actions to reduce impacts on Fraser sockeye salmon, as suggested by the ratings and evidence for potential causes of the Fraser sockeye situation given in Tables 5-1 and 5-2, as well as the monitoring and research recommended in Table 5-3. Also shown are risks associated with <u>not</u> taking the recommended actions. Each action listed below is given a High importance rating.

Potential Action	Life stage(s)	Risks associated with NOT implementing these actions.
<u>Contaminants</u>: Acquire data to construct chemical budgets within the Fraser watershed, improve accountability for their use, and assess impacts of contaminants in freshwater and marine environments.	Juvenile, smolts, and early marine rearing	The issue of contaminants is recognized as an unknown risk at this time and their usage is poorly documented. Current usage may be having direct lethal effects or more likely chronic sub-lethal effects that act synergistically with other stressors, in particular pathogens or increasing temperatures. These could be controllable impacts that are not currently being assessed.
<u>Pathogens (bacteria, parasites, and/or viruses)</u>: Create an on-going evaluation of pathogens in Fraser sockeye, and incorporate potential impacts from net-pen salmon farming. Ensure that new Aquaculture Regulations being developed by DFO include full reporting of fish health issues and production levels on farms.	Early marine rearing and the period during migration from in-shore to off-shore	Although pathogens were rated as possible to very likely contributors to the Fraser situation, direct evidence of this is limited (as seen by the variation of opinions). It is expected though, that in the future, with continued environmental change, pathogens could be a significant cause of reduction in sockeye productivity and sustainability. All sources of potential effects of pathogens must be assessed and opportunities for mitigation/control should be considered, including actions on fish farms and their processing plants.
<u>Harmful algal blooms</u>: Annually monitor and assess the frequency and intensity of blooms in the Strait of Georgia.	Early marine rearing	Management of some algal blooms has been undertaken using clay solutions to neutralize a bloom. These blooms are known to cause mortality of salmonids. Failure to acknowledge and assess this risk could cause direct mortalities in Fraser sockeye.
<u>Marine mammals</u>: If marine mammals prove to be a significant source of mortality to Fraser sockeye, then controls could be implemented.	Downstream migrants and early marine rearing	Production of yearling sockeye could be reduced and the sustainability of smaller sockeye populations could be put at risk. Predation poses a higher risk to smaller populations because typically a higher percentage of prey are killed as prey become less abundant (i.e., mortality is depensatory). Controls could be difficult to implement but may be limited to critical locations and periods.
<u>Delayed-density Hypothesis</u>: If the statistical evidence of this hypothesis is confirmed, then the current management policy for Fraser sockeye escapement goals should be re-examined. Wild Salmon Policy benchmarks also need to consider the effect of this hypothesis.	Returning adults and up-stream migrants	Interactions between brood years would reduce the productivity of some Fraser sockeye populations and reduce possible fishing opportunities (depending on the mechanism of interaction). Future environmental change could exacerbate these effects if not addressed.
<u>En-route mortality losses</u>: Continue monitoring and assessment of environmental conditions in-river and making the resulting adjustments to allowable harvest rates. Modify in-river fishing to minimize fishing-associated mortalities, and examine environmental mitigation where possible.	Adult up-stream migrants	Sockeye spawning escapement will be lower than desired and may threaten future sustainability of Fraser sockeye salmon.

Incorporate pink salmon into ecological research and fishing decisions: If evidence of competition between sockeye and pink salmon continues to accumulate, take action to optimize production of both species, possibly through limiting natural and hatchery production of pink salmon.	Early marine rearing and adult returns	An increasing abundance of pink salmon could depress sockeye productivity, and potentially undermine efforts to restore sockeye production. However, the importance of pink salmon to other species must be balanced with any efforts solely directed to sockeye salmon issues.

6.0 Glossary

AIC   Akaike Information Criterion: a measure of the goodness of fit of an estimated statistical model

alevins   Stage in the life cycle of salmon following emergence from the egg stage, characterized by the presence of a yolk sac attached to the body

CSAP   Centre for Science Advice - Pacific

CPUE   Catch Per Unit Effort (an index of abundance)

CU   Conservation unit

CWT   Coded Wire Tag: a small metal tag inserted into the nose of a juvenile salmon (usually a hatchery-reared fish) prior to release or migration to the ocean; the tag has encoded information that indicates the origin and year of release of the fish

depensatory mortality   Mortality is depensatory when its rate (i.e., proportion of population affected) increases as the size of the population decreases. This is in contrast to compensatory mortality where the mortality rate decreases as the population size decreases. Predation is a common source of depensatory mortality.

DFO   Fisheries and Oceans Canada

EFS   Effective female spawners: adjusts the initial estimate of female spawner abundance by the proportion of eggs that was _not_ laid

epilimnetic   Related to the top-most layer in a thermally stratified lake

escapement   The number of salmon returning to the spawning grounds

first-differencing   Process of replacing the data point x_t at time t with the difference $x_t - x_{t-1}$; reduces intra-series correlation (i.e., autocorrelation) and has been shown to greatly reduce the incidence of spurious between-series correlation

FRSSI   Fraser River Sockeye Spawning Initiative

fry   Stage in the life cycle of salmon following the "alevin" stage, characterized by the loss of the yolk sac and beginning of feeding on external prey

GSI	Genetic stock identification
HABs	Harmful Algal Blooms
jack sockeye	3-year-old sockeye, generally with 1 year of ocean growth and a small body size relative to older fish
J/EFS	Juvenile abundance (J) per effective female spawner (EFS)
Kalman filter	A statistical estimation method that attributes a portion of total variation in the observed data to systematic time trends and the rest to random variation arising from observation error and/or short-term, year-to-year natural process variation.
Kalman filter smoother	Produces the maximum likelihood estimates of the annual productivity parameter a_t
Larkin model	The Larkin model relates $\log_e$(recruits per spawner) to the number of spawners in a given brood year, as well as spawners in each of the preceding 3 years.
NPAFC	North Pacific Anadromous Fish Commission
Net pen	A fish-rearing enclosure used in lakes and marine areas.
NOAA	National Oceanic and Atmospheric Administration
outmigration	Movement of juvenile salmon from natal streams/lakes to rivers and then the ocean
parr	Stage in the life cycle of salmon following the "fry" stage, characterized by the presence of dark vertical bands on the side of the body
PBT	Persistent, bioaccumulative and toxic
PFOS	Perfluorooctanesulfonic acid or perfluorooctane sulfonate: a man-made fluorosurfactant and global pollutant
planktivory	Feeding on small (often microscopic) aquatic plants and animals, in fresh or salt water
productivity	The number of mature adult fish produced per spawner
PSC	Pacific Salmon Commission: a joint Canada/U.S. commission established under the Pacific Salmon Treaty to oversee the implementation of the Treaty

PST	[Pacific Salmon Treaty](): a treaty between Canada and the United States concerning the conservation, management, restoration and enhancement of Pacific salmon resources
R/EFS	Adult recruits per effective female spawner (see Glossary)
Ricker model	The Ricker model relates $\log_e$(recruits per spawner) to the number of spawners only in the brood year.
Ricker a_t	Represents the maximum rate of increase that a population could have with no fishing and low spawner abundance
R/J	Adult recruits per juvenile
recruitment	The process whereby young fish are added to an adult population
TAM	Total Allowable Mortality
underyearling	A juvenile salmon in the year following spawning
viral hemorrhagic septicaemia	A deadly infectious fish disease caused by the viral hemorrhagic septicaemia virus
WCVI	West Coast Vancouver Island
seawater challenge test	An experiment to measure seawater adaptability of juvenile salmon
scale pattern analysis	A stock identification technique based on the premise that rearing areas can result in unique scale patterns that allow point-of-origin assessments to be made
smolt	Stage in the life cycle of salmon following the "parr" stage, characterized by hormonal and other physiological changes that prepare the fish for its seaward migration and life in salt water, the loss of parr marks, and appearance of a silvery color
SDU	Standard deviation unit

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Appendix A: Structure of Assignment given to Speakers

Staff at the Pacific Salmon Commission (PSC) will be sending you background data on Fraser River sockeye well in advance of the workshop. These data will include response variables for which we are seeking explanations. Variables will include, among others, spatial and temporal patterns in salmon survival rates at various life history stages (freshwater and smolt-to-adult return rates), as well as adult recruits, total spawners, effective female spawners, recruits/effective female spawner (productivity), and residuals from Ricker models fit to loge(recruits per effective female spawner). [The latter variable removes confounding effects of within-stock density-dependent changes in productivity.] Some information will also be provided regarding potential explanatory variables, such as annual timing of downstream migration of smolts and upstream migration of adults. Most speakers will also have their own explanatory variables to discuss. We refer to all of this information as *the Fraser sockeye situation.*

Each speaker has been contacted by one of the organizers of the workshop to identify the topic to present. That topic is shown in the attached draft list of talks. Each speaker is asked to address that specific hypothesis (or combination of hypotheses) in a short, **15-minute** talk that will be followed by 15 minutes of questions and discussion. Such short talks are required because 18 speakers have been invited. There will also be opportunities to add information during 20-minute *thematic discussions* after each group of talks, and during a 3-hour session on the second day of the workshop.

Without exception, we ask all speakers to focus directly on the four questions in the box below, both orally as well as in a 2-5 page (including text, figures and graphs) written summary of their talk. Other workshop participants who are not making formal presentations may choose to address these questions, or even introduce new hypotheses and evidence, with a 2-5 page written summary. For both groups, these written summaries should be submitted prior to the workshop, but you will be able to amend them after the workshop if desired. The 2-5 page summaries, as well as other documents with relevant information, should be submitted to Don Kowal (kowal@psc.org) by 4 PM on Thursday the 10th of June for distribution to all workshop participants. **We request all participants to review these materials in advance of the workshop.**

Four questions
(1) To what extent does the specific hypothesis (or hypotheses) about Fraser River sockeye salmon stocks that you have been asked to address explain the spatial and temporal trends of:
> **(i) adult recruits,**
> **(ii) adult recruits per effective female spawner, and/or**
> **(iii) residuals from Ricker models fit to $\log_e$(recruits per effective female spawner)?**

Preferably answer this question in the context of long-term trends, but you could also discuss hypotheses about the particularly poor returns in 2009 arising from the 2005 brood year. Please focus on these three response variables or their components and show how the explanatory variables that you are addressing have changed in ways that account for the observed responses. Remember that problems began to appear at different times in different stocks, as shown in the data that will be sent to you from the PSC.

(2) What **direct or indirect evidence** is there to support (or not support) the hypothesis you have been asked to address? Please see the section below called "Indirect methods ..".
- What is the relationship (over space and time) between changes in the indicators of sockeye mortality agent(s) you are considering (e.g., pollutants, predators, food), and changes in the three sockeye response variables (recruits, productivity, residuals in recruits per effective female spawner)?
- What is the evidence for a mechanism of impact (e.g., does the stressor kill fish directly, or does it increase their susceptibility to other sources of mortality)?

(3) What specific research needs to be done to change the degree of belief in the hypothesis that you have been asked to address? Specifically, what type of practical and feasible research is needed to reduce critical uncertainties affecting scientific advice to management?

(4) Can any management actions reduce the effect on Fraser sockeye salmon of the hypothesized mechanism that you have been asked to address?

Indirect methods to estimate strength of evidence about different mechanisms

All fisheries scientists are well aware that we are not able to conduct large human-controlled experiments on wild Pacific salmon to identify the relative importance of different causal mechanisms responsible for changes in abundance and productivity of salmon. Instead, we have to rely on comparisons of monitored indicators of salmon and purported causal factors across time and space to deduce which factors are important. In some cases, we have sufficient data to conduct statistical analyses that fit specific models. The resulting parameter values and uncertainties in them are the most desirable source of information. However, in the majority of cases, we do not have the luxury of detailed data to permit such quantitative statistical analyses. In such cases, we usually rely on more *indirect* means of deducing effects of different causal mechanisms. All of us have probably done this to some extent in our research, so the following list of criteria for useful indirect evidence is just a reminder of ways to structure or critique evidence about hypothesized mechanisms affecting Fraser sockeye salmon during the workshop. Feel free to use such a structure when identifying the strength of evidence that you present or that you critique.

Indirect lines of evidence have been used in many fields. For instance, early work in medical statistics (Hill 1965 and 1971, as reviewed by Stewart-Oaten 1996) identified several types of evidence that can contribute to increased confidence about interpretations of causal mechanisms. These types of evidence apply equally well to the case of Fraser sockeye salmon in which data have been collected from passive observational (i.e., non-experimental) monitoring programs.

(1) How **plausible** is the hypothesized causal mechanism? Based on known physical and biological principles, is the proposed mechanism realistic?

(2) What is the **strength of the estimated effect**? The stronger it is, the more likely we are to correctly distinguish the mechanism causing an observed response from background variation and observation error, as well as from changes arising from other simultaneously operating mechanisms. Note that in such analyses, emphasis here is on estimating the strength of some effect and uncertainty in that estimate, rather than on formally testing some null hypothesis about the mechanism.

(3) The **consistency** of direction, magnitude, and duration of observed effects across studies of similar systems also lends credibility to a hypothesis about a given mechanism causing those effects. For instance, does empirical evidence show such a mechanism working in the same way for other species or situations?

(4) The **specificity** of effects should match the proposed mechanism such that, for instance, species or life stages that should **not** be affected by the mechanism do **not** show change, whereas the stages that **should** be affected **do** show a response.

(5) The **timing** of observed changes should occur simultaneously with, or after, the change in the state variable of the proposed causal mechanism. If there is a time lag in the response, it should be on a realistic time scale based on what is known about the processes involved.

(6) Similar to lines of evidence #4 and #5, observed **changes along a physical or biological gradient** should be related to the exposure or strength of the purported causal mechanism at those locations.

(7) Also, **similarity or coherence of responses** across space, time, populations, species, and indicators can strengthen the case for a particular mechanism.

(8) **"Natural experiments"**, or at least contrasting dynamic behavior at different times or places, are excellent potential sources of fortuitously created comparison groups. These are not human-manipulated experiments, but they may create distinct enough contrasting situations to learn about mechanisms causing observed changes.

Reference

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HYPOTHESIS HANDOUT (to be completed and submitted by all presenters)

Stressor / Hypothesis:

Your name:

Analytical Task: Please evaluate how indices related to the stressor hypothesis that you are investigating (e.g., ocean temperatures, contaminant levels) correlate with the following two indicators of sockeye productivity:

Productivity Indicator 1: Residuals from a Ricker model fit to $\log_e$(adult recruits **per effective female spawner** as a function of effective female spawner abundance). Graphs of these residuals over time are shown in the right panel of graphs in the worksheet **Time series plots**, in the spreadsheet Frasersockeyedata.xls, e-mailed from the Pacific Salmon Commission on May 25. These graphs (available for all 18 stocks) show changes in productivity over the entire life cycle, relative to the expected amount of recruits per effective female spawner for a given number of those spawners.

Productivity Indicator 2: Residuals from a Ricker model fit to $\log_e$(adult recruits **per juvenile** as a function of juvenile abundance). Graphs of these residuals over time are shown in the middle panel of graphs in the above worksheet, for 8 of the 18 stocks. These graphs show changes in productivity over the post-juvenile portion of the life cycle, relative to the expected amount of recruits per juvenile for a given number of juveniles.

If productivity indicators #1 and #2 are highly correlated, overall stock productivity is driven by factors affecting the post-juvenile portion of the life cycle. In contrast, if indicator #1 is declining and indicator #2 shows no trend, then declines in overall stock productivity (indicator #1) are driven by factors affecting the spawner-to-juvenile portion of the life cycle.

Questions:

(1) Summarize how stressor indices related to the hypothesis that you are investigating correlate with the trends in overall life-cycle productivity (indicator 1) **for the group of 17 sockeye stocks which have shown declines since the 1990s** (i.e., all except Shuswap and Harrison). Circle only one reply below.

Stressor generally became <u>less harmful</u> for this group of 17 stocks from 1990s to present (e.g., contaminants declined while stock productivity declined). <u>Strong evidence against the hypothesis</u>.

Stressor generally showed <u>no trend</u> from 1990s to present for this group of 17 stocks. <u>Evidence against the hypothesis</u>.

Stressor generally became <u>more harmful</u> for this group of 17 stocks from 1990s to present (e.g., contaminants increased while stock productivity declined). <u>Evidence that stressor could be a contributing factor to declines</u>.

Change in stressor during this period is unknown for this group of 17 stocks. <u>No evidence.</u>

Explanation / Comment (e.g., inferences gained from examining indicator #2 as well as #1, variation among stocks in stressor-productivity correlations):

(2) Summarize how stressor indices related to the hypothesis that you are investigating correlate with the trends in overall life-cycle productivity (indicator 1) **for two stocks**: Shuswap (generally constant since the 1990s); and Harrison (increasing since the 1990s). **Circle only one reply below.**

Stressor generally became more harmful for these two stocks from 1990s to present (e.g., contaminants increased while stock productivity remained constant or increased). Strong evidence against the hypothesis; stock productivity should have declined if stressor were a key factor.

Stressor generally showed no trend from 1990s to present for these two stocks. Evidence consistent with hypothesis for Shuswap (no trend in productivity), and against hypothesis for Harrison (increasing productivity).

Stressor generally became less harmful for these two stocks from 1990s to present (e.g., contaminants decreased). Evidence that stressor could be a contributing factor to productivity increases in the Harrison, but was not important in Shuswap.

Change in stressor during this period is unknown for these two stocks. No evidence.

Explanation / Comment (including inferences gained from examining indicator 2):

Appendix B: Workshop Agenda and Participant Surveys

Workshop on the Decline of Fraser River sockeye

Vancouver Island Conference Centre
101 Gordon St., Nanaimo, B.C., V9R 5J8

June 15 – 17, 2010

Workshop Agenda

<u>June 15th, 2010</u>   (Day 1)

8:00 am   Workshop start [coffee and pastries]

Session 1   **Welcome** [30 minutes]

8:15 am   Introductions and review of workshop objectives, agenda, principles, and task
                 process. [Larry Rutter (Chair, PSC), Randall Peterman (SFU), Dave Marmorek
                 (ESSA)]

Session 2   **Overview of the Fraser Sockeye Situation** [1 hour 15 minutes]

8:45 am   Background information on Fraser Sockeye [Mike Lapointe; 30 minutes]

9:15 am   Questions

9:30 am   Background information on B.C., Washington and Alaskan salmon <u>other than</u>
                 Fraser River sockeye [Presenter Timber Whitehouse; 30 minutes]

10:00 am   **Break** [30 minutes]

Session 3   **Predators, parasites, and disease** [3 hours]

10:30 am   Hypothesis: Predation by marine mammals is an important contributor to the Fraser sockeye situation. [John Ford, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

11:00 am   Hypothesis: Sea lice, either naturally occurring or passed from fish farms, are an important contributor to the Fraser sockeye situation. [Simon Jones, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

11:30 am   Hypothesis: Pathogens, including sea lice and diseases such as bacteria and viruses, either naturally occurring or passed from fish farms, are an important contributor to the Fraser sockeye situation. [Alexandra Morton, *Raincoast Research Society*; 15 min, followed by 15 min for Q & A]

12:00 pm   **Lunch** [45 minutes]

Session 3   **Predators, parasites, and disease cont.** [3 hours]

12:45 pm   Hypothesis: Genomic studies suggest that some disease has infected sockeye and has become an important contributor to the Fraser River sockeye situation. [Kristi Miller, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

1:15 pm   Hypothesis: Diseases in freshwater and marine systems are an important contributor to the Fraser sockeye situation. [Kyle Garver, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

1: 45 pm   Thematic discussion [30 minutes]

Session 4   **Physical oceanographic conditions** [2 hours 25 minutes]

2:15 pm   Hypothesis: Physical oceanographic conditions **inside and/or outside** Georgia Strait are important indicators of contributors to the Fraser sockeye situation. [Rick Thomson, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

2:45 pm   Hypothesis: **Outside** of Georgia Strait, oceanographic conditions, food, and/or predators (including squid) are important contributors to the Fraser sockeye situation. [Marc Trudel, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

3:15 pm   **Break** [25 minutes]

3:40 pm   Hypothesis: **Inside** Georgia Strait, oceanographic conditions, food, and/or predators are important contributors to the Fraser sockeye situation. [Dick Beamish, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

4:10 pm   Hypothesis: Physiological and growth conditions affect marine survival of sockeye smolts in Alaska. [Ed Farley, *Alaska Fisheries Science Center/ National Oceanic and Atmospheric Administration*; 15 min, followed by 15 min for Q & A]

4:40 pm   Thematic discussion [25 minutes]

5:05 pm   Wrap-up and things to ponder over dinner [25 minutes]

5:30 pm   **End of Day 1**

June 16th, 2009 (Day 2)

8:00 am   Workshop start [coffee and pastries]

8:30 am   Introductory remarks, recap of previous day's main themes, and plan for Day 2 [Dave Marmorek; 15 minutes]

Session 5   Toxic Algae and pollutants [1 hour 15 minutes]

8:45 am   Hypothesis: Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation. [Jack Rensel, *Rensel Associates*; 15 min, followed by 15 min for Q & A]

9:15 am   Hypothesis: Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation. [Robbie Macdonald, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

9:45 am   Thematic discussion [15 minutes]

10:00 am   **Break** [25 minutes]

Session 6   Freshwater conditions [1 hour 50 minutes]

10:25 am   Hypothesis: Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation. [Daniel Selbie, *Fisheries and Oceans Canada*; 15 min, followed by 15 min for Q & A]

10:55 am   Hypothesis: Predation, food supply, overescapement, disease, and parasites are important contributors to the Fraser sockeye situation. [Carl Walters, *University of British Columbia*; 15 min, followed by 15 min for Q & A]

11:25 am   Hypothesis: En-route mortality during upstream migration, plus effects on fitness of the next generation, are important contributors to the Fraser sockeye situation. [Scott Hinch, *University of British Columbia*; 15 min, followed by 15 min for Q & A]

11:55 pm   Thematic discussion [20 minutes]

12:15 pm   **Lunch** [45 minutes]

Session 7   Other factors affecting Fraser sockeye [1 hour 15 minutes]

1:00 pm   Hypothesis: Unreported catch outside of the Pacific Salmon Treaty area is an important contributor to the Fraser sockeye situation. [Phil Mundy, Alaska Fisheries Science Center/ National Oceanic and Atmospheric Administration; 15 min, followed by 15 min for Q & A]

1:30 pm   Hypothesis: Competitive interactions among wild and hatchery fish (potentially all salmon species) are important contributors to the Fraser sockeye situation. [Greg Ruggerone, *Natural Resources Consultants Inc.*; 15 min, followed by 15 min for Q & A]

2:00 pm   Thematic discussion [15 minutes]

Session 8   Examination of hypotheses by subgroups [1 hour 15 minutes]

2:15 pm   Explanation of subgroup tasks and processes and discussion themes [Dave Marmorek; 10 minutes]
                 • Break out into subgroups by session themes (see Appendix A for list of hypotheses / subgroup)

2:25 pm   Silent synthesis [20 minutes]
                 • **Participants** complete SURVEY 1 for each hypothesis within your thematic area, as well as for any other hypotheses you would like to comment on (SURVEY 1 is located in Appendix B; read guidance in Appendix D).

2:45 pm   **Break** [25 minutes]

3:10 pm   Subgroup discussion of the hypotheses in the assigned session theme.
                 • Synthesize responses within subgroup [1 hour]

4:10 pm   Five subgroups to report back to plenary [1 hour; 10 minutes per subgroup + 10 minutes discussion]

5:10 pm   Silent synthesis [20 minutes]
                 • **Participants** complete SURVEY 2 evaluating the likely contribution of each hypothesis to observed spatial and temporal patterns in Fraser River sockeye population indicators (SURVEY 2 is located in Appendix C; read guidance in Appendix D).
                 • **Observers** complete SURVEY 3 in Appendix E.

5:30 pm   Closing remarks [10 minutes]

5:40   End of Day 2

<u>June 17th, 2009</u> (Day 3) **- To be attended only by the Expert Advisory Panel**

8:30 am   Workshop start

8:30 am   Review of day's agenda and objectives [Dave Marmorek; 10 minutes]
- Distribution of results from Day 1 and Day 2

8:40 am   Panel's finalization of assignments and roles, fine tuning of process [30 minutes]

- Assign groups of hypotheses within particular themes to 1-2 Panel members to write up their joint conclusions relative to the four key questions using all the inputs from Days 1 and 2

Morning session

9:10 am   Writing time [3 hours]; **all Expert Advisory Panel members to bring laptops**

12:10 pm   **Lunch** [50 minutes] – materials are copied for all Panel members

Afternoon session

1 pm   Read written materials [1 hour]

2 pm   Discuss individual conclusions by theme and overall conclusions across all hypotheses [2 hours]

4 pm   Discuss overall research and management priorities [1 hour, 15 minutes]

5:15 pm   Next steps and concluding remarks

5:30 pm   End of Day 3 – Workshop finished

WORKSHOP PARTICIPANT SURVEY 1: Hypothesis survey (one for each Hypothesis)

Name: [   ]

Hypothesis # X: <Please copy and paste a hypothesis from the agenda>

(1) Conclusion about explanatory power of the hypothesis. What is your conclusion about the likely contribution of this hypothesis to observed spatial and temporal patterns in Fraser River sockeye population indicators (check one box)? See end of this survey for guidance on estimating the likelihood of each hypothesis, i.e., degree of belief in it.

Very Likely	Likely	Possible	Unlikely	Very Unlikely	Insufficient evidence presented or knowledge on my part to judge

(2) Evidence. What is your rationale for your above conclusion (i.e., what evidence for or against the hypothesis did you find to be the most compelling)? Refer to the indirect methods for estimating strength of evidence provided in the guidance at the end of this survey (i.e., plausibility, strength of effect, consistency, specificity, timing, change along physical /biological gradient, coherence of responses, and contrast between natural scenarios).

(3) Importance of Research. How important is it to conduct research on this hypothesis, relative to other hypotheses being considered here?

Very Important	Important	Average Importance	Less Important	Much Less Important	Insufficient evidence presented or knowledge on my part to judge

(4) Evidence. What is your rationale for your conclusion on the relative importance of conducting research for this hypothesis?

(5) Form of Research. If you feel that research on this topic is worth doing, what specific research needs to be done to change the degree of belief in this hypothesis (i.e., what practical and feasible research should be done to reduce critical uncertainties affecting scientific advice to management)? Explain your rationale.

(6) Management Actions. Can any management actions reduce the effect on Fraser sockeye salmon of this hypothesized mechanism? Explain your rationale.

(7) Other Comments:

Guidance on Assigning a Likelihood or Degree of Belief to a Hypotheses

One way to assign a degree of belief to a given hypothesis is to consider what fraction of cases being examined can be explained by that hypothesis. For example, there are 18 Fraser sockeye stocks which have been observed for varying numbers of years over the last 6 decades. Although we might not have enough data to definitively answer the following question, we could ask: "In what fraction of these 18 stocks has the hypothesized factor been an important influence on observed patterns in survival and recruitment, especially on declines during the last 3 decades?". Alternatively, you might only be considering a subset of those 18 stocks, for instance, the ones that began declining in the early 1990s. Regardless of which set of stocks you are considering, if you think that the hypothesized factor has been important in a large fraction of these stocks' declines (i.e., affecting many of them), then you would rate this hypothesis *likely* or *very likely*. Conversely, if you think that the hypothesized factor was an important influence in only a very small proportion of these stocks (i.e., affecting only a few stocks), you would rate this factor *unlikely* or *very unlikely*.

In addition, please consider the comments and questions about using indirect lines of evidence that were outlined in Attachment 2 of the workshop invitation package, namely:

(1) How **plausible** is the hypothesized causal mechanism? Based on known physical and biological principles, is the proposed mechanism realistic?
(2) What is the **strength of the estimated effect**? The stronger it is, the more likely we are to correctly distinguish the mechanism causing an observed response from background variation and observation error, as well as from changes arising from other simultaneously operating mechanisms. Note that in such analyses, emphasis here is on estimating the strength of some effect and uncertainty in that estimate, rather than on formally testing some null hypothesis about the mechanism.
(3) The **consistency** of direction, magnitude, and duration of observed effects across studies of similar systems also lends credibility to a hypothesis about a given mechanism causing those effects. For instance, does empirical evidence show such a mechanism working in the same way for other species or situations?
(4) The **specificity** of effects should match the proposed mechanism such that, for instance, species or life stages that should **not** be affected by the mechanism do **not** show change, whereas the stages that **should** be affected **do** show a response.
(5) The **timing** of observed changes should occur simultaneously with, or after, the change in the state variable of the proposed causal mechanism. If there is a time lag in the response, it should be on a realistic time scale based on what is known about the processes involved.
(6) Similar to lines of evidence #4 and #5, observed **changes along a physical or biological gradient** should be related to the exposure or strength of the purported causal mechanism at those locations.
(7) Also, **similarity or coherence of responses** across space, time, populations, species, and indicators can strengthen the case for a particular mechanism.
(8) "Natural experiments", or at least contrasting dynamic behavior at different times or places, are excellent potential sources of fortuitously created comparison groups. These are not human-manipulated experiments, but they may create distinct enough contrasting situations to learn about mechanisms causing observed changes.

WORKSHOP PARTICIPANT SURVEY 2: Summary across all hypotheses

Name: [   ]

(1) What is your conclusion about the importance of the contribution of each hypothesis to observed spatial and temporal patterns in Fraser River sockeye population indicators (check one box for each hypothesis)? If applicable, you can comment on which stocks are most likely to have experienced each stressor. See *Attachment A* for guidance on estimating the likelihood of each hypothesis, i.e., degree of belief in it.

Hypothesis	Very Likely	Likely	Possible	Unlikely	Very Unlikely	Insufficient evidence presented or inadequate knowledge on my part to judge
1. Predation by marine mammals is an important contributor to the Fraser sockeye situation						
Comments:						
2. Sea lice, either naturally occurring or passed from fish farms, are an important contributor to the Fraser sockeye situation						
Comments:						
3. Pathogens, including sea lice and diseases such as bacteria and viruses, either naturally occurring or passed from fish farms, are an important contributor to the Fraser sockeye situation.						
Comments:						
4. Genomic studies suggest that some disease has infected sockeye and has become an important contributor to the Fraser River sockeye situation.						
Comments:						
5. Diseases in freshwater and marine systems are an important contributor to the Fraser sockeye situation.						

Hypothesis	Very Likely	Likely	Possible	Unlikely	Very Unlikely	Insufficient evidence presented or inadequate knowledge on my part to judge
Comments:						
6. Physical oceanographic conditions **inside and/or outside** Georgia Strait are important indicators of contributors to the Fraser sockeye situation.						
Comments:						
7. **Outside** of Georgia Strait, oceanographic conditions, food, and/or predators (including squid) are important contributors to the Fraser sockeye situation.						
Comments:						
8. **Inside** Georgia Strait, oceanographic conditions, food, and/or predators are important contributors to the Fraser sockeye situation.						
Comments:						
9. Physiological and growth conditions affect marine survival of sockeye smolts in Alaska.						
Comments:						
10. Harmful algal blooms in the Strait of Georgia and/or northern Puget Sound/Strait of Juan de Fuca are an important contributor to the Fraser sockeye situation.						
Comments:						
11. Contaminants in the Fraser River and/or Strait of Georgia are an important contributor to the Fraser sockeye situation.						

Hypothesis	Very Likely	Likely	Possible	Unlikely	Very Unlikely	Insufficient evidence presented or inadequate knowledge on my part to judge
Comments:						
12. Freshwater habitat conditions in the Fraser River watershed are an important contributor to the Fraser sockeye situation.						
Comments:						
13. Predation, food supply, overescapement, disease, and parasites are important contributors to the Fraser sockeye situation.						
Comments:						
14. En-route mortality during upstream migration, plus effects on fitness of the next generation, are important contributors to the Fraser sockeye situation.						
Comments:						
15. Unreported catch outside of the Pacific Salmon Treaty area is an important contributor to the Fraser sockeye situation.						
Comments:						
16. Competitive interactions among wild and hatchery fish (potentially all salmon species) are important contributors to the Fraser sockeye situation.						
Comments:						

(2) Based on your conclusions in question 1, what are the **five** most important research priorities? Explain your rationale.

	Research priority	Rationale
1		
2		
3		
4		
5		

(3) Based on your conclusions in question 1, what are the **five** most important management actions? Explain your rationale.

	Priority management action	Rationale
1		
2		
3		
4		
5		

Appendix C: Speakers' Presentations and Handouts

Appendix C is provided as two separate files to keep file sizes reasonably small for e-mailing. These two files are available from the Pacific Salmon Commission's web site at the same location as the main report.

Appendix C (Part 1 of 2): Background Speakers' Presentations

This 60-page pdf file contains background PowerPoint slides from:
- Mike Lapointe at the Pacific Salmon Commission (on Fraser River sockeye), and
- Arlene Tompkins at Fisheries and Oceans Canada (on non-Fraser salmon).

Appendix C (Part 2 of 2): Speakers' Handouts

This 90-page pdf file contains written documents from the 16 speakers who presented evidence related to different hypotheses about causes of decreases in productivity of Fraser River sockeye salmon.

**Appendix D: Stock-specific patterns in
Fraser sockeye productivity**

Note on mis-alignment of year labels in graphs in this Appendix D.

Years and tick marks on horizontal axes do not line up exactly underneath any particular data point. Instead, the years and tick marks are slightly offset to the left of the corresponding data point.

For example, on the first graph below for "Juvenile productivity index of Early Stuart", the highest Ricker residual in the time series of solid square data points is for brood year 2004. The label 2004 on the horizontal axis is <u>not</u> directly under that 2004 point; the label is offset slightly to the left of the data point.
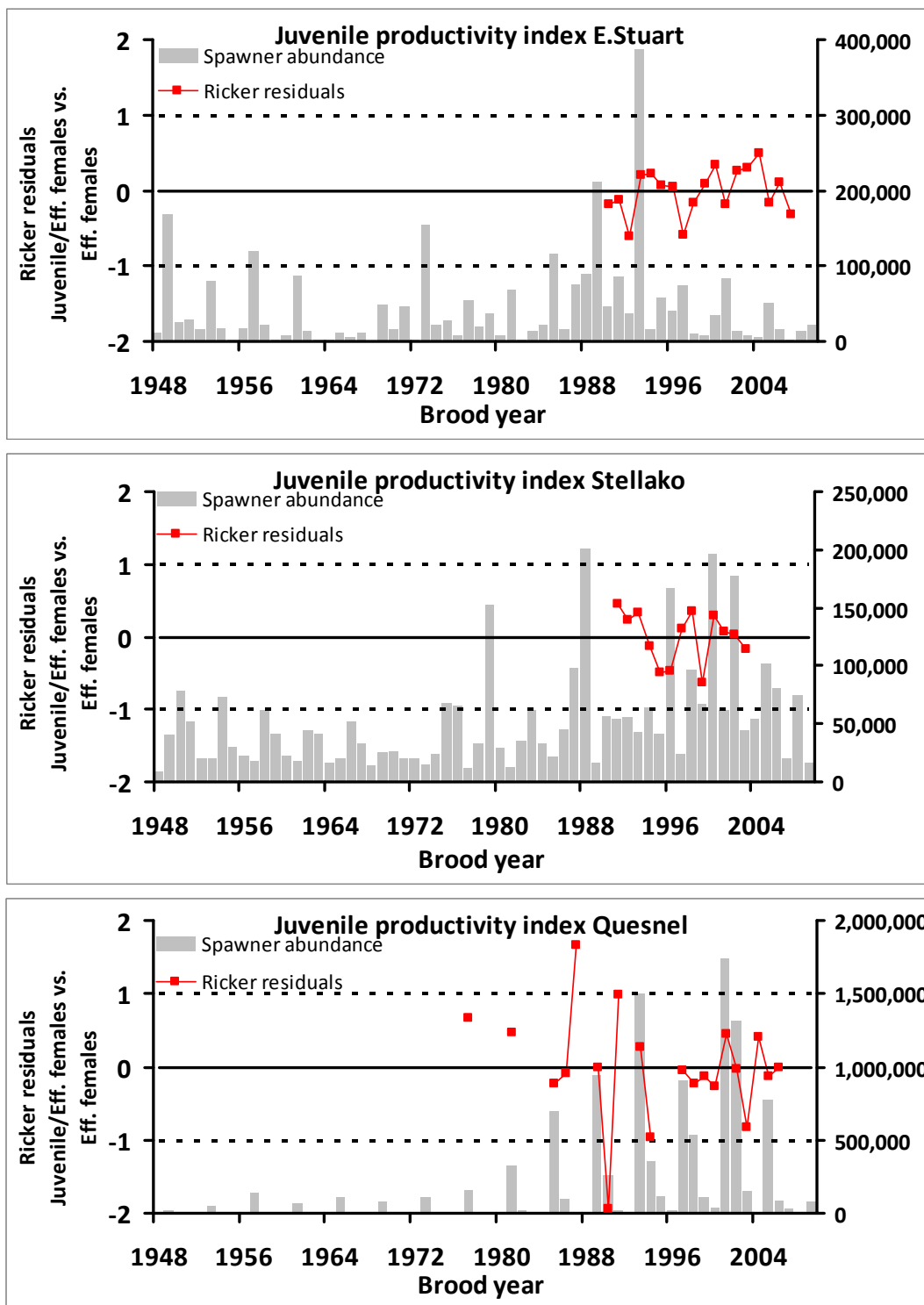
Figure D-J1. Indices of **juvenile productivity** for Early Stuart, Stellako and Quesnel sockeye stocks. Light gray bars show spawner abundance (right-hand scale). Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e$(J/EFS) vs. EFS, where J = estimate of the abundance of juveniles (fry), and EFS = estimate of abundance of Effective Female Spawners. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC.
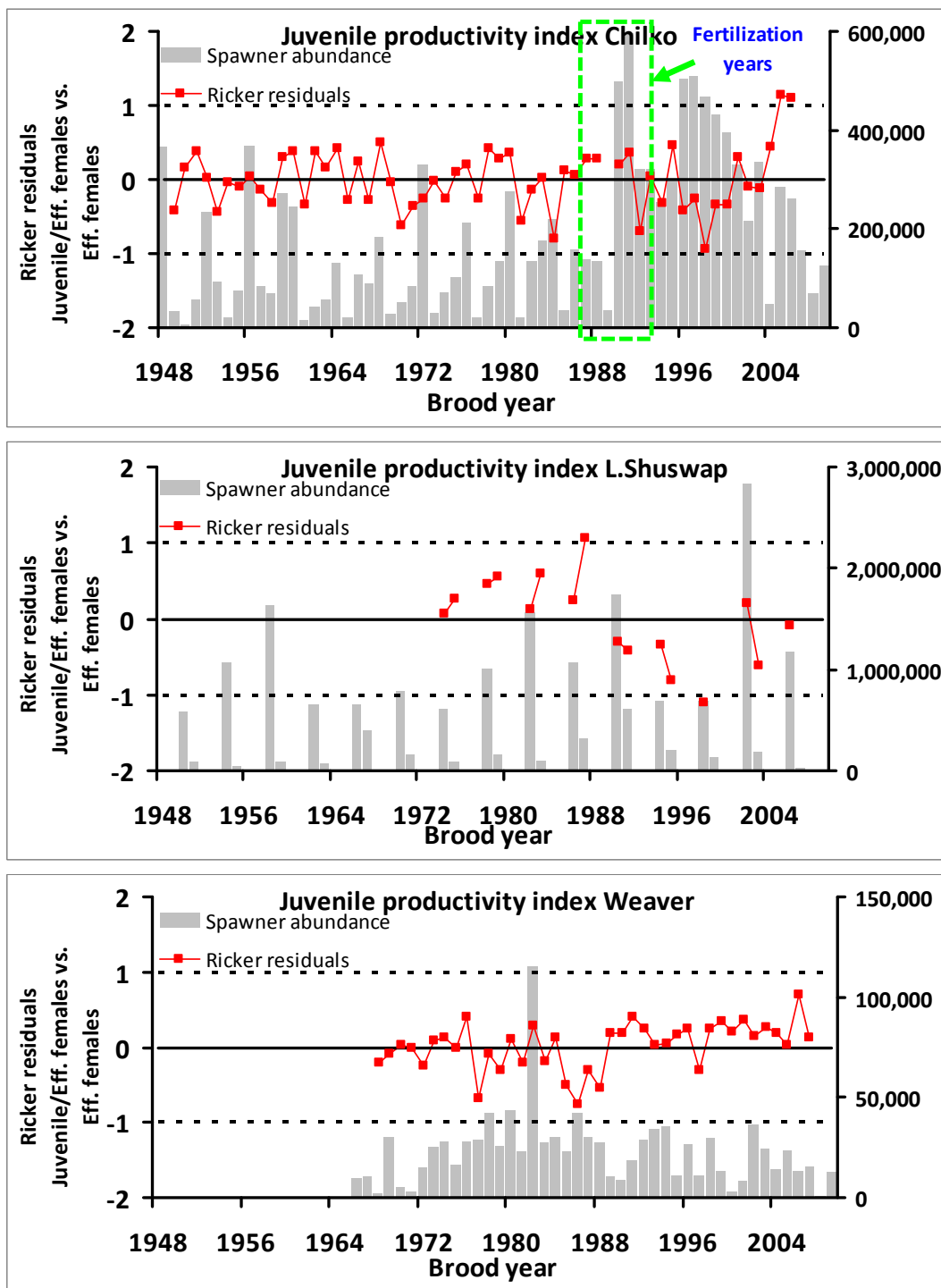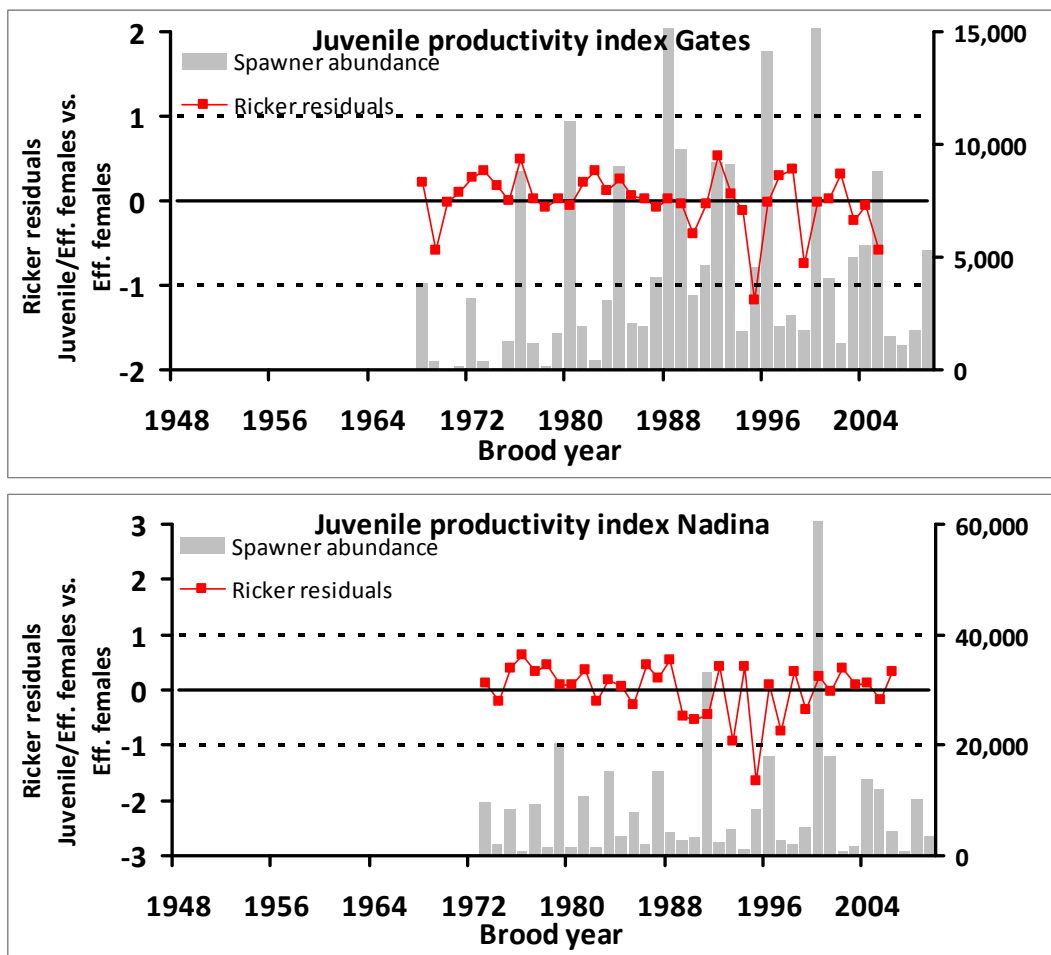
Figure D-J2. Indices of **juvenile productivity** for Chilko, Late Shuswap and Weaver sockeye stocks. Light gray bars show spawner abundance (right-hand scale). Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e$(J/EFS) vs. EFS, where J = estimate of the abundance of juveniles (smolts for Chilko; fry for Late Shuswap and Weaver), and EFS = estimate of abundance of Effective Female Spawners. Green dashed rectangle in Chilko graph is period of lake fertilization. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC.

Figure D-J3. Indices of **juvenile productivity** for Gates and Nadina sockeye stocks. Light gray bars show spawner abundance (right-hand scale). Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e(J/EFS)$ vs. EFS, where J = estimate of the abundance of juveniles (fry), and EFS = estimate of abundance of Effective Female Spawners. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC.
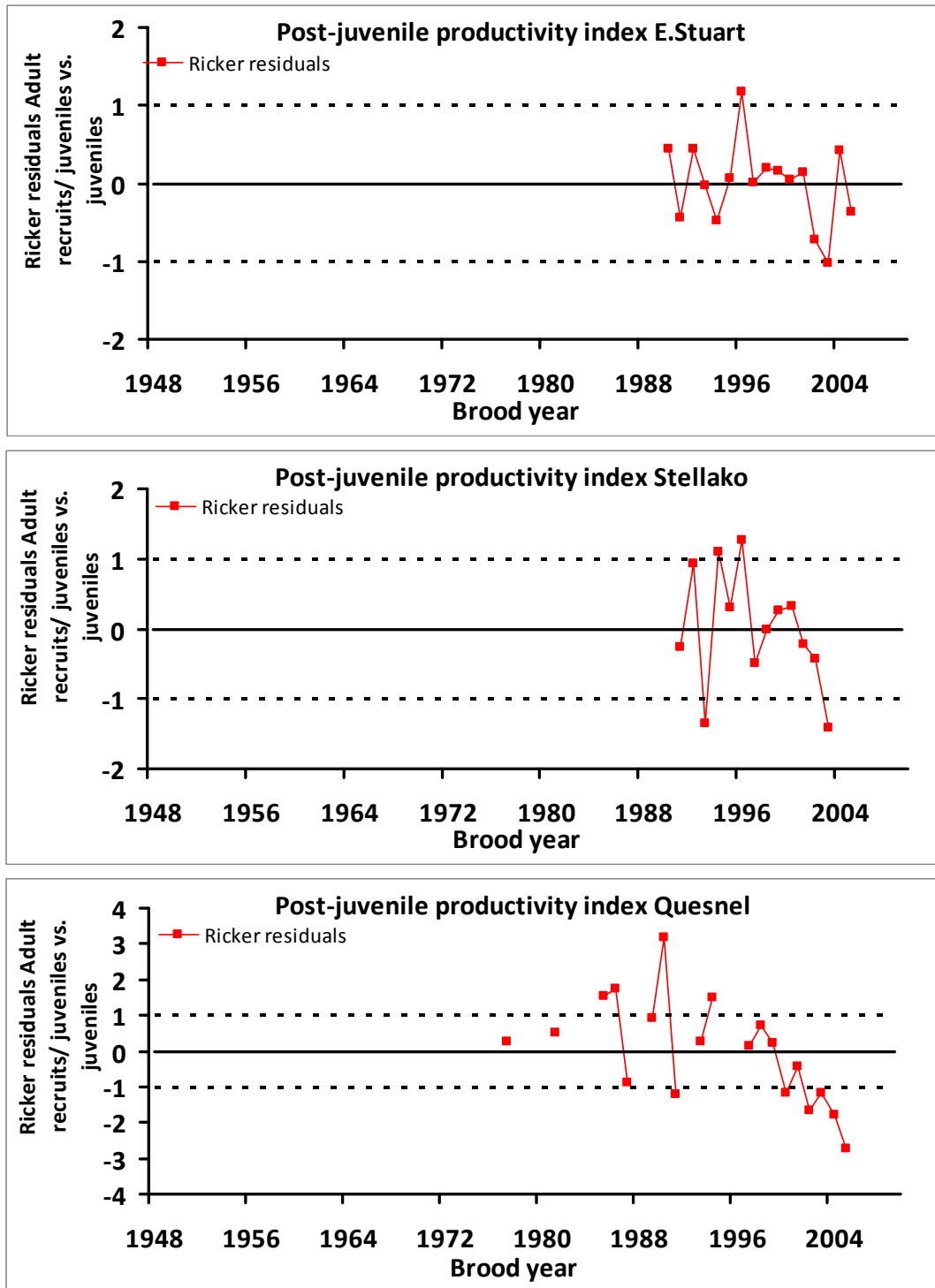
Figure D-P1. Indices of **post-juvenile productivity** Early Stuart, Stellako and Quesnel sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e(R/J)$ vs. J, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality); and J = estimate of the abundance of juveniles (fry). See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC
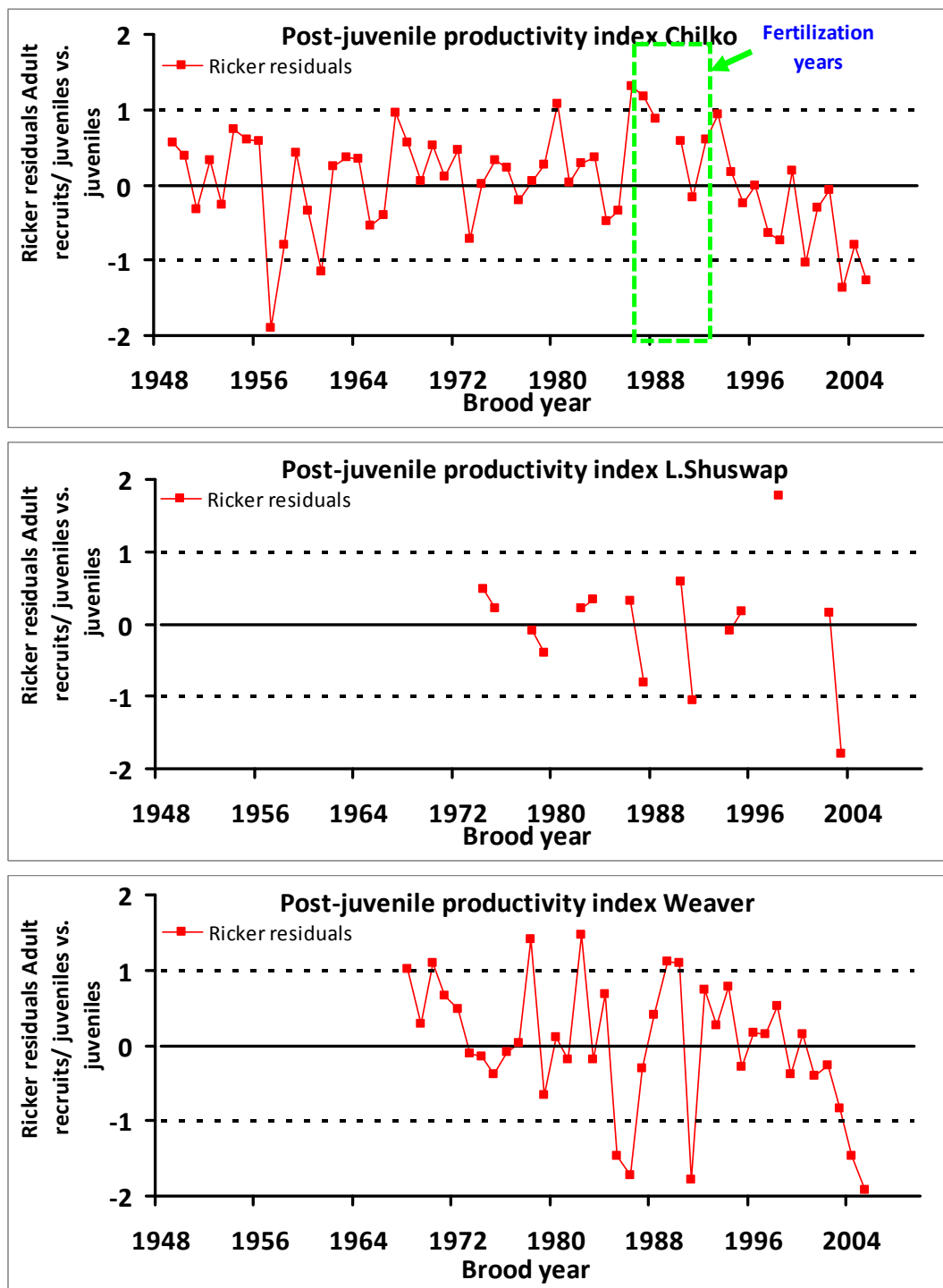
Figure D-P2. Indices of **post-juvenile productivity** for Chilko, Late Shuswap and Weaver sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e(R/J)$ vs. J, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality); and J = estimate of the abundance of juveniles (smolts for Chilko; fry for Late Shuswap and Weaver). See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC
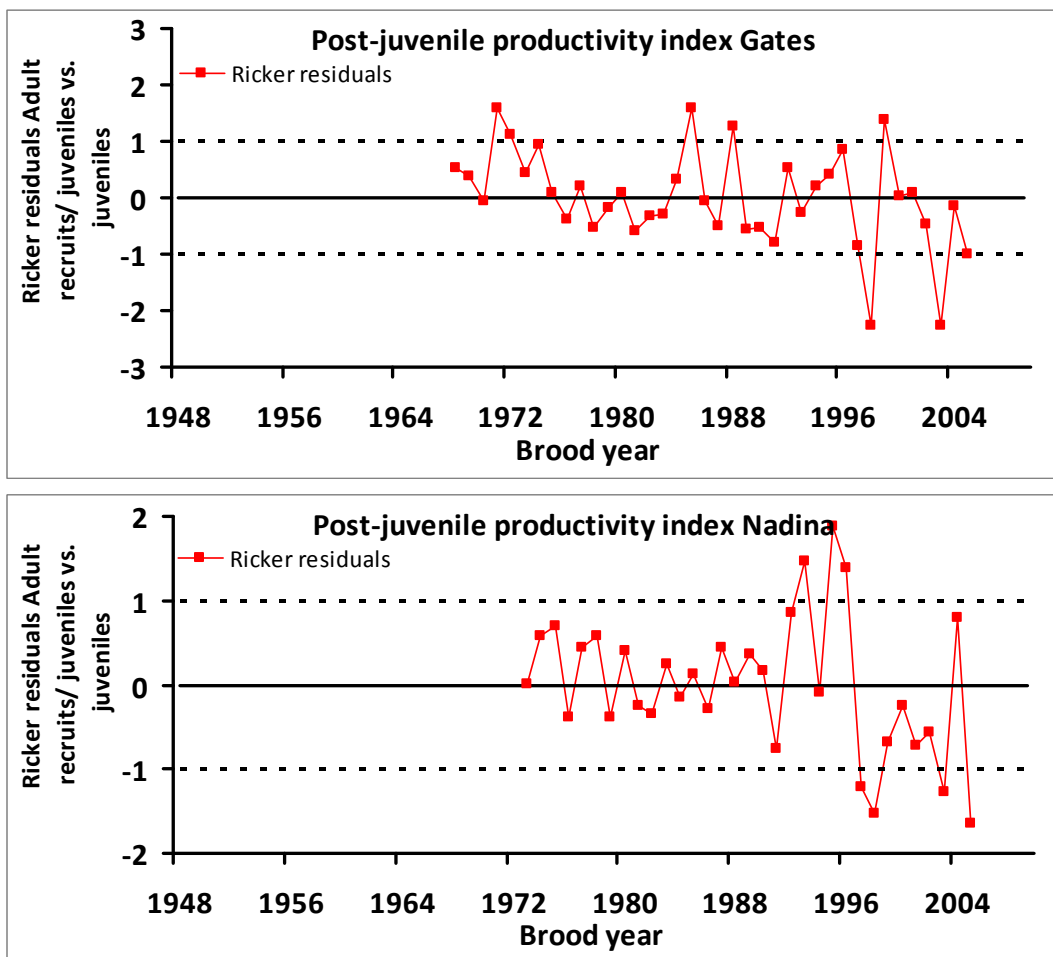
Figure D-P3. Indices of **post-juvenile productivity** for Gates and Nadina sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e(R/J)$ vs. J, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality); and J = estimate of the abundance of juveniles (fry). See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC
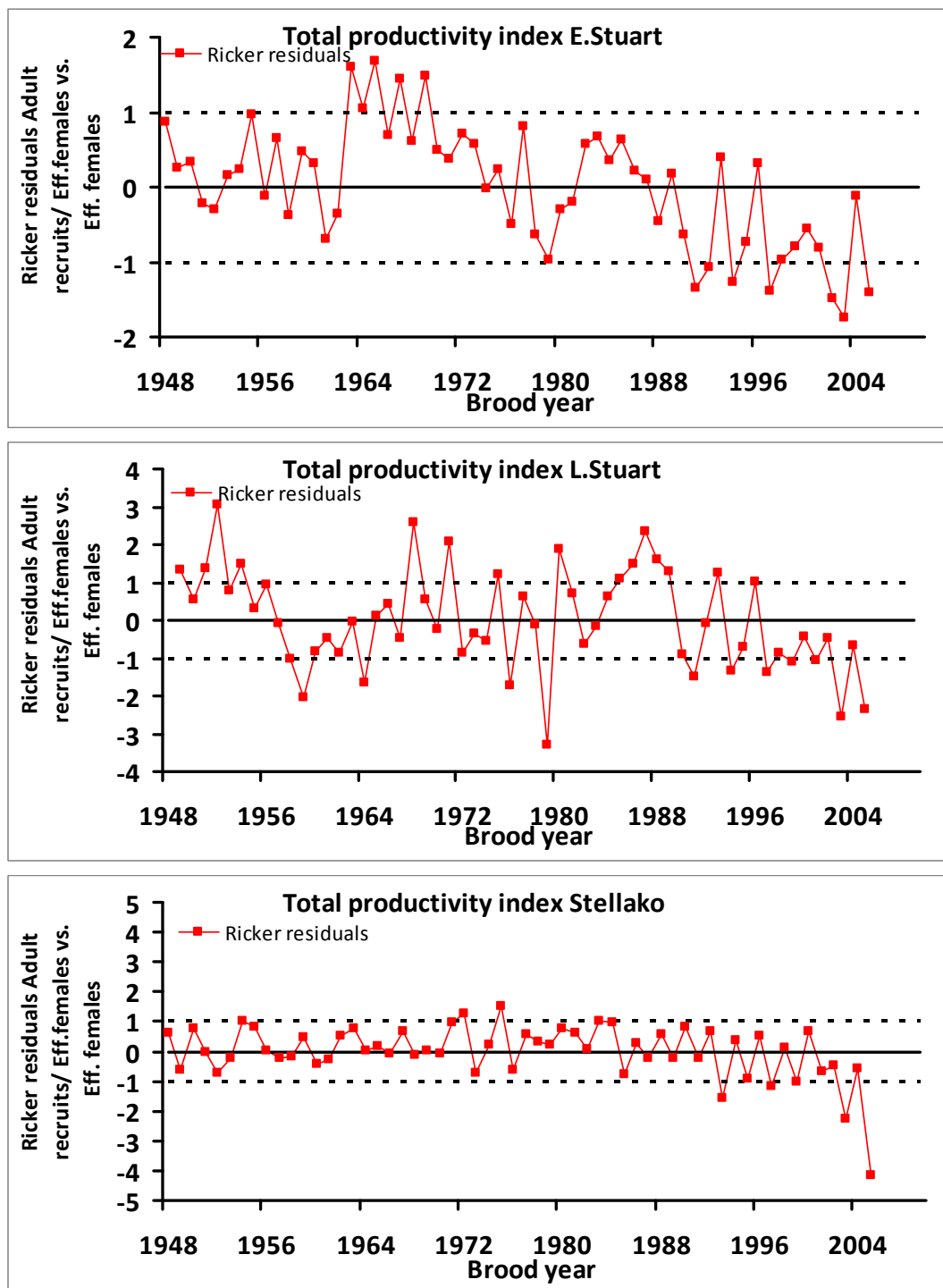
Figure D-T1.   Indices of **total life-cycle productivity** for Early Stuart, Late Stuart and Stellako sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e(R/EFS)$ vs. EFS, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality), and EFS = estimate of abundance of Effective Female Spawners. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC

Figure D-T2.   Indices of **total life-cycle productivity** for Bowron, Raft and Quesnel sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e$(R/EFS) vs. EFS, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality), and EFS = estimate of abundance of Effective Female Spawners. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC
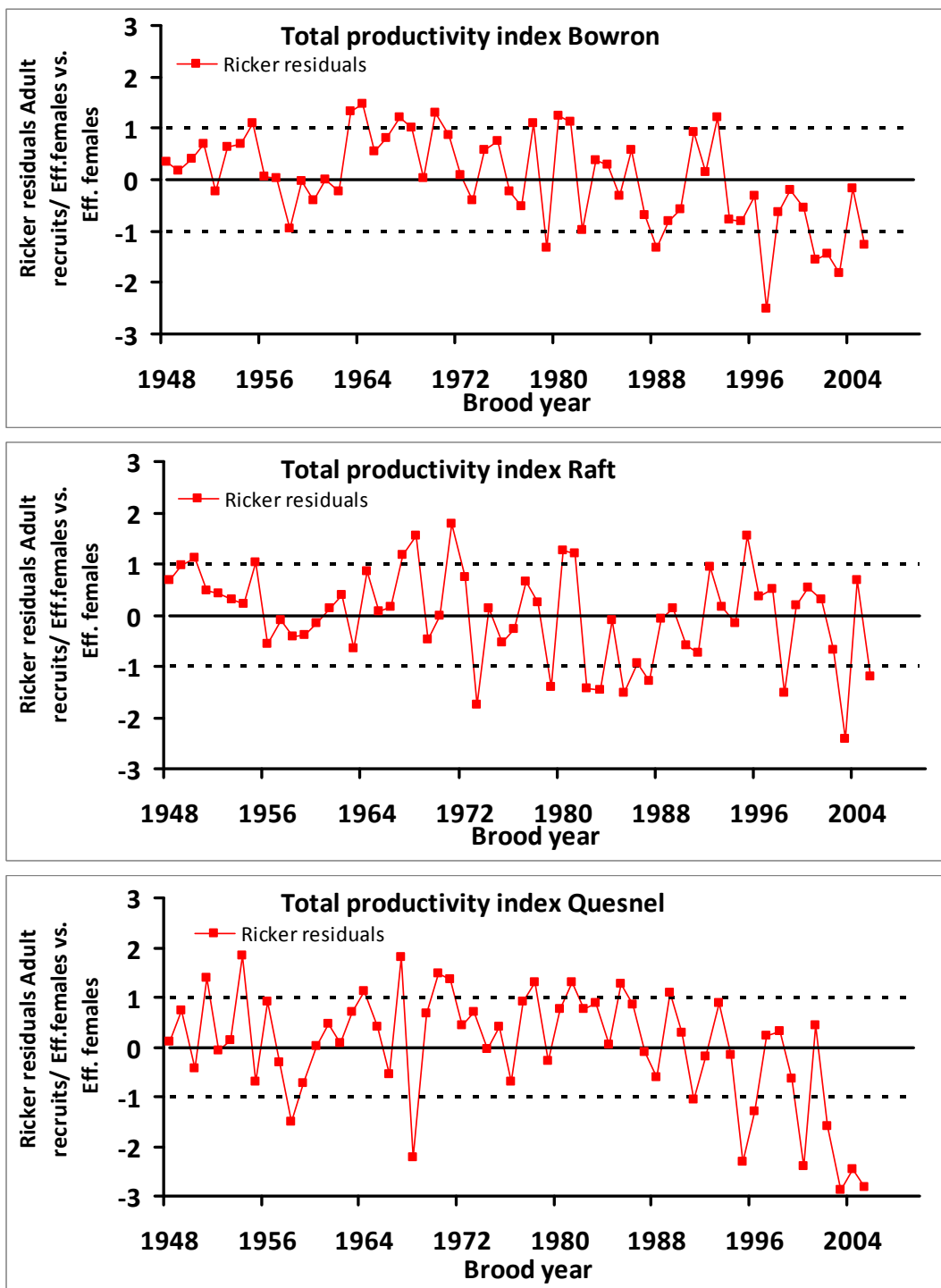
Figure D-T3. Indices of **total life-cycle productivity** for Chilko, Seymour and Late Shuswap sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to log_e(R/EFS) vs. EFS, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality), and EFS = estimate of abundance of Effective Female Spawners. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC
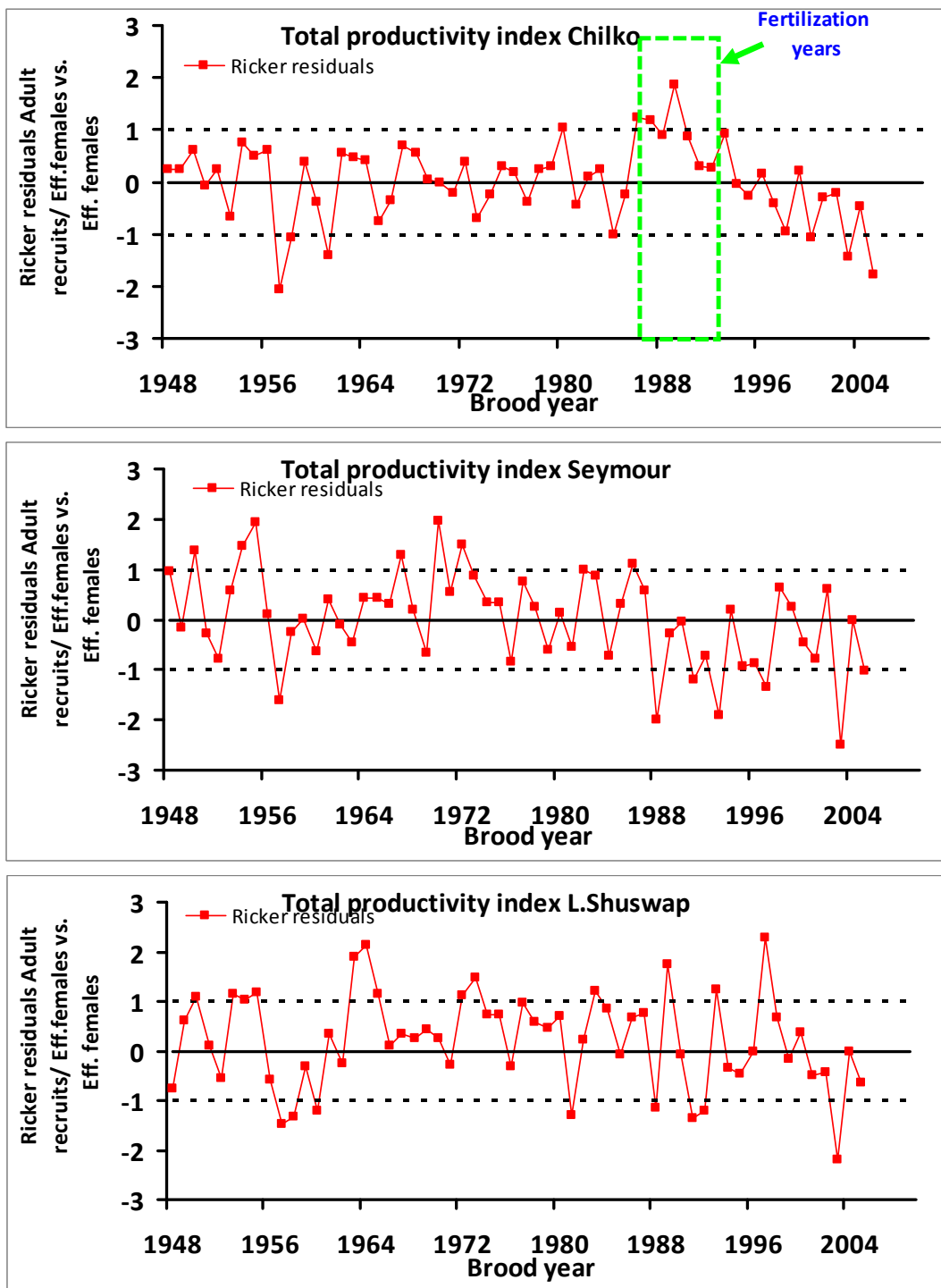
Figure D-T4. Indices of **total life-cycle productivity** for Birkenhead, Portage and Weaver sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e$(R/EFS) vs. EFS, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality), and EFS = estimate of abundance of Effective Female Spawners. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC
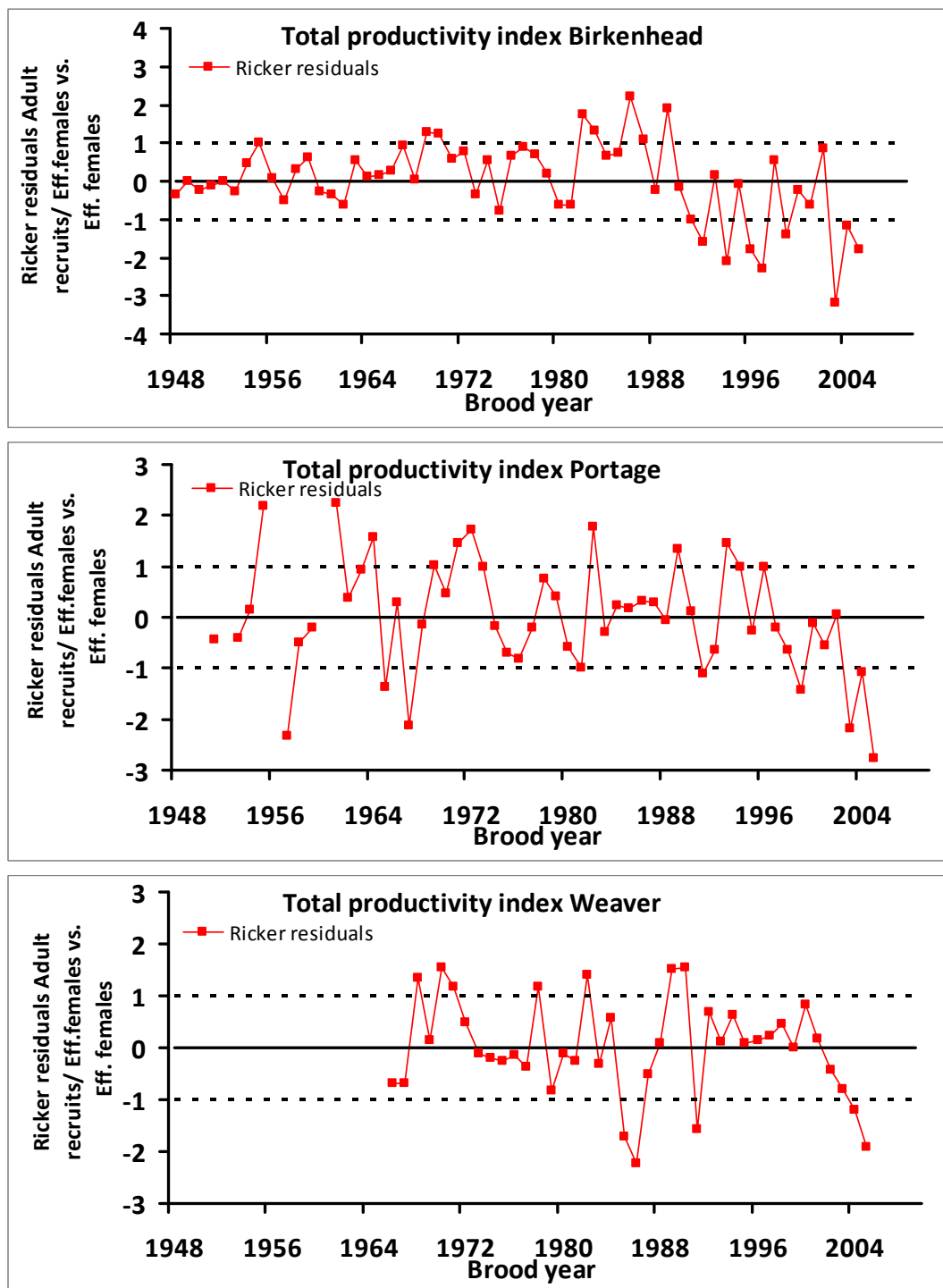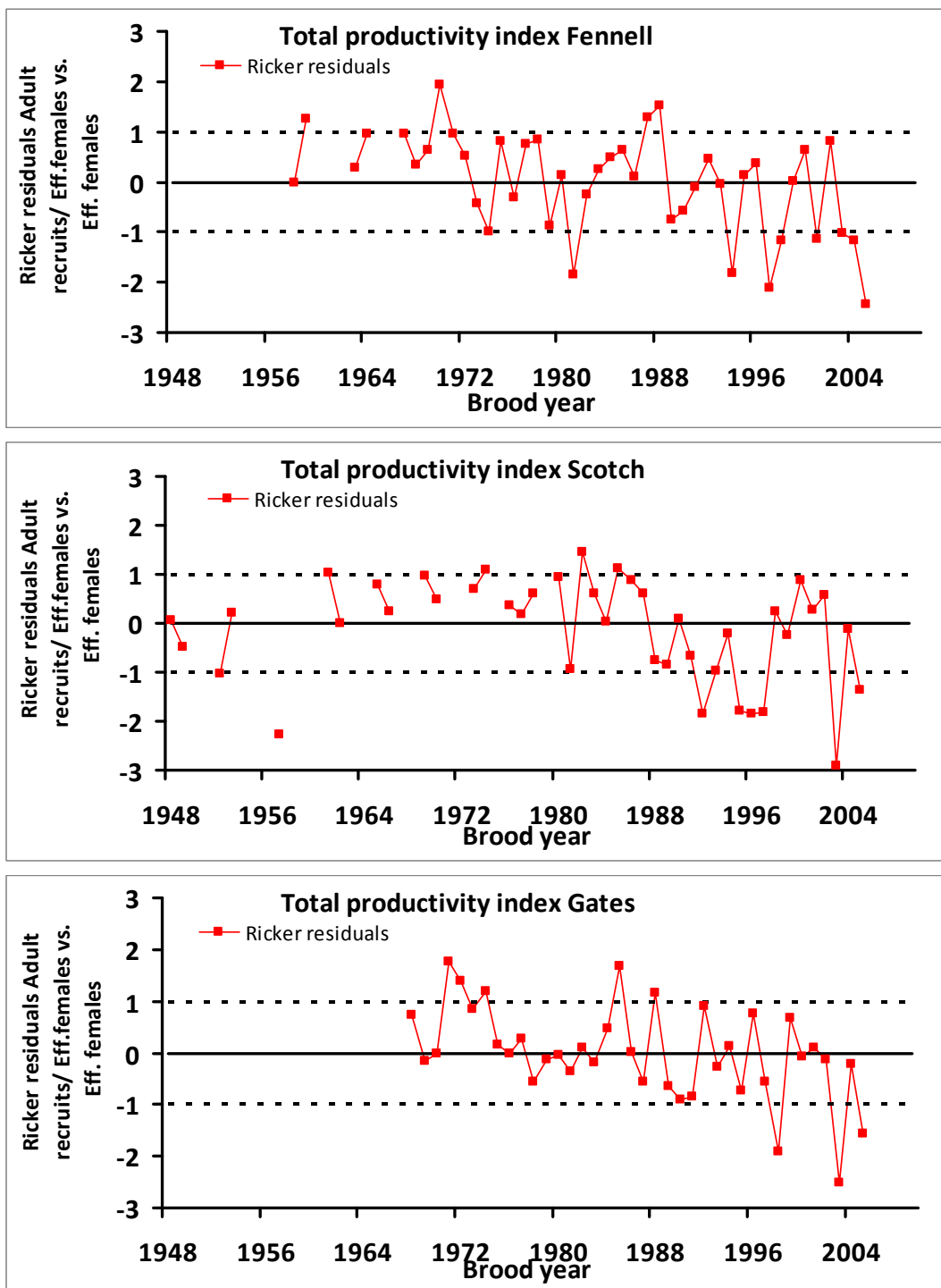
Figure D-T5. Indices of **total life-cycle productivity** for Fennell, Scotch and Gates sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e$(R/EFS) vs. EFS, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality), and EFS = estimate of abundance of Effective Female Spawners. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC

Figure D-T6. Indices of **total life-cycle productivity** for Nadina, Pitt and Harrison sockeye stocks. Solid red squares show residuals from the best fit of a Ricker stock-recruitment equation to $\log_e(R/EFS)$ vs. EFS, where R = estimate of the abundance of recruits (adult returns *prior to* both fish harvest and en-route mortality), and EFS = estimate of abundance of Effective Female Spawners. See Section 3.1.1 for further explanation. Source: Mike Lapointe, PSC
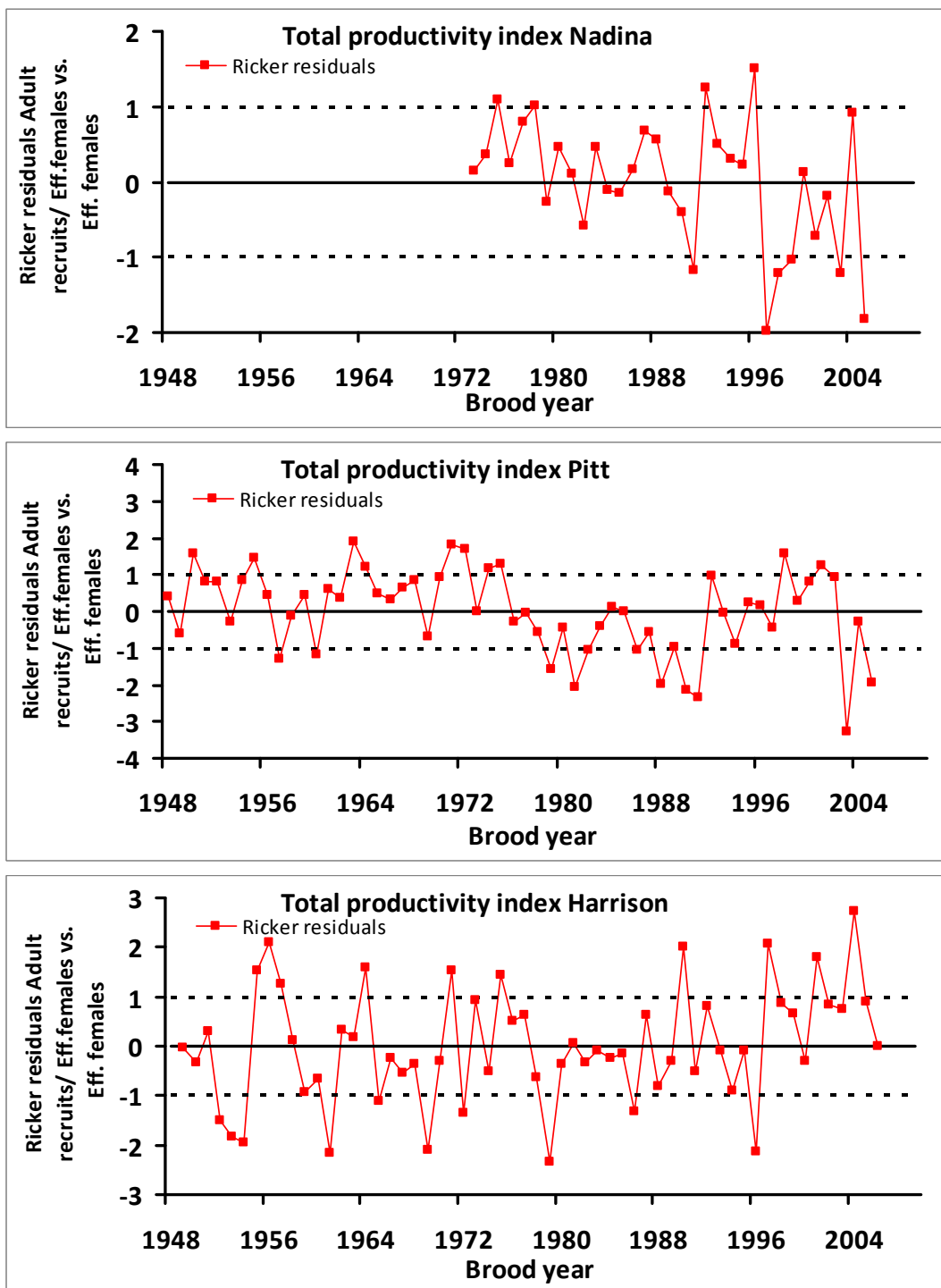
Appendix E: Summary of Observers' Comments

Affiliation

(1) Please indicate your primary affiliation by checking a box below:

	First Nation	Federal Government	Provincial Government	Industry	NGO	Academia	Cohen Commission
#	1	9	2	5	1	0	1
%[6]	5%	47%	11%	26%	5%	0%	5%

Overarching Questions

(2) Based on discussions heard during the workshop, do you think that this effort is on the right track in determining the causes of recent declines in Fraser sockeye stocks?

Response ⇒	1. Totally off track	2.	3. Need Adjustments	4.	5. On track
#	0	1	0	10	9
%	0%	5%	0%	50%	45%

(3) How confident are you that we will be able to move forward with regards to the leading hypotheses that emerged from the workshop?

Response ⇒	1. Not confident at all	2.	3. Not Sure Yet	4.	5. Very Confident
#	1	0	10	7	0
%	5%	0%	55%	39%	0%

(4) Did you find the workshop worthwhile and gain knowledge that will be useful to you subsequently?

Response ⇒	1. Not worthwhile	2.	3. Somewhat	4.	5. Very worthwhile
#	0	0	2	7	11
%	0%	0%	10%	35%	55%

(5) In your opinion, did we achieve the workshop's objectives?

Response ⇒	1. No	2.	3. Somewhat	4.	5. All objectives achieved
#	0	1	1	15	1
%	0%	5%	5%	83%	5%

Workshop format

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[6] Percentages may not sum up to 100 due to rounding. A total of 20 responses were received, but not all respondents answered all questions.

(6) Was sufficient time allocated to each thematic area?

Response ⇒	1. No	2.	3. Somewhat	4.	5. Yes
#	0	1	9	7	3
%	0%	5%	45%	35%	15%

(7) Were the discussion and silent generation components effective at getting participant feedback?

Response ⇒	1. No	2.	3. Somewhat	4.	5. Yes
#	0	0	3	12	3
%	0%	0%	16%	67%	16%

(8) Was the workshop well facilitated (e.g., well-organised, stuck to agenda, good use of available discussion time, good task process for dealing with differing opinions)?

Response ⇒	1. No	2.	3. Somewhat	4.	5. Yes
#	0	0	1	6	13
%	0%	0%	5%	30%	65%

Hypotheses

(9) Were there any hypotheses not covered which should have been included in the agenda? If so which hypotheses?
- The broader effects of climate change are an important contributor to the Fraser sockeye situation.
- The decline in inter and intra-stock biodiversity of Fraser sockeye is an important contributor to the Fraser sockeye situation.
- Harvest within Georgia Strait and the larger Pacific Salmon Treaty Area is an important contributor to the Fraser sockeye situation.
- Changing ocean pH is an important contributor to the Fraser sockeye situation.
- Increasing prevalence of freshwater invasive species is an important contributor to the Fraser sockeye situation.

(10) How adequate was the quality of the information provided to evaluate each hypothesis (i.e., presentation and handouts)?

Response ⇒	1. Insufficient	2.	3. Acceptable	4.	5. Excellent
#	1	2	4	8	2
%	5%	12%	24%	47%	12%

(11) Do you think the method of evaluating alternative hypotheses was well suited to this particular problem?

Response	1. Not at all	2.	3. Acceptable	4.	5. Right fit for

⇒					Issue
#	0	0	7	7	3
%	0%	0%	41%	41%	18%

(12) In your opinion, were uncertainties adequately addressed?

Response ⇒	1. Not at all	2.	3. Partially	4.	5. Right level of discussion
#	0	2	8	8	1
%	0%	10%	42%	42%	5%