



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

June 2011

TECHNICAL REPORT 5B

Examination of relationships between salmon aquaculture and sockeye salmon population dynamics

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Preface

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

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

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

Project

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

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

Executive Summary

The objective of this technical report is to quantitatively evaluate the relationship between Fraser River sockeye salmon productivity and (a) sea louse (*Lepeophtheirus salmonis* and *Caligus clemensi*) abundance on farmed salmon, (b) disease frequency and occurrence on farmed salmon, (c) mortalities of farmed salmon, and (d) salmon farm production. These analyses are intended to inform the work of other contractors who are preparing comprehensive reports on salmon aquaculture and Fraser River sockeye salmon dynamics for the Cohen Commission.

While the focus of this report is Fraser River sockeye salmon I included data on non-Fraser River populations insofar as they informed the analysis as reference populations for the aquaculture variables considered. The salmon farm data examined in this report was provided by the British Columbia Salmon Farmers Association, the British Columbia Ministry of Agriculture and Lands and the British Columbia Ministry of Environment and was compiled by Korman (2011). Because it is well established that oceanographic conditions can influence sockeye survival I attempted to account for their influence during early marine life when examining relationships between aquaculture and sockeye dynamics. Specifically, I calculated average sea surface temperature (SST) anomalies in the winter preceding the entry of juvenile sockeye into the marine environment, as a measure of oceanographic conditions in early marine life

The first part of this report relates sockeye survival anomalies to aquaculture variables. Survival anomalies were calculated as population specific residuals of the Ricker or Larkin stock recruit relationship (depending on which better described stock specific density-dependence) fit to spawner abundance and SST in early marine life. I related survival anomalies to (a) sea louse abundance on farmed salmon in the spring/summer of the year of sockeye marine entry, (b) the occurrence of high-risk pathogens on farmed salmon in the year sockeye migrate to sea, (c) the proportion of farmed fish that died of disease or unknown causes (“fresh silvers” in industry jargon) in the spring/summer in the year sockeye migrate to sea, and (d) the number of salmon being raised in salmon farms in the spring/summer in the year sockeye migrate to sea. My analyses found no statistical support for a relationship between these aquaculture variables and sockeye survival anomalies.

The analyses in the first part of this report are based on short time series of aquaculture variables, beginning no earlier than 2003, with low statistical power to detect relationships should they truly exist. One dataset that does span the entire sockeye time series is the production of farmed salmon (in metric tonnes) compiled by Fisheries and Oceans Canada management area since salmon farming began in British Columbia in the early 1980s. In the second part of this report I related sockeye productivity (i.e., the natural logarithm of the ratio of adult returns [recruits] to

the number of spawners that produced them) to this complete time series of salmon farm production as well as two other factors that have been independently identified as likely contributors to declines in Fraser River sockeye salmon: (1) oceanographic conditions and (2) competition with pink salmon in the North Pacific Ocean. This approach allowed for a quantitative comparison of the strength of the relationship between sockeye dynamics and salmon farm production while explicitly accounting for the influence of oceanographic conditions and the abundance of pink salmon in the North Pacific as well as interactions among these hypothesized drivers.

The results of this analysis suggest that increasing farmed salmon production, SST and pink salmon abundance increases sockeye salmon mortality. In addition, the influence of aquaculture production on sockeye mortality was predicted to be greater when SST anomalies are negative (i.e., cool for British Columbia populations) and when pink salmon abundance in the North Pacific Ocean is high. However, there was large uncertainty around these estimated effects, which precludes drawing strong inference from these results.

The relationships described in this report are correlative, do not on their own establish causation and should be re-examined as more information becomes available. An unavoidable consequence of the structure of the data sets I examined is that multiple populations are compared to environmental time series that have identical values for each population. This makes it more likely that some factor external to the analysis is responsible for the patterns observed. A stronger test of the relationship between sockeye salmon dynamics and aquaculture variables would include independent measures of salmon farm variables for each sockeye population. Because finer scale data on aquaculture are not available, the relationships described in this report should be interpreted with caution. Nonetheless, these findings should be considered a first step towards understanding the role open net pen salmon aquaculture may play in influencing Fraser River sockeye salmon population dynamics.

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Introduction

There has been much speculation about the role pathogens from farmed salmon along Fraser River sockeye salmon marine migration routes have played in contributing to declines in Fraser River sockeye salmon. Despite this widespread speculation, there has yet to be a quantitative evaluation of the relationship between open net pen salmon aquaculture and Fraser River sockeye salmon dynamics.

The objective of this technical report is to help address this knowledge gap by statistically examining the relationship between salmon aquaculture in British Columbia and Fraser River sockeye salmon population dynamics. The data on salmon farms considered in this report were provided by the British Columbia Salmon Farmers Association and the Province of British and were compiled by Korman (2011). Aquaculture variables considered in this report include (1) the distribution and abundance of pathogens on farmed salmon including parasites, viruses and bacteria, (2) farmed salmon mortality due to disease and unknown causes, and (3) the distribution and abundance of farmed salmon hosts. The analyses presented in this technical report are intended to inform the work of other contractors employed by the Cohen Commission to prepare comprehensive reports on salmon aquaculture and Fraser River sockeye salmon dynamics.

Methods

Data

Below I describe how I summarized the salmon aquaculture data provided to me by the Cohen Commission in order to relate it to sockeye dynamics. The original sources of data on aquaculture variables and length of time series are described in Table 1.

Sockeye data

The sockeye data considered in this report consists of the abundance of sockeye spawners and resulting adult recruitment (spawners plus catch, en-route and pre-spawn mortality). While the focus of this report is Fraser River sockeye salmon, I also included other sockeye salmon populations as reference populations for the aquaculture variables considered. The complete sockeye dataset considered in this report included 18 populations from the Fraser River as well as eight other populations from Washington State and British Columbia (BC) and five populations from the South East and Yakutat regions of Alaska (Figure 1 and Table 2). Analyses began with populations from BC that were within ~ 500 km of the mouth of the Fraser River, the scale at which sockeye populations have previously been shown to covary in survival (i.e., populations 1-24; Peterman et al. 1998). I repeated the analyses described in this report with other combinations of reference populations as part of sensitivity analyses. Detailed descriptions

of the populations considered in this report including the length of time series are provided in Peterman and Dorner (2011).

Table 1. Summary of aquaculture variables considered in this report. Sources include the British Columbia Salmon Farmers Association (BCSFA), the British Columbia Ministry of Agriculture and Lands (BCMAL) and the British Columbia Ministry of Environment (BCMOE). The length of time series refers to the number of years for which there was corresponding sockeye stock recruit data.

Variable	Length of time series	Source
Sea louse abundance	2004-2007	BCSFA
Farmed salmon mortality	2003-2007	BCSFA
Fish health events	2003-2007	BCSFA
Fish health audits	2003-2007	BCMAL
Farmed salmon production (number of fish)	2003-2007	BCSFA
Farmed salmon production (metric tonnes)	1950-2007	BCMOE

This dataset includes data on sockeye salmon populations from the Fraser River, up to and including the 2004 brood year for which there is complete adult returns for three-, four- and five-year olds. However, returns in 2009 (which were likely dominated by 4-year olds from the 2005 brood year) were the lowest in at least 5 decades and were followed in 2010 with what were likely the largest returns to the Fraser River in several decades. These stark differences in returns (and likely survival) would provide a powerful contrast to include in any analysis of aquaculture variables. Unfortunately, at the time of writing survival could not be calculated for the brood years that produced these returns because the responsible agencies are still processing samples for age class determination for sockeye that returned in 2010 and 5-year olds from the 2006 brood year will not return until the summer and fall of 2011. In order to include the 2005 brood year I used the average proportion of 5-year olds from each population to estimate the number of 5-year olds that returned in 2010 and then calculated total recruits from the 2005 brood year for each sockeye population in the Fraser River. Age class information for populations outside the Fraser River was not provided and so for these populations the final year in the time series was the 2004 brood year.

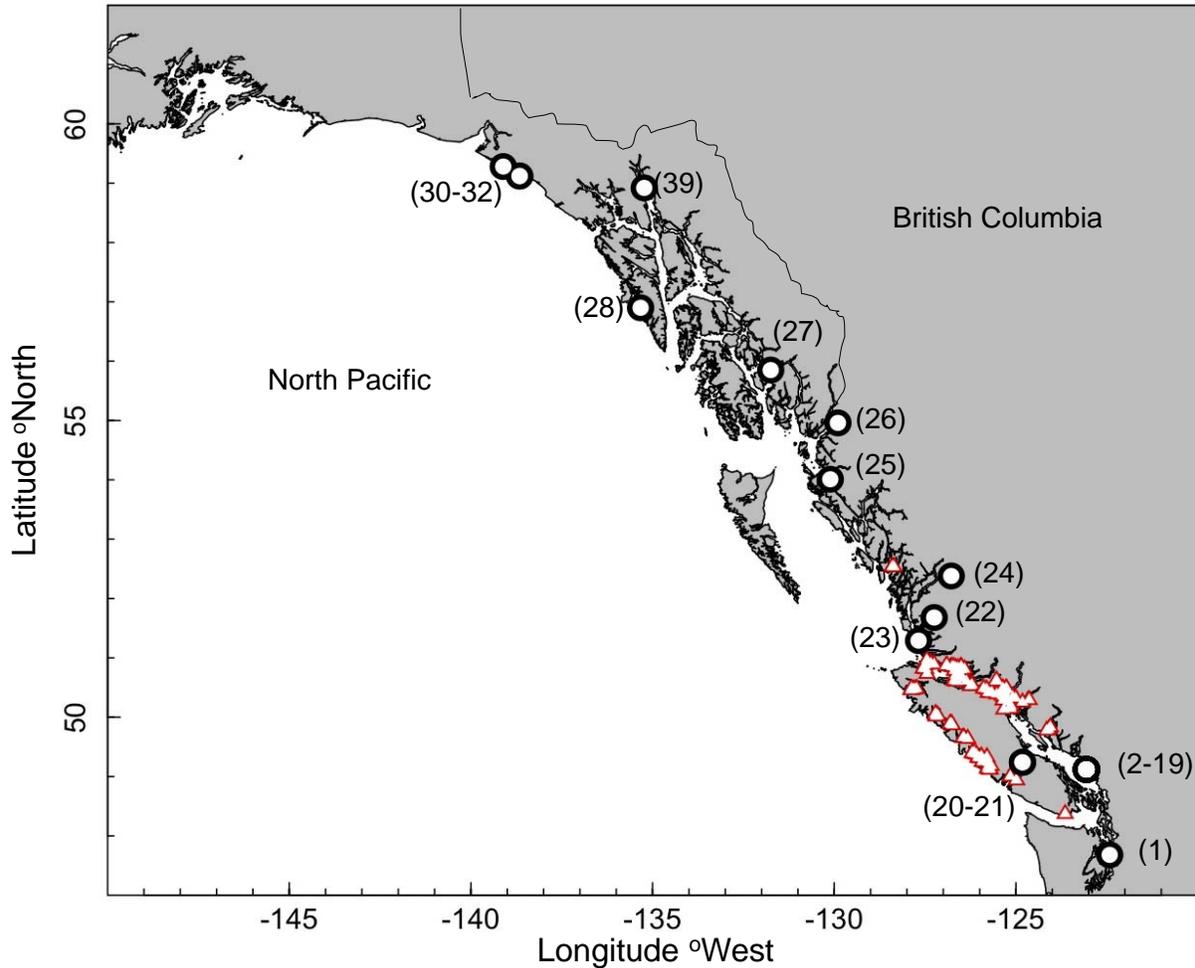


Figure 1. Location of sockeye populations whose dynamics were examined (open circles) in relation to data from salmon farm (open red triangles). See Table 2 for the names of the populations. Not all salmon farms for which data was included in the analyses are plotted because coordinates of all farms were not made available.

Migration routes and age at marine entry

In order to examine relationships between salmon aquaculture and sockeye survival I had to make assumptions about the routes juvenile sockeye take as they migrate to the open ocean from their natal watersheds. Assumed migration routes are detailed in Table 3. All population were assumed to enter the marine environment in their second year of life except for Harrison River (Birtwell et al. 1987) and East Alsek River (McBride and Brogle 1983) sockeye which were assumed to enter the ocean in their first year of life

Table 2. Summary of sockeye salmon populations considered in this report. Sea surface temperature (SST) grid cell coordinates correspond to those used to calculate SST anomalies experienced by sockeye in the year of marine entry. Region refers to the level at which aquaculture production and SST were measured with populations within a region sharing the same SST and aquaculture value in a given year.

Population	Number	Region	<u>Ocean entry point</u>		<u>SST grid cell</u>			
			Latitude	Longitude	Latitude 1	Longitude 1	Latitude 2	Longitude 2
Lake Washington	1	Washington	47.68	-122.42	50.50	-129.40	48.60	-125.70
Early Stuart	2	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Late Stuart	3	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Stellako	4	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Bowron	5	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Raft	6	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Quesnel	7	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Chilko	8	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Seymour	9	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Late Shuswap	10	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Birkenhead	11	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Cultus	12	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Portage	13	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Weaver	14	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Fennell	15	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Scotch	16	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Gates	17	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Nadina	18	Fraser	49.12	-123.06	50.50	-127.50	52.40	-129.40
Harrison River	19	Harrison	49.12	-123.06	50.50	-129.40	48.60	-125.70
Great Central Lake	20	Barkley Sd.	49.24	-124.82	50.50	-129.40	48.60	-125.70
Sproat Lake	21	Barkley Sd.	49.24	-124.82	50.50	-129.40	48.60	-125.70
Owikeno Lake	22	Central Coast	51.68	-127.25	52.40	-129.40	54.30	-131.20
Long Lake	23	Central Coast	51.29	-127.68	52.40	-129.40	54.30	-131.20
Atnarko	24	Central Coast	52.38	-126.78	52.40	-129.40	54.30	-131.20

Skeena	25	North Coast	54.01	-130.11	52.40	-129.40	52.40	-131.20
Nass	26	North Coast	54.96	-129.90	52.40	-129.40	52.40	-131.20
McDonald	27	SEAK	55.85	-131.75	56.20	-135.00	58.00	-137.00
Redoubt	28	SEAK	56.90	-135.33	56.20	-135.00	58.00	-137.00
Chilkat	29	SEAK	58.92	-135.23	56.20	-135.00	58.00	-137.00
Klukshu	30	Yakutat	59.12	-138.66	58.00	-139.00	58.00	-141.00
East Alsek	31	Yakutat	59.12	-138.66	58.00	-139.00	58.00	-141.00
Italio	32	Yakutat	59.28	-139.11	58.00	-139.00	58.00	-141.00

Table 3. Summary of the BCMAL fish health zones and Fisheries and Oceans Canada (DFO) management areas juvenile sockeye are assumed to migrate through on their way to the open ocean. See Figures 2 and 3 for maps of fish health zones and DFO management areas.

Population	Number	Fish health zone	DFO management area
Lake Washington	1	2.1	20
Early Stuart	2	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Late Stuart	3	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Stellako	4	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Bowron	5	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Raft	6	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Quesnel	7	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Chilko	8	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Seymour	9	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Late Shuswap	10	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Birkenhead	11	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Cultus	12	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Portage	13	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Weaver	14	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Fennell	15	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Scotch	16	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Gates	17	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Nadina	18	3.1, 3.2, 3.3, 3.4	11-17, 28, 29
Harrison River	19	2.1	20
Great Central Lake	20	2.3	23
Sproat Lake	21	2.3	23
Owikeno Lake	22	3.5	9
Long Lake	23	3.5	10
Atnarko	24	3.5	8
Skeena	25	-	4
Nass	26	-	3
McDonald	27	-	-
Redoubt	28	-	-
Chilkat	29	-	-
Klukshu	30	-	-
East Alsek	31	-	-
Italio	32	-	-

Aquaculture Variables

Sea lice

I estimated the total number of sea lice (in the millions) on farmed fish in a given month by multiplying the average abundance of lice on fish examined for lice (usually 60 fish, 20 from each of 3 pens; BCMAL 2009) by the total number of salmon in the farm at the time louse abundance was quantified. Four measures of louse abundance were calculated by month: (1) motile *Lepeophtheirus salmonis* abundance (preadult I, II and adult developmental stages), (2) gravid female *L. salmonis* abundance, (3) motile *Caligus clemensi* abundance and (4) total abundance of motile lice of both species (i.e, sum of 1-3). With these estimates of louse abundance, I estimated the total number of lice in each BCMAL fish health zone (Figure 2) from April to June in each year (Figure 3).

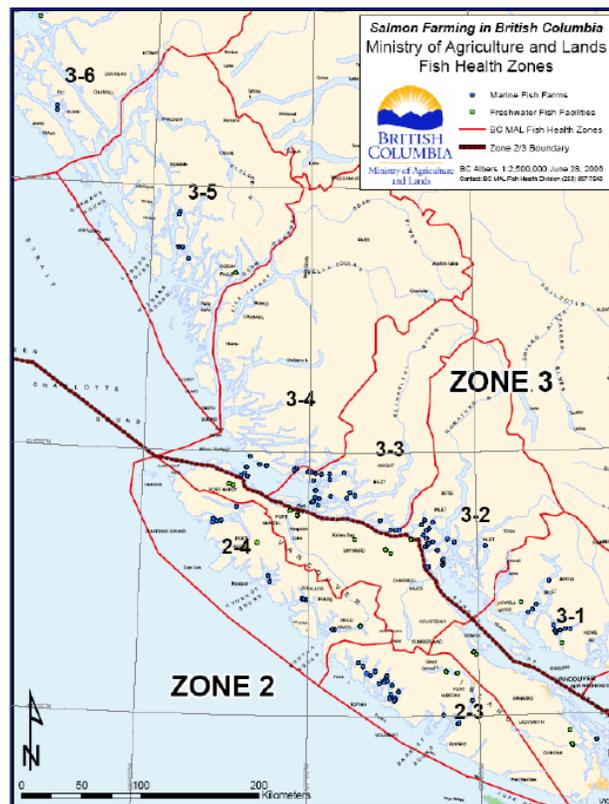


Figure 2. British Columbia Ministry of Agriculture and Lands fish health zones (from BCMAL 2009).

Viruses and bacteria

There are two primary sources of data on viral and bacterial pathogens on farmed salmon in British Columbia: (1) fish health events reported by the British Columbia Salmon farmers Association (BCSFA) and (2) fish health audits reported by BCMAL. Fish health events are defined as “an active disease occurrence or a suspected infectious event on a farm that triggers veterinary involvement and an action, such as: lab diagnosis, recommendation/report, husbandry change, prescription medication, further investigation, etc. where such action is intended to reduce or mitigate risk associated with that event” (BCMAL 2009).

I calculated the number of high-risk fish health events, as defined in the Cohen Commission technical report by Kent (2011; i.e., *Aeromonas salmonicida*, IHN virus, *Renibacterium salmoninarum*, and *Vibrio anguillarum*) as well as individual high-risk fish health events that were common (i.e., greater than 20 fish health events in the time series: *A. salmonicida*, IHN virus and *R. salmoninarum*) for each year in each BCMAL zone (Figure 3). In some instances there were multiple fish health events for a single pathogen on a salmon farm over time. These were considered unique events and treated as independent data points.

The second source of information on pathogen occurrence on salmon farms comes from provincial fish health audits which include screening of farmed fish for specific “diseases-of-concern” (BCMAL 2009). I calculated the number of farm level positive diagnoses for high-risk pathogens in each BCMAL zone (Figure 3). This was repeated for all documented high-risk pathogens combined (*A. salmonicida*, IHN virus, and *R. salmoninarum*) as well as for *R. salmoninarum* individually because it was the only common high-risk pathogen that was diagnosed. Fish health events and positive fish health audit diagnoses were calculated by year instead of by month because the data was not always available by month and, unlike sea lice and salmon farm production or mortalities which are monitored and calculated monthly, fish health events and audits only occurred when veterinary involvement was needed or a random audit occurred. As such, it is possible that a pathogen was present before or after a diagnosis was made making it difficult to assign a month to the event.

Farmed salmon mortalities

Farm fish mortalities are classified based on the cause of mortality including predators, handling/transport, algal blooms, and “fresh silvers” which are fresh carcasses that are suspected to have died due to disease or unknown causes (BCMAL 2009). I calculated the number of “fresh silver” mortalities in April to June by BCMAL zone and year and then calculated a “fresh silver” mortality rate by dividing mortalities by the total number of farmed fish present during the same time period.

Farmed salmon production

Any pathogen transmission from farmed to wild salmon is likely to be mediated by both the abundance and spatial and temporal distribution of farmed salmon hosts. I considered two sources of information on the distribution and abundance of farmed salmon. The first was the number of salmon in each farm by month from 2003 to 2007. Specifically, I calculated the number of farmed fish, in the millions, by genus (*Oncorhynchus spp.* or *Salmo spp.*) in each BCMAL zone between April and June in each year for which data was available (Figure 3).

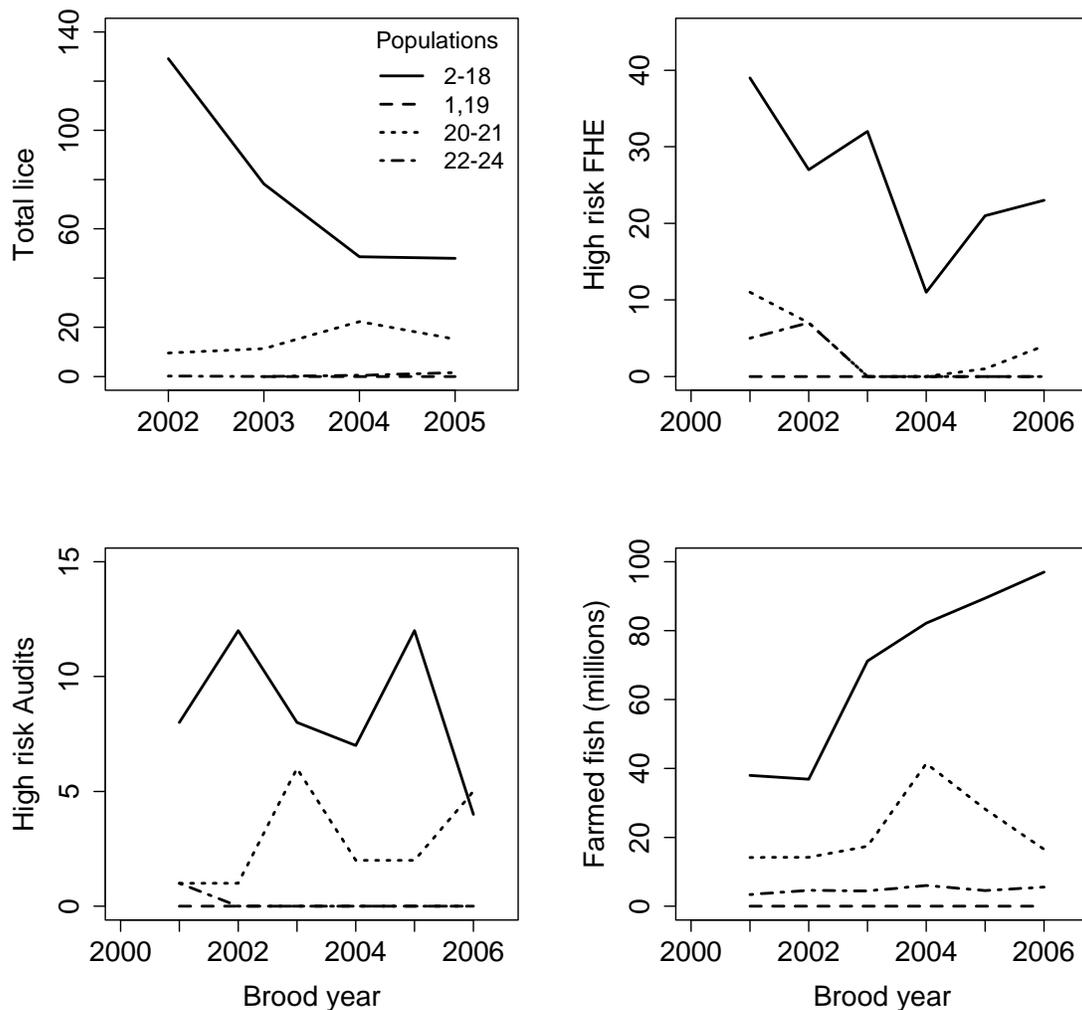


Figure 3. Time series of aquaculture variables including the total number of lice on farmed salmon (Total lice), high risk fish health events (High risk FHE) and positive provincial audit diagnoses (High risk Audits), and total number of farmed salmon along juvenile sockeye salmon outmigration routes. Names of populations are shown in Table 2.

The second source of data on the abundance of farmed salmon was the production of farmed fish (in 1000s metric tonnes) by Fisheries and Ocean Canada management area since the inception of salmon aquaculture in 1982. Production prior to 1982 was assumed to be negligible and production after 1982 was assigned to assumed early marine migration routes by summing production in all management areas that juvenile sockeye must pass through on their way to the open ocean (Table 3 and Figure 5). In some years, for proprietary reasons, production was aggregated across more than one management area. In these cases I assumed production was distributed equally across aggregated areas.

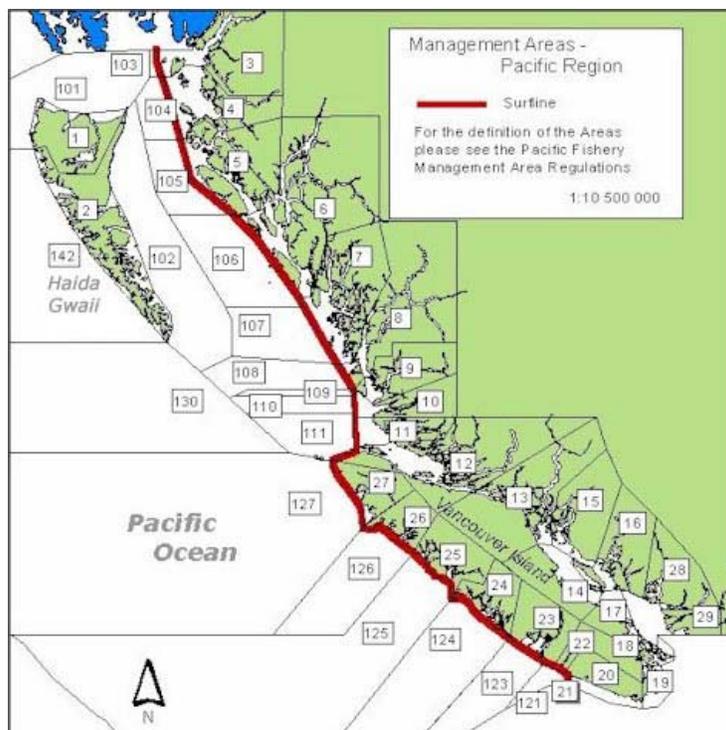


Figure 4. Fisheries and Oceans Canada management areas (from www.pac.dfo-mpo.gc.ca).

Environmental covariates

In addition to pathogens and delayed density-dependence, an independent expert panel identified oceanographic conditions and competition with pink salmon as possible contributing factors to declines in Fraser River sockeye salmon productivity (Peterman et al. 2010). When examining relationships between aquaculture and sockeye dynamics I included these variables in an effort to control for their possible confounding influence on any relationships observed.

Oceanographic conditions

Notwithstanding the spatial scale of covariation recently described by Peterman and Dorner (2011), sockeye populations have historically covaried at scales of several hundred kilometres suggesting that sockeye survival is primarily linked to conditions at regional spatial scales. Regional scale sea surface temperature (SST) in the winter preceding marine entry is negatively correlated with sockeye survival in British Columbia (Mueter et al. 2002) and is a better predictor of sockeye survival than SST during the spring and summer of the first year at sea (Mueter et al. 2005), larger-scale climate anomalies associated with the Pacific Decadal Oscillation, sea surface salinity or upwelling indices (PDO; Mueter et al. 2002). In order to account for the influence of coastal oceanographic conditions in my analysis of aquaculture variables I calculated average SST anomalies from January to May in the year of marine entry from National Oceanographic and Atmospheric Administration-reconstructed SST time series for 2 °latitude by °longitude cells that encompassed the marine entry points of each sockeye population (Table 2 and Figure 1). The sign of SST anomalies for populations north of the Atnarko (populations 24 in Figure 1) were reversed, prior to being used in the analyses described below, to account for the opposite effect of SST on sockeye survival north of the central coast of British Columbia (Mueter et al. 2002).

Pink salmon abundance

Pink salmon are competitively dominant over other salmon and can alter the abundance of prey available to other salmon species including sockeye (Ruggerone and Nielsen 2004). Pink salmon abundance in the North Pacific Ocean is negatively correlated with Alaskan sockeye salmon growth and survival (Ruggerone et al. 2003) and this may also be the case for Fraser River sockeye (Peterman et al. 2010). Increases in pink salmon abundance over the past three decades (Ruggerone et al. 2010) may therefore result in increased competition with sockeye salmon from North America, particularly in odd years when pink salmon abundance is particularly high (Figure 4). I obtained estimates of the number of pink salmon whose oceanic distribution overlaps with North American sockeye (Myers et al. 2007) in the North Pacific Ocean from 1950-present (G. Ruggerone, Natural Resource Consultants, Seattle, WA, USA). Pink salmon abundance was standardized (by dividing by the time series mean) to simplify the interpretation of other coefficients (and interactions) in models in which pink salmon abundance was considered.

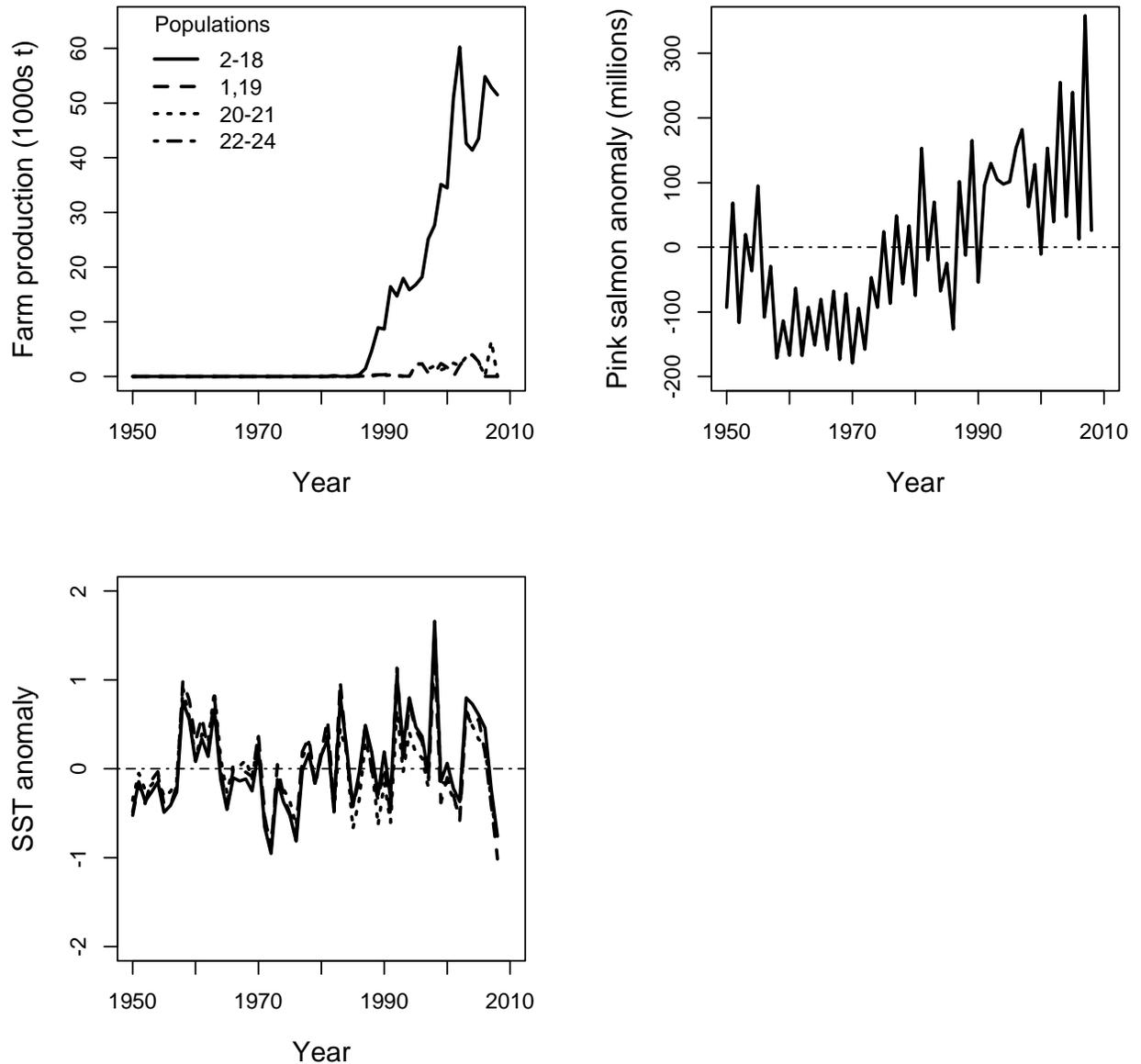


Figure 5. Time series of aquaculture production, pink salmon abundance in the North Pacific Ocean and SST anomalies. The last year of data in the farmed salmon and SST plots is 2008 while it is 2010 in the pink salmon plot. SST anomalies for populations north of the Atnarko are not plotted.

General statistical framework

As opposed to examining the relationship between aquaculture and sockeye dynamics on a population-by-population basis, I considered multiple populations simultaneously. This approach looks for commonality in the response of each population to the independent variable(s) under

consideration. Considering multiple populations simultaneously increases the chance of finding true relationships by allowing for common responses to be more easily isolated from random demographic noise and sampling errors (Myers and Mertz 1998, Walters and Martell 2004).

This approach begins with the Ricker stock recruit relationship (Ricker 1954):

$$\log_e \left[\frac{R_{i,t}}{S_{i,t}} \right] = \alpha - b_i S_{i,t} + \varepsilon_{i,t} \quad (1)$$

where $R_{i,t}$ is the total number of adult recruits to population i produced by spawners ($S_{i,t}$) in year t , α is the intrinsic rate of population growth (i.e., productivity at low spawner abundance), b_i is within-population density-dependence in relation to the carrying capacity of population i , and $\varepsilon_{i,t}$ is residual error.

The Ricker stock recruit relationship can be extended to include between cohort within population density-dependence (Larkin 1971):

$$\log_e \left[\frac{R_{i,t}}{S_{i,t}} \right] = \alpha - b_i S_{i,t} - b1_i S_{i,t-1} - b2_i S_{i,t-2} - b3_i S_{i,t-3} + \varepsilon_{i,t} \quad (2)$$

where $b1_i$, $b2_i$, and $b3_i$ are population specific density-dependent effects of spawner abundance at lags of 1, 2, and 3 years respectively.

Independent variables we are interested in relating to sockeye productivity can be added to the preceding equation:

$$\log_e \left[\frac{R_{i,t}}{S_{i,t}} \right] = \alpha - b_i S_{i,t} - b1_i S_{i,t-1} - b2_i S_{i,t-2} - b3_i S_{i,t-3} + \delta E_{j,t+x} + \varepsilon_{i,t} \quad (3)$$

where E is one or more of j time series of independent variables experienced in year x of the sockeye salmon life cycle and δ is the slope of the relationship between E and sockeye productivity.

Before proceeding further, two important forms of non-independence in the data need to be accounted for. The first is due to repeated observations of the same populations through time. The second arises when the explanatory variables are measured at a larger spatial scale than the individual sockeye populations whose productivity we are interested in explaining. To account for the non-independence of observations in each population through time and between populations at the scale at which the independent variables are measured, equation 3 was modified to include crossed random effects (Pinheiro and Bates 2000):

$$\log_e \left[\frac{R_{i,t}}{S_{i,t}} \right] = (\alpha + \theta_i + \theta_t + \theta_{t,r}) - b1_i S_{i,t} - b2_i S_{i,t-1} - b3_i S_{i,t-2} - b4_i S_{i,t-3} + \delta E_{j,t+x} + \varepsilon_{i,t} \quad (4)$$

where θ_i is intrinsic variation in productivity among populations, θ_t is intrinsic variation in productivity common to all populations among years and $\theta_{t,r}$ is intrinsic variation in productivity among regions within year. These crossed random effects structure the analysis to recognize that (a) observations within regions in a given year and (b) observations within populations among years, are not independent but instead are correlated. The random effects were assumed to follow joint normal distributions with a mean of zero and variance and covariance that was estimated (Pinheiro and Bates 2000). Parameters in these equations could then be estimated using linear mixed effects models in *R* using the *lmer* function in the *lme4* package (R Development Core Team 2011).

Equation 3 can be rewritten (in this case without delayed density-dependence) as:

$$R_{i,t} = S_{i,t} * e^{\alpha - b_i S_{i,t}} * e^{-\delta E_{j,t+x} + \varepsilon_{i,t}} \quad (5)$$

where each term raised to base of the natural logarithm is a component of mortality. It follows that the predicted mortality attributable to independent variable E is:

$$M = \left(1 - e^{-\delta E_{j,t+x}} \right) * 100 \quad (6)$$

where M is the percent decrease in spawner abundance predicted by the value of E experienced by population j in year $t + x$ where x corresponds to the lag between spawning and experiencing the conditions described by E . For example, if the SST anomaly for sockeye populations from the Fraser River that migrate up the east coast of Vancouver Island in 1998 was 2°C and the estimated SST coefficient is -0.2, then the SST encountered in 1998 is predicted to increase sockeye mortality by 33% (i.e., $[1 - \exp(-0.2 * 2)] * 100$).

Analysis of pathogen occurrence, farmed salmon production and mortalities

Most of the aquaculture variables compiled for the Cohen Commission consisted of short time series of 4 to 5 years. Prior to examining the relationship between these variables and sockeye dynamics I computed survival anomalies for each population. These survival anomalies were population specific brood year residuals from the fit of the Ricker (equation 1) or Larkin (equation 2) stock recruit relationship. The specific stock recruit relationship chosen for each population was based on which relationship best fit the full time series of data for each populations as determined by Peterman and Dorner (2011; Table 3 in their report). This approach allowed me to account for density-dependence prior to fitting models with aquaculture terms thereby substantially reducing the number of parameters being estimated (density-dependence is

otherwise estimated for each population individually in the multi-population framework). Computing survival anomalies this way also more appropriately accounts for density-dependence because it is estimated over the entire stock-recruit time series for each population as opposed to the 4-5 years for which we had data on aquaculture variables.

In order to also account for the influence of oceanographic conditions when examining relationships between sockeye dynamics and aquaculture variables I calculated population specific residuals of the Ricker or Larkin stock recruit relationship fit to spawner abundance *and* SST in early marine life. The resulting residuals were then related to (a) sea louse abundance on farmed salmon, (b) disease frequency and occurrence on farmed salmon, (c) mortalities of farmed fish, and (d) the number of farmed salmon. For each aquaculture variable a model with and without (the null model) the variable was fit by maximum likelihood and the statistical significance of the aquaculture variable was evaluated by likelihood ratio test (Hilborn and Mangel 1997).

Analysis of farmed salmon production, sea surface temperature and pink salmon abundance

A limitation of the preceding approach is that it is possible that variation in sockeye productivity may be misattributed to spawner abundance or SST when it is in fact due to some other unmeasured variable. Because of this, when examining the time series of aquaculture production that spans the full Fraser River sockeye salmon time series survival anomalies were not computed before hand. Instead the natural logarithm of adult recruits per spawner (i.e., $\log_e[R/S]$ or productivity) was related to farmed salmon production in management areas in the year of marine entry while simultaneously considering the influence of oceanographic conditions and competition with pink salmon in the open ocean. The abundance of pink salmon was lagged by 4 years from each sockeye brood year because this value best reflects the number of pink salmon that sockeye might compete with in their second growing season at sea (Ruggerone and Nielsen 2004).

For this analysis I took a multi-model inference approach (Burnham and Anderson 2002), which allowed for a quantitative comparison of the strength of the relationship between sockeye productivity and salmon farm production, oceanographic conditions, and the abundance of pink salmon in the North Pacific Ocean. This approach is not statistical null hypothesis testing (as in the preceding section) but instead an alternative approach where model uncertainty is explicitly accounted for by weighting parameter estimates by the support for the models in which they occur.

I considered models with and without terms for salmon aquaculture production, SST, and pink salmon abundance separately, as well as interactions among SST, farmed salmon production, and pink salmon abundance (Table 5). These models were fit to the data using maximum likelihood.

In order to account for model uncertainty, model averaged weighted parameter estimates were generated based on parameters in models within 4 AIC_c of the top model (Akaike Information Criterion with small sample correction; Burnham and Anderson 2002). Parameters from the top set of models were re-estimated using restricted estimate maximum likelihood prior to calculating the model averaged parameter estimates (Burnham and Anderson 2004). I accounted for uncertainty in the underlying form of population specific density-dependence in the models by rerunning this analysis with terms for delayed density-dependence.

Sensitivity analyses

I examined the sensitivity of the results of all analyses to the spatial extent to which reference populations were included in the analysis. This included repeating each analysis with (a) Fraser River populations excluding the Harrison River (i.e., populations 2-18) and (b) the populations identified by Peterman and Dorner (2011) to have declined in synchrony with Fraser populations over the past two decades (i.e. populations 1-32).

I also examined the sensitivity of any relationships observed between sockeye productivity and the independent variable(s) to the inclusion of the 2005 brood year, for which I had to estimate 5-year old returns, by rerunning the analyses without the 2005 brood year. Finally, I verified that the underlying assumptions of the statistical models used were met, i.e., residuals were normally distributed and not autocorrelated within populations by plotting residuals and observed productivity versus fitted values as well as the autocorrelation of residuals in each population at multiple lags.

Results

Analysis of pathogen occurrence, farmed salmon production and mortalities

Sockeye salmon survival anomalies were not significantly correlated with (1) motile or gravid female *Lepeophtheirus salmonis* abundance, (2) motile *Caligus clemensi* abundance or (3) total abundance of motile lice of both louse species on farmed salmon in April to June in the year that juvenile sockeye migrate to sea (Table 4). Sockeye survival anomalies were also not significantly correlated with the occurrence of high risk fish health events or positive audit diagnoses, nor were they significantly correlated with the occurrence of *A. salmonicida*, IHN virus, or *R. salmoninarum* in the year sockeye went to sea (Table 4). The total number of farmed Atlantic or Pacific salmon as well as the “fresh silver” mortality rate in April to June along juvenile sockeye outmigration routes in the year of marine entry was also not significantly correlated with sockeye salmon survival anomalies (Table 4). The reference populations included in this analysis did not influence these results (Appendix 3).

Analysis of farmed salmon production, sea surface temperature and pink salmon abundance

Terms for aquaculture production, SST, and pink salmon abundance appeared in all top models and no single model best fit the data (Table 5). Examination of the model averaged parameter estimates derived from the top set of models suggests that aquaculture production, SST and pink salmon abundance influence sockeye productivity (Table 6). Increasing farmed salmon production, SST anomalies, and pink salmon abundance were all predicted to increase sockeye salmon mortality (Figure 6). In addition, the influence of aquaculture production on sockeye mortality was predicted to be greater when SST anomalies are negative (i.e. cool for BC populations) and pink salmon abundance is high. There was large uncertainty around these estimated effects, particularly around the direct influence of aquaculture on sockeye mortality (Figure 6).

These patterns were robust to the spatial extent to which reference populations were included in the analysis. When the analysis was repeated with just Fraser River sockeye populations (excluding the Harrison River) the predicted direct effect of farmed salmon production on mortality increased and the uncertainty around the effect decreased (Appendix 4.1). Interestingly, when only the Fraser River populations were considered the direct effect of pink salmon abundance was reversed, although there was still substantial uncertainty in its predicted effect on mortality. When the spatial scale of reference populations was increased through to the Yakutat region of Alaska the predicted direct effect of farmed salmon production decreased and the uncertainty in the interaction between farmed salmon production and pink salmon abundance decreased (Appendix 4.2).

Table 4. Summary of models relating aquaculture variables to sockeye salmon survival anomalies. Variables include the number of farmed Atlantic and Pacific salmon as well farmed salmon mortality rates, the occurrence of individual and total high risk fish health events (FHE) and Provincial health audits (Audits), and the abundance of sea lice on farmed fish. Shown are the number of parameters (k), the negative log likelihood (Log Lik) and likelihood ratio statistic (Lik Ratio) and corresponding p-value based on a likelihood ratio test in relation to the null model. Also shown are the coefficients for each variable (coef), standard error (SE) and the effective sample size (Effective n), which is the number of independent regional measures of the variable of interest in the time series.

Model	k	Log Lik	Lik Ratio	df	p-value	coef	SE	Effective n
Null	5	-123.69						
Number of Atlantic salmon	6	-123.11	1.15	1	0.285	-0.008	0.007	22
Number of Pacific salmon	6	-123.68	0.02	1	0.893	0.003	0.024	22
Mortality rate	6	-123.51	0.35	1	0.553	-84.00	133.82	22
High Risk FHE	6	-123.47	0.44	1	0.509	-0.010	0.014	22
Furunculosis FHE	6	-123.20	0.96	1	0.327	-0.080	0.076	22
BKD FHE	6	-123.53	0.30	1	0.584	-0.011	0.018	22
IHNV FHE	6	-123.58	0.21	1	0.647	-0.016	0.034	22
High Risk Audit	6	-123.30	0.76	1	0.382	-0.041	0.044	22
BKD Audit	6	-123.39	0.58	1	0.446	-0.038	0.046	22
Null	5	-93.28						
Motile <i>L. salmonis</i>	6	-93.36	0.00	1	1.000	0.000	0.010	16
Gravid <i>L. salmonis</i>	6	-93.36	0.00	1	1.000	0.001	0.027	16
<i>C. clemensi</i>	6	-93.20	0.16	1	0.692	-0.020	0.049	16
All lice	6	-93.36	0.00	1	1.000	-0.001	0.009	16

Table 5. Summary of models considered to explain Fraser River sockeye salmon declines in productivity, ordered by ΔAIC_c . Terms in the models are farmed salmon production (F), abundance of pink salmon (P), and sea surface temperature (SST). Also shown are the number of parameters (K) for each model, the corresponding log likelihood values (Log Lik), small-sample Akaike Information Criteria differences (ΔAIC_c), Akaike model weights (w_i) and coefficients of determination (R^2). All hypotheses included density-dependence and hypotheses with interactions included lower-order main effects (e.g., “SSTxPxP” signifies a model that includes all possible two-way interactions as well as single variables for SST, P and F), as well as random effects. The null model is population-specific density-dependence and random effects.

#	Hypothesis	K	Log Lik	ΔAIC_c	w_i	R^2
1	(PxP) + (SSTxF)	34	-1301.61	0.00	0.29	0.69
2	SST + (PxP)	33	-1303.18	1.00	0.18	0.70
3	(PxP) + (SSTxP) + (SSTxF)	35	-1301.58	2.09	0.10	0.69
4	P + (SSTxF)	33	-1303.80	2.24	0.10	0.70
5	(PxP) + (SSTxP)	34	-1303.16	3.10	0.06	0.70
6	SST + P + F	32	-1305.42	3.34	0.06	0.70
7	SST + P	31	-1306.76	3.89	0.04	0.70
8	(SSTxPxP)	36	-1301.51	4.10	0.04	0.69
9	(SSTxP) + (SSTxF)	34	-1303.77	4.32	0.03	0.70
10	F + (SSTxP)	33	-1305.40	5.43	0.02	0.70
11	(PxP)	32	-1306.55	5.60	0.02	0.70
12	(SSTxF)	32	-1306.55	5.60	0.02	0.70
13	(SSTxP)	32	-1306.74	5.98	0.01	0.70
14	P + F	31	-1308.09	6.55	0.01	0.70
15	SST + F	31	-1308.29	6.94	0.01	0.70
16	P	30	-1309.58	7.40	0.01	0.70
17	F	30	-1311.53	11.29	0.00	0.70
18	SST	30	-1312.23	12.68	0.00	0.71
19	null	29	-1315.99	18.08	0.00	0.71

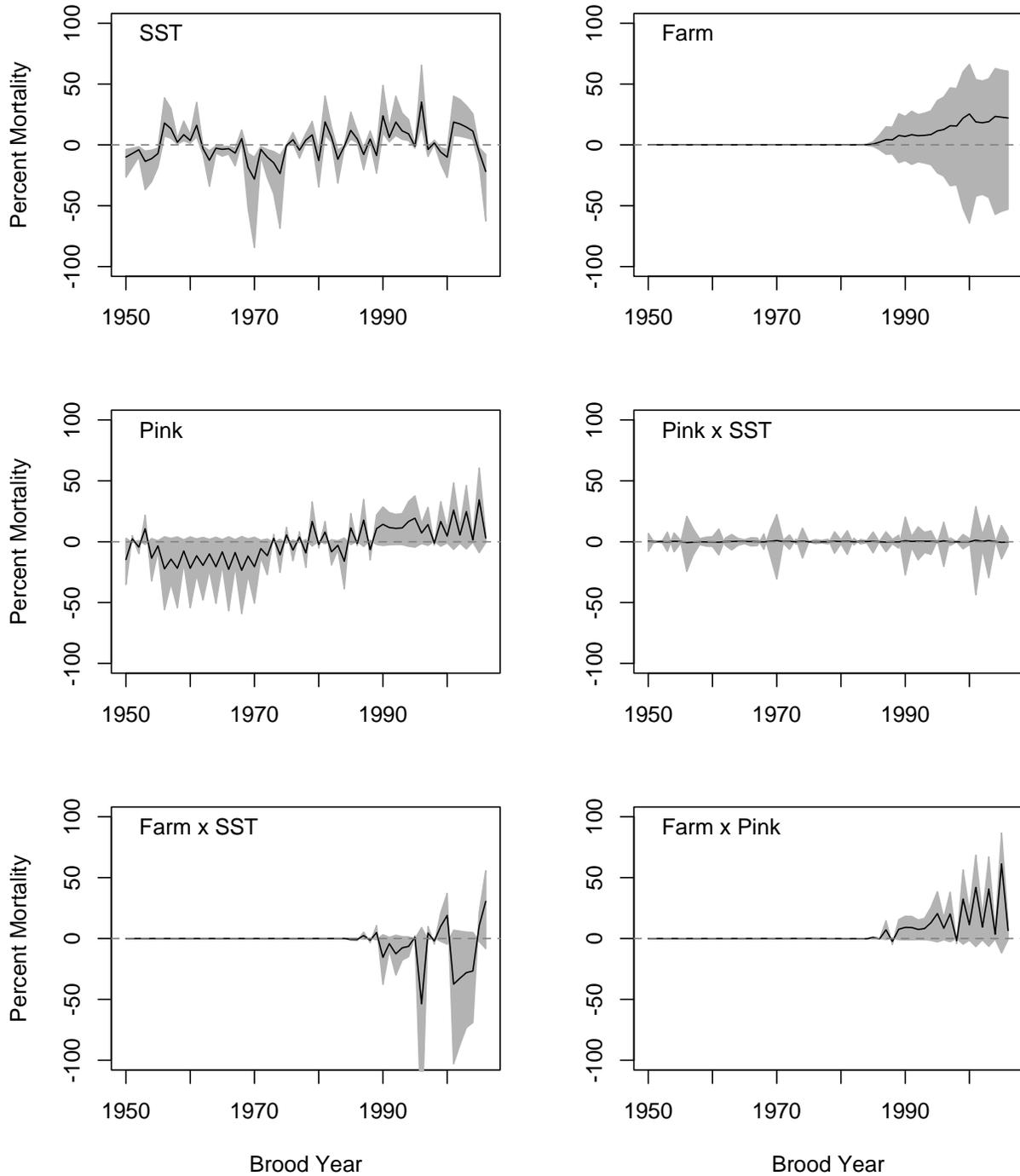


Figure 6. Estimated effect on mortality (\pm 95% confidence intervals; see main text for description of how mortality is estimated) of Fraser River sockeye salmon that migrate up the inside of Vancouver Island due to sea surface temperature (SST), farmed salmon production (Farm), pink salmon abundance in the North Pacific Ocean (Pink) and interactions between the variables. The baseline values for SST and pink salmon abundance are equal to the time series mean while the baseline value for farmed salmon production is zero. This means that, for example, the predicted influence of farmed salmon production (top right panel) is at

average SST and pink salmon abundance. Predictions are based on model averaged parameter estimates (Table 6) from the best-supported models (Table 5). Predicted mortality is plotted through the 2006 brood year, although the parameters are based on models fit to data through 2005.

Rerunning the analysis by constraining the models to include population specific delayed density-dependence slightly reduced the predicted direct effect of aquaculture as well as the uncertainty around the predicted effect of the interaction between salmon farm production and pink salmon abundance, otherwise the patterns that arose from the analysis assuming Ricker dynamics remained the same (Appendix 4.3 to 4.5). That the results were unchanged by when terms for delayed density-dependence were included in the models suggests that any influence delayed density-dependent processes have on sockeye dynamics is independent of the effects of aquaculture, SST and pink salmon abundance.

Excluding the 2005 brood year from the analysis substantially reduced the predicted effect of the farmed salmon production by pink salmon abundance interaction but otherwise had little influence on the patterns described above (Appendix 4.6). Plots of observed versus fitted values and residuals versus fitted values did not reveal strong departures from normality (Appendix 5). There was also little evidence of autocorrelation in residuals within populations (Appendix 5).

Table 6. Multi-model averaged parameter estimates, standard errors (SE), and lower and upper 95% confidence intervals (CI) for parameters appearing in models within $4 \Delta AIC_c$ of the top model (Table 5). Productivity at low spawner abundance is α and variables are farm production (Farm), pink salmon abundance in the North Pacific (Pink), sea surface temperature (SST), and their interactions.

	Coefficient	SE	Upper CI	Lower CI
α	2.16E+00	1.81E-01	2.51E+00	1.80E+00
Farm	-4.87E-03	6.68E-03	8.23E-03	-1.80E-02
Pink	-1.18E-03	7.23E-04	2.41E-04	-2.59E-03
SST	-3.71E-01	1.38E-01	-1.01E-01	-6.41E-01
Farm x Pink	-5.00E-05	2.85E-05	5.92E-06	-1.06E-04
Farm x SST	9.36E-03	5.83E-03	2.08E-02	-2.06E-03
Pink x SST	-5.75E-05	8.81E-02	1.73E-01	-1.73E-01

Discussion

The analyses detailed in this technical report did not find evidence of a relationship between sockeye survival anomalies and (1) sea louse abundance on farmed salmon in the spring/summer juvenile sockeye migrate to sea, (2) *A. salmonicida*, *R. salmoninarum*, IHN virus or total high risk pathogen occurrence on farmed fish in the year sockeye migrate to sea, and (3) the number of farmed salmon or farmed salmon mortality rates along migration routes in the spring/summer sockeye migrate to sea. As nicely illustrated in the technical report prepared for the Cohen Commission by Korman (2011), with short time series of aquaculture variables (like those considered in this report) there is low statistical power to detect a relationship between the aquaculture variables and sockeye survival, should such a relationship actually exist. Consequently, the inference we can draw from these analyses is limited.

One aquaculture variable that was available over a longer time scale was aquaculture production (in metric tonnes) spanning the entire Fraser River sockeye salmon time series. I related sockeye productivity to this measure of aquaculture production along with two other hypothesized contributors to the decline in Fraser River sockeye: (1) oceanographic conditions during early marine life and (2) competition with pink salmon in the open ocean. The results of this analysis suggest that increases in aquaculture production, SST, and pink salmon abundance all increase sockeye salmon mortality with the predicted effects of aquaculture production further influenced by the abundance of pink salmon in the open ocean and SST in the winter preceding marine entry. However, the large uncertainty around these estimated effects makes drawing definitive conclusions from these findings tenuous.

The salmon aquaculture variables examined in this report consist of estimates over broad spatial scales. An unavoidable consequence of this is that multiple sockeye populations are unavoidably compared to aquaculture/environmental time series that have identical values for each population. This makes it more likely that some factor external to the analysis may be responsible for the relationships observed. A stronger test of the relationship between sockeye salmon dynamics and aquaculture variables would include independent measures of farm variables for each sockeye population. In the absence of this finer scale data the relationships described in this report should be interpreted with caution.

It is strongly recommend that the analyses described in this report be revisited once all samples are processed from the 2010 Fraser sockeye returns such that the total number of recruits from the 2005 brood year can be calculated and 5 year olds from the 2006 brood year can be estimated. In addition, it is recommended that the analyses described in this report be refined to include other pacific salmon species, and to accommodate possible non-linear relationships between aquaculture and sockeye dynamics.

This report is not intended to be an exhaustive examination of all possible relationships between salmon aquaculture and sockeye salmon dynamics. Instead I chose to focus on a few plausible relationships that could be examined within the scope of this report. It is important to note that the relationships that are described in this report are correlative and do not on their own establish causation. Nonetheless, these findings should be considered a first step towards understanding the role open net pen salmon aquaculture has played in influencing Fraser River sockeye salmon population dynamics.

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Appendix 1: Statement of work for this contract.

Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (the “Commission”)

“Impacts of Salmon Farms on Fraser River Sockeye Salmon: Assessment by Connors Consulting (the “Contractor”)”

SW1 Background

- 1.1 The Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (www.cohencommission.ca) was established to investigate and report on the reasons for the decline and the long term prospects for Fraser River sockeye salmon stocks and to determine whether changes need to be made to fisheries management policies, practices and procedures.
- 1.2 An assessment of the impacts of salmon farms on Fraser sockeye is required to evaluate their importance to the ecology and survival of Fraser sockeye and to determine their role, if any, in the reductions in Fraser sockeye abundance.

SW2 Objective

- 2.1 To provide statistical support services to evaluate salmon farm impacts on Fraser River sockeye.

SW3 Scope of Work

- 3.1 The Contractor will quantitatively evaluate the relationship between Fraser River sockeye salmon productivity and (a) disease frequency and occurrence on farmed salmon, (b) sea louse densities on farmed salmon, (c) mortalities of farmed fish, and (d) salmon farm production levels
- 3.2 The Contractor will review and analyze data that will be organized and provided by Dr. Josh Korman of Ecometrics Ltd, as described in the Statement of Work “Impacts of Salmon Farms on Fraser River Sockeye Salmon: Assessment by Josh Korman, Ph.D.” attached here as Annex A.

SW4 Research methods and sources of information

- 4.1 The Contractor will use established tools for modeling salmon population dynamics (e.g. multi-stock mixed effects models of stock recruit dynamics) to relate salmon farm data (as described in 3.1) to sockeye productivity. The Contractor will use all available time series of abundance of spawners and recruits (catch plus escapement) for Fraser River stocks as well as from other sockeye populations insofar as it informs the analysis with respect to Fraser River sockeye. The salmon farm data analyzed will be that organized and provided by Dr. Josh Korman of Ecometrics Ltd. The sockeye spawner and recruit data will be provided by Canada via the commission (e.g. from Science project #10).

SW5 Deliverables

- 5.1 The Contractor will participate in a Project Inception Meeting to be held within 2 weeks of the contract date in the Commission office. The meeting will involve Commission scientific staff and 3 researchers, Dr. Don Noakes, Dr. Larry Dill and Dr. Josh Korman, who are also being engaged by the Commission to evaluate and report on salmon farm impacts.
- 5.2 The Contractor will participate in a second Project Development Meeting to be held on, or around March 15, 2011 involving Commission scientific staff and Dr. Don Noakes, Dr. Larry Dill and Dr. Josh Korman. The objective of this meeting is to ensure the integration of the statistical analysis into the work product of Dr. Dill and Dr. Noakes as necessary.
- 5.3 The main deliverables of the contract are statistical analyses of sockeye salmon productivity data and metrics associated with salmon farms.
- 5.4 The Contractor will provide a draft Final Report to the Commission in pdf and Word formats by May 1, 2011. The draft Final Report should contain an expanded Executive Summary of 1-2 pages in length. The Commission may obtain and forward comments on the draft Final Report to the Contractor by May 15, 2011. The Contractor will provide any revisions to the Commission by June 1, 2011.

5.5 The Contractor will make himself available to Commission Counsel during hearing preparation and may be called as a witness.

ANNEX A

“Impacts of Salmon Farms on Fraser River Sockeye Salmon: Assessment by Josh Korman, Ph.D. (the “Contractor”)”

SW1 Background

- 1.1 The Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River (www.cohencommission.ca) was established to investigate and report on the reasons for the decline and the long term prospects for Fraser River sockeye salmon stocks and to determine whether changes need to be made to fisheries management policies, practices and procedures.
- 1.2 An evaluation of the impacts of salmon farms on Fraser sockeye is required to determine their importance on the ecology and survival of Fraser sockeye and to determine their role in the reductions in Fraser sockeye abundance.

SW2 Objective

- 2.1 To undertake quantitative analysis of fish farm and environmental data related to fish disease frequency and sea lice densities at, or adjacent to, salmon farms. The investigation will evaluate salmon disease frequency and occurrence, sea lice densities and mortalities of farmed fish.

SW3 Scope of Work

- 3.1 The Contractor will review data, reports and other information provided by the Commission. This will include information that the Commission receives from the B.C. Salmon Farmers Association, the Province of BC and Canada, as follows:
 - 3.1.1 Data to be furnished by the BC Salmon Farmers Association is expected to include: (1) documents and data relating to fish health, mortality, and pathogens, including sea lice and disease for 120 fish farm sites identified below; and (2) documents and data relating to the stocking of salmon farms identified below including number of fish, species, location, dates of entry into the facility, harvesting, mortality and age-class.
 - 3.1.2 Data to be furnished from BC is expected to include documents and data related to fish health, mortality and pathogens, including sea lice and

disease for the sites identified below. This includes the data from the Province's Fish Health Database.

- 3.1.3 Data and documents to be furnished by Canada is expected to include: (1) case reports pertaining to wild sockeye salmon health; (2) documents from CFIA related to the National Aquatic Animal Health Program; (3) Canada's submissions to the World Organization for Animal Health related to salmon diseases; and, (4) the summary created by CFIA officials of test results related to therapeutic use in finfish aquaculture facilities.
- 3.2 The time period of reference for the data and the quantitative analysis contemplated by this Statement of Work is January 1, 2000 – September 1, 2010.
- 3.3 The salmon farms subject to investigation are the 21 sites referenced in the Commissioner's October 20, 2010 Interim Ruling plus an additional 99 sites identified in the Commissioner's December 8, 2010 Final Ruling. The rulings are attached to this Statement of Work as Annex 1 and 2.

The salmon farms identified in the Interim Ruling are as follows:

- Discovery Islands: Conville Bay; Conville Point; Read Island; Dunsterville; Owen Point; Bickley; Chancellor; Lees Bay; Hardwick Site B; Homfray; Raza; Brent Island; Yellow Island Aquaculture.
- Queen Charlotte Strait: Shelter Pass; Duncan; Bell; Doyle; Shelter Bay; Robertson; Marsh Bay; Raynor.

The additional 99 sites described in the December 8 Final Ruling include the following:

- In Johnstone Strait and eastern Queen Charlotte Strait: Wehlis Bay; Mt. Simmonds; Maude; Cecil; Cypress; Sir Ed; Simoom Sound; Cliff Bay; Smith Rock; Burdwood; Deep Harbour; Wicklow; Blunden; Upper Retreat; Arrow Pass; Midsummer; Potts Bay; Port Elizabeth; Larsen Island; Swanson; Bennett Point; Bocket & Lily; and Mistake Island.
- Along the Central Coast: Jackson Pass and Lochalsh.
- In the Discovery Islands and Johnstone Strait: Poison Creek; Jack Creek; Althorp; Shaw Point; Phillips Arm; Freddie Arm; Egerton; Farside; Sonara

Point; Thurlow; Brougham; Young Pass; Mayne Pass; Venture; Sonora; Cyrus Rocks; Barnes; Doctor Bay; and Church House.

- Along the northern portion of the West Coast of Vancouver Island: Markale Pass; Charlie's Place; Amai; Centre Cove; Hohoae; Monday Rocks; Koskimo Bay; Mahatta West; Mahatta East; and Cleagh.
- In Georgia Strait: Ahlstron; Culloden; and St. Vincent Bay.
- Along the southern portion of Vancouver Island: Sooke Basin; Goodridge Island; and Saltspring.
- In Queen Charlotte Strait: Hardy Bay.
- Along the central portion of the West Coast of Vancouver Island: Cliff Cove; Esperanza; Lutes; Hecate; Steamer Point; Conception Point; Williamson Passage; Muchalat North; Muchalat South; Gore Island; Atrevida; Shelter Inlet; Dixon; Millar; South Shelter; Ross Pass; Binns Island; Bare Island; Bawden; Westide; Cormorant; Saranc; Bare Bluff; MacIntyre Lake; Bedwell; Rant Point; Mussel Rock; Fortune Channel; Tranquill; McCall; Eagle Bay; Indian Bay; Warne Island; Baxter; Dawley Passage; Jane Bay; Barkley; and San Mateo.

3.4 The Contractor will integrate his work with that of Dr. Don Noakes and Dr. Larry Dill who are evaluating and analyzing the impacts of salmon farms on Fraser River sockeye.

SW5 Deliverables

5.1 The Contractor will participate in a Project Inception Meeting to be held within 2 weeks of the contract date in the Commission office. The meeting will involve Commission scientific and legal staff and 2 researchers, Dr. Don Noakes and Dr. Larry Dill, who are also being engaged by the Commission to evaluate and report on salmon farm impacts on Fraser sockeye. The work of the latter researchers will be based, in part, on the results of the present statistical analysis contract.

- 5.2 The Contractor will participate in a second Project Development Meeting to be held on, or around March 15, 2011 involving Commission scientific and legal staff and Dr. Don Noakes and Dr. Larry Dill. This objective of this meeting is to ensure the integration of the statistical analysis results with the work of the latter two researchers.
- 5.3 The main deliverable of this contract is a report describing disease and parasite frequency data on salmon, in and adjacent to salmon farms, and their potential relationship to Fraser River sockeye survival.
- 5.4 The contractor will provide a draft Final Report to the Commission in pdf and Word formats by March 15, 2011. The draft Final Report should contain an expanded Executive Summary of 1-2 pages in length as well as a 1-page summary of the "State of the Science". The Commission will obtain and forward comments on the draft Final Report to the contractor by March 22, 2011. The contractor will provide any revisions to the Commission by March 31, 2011.
- 5.5 The Contractor will make himself available to Commission Counsel during hearing preparation and may be called as a witness.

ANNEX 1 - INTERIM RULING RE: R. 19 APPLICATION FOR PRODUCTION OF

AQUACULTURE HEALTH RECORDS, OCTOBER 20, 2010

1. Pursuant to Rule 18 of the commission's rules of procedure and practice, two participant groups, the Conservation Coalition and the Aquaculture Coalition (the "applicants"), sought to have commission counsel request copies of the following documents from the Province of British Columbia, the Government of Canada, and the British Columbia Salmon Farmers' Association ("BCSFA") (the "respondents"):

- i. Documents in the possession or control of the Department of Fisheries and Oceans, the Canadian Food Inspection Agency, Environment Canada and/or any other federal department relating to the occurrence of, monitoring of, and response to pathogens, including sea lice and disease (in particular, infectious hematopoietic necrosis virus, bacterial kidney disease, infectious salmon anemia and furunculosis) in wild salmon stocks. Included in the document request are any documents submitted to the World Organization for Animal Health relating to disease in salmon in British Columbia waters in compliance with reporting obligations to that organization;
- ii. Documents in the possession or control of the federal government (particularly DFO), and the provincial government (particularly the Ministry of Agriculture and Lands and the Ministry of Environment and their respective predecessors), relating to fish health, mortality and the occurrence of, monitoring of and response (including treatment, enforcement, and authorizations) to pathogens, including sea lice and disease (in particular infectious hematopoietic necrosis virus, bacterial kidney disease, infectious salmon anemia and furunculosis) in finfish aquaculture facilities;

- iii. Documents in the possession or control of the BCSFA relating to fish health, mortality, and the occurrence of, monitoring of and response (including treatment, enforcement, and authorizations) to pathogens, including sea lice and disease (in particular infectious hematopoietic necrosis virus, bacterial kidney disease, and furunculosis) in finfish aquaculture facilities; and
- iv. Documents in the possession or control of the BCSFA relating to the stocking of finfish aquaculture facilities including: number of fish, species, location, dates of entry into facility and harvesting or mortality, as well as age-class.

2. On August 19, 2010 commission counsel wrote to the respondents requesting the documents proposed by the applicants, but limited to the period 2004–2009, and to 21 identified fish farms. This limitation was based on commission counsel's assessment of the material available to them at that time, and of the relevance and necessity of the requested documents. In limiting the requests, commission counsel advised that they were attempting to balance the following competing considerations:

- This is a public inquiry which should permit a full public examination of the issues arising in the terms of reference.
- The Commissioner is to investigate and make findings of fact regarding the causes for the decline of Fraser River sockeye.
- There is a lively public debate surrounding aquaculture and its impact, if any on the Fraser River sockeye.
- The terms of reference explicitly list aquaculture as a potential cause for decline that the Commissioner shall investigate (cl. A(i)(C)(i))
- The Commissioner has granted participant status to organizations that focus exclusively on aquaculture issues (such as the Aquaculture Coalition and the BCSFA). There will be hearings addressing this topic in order to permit the

Commissioner to investigate and make findings of fact and if warranted to make recommendations for improving the future sustainability of the sockeye salmon fishery.

- Counsel's assessment of what documents are relevant and necessary must strike a balance between (1) ensuring a full and informed investigation of the issue, and (2) avoiding a prolonged and tangential review of the documents with little or no connection to the commission's work.
- Documents produced to the commission do not enter the public domain, but are provided to participants on the basis of undertakings of confidentiality which ensure they cannot be used for purposes beyond the commission (see Rule 17).

3. The respondents support the request made by commission counsel (21 identified fish farms for a five year period), with one qualification: the respondent BCSFA asks that I consider ordering that its documents be produced on an aggregate basis. Moreover, this respondent resists the application on the basis that the order sought for a broader time frame and additional fish farms would have the effect of making the work of the commission on this issue unmanageable and greatly delay disclosure, thus prejudicing the inquiry process and the public interest.

4. The respondent Canada supports the document request made by commission counsel. It takes no position on the geographic scope of production but asserts that the five year time period is consistent with the initial approach this respondent and commission counsel settled upon for its document production.

5. The respondent Province supports commission counsel's request, and raises concerns regarding the practicality of extending the request further back in time.

6. The participants, Area D Gillnetters Association/Area B Seine Society and the Heiltsuk Tribal Council, both filed written submissions supporting the applicants' position.

7. At the hearing, counsel for the respondent Province said that this respondent would be in a position to produce the documents sought by commission counsel within two weeks. Thus I order that this respondent's documents be produced forthwith.

8. Counsel for the respondent BCSFA said at the hearing that this respondent, if ordered, could produce the documents sought by commission counsel forthwith. Thus I order that the documents sought from this respondent be produced forthwith. I also order that this respondent produce the documents in the form requested by commission counsel as I am not persuaded that providing the documents only in the aggregate as proposed by this respondent will be sufficient.

9. With respect to the respondent Canada, it is engaged with the commission in an extensive document production process. As such I will not make a similar order with respect to the timing of the production of the documents. I would, however, ask that this respondent provide the documents to the commission counsel at the earliest possible date, but without causing undue disruption to the broader process of document production. Thus I order that this respondent advise commission counsel within one week of the date of this ruling of its estimate of time for delivering the documents sought by commission counsel. The other respondents, the applicants and commission counsel have liberty to seek directions from me if the respondent Canada's estimate of time for delivery of the documents is considered by any of them to prove problematic.

10. I should add that it has been brought to my attention since the date of the hearing that some of the fish farms identified by commission counsel may not have been stocked during the relevant time period. In this respect, my order only requires production of documents to the extent that they exist.

11. Finally, while I am satisfied that the material filed by the applicants and respondents necessitates my consideration of the limitation placed by commission counsel on the documents sought by the applicants, I have concluded that I need some further evidence before issuing my ruling.

12. In my consideration of the temporal and geographic limits to be applied to the requested documents, I intend to apply the principles adopted by commission counsel reproduced at paragraph 2, in particular, that I must strike a balance between ensuring a full and informed investigation of the issues while avoiding a prolonged and tangential review of the documents with little or no connection to the commission's work.

13. While I heard submissions of counsel regarding the impact the order sought might have on the respondents and the conduct of this inquiry, some of these submissions were not supported by evidence.

14. In this regard, I invite counsel for the respondents to provide me with additional evidence addressing any hardship that would be occasioned by the collection and production of a broader set of documents than that now sought by commission counsel.

15. Further, I invite counsel for the applicants, the respondents and the commission to provide me with evidence addressing any consequences in terms of timeliness and cost associated with the analysis and presentation of the evidence on this topic which may flow from me ordering a broader production of documents than that now sought by commission counsel.

16. Such additional evidence may be delivered to the commission by 4:00 p.m. Monday November 1, 2010. The commission shall promptly distribute the evidence to all participants. Supplemental written submissions from the applicants, respondents, participants or commission counsel may be delivered to the commission by 4:00 p.m. Monday November 8, 2010.

17. It should be noted that all documents disclosed to participants are subject to an undertaking of confidentiality and all counsel shall abide by this undertaking and ensure that their clients understand the limited use to which the disclosed documents may be put.

Signed 20 October 2010

The Honourable Bruce I. Cohen
Commissioner

**ANNEX 2 - RULING RE: RULE 19 APPLICATION FOR
PRODUCTION OF AQUACULTURE HEALTH RECORDS, DECEMBER 8, 2010**

Background to the application:

18. On July 5, 2010, pursuant to Rule 18 of the commission's rules of practice and procedure, the Aquaculture Coalition and the Conservation Coalition (the "applicants") asked commission counsel to request of the Province of British Columbia (the "Province"), the Government of Canada ("Canada") and the British Columbia Salmon Farmers' Association ("BCSFA") (together, the "respondents") certain documents (the "Initial Request").

19. The Initial Request sought documents relating to fish health, pathogens and disease, as well as stocking data in farmed salmon. The applicants also requested fish health data for wild salmon. The geographic and temporal scope of the Initial Request was for fish farms and "wild salmon on the Fraser River migration route (including both sides of Vancouver Island and north of Vancouver Island through Klemtu) dating from 1980 to the present."

20. The BCSFA wrote to commission counsel on July 30, 2010, advising that it found the Initial Request "overreaching in its scope, both in terms of the kinds of documents requested and the period of time which the request covers." The BCSFA expressed concern about the temporal scope of the Initial Request:

We are concerned that expanding the timeframe of the evidence placed before the Commission will detract from the Commission's process and will place additional financial pressures on all participants. As a practical consideration, the Commission should seek to limit the scope of the

investigation to material times, which based upon our understanding of the Terms of Reference, would be within the last five to ten years.

21. In its letter, the BCSFA proposed providing the commission with “aggregated data for the years 2007 to 2009 from the Fish Health Documents with a report summarizing and explaining the raw data ...”

22. On August 11, 2010, Canada responded to the Initial Request, noting that it had relevant documents (i.e. fish health records for Fraser sockeye covering 2004-2009) which it was in the process of producing to the commission, but it expressed concern about a request reaching further back in time from 2004, as it would delay the production of other relevant documents.

23. On August 18, 2010, the applicants wrote in response to the positions of the respondents. They reiterated their request for information from individual salmon farms (as opposed to aggregated data proposed by BCSFA); however, they revised their request, seeking documents going back 22 years (to 1988). The applicants also accepted a suggestion of the Province that the scope be limited to “documentation, and hence farm data, in the Fraser River and along the migration routes of the Fraser River sockeye.”

24. Although commission counsel supported the Initial Request, on August 19, 2010, commission counsel wrote to the respondents requesting the documents sought by the applicants, but limiting the request to documents from the period 2004-2009 and from 21 identified fish farms explaining as follows:

At a broad level, the Applicants’ request touches on a topic that is expected to be the subject of hearings which may be controversial. There is likely to be disagreement and debate on whether, for instance, the presence of salmon farms – in the migration routes of Fraser River sockeye – has a deleterious impact on migrating salmon. To attempt to answer this question, it becomes relevant and necessary to have an understanding of the type of information sought in this application.

Given this, commission counsel have agreed in many respects with the Applicants' request for documents. There are, however, several parameters that may properly be placed on the request that commission counsel are making through this letter. ...

First, in obtaining general documentary production from Canada, the commission has commenced with a five-year time frame (2004-2009), though the production to date from Canada contains many relevant documents that pre-date this period. The five-year time frame permits a good understanding of the recent documentary record, and strikes a balance by not going back decades. Unless otherwise noted, our requests below employ this five-year period.

Second, insofar as the documents at issue deal with wild salmon, relevant materials will be those dealing with Fraser River sockeye, as opposed to other species of Pacific salmon.

Third, geographically, relevant materials relate to the migration routes of Fraser River sockeye, rather than Fraser River salmon generally.

...

For both the Province and the BCSFA, commission counsel have, with the assistance of the commission's science staff, identified aquaculture facilities which are proximate to the migration routes of Fraser River sockeye. The enclosed maps detail these areas and facilities. ...

25. The specific requests of the respondents for documents for the time period from 2004 to 2009 made by commission counsel were:

the Province:

...

- Documents relating to fish health, mortality and pathogens including sea lice and disease, for the farms in the area identified above and in the maps appended to this letter. This includes the data from the Province's Fish Health Database.

the BCSFA:

...

- Documents relating to fish health, mortality, and pathogens including sea lice and disease, for the sites in the area identified above and in the maps appended to this letter; and
- Documents relating to the stocking of salmon farms identified above, including the number of fish, species, location, dates of entry into the facility, harvesting, mortality, and age-class.

The BCSFA is requested to supply the above information at a farm-specific level, rather than as aggregated information. ...

Canada:

... Commission counsel confirm that we seek the following documents

- Case reports pertaining to wild sockeye salmon health;
- Documents from CFIA [Canada Food Inspection Agency] related to the National Aquatic Animal Health Program;
- Canada's submissions to the World Organization for Animal Health related to salmon diseases; and
- The summary created by CFIA officials of test results related to therapeutant use in finfish aquaculture facilities.

The Rule 19 application:

26. In response to commission counsel's request, the applicants brought this application under Rule 19 to compel production of the documents they initially sought (as revised in the letter of August 18, 2010). A hearing date of September 22, 2010 was set and the applicants and respondents, as well as any other participants and commission counsel were invited to provide written submissions.

27. In addition to their written submissions, the applicants tendered the affidavits of Stan Proboszcz, fisheries biologist with Watershed Watch Salmon Society, and of Alexandra Bryant Morton, fisheries biologist, both affirmed September 9, 2010. The applicants objected to the five year and 21 farms approach of commission counsel, maintaining that "a longer time span of production is necessary for the Commission to assess the impact and causation between health of fish in aquaculture facilities and health of wild sockeye stocks [and] there are additional fish farms that are of sufficient

proximity to Fraser sockeye migration routes to potentially impact Fraser sockeye which ought to be included in the production request.”

28. The applicants objected to the geographic limits of commission counsel’s request, which covered only 21 fish farms:

25. In the Applicants’ submission, a proximate fish farm is one that can potentially impact Fraser sockeye stocks. In this regard, a 2005 study entitled *Transmission dynamics of parasitic sea lice from farm to wild salmon* Krkosek et al found that infection pressure from salmon farms caused sea lice levels to exceed ambient levels for an average of thirty kilometres. Therefore, a reasonable and scientifically sound way to determine which farms are potentially relevant to declining stocks is to identify which farms are within thirty kilometres of Fraser River sockeye salmon migration routes.

26. In the Applicants’ submission, all farms within thirty kilometres of Fraser sockeye migration routes could potentially impact Fraser sockeye and are therefore sufficiently proximate to warrant ordering the production of all fish health and stocking documents.

29. The applicants relied on the affidavit of Mr. Proboszcz, seeking information from an additional 99 fish farms which he identified as within 30 kilometres of Fraser River sockeye migration routes.

30. The applicants criticized commission counsel’s request for documents from the five-year period of 2004-2009:

30. There is no biological or scientific basis to limit the examination of fish health data to a five-year time frame. It is only with an examination of multiple life-cycles of specific salmon stocks that any comprehensive and reliable scientific determinations can be made regarding long-term impacts of disease and parasite exposure. Absent multiple comparator years of specific Fraser sockeye runs, any determination of the relationship between the health and stocking of fish farms and declining salmon stocks will be of limited value. ...

31. The participant groups, Area D Salmon Gillnet Association and Area B Seine Society, and the Heiltsuk Tribal Council filed brief written submissions supporting the application.

32. The Province did not provide written submissions in response to the application, though orally supported the parameters set by commission counsel.

33. Canada provided written submissions on September 14, 2010, reinforcing its position that an extension of the time period beyond November 1, 2004 would “entail a significant restructuring of the document production work, both by having to add resources to assemble further documents and by diverting existing resources away from current document processing work”. Canada supported its submissions with affidavits sworn on September 14, 2010, from Rachelle Haider and Christina Gallo, support staff at the Department of Justice.

34. The BCSFA provided written submissions objecting to the application, but offering to provide “the requested documents on the terms in the Commission’s Request of August 19, 2010, subject [to] the Commissioner’s consideration of the BCSFA’s affidavit materials ... explaining the scientific basis for aggregating the requested fish farm data.” In support of its submissions, the BCSFA tendered the affidavits of Kenneth M. Brooks, a fisheries biologist and environmental scientist, affirmed September 16, 2010, and of Tom Watson, a biologist, affirmed September 13, 2010.

35. The affidavit material filed by the BCSFA took issue with the 30 kilometre limit identified in the affidavit of Mr. Proboszcz, asserting that there is no evidence disease or lice from fish farms can travel this distance and subsequently infect wild sockeye salmon.

36. Commission counsel provided written submissions on September 17, 2010, in which they expanded their reasons for limiting the Initial Request to 21 identified fish farms and for a period from 2004-2009, as follows:

The Fish Farms Selected for Specific Document Disclosure

6. Commission counsel limited the Request for documents from fish farms to 21 aquaculture facilities proximate to the sockeye migration route along the east side of Vancouver Island. With reference to scientific articles (cited in the Request at footnote 1, page 5), and in particular to the map on p. 58 of the article by Groot and Cooke (reproduced at Exhibit “E” of Affidavit #1 of Stan Proboszcz), commission counsel identified aquaculture facilities located along the assumed migratory routes of Fraser River sockeye smolts. The 21 fish farms identified in the Request are comprised of (1) those that are closest to the sockeye routes identified on the Groot and Cooke map through the Discovery Islands; and (2) those that border the waters of the Queen Charlotte Strait, through which the smolts migrate.

...

9. The Applicants have pointed out, correctly, in their submissions, that Fraser River sockeye sometimes use an alternative migratory route along the west side of Vancouver Island. Therefore, they say, fish farm data from the west side of Vancouver Island must also be disclosed to the commission. Commission counsel did not include farms from the west side of Vancouver Island in the Request for the following reasons. We understand the “inside” route to be the preferred and primary route for migrating Fraser River sockeye. Also, unlike the Discovery Islands where the migrating salmon are forced by geography to swim through narrow channels which bring them into proximity with fish farms, we had no scientific information available to us concerning how close the sockeye smolts come to fish farms along the west coast of Vancouver Island. Furthermore, we determined that the objective of testing for relationships between fish farms and the health of Fraser River sockeye could be accomplished with a data set collected from fish farms along the main sockeye migration route.

10. The Applicants have also suggested that the commission should be seeking fish health data from all fish farms within a 30 km radius of sockeye migration routes. In our view, the question that should be asked on this application is whether the 21 sites identified will adequately inform the understanding of salmon-farm disease and sea lice frequency adjacent to sockeye smolt migration routes. We have deliberately selected 21 “worst-case scenario sites” in terms of pathogen exposure. If a trend cannot be

demonstrated at these sites, there is little value in studying other locations that are situated at greater distances from these routes.

...

The Time Frame for the Document Requests

12. Commission counsel limited the Request to documents produced in the five years leading up to the announcement of the Inquiry (November 2004-2009). Commission counsel chose to employ the five-year period reflected in the commission's current approach to initial disclosure from Canada.

...

14. Commission counsel acknowledge the possibility that the temporal limits placed around the document request may prevent some effects from being determined through the planned analyses (which we describe below). But given the number and complexity of the issues under investigation by this Inquiry, we felt it acceptable to proceed in the face of this risk. A five-year data set will provide an opportunity to understand relationships between fish farms and the 2009/2010 returns. A sufficient picture of aquaculture effects, proportionate to the topic's place in the Inquiry, can be provided through data for the last five years.

37. In the reply submissions filed by the applicant Conservation Coalition on September 17, 2010, it noted that the only issue before me at this stage "is whether the scope of the production of documents as requested by Commission Counsel ought to be expanded along geographic and temporal planes." In support of expanding the scope of the request it wrote:

6. It is worth pointing out that the same scientific studies and publications relied upon by the Commission Counsel in his letter of August 19 are in fact relied upon by the Applicant in its evidence.

7. A close examination of those publications shows that the out migration path of the juvenile sockeye salmon from the Fraser River predominantly occurs through the Strait of Georgia in a northerly direction. However the publications also support a finding that juvenile sockeye from the Fraser River are to be found along the West coast of Vancouver Island and the central coast of British Columbia. The in migration of adult sockeye to the

Fraser occurs either along the West Coast of Vancouver Island or through the Strait of Georgia.

...

10. Thus there is ample authority to expand the production of records from salmon farms located along all of the migration paths of Fraser River sockeye and not just the ones as delimited in Commission Counsel's letter of August 19.

38. The co-applicant, the Aquaculture Coalition, also filed its reply submissions on September 17, 2010 stressing that the temporal scope of the documents requested must be extended back to 1988:

21. The appropriate time-line must take into account that, although individual year returns have varied, it is clear that productivity has been declining steadily since 1992. It is in 1992 that salmon farms first reported disease events. Nothing less than a full examination, starting from 1988 (the generation preceding to the 1992 returns) will provide a fair examination of the possibility that disease and pathogens have played an important part in the as yet unexplained variability and declines.

39. On September 22, 2010, I heard argument on the application and on October 20, 2010, I issued my Interim Ruling.

The Interim Ruling:

40. In my Interim Ruling, I noted at paragraph two the rationale of commission counsel for limiting the applicants' initial request temporally and geographically, in

particular, that counsel's assessment of what documents are relevant and necessary "must strike a balance between (1) ensuring a full and informed investigation of the issue, and (2) avoiding a prolonged and tangential review of the documents with little or no connection to the commission's work."

41. At the hearing, the respondents acknowledged that they could produce the documents as requested by commission counsel. Thus, I ordered that the Province produce the documents requested by commission counsel forthwith, and that the BCSFA produce forthwith the documents requested by commission counsel and in the form requested by commission counsel.

42. Given the extensive document production process engaged in by the respondent Canada, I ordered Canada to advise commission counsel within one week from the date of my Interim Ruling of its estimate of time for delivering the documents sought by commission counsel.

43. With respect to the applicants' assertion that the requested documents should be expanded geographically and temporally to conform to their initial request, I concluded that I needed further evidence before issuing my final ruling. Accordingly, I invited counsel for the respondents to provide me with additional evidence by November 1, 2010, addressing any hardship that would be occasioned by the collection and production of a broader set of documents than that sought by commission counsel.

44. I further invited counsel for the applicants, the respondents and the commission to provide me with evidence addressing any consequences in terms of timeliness and cost associated with the analysis and presentation of the evidence on this topic which may flow from me ordering a broader production of documents than that sought by commission counsel.

Additional Evidence following Interim Ruling

45. In her affidavit sworn October 29, 2010, filed on behalf of Canada, Annie Champagne, Director of the Aquatic Animal Health Division of the Canadian Food Inspection Agency (“CFIA”), deposed that with respect to the temporal limits, the Fish, Seafood and Production Division of the CFIA holds documents relating to therapeutant and toxin level test results dating from 1990 and could produce these documents in a few days to a week. In the affidavit of Alan Cass, a DFO biologist, sworn November 2, 2010, he deposed that Canada holds records for wild sockeye case reports from 1962-2009 (and they have started scanning the case reports from 1998-2004), parvicapsula-related documents from 2000-2004, and infectious hematopoietic necrosis virus documents from 1987-2009. The estimate of time to collect and produce these documents to the Department of Justice for uploading to Ringtail varies, but it is generally under a month.

46. However, in her affidavit sworn November 1, 2010, Ms Haider deposed that expanding the request beyond five years would result in further delay of the ongoing production of documents by Canada relevant to the hearings and would result in upwards of “several hundred thousand documents for each additional five year period” requested. I note that Ms Haider does not distinguish in her affidavit between documents related to aquaculture and general documents related to the work of the commission. This application, of course, only deals with the limited set of aquaculture documents being sought.

47. In his affidavit sworn November 2, 2010, Mark Sheppard, Aquatic Animal Health Veterinarian, Ministry of Agriculture and Lands, deposed that the Province’s Fish Health Program was initiated in 2001 and that the Province can produce relevant records from 2002 forward in approximately 24 days. Raveen Sidhu, staff with the Legal Services Branch of the Ministry of Attorney General, deposed that relevant records from 2000 forward are stored electronically in an archived database; however, relevant records prior to 2000 have been destroyed.

48. The BCSFA also asserted that prior to the implementation of provincial regulation, the aquaculture industry's record keeping is difficult to ascertain and in the affidavit of Stephen Budgeon, IT Manager of Marine Harvest Canada Ltd., sworn November, 1, 2010, he said that it would take "many months" to determine whether data exists and to put it into useable form.

49. The BCSFA estimates between \$12,000 - \$19,000 per month in "lost productivity" if the request for documents were to reach back before the early 2000s (affidavit of Budgeon, paragraphs 6 & 7; affidavit of Mia Parker, Manager, Regulatory Affairs, Grieg Seafood B.C. Ltd., sworn November 2, 2010, paragraphs 5 & 6; and affidavit of Frank Bohlken, environmental scientist for Triton Environmental Consultants Ltd., sworn November 2, 2010, paragraph 7). I note that this affidavit material does not define "lost productivity" and does not provide sufficient details for me to assess the likely magnitude of any hardship which would be occasioned. It does, however, provide some evidence of potential hardship to the BCSFA should I order the production of documents from the 1990s or earlier.

50. In his affidavit provided at the request of commission counsel, Josh Korman, a fish biologist at Ecometric Research Inc., sworn November 1, 2010, noted the difficulty in limiting the requested information to a five-year data set and commented upon the timeliness and cost of expanding the information:

10. Hypothetically, it would be helpful to consider a longer time series of data. It is reasonable to expect that the expanded dataset would substantially strengthen inferences regarding the effects of salmon farms on Fraser sockeye returns. A key part of such an analysis would likely entail relating temporal variation in disease and lice frequency with marine survival rates (as indexed by variation in recruits/spawners). Such an analysis could be undertaken using an expanded 20-year dataset, if those data were available in a consistent format, but is not possible with the current five-year dataset because of insufficient replication.

...

13. Currently, given my other commitments and the later-than-expected start to this project, I expect the assessment of the data from 21 farms for five years to be completed by March 31, 2011. If the additional data were available with sufficient consistency, I would expect a 50 per cent increase in the amount of time required to do my analytical work. Despite this, I anticipate that I could still complete the work by March 31, 2011. The cost of the analysis would also increase by approximately 50 per cent.

Analysis

51. I am satisfied, on the whole of evidence that the geographic and temporal limits imposed by commission counsel ought to be broadened for the reasons that follow.

52. First, with respect to the geographic scope of the request, while I understand the approach of commission counsel to limit the request to 21 identified fish farms along the out-bound northern migration route, I have concluded that information from fish farms in proximity to other potential migration routes (such as the western or southern portion of Vancouver Island) would be relevant and contribute to a full and informed investigation of this issue.

53. The applicants urged me to adopt the approach set out by Mr. Proboszcz in paragraph 15 of his affidavit:

According to my research and understanding of the transmission of disease and parasites, in order to assess the impact of aquaculture on declining Fraser River sockeye, including the impact of diseases and sea lice from salmon aquaculture facilities, fish health and stocking records of all those facilities that are sufficiently proximate to the various Fraser sockeye migration routes as to potentially transmit pathogens, including disease or sea lice must be reviewed. In this regard, a reasonable and scientifically

sound way to determine which farms are potentially relevant to declining stocks is to identify which farms are within thirty kilometres of Fraser River sockeye salmon migration routes.

54. The respondent BCSFA takes strong issue with Mr. Proboszcz's opinions and with the literature upon which Mr. Proboszcz relied to reach his opinions, particularly the conclusion that a reasonable and scientifically sound way to determine which farms are potentially relevant to declining stocks is to identify which farms are within thirty kilometres of the Fraser River sockeye salmon migration routes.

55. In my view, this ruling is not the time or place for me to decide the serious conflict in the parties' positions regarding the evidence on this point. However, I think that data from the additional fish farms identified in the affidavit of Mr. Proboszcz may assist me in assessing such issues as the impact of fish farms on Fraser River sockeye salmon (if any) and in determining the degree of proximity required for a risk of infection to exist.

56. Moreover, neither the Province nor the BCSFA identified any hardship to them or delay of the commission's proceedings which would be occasioned by broadening the geographic reach of the documents ordered to be produced by the respondents. On this point, the respondent Canada stated:

5. ... Canada has not taken a position on the geographic reach of any Order made. Further, the breadth of the geographic reach, whether it be 21 farms as set by Commission counsel in his letter or a larger number requested in the motion, will not have a significant impact on the work entailed or timing to produce documents.

57. Second, in considering the temporal scope of the request and whether it should be expanded past the five years, I am of the opinion that there is substantial utility in

obtaining documents from a broader period, especially to the extent that they can be obtained in a timely way and useful format.

58. In assessing the need for further documents, I note the evidence of Dr. Korman, who opined that it is reasonable to expect that an expanded data set would substantially strengthen inferences regarding the impact of salmon farms on Fraser sockeye.

59. The benefits of a larger data set going back further in time were also identified in the affidavit of Gordon Fredric Hartman, fisheries scientist, sworn November 1, 2010, filed on behalf of the applicants:

4. It is also my opinion that there is a greater chance that a subset of data (instead of all spatially and temporally relevant information) may produce inconclusive results, thereby producing a need for additional data to substantiate scientific findings. In addition, the statistical analysis of a subset of data will often produce results with larger associated error relative to the same analysis of a larger data set. Thus, there will likely be greater confidence in scientific findings derived from a larger data set. Moreover, solely analyzing a subset of data increases the likelihood of coming to erroneous conclusions. It is therefore most efficient to obtain a more robust data set at the outset and avoid inconclusive or erroneous scientific findings.

5. Furthermore, five-years of data cover only one and one quarter life cycles of the common run component among Fraser River sockeye salmon. As such, in my opinion, analyzing five-years of data respecting the environmental conditions faced by out-migrating Fraser sockeye salmon is unlikely to provide a reasonable basis for the meaningful evaluation of sockeye salmon population fluctuations. ...

60. I note the opinion of Dr. Brooks that “examining arbitrary time periods in temporally cycling data can lead to misleading results that depend on the period examined”, however, none of the affidavit material filed by the respondents persuades me that an expanded data set (if available) would not strengthen the analysis.

61. On the issue of the quality and availability of data, I note the evidence from the Province that it did not regulate the aquaculture industry until 2001, and that documents from prior to 2000 have been destroyed. In her affidavit, Ms. Sidhu deposed that she had been advised by Gary D. Marty, D.V.M., Ph.D., Diplomate, A.C.V.P. Fish Pathologist that:

1.:

- (a) The Cases from 2000-2002 - ... These records are stored electronically in an archived database. ... We would be able to provide individual case reports, but these case reports would not be summarized on a spreadsheet ...
- (b) Note that many of these case reports will have no information about the farm of origin. ...
- (c) Cases before 2000 – we have no records from cases before 2000 (they have all been destroyed).

62. In his affidavit, Dr. Sheppard deposed:

12. The BCMAL [British Columbia Ministry of Agriculture and Lands] maintains a Fish Health Audit and Surveillance Database dating 2004-2009. ...

...

19. To my knowledge the randomized overseeing audit information was not collected by BCMAL prior to 2002.

20. In the pre 2002 period, the Province may have some scattered project and case by case diagnostic confidential medical records from fish samples submitted by owners of aquaculture facilities on an as needed basis for diagnostic analysis. This material is submitted when an individual owner or private veterinarian would like to investigate or confirm fish lesions. If the private veterinarian was not in need of confirming the diagnosis the samples would not be submitted to the BCMAL.

21. These non random submissions are sometimes submitted without specific site of origin information and would not be considered representative of the farm or general area, or region, or of population dynamics.

...

23. If the Commission decides to order additional disclosure from the 21 specific farms along the Fraser River migration route subject to this commission from 1988 onwards, I do not know what information may be located if any, or how long it would take to find and collate these materials if they exist.

24. If the Commission decides to order additional disclosure from all farms subject to this Commission from 1988 onwards, I do not know what information may be located if any, or how long it would take to find and collate these materials if they exist.

63. The BCSFA also provided evidence regarding the likely state of documents prior to 2000 and the time and hardship associated with collecting these documents. In his affidavit, Mr. Budgeon stated:

6. I am informed by Clare Backman, Environmental and Sustainability Director for Marine Harvest, that the present Marine Harvest is composed of at least twenty-four now-defunct companies, and that in the course of numerous purchases and amalgamations the fish health and fish stocking records of those former companies, which would have been kept in paper form, were likely lost, or were not transferred as part of any asset purchase agreements. I am also informed by Mr. Backman that it would require considerable time and expense just to determine whether any of these former companies' records dating back to the 1990s or earlier even exist and could be obtained for the Commission.

7. I am informed by Clare Backman that there are 5 of Marine Harvest employees who would be somewhat qualified to engage in such a search for the documents the Aquaculture and Conservation Coalitions have requested. Were they to devote half of their work week to searching for these documents, I roughly estimate that it could take many months to determine whether the data exists and, assuming it is decipherable and coherent, to put it into a useable form. At those employees' hourly rates, such an undertaking could cost Marine Harvest as much as an estimated \$12,000 dollars per month in lost productivity.

64. In his affidavit, Mr. Bohlken deposed:

7. On November 1 2010 I spoke with Dr. Dianne Morrison, a veterinarian employed by Marine Harvest Canada Ltd., concerning data collection by the B.C. aquaculture industry. Dr. Morrison stated, and I verily believe it to be true, that an initiative by the B.C. aquaculture industry in the early 2000s resulted in standardized reporting of aquaculture data including inventory, mortality (number and cause), and fish health events. Dr. Morrison stated, and I verily believe [it] to be true, that prior to this standardization, fish farms may have used a variety of methods for compiling data, including paper files and spreadsheet files. Dr. Morrison further stated, and I verily believe [it] to be true, that prior to the aquaculture industry initiative of the early 2000s there was no regulatory requirement to maintain data on fish health or mortality rates.

65. In the affidavit of Ms. Parker, she stated:

5. Records from before Grieg began using the fish health database, if they even exist, are likely in paper format or held within legacy data systems that are incompatible with current operating systems and software. These records may also hold different types of information than that submitted to the current fish health database, as there was no prior comprehensive reporting scheme in place and no regulation saying what data had to be collected.

6. It would require considerable time and effort to determine whether or not these records even exist. There are 3 employees at Grieg who may be able to identify such records in various forms and formats. At those employees' hourly rates, such an undertaking could cost Grieg as much as an estimated \$19,000 dollars per month in lost productivity.

7. Due to the likely gaps or non-existence of older data, interpretation of the data would be very difficult and time consuming and may not result in an accurate and reliable analysis. Furthermore, there is a real risk that older data collected using different methods, missing data, and data lacking context could inadvertently cause confusion or be misused.

66. Canada provided the evidence of Mr. Cass that it had assigned resources to scan the wild sockeye salmon case reports from 1998 through 2004, but that

documents prior to 1998 are in hard copy and additional resources and time would be required to scan the hard copy reports, because “the paper size varies among reports and each page must be scanned manually.”

67. In their submissions on this point, the applicants assert, *inter alia*, that “the evidence shows that the increase in cost or time is difficult to assess, but is not such that it outweighs the increased scientific value and public benefit” in having an expanded set of data dating back to 1988.

68. Commission counsel submitted that I weigh the likely quality, availability and format of data from a period prior to 2004, against the value of that additional evidence in determining the temporal scope of an order for production of documents from a period prior to 2004:

- a) The likely quality of data prior to 2004. Is the data prior to 2004 comprehensive, or is it haphazard and uneven? Was it collected and recorded in ways that would allow for a continuous data set? One of the themes running through various affidavits, particularly with respect to the fish-health data under control of the Province or the BCSFA, is that the quality (and availability) of the data decreases when one reaches back in time beyond 2002 – even more so in the years before 2000. Working backward in time, this apparent reduction in quality and availability appears to correspond to the period prior to the Province’s implementation of mandatory reporting requirements for finfish aquaculture facilities.
- b) The likely availability of data prior to 2004. Do records exist prior to 2004? How far back in time? Are the data sets consistent? If pre-2004 data are inaccessible from participants, and inconsistent in nature, the older records are of less assistance. In contrast, if the earlier data are consistent and available, they may permit a more detailed examination.

...

d) The likely format of additional information. Are the documents and data prior to 2004 likely to be in a paper format, such that they would require extensive data input to be presented in an electronic form? Are the documents in a compatible electronic format? How much work would it take to make the data compatible? As some of the affiants point out, if data are available and can be provided in the same format as the current request, they can be accommodated into the analysis of post-2004 data (see Affidavit of Josh Korman #1, at para. 13; Affidavit of Gordon Fredric Hartman #1, at para. 3). But variable formats could greatly increase the scope of work required to get the data in shape for analysis and if the earlier data are not available in a comparable or consistent format, “the utility of reaching back to 1992 is greatly diminished” (see Affidavit of Josh Korman #1 at para. 11; see also paras. 9, 12 and 14).

...

f) The delay to the commission’s work that may be occasioned by seeking further documents. Dr. Korman does not suggest any difficulty associated with adding data from the 2002-2004 period into his analysis, but does note potential difficulties and delays if data from the pre-2002 are included, given his understanding of the nature of the earlier data. He cannot comment on the extent of that delay without seeing the data, but notes that it could result in a “substantial increase in the amount of work required to complete the analysis” (Affidavit of Josh Korman #1 at para.12). The documents at issue are to be considered not only by participants, but also (1) by Dr. Korman in his statistical analysis, and (2) by contracted scientific researchers who will engage in a further assessment of the effects of fish farms on wild sockeye salmon. For these contracted researchers, who have yet to be retained, it is expected that their work will rely on Dr. Korman’s analysis, and that it is realistic to expect their conclusions to be provided some time *after* Dr. Korman’s report is complete. If the additional data would delay Dr. Korman’s analysis, this could have a cascading effect on the timing of the contracted researcher’s work.

69. The evidence provided by Ms. Sidhu, Dr. Sheppard, Mr. Cass, Mr. Budgeon, Mr. Bohlken and Ms. Parker persuades me that there is a likelihood that the respondents possess documents in a useable format from 2000 to the present which will assist me in making findings regarding the impact, if any, of salmon farms on Fraser River sockeye salmon, and which can be obtained without impacting disproportionately on the participants or the conduct of the commission. However, I am not persuaded that I should order the production of documents sought by the applicants prior to 2000.

70. In my view, there is much uncertainty regarding the quality, availability and format of data from the years prior to 2000 as established by the evidence of Ms. Sidhu, Dr. Sheppard, Mr. Budgeon, Mr. Bohlken, Ms. Parker and Dr. Korman. Their evidence suggests that even if available, such data is likely to be in a format which is not helpful. Further, according to the evidence of Drs. Korman and Sheppard, Mr. Budgeon, Ms. Parker, Ms. Haider and Mr. Cass, the search for, production and analysis of documents from this earlier period is likely to occasion significant delay in the commission's process and some hardship to the respondents. I do not think such delay and hardship is warranted given that the outcome of this expenditure of time and effort is unlikely to advance my understanding of this complex issue.

71. In the result, I find that the respondents should produce those documents sought in this application, which are in their possession and control, for the period of January 1, 2000 to September 1, 2010, for

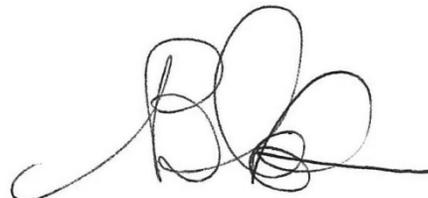
- i. the 21 fish farms originally identified by commission counsel; and
- ii. the additional 99 farms, identified in Mr. Proboszcz's affidavit, specifically:
 - In Johnstone Strait and eastern Queen Charlotte Strait: Wehlis Bay; Mt. Simmonds; Maude; Cecil; Cypress; Sir Ed; Simoom Sound; Cliff Bay; Smith Rock; Burdwood; Deep Harbour; Wicklow; Blunden; Upper

Retreat; Arrow Pass; Midsummer; Potts Bay; Port Elizabeth; Larsen Island; Swanson; Bennett Point; Bocket & Lily; and Mistake Island.

- Along the Central Coast: Jackson Pass and Lochalsh.
- In the Discovery Islands and Johnstone Strait: Poison Creek; Jack Creek; Althorp; Shaw Point; Phillips Arm; Freddie Arm; Egerton; Farside; Sonara Point; Thurlow; Brougham; Young Pass; Mayne Pass; Venture; Sonora; Cyrus Rocks; Barnes; Doctor Bay; and Church House.
- Along the northern portion of the West Coast of Vancouver Island: Markale Pass; Charlie's Place; Amai; Centre Cove; Hohoae; Monday Rocks; Koskimo Bay; Mahatta West; Mahatta East; and Cleagh.
- In Georgia Strait: Ahlstron; Culloden; and St. Vincent Bay.
- Along the southern portion of Vancouver Island: Sooke Basin; Goodridge Island; and Saltspring.
- In Queen Charlotte Strait: Hardy Bay.
- Along the central portion of the West Coast of Vancouver Island: Cliff Cove; Esperanza; Lutes; Hecate; Steamer Point; Conception Point; Williamson Passage; Muchalat North; Muchalat South; Gore Island; Atrevida; Shelter Inlet; Dixon; Millar; South Shelter; Ross Pass; Binns Island; Bare Island; Bawden; Westide; Cormorant; Saranc; Bare Bluff; MacIntyre Lake; Bedwell; Rant Point; Mussel Rock; Fortune Channel; Tranquill; McCall; Eagle Bay; Indian Bay; Warne Island; Baxter; Dawley Passage; Jane Bay; Barkley; and San Mateo.

72. Further, said documents shall be produced by the respondents by January 21, 2011.

73. I wish to make it clear that this ruling is not to be construed in any manner as a finding on whether aquaculture is a cause for the decline of Fraser River sockeye salmon.

A handwritten signature in black ink, consisting of several loops and a long horizontal stroke at the end.

Dated December 8th, 2010

The Honourable Bruce I. Cohen
Commissioner

Appendix 2: Reviewers evaluations and authors responses

Review 1:

Report Title: Examination of relationships between salmon aquaculture and sockeye salmon population dynamics

Reviewer Name: Trevor A. Branch

Date: 12 May 2011

1. Identify the strengths and weaknesses of this report.

Strengths: well written, good methodology, comprehensive, and clear. It's a pleasure to read through a report that outlines everything clearly so that the analysis can be understood and critically examined.

Weaknesses: there are some minor typographical errors, but mainly I would focus on three issues as deserving of more attention, (1) the large 2010 returns were not included in the analysis and will obviously have a dominant effect on the results when they are, (2) including as control populations only the declining sockeye populations and those that covary with Fraser sockeye (instead of all populations), (3) reversing the sign of sea surface temperature (SST) for populations north of Atnarko River instead of estimating this relation within the model.

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

The interpretations are measured and not overstated, and yes, I believe they are the best interpretation of the available data (subject to the points I raise).

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

1. Include the 2010 runs.

Response: See Section 6.1 below.

2. Adding all B.C. sockeye runs with survival information, not just the declining runs.

Response: See Section 6.3 below.

3. Estimating the latitudinal relation between SST and survival.

Response: See Section 6.4 below.

4. I would be tempted, as a follow-on analysis, to do some speculative modelling. Primarily, this is

because the relatively short time series of explanatory variables (most starting in 2002-2004) do not offer much power to detect significant relations between aquaculture and survival. In so doing, the analysis rests on well-supported foundations and is justified. On the other hand, there is some information value in knowing that each of the time series in Table 1 (except total farmed production) must have been zero before about the mid-1980s, and related in some sense to total farmed production between the mid-1980s and early 2000s. The speculative modelling would assume no disease before the mid-1980s and then (for example) three scenarios between total farmed production and motile lice or disease, (1) LOW: no disease from mid-1980s to data start year, (2) MEDIUM: disease increased proportionately with farmed salmon production from mid-1980s to data start year, (3) HIGH: disease frequency during mid-1980s to data start year was equal to the average observed during the data period. Then these disease scenarios could be modelled against the salmon survival anomalies over the entire time period from 1950.

Response: I agree this would be an informative analysis but is beyond scope of the terms of reference set out in the Statement of Work for my contract with the Cohen Commission.

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

I believe the results are straightforward. Based on the analysis done, there appears to be a relation between sockeye salmon survival and the combined effects of pink salmon, SST and aquaculture production. The caveats are clearly laid out: correlation between these factors does not imply causation, and thus there may be other factors that increase over time that could also explain the declines in survival.

There could also be a relation between various metrics of disease / parasites and survival but this seems to be hard to detect (short time series), dependent on a particular year (2005 year class), and likely to be greatly affected by the high returns of the 2006 year class.

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

1. Continue collecting and requiring operators to collect, information on disease prevalence and occurrence.
2. Start a field sampling program to sample wild sockeye before and after they pass the aquaculture facilities to detect disease occurrence and parasite prevalence.

6. Please provide any specific comments for the authors.

General comments

1. The brood year in 2005 (poor returns in 2009) obviously has a large influence on the findings. Similarly, the brood year in 2006 (huge returns in 2010) should be expected to have a huge impact on the results. I personally wonder if any of the significant results will continue to hold when the 2006 returns are factored into the analysis. An obvious sensitivity is to run the model again with two values for the 2010 survivals that span the likely very high survival anomalies, to see whether the current results still

apply. Of course the very existence of the huge 2010 returns undercuts the fundamental premise of the Cohen commission itself: to study reasons for the *decline* in sockeye salmon.

Response: Unfortunately, at the time of writing (May 31, 2011) I have not been provided with estimates of population specific returns to the Fraser River or reference populations for 2010. While I agree that examining the sensitivity of the findings in this report to the inclusion of estimated 2010 returns would be informative, generating estimates of upper and lower bounds of returns, catch and pre-spawn/en-route mortality for each population in the 2006 brood year is beyond the terms of reference set out in the Statement of Work for my contract with the Cohen Commission. In the final report I point out that as soon as 2010 return, catch and pre-spawn/en-route mortality data become available the analyses in this report should be revisited.

2. It is assumed that decreased survival is related to SST, pink salmon abundance and Atlantic salmon in pens. The problem is that the latter two factors are the only two explanatory variables that show increases in recent years. Surely there are other possible explanatory factors that also increase in recent years? (This goes to the heart of the correlative vs. causative relations that the author talks about.)

Response: Salmon farm production was chosen as an explanatory variable because it is the focus of this report. While there are likely other factors that have shown increases through time in recent years, I chose to add two other hypothesized drivers of the Fraser sockeye salmon decline (i.e., SST, and pink salmon abundance) because an independent expert panel identified them as “likely to very likely” contributors (out of a total of 13 possible drivers considered; Peterman et al. 2010) and it is plausible that both environment (i.e., oceanographic conditions) and competition (i.e. the number of pink salmon competitors) could mediate the influence of pathogen transmission from farmed salmon.

3. Lines 285-291. I am baffled by the inclusion of control populations that only conform to these two conditions (1) covary with Fraser River sockeye, and (2) have shown a decrease in productivity over the past two decades. If the theory is that salmon farms cause declines, and salmon farms occur mainly on the Fraser, and you exclude all the salmon runs that are not the Fraser, do not have salmon farms, and are increasing, this causes an obvious bias in the analysis towards finding no effect of salmon farms. For example, if 10 Fraser stocks are declining, 10 non-Fraser stocks are declining, and 100 non-Fraser stocks are increasing, then including all stocks will tend to show that factors fairly unique to the Fraser (i.e. salmon farms) are significant, while including only declining stocks will tend to show that only factors that jointly affect all declining populations (i.e. SST) are significant.

Response: This is a misunderstanding due to a lack of clarity in my draft report. All sockeye populations for which data was available from Washington State to the Yakutat region of Alaska are included in the analyses in this report. The reason I chose to include populations as far north as the Yakutat Region is because Peterman and Dorner (2011) provided evidence to suggest that the productivity of Fraser Sockeye salmon has followed a shared downwards trends over a much larger area than just the Fraser River system (as far north as the Yakutat). For the reasons you describe above, including all these populations (which also happen to be declining to some degree) might be

considered a stronger test of the hypothesis that salmon aquaculture is correlated with Fraser declines than just considering Fraser river populations on their own. However, as pointed out by the two other reviewers, the inclusion of non-informative “controls” may actually confound any inference from my analysis. In the final report I examine the sensitivity of my findings to the spatial extent to which reference populations are included in the analyses.

4. Lines 332-336. I don't understand why the sign of SST anomalies was reversed for populations north of the Atnarko River. If you a priori suspect that SST affects populations differently, then there are better alternatives in modelling this effect. You could include a variable to estimate the effect of SST separately for each region. Or you could include a variable that varies linearly or by logistic curve with latitude. No maps show where Atnarko River is, so I can't tell if all the salmon stocks with farms are south of north of this artificial boundary in the analysis.

Response: The boundary is north of population #24 in Figure 1. Meuter et al. (2004) showed that the influence of SST on sockeye survival is sharply reversed between the Atnarko and the Skeena rivers. The change in the relationship between SST and survival rates does not follow a gradual shift but appears instead to be breakpoint; remarkably the coefficient is almost identical but reversed between the southern (-0.186) and northern (0.169) regions. Including a variable that allowed for the effect of SST to be estimated separately for each region for each term that included SST did not improve model fit (based on ΔAIC) and so I felt justified in reversing the anomaly prior to conducting the analysis. Importantly, excluding the populations that respond in the opposite manner to SST from the analysis also had no little influence on the results (Appendix 4).

5. I was a little surprised to see no mention at all of the analyses done by Krkošek and others (Krkošek et al. 2006, Krkošek et al. 2007a, Krkošek et al. 2007b, Krkošek et al. 2008b, a, Krkošek 2009), but I guess that the authors were not intending to place this analysis in context. In particular there seems to be no attempt to use the longer time series of sea lice collected by Krkošek to predict their effect on migrating sockeye salmon.

Response: The Krkošek time series on louse abundance on juvenile pink and chum salmon begins in 2001 (3 years earlier than the time series I use in this report) but is of limited use for the purposes of this report because I do not have corresponding sea louse information for the other sockeye populations I considered in the analyses.

Detailed comments

Title page, “finl draft” should be “final draft” **Response:** Corrected.

22 “The first measure” Nowhere in the abstract does it mention a “second” measure.

Response: Corrected.

31,34 Give the full scientific name of these pathogens, also indicate what they are, e.g. bacteria, virus, crustacean. Also give the scientific name/s of the sea louse/s.

Response: Corrected.

69 Capitalize “Pacific” **Response: Corrected.**

218 This reference should be Ricker (1954) not Ricker (1975). **Response: Corrected.**

219 The brackets are missing their top edges in my copy. **Response: Corrected.**

219 How much evidence is there that recruitment follows a Ricker curve as opposed to a Beverton-Holt curve (Beverton and Holt 1957), or random scatter of points? Some evidence should be cited. **Response: This is a good point. The Beverton-Holt curve has been shown to better fit salmon stock-recruit data (e.g. Pyper et al. 2001) but the residuals of the Beverton-Holt curve are highly correlated with the residuals of the Ricker curve. One of the main reasons for using the Ricker model (or Larkin) was not biological, but rather statistical as it could be transformed to a linear form with normally distributed errors that allowed parameters to be estimated using linear mixed models.**

260 “less parameters” should be “fewer parameters”. **Response: Corrected.**

265-266 “...per spawner and sockeye survival anomalies were not computed before hand, instead the” should be “...per spawner, sockeye survival anomalies were not computed beforehand. Instead, the”.

Response: Corrected.

273-275 I would think that multi-model inference would involve using Akaike weights of all models, but that in this case the weights of the poor models would be essentially zero.

Response: This was a typo. In the revised report I clarify that the multi-model inference is based on models within 4 AICc of the top model. A cutoff of 4 AICc corresponds to ~90% of the model probabilities from the candidate set of models considered

276 delete “estimate”. **Response: Corrected.**

278 reference should be “R (R development core team 2011)”. **Response: Corrected.**

282 “dynamics: the” should be “dynamics. The” **Response: Corrected.**

286 should be “pre-spawning mortality” **Response: Corrected.**

338-340 This sentence is vague; also does this mean a total sample of 180 fish, or 20 fish from each of 3 pens? **Response: Corrected to read 20 fish from each of three pens.**

366-367 At some point in the manuscript it would be helpful to have a table with a list of the pathogens, their common name, basic taxonomy, and the disease they cause.

Response: These are provided in the technical report prepared for the Cohen Commission by Kent

(2011).

369 I found it confusing to have a “positive” audit with negative connotations. **Response: While this may be confusing I would still argue that it is the most appropriate way to describe a diagnosis that identifies a pathogen.**

406 “Pink” should be “pink”. **Response: Corrected.**

415-416 “I compiled” should be “I obtained” since these data come from G. Ruggerone. **Response: Corrected.**

422 Add comma before Akaike. **Response: Corrected.**

434-436 This sentence needs to be split into different parts to make sense. **Response: Corrected.**

456,461 “it’s” should be “its” in these two lines. **Response: Corrected.**

474 insert “when” before sockeye; change “mortalities rates” to “mortality rates”. **Response: Corrected.**

495-500 This sentence needs to be split into several smaller sentences. **Response: Corrected.**

500-503 Or, the factors that increase disease also increase pink salmon. Or, the environmental factors that increase pink salmon decrease sockeye survival. **Response: This speculation is removed from the final report.**

528-530 The journal name is wrong, it should be “Canadian Special Publication of Fisheries and Aquatic Sciences” **Response: Corrected.**

553 “ssp.” should not be in italics. **Response: Corrected.**

576-577 “Pink” and “Salmonids” should be in lower case. **Response: Corrected.**

596 insert “each” before “time series”. **Response: Corrected.**

Table 4: delete the column with AIC. This is meaningless since arbitrary constants can increase or decrease log likelihood values; only ΔAIC has meaning (same applies to all other tables). Also it can be reconstructed from Log Lik and k. **Response: Corrected.**

Table 4: since the greatest effects are from *C. clemensi*, I would group by species (not time period) or else order from best to worst model. **Response: Corrected.**

Table 7: explanation needed in caption that “Atlantics” means “Number of farmed Atlantic salmon”, similarly for “Pacifics”. **Response: Corrected.**

645 “top model set of models” should be “top set of models”. **Response: Corrected.**

Table 8: I am a little uneasy that some models with AIC weights (w_i) greater than a few percent might be excluded from these model-weighted averages. **Response: As described above this was as typo.**

Table 9: are any of these variables transformed in the model? e.g. log or square root etc. **Response: No.**

Figure 1: when printed in black and white, the red triangles merge with the background. I suggest plotting them with a black border, or in transparent color so that they can be more easily seen.

Response: Corrected.

Figure 7: the vertical axis needs a different caption. “Mortality (%)” suggests this is the mortality the salmon experience, in which case a negative value is puzzling. This should be “Change in mortality”. Also it is unclear if 50% means that mortality went from e.g. 20% to 70%, or that it increased by a factor of 1.5 to 30%.

Response: I now dedicate a portion of the main text to describing in detail how mortality is calculated.

Figure 8-10: since these are data going into the analyses, they should come before the results.

Response: Corrected.

Figure 9: it would be better to plot predicted R/S rather than predicted $\log(R/S)$.

Response: This figure was removed from the final report.

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Review 2:

Report Title: Review of "Examination of relationships between salmon aquaculture and sockeye salmon population dynamics" by Dr. Brendan Connors.

Reviewer Name: Murdoch McAllister

Date: May 16th, 2011.

Preface

The request to review this report came at very short notice and I have had very little time to review the report and formulate my review. I therefore apologize in advance for any misinterpretations of the extensive amount of analysis done and any apparent undue harshness in my review.

Response: The criticisms raised in this review are generally fair and greatly improved the report.

1. Identify the strengths and weaknesses of this report.

Strengths

The strengths were twofold. First, numerous datasets were compiled and these were generally appropriately prepared and suitable for the purposes of the investigation. Second, there were several elements of statistical rigour in the analyses which serve to enhance the scientific basis for assessing potential relationships between salmon aquaculture and sockeye salmon production. The models were formulated appropriately to isolate various important sources of variation in sockeye salmon survival anomalies from variation in survival anomalies that could be caused by variation in salmon farm production in disease events. These are commented on below.

a. Stock-recruit data sets for multiple Fraser River sockeye salmon (FRSS) populations from the lower, middle and upper reaches of the watershed were included in the analysis to obtain estimates of cohort-specific marine survival anomalies by stock. Having a fairly large number of FRSS populations included in the analysis including ones from different reaches and of different abundances offers breadth to the evaluation of correlations between farm salmon production and disease indicators and FRSS salmon "survival rate residuals" as they are called in the document or as I refer to them below, "survival rate anomalies".

b. Appropriate protocols were applied to remove potential within-stock density dependent effects on survival anomalies for the salmon populations included in the analyses. This was done

by using the full time series of available stock and recruitment data for each of the salmon populations to estimate the density-dependent component of the cohort-, and stock-specific index of survival anomalies, i.e., $\text{Log}(\text{Recruits}/\text{Spawner})$. The survival rate anomalies after removal of density-dependent effects could then be further processed and evaluated for correlations with salmon farm production/ disease covariates.

c. It was appropriate to try to remove from the annual survival rate anomalies the shared variation in these anomalies that could result from commonly experienced environmental conditions (i) by all of the populations, (ii) all populations within each region and (iii) different sets of populations within each region. Presuming the model structure for this was set up correctly, the remaining variation could then be more cleanly related to variation in various indices associated with farmed salmon production.

d. It has been hypothesized that very high abundances of hatchery pink and other farmed salmon species in the North Pacific Ocean could negatively impact wild salmon production and it is well established that pink salmon have in the last several decades been the most abundant salmon species in the North Pacific Ocean (Ruggerone et al. 2010). It is thus appropriate to try to isolate the effects of variation in pink salmon abundance from the potential effects of fish farm production on survival rate anomalies for FRSS.

e. This was an exploratory analysis with the aim of trying to identify potential a potential causal relationship between fish farm production and variation in FRSS survival anomalies . It was thus appropriate to formulate a variety of variables representing plausible mechanisms for fish farm impacts on FRSS survival anomalies and to explore different permutations of these variables. The inclusion of interaction effects such as Farm x total North Pacific pink salmon abundance is a good example of a careful search for plausible mechanisms.

Weaknesses

Response: Below Dr. McAllister raises the concern that I treat each sockeye population related to the explanatory variables of interest (e.g. the number of farmed salmon in a region) as independent observations. The reason this is a concern is because the explanatory variables are measured at a broader spatial scale than individual sockeye populations. As a result, not accounting for correlations in observations at the region scale (i.e. treating each population as an independent observation) would result in an “exaggerated estimate of statistical significance”.

My original analyses included “random” effects for regions and for sockeye populations within regions. One of the reasons I included these random effects was to account for the non-independence of observations both within populations through time and among

populations in a given year. However, this was not adequately described in the draft report Dr. McAllister reviewed, and despite my best intentions the random effects structure in the original analyses did not appropriately account for this non-independence of observations. Fortunately Dr. McAllister identified this shortcoming of the original analyses and the final report now appropriately accounts the non-independence of observations inherent in the data. I describe this in detail in the final report.

a. It appears that all of the statistical tests reported are invalid due to pseudo-replication within each year (Hurlbert 1984). "The error consists of assigning an exaggerated estimate of the statistical significance of a set of measurements by treating the data as independent observations when they are in fact interdependent" (Wikipedia). In each year, smolts from 17 of the FRSS populations in the analysis were assumed to migrate through the same "fish health zone", i.e., area containing salmon farms in the Johnston Strait - Broughton Archipelago area (stocks 2-18 in Table 3). In this "fish health zone" a single value for a given covariate or set of covariates was applied in each statistical analysis, e.g., a single value for total salmon farm production for each year was applied as the independent or explanatory variable. It appears that the set of survival rate residuals (anomalies) for each of these 17 FRSS populations (plus those for the control populations) was applied as the dependent variable with the anomalies for the 17 FRSS stocks in a given year treated as if they were a set of independent observations or events. The relationship between these anomalies and the annual fish farm covariates were then evaluated. It thus appears as if the product of the likelihoods (or probabilities) of the survival rate anomaly for each population given the annual fish farm covariate value for all 17 FRSS populations migrating through the salmon farm area was computed in the computation of the likelihood function.

In contrast, in the fish health zone of interest, there is only one independent salmon farm "treatment" event per year and the different measurements of survival rate deviates per stock should thus be modeled as repeated measures of a single "experimental" manipulation. Rather than treating each population's apparent survival rate response as an independent event, it would instead be appropriate to consider a single years' fish farm event as an independent event. Thus the mean survival rate anomaly of the 17 FRSS stocks in a given year could be considered to be independent across years, but not each of the 17 individual FRSS stock anomalies within a single year. Treating all 17 responses in a single year independent events in the likelihood function would tend to exaggerate the significance of a potential fish farm effect on FRSS survival anomalies .

It is not possible to know from the description of the methodology the exact form of the likelihood function applied and to verify from inspection of equations that there was indeed pseudo-replication in the statistical analyses. However, from the text on lines 251-255, this appears to have been done: "... I calculated population specific residuals of the Ricker stock-

recruit relationship fit to spawner abundance and SST in early marine life The resulting residuals (subsequently referred to as survival anomalies) were then related to the independent variables as described above." The number of independent statistical units or effective sample size applied in statistical tests e.g. where p-values and AIC values are reported were also not shown, so there is no direct evidence of pseudo-replication. However, the results presented in Tables 5 and 7 provide indications of pseudo-replication. Take for example, Table 5 that reports the results of models relating, e.g., "fish health events ... to sockeye salmon survival anomalies " where in part a, the 2005 brood year was included and in part b the 2005 brood year was excluded from the analysis. For part b, the p-values were all in the range of 0.32-0.62 depending on the model applied. When the 2005 brood year was applied the p-values all dropped with p-values for four out of six sets of six of the analyses dropping to very small values of 0.000 to 0.017 providing support for a significant correlation between sockeye survival anomalies and fish health events. This very large drop in p-values when only one additional brood year is added to the analysis is an indication that the stocks within a given year were pseudo-replicated. For these analyses there were a maximum of six years of independent events for a given covariate (e.g., 2002-2007 for BCSFA fish health events). Thus for example, for BCSFA fish health events, the total number of independent treatment events is six. It is peculiar that a p-value should drop so markedly from a value of 0.354 to 0.000 by adding to the analysis one additional treatment event. The differences in AIC values when comparisons are made across models will also be exaggerated due to pseudo-replication of FRSS within each year (i.e., with differences being as large as -11.9). The product of likelihoods for 17 events (stock responses) within a single year that are incorrectly presumed to be independent events will cause this exaggeration since the apparent treatment effect for a single year should be counted once, not seventeen times within a single year.

There are a variety of different statistical modeling approaches that could potentially be applied to avoid pseudo-replication and rectify the error in the analyses. These include (i) repeated measures analysis of covariance (e.g., Vonesh and Chinchilli 1997) where for example, the response by stock within a given year exposed to the same treatment event would be treated as repeated measures of the same single treatment event and the sample size for the computation of the degrees of freedom would be one, not, e.g., 17. (ii) Multivariate Analysis of Variance or Multivariate Analysis of Covariance (e.g., Stevens 2002) has also been designed to account for lack of independence between groups of measured response variables. (iii) Within a mixed-effect modeling approach, a single time effect variable common to all seventeen stocks that migrate through the same fish farm area could be related to each single annual index value of fish farm production.

Given that there are a maximum of seven years of fish farm disease indices for each different fish farm index and the number of estimated parameters range between six and seven (e.g., in

Tables 5, 6 and 7), it is possible that there are insufficient degrees of freedom to carry out proper statistical tests of hypotheses on the potential effects of fish farms on FRSS survival anomalies . Also, should new models be identified that are appropriate for the relatively few years of detailed salmon farm covariate data, it is likely that the statistical power to detect effects will be very low due to the few years of covariate data, and apparent low degree of contrast in many of the covariates. For example, the average number of motile lice per Atlantic salmon in Table 2 in Korman's (2011) data report range best between about 5.1 and 10.6) but most of the variation is between about 6.6 and 8.1. The same goes for the total number of salmon mortalities per farm with most values ranging between about 1.5 and 4 (Fig. 4, Korman 2011). It is likely that there is measurement error in all of the covariates due to incomplete sampling, though I could not find estimates of standard errors in the estimates of covariates in Korman (2011). This errors-in-variables issue will also tend to reduce the statistical power of the analysis.

Response: I agree that the short time series, low degree of contrast in salmon farm covariates and errors in variables will all reduce the power to detect true relationships should one exist. This is now explicitly stated in the final report.

b. There is potential to spuriously conclude that there is e.g., a fish farm effect, when one might not exist due to treating environmental effects as “random”. This approach looks for commonality in the response of each population to the independent variable(s) under consideration thereby increasing the chance of finding true relationships by allowing for population responses to be more easily isolated. Maximum likelihood estimation in “mixed effects” models leads to the “most parsimonious” parameter estimates, because the approach minimizes the variance in the response variables due to random effects. In other words the approach attempts to explain as much of variation as possible as being due to structural effects. This can lead to underestimation of shared effects (other than those due to explanatory variables like farm production) when so-called “control” stocks are included that do not in fact share such effects. In other words, adding inappropriate control stocks results in spurious strengthening of estimated “treatment” effects. See Figure 3 below for an indication of potential overestimation of salmon farm related effects on FRSS survival anomalies . The analyses need to be redone without these so-called control stocks to demonstrate whether more of the variation is attributed to shared effects other than those caused by farming.

Response: In the revised report I now examine how sensitive my findings are to the “control” populations included in the analysis. Specifically, I begin the analysis with those populations that have previously been shown to covary in productivity with Fraser River popularions (i.e. 1-24; Peterman et al. 1998). I then repeated each analysis with (a) all populations originally considered (i.e. populations 1-32), and (b) just Fraser River populations (i.e., populations 2-19).

c. The analyses fail to adequately address uncertainty in the structural form of the key statistical models applied. For example, there is a possible inappropriate use of only the Ricker model to correct for density-dependent effects, despite considerable statistical support for the more complex Larkin (delayed density-dependence, ecosystem interaction effects) model (Collie and Walters 1987). The Larkin model estimates substantially different productivity trends for some stocks (see Figure 1 below); it would be appropriate to present main results about Atlantic x pink estimated effect for Larkin as well as Ricker model. Figure 2 below provides a comparison of results obtained from these two alternative models (pers. commn Carl Walters). Barely significant results were obtained from the evaluation of recruitment anomalies from the Ricker model; in contrast, no significant relationship was obtained in the evaluation using the recruitment anomalies from the Larkin model.

Response: This was a limitation of the original analyses. The final report now accounts for Ricker and Larkin forms of density-dependence in two ways. First, in the analyses that relate survival anomalies to salmon farm covariates I calculated the survival anomalies as residuals from the stock recruit relationship that best fits each population's dynamics (Table 3 in Peterman and Dorner 2011). Secondly, for analyses that related salmon farm production, SST and pink salmon abundance to sockeye productivity I repeated the analysis with and without terms in the models for delayed density dependence.

d. There appears to be an inappropriate use of the Harrison Rapids stock as a “control” for salmon farm effects; its departures in recruitment success from the other stocks could be due to a wide variety of other factors that were not included in the model. It is recommended that the analysis be redone without this stock (and without the other so-called control stocks).

Response: While it is likely that variation in recruitment success for all populations considered in the analyses is due at least in part to factors not included in the models, I do agree that the Harrison is particularly anomalous. In the revised report I examine the sensitivity of my findings to the inclusion of the Harrison River population.

e. There is the use of a relatively poor surrogate for “known” causes of environmental effects, namely SST in "2° longitude by latitude cells that encompassed the marine entry points of each sockeye salmon population". In contrast, McKinnell et al. (2011) suggest that effects occur in very particular areas, e.g., Queen Charlotte Sound. This Cohen Enquiry report suggests that abnormal (warm) ocean conditions in Queen Charlotte Strait in 2007 that may have been partly responsible for the poor 2009 return. It may thus be appropriate to consider some alternative oceanographic covariates as supported by other investigations (McKinnell et al. 2011).

Response: SST is more strongly correlated with sockeye survival than the PDO, sea surface salinity or upwelling indices (Mueter et al. 2002). Because of the well-established

relationship between SST and sockeye survival I would argue it is a suitable proxy for oceanographic conditions experienced early in marine life. However, this is not to say it is the only proxy.

McKinnell et al. (2011) speculate that abnormally warm conditions in Queen Charlotte Strait in 2007 contributed to poor survival of Fraser population who entered the sea in 2007. This was based on a qualitative examination of oceanographic conditions that were anomalous in 2007. The abnormally warm conditions reported by McKinnell et al (2011) are based on SST, but at a finer scale (1 degree grid cells) and in the summer. Like SST in the McKinnell report the SST anomalies included in my analyses are also strongly positive in 2007 (Figure 3). The 1 degree grid cells McKinnell used to estimate SST do not go back as far in time (1980) as the time series of the sockeye populations examined in this report (1950), nonetheless it is likely that the two measures of SST are highly correlated.

f. While the report focuses on the possibility of negative impacts of salmon farming on FRSS, it ignores apparently contradictory data for other salmon species that migrate through these same waters as juveniles. For example, there appears to be no negative effect of total Atlantic salmon production in the Broughton Archipelago on other species like pink salmon; the odd year stocks of pink salmon (e.g., Fraser River pinks and odd-year pink stocks that spawn in rivers close to the Broughton Archipelago) whose fry migrate through this area apparently have either increased or not changed in abundance over the last few decades (Krkosek and Hilborn 2011; McKinnell et al. 2011, Figs. 40, 41). Total farm production, for example, will thus be unlikely to work as explanatory variable even for the pink stocks most immediate to the Broughton Archipelago fish farm area.

Response: I agree the examination of other salmon species that migrate past salmon farms would be informative. However, this is beyond the terms of reference set out in the Statement of Work for my contract with the Cohen Commission. I do recommend this as an important avenue of further investigation at the end of the report.

I do not agree with the statement:

“there appears to be no negative effect of total Atlantic salmon production in the Broughton Archipelago on other species like pink salmon; the odd year stocks of pink salmon (e.g., Fraser River pinks and odd-year pink stocks that spawn in rivers close to the Broughton Archipelago) whose fry migrate through this area apparently have either increased or not changed in abundance over the last few decades (Krkosek and Hilborn 2011; McKinnell et al. 2011, Figs. 40, 41)”

Krkosek and Hilborn (2011) do not show that the abundance of pink salmon that migrate

through the Broughton Archipelago has increased or remained stable over that past few decades. The McKinnell figures plot (1) total BC and Washington Pink salmon through time, which actually appear to have declined in abundance since the mid to late 1990s (Figure 40) and (2) Gulf of Alaska Pink salmon catch of unknown origin through time (Figure 41). Interestingly, the pink salmon abundance by farmed salmon production interaction identified in this report suggests that species identity may be an important determinant of the influence of aquaculture on wild Pacific salmon. As a result we might predict a-priori that the relationship between aquaculture and wild Pacific salmon dynamics may not be the same across species.

g. When the relationship between survival rate anomalies and total salmon farm production was evaluated, no significant effect was obtained (Table 9). While there could be a relationship between total farmed salmon or total farmed Atlantic salmon production and pathogen transmission to wild fish, why should this relationship be linear as assumed in the analysis? It may be appropriate to consider some alternative non-linear models for this relationship.

Response: I agree that there is reason to suspect that if a relationship between aquaculture and wild salmon dynamics exists it may not be linear. There is an abundance of evidence for non-linear relationships in epidemiology (e.g., host density thresholds and epidemiological breakpoints). However, consideration of more complex non-linear dynamics and interactions among covariates is beyond the terms of reference set out in the Statement of Work for my contract with the Cohen Commission. I identify this as an important avenue of further investigation at the end of the report.

h. Why use total north Pacific pink salmon abundance as a covariate? What happens to the farm x pink salmon interaction effect estimate if only Fraser River and/or Fraser River plus central B.C. pink salmon abundance is included in the regression? It appears that the effect of the Pink x Farm salmon interaction on FRSS survival anomalies may have been over estimated when FRSS survival rate anomalies are back-corrected for Connors' estimated pink x fish farm mortality effect (see Figure 3).

Response: I used total North Pacific pink salmon abundance as the covariate because there is evidence to suggest that it is during the second year of marine life in the open ocean when competition with pink salmon is most likely to be greatest (Ruggerone and Nielson 2004; Peterman et al. 2010).

A logical next step to the analyses described in this report is to examine pink salmon abundance at multiple spatial and temporal scales. However, this is beyond the terms of reference set out in the Statement of Work for my contract with the Cohen Commission.

i. This was an exploratory analysis with the aim of trying to identify potential a potential causal relationship between fish farm production and variation in FRSS survival anomalies. It was thus appropriate to formulate a variety of potential indicators or fish farm impacts on FRSS survival anomalies and to explore different permutations of these potential sources of mortality. However, there is potential to arrive at incorrect conclusions via false positives when many different candidate covariates are evaluated since the chance of false positives increases with the number of different covariates evaluated as potential explanatory variables. Furthermore, it is common place for significant correlations for example between recruitment anomalies and oceanographic variables not stand up well over time after more data have been acquired or refinements introduced later on (Lapointe and Peterman 1991; Myers et al. 1995).

Response: I agree completely, this is why I state at the end of the executive summary and main text I state that the relationships described in this report are correlative and do not on their own establish causation and should be re-examined as more information becomes available.

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

(1) As mentioned above it appears that all of the conclusions made based on the statistical results are invalid due to inappropriate formulation of the statistical models and pseudo-replication in all of the statistical analyses carried out. The report therefore does not represent the best scientific interpretation of the available data.

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

(1) It is recommended that the author reformulates his statistical analyses so as to avoid pseudo-replication in his statistical analyses (if indeed it is present in the statistical analyses).

Response: See response in section 1.

(2) The author's interpretations of the available data are limited due to applying only one of the candidate models for accounting for density dependence in survival anomalies. As mentioned above, only the Ricker stock-recruit model was applied for this purpose when at least one other model particularly the Larkin stock-recruit model should also have been considered and applied.

Response: See response in section 1.

(3) The author considers only the abundance of North Pacific pink salmon in his evaluation of

the potential impacts of pink salmon, pink x farm production and pink x SST effects on FRSS survival anomalies. As mentioned above other plausible pink salmon abundance covariates should also have been considered such as Fraser River pink salmon abundance only and Fraser River pink salmon and central coast pink salmon.

Response: See response in section 1.

(4) If it is hypothesized that salmon farming negatively impacts FRSS survival anomalies, it would be fair to hypothesize that it should also negatively impact the survival anomalies of other salmon species whose juveniles follow the same migratory route though the northern Vancouver Island inside waters as those of the FRSS. The analysis could thus be extended to include statistical analyses of the potential relationships between the marine survival anomalies of other salmon species whose juveniles migrate through the same set of fish farms.

Response: See response in section 1.

(5) Further diagnostics analyses could be applied to evaluate the plausibility of the apparent relationships found between e.g., the pink x farm salmon production covariate. An example of such a diagnostic analysis is illustrated below in Figure 3. In this illustrative analysis the apparent mortality rates suggested by the pink x farm salmon production variable were obtained off of the lower panel of Fig. 7 and this was removed from the survival rate anomalies for several FRSSs. The reconstructed recruitment anomalies show a net positive increasing trend instead of no trend as one might expect. These FRSS datasets are not from all 18 stocks so this may be a reason for the apparent perverseness of the back-calculated anomalies corrected for farm x pink interaction mortality effects. This mainly serves as an example of the type of diagnostic test that would be appropriate to apply to the results obtained by the statistical analyses.

Response: I now provide diagnostic plots (in Appendix 5) to illustrate the fit of the models to the data and to help identify if the models over (or under) predict sockeye productivity.

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

I do not believe that the recommendations provided in this report are supportable due to the apparent pseudo-replication in all of the statistical analyses performed and relatively limited scope of the statistical analyses carried out.

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

Should resources permit, POST (<http://www.postprogram.org/>) tracking of sockeye salmon smolts traveling through the salmon farm production area and then returning as adults through this area for several cohorts of FRSS could help to provide improved estimates of the survival anomalies of juvenile survival anomalies and juvenile to adult survival anomalies. Experimental manipulation of salmon farm production where there were for example one or two fallow years with no salmon farm production followed by a few years of full production could also help to improve the scientific basis for evaluation of the impacts of fish farm production on FRSS survival anomalies.

6. Please provide any specific comments for the authors.

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Figure 1. Estimates of Connors' alpha+gamma+delta effects (lnR/S corrected only for density-

dependent effects), MA3 smoothed to suppress epsilon noise effects, for selected Fraser sockeye stocks. Estimates from Ricker model are compared to estimates from Larkin model that attempts to account for delayed density dependent (ecosystem interaction) effects as well as direct effects of parental spawning abundance. Source: Carl Walters.

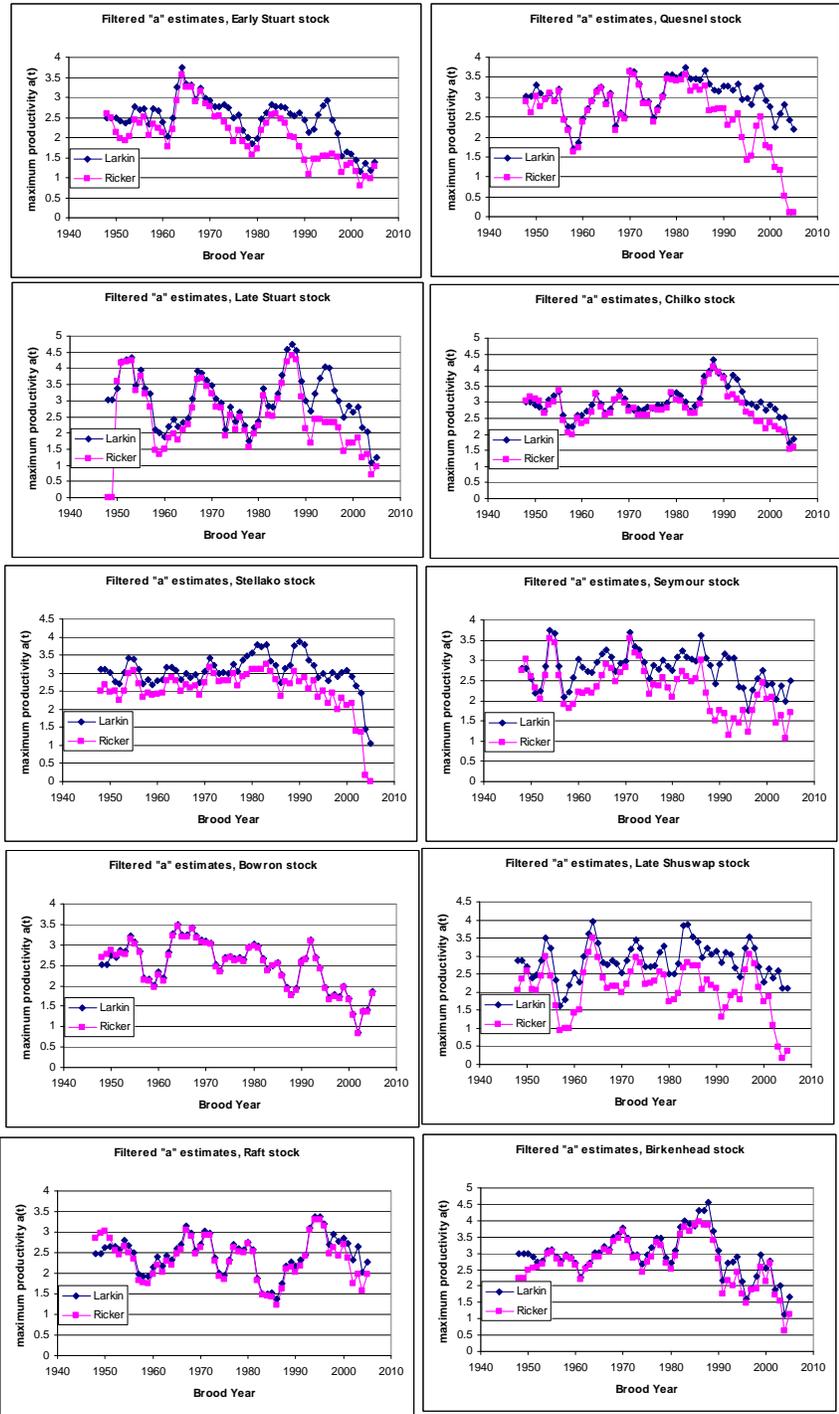


Figure 2. Two plots showing regression effect on $\ln(R/S)$ anomalies from the Ricker and Larkin

models, vs total Atlantic salmon production. The Atlantic salmon production effect is barely significant when all brood years are included and when shared anomalies are computed with the Ricker model. No significant effect is obtained when shared effects are computed with Larkin model. Source: Carl Walters.

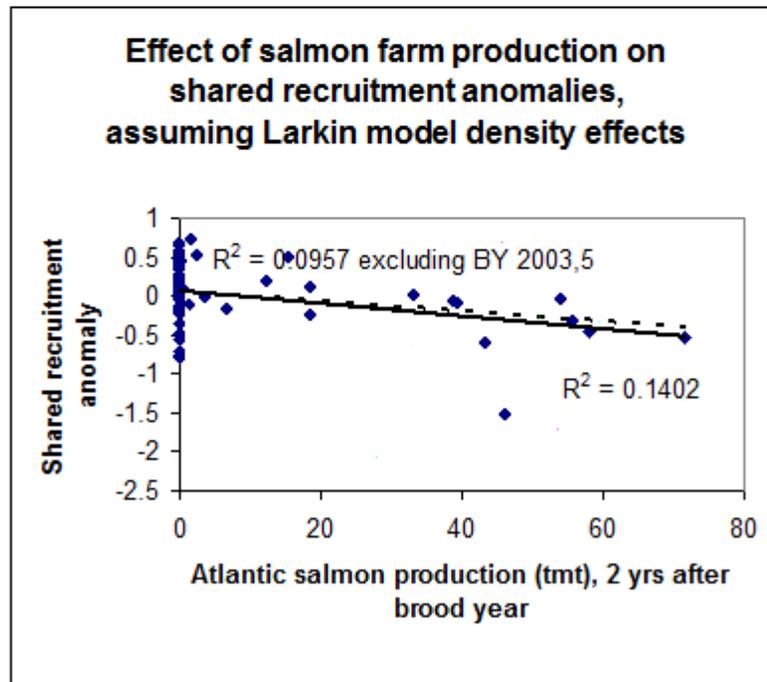
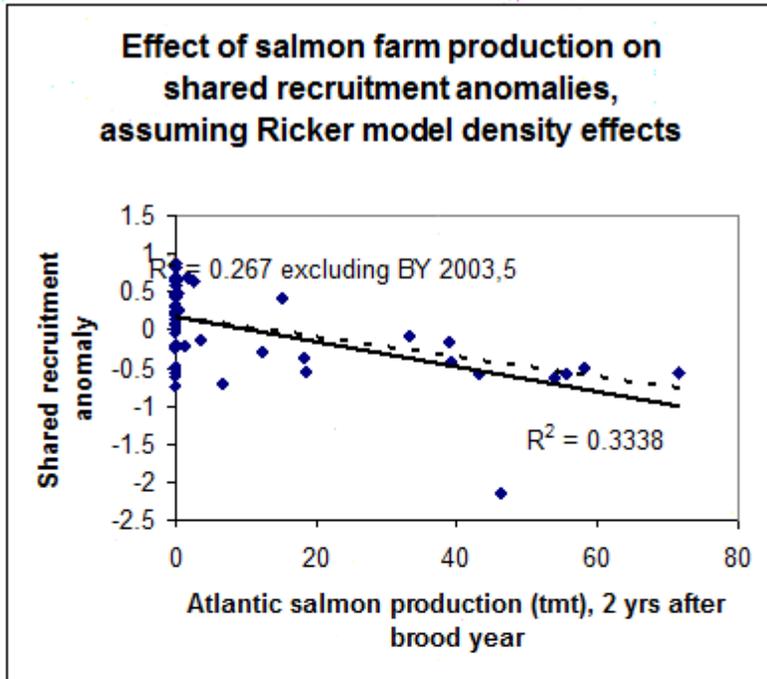
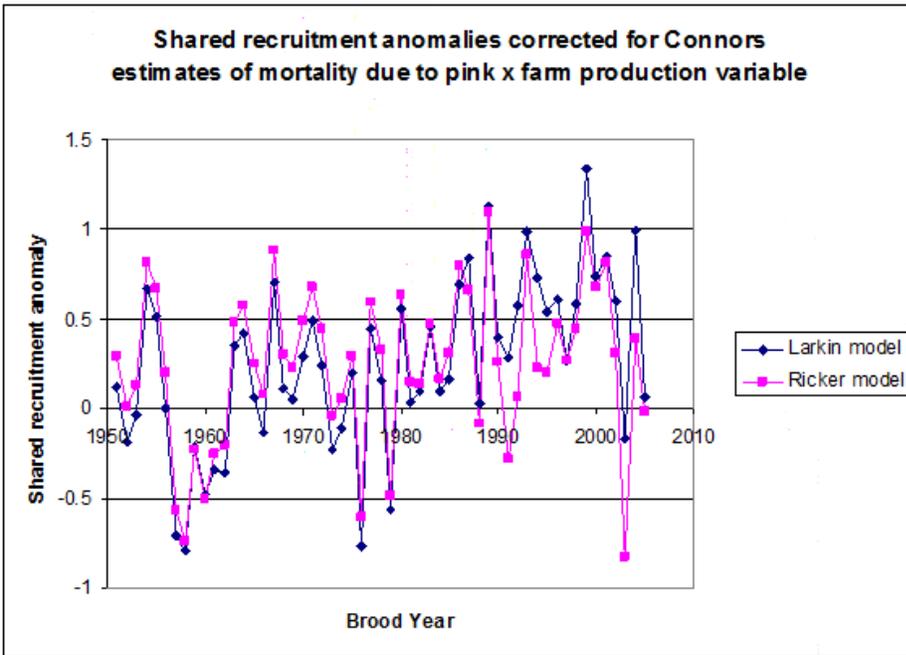
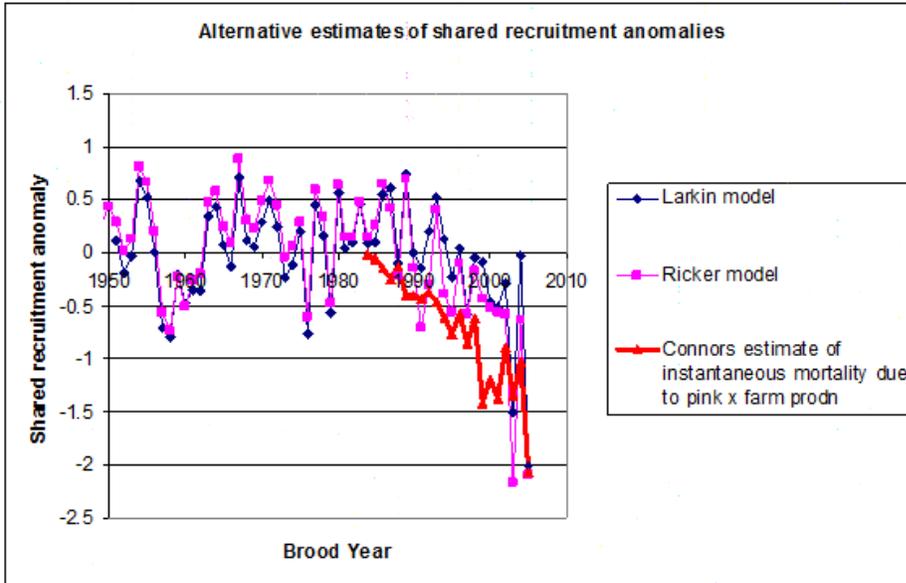


Figure 3. Top panel: The shared recruitment anomaly patterns predicted by the Ricker and

Larkin models for ten major Fraser sockeye stocks (all of the large ones, plus some small ones) compared to the mortality rates that Connors claims are explained by his pink x farm production variable. Bottom panel: Shared recruitment anomalies after correcting for Connors' rates (obtained from Connors' Figure 7). The shared anomaly pattern shows positive net anomalies and predicts that stocks would have done progressively better without that estimated effect. It would appear that the total shared effect (explained by pink x farm production plus unexplained shared residual) could instead be expected to be the same either way. That it is not indicates that Connors may have overestimated the mortality rates even if there is a real effect. Source: Carl Walters.



Review 3:

Report Title: Examination of the relationships between salmon aquaculture and sockeye salmon population dynamics

Reviewer Name: Tom Carruthers

Date: May 12, 2011

1. Identify the strengths and weaknesses of this report.

Strengths

The simultaneous consideration of density dependence, pink salmon abundance and oceanographic covariates such as sea surface temperature serve to reduce confounding by important factors and lend credibility to the method and results. By simultaneously considering other factors that might affect Fraser sockeye survival the report offers a basis with which to quantitatively compare the relative strength of hypothetical relationships.

The report investigates the sensitivity of results to the inclusion of different subsets of data, which helps to reveal the importance of modelling and statistical assumptions.

Weaknesses

It is not correct to assume that the multiple sockeye stocks represent independent replicate responses to the farmed salmon and environmental covariates in each year. In traditional experimental design and statistical analysis, the assumed number of replicates would be assumed to be much lower than used in calculations, (potentially just 1) due to their non-independence in response to a single treatment effect (e.g. salmon production in a given year). The effect of this 'pseudo replication' is to overestimate precision in analyses that may lead to incorrectly identifying a relationship with an environmental or salmon farming covariate.

Response: See response to concerns of pseudo replication in preceding review (Dr. McAlister).

The paper does not describe standard statistical quantities such as power and experiment-wise rate of detecting false positives that would be insightful. These inform the reader of the extent to which an analysis can be expected to erroneously identify at least one relationship or fail to detect real relationships (in this case both probabilities may be high).

Response: The technical report prepared for the Cohen Commission by Korman (2011) nicely illustrates the power, or lack there of, to detect relationships (should they exist) with time series like those considered in this report. I now reference the Korman report in my

final report. Had the relationships described in the draft report remained significant in the final report a description of the experiment-wise false positive rate would have been instructive, However, because significant relationships were not observed in the null-hypothesis testing section of my report, I feel reporting an experiment wise type I error rate is uninformative.

Despite undertaking an analysis including environmental covariates of survival such as sea surface temperature and salmon farming covariates, there is a limited discussion of the relative strength of significant effects. For example, a significant effect may be detected (e.g. $p < 0.05$) for a salmon farming covariate but the relationship may be very weak in comparison to other factors.

Response: I now discuss the strength of the relationships observed in the discussion and provide plots of the predicted influence of the variables considered on sockeye mortality. These plots illustrate the relative strength of the effect of each variable on sockeye mortality.

The selection and number of control populations has the potential to affect the outcome of the analysis. For example controls that are not correlated with an independent variable (e.g. salmon productivity) and exhibit relatively low variability in ‘survival’, will increase the probability of concluding that a relationship exists. There is no exploration of the sensitivity of the results to the selection of controls which would be useful.

Response: In the revised report I examine how sensitive my findings are to the reference populations included in the analysis.

The most important weakness of the report is one that is clearly identified by the author: that without experimental manipulation the quantitative work can evaluate correlations but cannot logically evaluate causal relationships.

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

The report offers a preliminary ‘first step’ exploratory analysis of the available data regarding sockeye salmon survival and independent variables associated with salmon farming.

The report offers a frank account of the limitations of the method in terms of evaluating causal relationships. However a lack of consideration for pseudo-replication in addition to a lack of reporting of the potential rate of false positive and false negative errors justifies caution in accepting the central conclusions of the report that are outlined in the first paragraph of the

Discussion (lines 467-476). This caution is best underlined by the worrisome sensitivity of results to the removal of the data for a single brood year (2005, Table 5 lines 607-615) which indicates that a single treatment year is dominating the analysis.

A more thorough scientific interpretation of the data could include further sensitivity analyses (e.g. conducting the analysis with fewer treatment population or fewer or no controls) to provide a better understanding of the robustness of conclusions to statistical and model assumptions.

Response: The final report now includes examination of the sensitivity of the results to the reference populations included, the inclusion of the 2005 brood year, and the assumed underlying stock recruit relationship. I also provide diagnostic plots to check for violations of the assumptions of the statistical models used.

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

Given the short time series that are available for aquaculture variables (4-6 years) and the high level of natural variability that is likely, the statistical power to correctly identify a relationship between ‘survival’ and other explanatory factors is probably fairly low. A simple power analysis might highlight this point and be a useful addition to the report.

Response: As mentioned above, the Korman (2011) report, which summarizes the aquaculture data provided to the Cohen Commission, includes simulations that highlight the low power to detect a relationship should one exist.

By considering many hypothetical relationships simultaneously the probability of falsely identifying at least one correlation when none exists may be large (experiment-wise Type I error). It is not clear exactly how many competing relationships were considered. However consider the example of 95% confidence intervals (lines 274-275) for each of 10 hypothetical relationships considered simultaneously. In this case even if the data were generated randomly with no underlying relationship, by chance alone 4 in every 10 times it would be concluded that at least one correlation existed. It would be useful to include this error calculation in the report.

Response: The number of different hypotheses considered is now reported in Table 5 and in Appendix 4. This analysis takes an information theoretic approach to account for model and parameter uncertainty. This is not the same as classical statistical null hypothesis testing where experiment wise type 1 error is readily interpretable and it is not immediately obvious (to me) how this would be extended to multi-model inference.

It seems that other related salmonid species with migration routes similar to the treatment Fraser sockeye populations might also be affected by the hypothesized pathogens. It might be beneficial to include data for such species to broaden the analysis.

Response: I agree the examination of other salmon species that migrate past salmon farms would be very informative. However this is beyond the terms of reference set out in the Statement of Work for my contract with the Cohen Commission. I identify this as an important avenue of further investigation at the end of the report.

The report considers only one formulation of the stock-recruitment curve (the Ricker model). It would be relatively straightforward to evaluate the sensitivity of results to this assumption by undertaking the same analyses based on the residuals of the Larkin stock-recruitment model.

Response: This was a limitation of the original report. The revised report considers an alternate formulation of the stock-recruitment relationship (i.e., the Larkin model). See response in preceding review (Dr. McAlister).

It is not clear why it should be assumed that sockeye survival should be linearly related to the explanatory factors, particularly viral and bacterial pathogens. A greater discussion of this assumed relationship included alternative functional forms would be instructive.

Response: I agree that there is good reason to suspect that a relationship between aquaculture and wild salmon dynamics may not be non-linear. Consideration of more complex non-linear dynamics and interactions among covariates is beyond the terms of reference set out in the Statement of Work for my contract with the Cohen Commission. I identify this as an important avenue of further investigation at the end of the report.

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

The recommendation to repeat the analyses including the 2010 Fraser sockeye return data (lines 513-517) is sensible. As explained in the report these data may offer greater contrast with which to identify factors correlated with sockeye survival.

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

In order to establish a causal link between Fraser sockeye salmon survival and salmon farming, manipulative experimentation is required. Given the large degree of natural variability and confounding of other factors, strong contrast in treatment effects (i.e. strong reductions and then increases in salmon farming) might be necessary to discern and reliably quantify effects. Such

treatments would have to be considerate of the pink salmon cycle (for example carried out in two year blocks). Clearly such a recommendation does not account for economic considerations.

A better understanding of the functional form of the relationship between pathogens and salmon survival would increase the credibility of such analyses. For example, the relationship may well be non-linear or entail threshold levels beyond which survival does not decrease appreciably.

6. Please provide any specific comments for the authors.

There is a requirement for greater clarity regarding the linear modeling (Eqn. 3, line 228). The nested random effect terms have particular constraints to be readily interpreted marginally. For example, to easily interpret $\theta(t,w)$ terms, the sum over i of $\theta(t,w,i)$ terms must be zero. If the sum over i , t and w of $\theta(t,w,i)$ equals zero then these terms are confounded with higher level additive random effects such as θ_i and cannot be interpreted marginally. This is a common mistake in random effects modelling and while I'm sure your method was correct, greater clarity here would be useful.

Response: For the analyses in the final report I verified that individual random effects within each group (i.e. within population, within year and within region nested in year) summed to zero.

Appendix 3. Alternate analyses of pathogen occurrence, farmed salmon production and mortalities

This appendix details the results of analyses that examine the sensitivity of the “Analyses of pathogen occurrence, farmed salmon production and mortalities” section in the main text to the inclusion of alternate reference populations.

Each table in this appendix includes variables for the number of Farmed Atlantic and Pacific salmon as well farmed salmon mortality rates, the occurrence of individual and total high risk Fish Health Events (FHE) and Provincial health Audits (Audits) as well as the abundance of sea lice on farmed fish. Shown are the number of parameters (k), the negative log likelihood (Log Lik) and likelihood ratio statistic (Lik Ratio) and corresponding p-value based on a likelihood ratio test in relation to the null model. Also shown are the coefficient for each variable (coef), standard error (SE) and the effective sample size which is the number of independent regional measures of the variable of interest times in the time series.

Table A3.1. Summary of analyses that include sockeye survival anomalies from all Fraser River sockeye salmon populations (excluding the Harrison River).

Model	k	Log Lik	Lik Ratio	df	p-value	coef	SE	Effective n
Null	5	-72.43						
Atlantic salmon	6	-71.39	2.07	1	0.150	-0.016	0.010	5
Pacific salmon	6	-71.71	1.43	1	0.232	0.071	0.055	5
Mortality rate	6	-71.26	2.34	1	0.126	550.791	318.517	5
High Risk FHE	6	-72.42	0.02	1	0.888	-0.005	0.034	5
Furunculosis FHE	6	-72.41	0.03	1	0.864	0.022	0.128	5
BKD FHE	6	-72.20	0.46	1	0.498	-0.031	0.045	5
IHNV FHE	6	-72.40	0.05	1	0.815	0.008	0.034	5
High Risk Audit	6	-72.08	0.69	1	0.407	-0.120	0.140	5
BKD Audit	6	-72.03	0.79	1	0.375	-0.119	0.129	5
Null	5	-60.06						
Motile <i>L. salmonis</i>	6	-59.64	0.85	1	0.356	0.011	0.011	4
Gravid <i>L. salmonis</i>	6	-59.68	0.76	1	0.383	0.023	0.025	4
<i>C. clemensi</i>	6	-59.98	0.16	1	0.685	-0.051	0.125	4
All lice	6	-59.65	0.81	1	0.367	0.010	0.011	4

Table A3.2. Summary of analyses that include sockeye survival anomalies from all populations from Washington State to the Yakutat region of Alaska.

Model	k	Log Lik	Lik Ratio	df	p-value	coef	SE	Effective n
Null	5	-139.87						
Atlantic salmon	6	-138.95	1.84	1	0.175	-0.008	0.006	33
Pacific salmon	6	-139.84	0.05	1	0.815	0.005	0.020	33
Mortality rate	6	-139.82	0.11	1	0.744	-32.499	96.361	33
High Risk FHE	6	-139.69	0.36	1	0.548	-0.007	0.012	33
Furunculosis FHE	6	-139.64	0.47	1	0.493	-0.052	0.754	33
BKD FHE	6	-139.66	0.43	1	0.511	-0.010	0.015	33
IHNV FHE	6	-139.84	0.06	1	0.813	-0.008	0.033	33
High Risk Audit	6	-139.29	1.15	1	0.283	-0.038	0.035	33
BKD Audit	6	-139.44	0.87	1	0.350	-0.034	0.034	33
Null	5	-105.11						
Motile <i>L. salmonis</i>	6	-105.09	0.04	1	0.834	-0.002	0.007	24
Gravid <i>L. salmonis</i>	6	-105.11	0.01	1	0.913	-0.002	0.019	24
<i>C. clemensi</i>	6	-104.92	0.38	1	0.539	-0.022	0.035	24
All lice	6	-105.08	0.06	1	0.810	-0.001	0.006	24

Appendix 4. Alternate analyses of farmed salmon production, sea surface temperature and pink salmon abundance

This appendix details the results of analyses that examine the sensitivity of the “Analyses of farmed salmon production, sea surface temperature and pink salmon abundance” in the main text to the inclusion of alternate reference populations (A4.1-2) and delayed-density dependence (A4.3-4.5).

Each section includes a model selection table ordered by ΔAIC_c (AIC Table). Terms in the models are farmed salmon production (F), abundance of pink salmon (P), and sea surface temperature (SST). Also shown is the number of parameters (K) for each model, the corresponding log likelihood values (Log Lik), AICc differences (ΔAIC_c), Akaike model weights (w_i) and coefficients of determination (R^2). All hypotheses included density-dependence and hypotheses with interactions included lower-order main effects (e.g., “SSTxPxP” signifies a model that includes all possible two-way interactions as well as single variables for SST, P and F), as well as random effects. The numbers next to each model correspond to the order of models from the analysis based on populations 1-24 and Ricker density-dependence (Table 5). The null model is population-specific density-dependence (A4.1-2) or delayed density-dependence (A4.3-4.5) and random effects.

Each section also includes model averaged weighted parameter estimates (Parameter Estimates), standard errors, and lower and upper 95% confidence intervals for parameters appearing in models within 4 ΔAIC_c of the top model. Productivity at low spawner abundance is α and variables are farm production (Farm), pink salmon abundance in the North Pacific Ocean (Pink), sea surface temperature (SST), and their interactions.

The final component to each section is a plot of the estimated effect on mortality (+/- 95% confidence intervals; see main text for description of how mortality is estimated) of Fraser River sockeye salmon that migrate up the inside of Vancouver Island due to sea surface temperature (SST), farmed salmon production (Farm), pink salmon abundance in the North Pacific Ocean (Pink) and interactions between the variables. The baseline values for SST and pink salmon abundance are equal to the time series mean while the baseline value for farmed salmon production is zero. This means that, for example, the predicted influence of farmed salmon production (top right panel) is at average SST and pink salmon abundance. Predictions are based on model averaged parameter estimates from the best-supported models. Predicted mortality is plotted through the 2006 brood year, although the parameters are based on models fit to data through 2005.

A4.1. Summary of analyses that include Fraser River sockeye salmon populations (excluding the Harrison River) assuming no delayed density-dependence.

Table A4.1. AIC Table

#	Hypothesis	K	Log Lik	ΔAIC_c	w_i	R^2
2	SST + (PxF)	25	-946.42	0.00	0.31	0.49
1	(PxF) + (SSTxF)	26	-945.46	0.21	0.28	0.49
5	(PxF) + (SSTxP)	26	-945.58	0.46	0.24	0.49
3	(PxF) + (SSTxP) + (SSTxF)	27	-945.31	2.07	0.11	0.49
8	(SSTxPxP)	28	-945.30	4.20	0.04	0.49
11	(PxF)	24	-950.27	5.55	0.02	0.49
15	SST + F	23	-954.73	12.34	0.00	0.49
6	SST + P + F	24	-953.72	12.45	0.00	0.49
12	(SSTxF)	24	-953.89	12.81	0.00	0.49
4	P + (SSTxF)	25	-952.89	12.93	0.00	0.49
10	F + (SSTxP)	25	-952.91	12.98	0.00	0.49
14	P + F	23	-955.67	14.23	0.00	0.49
9	(SSTxP) + (SSTxF)	26	-952.72	14.74	0.00	0.49
17	F	22	-956.99	14.74	0.00	0.50
7	SST + P	23	-959.56	22.01	0.00	0.50
13	(SSTxP)	24	-958.76	22.53	0.00	0.50
16	P	22	-961.83	24.42	0.00	0.50
18	SST	22	-966.78	34.33	0.00	0.50
19	null	21	-970.61	39.86	0.00	0.50

Table A4.1. Parameter Estimates

	Coefficient	SE	Upper CI	Lower CI
α	2.69E+00	1.10E-01	2.90E+00	2.47E+00
Farm	-7.81E-03	4.62E-03	1.25E-03	-1.69E-02
Pink	4.28E-04	6.89E-04	1.78E-03	-9.21E-04
SST	-3.64E-01	1.38E-01	-9.35E-02	-6.34E-01
Farm x Pink	-1.04E-04	2.67E-05	-5.16E-05	-1.56E-04
Farm x SST	2.65E-03	3.24E-03	9.00E-03	-3.71E-03
Pink x SST	4.80E-04	5.24E-04	1.51E-03	-5.48E-04

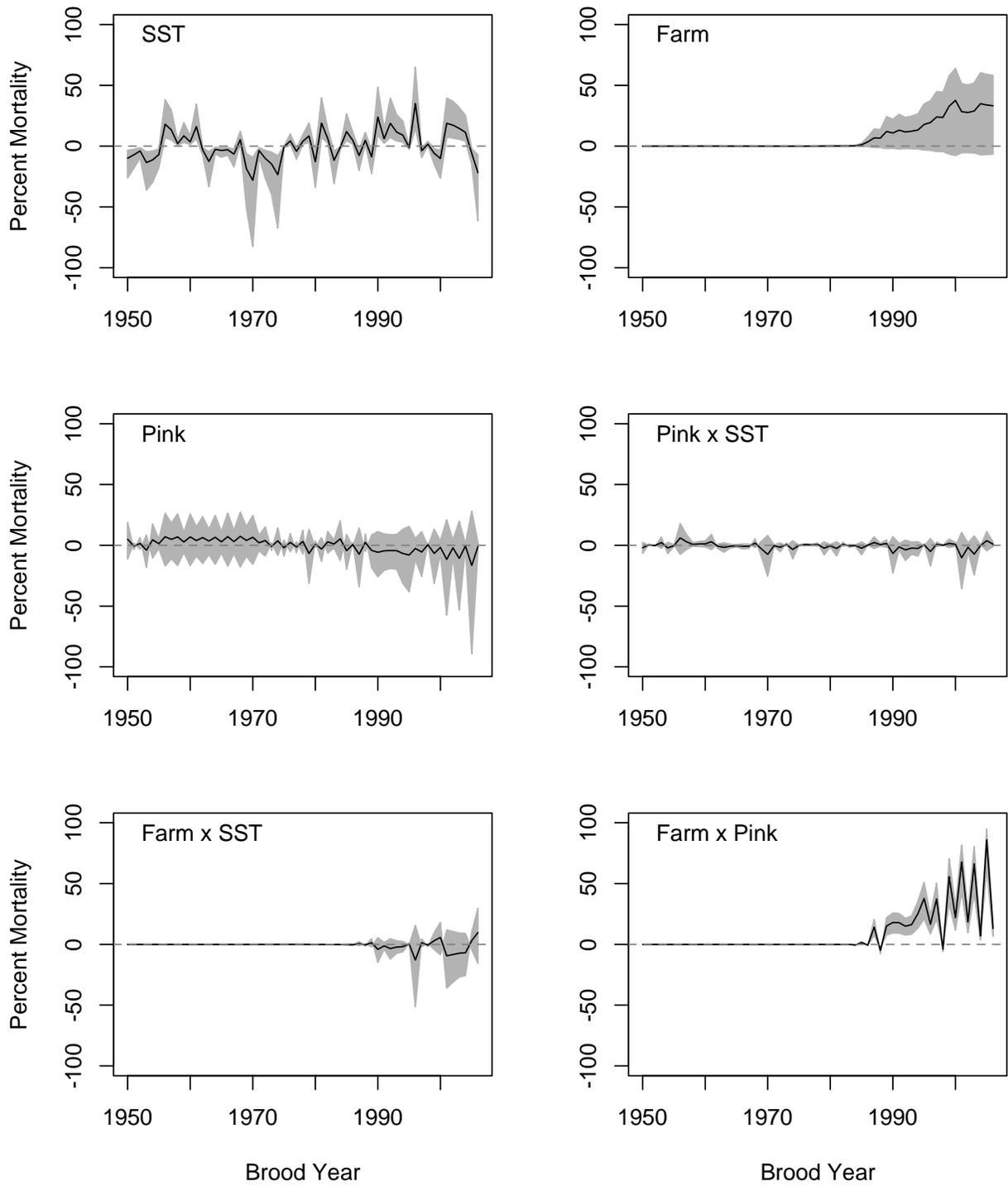


Figure A4.1. Estimated Mortality

A4.2. Summary of analyses that all sockeye populations from Washington to the Yakutat region of Alaska assuming no delayed density-dependence.

Table A4.2. AIC Table

#	Hypothesis	K	Log Lik	ΔAIC_c	w_i	R^2
1	(PxF) + (SSTxF)	42	-1509.86	0.00	0.25	0.72
3	(PxF) + (SSTxP) + (SSTxF)	43	-1509.14	0.72	0.17	0.72
5	(PxF) + (SSTxP)	42	-1510.67	1.61	0.11	0.72
2	SST + (PxF)	41	-1511.91	1.95	0.09	0.72
4	P + (SSTxF)	41	-1511.96	2.05	0.09	0.72
8	(SSTxPxP)	44	-1509.08	2.76	0.06	0.72
9	(SSTxP) + (SSTxF)	42	-1511.41	3.09	0.05	0.72
7	SST + P	39	-1514.98	3.79	0.04	0.72
13	(SSTxP)	40	-1513.96	3.89	0.04	0.72
6	SST + P + F	40	-1514.08	4.14	0.03	0.72
10	F + (SSTxP)	41	-1513.03	4.19	0.03	0.72
11	(PxF)	40	-1514.55	5.08	0.02	0.72
16	P	38	-1517.49	6.67	0.01	0.72
14	P + F	39	-1516.42	6.68	0.01	0.72
12	(SSTxF)	40	-1517.04	10.06	0.00	0.72
15	SST + F	39	-1519.30	12.43	0.00	0.72
17	F	38	-1521.85	15.39	0.00	0.73
18	SST	38	-1522.40	16.49	0.00	0.73
19	null	37	-1525.26	20.07	0.00	0.73

Table A4.2. Parameter Estimates

	Coefficient	SE	Upper CI	Lower CI
α	1.96E+00	3.45E-01	2.64E+00	1.29E+00
Farm	-1.96E-03	5.41E-03	8.66E-03	-1.26E-02
Pink	-1.62E-03	6.19E-04	-4.07E-04	-2.83E-03
SST	-2.60E-01	9.81E-02	-6.80E-02	-4.53E-01
Farm x Pink	-4.62E-05	2.48E-05	2.41E-06	-9.49E-05
Farm x SST	8.52E-03	5.59E-03	1.95E-02	-2.43E-03
Pink x SST	4.77E-04	4.61E-04	1.38E-03	-4.27E-04
Farm x Pink x SST	1.54E-06	4.79E-06	1.09E-05	-7.85E-06

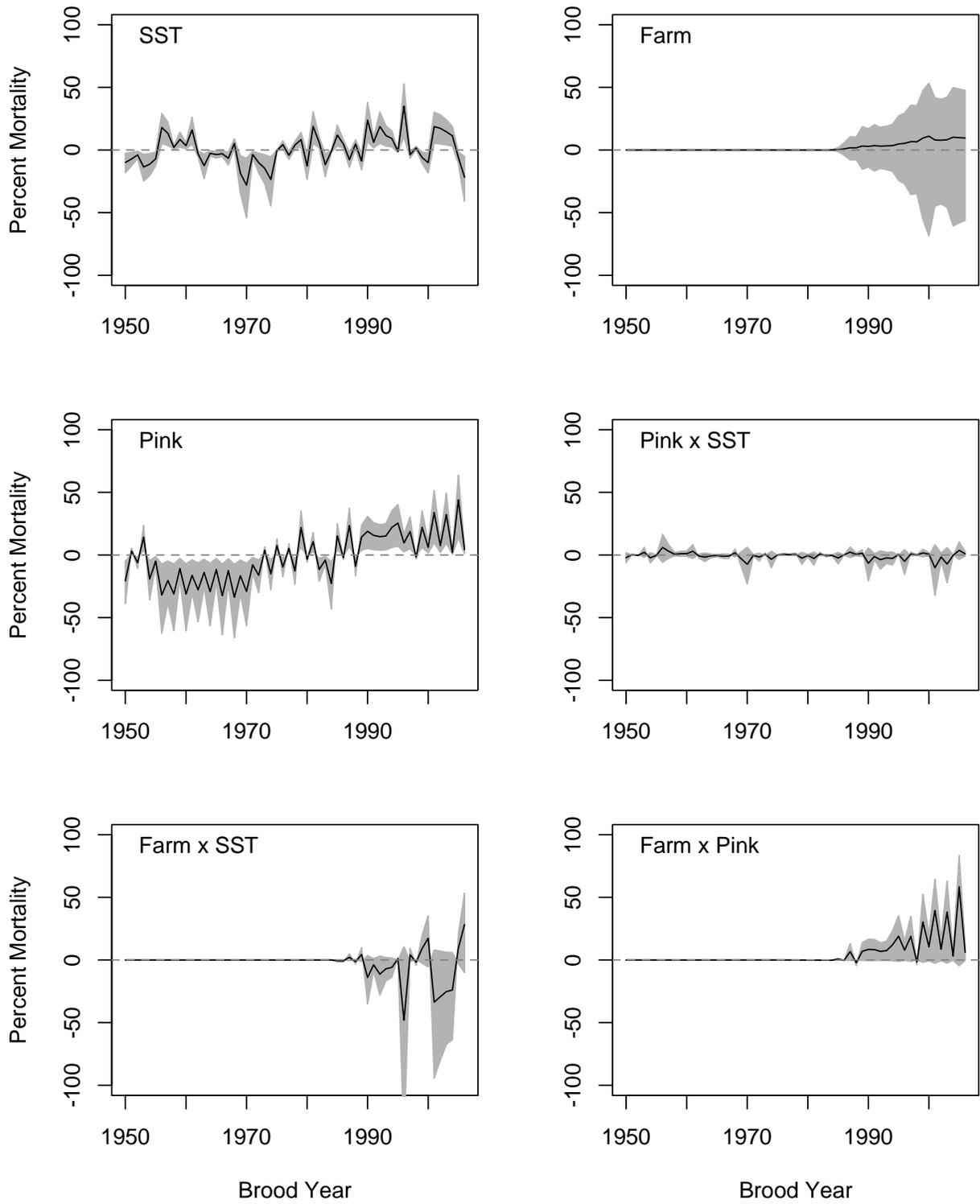


Figure A.4.2. Estimated Mortality. Note the estimated effect of Farm x Pink X SST is negligible and not plotted.

A4.3. Summary of analyses that include all populations in BC south of the Skeena River assuming delayed density-dependence.

Table A4.3. AIC Table.

#	Hypothesis	K	Log Lik	ΔAIC_c	w_i	R^2
1	(PxF) + (SSTxF)	106	-1232.52	0.00	0.29	0.75
2	SST + (PxF)	105	-1234.42	1.29	0.15	0.75
7	SST + P	103	-1237.26	1.98	0.11	0.75
3	(PxF) + (SSTxP) + (SSTxF)	107	-1232.48	2.42	0.08	0.75
4	P + (SSTxF)	105	-1235.01	2.47	0.08	0.75
5	(PxF) + (SSTxP)	106	-1234.40	3.76	0.04	0.75
6	SST + P + F	104	-1236.99	3.93	0.04	0.75
13	(SSTxP)	104	-1237.25	4.44	0.03	0.75
16	P	102	-1239.80	4.57	0.03	0.75
12	(SSTxF)	104	-1237.31	4.58	0.03	0.75
9	(SSTxP) + (SSTxF)	106	-1234.96	4.88	0.02	0.75
8	(SSTxPxP)	108	-1232.48	4.93	0.02	0.75
11	(PxF)	104	-1237.57	5.09	0.02	0.75
15	SST + F	103	-1239.43	6.31	0.01	0.75
14	P + F	103	-1239.47	6.40	0.01	0.75
10	F + (SSTxP)	105	-1236.98	6.40	0.01	0.75
18	SST	102	-1241.07	7.11	0.01	0.76
17	F	102	-1242.49	9.95	0.00	0.75
19	null	101	-1244.50	11.48	0.00	0.76

Table A4.3. Parameter Estimates.

	Coefficient	SE	Upper CI	Lower CI
α	2.44E+00	1.89E-01	2.81E+00	2.07E+00
Farm	3.08E-04	6.61E-03	1.33E-02	-1.27E-02
Pink	-9.94E-04	7.70E-04	5.15E-04	-2.50E-03
SST	-3.63E-01	1.45E-01	-7.94E-02	-6.46E-01
Farm x Pink	-6.02E-05	3.18E-05	2.18E-06	-1.23E-04
Farm x SST	9.64E-03	6.53E-03	2.24E-02	-3.16E-03
Pink x SST	-1.48E-04	6.29E-04	1.08E-03	-1.38E-03
Farm x Pink x SST	-	-	-	-

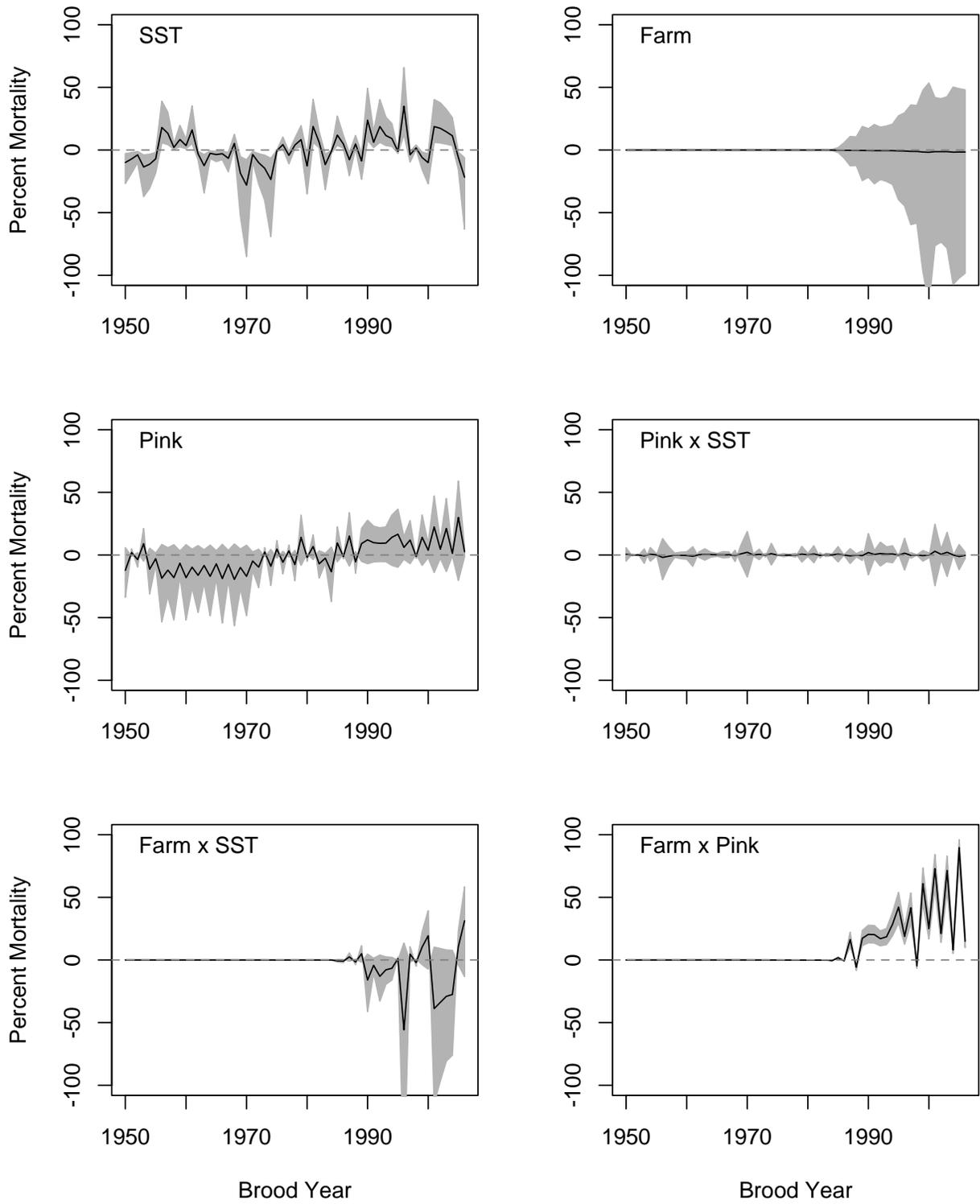


Figure A.4.3. Estimated Mortality.

A4.4. Summary of analyses that include Fraser River sockeye salmon populations (excluding the Harrison River) assuming delayed density-dependence.

Table A4.4. AIC Table.

#	Hypothesis	K	Log Lik	ΔAIC_c	w_i	R^2
2	SST + (PxF)	76	-885.75	0.00	0.30	0.57
5	(PxF) + (SSTxP)	77	-884.61	0.20	0.27	0.57
1	(PxF) + (SSTxF)	77	-884.75	0.47	0.23	0.57
3	(PxF) + (SSTxP) + (SSTxF)	78	-884.44	2.32	0.09	0.57
11	(PxF)	75	-888.34	2.72	0.08	0.57
8	(SSTxPxF)	79	-884.22	4.38	0.03	0.57
17	F	73	-897.44	16.03	0.00	0.57
15	SST + F	74	-896.32	16.24	0.00	0.57
12	(SSTxF)	75	-895.40	16.84	0.00	0.57
14	P + F	74	-896.78	17.15	0.00	0.57
6	SST + P + F	75	-895.83	17.71	0.00	0.57
4	P + (SSTxF)	76	-894.91	18.33	0.00	0.57
10	F + (SSTxP)	76	-894.95	18.41	0.00	0.57
9	(SSTxP) + (SSTxF)	77	-894.73	20.44	0.00	0.57
16	P	73	-901.27	23.68	0.00	0.57
7	SST + P	74	-900.11	23.80	0.00	0.57
13	(SSTxP)	75	-899.20	24.44	0.00	0.57
18	SST	73	-904.84	30.83	0.00	0.57
19	null	72	-907.06	32.83	0.00	0.58

Table A4.4. Parameter Estimates.

	Coefficient	SE	Upper CI	Lower CI
α	2.93E+00	1.30E-01	3.18E+00	2.67E+00
Farm	-4.05E-03	4.55E-03	4.86E-03	-1.30E-02
Pink	9.19E-04	6.77E-04	2.25E-03	-4.08E-04
SST	-2.67E-01	1.24E-01	-2.40E-02	-5.10E-01
Farm x Pink	-1.20E-04	2.60E-05	-6.88E-05	-1.71E-04
Farm x SST	6.89E-03	5.90E-03	1.85E-02	-4.68E-03
Pink x SST	3.46E-04	9.16E-04	2.14E-03	-1.45E-03
Farm x Pink x SST	-	-	-	-

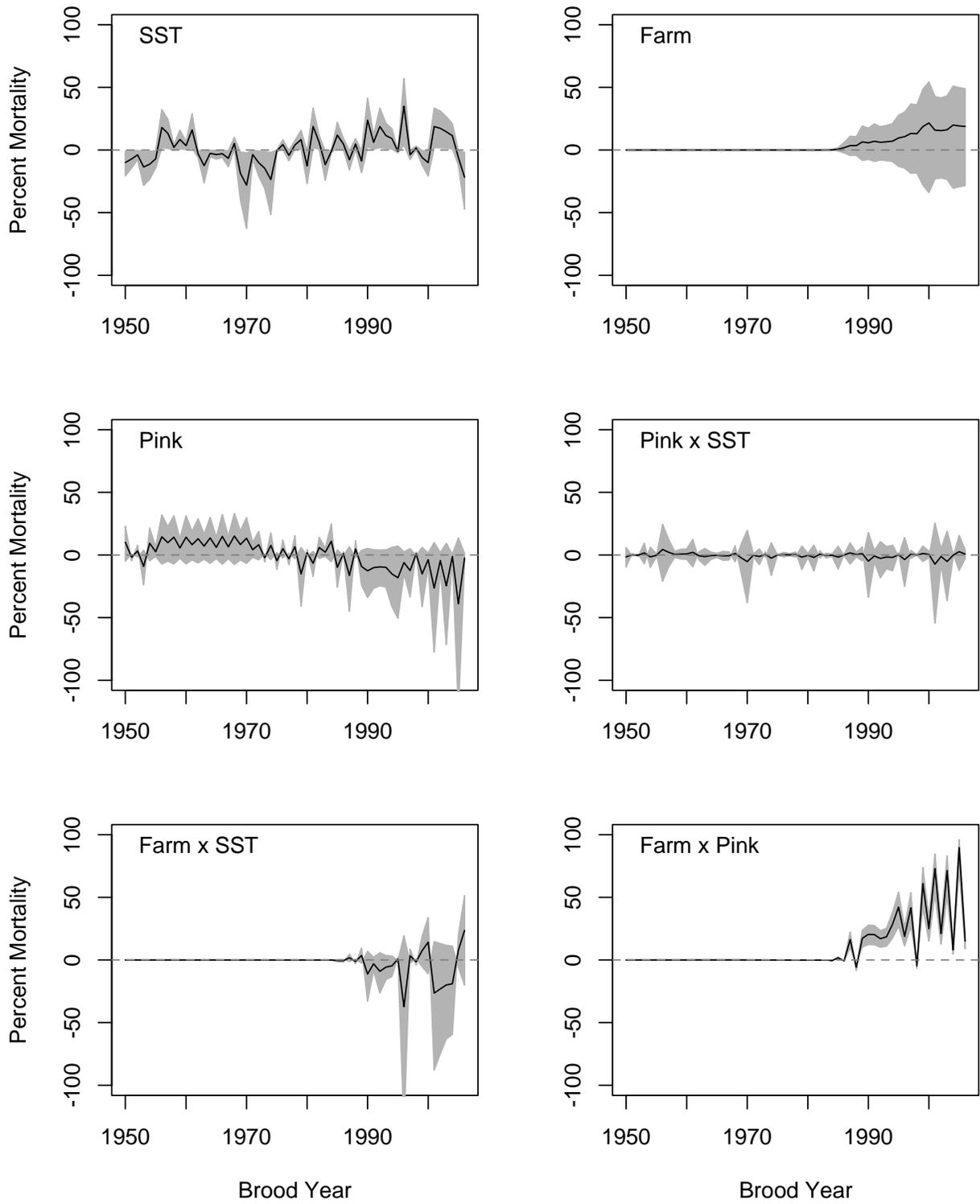


Figure A.4.4. Estimated Mortality.

A4.5. Summary of analyses that include all populations from Washington to the Yakutat region of Alaska assuming delayed (Larkin) density-dependence.

Table A4.5. AIC Table

#	Hypothesis	K	Log Lik	ΔAIC_c	w_i	R^2
1	(PxF) + (SSTxF)	138	-1433.38	0.76	0.00	0.29
3	(PxF) + (SSTxP) + (SSTxF)	139	-1432.50	0.76	0.80	0.20
5	(PxF) + (SSTxP)	138	-1434.67	0.77	2.58	0.08
4	P + (SSTxF)	137	-1435.96	0.77	2.59	0.08
2	SST + (PxF)	137	-1436.21	0.77	3.09	0.06
8	(SSTxPxP)	140	-1432.50	0.76	3.38	0.05
7	SST + P	135	-1438.93	0.77	3.40	0.05
13	(SSTxP)	136	-1437.65	0.77	3.41	0.05
9	(SSTxP) + (SSTxF)	138	-1435.28	0.77	3.80	0.04
16	P	134	-1441.28	0.77	5.55	0.02
11	(PxF)	136	-1438.76	0.77	5.62	0.02
10	F + (SSTxP)	137	-1437.55	0.77	5.78	0.02
6	SST + P + F	136	-1438.84	0.77	5.78	0.02
14	P + F	135	-1441.13	0.77	7.80	0.01
12	(SSTxF)	136	-1440.14	0.77	8.39	0.00
18	SST	134	-1444.37	0.77	11.73	0.00
15	SST + F	135	-1443.23	0.77	12.01	0.00
17	F	134	-1445.72	0.77	14.43	0.00
19	null	133	-1447.11	0.77	14.66	0.00

Table A4.5. Parameter Estimates.

	Coefficient	SE	Upper CI	Lower CI
α	2.20E+00	1.84E-01	2.56E+00	1.84E+00
Farm	-1.52E-03	4.74E-03	7.77E-03	-1.08E-02
Pink	-1.14E-03	5.87E-04	6.16E-06	-2.29E-03
SST	-2.94E-01	9.32E-02	-1.11E-01	-4.76E-01
Farm x Pink	-7.40E-05	2.59E-05	-2.31E-05	-1.25E-04
Farm x SST	1.24E-02	5.70E-03	2.36E-02	1.27E-03
Pink x SST	6.76E-04	5.27E-04	1.71E-03	-3.56E-04
Farm x Pink x SST	-2.35E-06	6.69E-06	1.08E-05	-1.54E-05

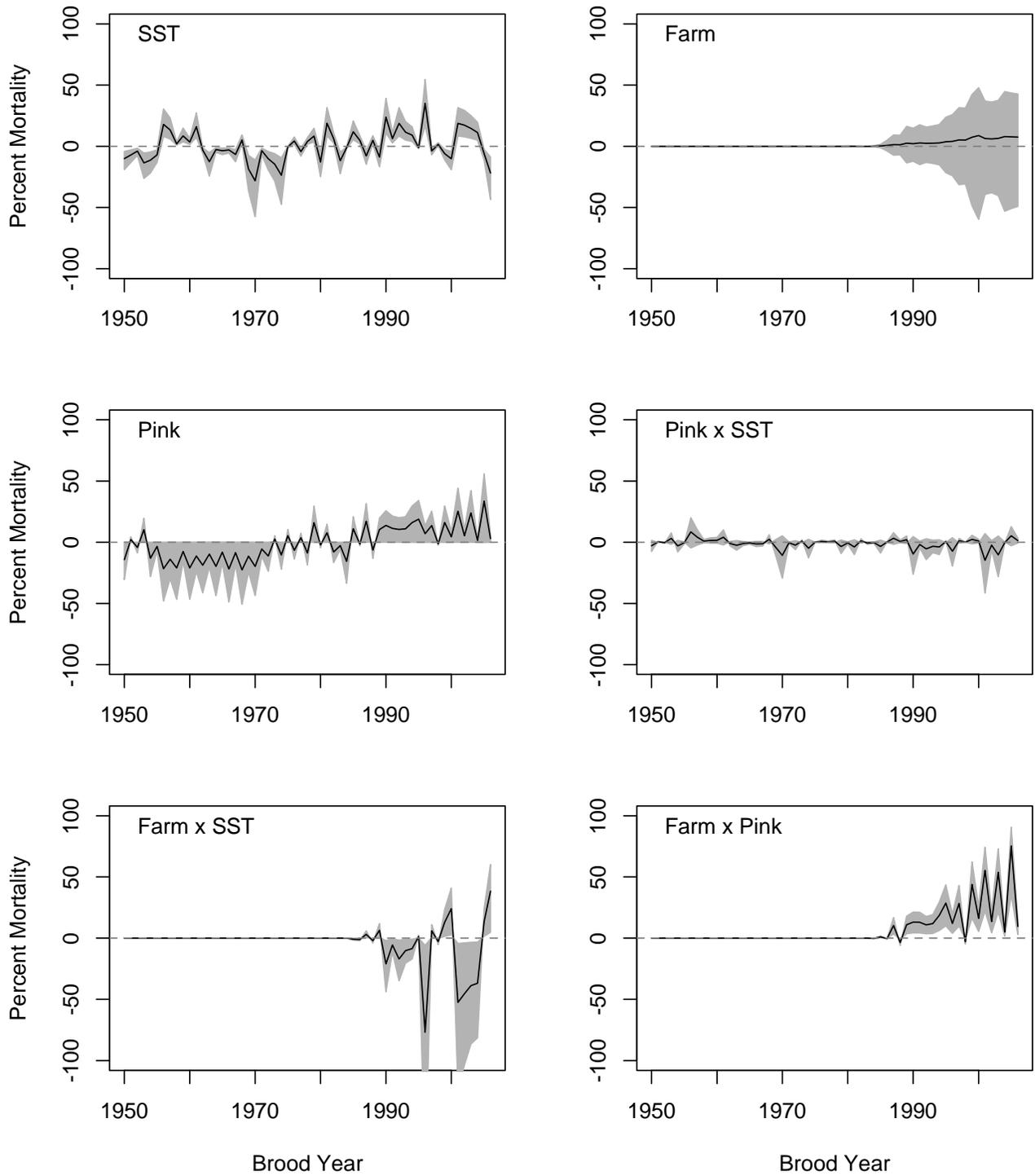


Figure A.4.5. Estimated Mortality.

A4.6. Summary of analyses that include all populations in BC south of the Skeena River, assume no delayed density-dependence and exclude the 2005 brood year.

Table A4.6. AIC Table.

#	Hypothesis	K	Log Lik	ΔAIC_c	w_i	R^2
7	SST + P	31	-1276.04	0.00	0.20	0.69
6	SST + P + F	32	-1275.15	0.35	0.17	0.69
4	P + (SSTxF)	33	-1274.45	1.10	0.12	0.69
13	(SSTxP)	32	-1275.93	1.91	0.08	0.69
2	SST + (PxP)	33	-1274.89	1.97	0.07	0.69
1	(PxP) + (SSTxF)	34	-1273.98	2.30	0.06	0.69
10	F + (SSTxP)	33	-1275.06	2.31	0.06	0.69
5	(PxP) + (SSTxP)	34	-1274.19	2.72	0.05	0.69
15	SST + F	31	-1277.41	2.74	0.05	0.69
12	(SSTxF)	32	-1276.75	3.55	0.03	0.69
9	(SSTxP) + (SSTxF)	34	-1274.85	4.04	0.03	0.69
3	(PxP) + (SSTxP) + (SSTxF)	35	-1273.82	4.13	0.03	0.69
18	SST	30	-1279.82	5.43	0.01	0.70
14	P + F	31	-1278.80	5.51	0.01	0.69
16	P	30	-1279.90	5.60	0.01	0.70
8	(SSTxPxP)	36	-1273.71	6.07	0.01	0.69
11	(PxP)	32	-1278.60	7.25	0.01	0.69
17	F	30	-1281.90	9.58	0.00	0.69
19	null	29	-1284.99	13.63	0.00	0.70

Table A4.6. Parameter Estimates.

	Coefficient	SE	Upper CI	Lower CI
α	2.09E+00	1.80E-01	2.53E+00	1.82E+00
Farm	-4.71E-03	4.20E-03	1.71E-03	-1.34E-02
Pink	-1.26E-03	6.00E-04	-2.80E-04	-2.43E-03
SST	-3.35E-01	1.27E-01	-1.43E-01	-5.98E-01
Farm x Pink	-5.76E-06	8.54E-06	8.24E-06	-2.24E-05
Farm x SST	2.49E-03	3.04E-03	7.81E-03	-3.12E-03
Pink x SST	-1.22E-04	2.55E-04	2.96E-04	-6.20E-04
Farm x Pink x SST	-	-	-	-

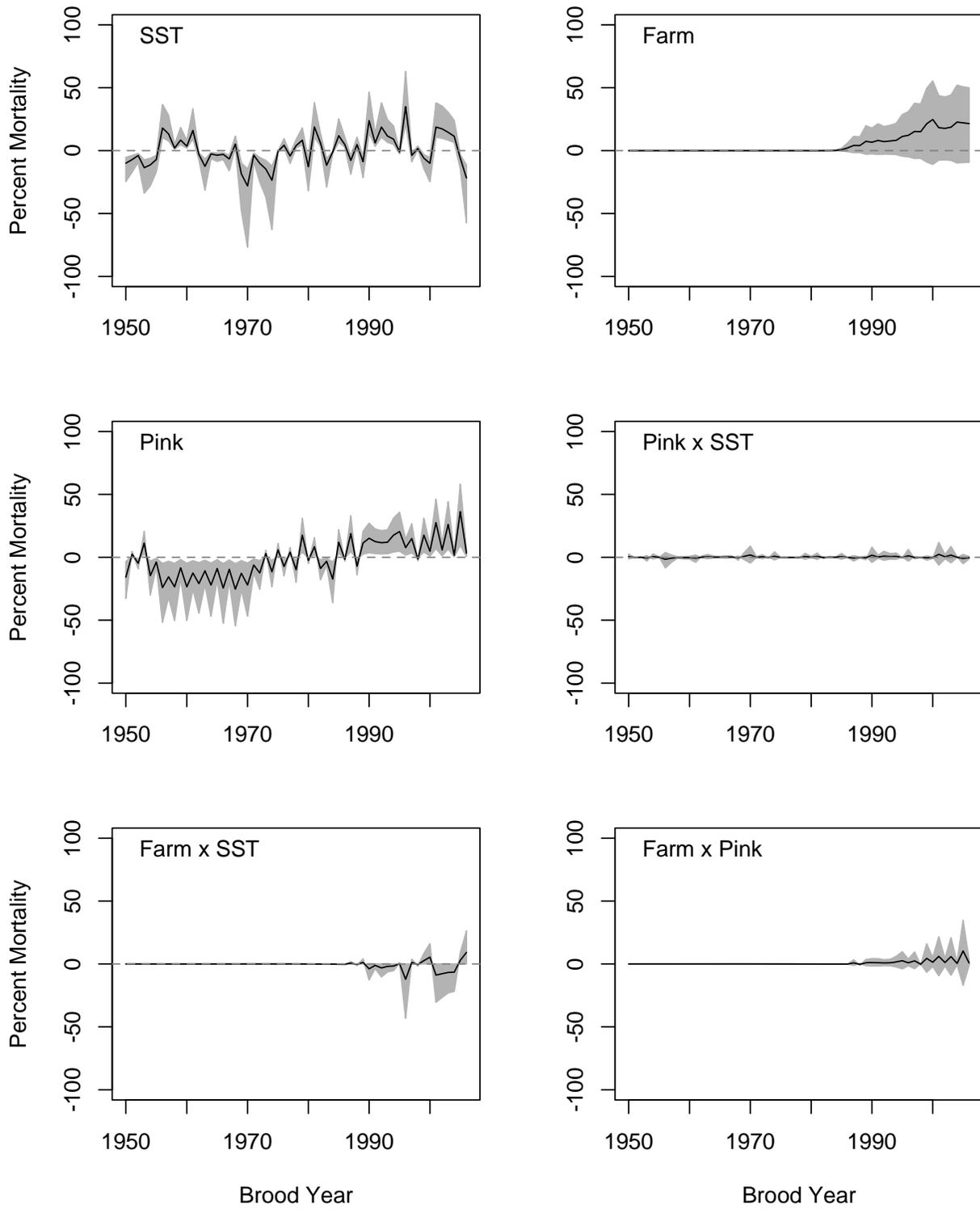


Figure A.4.6. Estimated Mortality.

Appendix 5. Model diagnostics.

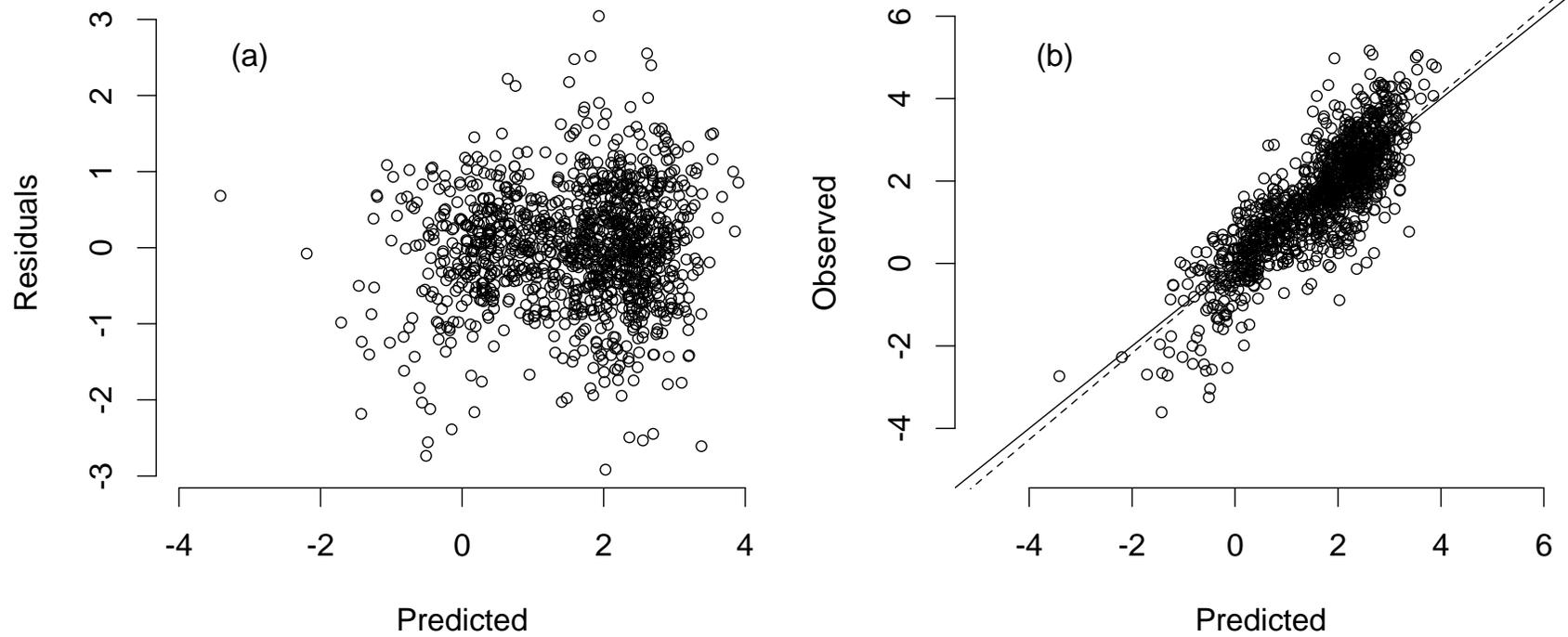
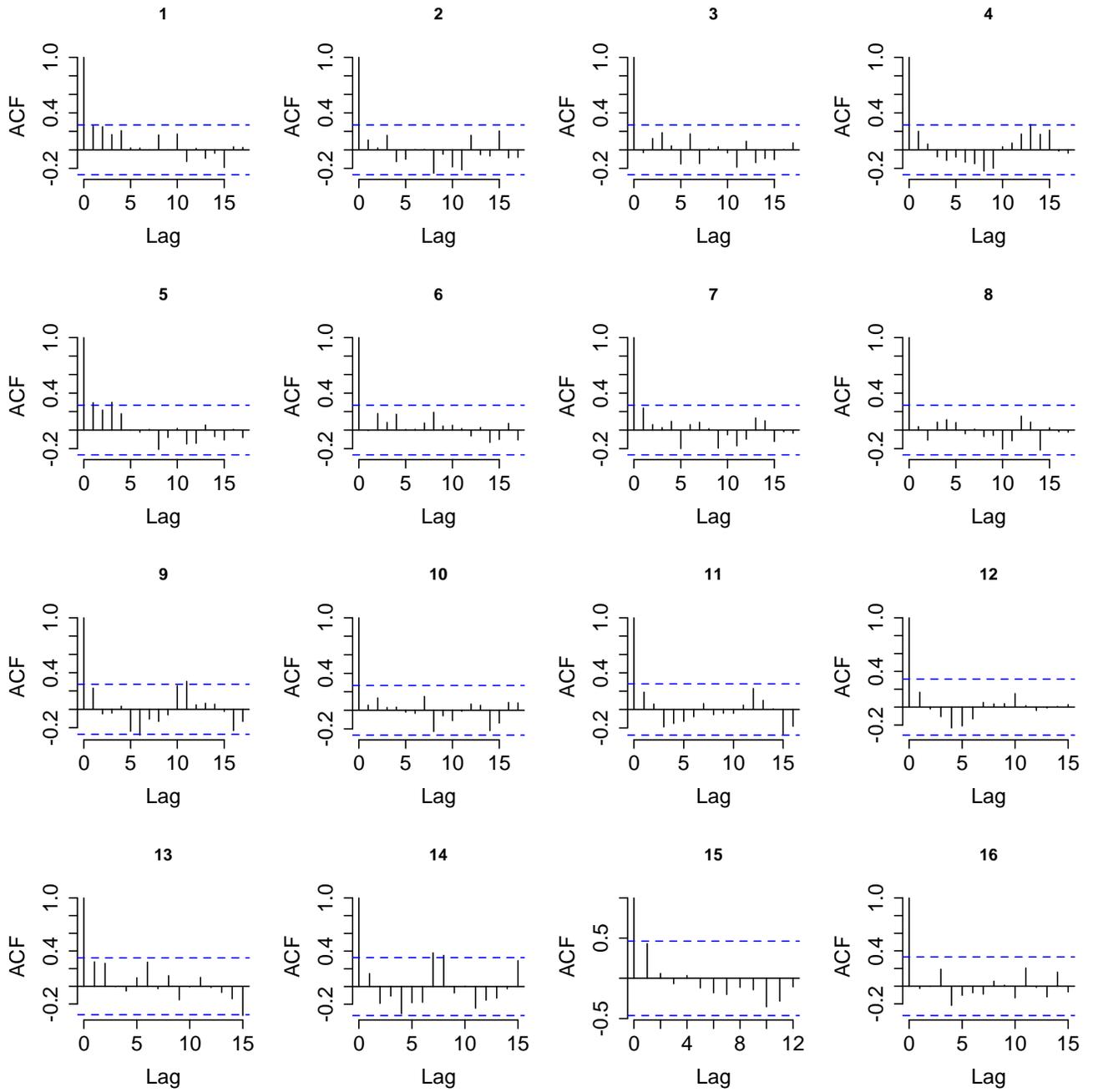


Figure A5.1. Diagnostic plots of the best fit model (Appendix 4.2) fit to the entire sockeye dataset (i.e. all populations). (a) Model residuals versus predicted values. (b) Observed ($\log_e[R/S]$) versus predicted values, the solid line is the 1:1 relationship and the dashed line is the actual slope of relationship between observed and predicted.



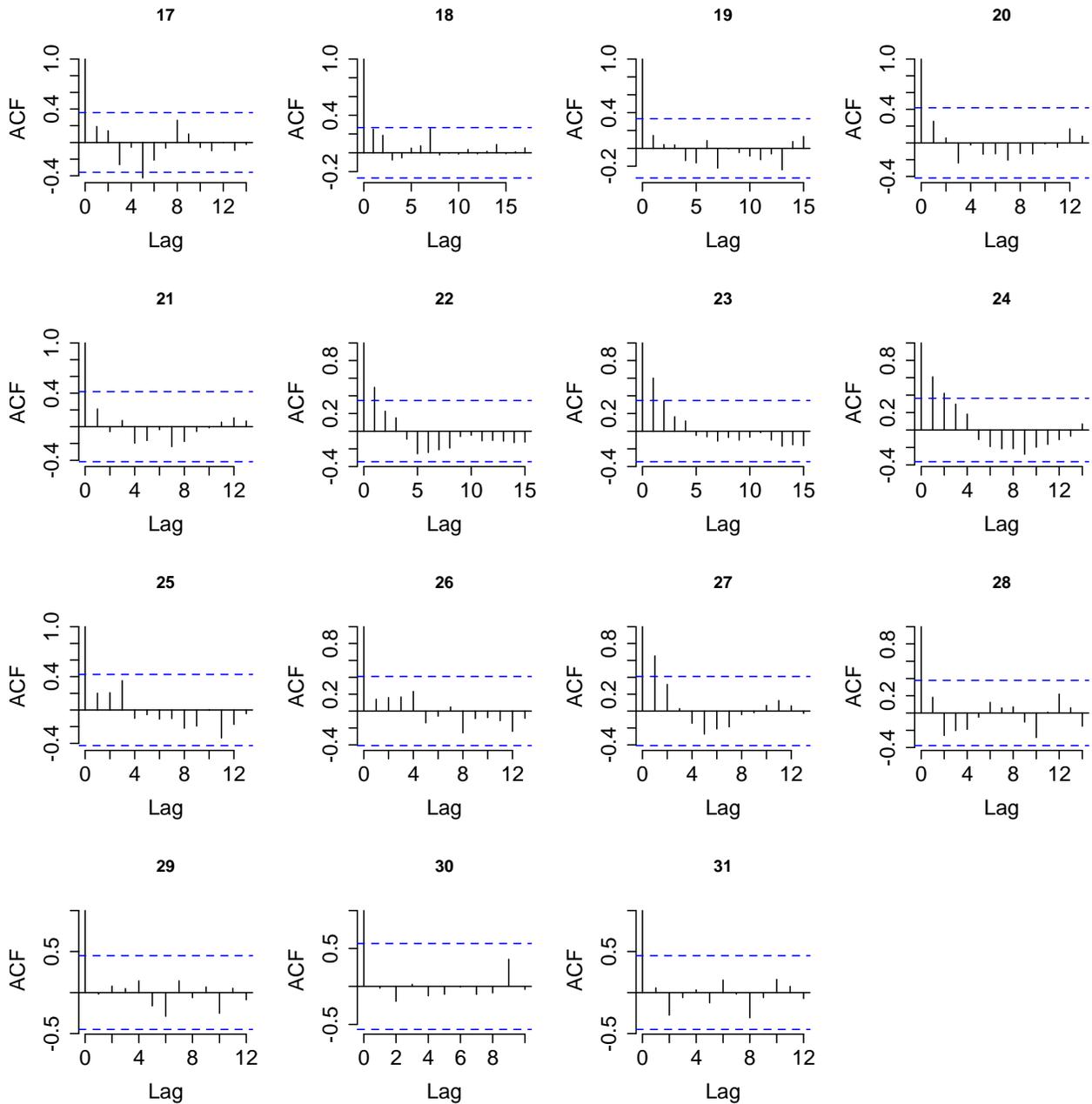


Figure A5.2. Autocorrelation of residuals by population from model fit in A5.1. Plotted is the partial correlation coefficient between residuals in year 0 and lagged year x . Correlations above the dashed blue line are significant. Three populations have significant lag 1 autocorrelation in their residuals (27, 28 and 31). It is not yet possible to specify a lag-1 autocorrelation structure in the lmer package in R, however, exclusion of these populations from the analysis did not influence the results (Appendix 4).