

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

An appendix to the report:

Peterman R.M., D. Marmorek, B. Beckman, M. Bradford, N. Mantua, B. Riddell, M. Scheuerell, M. Staley, K. Wieckowski, J. Winton, C. Wood. 2010. Synthesis of evidence from a workshop on the decline of Fraser River Sockeye. June 15-17, 2010. Vancouver Island Conference Centre, Nanaimo B.C., 123 pp. + 35 pp. appendices.

The list of presenters is followed by a hypertext link to their written documents, which were submitted to the Expert Panel. These documents are listed in order of the analogous oral presentations at the workshop.

Session A: Predators, parasites, and disease

1. [John Ford, DFO](#)
2. [Simon Jones, DFO](#)
3. [Alexandra Morton, Raincoat Research Society](#)
4. [Kristi Miller, DFO](#)
5. [Kyle Garver, DFO](#)

Session B: Toxic algae and pollutants

6. [Jack Rensel, Rensel Associates](#)
7. [Robie Macdonald, DFO](#)

Session C: Physical oceanographic conditions

8. [Rick Thomson, DFO](#)
9. [Marc Trudel, DFO](#)
10. [Dick Beamish, DFO](#)
11. [Ed Farley, NOAA](#)

Session D: Freshwater conditions

12. [Daniel Selbie, DFO](#)
13. [Carl Walters, UBC](#)
14. [Scott Hinch, UBC](#)

Session E: Other factors affecting Fraser sockeye

15. [Phil Mundy, NOAA](#)
16. [Greg Ruggerone, Natural Resources Consultants Inc.](#)

Session A: Predators, parasites, and disease; John Ford, DFO

Hypothesis: Predation by marine mammals is an important contributor to the Fraser sockeye situation

Summary of presentation at the Workshop on the Decline of Fraser River Sockeye,
15-17 June 2010, Nanaimo, B.C.

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Of the 31 species of marine mammals recorded for waters off the west coast of Canada, seven species are known to prey on salmonids. In this presentation, we assess the potential for these species to have played a significant role in declines in Fraser River sockeye salmon abundance.

Killer whale

Three distinct ecotypes of killer whales (*Orcinus orca*) exist in coastal waters of the NE Pacific. Of these, only the so-called 'resident' killer whales, which currently total approximately 350 animals in BC waters, are known to consume salmon. This ecotype can be considered a salmonid specialist, and groups of resident killer whales congregate during summer and fall in specific areas to intercept salmon migrating to natal spawning rivers. Although these congregations are spatially and temporally correlated with the abundance of migrating pink and sockeye salmon, extensive field studies of foraging behaviour of resident killer whales using identification of prey fragments recovered from predation events indicate that these prey species do not represent a significant component of the whales' diet. Instead, the whales forage selectively for Chinook salmon and, to a lesser extent, chum salmon (Fig. 1). There is no evidence that this selectivity has changed in recent years, including 2009. It can thus be concluded that resident killer whales have not played a significant role in declines of Fraser River sockeye.

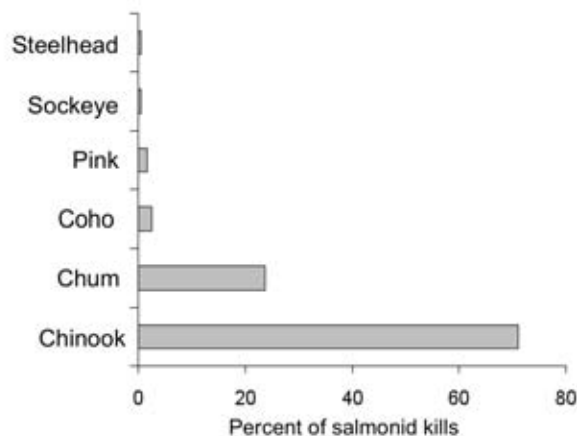


Figure 1. Species composition of salmonids consumed by resident killer whales. N = 806 predation events. (Data from Ford et al. 2010).

Dall's porpoise

Dall's porpoises (*Phocoenoides dalli*) range widely throughout coastal and offshore waters of the North Pacific. Overall abundance in the North Pacific is in excess of 1,000,000 animals; total numbers and abundance trends in Canadian waters are unknown. Dall's porpoises have been documented to feed on sockeye salmon in the NW Pacific and W Bering Sea. Knowledge of the diet of Dall's porpoise in coastal waters of the NE Pacific is based on analyses of prey remains identified in the stomachs of animals collected specifically for diet studies, or from carcasses recovered from strandings or bycatch in net fisheries. Samples from Washington and British Columbia waters examined to date have revealed that Dall's porpoise diet is dominated by small schooling fish such as Pacific herring as well as squid; no samples have contained remains of any salmonid species (Fig. 2). It is possible that Dall's porpoises prey occasionally on out-migrating sockeye smolts, but it is unlikely that they consume returning adults. It can be concluded that Dall's porpoises are unlikely to have had a significant role in Fraser sockeye declines.

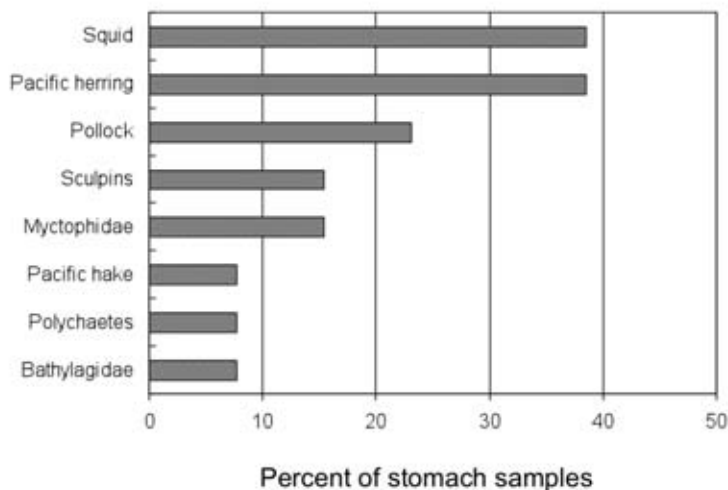


Figure 2. Prey species identified from stomach contents of stranded Dall's porpoises collected from southern British Columbia. N = 13 stomachs. (Unpubl. data, Cetacean Research Program, Pacific Biological Station)

Pacific white-sided dolphin

Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) are found throughout the North Pacific. Estimated abundance is about 1,000,000 animals in the North Pacific, and roughly 25,000 (95% CI 12,900-52,100) in British Columbia waters. This species was seldom seen in nearshore waters of the BC coast prior to the mid 1980s, but became increasingly sighted on the central and north coasts in the late 1980s through early 1990s. Stomach content analysis and identification of prey remains from feeding events indicate that Pacific white-sided dolphins prey on a variety of squid and fish species, including both juvenile and adult salmonids (Fig. 3).

Although sockeye salmon has been identified in the diet of this species, the extent of such predation and thus their potential role in the decline of Fraser sockeye is unknown.

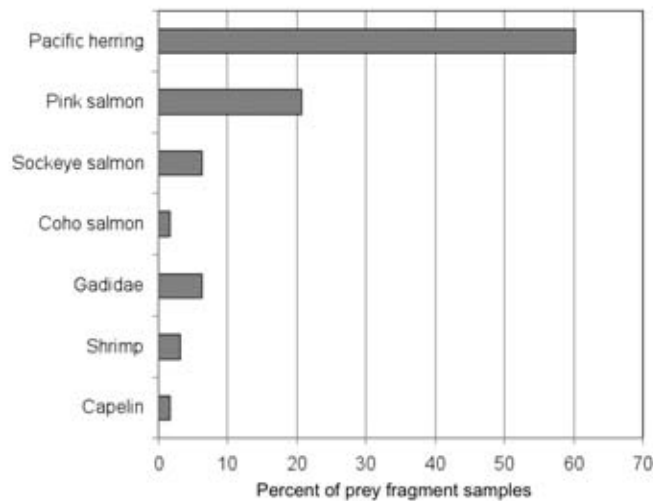


Figure 3. Prey species identified from feeding events sampled from Pacific white-sided dolphins, 1994-95. N = 63 events. (Data from Heise 1997).

Northern fur seal

The northern fur seal is an abundant pinniped in the North Pacific. It breeds on rookeries in the Bering Sea during summer and subadults and adult females migrate to lower latitudes for feeding during fall through spring. It is found mostly in continental shelf and pelagic waters. Abundance in the NE Pacific has declined by approximately 30% over the past 30 years, and is currently about 700,000 animals. Causes of this decline are unknown. Diet of northern fur seals off the west coast of North America was studied during 1958-74 based on prey species identified from stomach contents. In stomachs collected off BC, salmon was the third most common prey type after herring and squid, being identified in 16% of 354 stomach samples. Of the salmonids that were identified to species (13% of samples), all Pacific salmon species except sockeye were consumed. Given the declining abundance of northern fur seals in the NE Pacific and the apparent low predation rates on sockeye salmon, this species is not likely to have played a role in the Fraser sockeye declines.

Steller sea lion

Steller sea lion abundance in British Columbia has increased approximately three-fold since control programs and harvesting ended in the late 1960s. Abundance in recent years has been increasing at 5% per annum and, based on pup production, current abundance in BC and adjacent waters of SE Alaska is approximately 60,000. Steller sea lions range widely in coastal waters but during summer the majority congregate at traditional breeding rookeries, the largest of which are found in the Scott Islands, off Cape St. James, and at Forrester Island just north of the Queen Charlotte Islands. Diet studies using prey remains found in scats collected at these rookeries and other haul-out sites indicate that Steller sea lions feed on a variety of fish and cephalopods, and that salmon constitutes a significant portion of their diet particularly in summer and fall (Fig. 4). Studies are currently underway to develop bioenergetics models to estimate salmon consumption and determine the relative proportions of different salmonid species consumed using DNA

analysis. Until these studies are completed, it is not possible to assess the extent of predation on sockeye salmon and the potential role of Steller sea lions in the Fraser sockeye situation. However, it is reasonable to conclude that given the substantial increase in Steller sea lion abundance over the past 40 years, predation levels by this species have increased generally.

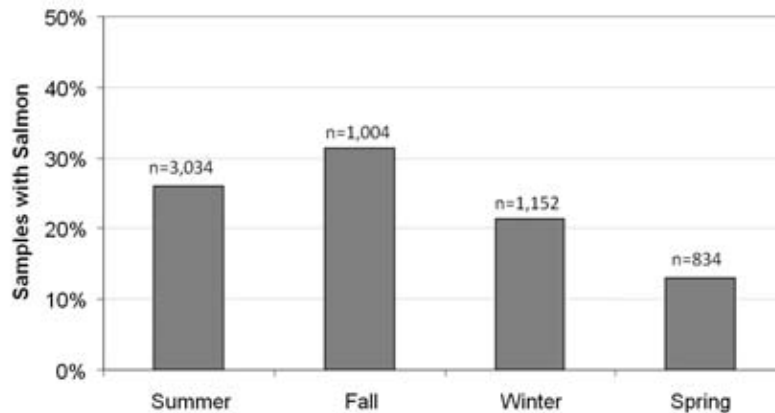


Figure 4. Prevalence of salmon in diet of Steller sea lions by season. Sample sizes are number of scats analyzed. (Unpubl. data, Olesiuk, Jeffries, Lance, Trites, Gearin and Riemer).

California sea lion

California sea lions are present seasonally in waters off southern Vancouver Island and in the Strait of Georgia. Subadult and adult males arrive in the area in fall and depart in spring. Studies have shown that the diet of California sea lions and Steller sea lions during this wintering period is dominated by herring, gadids (hake and pollock) and dogfish, but salmon may represent about 10% of their diet. However, most sea lions arrive in the Strait of Georgia after returning adult sockeye have entered the Fraser River, and most sea lions have departed before out-migrating smolts enter the Strait. Thus, California sea lion predation is not a significant factor in Fraser sockeye declines.

Harbour seal

Harbour seals were severely depleted in BC waters by control programs and harvesting prior to being protected in 1970. Since then, abundance has increased dramatically, especially in the Strait of Georgia where abundance increased at 11.5% per year before stabilizing in the mid 1990s at about 40,000 animals. This trend is typical of the BC coast generally, with current total abundance estimated at 105,000 animals. Extensive scat collections during the 1980s indicated that harbour seals in the Strait of Georgia consumed a wide variety of prey species, but their diet was dominated by herring and hake. Overall, salmonids represented only about 4% of their diet, with salmonid consumption concentrated on pre-spawning adult salmon in estuaries and rivers. Such predation can potentially be a major source of mortality of returning adults in cases where run size is small and habitat modification increases vulnerability to predation. Extensive predation on out-migrating smolts appears to be largely confined to artificial situations (e.g., Puntledge River). Given the stable population abundance of harbour seals over the last 15 years, the apparent shift in distribution away from the Fraser River estuary, and the relatively minor role of salmonids in their diet, harbour seals are unlikely to have had a significant role in recent Fraser sockeye declines.

Conclusions and Research Needs

Of 31 marine mammal species in region, only Steller sea lions and Pacific white-sided dolphins appear to be potentially significant predators of sockeye salmon. Increasing abundance of Steller sea lions has resulted in greater predation rates generally, though impact on sockeye unknown. Potentially increased predation by Steller sea lions may be a contributing factor in long term declines of sockeye, but is unlikely to be an important contributor to the particularly poor returns in 2009. Lack of data on abundance trends and diet of Pacific white-sided dolphins precludes assessment of their potential role in Fraser sockeye declines.

Additional data are needed on current abundance, distribution, and seasonal diets of piscivorous marine mammals throughout coastal waters, especially on proportions of different salmonid species. Diet information should be incorporated into bioenergetic models to estimate consumption rates for each species.

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Sea lice, either naturally occurring or passed from fish farms, are an important contributor to the Fraser sockeye situation

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Introduction

Sea lice are parasitic copepods that feed on superficial fish tissues and occasionally blood of marine fishes. Sea lice undergo development on the fish, moulting through several stages, each becoming larger and potentially more harmful to the fish. The impact of sea lice on individual fish is highly variable and ranges from mild stress, osmotic imbalance due to skin damage, increased susceptibility to other infections, impaired swim performance and in severe cases, death. The likelihood of these outcomes depends on the species, number and developmental stage of the parasite. The outcome also depends on the host fish as some species are more resistant to sea lice than others. Also, smaller fish and those that are compromised, for example by poor water quality or inadequate nutrition, will be at greater risk of the negative effects of sea lice infections.

Two species of sea lice are most commonly reported from salmonids in British Columbia: *Lepeophtheirus salmonis* and *Caligus clemensi*. *Lepeophtheirus salmonis* in British Columbia (B.C.) represents a unique Pacific Ocean type that is genetically distinct from the Atlantic Ocean type¹. In B.C. the salmon louse occurs on all species of marine salmonids and on 3-spine sticklebacks. In contrast, *C. clemensi* is reported from 15 salmonid and non-salmonid fish species and is common on herring. Both louse species also occur on farmed Atlantic salmon in B.C.^{2,3}. On salmon farms, levels of infection are routinely monitored by farm staff and government audit. If the number of adult and preadult stages of *L. salmonis* exceeds a previously established threshold trigger, management actions, such as treatment or harvest are required, as specified by the company's Fish Health Management Plan which is required as a condition of farm licence. There is a concern that amplification of the number of infective *L. salmonis* larvae present in the marine environment during the migration of juvenile salmon, caused by infections on farmed salmon, has increased the risk of mortality among juvenile Pacific salmon.

Direct evidence related to the hypothesis linking sea lice with the abundance of sockeye salmon can be organised into:

1. occurrence of sea lice infections on sockeye salmon,
2. effects of sea lice infections on sockeye salmon, and
3. origins or sources of sea lice infections on sockeye salmon.

Occurrence of sea lice infections on sockeye salmon

In 2005, infections with *C. clemensi* were nearly 3-times as abundant as those of *L. salmonis* on juvenile sockeye in the Discovery Passage area of the northern Strait of Georgia⁴. At the same time, the abundance of *C. clemensi* on juvenile pink and chum salmon collected from the same area was approximately half that of *L. salmonis*. The findings for juvenile sockeye appear to have been confirmed in more recent research⁵.

Sea lice infections on juvenile salmon from the southern Gulf Islands were examined in a study conducted in 2008⁶. More than 70% of 219 juvenile salmon (pink, chum, chinook, sockeye) were infected with sea lice with a mean abundance of 2.9 lice per fish. The estimated number of sockeye salmon in the Gulf Islands at the time was relatively low, but sea lice were observed on all three sockeye examined. Overall, the abundance of *C. clemensi* on salmon was nearly 60-times greater than that of *L. salmonis*.

In contrast, infections with *L. salmonis* predominate on sub-adult and adult sockeye in B.C. coastal waters^{7,8,9}.

Effects of sea lice infections on sockeye salmon

The impact of *L. salmonis* on adult sockeye salmon returning to spawn in the Sproat and Stamp Rivers on Vancouver Island has been reported¹⁰. Low river water levels resulted in high densities of fish that were unable to enter freshwater and forced to remain in warm, poorly oxygenated seawater. Virtually all salmon were infected with an average of 300 *L. salmonis* per fish. The parasites caused severe skin ulcerations resulting in the exposure of underlying muscle in 87% of the fish. There are no studies on the impacts of sea lice to juvenile sockeye salmon.

Origins of sea lice infections on juvenile sockeye salmon

Sea lice larvae spend several days within the plankton before they become infective. Therefore spatial distributions of sea lice infections result from proximity to and magnitude of a source of infection combined with hydrodynamic dispersal. The rate of larval development is governed by water temperature and larval survival depends on salinity. There are two areas of relative dense salmon aquaculture in coastal B.C., the Broughton Archipelago and the Discovery Passage areas. Characteristics of water flow have been modeled in the former¹¹ but not in the latter area.

Caligus clemensi has a wide range of natural hosts¹². Approximately 95% of 62 herring collected from the Gulf Islands⁶ were infected with *C. clemensi* at an abundance of 4.6 lice per fish. The results of sea lice monitoring on farmed salmon are posted on the BC Ministry of Agriculture and Lands web site (http://www.al.gov.bc.ca/ahc/fish_health/sealice_monitoring_results.htm). On farmed salmon, the overall abundance of *C. clemensi* tended to be lower in year-class 2 compared with year-class 1 salmon (Fig. 1). In year-class 1 salmon, the abundance of *C. clemensi* displayed a pattern of interannual variation, being higher overall in 2005, 2007 and 2009. In year-class 2 salmon, the abundance was elevated in 2007. The abundance of *C. clemensi* is higher on farmed salmon from the Discovery Passage area compared with the Broughton Archipelago.

The abundance of adult female *L. salmonis* in year-class 1 and 2 farmed salmon in Fish Health subzone 3-2 (Campbell River-Discovery Passage) are shown (Fig. 1). The number of adult females is an estimate of the *L. salmonis* reproductive potential. Salmon production data were not available and a change in production between 2004 and 2009 would influence the accuracy of the estimated reproductive output of *L. salmonis*. Abundance data are shown for April, May and June, coinciding with data available for *L. salmonis* infections on juvenile sockeye salmon in the area⁴. Abundance tended to be lower in year-class 1 salmon and in both year classes, with the exception of April 2005 for year-class 2 salmon, remained at or below 1 louse per fish. The abundances of adult females in 2007, the ocean entry year for Fraser River sockeye returning in 2009, appeared equal to or lower than in adjacent years.

Other sources of information provide indirect evidence that inform this hypothesis:

1. Infections on wild pink and chum salmon in another area of salmon aquaculture,
2. Effects of *L. salmonis* on juvenile pink salmon.

Infections on wild pink and chum salmon in another area of salmon aquaculture

Lepeophtheirus salmonis infection on juvenile pink and chum salmon in the Broughton Archipelago have declined since 2004 (Fig. 2)¹³. Only the smallest (<0.7g) pink salmon were shown in controlled laboratory experiments^{14,15} to be at risk of mortality and other consequences of *L. salmonis* infection. When this threshold was applied to infection levels on wild pink salmon, no fish were found to be at risk of sea lice associated mortality in 2008¹³ and 2009. During this time, approximately 20,000 tonnes of farmed salmon were produced in the area but anecdotal evidence indicates that coordinated management actions near juvenile pink salmon migratory routes reduced the reproductive potential of *L. salmonis*. The risk of farmed salmon as

a source of *L. salmonis* remained non-zero when the Fish Health subzone as a whole was considered (Fig. 3).

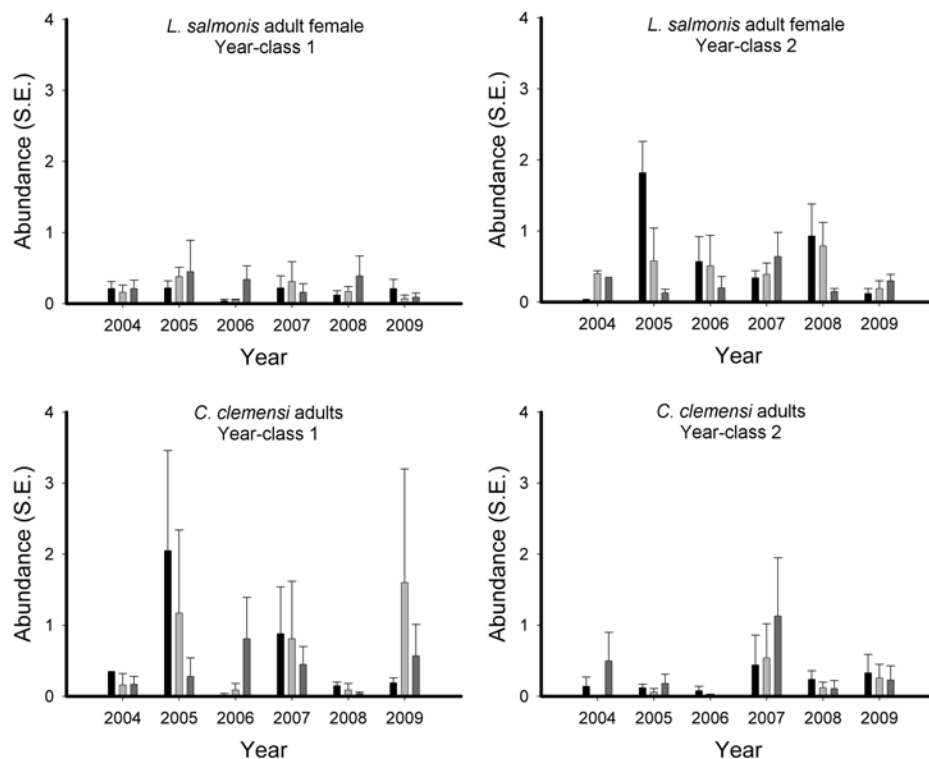


Figure 1. Mean abundance (S.E.) of adult female *L. salmonis* and adult *C. clemensi* on farmed Atlantic salmon in Fish Health Zone 3-2 (Discovery Passage), based on data at the BCMAL web-site. Within each year bars are April, May and June. (http://www.al.gov.bc.ca/ahc/fish_health/sealice_monitoring_results.htm).

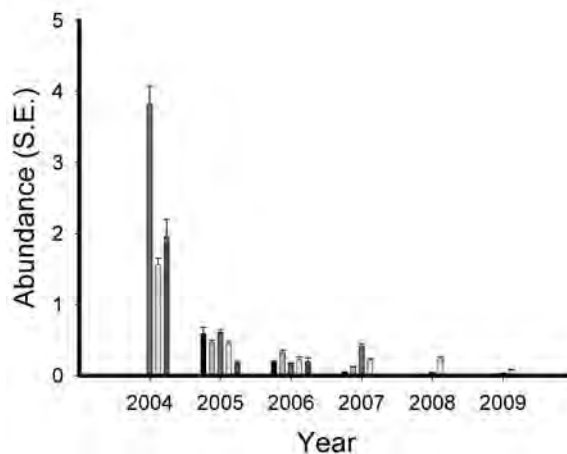


Figure 2. Mean abundance of *L. salmonis* on juvenile pink salmon in the Broughton Archipelago between 2004 and 2009. Within each year, bars are March, April, May, June and July (no samples in March or April in 2004 or in July in 2007, 2008 and 2009).

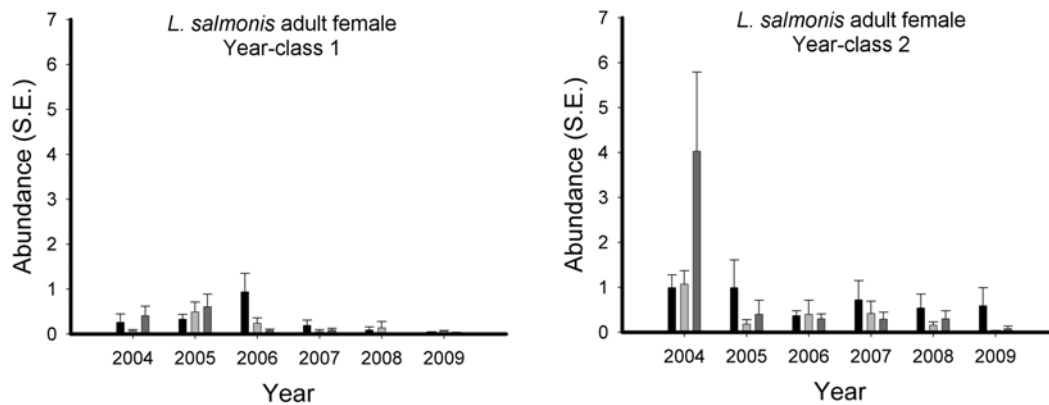


Figure 3. Mean abundance (S.E.) of adult female *L. salmonis* on farmed Atlantic salmon in Fish Health Zone 3-3 (Broughton Archipelago), based on data at the BCMAL web-site. Within each year bars are March, April and May (http://www.al.gov.bc.ca/ahc/fish_health/sealice_monitoring_results.htm).

Conclusions

Infections with the sea lice species *Lepeophtheirus salmonis* and *Caligus clemensi* have been observed on juvenile sockeye salmon. There are no multi-year datasets and the effects of these infections on individual juvenile sockeye salmon or their populations are not known.

Lepeophtheirus salmonis is a pathogen of adult sockeye salmon under adverse environmental conditions. Small size (<0.7g) is an important determinant of susceptibility to salmon lice in juvenile pink salmon. Juvenile sockeye salmon are more than 10-times heavier than juvenile pink salmon when they enter the ocean and the larger size may confer increased resistance to *L. salmonis* in the sockeye salmon smolt.

The evidence indicates that *C. clemensi* is the most abundant sea louse on salmonids and other species in the Strait of Georgia. Herring are a source of *C. clemensi* in the Gulf Islands and possibly throughout the Strait of Georgia. In contrast, farmed Atlantic salmon are a source of *L. salmonis* larvae in the Discovery Islands area.

The number of infective sea lice larvae to which a fish is exposed will depend on the magnitude of the source of viable larvae and the capacity of the environment to disperse and sustain these larvae during their development. There is not enough information to predict the distribution and fate of farm- or natural-sourced *L. salmonis* or *C. clemensi* larvae in the Discovery Passage area.

There is insufficient evidence to conclude that sea lice, whether from natural or farmed sources, are an important contributor to the Fraser sockeye situation. It is highly likely that any effects of sea lice on juvenile sockeye will be the result of multiple factors, including other infections, nutritional or other environmental stressors to which the fish are exposed. To adequately address this hypothesis will require a coordinated, multi-year research effort that involves the monitoring and assessment of sea lice and other potential pathogens on juvenile sockeye in the Strait of Georgia. This effort should also collect information from herring and marine 3-spine stickleback populations, also implicated in the ecology of sea lice in B.C., as well as from farmed salmon. Furthermore, controlled laboratory experiments will help elucidate harmful sea louse infection thresholds on juvenile sockeye salmon.

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Hypothesis: Salmon farm-origin pathogens as a dominant driver in Fraser sockeye declining productivity

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Introduction

Assessing impact of salmon farm-origin pathogens on individual Fraser sockeye stock productivity is not possible, because site-specific salmon farm disease information is rarely available. The simple presence/absence of a salmon farm does not provide information on presence of elevated bacterial, viral or parasite organisms as it could be empty, or stocked with uninfected fish. However, the temporal and geographic correlation between declining productivity in Fraser sockeye and farm salmon IHN outbreaks deserves immediate and very close scrutiny.

Salmon farm-origin pathogens will have both direct and indirect impact on both adult and juvenile sockeye. Bacterial and viral amplification can impact both juvenile and adult Fraser sockeye and sea lice amplification can primarily impact juvenile salmon. Farm salmon –origin pathogen stressors are likely increasing as the industry’s production has been generally growing annually <http://www.dfo-mpo.gc.ca/aquaculture/stats/stats-eng.htm>. In the Broughton Archipelago, sea lice were not a visible problem to wild salmon at the lower farm salmon stocking levels (pers. obs.) It is probable that farm salmon pathogens remain inconsequential to wild populations until a certain stocking threshold is reached.

Sea Lice

Salmon farm-origin sea lice impact juvenile wild salmon directly and indirectly causing mortality and increased high-risk behavior (Krkosek et al. 2008, Mages, 2008, Morton et al. 2005). Salmon farmers can reduce sea lice with drug treatment, but this is not always effective. Drug resistant sea lice are a growing global problem resulting in increasing drug use. Sea lice abundance on juvenile wild salmon increases with the age of the adjacent farm salmon (Morton et al 2004). Prevalence of sea lice on juvenile salmon is very low where there are no salmon farms and when the salmon farms are empty (Morton et al. 2004; Morton et al. 2005). There are two species of sea lice of concern and both occur on the farmed and wild salmon, but due to their size difference they may not represent equal consequence to juvenile wild salmon. The size at which young wild salmon become infected is critical to their survival (Jones et al. 2008). The smaller louse *C. clemensi* demonstrates an affinity for juvenile sockeye, but its generalist ability makes it more difficult to track to source. *C. clemensi* jumps more readily between hosts, thus could be a more effective disease vector.

The debate over the source of sea lice on BC’s juvenile wild salmon stems from different methods of analysis. When sea lice infestation rates are clumped over geographic areas of dissimilar habitat, they appear correlated with increasing salinity (Jones and Hargreaves, 2007). When the same infestation rates are broken down by lice age-classes at point intervals passing salmon farms the most juvenile stages of lice on wild salmon

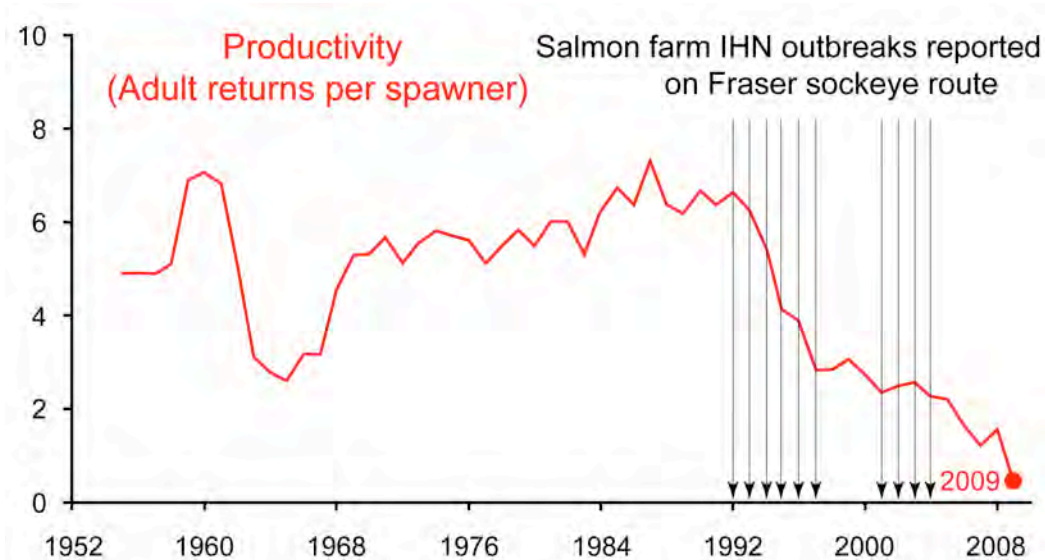
consistently peak near stocked salmon farms (Krkosek et al. 2006). This pattern is not evident in absence of farm salmon (Morton et al. 2005).

Juvenile sockeye in the Fraser migratory corridor are infected with sea lice in a pattern correlated with salmon farms (Morton et al. 2008). Due to the range of variables involved, including drug treatment/efficacy, age of farm salmon, stocking density and fallowing and the difficulty in harmonizing different companies with 70 salmon farm sites from Campbell River past Port Hardy, an on/off test of farm-origin sea lice is logistically impossible. The only clear test would be repeat of the Provincial Pink Salmon Action Plan applied in the Broughton Archipelago in 2003 wherein the majority of farm salmon were removed from the primary migration route. This resulted in a clear decline in sea lice and positive response by the local pink salmon populations (Morton et al. 2005; Beamish et al. 2006).

Disease

While BC salmon farm site disease information is only sporadically available, disease transfer from farm to wild populations has been well documented. Johnsen and Jensen (1994) report spread of disease from farm salmon to wild salmon in 74 rivers over 7 years. Needham (1994) reported furunculosis spreading farm to farm in BC. Jarp et al. (1993) report salmon farms are a disease risk to hatcheries. The BC Ministry of Agriculture and Lands website reports several types of infectious diseases in salmon farms every year since reporting began in 2003. Of interest, a series of IHNV (Infectious Hematopoietic Necrosis virus) outbreaks was first reported in salmon farms in 1992 at the onset of the sustained Fraser sockeye decline and correlates closely with the continued Fraser sockeye decline.

These outbreaks consistently correlate closely with overall Fraser sockeye productivity decline.



1992 – 1994 - 13 sites within 20 km on Fraser migration route (St-Hilaire et al. 2002).
1995 - Campbell River http://www.al.gov.bc.ca/ahc/fish_health/IHNV.htm
1996 - Campbell River http://www.al.gov.bc.ca/ahc/fish_health/IHNV.htm
1997 - Campbell River http://www.al.gov.bc.ca/ahc/fish_health/IHNV.htm
2001-2003 –36 sites Clayoquot and Johnstone St. through Klemtu (Saksida 2006)

Only the Fraser sockeye stocks that migrate through the narrow passages where salmon farms are sited are in decline. The Fraser Harrison stock, which do not appear to migrate through the salmon farming regions off eastern Vancouver Island (Tucker et al. 2009) are increasing. Salmon farm-origin pathogens can turn on and off independent of other farm sites and this could explain the different timing of onset of decline among the Fraser stocks. Individual stock cohorts may have avoided farm-disease exposure in some years due to their route through the myriad watercourses of the Discovery Islands.

Fraser sockeye that pass through a disease outbreak could become carriers and expose other stocks further north, such as Skeen and Rivers Inlet.

Of additional concern is blood-water release from farm salmon processing plants off eastern Vancouver Island. A sample taken from this pipe near Campbell River contained blood, live sea lice eggs and tissue (March 2010). It would seem probable this effluent also carries bacteria and viruses. At 90' the blood appears black in this photo.



In Summary

The effect of salmon farm-origin pathogens has increased since the 1990s as farm salmon production increases. The presence of salmon farms alone is not the stressor, it is the combination of pathogen outbreaks, age of the livestock and siting. The dynamic of endemic pathogen amplification and release has been well studied in sea lice and would also apply to bacteria and viruses. The alarming correlation between declining Fraser sockeye productivity and exposure to IHN in salmon farms must be further studied to fully evaluate the why Fraser sockeye are in decline. VHS, BKD, Furunculosis and Vibrio are also of concern, as well as, the potential for ISA to arrive in egg shipments from the Atlantic region.

The hypothesis that farm salmon pathogens are the primary driver for the Fraser sockeye decline can be tested:

1. Remove all farm salmon from the migratory path of the Fraser sockeye and test every other salmon farm rigorously for disease. This would also serve to relieve this pressure on the Fraser sockeye.
2. Use complete farm salmon disease and stocking records (BC Salmon Farmers Association) to compare occurrence of specific farm pathogens with specific Fraser sockeye stock productivity trends. Also test for spatial and temporal relationships between farm salmon and enhancement salmon pathogens.

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Session A: Predators, parasites, and disease; Kristi Miller, DFO

Kristi Miller declined to have her document included in this report

Hypothesis: Diseases in freshwater and marine systems are an important contributor to the Fraser sockeye situation

Kyle Garver

Fisheries and Oceans Canada

Pacific Biological Station

June 2010

A pathogen can be defined as an agent (e.g. virus, bacterium, fungi or parasite) that has the potential to cause disease. Whereas, disease refers to a pathological condition, that has characteristic signs, that can result from various causes including infection with pathogens. For the purposes of this discussion it is important to remember that the presence of a pathogen doesn't always mean that a disease condition exists. The factors that lead to the development of disease due to a pathogen are outlined in more detail below.

Infectious diseases are recognized as being a dominant selective force in influencing human populations; however, the role that disease plays in wildlife populations is much less understood. In fact there are relatively few examples that have demonstrated a role for infectious disease in the structuring of terrestrial and aquatic animal populations. With respect to fish, studies examining *Schistocephalus solidus* in three-spined stickleback, and viral hemorrhagic septicemia virus and *Ichthyophonus hoferi* in Pacific herring have documented population level impacts (Pennycuik 1971, Marty et al. 2010).

A diverse range of pathogens including viruses, bacteria, fungi and parasites have been shown to infect sockeye salmon. Some common pathogens of sockeye salmon are listed in Table 1. This table is not a comprehensive list of all infectious agents of sockeye salmon as more than 50 other pathogens, whose pathogenicity is not well known, have been reported from sockeye salmon in British Columbia.

Table 1. Common pathogens of sockeye salmon. Pathogens detected in the Fraser River are highlighted in green.

	Pathogen	Disease
Bacteria	<i>Renibacterium salmoninarum</i>	Bacterial Kidney Disease (BKD)
	<i>Aeromonas salmonicida</i>	Furunculosis
	<i>Yersinia ruckeri</i>	Enteric Redmouth Disease (ERM)
	<i>Flavobacterium branchiophila</i>	Bacterial Gill Disease (BGD)
	<i>Vibrio Spp.</i>	Vibriosis
	<i>Pseudomonas Spp.</i>	
	<i>Flexibacter</i>	Columnaris disease
Viruses	Infectious hematopoietic necrosis virus	Infectious hematopoietic necrosis (IHN)
	Erythrocytic necrosis virus	Erythrocytic necrosis (ENV)
	Salmonid herpesvirus	
Parasites	<i>Parvicapsula minibicornis</i>	
	<i>Ichthyophthirius multifiliis</i>	Ich or white spot disease
	<i>Loma salmonae</i>	

	<i>Eubothrium salvelini</i>	
	<i>Myxobolus articus</i>	
	<i>Tetracapsula bryosalmonae</i>	Proliferative kidney disease (PKX)
	<i>Lepeophtheirus salmonis</i>	
	<i>Caligus clemensi</i>	
	<i>Cryptobia salmositica</i>	
	<i>Kudoa thyrsites</i>	
	<i>Myxobolus cerebralis</i>	
Fungus	<i>Ichthyophonus hoferi</i>	
	<i>Phoma herbarum</i>	

As mentioned previously the presence of a pathogen in a sockeye salmon does not necessarily equate to disease or compromised health conditions. The determinants of disease are multifactorial and whether a sockeye salmon becomes diseased depends upon complex interactions between the host, the pathogen, and the environment in which these interactions take place. Due to this complexity, it is extremely difficult to predict occurrence and severity of disease and what if any role disease plays in structuring Fraser River sockeye populations.

Based on our knowledge of infectious diseases of fish, potential impacts on Fraser sockeye salmon populations can occur directly through mortality of individuals or indirectly through changes in various performance parameters including, but not limited to, swimming ability, growth, osmocompetence and reproduction. However, quantification of these disease impacts in wild fish can be difficult. Often fish mortality due to disease can go unnoticed or underestimated due to the difficulties in finding and recovering carcasses. Additionally, if the impact is indirect then the roles of numerous factors may be difficult to tease apart (i.e. infectious disease increases susceptibility to predation due to reduced swimming performance). The impacts of infectious disease can be difficult to assess because for many pathogens the relationship between ‘infection’ and ‘disease’ is unknown. Thus predicting a disease consequence based only on the observation of a pathogen is rarely possible.

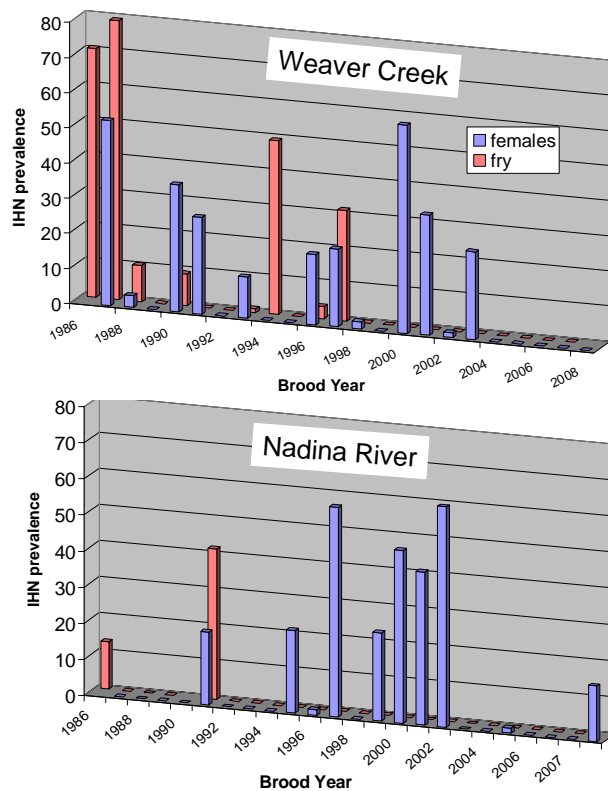
To understand and predict the role of infectious diseases in Fraser Rive sockeye population dynamics requires:

1. Long term data on the prevalence and abundance of pathogens within the various populations of sockeye throughout their life cycle.
2. For each pathogen, an understanding what conditions trigger the development of disease (e.g. pathogen load, poor environmental conditions etc.)
3. For each disease, the mortality rate and non-lethal effects of the disease in fish of various ages and under various environmental conditions.

Unfortunately much of this information does not exist for most salmonids including Fraser River sockeye.

There are three pathogens of Fraser River sockeye for which we have some data regarding prevalence and disease occurrence in various populations. This allows a limited assessment of their impact to be conducted. This report will discuss these

Figure 1. Graphs showing annual prevalence of IHNV positive spawning females (in blue) and fry (in red) sockeye salmon in Weaver Creek and Nadina River spawning channels from 1986-2009.



pathogens; infectious hematopoietic necrosis virus, *Ichthyophthirius multifiliis*, and *Parvicapsula minibicornis*, and their impact on Fraser River sockeye.

Infectious hematopoietic necrosis virus (IHNV) is an aquatic rhabdovirus that is enzootic (constantly present) in sockeye salmon populations in the Pacific Northwest of North America. The virus infects all life stages of sockeye salmon, however IHN disease is predominantly observed in fry while adult spawning sockeye although carriers of virus remain asymptomatic. Mass mortality events due to IHN disease have been reported in two lower Fraser River sockeye stocks. The first IHNV mortality event

occurred in the spring of 1973 at Chilko Lake and resulted in an estimated loss of 23.7 million fry. Subsequently, in 1987 an IHNV epizootic occurred at Weaver Creek spawning channel resulting in nearly 50% mortality (8.3 million fry died out of a total 16.8 million) of all migrating fry within days of leaving the spawning channel. Despite these significant impacts incurred in Fraser sockeye fry due to IHN disease, long-term monitoring of Nadina River and Weaver Creek spawning channels has revealed that over a 24 year period (1986-2009), IHNV prevalence varies annually within the same sockeye stock and is inconsistent between stocks (Figure 1). There is no correlation with IHNV prevalence in adults and the occurrence in fry. Additionally, the data set illustrates that the occurrence of IHN disease outbreaks in fry have not increased over the 24 year monitoring period for either Weaver Creek or Nadina River stocks (Figure 1). Our inability to detect IHNV in sockeye salmon fry from Weaver Creek and Nadina River over the past 10 (1998-2007) and 16 (1992-2007) years; respectively, suggests that IHNV is not a major contributor to the long-term decline of these two stocks.

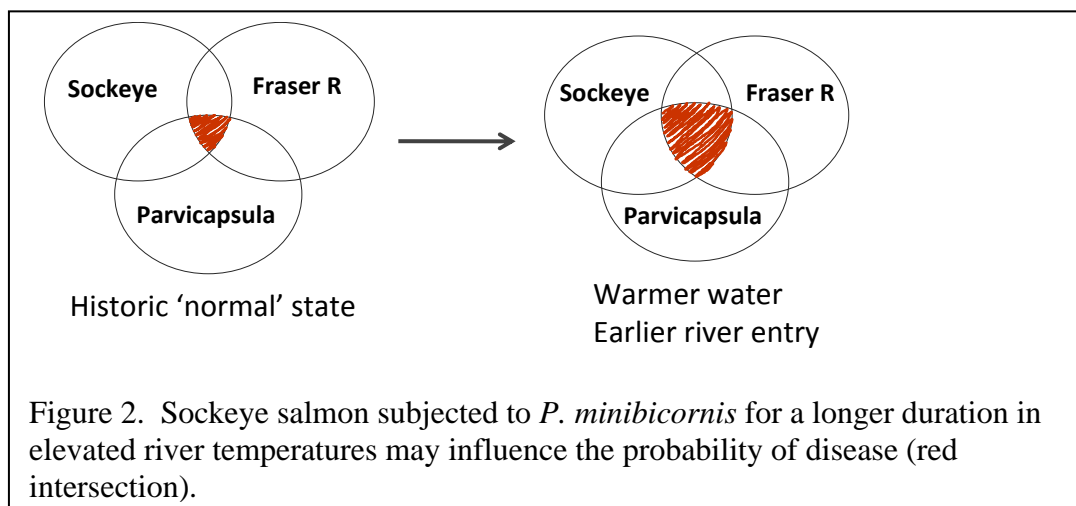
Ichthyophthirius multifiliis (ICH) is a naturally occurring freshwater ciliate protozoan that causes a disease commonly referred to as “ich” or “white spot disease”. The pathogen typically does not cause disease in sockeye salmon. However, if conditions such as warm

water, reduced flows, and adult crowding exist then disease can occur due the development of high numbers of this pathogen. Such disease events have been documented in Fraser and Skeena River sockeye salmon and have resulted in severe pre-spawn mortalities of up to 80% (Table 2). However, as with IHN disease, ICH disease prevalence has been inconsistent and varies between stocks. Additionally, the frequency of ICH epizootic disease events at Weaver Creek and Nadina River have not increased since 1990, suggesting that ICH disease is not a major factor contributing to the long term decline of these two stocks.

Table 2. Years in which *Ichthyophthirius multifiliis* was associated with elevated pre-spawning mortality at various sockeye spawning channels

Watershed	Spawning Channel	Year of epizootic	Pre-spawning losses
Fraser River	Weaver Creek	1995	30%
	Nadina River	1978, 1987, 1995, 2008	25-70%
Skeena River	Fulton River	1994, 1995, 1997, 2000, 2001, 2009	35-80%

Parvicapsula minibicornis is a myxozoan parasite that is enzootic in Fraser River sockeye stocks. Surveys for the parasite has revealed that transmission occurs at or near the river estuary and that adults and juvenile salmon become infected with the parasite as they migrate through this area. In adult salmon, the prevalence and severity of infection is affected by time and temperature, such that migrating sockeye holding in the river under elevated river temperatures are at higher risk of more severe infections (Figure 2). Severe *P. minibicornis* infections may interfere with renal osmoregulatory function and



increase the probability of pre-spawning mortality. However, assigning a clear negative impact due to this parasite is difficult, as severe *P. minibicornis* infections are also

evident in successfully spawning fish. There are no data on the severity of infection of juvenile sockeye in marine waters with *Parvicapsula*. In the absence of information regarding the relationship between *Parvicapsula* infection and disease in sockeye salmon, its contribution to migratory behaviour and/or high mortality remains unknown. Additionally, the lack of historical *P. minibicornis* infection data makes it difficult to understand the significance of present day observations.

In summary, pathogens are a natural component of all ecosystems and not all infections lead to disease. Often enzootic pathogens are 'well-adapted' in that they do little to harm their host, however, the incidence and severity of disease from such pathogens may increase if abnormal conditions and/or adverse factors ("stressors") occur. Epizootic disease events caused by IHNV and ICH have resulted in sporadic and significant mortality events in populations of Fraser River sockeye populations in that millions of fish suffered mortality. Long term monitoring, since 1986, of IHNV and ICH in Weaver Creek and Nadina River sockeye has indicated that no increase in the prevalence of IHN or white spot disease in these populations. Our data suggests that neither IHNV nor ICH are solely responsible for the long-term declines of these stocks.

It should be noted that only very limited information is available concerning the numerous other enzootic pathogens listed in Table 1. It is therefore not possible to comment on any potential effect of these on Fraser River sockeye salmon. To ascertain disease impacts of enzootic pathogens, it is necessary to study their long-term effect on growth, reproduction and survival of sockeye salmon. Currently, there is insufficient fish health data to predict what, if any, role disease has played in the long-term decline of Fraser River sockeye.

Research efforts aimed at determining the prevalence and abundance of pathogens, through comprehensive health assessments for multiple Fraser River sockeye stocks, are required. Additionally, health assessments need to investigate multiple sockeye salmon life-stages, in particular the marine phase. Research is also required to better understand the relationship between infection and disease, especially the role of unfavorable environmental conditions in influencing disease occurrence. Lastly, disease impacts need to be incorporated into fisheries models.

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Session B: Toxic algae and pollutants; Jack Rensel, Rensel Associates

Fraser River Sockeye Salmon Marine Survival Decline and Harmful Blooms of *Heterosigma akashiwo*

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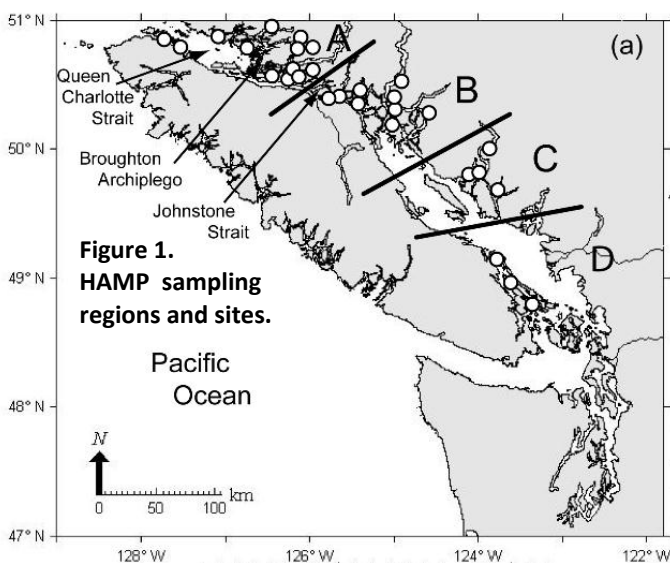
Abstract: A two-decade decline of Fraser River sockeye salmon, historically the most valuable west coast Canadian and United States salmon fishery, was correlated with blooms of the harmful raphidophyte flagellate *Heterosigma akashiwo* in the Southern Strait of Georgia (herein, the Strait). The alga has occurred for several decades in British Columbia and adjacent marine waters but since 1989, large-scale blooms have caused severe mortality of farmed fish and some observed wild fish mortality throughout the region. Marine survival of Chilko stock Fraser River sockeye salmon averaged 2.7% in years when their seawater entry coincided with major *Heterosigma* blooms vs. 10.9% in the same timing in years when no bloom or only minor-blooms occurred. Separate evidence that juvenile sockeye salmon marine mortality occurs in the Strait was found by comparing young of the year herring survey catch to marine survival of Chilko stock. This yielded a highly significant correlation ($r = 0.90$, $p = 0.0001$) from 1997 through 2007. *Heterosigma* blooms that annually began in late June or later have in recent years commenced earlier, as early as late May or early June, coinciding more completely with juvenile sockeye salmon migration in the Strait. Fraser River discharge was significantly larger and earlier in major bloom years compared to minor or non-bloom years and appears to be a primary forcing factor. *Heterosigma* is among the most versatile and allelopathic harmful algal bloom species and may adversely affect sockeye salmon through acute or chronic toxicity, food web and prey impoverishment, or a combination of these factors.

Introduction: The most significant fish-killing harmful algal bloom (HAB) species in coastal waters of the Pacific Northwest, i.e., British Columbia (B.C.) and Washington State, is the golden brown, raphidophyte flagellate *Heterosigma akashiwo* (Hada) Sournia (herein, *Heterosigma*). In addition to farmed fish kills, observations of dead wild salmonids in shallow inlets of South Puget Sound or along beaches of deeper areas of North Puget Sound coincided with every observed, major *Heterosigma* bloom since 1989. Recurring wild fish kills have also occurred in bays and coastal areas of North Carolina, Georgia, Delaware, and Texas (see review in Rensel et al. in press). *Heterosigma* has been termed the most versatile and allelopathic harmful algal bloom species for many reasons including its antagonistic effects on organisms with sizes ranging from bacteria to fish (Smayda 1998, 2006) and its ability to rapidly vertically migrate (Hershberger et al., 1997a; Bearon et al., 2004). *Heterosigma* is euryhaline, growing at 5 psu salinity but significantly faster at 10 psu or above, depending on strain, as determined with four different Puget Sound strains (Fredrickson et al., in press). Etiology of fish mortality from *Heterosigma* exposure is uncertain and possibly variable but is thought to involve gill damage and respiratory failure caused by algal production of reactive oxygen species (ROS), including hydrogen peroxide, hydroxyl free and superoxide radicals (Oda et al., 1997). It is also possible that different clones or strains of *Heterosigma* have different toxin-producing capabilities that may be expressed in different locations and times. For example, brevetoxins have been found in some Japanese strains. Salmonid fishes including chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), and chum salmon (*O. keta*), rainbow trout (*O. mykiss*) and Atlantic (*Salmo salar*) salmon are all susceptible to the alga with varying survival rates in different blooms (e.g., Hershberger et al., 1997b; Pacific Biological Station, 1999; Anderson et al., 2001). Sockeye salmon (*O. nerka*) may be at enhanced risk of gill injury or other adverse effects from harmful algae as they have numerous and closely spaced gill rakers used to strain the water for plankton. Other salmonids including those reared in B.C. fish farms (Atlantic and chinook salmon), have fewer and more widely-spaced gill rakers.

Taylor and Haigh (1993) note that vegetative *Heterosigma* cells have regularly appeared in late spring in English Bay, Vancouver, B.C. since 1967 when phytoplankton surveys were first initiated, several years before commercial aquaculture net pens were used in Salish Sea waters (i.e., Strait of Georgia north through Queen Charlotte Strait, Strait of Juan de Fuca and Puget Sound). A few large and persistent blooms were documented in

Departure Bay and the Strait of Georgia in the 1990s as HABs and effects on aquaculture was a research priority at that time (Pacific Biological Station, 1999). Large but relatively brief *Heterosigma* blooms in Puget Sound commenced in 1989. There were multiple year gaps with no major blooms in Puget Sound (Rensel, 2007), which contrasts with frequent and extended major blooms in B.C. waters in the post 1989 era. Routine recording of cell density throughout B.C. waters began in 1999 with the initiation of the Harmful Algae Monitoring Program (herein HAMP, the primary data source for this paper). Fraser River sockeye salmon abundance began to decline after peaking in the late 1980s, coinciding with commencement of major, basin-wide, Salish Sea *Heterosigma* blooms. Here we combine HAMP and Pacific Biological Station (1999) *Heterosigma* density/timing data with observations from Puget Sound and compare to annual marine survival of Fraser River sockeye salmon in the post 1989 period.

Methods: HAMP database regions include, from north to south: (A) Broughton Archipelago and Queen Charlotte Strait, (B) Johnstone Strait and Quadra Island areas, (C) Sechelt and Jervis Inlets and (D) Southern Strait (Fig. 1). Region D was sampled along western nearshore waters from Departure Bay to Salt Spring Island, in one of several known juvenile sockeye salmon migration pathways. Water bottle samples from 1, 5 and 10 meters depth were preserved with Lugol's iodine solution. All HAB species were enumerated using a Sedgwick-Rafter counting slide and a standard transmitted light microscope by N. Haigh, who has managed the HAMP program since its initiation in 1999. *Heterosigma* cell counts are ranked by density as follows: 0 = no cells, 1 = low number of cells (i.e., not bloom levels, 0 to 10 cells/ml), 2 = moderate numbers of cells (possible to certain blooms, 11 to 999 cells/ml) and 3 = large numbers of cells (blooms of >1,000 cells/ml). The concentration of cells causing salmon mortality is uncertain but is thought to occur in the level 2 range (e.g., Rensel and Whyte 2003) but is apparently variable. A "bloom index" was constructed by summing different bloom rankings for known sockeye migration periods and regions, only level 2 and 3 rankings were utilized. Data from three annual periods were compiled separately: (1) May through October, (2) mid May through June for juvenile sockeye migration timing, and (3) July and August for adult sockeye migration timing in the Salish Sea. Months were divided into four periods each, herein termed "weeks".



annual marine survival data for Chilko Lake stock sockeye salmon. Marine survival is defined as number of returning adults divided by the number of smolts migrating out of Chilko Lake, where adults are the total age-four adult run that includes the total fishery catch plus the observed spawning escapement plus the estimated freshwater adult en route loss (i.e., fish that entered the river and were estimated in the lower river by hydroacoustic methods but are assumed to have died before spawning). The period of mid-May through the end of June was selected as representative of the time that juvenile fish would be sequentially migrating into and through Regions D and B, from south to north, based on literature (Groot and Cooke, 1987) and advice from Pacific Salmon Commission (PSC, M. Lapointe), with an extra week for lag time to pass through Region A.

For returning adult Chilko stock sockeye, we estimated that the annual migration passes through Regions A, B and D in July and August, based on the literature and PSC unpublished data (M. Lapointe, pers. comm. 2009). Statistical associations, using Pearson's correlations, were tested between the sum of annual bloom index levels 2 and 3 for juvenile and adult migration periods (described above) and the Chilko sockeye marine survival rate estimates. Daily Fraser river discharge during the juvenile migration period was compared using Student-t tests.

Results and Discussion: *Heterosigma* blooms in sampled regions of British Columbia waters were remarkably frequent, particularly during the mid-June through October period. Table 1 illustrates weekly bloom index ranking with black rectangles for juvenile (left) and adult (right) migration timing. Blanks indicate no data.

A. Broughton- Q.C. Strait	MAY			JUNE			JULY			AUGUST			SEPT			OCT								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1999									1	0	1	0	0	0	1	0	1	1	0	0	0	0	0	0
2000		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	1	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	2	0	1	1	1	0	0	0
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0
2003			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	1	
2004				0	0	0	0	0	0	1	0	0	0	0	0	0	1	3	3	1	1			
2005	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2								
2006	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	3	2	2	0	1	0	0	0	0
2007	0	0	0	0	0	0	2	0	2	3	2	3	2	1	1	2	0	0	1	1	1	1	0	
2008	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	2	0	0	0	0	1	0	0	0
2009	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	2	1	1	1	2	2	0	0

B. Johnstone Strait	MAY			JUNE			JULY			AUGUST			SEPT			OCT								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1999									0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
2000		0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	2	2	0	0	0
2001	0	0	0	0	0	0	0	0	0	2	2	0	1	0	1	1	1	1	1	0	0	0	0	0
2002	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	2	0	0	1	0	0	0	0	0
2003			0	0	0	0	1	1	2	2	2	1	0	0	0	0	2	1	0	0	0	2	1	0
2004				0	0	0	2	3	1	1	0	0	0	0	0	0	1	2	2	0	0	0	0	0
2005	0	0	0	0	0	0	2	2	1	0	1	0	0	0	1	0	2	1	0	0	0	0	0	0
2006	0	0	0	0	0	0	2	0	0	0	0	1	2	1	2	0	0	0	2	1	1	1	0	0
2007	0	0	0	0	0	1	0	0	0	0	2	3	2	3	1	1	1	1	1	1	1	0	1	
2008	0	0	0	0	1	0	1	2	2	2	2	1	2	1	2	1	2	2	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	2	2	2	1	2	1	2	1	0	0	0	0	0	0	0	0

C. Sechart & Jervis Inlets	MAY			JUNE			JULY			AUGUST			SEPT			OCT								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1999										0	0	1	2	2	2	1	0	0	0	0	0	0	1	
2000	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	2	2	2	2	1	0	1	0	2	2	0	1	1	0	1	0
2002	0	0	0	0	0	0	0	0	2	2	0	0	0	1	0	0	0	0	0	1	0	1	0	0
2003			0	0	0	2	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	0	0	0	1	0	0	0	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	3	2	0	0	0
2007	0	0	0	0	0	0	0	0	0	2	2	2	2	0	0	0	0	0	2	1	0	0	0	0
2008	0	0	0	0	1	1	2	2	2	1	1	2	1	0	2	2	3	1	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0	1	0

D. South Strait of Georgia	MAY			JUNE			JULY			AUGUST			SEPT			OCT								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1999									3	3	2	3	0	3										
2000																								
2001	0	0	0	0	0	0	0	0	1	2	0	1	1	0	2	1	2	1	1	0	2	0	0	0
2002	0	0	0	0	0	0	2	3	0	2	2	0	1	1	1	1	1	1	0	0	0	0	0	0
2003	0	0	0	0	0	0	2	2	1	1	2	2	1	2	0	0	0	0	0	0	0	0	0	0
2004																								
2005																								
2006							3	3	2	0	1	0	0	0	1	2	0	1	0	0	0	0	0	0
2007	0	0	0	3	2	2	1	0	1	1	2	3	2	0	0	0	0	2	2	1	1	1	0	0
2008	0	0	0	0	1	2	3	1	2	2	2	2	0	0	2	2	1	0	2	0	1	1	1	0
2009							0	0	1	2	0	0	0	0	1	1	2	1	1	1	0	1	0	0

Table 1. Weekly *Heterosigma* bloom rankings for four HAMP sampling regions of British Columbia.

The largest frequency of detection occurred in the South Strait region where 48% of the sampling weeks throughout the May through October period tested positive for *Heterosigma*. Region B, Johnstone Strait averaged 35% cell detection, followed by Regions A and C with 29% and 24% occurrence, respectively (Table 2). For estimated juvenile sockeye migration timing, mean annual level 2+3 bloom index increased from north (Region A) to south (Region D) with 40% of the sampled weeks in Region D, South Strait, for the mid May through June period ranked as bloom levels 2 or 3. When ranked by potentially fish-killing *Heterosigma* bloom levels 2 and 3 during adult sockeye timing, the South Strait was also highest; 30% of the sampled weeks were observed to be bloom levels 2 or 3 followed by 24% occurrence in Region B. These data indicate significantly more frequent occurrence of level 2 and 3 blooms in the South Strait, compared to all other regions for both juvenile and adult timing.

Table 2 <i>Heterosigma</i> percent weekly occurrence, regions A - D, HAMP database, for time periods with no missing data		
Migration Timing, Bloom Levels	Region	Percent Detection
May thru Oct. Bloom Levels 1, 2, 3	A	29%
	B	35%
	C	24%
	D	48%
Juvenile Sockeye Salmon Timing, Bloom Levels 2, 3	A	3%
	B	18%
	C	18%
	D	40%
Adult Sockeye Salmon Timing, Bloom Levels 2, 3	A	13%
	B	24%
	C	15%
	D	30%

Bloom index level 2 and 3 occurrences were summed for each year's estimated juvenile or adult sockeye migration period by region and compared to the Chilko sockeye salmon marine survival rate for relevant smolt seawater entry or adult return years. For juvenile fish, the correlation between South Strait *Heterosigma* bloom index in smolt year and Chilko marine survival rate was -0.83 ($p = 0.04$, $n = 6$). No other regions had significant correlations for juvenile migration periods and all areas were not significant for adult timing. To increase sample size we utilized weekly data from the Pacific Biological Station in the Southern Strait (PBS 1999) in the 1990s. Four-month-long *Heterosigma* blooms were documented in 1993 and 1997 in the Strait and the latter year had May and June data, but not the former. Chilko stock juvenile sockeye salmon entering the sea during these two years produced the two lowest marine survival rates for the 1989-1999 period (2.9% and 2.6%, respectively).

For comparison, marine survival averaged 12.3% during non-bloom or minor bloom years of the same time period. Adding 1997 data to the correlation analysis described above and using only years with no missing juvenile migration weekly data ($n = 5$), the correlation coefficient between “bloom index” and Chilko stock marine survival was -0.88 ($p = 0.05$). Finally, we reconfigured the same data into four bloom levels by splitting bloom level 2 in two levels (11 to 499 cells/ml and 500 to 999 cells/ml) and for complete data years in the Strait found the correlation to improve ($r = -0.91$, $p = 0.03$, $n = 5$).

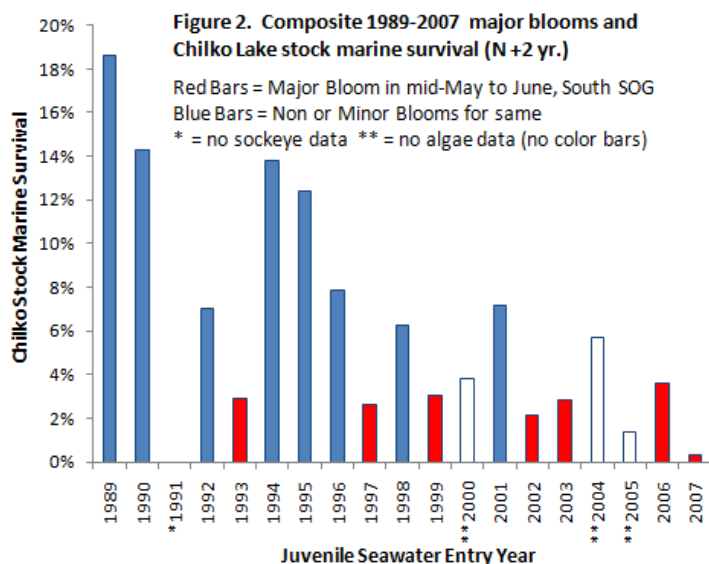
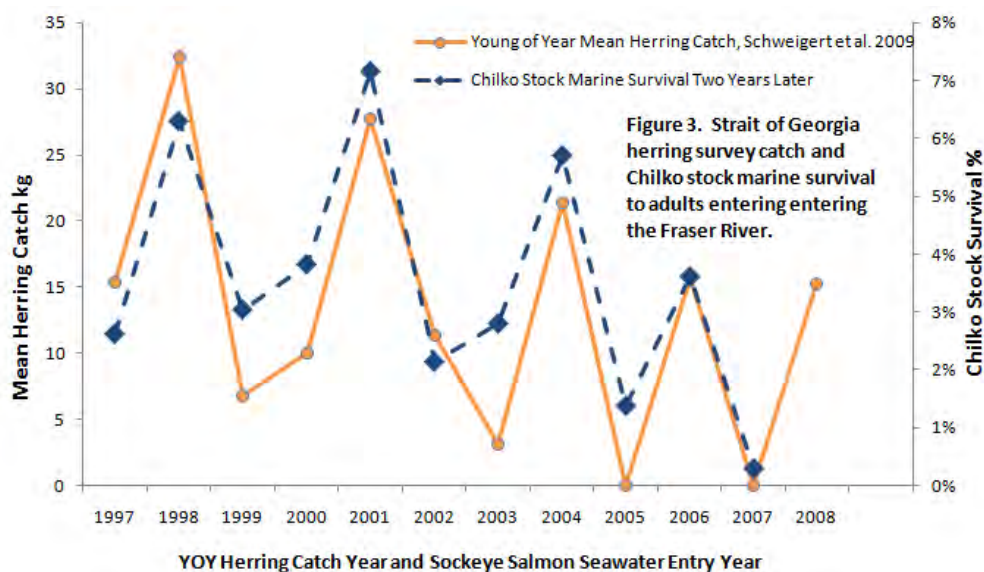


Figure 2 summarizes major blooms in the juvenile sockeye salmon migration period that occurred during the HAMP (1999+) and PBS (1989-1999) observations (Rensel et al. in press). During the 19 year period of 1989-2007 marine survival of Chilko Stock averaged 10.9% in non-bloom or minor bloom years versus 2.7% in years with major blooms during juvenile migration in the Southern Strait. 1989 and 1991 were reportedly major bloom years (Taylor and Haigh, 1993) but no timing or data were reported for the former and no sockeye marine survival data were collected for the latter. Year 2003 was equivocal with regard to bloom status, major or minor.

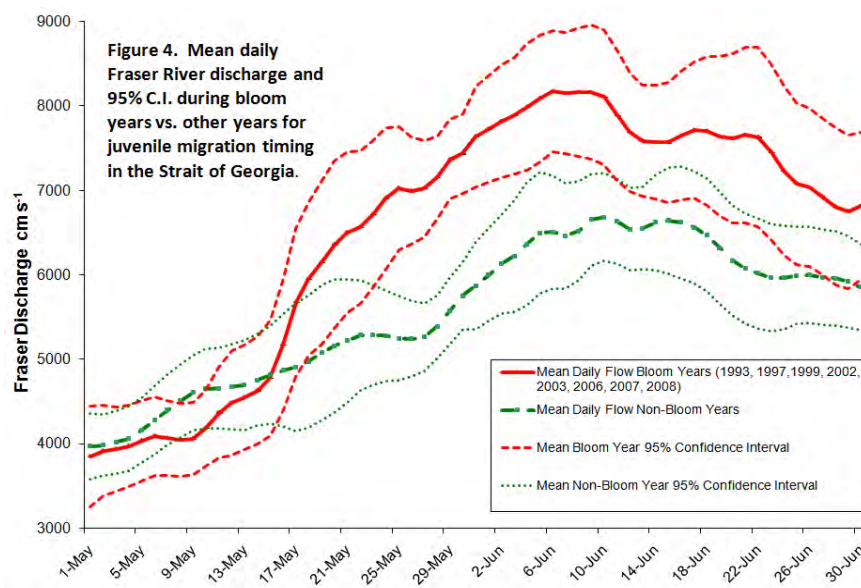
If mortality of sockeye smolts was occurring in the Strait during bloom years, resident fish that inhabit near-surface water may also be expected to be affected concurrently. We examined young of the year (YOY) September herring survey catch data published by Schweigert et al. (2009) extending from 1992 to 2007 (1991 purposely excluded for method differences, 2008 data point provided by J. Schweigert, pers. comm.). Beginning in 1997 and extending through the herring data set to 2007 there was a highly significant correlation between YOY herring catch and Chilko sockeye salmon marine survival ($r = 0.90$, $p = 0.0001$, Fig. 3).



Including earlier years (1992-1994) in the analysis resulted in a non-significant correlation (e.g., $r = 0.26$ for 1992-2007 $p = 0.36$) but using the period 1995-2007 resulted in statistically significance ($r = 0.66$ $p = 0.02$) and

increased to $r = 0.93$ for 1998-2007 period. The reasons for this shifting pattern are not known. During the period of declining productivity of Fraser sockeye salmon (since mid 1990s), these data suggest that marine survival rates are principally determined within the Strait of Georgia and likely within the first six weeks of sockeye seawater rearing. The concept of significant early marine mortality of sockeye salmon is not new (e.g., Furnell and Brett, 1986). However, these data are remarkably strong, supporting the notion that most Chilko stock sockeye salmon mortality occurred in the Strait.

To evaluate effects of varying Fraser River discharge volume on *Heterosigma* blooms during the juvenile sockeye salmon migration period, we plotted river discharge from years of known major blooms versus non-bloom or minor-bloom years in the Strait for the 1989 through 2009 period. Mean and confidence interval discharge plots and a Student's t-test of two data sets indicate significantly greater river discharge ($p < 0.001$) in the May-June period of major *Heterosigma* bloom years versus other years (Fig. 4). These data suggest a probable linkage between May-June *Heterosigma* blooms and larger/earlier than normal peak river discharge.



Based on these results, we suggest that *Heterosigma* is at least partially responsible for acute or chronic toxicity of the sockeye salmon, food web and prey impoverishment, or some combination of these factors in the Strait. Adult sockeye may be affected too, but our data are insufficient to assess this due to differences in migration paths and algal sampling locations. In the past scientists have not investigated wild fish interaction with *Heterosigma*, but assumed that the wild salmon would swim under or around blooms (Taylor and Harrison, 2002) although this was conjecture (P.J. Harrison, pers. comm. 2009). *Heterosigma* blooms do concentrate very near the surface at times, such as in quiescent summer periods during daylight hours that would allow fish to pass underneath. But at other times and locations in B.C. they may be mixed throughout the water column (Gaines and Taylor, 1986) as well as in Puget Sound (Rensel, 2007). Moreover, *Heterosigma* may vertically migrate at night to the shallow (~10m) nutricline, a depth range that corresponds with the reported maximum depth distribution of juvenile sockeye salmon throughout the Strait (Groot and Cooke, 1987). Since moribund and dead salmon sink rather than float and exposure to the alga may induce chronic effects in addition to acute mortality, the losses may easily go undetected over broad areas. Means to further investigate and possibly mitigate blooms of *Heterosigma* in the Salish Sea, a literature review of modes of toxicity, vertical distribution of the sockeye salmon and the alga and related topics are addressed by Rensel, Haigh and Tynan (in press).

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Session B: Toxic algae and pollutants; Robie Macdonald, DFO

Draft discussion paper June 10 2010:

Salmon and Contaminants

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Contaminants are known to have a number of effects on fish including lethality. Although there have historically been clear examples of fish kills, including in BC, the issue of dwindling sockeye returns is highly unlikely to involve such a direct mechanism. Toxic chemicals can induce a wide range of other effects including endocrine disruption, neurotoxicity, olfactory damage, osmoregulation problems, reproductive impairment and loss of immune function (Table 1). These sorts of chemically-induced effects may have no immediate manifestation but ‘kick in’ later when the fish is challenged by another environmental factor like high temperatures or nutritional stress.

Broadly speaking, we can distinguish two classes of contaminants; those that are *persistent, bioaccumulate* and *toxic (PBT)*, and those that tend to be soluble and less persistent but also toxic. This distinction is important in the context of sockeye salmon as these two categories of contaminants behave differently in the environment and exert their effects in different ways.

Table 1: Salmon have been affected in different ways by exposure to a variety of endocrine disrupting contaminants.

Effect observed	Causal chemical	Reference
Immunotoxicity (increased disease)	PCBs, urban runoff	(Arkoosh et al. 1998; Collier et al. 2000)
Impaired olfaction	Linuron, carabaryl, IPBC, atrazine, glyphosate	(Tierney et al. 2006; Tierney et al. 2005; Tierney et al. 2007c; Tierney et al. 2007b; Tierney et al. 2008)
Reproductive toxicity (feminization)	Dioxins, furans and PCBs	(Cook <i>et al.</i> 2003)
Reduced swimming performance	Chlorpyrifos	(Tierney et al. 2007a)
Impaired smoltification and osmoregulation	Aminocarb (4-nonylphenol adjuvant)	(Arsenault et al. 2004; Fairchild et al. 1999)
Reduced predator avoidance and homing behaviour	Diazinon	(Scholz <i>et al.</i> 2000)

Persistent, bioaccumulative and toxic (PBT) contaminants

The first class of contaminants of concern are the PBTs, which include many of the classical contaminants like PCBs DDT and dioxins. These are subject to global transport and now pervade

soil, vegetation, and water. These highly persistent contaminants continue to cycle decades after their peak use (1960s-1970s), despite regulations at the national and international level. PBTs are fat-soluble, meaning that they seek to escape from water and attach to lipids or organic materials. In this way, PBTs readily accumulate in aquatic food webs, and can reach relatively high concentrations in some fish species.. Fish such as sockeye salmon do not easily metabolize these contaminants, and they accordingly *carry the risk* from these contaminants with them through their entire life cycle (Figure 1). Returning from their time at sea, sockeye concentrate these chemicals in their dwindling fat reserves and transfer them to their reproductive tissues.

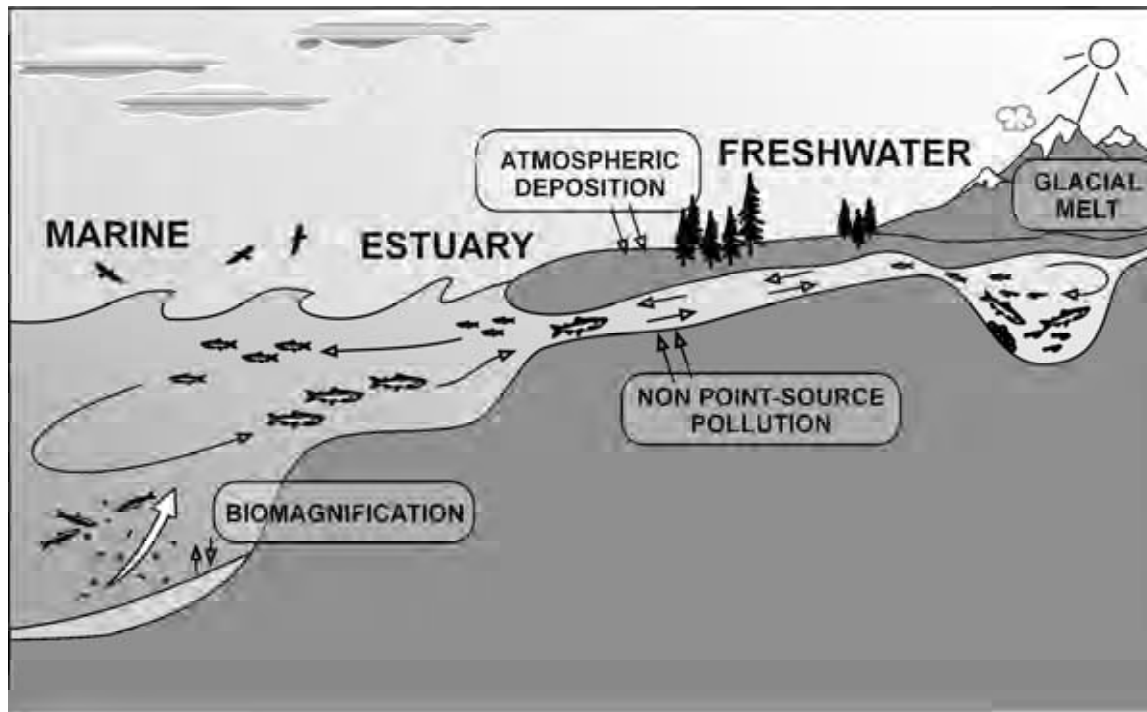


Figure 1: Sockeye salmon *carry the risk* associated with a lifetime exposure to, and accumulation of, contaminants that are *persistent, bioaccumulative and toxic* (PBT). The risk of adverse health effects lingers for these largely banned chemicals, owing to their very high persistence, lingering sources in some parts of the world, and their ready transport in the global environment.

The migratory fish pathway is the dominant route of exposure for PBTs (Krümmel et al. 2003; Cullon et al. 2009). with these chemicals partitioning into eggs, thus leading to risk of egg mortality (Kelly *et al.* 2007) or toxic effects later in life. Given that the highest emissions for these contaminants occurred decades ago, one might expect that associated health effects at the population would be on the decline. However, two aspects bear consideration. Firstly, not all PBT chemicals have been regulated in Canada, and studies have shown that air pollution from Asia and migrating salmon can ‘import’ legacy and new PBTs into coastal British Columbia. Secondly, PBT-associated toxicity reduces fitness, but impacts may only be felt when combined with a secondary insult, such as a disease (i.e. PBT-associated immunotoxicity + pathogen) or food limitation (metabolic stress + contaminant-associated disruption) (Arkoosh et al. 1998). That is, the fish carried the risk but were lucky for a while in that additional factor arrived.

Non-persistent contaminants

The second class of contaminants of concern tends not to be carried by the fish because they are either less persistent, less fat-soluble or do not move readily through the environment. These contaminants may be fairly localized with usage or discharge and can affect fish during sensitive developmental stages (Harris *et al.* 2008). As sockeye transit from lake to river to estuarine to marine environments, they *run the gauntlet* associated with multiple human-associated releases of such contaminants (Figure 2). Fish can therefore be affected by these sorts of contaminants during hatching, rearing or migrating phases of their life.

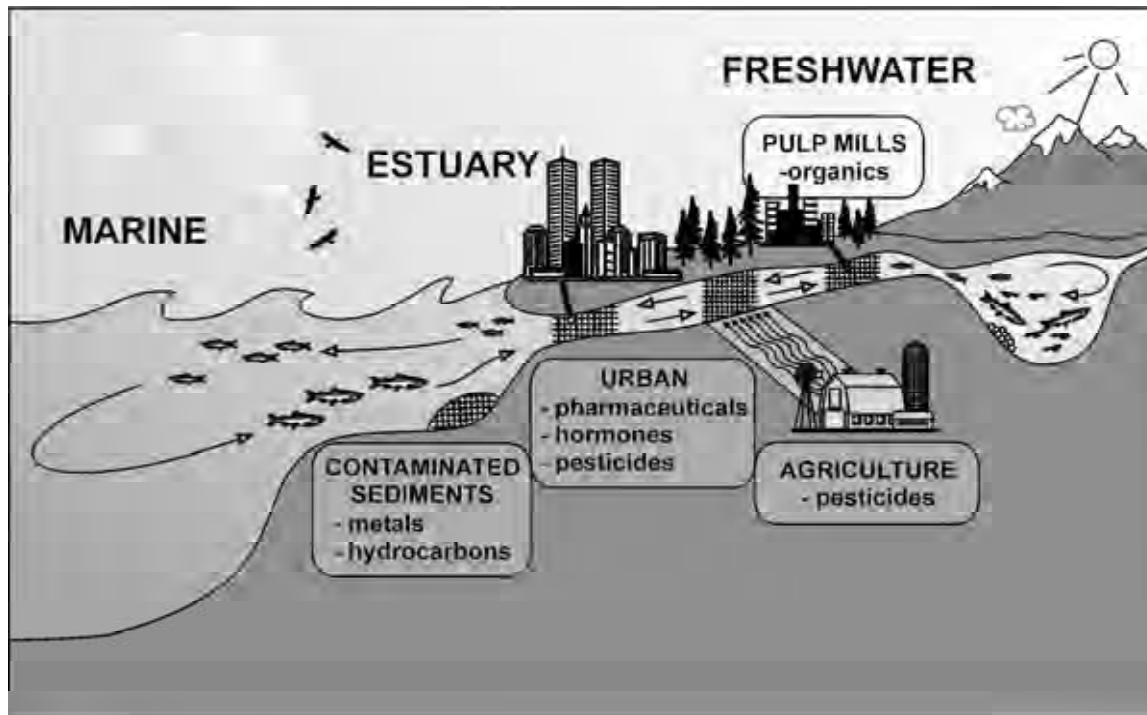


Figure 2: Sockeye salmon *run the gauntlet* of zones (hatched areas) affected by the release of point sources of contaminants deemed to be less persistent and less mobile than the PBT chemicals. These non-PBT contaminants may directly affect the health of fish at different sensitive life stages of sockeye, or disrupt endocrine processes and render the fish more vulnerable to a secondary stressor later in life. Most of the chemicals in this category leave little or no trace in the fish themselves, complicating an understanding of cause-and-effect in the real world.

Contaminants as endocrine disruptors in salmon

Both PBT and non-PBT contaminants affect fish health, notably through a mechanism generally referred to as *endocrine disruption*. (Jobling and Tyler 2003; Colborn *et al.* 1993) Endocrine disrupting chemicals are those chemicals that mimic or interfere with normal hormone functions in such a way as to affect its health or that of its progeny. While PBT chemicals have been subject to increasing regulations (e.g. (Ross *et al.* 2009; Johannessen *et al.* 2008)), a wide variety of non-PBT chemicals are in use (Canada has ~25,000 chemicals on its Domestic Substances List, with most of these being non-PBTs).

Contaminants that mimic hormones are especially noteworthy as they can impact fish at the population level, even at part-per-trillion concentrations (Kidd *et al.* 2007) and yet show little or no chemical evidence afterward. In this way, evidence for causal relationships between specific chemicals and salmon health impact have been demonstrated in laboratory experiments.

Because most exposures do not have an immediate effect on salmon but, rather, compromise the salmon's survival when it is later challenged by an additional stressor, simple hypotheses connecting single-chemical exposures or body burden, and survival success are unlikely to resolve the complex manner in which contaminants affect populations. Under relatively simple circumstances, careful detective work including field and lab studies has been able to demonstrate the circumstances under which contaminants have compromised wild fish populations.

In Canada, a clear example has been the use of 4-nonylphenol as a carrier for pesticide application to forests on the East Coast (Fairchild et al. 1999; Arsenault et al. 2004). There, Atlantic salmon smolts were chemically compromised before going to sea, not by a pesticide but by a chemical used to disperse a pesticide, and then they did not return from the ocean. Likewise, the application of minute amounts of a synthetic estrogen (~5 parts per trillion) to an experimental lake resulted in feminized males, which led to a complete reproductive collapse and a near extirpation of the species (Kidd et al. 2007). Therefore, setting contaminant use trends against fish populations might identify a circumstance where direct cause and effect are at play, but lack of a relationship would provide no basis for disqualifying a contaminant from further consideration.

A Great Lakes example highlights the important role that a single class of chemicals can play in affecting fish populations, and the ways in which contaminants, together with another set of stressors, can combine to overwhelm an ecosystem's ability to recover. Cook et al. (Cook et al. 2003) showed that exposure to dioxin like chemicals explained a complete reproductive failure in lake trout during the period 1940-85. Not only was there a relationship between fish populations and chemical loadings, but laboratory work revealed the toxic mechanism and predictions of mortality in fry based on chemical exposures. Further to the impact of dioxin-like contaminants on fish reproduction, other stresses included a wide range of chemicals, foodweb alteration and habitat destruction. The experience in the Great Lakes, while perhaps more extreme due to the setting of a confined water body surrounded by a large population engaged in industrial and agricultural activities, serves a clear warning that chemical exposure can decimate fish populations, especially in the circumstances of multiple stressors.

Emerging contaminant concerns in British Columbia

During the past decade, there have been increasing concentrations of a variety of chemicals in British Columbia waters, including current use pesticides, flame retardants, pharmaceuticals and personal care products (Daughton and Ternes 1999; Koplín et al. 2002; Ternes et al. 2004). These, together with legacy PBTs and other system changes (climate, foodwebs, habitat, etc.) provide ample room for contributing to the failure of smolts to return from sea as adults. It is worth noting that information on the quantities and types of pesticides used in British Columbia agricultural and forestry sectors, and their carrier compounds, is lacking, making it difficult to characterize risks to salmon and their habitat. Although research is carried out on some priority contaminant concerns in British Columbia, the examples drawn in this brief overview have come without exception from other locations where more thorough studies have been funded.

Conclusions

Our conclusions based on these studies and the contaminant work done in BC are that:

- We cannot identify any single contaminant as a probable cause for the recent declines in Fraser River sockeye salmon;
- Many of the contaminants entering sockeye habitat have been shown to affect olfaction, behaviour, immune function and osmoregulation in salmonids, underscoring the real-world risk implications of current human practices;
- Persistent, Bioaccumulative and Toxic (PBT) contaminants could predispose salmon to mortality by reducing their ability to meet challenges (e.g., temperature, nutrition, predator avoidance, virus infection) through a range of sublethal effects on eggs, fry, smolts and/or adults;
- Non-PBT contaminants including the 286 pesticides registered for use in Canada are increasingly favoured by regulators because they are mobile, may break down easily, dissolve in water, and leave little or no trace. These are poorly monitored, may render smolts unfit for survival, and do not provide a chemical fingerprint;
- Aquatic birds and mammals often leave a visible and well-documented legacy of contaminant effects; fish frequently do not leave a visible legacy...;
- Emerging concerns: A number of chemicals and chemical classes have been increasing over the past decade and merit further scrutiny in the context of sockeye salmon populations. Leading among these are fire retardants, pharmaceuticals, natural hormones, and surfactants (e.g. PFOS) associated primarily with municipal outfalls, and currently used pesticides;
- Where salmon face multiple stresses, chemicals are likely to fall into the category of stressors we can control (Brander 2008).

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Session C: Physical oceanographic conditions; Rick Thomson, DFO

**Pacific Salmon Commission Fraser River Sockeye Salmon Workshop
Summary of 15 June Presentation
Richard Thomson, Fisheries and Oceans Canada
9 June 2010**

I was asked to address the hypothesis that “Physical oceanographic conditions inside and/or outside Strait of Georgia are important indicators or contributors to the Fraser sockeye situation”. Although it seems more a statement of fact than a hypothesis that ocean properties and dynamics should play a key role in the survival, production, and migration of Fraser River sockeye salmon, it is clear that the oceanic processes that are contributing to the observed changes in the fish stocks are highly complex. It also appears clear that the 15-year *e*-folding demise in adult Fraser River returns that began in the mid 1990s is likely distinct from the abrupt event-like changes that occur in selected years. I have therefore attempted to distinguish factors effecting the decreasing trend in the 17 identified stocks from those effecting the 2005 brood year. The talk further emphasizes the marked differences in physical processes determining ocean conditions as one proceeds seaward from the inner coastal waters of the Strait of Georgia, to the outer coastal waters along the west coast of British Columbia, to the open northeast Pacific (Figure 1).



Figure 1: Prevailing currents and coastal upwelling/downwelling favourable zones for the west coast of North America. The Alaska coast is a permanent wind-driven downwelling zone while the California coast is a permanent wind-forced upwelling zone. The Central Pacific Gyre (also, Subtropical Gyre) and Alaskan Gyre (Subarctic Gyre) are also noted.

The spatial and temporal scales of oceanic variability generally increase seaward from the inner coast to the open Pacific. Regional effects associated with seasonally varying river discharge and strong fortnightly modulated tidal currents are most dominant within the inner coastal waters while large-scale, slowly varying wind-driven features such as the California and Alaska

currents are dominate the offshore region. Along the outer coast, topographic effects and alongshore winds become dominant factors. In addition to a general seaward reduction in the amplitudes of physical oceanographic variability, there is a general seaward reduction in the phase variability of oceanic processes. Because salmon are highly vulnerable to their environment during their first year of marine life, it seems reasonable to assume the highly variable coastal waters factor strongly in the marine survival of the salmon stocks.

In my talk, I have assumed that nutrient supply to upper ocean and accompanying primary production are key to understanding the survival of salmon stocks. Primary production in the northeast Pacific is partially determined by the upward flux of nutrients into the surface wind mixed layer in late winter and by the depth of the mixed layer from spring through fall. Although there is some indication of a shoaling mixed layer depth in the northeast Pacific in winter (and possibly reduced nutrient entrainment from below), we found no evidence for trend in the wind mixed surface layer depth in non-winter months at the central Station “P” site over the past 60 years (Figure 2). Thus, nutrient supply to the upper ocean in the offshore region is not considered a factor in the sockeye salmon problem and results were not presented in the talk because of a lack of time. Nor does my talk address the effect of climate change on ocean temperature, the physical parameter commonly selected to serve as the proxy variable for bottom-up trophic level dynamics. Time series of water temperature have been examined for all regions but are not considered to be of primary importance for understanding either the long-term demise of the stocks or the event-like changes that have occurred in specific years.

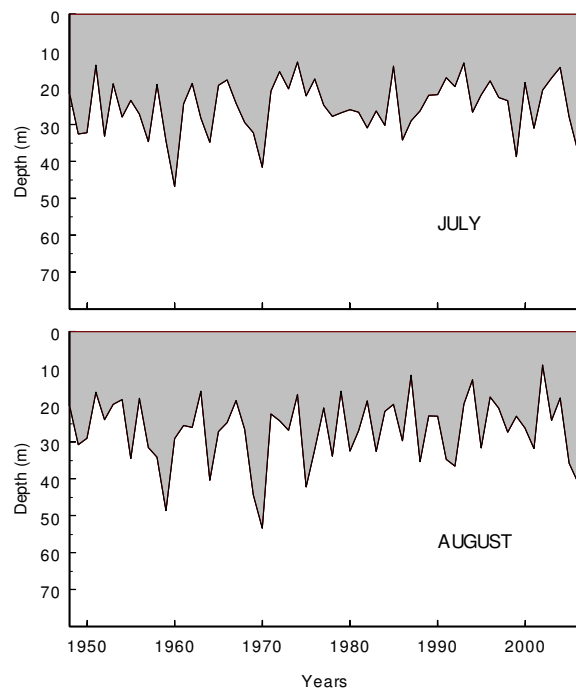


Figure 2: Mixed layer depth estimates for July and August at Ocean Station “P” (50° N, 145° W) from 1949 to 2008 (from *Thomson and Fine, 2009*).

The first process-related question addressed in the talk is whether climate-scale wind-generated upwelling and downwelling along the outer coast of western North America (Figure 3) may have been responsible for the long-term decrease in the salmon stocks. I show that the decrease in

survival that began in the mid 1990s was unlikely associated with the decadal scale changes in coastal upwelling – which entered a weak phase in the mid 1970s and a strong phase in the early 2000s – but rather with the onset of stronger and more protracted downwelling favourable winds beginning in the mid 1990s. This coastwide event is the most intensive within the entire 60-year record. Stronger and longer duration downwelling winds off the coast of British Columbia may have led to a reduction of nutrient entrainment into the euphotic zone in winter and early spring which, in turn, may have led to reduced phytoplankton and/or zooplankton abundance. In addition, stronger downwelling favourable coastal winds imply stronger wind-driven poleward flow along the continental margin and a possible poleward displacement of the dominant zooplankton species in spring. Relatively large cooler water northern zooplankton species may have been replaced by relatively small warmer water southern zooplankton species, leading to a reduction in high energy food source for outmigrating juvenile salmon over the past decade. Enhanced downwelling favourable winds would also affect the deliver of nutrients to the Strait of Georgia. This arises because increased downwelling means that less of the relatively warm nutrient-rich water being delivered poleward from the equatorial region along the continental slope by the California Undercurrent is able to enter the inner coastal waters within the estuarine inflow occurring in the lower layer of Juan de Fuca Strait. It is the estuarine inflow within the strait that transports nutrient-rich water supplied by the undercurrent inward toward the Strait of Georgia. During weak (neap) stages of the fortnightly tidal cycle in the inner coastal waters, this high nutrient water is then able to slip into the Strait of Georgia at mid-depth (*Griffin and LeBlond, 1990*) where it becomes available for entrainment into the overlying euphotic zone. The route is circuitous but vital for the maintenance of high productivity in the Strait of Georgia.

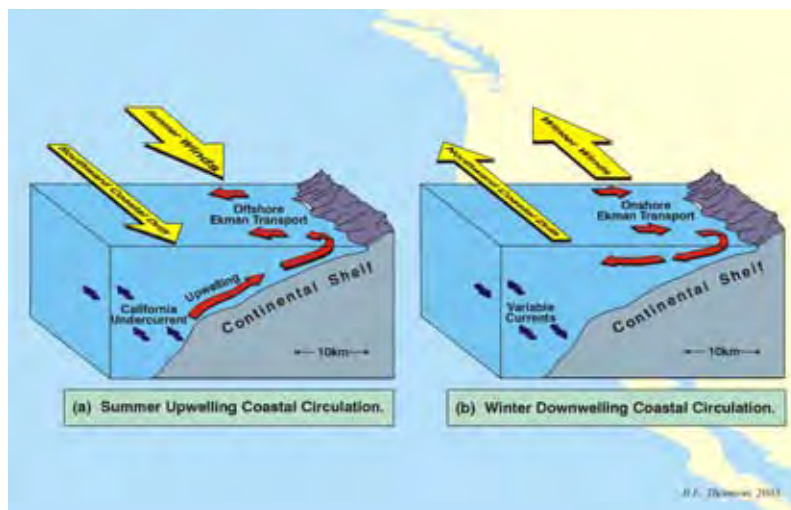


Figure 3: Schematic of wind-driven upwelling and downwelling along the west coast of North America (adapted from *Thomson, 1981*).

The talk then shows that physical oceanographic events beginning in the mid 1990s were also responsible for another important fisheries event, the onset of earlier than normal return migration timing (and hence spawning success) of the Adams River and Weaver Creek Late-run Fraser River sockeye salmon stocks. This study, which is under final review (*Thomson and Hourston, 2010*), indicates that changes in the California Current in July in the central northeast

Pacific, combined with a marked decrease in sea surface salinity (and accompanying increase in sea surface temperature) in early August along the west coast of British Columbia, caused late-run stocks to skip their normal 4 to 6 weeks delay in the Strait of Georgia prior to entering the river (Figure 4). For Adams stocks, maximum correlation is between entry timing and offshore winds such that the weaker the wind-stress in the direction of the prevailing surface currents in early July, the earlier the river entry in late summer. For Weaver stocks, maximum correlation is with salinity such that the lower the surface salinity along the coast in August the earlier the river entry.

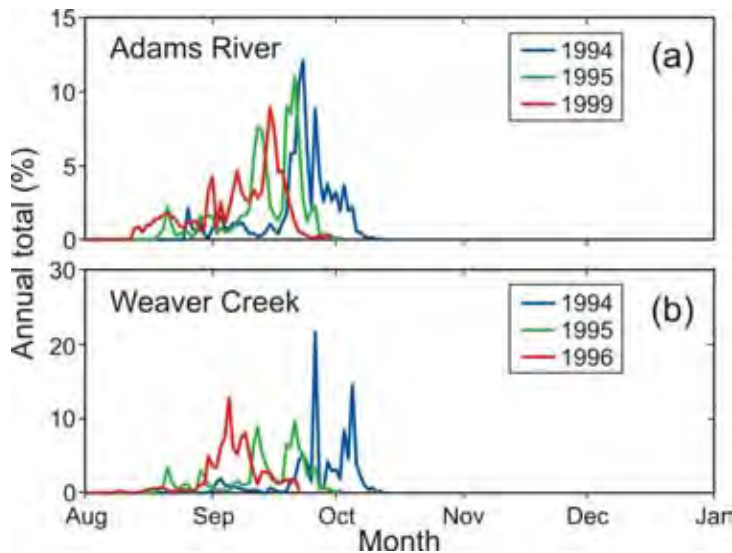


Figure 4: Examples of daily fish count (percentage of the total annual count) measured at Mission City in the lower Fraser River for three consecutive late-run return years centered at the transition year, 1995. (a) Adams River and (b) Weaver Creek stocks. (from Thomson and Hourston, 2010).

The final example in the talk shows a strong correlative link between the survival of adult Chilko Lake stocks and chlorophyll concentrations during April two years earlier when the smolts are migrating through southern Queen Charlotte Sound (the year of marine entry). Low chlorophyll concentrations in April (several months prior to the arrival of the smolts during their migration northward out the Strait of Georgia) give rise to poor adult returns two years later. The extremely poor adult survival in 2009 of the 2005 brood year was due to the anomalously low chlorophyll concentrations in the Sound in April 2007. In contrast, the high survival of these stocks in 2001 appears to have been due to high concentrations of chlorophyll in the Sound in 1999. This model explains 87% of the signal variance for the 12 years of data. We note that the affect on smolt survival in Queen Charlotte Sound does not exclude comparable affects on smolt survival in the Strait of Georgia, as suggested by Beamish et al. (this workshop) and points to a serial process whereby the impact in one region can augment (or mitigate) that in the previously transited region.

The final slide in my talk is a summary of the research needed to address some of the problems covered in the workshop. In particular:

- We should focus research on coastal regions where circumstantial “evidence” suggests that the *timing* and/or *intensity* of physical oceanographic processes might be key factors in the marine survival of Fraser River Sockeye salmon stock. Bottom-up trophic level dynamics might be more sensitive to oceanic changes in coastal regions.
- *We need to know fish movement as functions of time and space.* In order to link salmon productivity and migration to *in situ* marine conditions, we need *fish coordinate* data in both coastal and open ocean regions.
- There needs to be greater emphasis on multi-disciplinary, multi-institutional *process-related* (hypothesis testing) studies.

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Hypothesis: Outside of Georgia Strait, oceanographic conditions, food, and/or predators (including squid) are important contributors to the Fraser sockeye situation.

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1.0. Background: Recruits per spawner (further referred to as productivity) time series started to decline in the early 1990's for most Fraser R. sockeye stocks with the exception of Harrison River sockeye which showed the opposite trend, and Lower Shuswap sockeye which remained relatively stable during that time¹. Hence, the poor return observed in 2009 for the 2005 brood year was the continuation of a general trend, though much greater than was anticipated. Populations of sockeye from the central (Rivers and Smith Inlet) and south coast (Barkley Sound and Columbia) areas of BC also exhibited production declines beginning in the early 1990s. However, in contrast to Fraser R. sockeye, the returns of Barkley Sound and Columbia River sockeye were respectively near and well above the long-term average in 2009. Can these patterns be explained by the biological and oceanographic conditions that Fraser R. sockeye encounter outside the Strait of Georgia?

In this paper, we first describe the migration routes of juvenile Fraser R. sockeye salmon relative to other stocks of sockeye salmon. Using published acoustic tag data, we then consider the significance of the mortality that occurs inside and outside the Strait of Georgia for Fraser R. sockeye. Finally, we explore how trends in Fraser R. sockeye productivity are related to ocean productivity, the abundance of potential competitors (e.g. sardine, *Sardinops sagax*), and the distribution and abundance of potential predators in BC waters (e.g. hake, *Merluccius productus*, mackerel and Humboldt squid, *Dosidicus gigas*), and conclude with some recommendations for future research.

2.0. Migration: In order to understand the effects of ocean conditions on salmon survival, we must know the areas where salmon live in and migrate through, how much time they spend in various areas, and the physical and biological conditions they encounter at these locations [1]. The DNA from 6,058 juvenile sockeye from 3,110 stations has been analyzed to determine their stock of origin and migration behaviour. Two thirds of these data have already been published in [2]; the remaining samples were processed shortly after this publication.

In summer, we tend to see a rapid northward progression of sockeye from the Fraser R., Barkley Sound and Columbia River (Fig. 1). Fraser R. sockeye are found as far north as Baranof Island (Alaska) and are also found off the west coast of Haida Gwaii (formerly Queen Charlotte Islands), but few are recovered off the west coast of Vancouver Island (WCVI). By fall, most of the of Fraser R., Barkley Sound and Columbia River sockeye have moved out of our sampling areas; an exception being a few Fraser (primarily Harrison River) sockeye recovered in Juan de Fuca Strait in late November 2008. A few juvenile sockeye, again primarily from the Harrison River, have been recovered off WCVI during winter each year since 2003. These results suggest that juvenile Fraser R. sockeye migrate out of the Strait of Georgia in the spring and summer

¹ Analysis performed by M. Lapointe (Pacific Salmon Commission, Vancouver, BC)

primarily through Johnstone Strait, except juvenile Harrison River sockeye which appear to remain longer in the Strait of Georgia and leave via Juan de Fuca Strait in late fall/early winter [2]. Hence, the unique life history of Harrison sockeye, including their migratory behavior, might be expected to result in differences in their productivity relative to many other Fraser R. sockeye stocks.

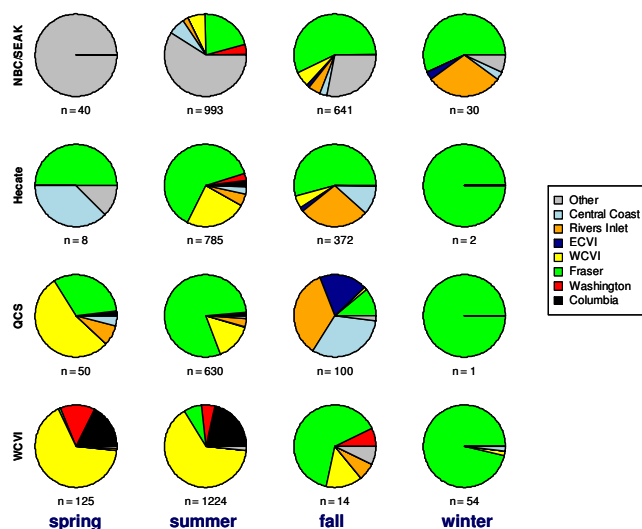


Figure 1. Stock composition of juvenile sockeye salmon collected off the west coast of Vancouver Island (WCVI), Queen Charlotte Sound (QSE), Hecate Strait (Hecate), and northern British Columbia and Southeast Alaska (NBC/SEAK) during spring (May-June 15), summer (June 15-August), fall (October-November), and winter (February-March) between 1998 and 2009.

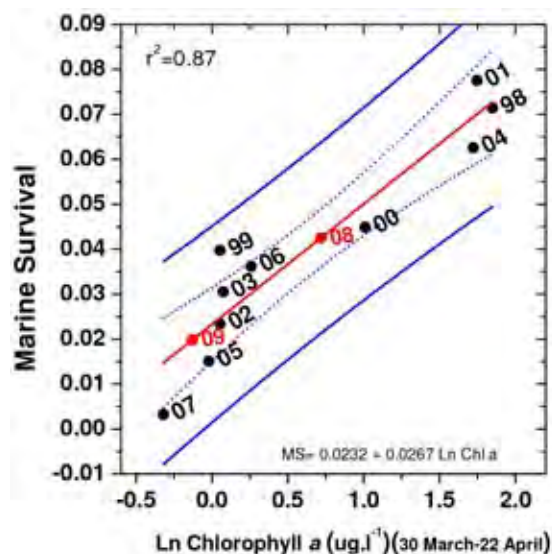


Figure 2. Relationship between the marine survival of Chilko Lake sockeye salmon and the April chlorophyll concentration in Queen Charlotte Sound during the ocean entry year. Black dots: observations; red dots: forecast. Dotted blue line: 95% confidence interval of the regression; solid blue line: 95% confidence interval of the prediction. Satellite used to generate these chlorophyll estimates was not operating prior to 1998.

3.0. Partitioning Mortality: Time series that partition freshwater and “marine” survival rates are available for only a limited number of BC salmon stocks in general and sockeye in particular (< 10 stocks in BC). The degree of covariance of freshwater or marine survival observations between and among sockeye stocks that exhibit either similarities or differences in time of sea entry, area of sea entry, and co-occurrence in coastal marine zones provide one means of testing hypotheses about the time, place and potential identity of mechanisms controlling survival. For example, the 2005 sea entry year was associated with strongly sub-average marine survivals for sockeye stocks returning throughout the BC south-to-central coast in 2007 suggesting the action of a common mechanism operating over large spatial and temporal intervals [3]. However, these same stocks exhibited widely divergent marine survival values in association with the 2007 ocean entry year that saw strongly sub-average survival (and returns) of Chilko sockeye (Fraser), far above average survival for Okanagan sockeye (Columbia R.), and near average survival of Barkley Sound (WCVI) and Smith Inlet (Central coast) sockeye (Hyatt et al., unpublished data). Thus, the factor(s) controlling the surprisingly poor returns to the Fraser R. in 2009 had little to no impact on many non-Fraser sockeye stocks suggesting the operation of factors in areas uniquely occupied by Fraser sockeye (e.g. Fraser R. migration corridor or Georgia Strait).

Developments in the miniaturization of acoustic tags have recently allowed researchers to partition the mortality that occurs during the downstream migration from the mortality in the ocean, as well as partitioning the mortality in different regions of the oceans. Welch et al. [4] tagged Cultus Lake sockeye smolts with acoustic tags in 2004-2007² and tracked their downstream migration as well as through the Strait of Georgia, Queen Charlotte Strait (QCSt), and Juan de Fuca Strait. Overall, their analyses indicate that Cultus Lake sockeye smolts took 4-6 days to complete their downstream migration and remained in the Strait of Georgia for 25-35

² A power failure occurred at the hatchery in 2005. As a result, all the tagged fish died. A second batch of fish was tagged after the normal migration window [4]. Thus, no comparisons are made between the fish that were tagged in 2005 and other years in this paper. 100 smolts were tagged in 2004 and 200 in both 2006 and 2007.

days. The speeds of these large smolts (15-19 cm) were equivalent to the migration speeds of wild smolts found during trawl surveys in body length per seconds (M. Trudel, unpublished data). So residence times of the normal-sized smolts (~10 cm) would be approximately 42~60 days. Most of the smolts migrated out of the Strait of Georgia through Johnston Strait rather than through Juan de Fuca Strait. Marine survival of Cultus Lake sockeye from the mouth of the Fraser R. to the QCSt transect was not unusually low in 2007 relative to 2004 and 2006 [4]. Overall, 28% of the Cultus Lake sockeye salmon smolts that were tagged these years reached QCSt. Hence, daily mortality rates prior to reaching QCSt were in the order of 4%/day, which is at the high end of the values derived for pink salmon smolts in Bella Coola [5]. As approximately 1% of the sockeye smolts that left Cultus Lake in 2007 returned in 2009, total mortality of these large smolts after leaving the Strait of Georgia was approximately 7-8 times greater than within the Strait of Georgia³.

The interpretation of these results is highly dependent on the assumptions used to extrapolate the survival of tagged fish to untagged fish. First, it is not known whether or not the results obtained Cultus Lake sockeye can be extrapolated to other stocks within the Fraser R. Second, they tagged the largest fish of the cohort (~90 g vs 10 g). As larger salmon tend to have higher marine survival [6-8], their estimates for the marine survival to QCSt is likely to be biased high and not reflective of the population as a whole. Although the total marine survival of the tagged and untagged fish was similar⁴, the early marine survival of untagged fish remains unknown (i.e. first 30-60 days). If we assume a mortality rate of 4%/day and that it takes 50 days for the normal-size smolts to reach the QCSt line, the survival inside and outside the Strait of Georgia would both be approximately the same at 10%. Using a higher instantaneous mortality rate (because normal-size fish are smaller) would result in a higher mortality within the Strait of Georgia. Clearly, further work is required to assess the early marine survival of juvenile Fraser R. sockeye.

The proportion of juvenile Barkley Sound and Fraser R. sockeye in Hecate Strait, an area where both stocks mix, relative to their parental stocks may be used as an index to evaluate the relative mortality of these stocks. Assuming that Barkley Sound and Fraser R. sockeye entered the marine environment on the same day and migrate northward at the same speed, we expected that juvenile Fraser R. sockeye would be about 9-10 times more abundant than Barkley Sound sockeye where these stocks mix (i.e. Hecate Strait) in 2007⁵. Yet, the ratio was close to 1:1 in June 2007 (S. Tucker, unpublished data), which implies that Fraser R. sockeye were disproportionally underrepresented in this area, possibly because they sustained high mortality prior to reaching Hecate Strait. In contrast to 2007, the proportion of Fraser R. sockeye relative to Barkley Sound in 2008 and 2009 was respectively 2:1 and 4:1.

4.0. Ocean Productivity: As most juvenile Fraser R. sockeye [other than Harrison River sockeye] appear to migrate through Johnston Strait, followed by QCSt, and Queen Charlotte Sound (QCSd) before arriving in Hecate Strait, it is possible that the ocean conditions in any of these areas may affect their survival. For instance, phytoplankton blooms may occur too early or

³ Marine survival = Survival in the Strait of Georgia times Survival outside the Strait of Georgia. Here, $\sim 1/100 = 1/4 \times 1/25$.

⁴ D. Welch (unpublished data) and M. Bradford (unpublished data)

⁵ Effective female spawner was 9-10 times higher for Fraser R. than Barkley Sound sockeye in 2005. Data for adult Fraser R. sockeye are from M. Lapointe (Pacific Salmon Commission, Vancouver, BC), and for and Barkley Sound sockeye from D. Dobson and K. Hyatt (Fisheries and Oceans Canada, Nanaimo, BC).

too late to fuel appropriately timed but temporally-lagging secondary production of zooplankton. Chilko sockeye marine survivals tend to be high when there is a strong chlorophyll bloom in QCSd in late March to April, and low when chlorophyll levels are also low (Fig. 2). However, limited sampling performed in QCSd and Hecate Strait indicates that zooplankton biomass was not unusually low in June-July 2007 (M. Trudel, unpublished data) and the breeding success of Cassin's auklet (*Ptychoramphus aleuticus*), a planktivorous species feeding primarily on copepods and euphausiids in QCSd, was about what would be expected given the spring temperature [9]. Furthermore, both Barkley Sound and Fraser R. sockeye are commonly found together in QCSd and Hecate Strait through the summer and fall. Yet, marine survival of Barkley Sound sockeye that migrated seaward in the spring of 2007 was very close to the all year average of 3-4% (K. Hyatt, unpublished data). Therefore, we cannot say for sure whether this correlation is spurious, or if it indicates a mechanistic relationship in QCSd or some other area correlated with conditions in QCSd.

Late June-early July trawl surveys conducted by DFO in QCSd and Hecate Strait since 1998 shows that juvenile Fraser R. sockeye were the smallest on record in 2007. An ANOVA followed by a posteriori tests indicate that juvenile Fraser R. sockeye were significantly smaller in 2007 compared to all other years that were sampled. This suggests that these fish grew poorly prior to reaching this area and that poor ocean conditions prevailed in the Strait of Georgia in the spring and summer of 2007.

5.0. Competition: The productivity of sockeye stocks throughout BCs south coast including, Fraser R. sockeye, started to decline following the onset of the 1989 regime shift. Several changes occurred in coastal marine ecosystems throughout the west coast of North America following that regime shift [10]. Most notably, Pacific sardines returned to BC in 1992 after nearly 50 years of absence [10]. Feeding grounds of Pacific sardines are primarily concentrated on the west coast of Vancouver Island, though high abundance of Pacific sardines have also been noted in QCSd and Hecate Strait, and as far north as Icy Strait in Alaska in exceptionally warm years [10-11]. Along with Pacific herring (*Clupea pallasii*) and northern anchovies (*Engraulis mordax*), Pacific sardines are the dominant pelagic species in the California Current System [12]. As they consume similar prey as juvenile salmon, they may compete with juvenile salmon for food [13].

To assess the potential impacts of Pacific sardines on Pacific salmon, we correlated the marine survival of salmon stocks that migrate directly in the California Current System with the total biomass of Pacific sardines in the California Current System. All of the salmon marine survival series that we examined exhibited a positive correlation with Pacific sardine biomass, though these relationships were significant for only half of the stocks (Table 1). Thus, it is highly unlikely that competition with Pacific sardines led to the decline of Fraser R. sockeye since the early 1990s. Hence the timing of the reappearance of Pacific sardines and the decline of Fraser R. sockeye is likely coincidental and indicative of other changes that occurred during the same period in coastal marine ecosystems.

6.0. Predation: It has been suggested that the occurrence of Humboldt squid in BC in recent years may have led to the poor return of Fraser R. sockeye in 2009. These voracious sub-tropical predators can grow up to 30-50 kg in a single year. Hence, Humboldt squid need to consume large quantities of food to fuel their high energy demands. Humboldt squid typically feed on myctophiids, clupeids, hake, and euphausiids [14], and may also prey on salmon. Evidence of predation on salmon includes the presence of salmon otoliths in Humboldt squid gut collected in Puget Sound and bite marks on a Chinook salmon jack caught in the Columbia River. However, their impacts on marine ecosystems and salmon are largely unknown.

Humboldt squid appeared in BC and Southeast Alaska in 2004 [11]. The incidental catches appear to have been increasing from 2004 to 2007 [15], and then again in 2009 (Fig. 3). They normally appear on the BC coast around mid to late July, and seem to concentrate on the shelf break. To date only a few Humboldt squid have been recovered in the Strait of Georgia. Thus, it is unlikely that they are responsible for eating a large number of sockeye smolts, and that even if they do consume sockeye, that they would have a greater impact on Barkley Sound and Columbia River sockeye stocks than to be able to focus on Fraser R. sockeye.

With respect to returning adult sockeye salmon, Humboldt squid were abundant in hake trawl surveys conducted off BC during the summer of 2009 (Fig. 3). As their geographic distribution overlapped with sockeye that returned to the Fraser R., predation of adult Fraser R. sockeye by Humboldt squid may have been high. However, we feel that this is unlikely, as adult sockeye that returned to Barkley Sound and the Columbia River also overlapped with Humboldt squid, but returned at average to near historical level. In addition, the returns of spring and

Table 1. Correlation coefficient of the relationship between marine survival of 8 different stocks of Pacific salmon and the biomass of sardines (1998-2005, 2006, 2007). CR: Columbia River. r: correlation coefficient; n: sample size; p: probability.

Stock	r	n	p
Barkley Sound sockeye	0.74	8	0.04
Carnation Creek coho	0.72	10	0.02
Robertson Creek coho	0.59	10	0.07
Robertson Creek Chinook	0.59	9	0.10
CR Spring Chinook	0.36	9	0.3
CR Summer Chinook	0.66	9	0.05
CR Fall Chinook	0.84	9	0.004
Oregon Production Index coho	0.77	9	0.02

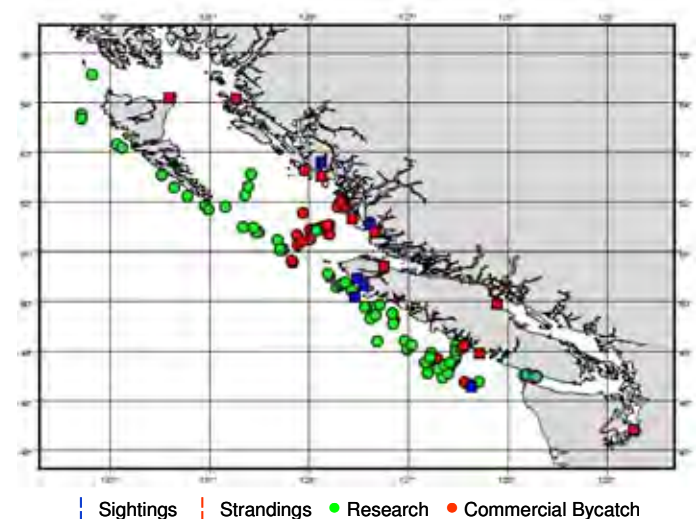


Figure 3. Recovery location of Humboldt squid off British Columbia in 2009.

summer Chinook salmon jacks to the Columbia River were at historical levels⁶. Jacks are generally smaller than mature salmon, and as such, are expected to be easier to catch by predators and sustain higher mortality rates.

7.0. Additional Research: Taken together, these results suggest that the poor return of Fraser R. sockeye salmon in 2009 and decline in productivity since the early 1990s are linked to conditions that they experience prior to reaching Hecate Strait. The low catches of juvenile Fraser R. sockeye in Hecate Strait and the Strait of Georgia in 2007⁷, the strong positive correlation between adult Fraser R. sockeye return with juvenile sockeye salmon in the Strait of Georgia⁷, and small size of juvenile Fraser R. sockeye in Hecate Strait are consistent with this interpretation. The evidence for a significant effect of ocean conditions on Fraser R. sockeye once they leave the Strait of Georgia is currently equivocal with respect to the magnitude of the mortality outside the Strait of Georgia and the relationship between Chilko survival and chlorophyll concentration in QCSd. Nevertheless, further effort is required to determine where areas of significant mortality occurs in freshwater and the marine environment to monitor zooplankton dynamics in QCSd. Acoustic tagging work will be required to determine the migration routes and timing of different stocks of Fraser R. sockeye, such as Harrison River sockeye, which appear to take a different migration route. As marine survival is expected to be driven by changes in growth, analysis of archived otolith microstructure of juvenile Fraser R. sockeye might shed light onto the early growth and survival of juvenile Fraser R. sockeye inside and outside the Strait of Georgia.

8.0. References:

[1] Trudel et al. 2009. Trans. Am. Fish. Soc. 138: 1369; [2] Tucker et al. 2009. Trans. Am. Fish. Soc. 138: 1458; [3] Hyatt et al. 2008. pp. 73-77, In DFO Science. Ocean Status Report. 2008/001; [4] Welch et al. 2009. Can. J. Fish. Aquat. Sci. 66: 736; [5] Parker. 1968. J. Fish. Res. Board. Can 25: 757; [6] Lorenzen. 1996. J. Fish Biol. 49: 627; [7] McGurk. 1996. Fish. Bull. 94: 77; [8] Koennigs et al. 1993. Can. J. Fish. Aquat. Sci. 50: 611; [9] Hipfner. 2010. pp. 72-73, In DFO Can. Sci. Advis. Sec. Res. Doc. Ser. 2010/053; [10] MacFarlane et al. 2000. Prog. Oceanogr. 47: 147; [11] Trudel, M. et al. 2006. pp. 53, In DFO Science. Ocean Status Report. 2006/001; [12] Orsi et al. 2007. Am. Fish. Soc. Symp. Ser. 57 : 105; [13] MacFarlane et al. 2005. CalCOFI Inv. Rep. 46: 144; [14] Field et al. 2007. CalCOFI Inv. Rep. 48: 131; [15] Holmes et al. 2008. CalCOFI Inv. Rep. 49: 129.

⁶ <http://www.fpc.org/>. Chinook salmon jack counts at the Bonneville dam started in 1960.

⁷ Beamish et al. (unpublished data)

An explanation for the poor return of sockeye salmon to the Fraser River in 2009

R. Beamish, R. Sweeting, K. Lange, C. Neville, D. Preikshot, R. Thomson and T. Beacham

The low returns of sockeye salmon in 2009 were likely the result of poor early marine survival of juveniles in the Strait of Georgia in 2007. The poor marine survival probably resulted from a lack of food in the first few months after the juvenile sockeye salmon entered the Strait of Georgia. A very poor production of food is also the most likely explanation for the poor growth of juvenile coho and chinook salmon in the spring of 2007. The poor early marine survival of juvenile chum salmon in 2007 is additional evidence that all juvenile Pacific salmon entering the Strait of Georgia experienced poor feeding conditions in the spring of 2007. Reduced food production would affect other species and there is evidence that larval Pacific herring experienced very poor survival in the spring of 2007. Island Scallops reported that their cultured scallops grew so poorly in 2007 that marketing was delayed by one year.

There is a weak relationship between the trawl catches of juvenile sockeye salmon in July and total returns, two years later. The reliability of this relationship will be confirmed if the total return of sockeye to Fraser River in 2010 and 2011 is about 8 to 10 million fish. The improved catches of juvenile sockeye salmon in 2008 and 2009 were consistent with improved catches of other juvenile Pacific salmon. For example, pink salmon that went to sea in 2008 returned to the Fraser River in 2009 at historic high abundances. This indicates that the factors affecting juvenile salmon in the Strait of Georgia in 2007 were the result of an extreme stress in 2007.

The environmental forcing that resulted in the poor food production was probably caused by a combination of large, early flows from the Fraser River and relatively weak winds. High freshwater discharge combined with weak or moderate southerly winds that help confine the brackish surface waters within the strait would affect the stability of a surface mixing layer. This would result in a very shallow or “freshwater” capped mixed layer depth in the spring and reduced plankton production. Analysis shows that the spring of 2007 was highlighted by weak, moderately strong southerly winds and a mixing layer depth that was the shallowest in 30 years.

Juvenile Harrison River sockeye salmon were 24 times more abundant in the trawl survey in September 2007 than all other juvenile sockeye salmon were in July. Harrison River sockeye salmon are sea type salmon that do not rear in a lake for one year prior to entering the Strait of Georgia. Instead, they remain in the river after hatching and enter the Strait of Georgia in the same year that they hatch, approximately 8-10 weeks later than most other juvenile sockeye salmon. Very few juvenile Harrison sockeye salmon were caught in the July surveys, but virtually all of the juvenile sockeye salmon caught in the survey in September 2007 were Harrison River sockeye. There is a weak relationship between the trawl catches of juvenile Harrison River sockeye in September and the total returns for each brood year. There were very large catches of juvenile Harrison River sockeye salmon in September 2007 and 2008. Thus, there could be a large return to the Harrison River in 2010 and 2011.

South Thompson River chinook salmon have a life history that is similar to the Harrison River sockeye salmon. There are seven populations in the aggregate of South Thompson chinook salmon and these populations are also experiencing very good survival as indicated by the exceptionally large escapements relative to most other chinook populations in the Fraser River drainage. South Thompson chinook salmon enter the Strait of Georgia in early July, 8-10 weeks after most other chinook salmon. Juveniles from these stocks increase in abundance through the summer and by September they represent 70% to 80% of all juvenile chinook salmon in the Strait of Georgia. In September 2007, juvenile Harrison sockeye salmon and South Thompson chinook salmon represented 48 % of all juvenile Pacific salmon in the survey. The very good survival of the juvenile salmon that entered the Strait of Georgia in late spring or early summer indicates that food was available later in the year in 2007.

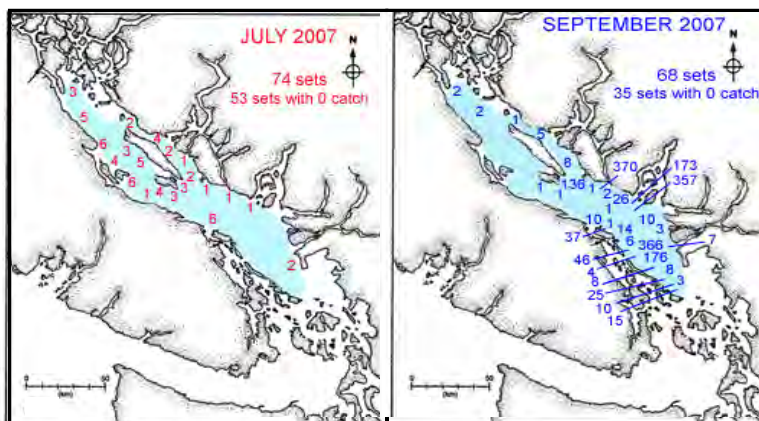
There has been a clear declining trend in the total production of sockeye salmon in the Fraser River since 1994. There is also a declining trend in the early marine survival of coho salmon at this time, indicating that the most likely cause of the declining trend is related to climate. There is a relationship between the total mortality of coho

salmon and the catch of juvenile coho salmon in the September trawl surveys. This indicates that conditions in the Strait of Georgia in recent years are directly related to the total return of coho salmon.

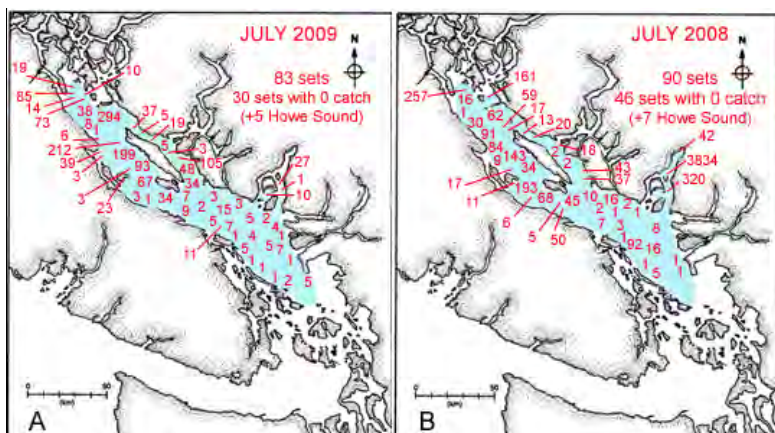
The decline in the abundance of Fraser River sockeye salmon since 1994 is associated with increased abundances of juvenile pink and chum salmon that compete with juvenile sockeye salmon for some of the same prey. The size of juvenile sockeye salmon in July is smaller in years when juvenile pink salmon are in the Strait of Georgia. More Harrison River sockeye salmon return as 4-year-olds in years in which juvenile pink salmon are in the Strait of Georgia. This competition between juvenile pink and sockeye salmon is evidence that conditions in the early marine period in the Strait of Georgia affect their growth and probably their survival. Rapid growth in the early marine period is critical for survival, thus slow growth most likely results in higher early marine mortality.

There were other anomalous years, such as 2005, but the events that affected all juvenile Pacific salmon entering the Strait of Georgia in the spring of 2007 appear to be unique. The reduced production of sockeye salmon since the early 1990s, however, appears to be part of a general trend that has also reduced the productivity of coho and chinook salmon and increased the productivity of pink and chum salmon. Thus, it is important to recognize that the long-term changes are ecosystem changes and not specific to sockeye salmon.

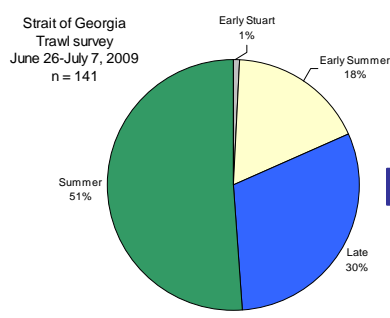
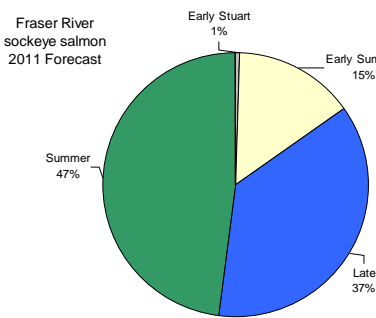
Future stock assessments of sockeye salmon should include a series of indices that identify the return as good, average or poor. Juvenile Pacific salmon abundance surveys provide one index of adult production and should continue. An index of plankton production would be most useful in assessing adult salmon production. Research needs to continue to identify how disease may be related to the increased mortality of coho, chinook and sockeye salmon as well as the reasons for the increased survival of pink and chum salmon.



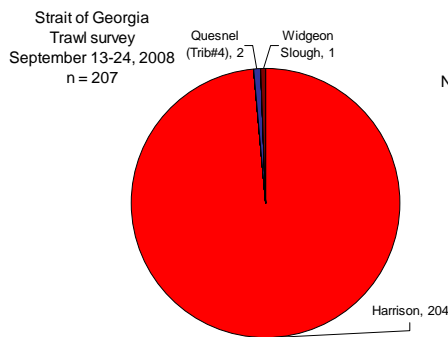
Sockeye salmon catches in the trawl surveys in July 2007 and September 2007 showing the large increase in catches in September compared to July in 2007.



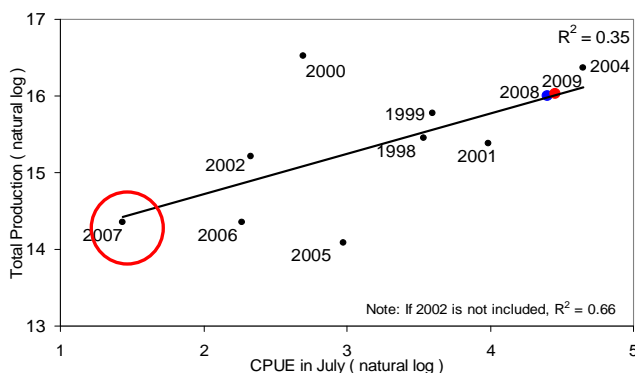
Sockeye salmon catches in the July trawl surveys in 2008 and 2009 were considerably larger than in July 2007. The trawl survey also showed that there were large abundances of juvenile pink salmon in 2008 which resulted in record returns in 2009. In early June 2010, a trawl survey confirmed that juvenile pink and sockeye salmon are abundant within the surface waters of the northern Strait of Georgia including the Discovery Passage area.



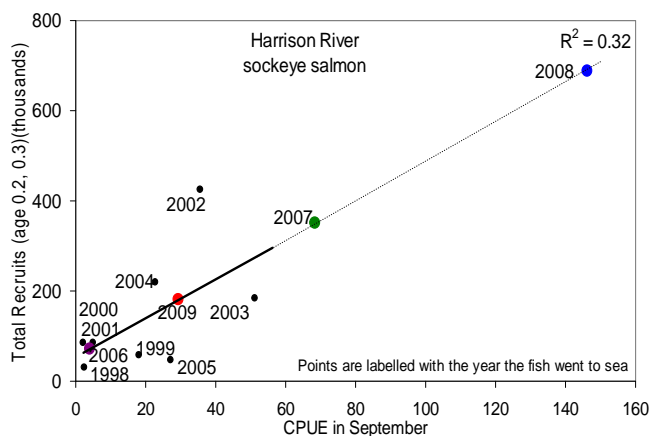
Composition of aggregates of sockeye salmon populations determined from DNA analysis for fish captured in the Strait of Georgia July 2009 survey and the expected proportions of the aggregate of specific run timings based on the 2011 stock assessment forecast, showing that the samples in the survey are representative of the expected population composition.



Population composition for juvenile sockeye salmon in the September survey showing that fish are virtually all Harrison River sockeye salmon

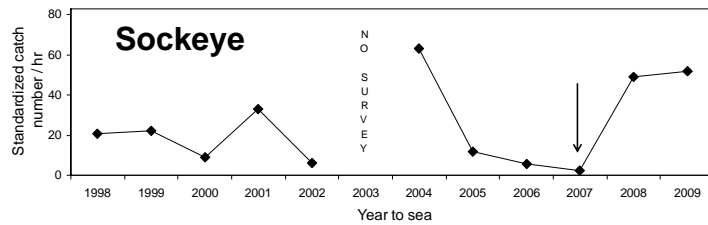


Relationship between catch in July, standardized to one hour or CPUE, and the total production for Fraser River. The years are the ocean entry years and the return year will be two years later. The poor return in 2009 corresponds to the ocean entry year of 2007, circled in red. Catches in 2008 (blue dot) and 2009 (red dot) indicate that the return in 2010 and 2011, respectively, could be about 10 million fish.

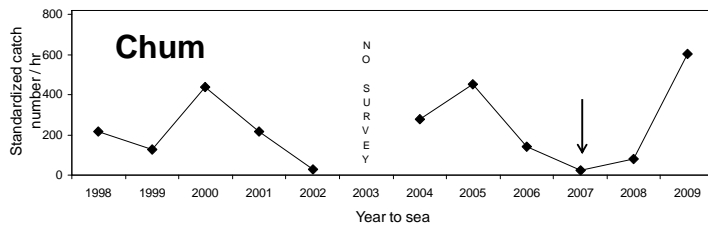


The relationship for sockeye salmon from the Harrison River. The years are the ocean entry years and the total production includes fish that return as age 3 (0.2) and age 4 (0.3). The production for ocean entry year 2006 (purple dot) is preliminary. The ocean entry years of 2007 (green dot), 2008 (blue dot) and 2009 (red dot) will return as adults between 2010 and 2012. The values for 2007 and 2008 are outside of the existing relationship and included to show that returns in the next few years could be large.

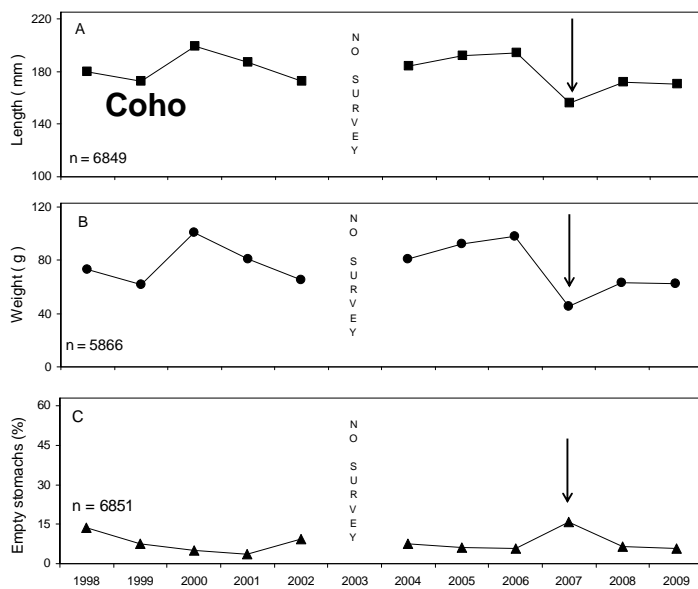
All juvenile salmon were affected by poor feeding conditions in the spring of 2007



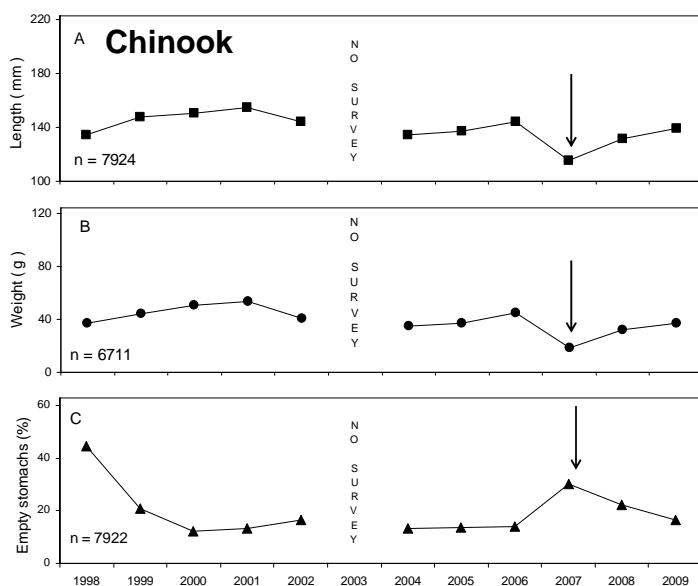
Catch of juvenile sockeye salmon in the July surveys in the Strait of Georgia 1998 – 2009. Arrow shows the low catch in 2007.



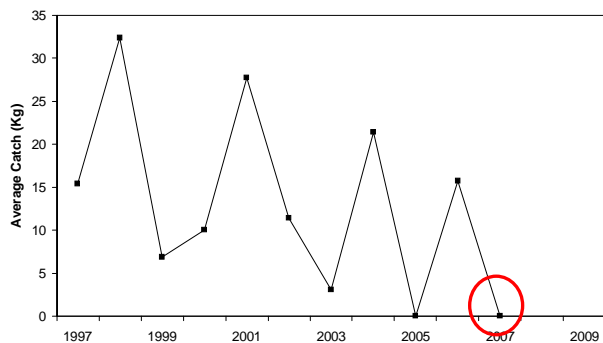
Catch of juvenile chum salmon in the July surveys in the Strait of Georgia 1998-2009. Arrow shows the low catch in 2007.



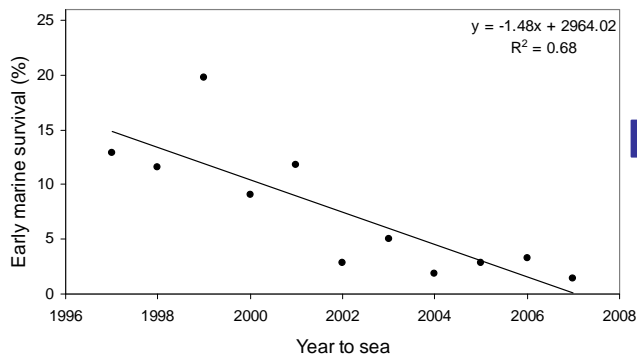
(A) Average fork length (mm), (B) weight (g) and (C) percentage of empty stomachs of juvenile coho salmon in the July surveys in the Strait of Georgia. Arrows show the small length and weight and high percentage of empty stomachs in 2007.



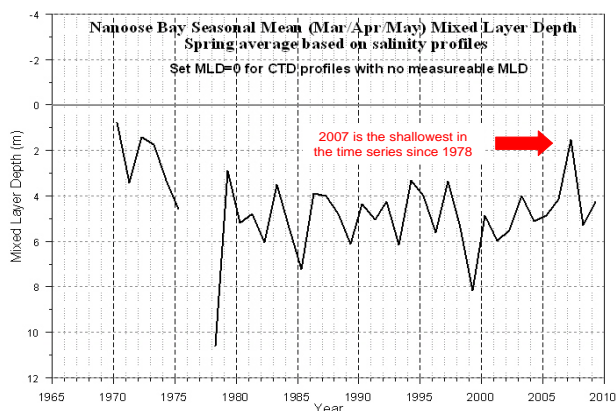
(A) Average fork length (mm), (B) weight (g) and (C) percentage of empty stomachs of juvenile chinook salmon in the July surveys in the Strait of Georgia. Arrows show the small length and weight and high percentage of empty stomachs in 2007.



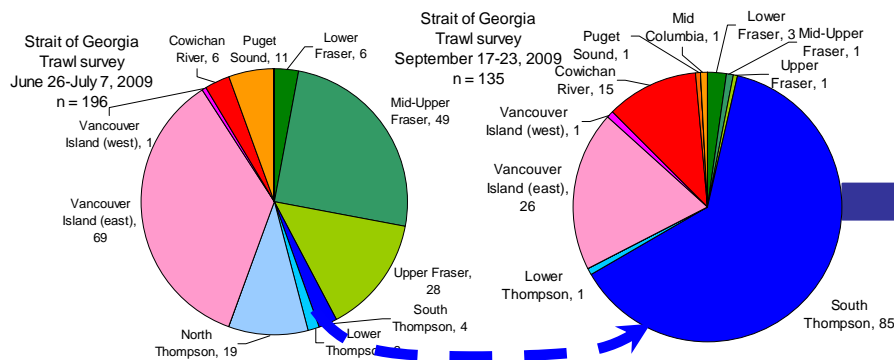
Estimated abundance of age 0+ Pacific herring from the September Pacific herring survey showing that in 2007 there was poor survival of age 0+ Pacific herring in the Strait of Georgia.



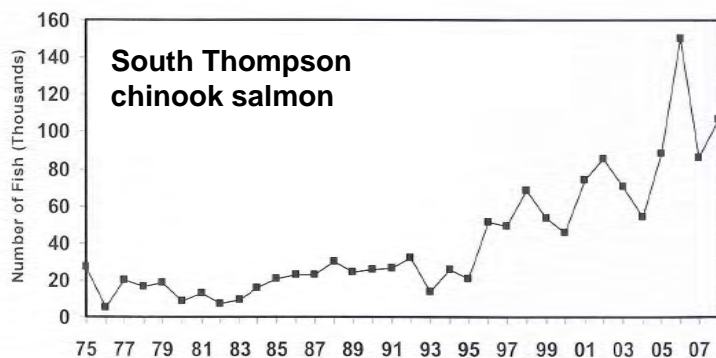
Early marine survival of coho salmon from mid-May to mid-September has declined from about 15% to 1% since 1998



The monthly mean mixed layer depth at Nanoose Bay in spring (March-April-May) from 1978 to 2009. The arrow identifies the extremely shallow mixing layer depth in 2007.

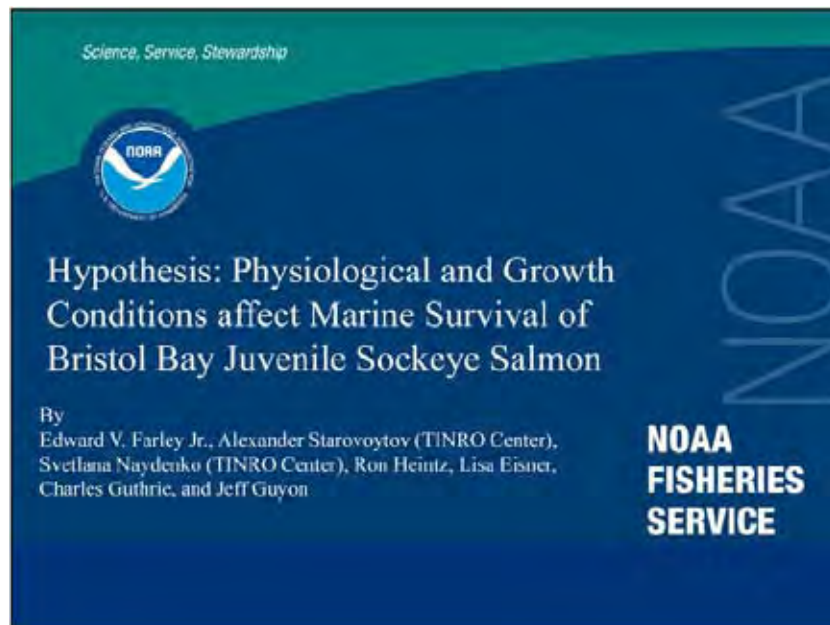


Stock composition of Chinook salmon captured in the Strait of Georgia in the July and September surveys in 2009 showing the increase in the percentage of South Thompson populations in September.

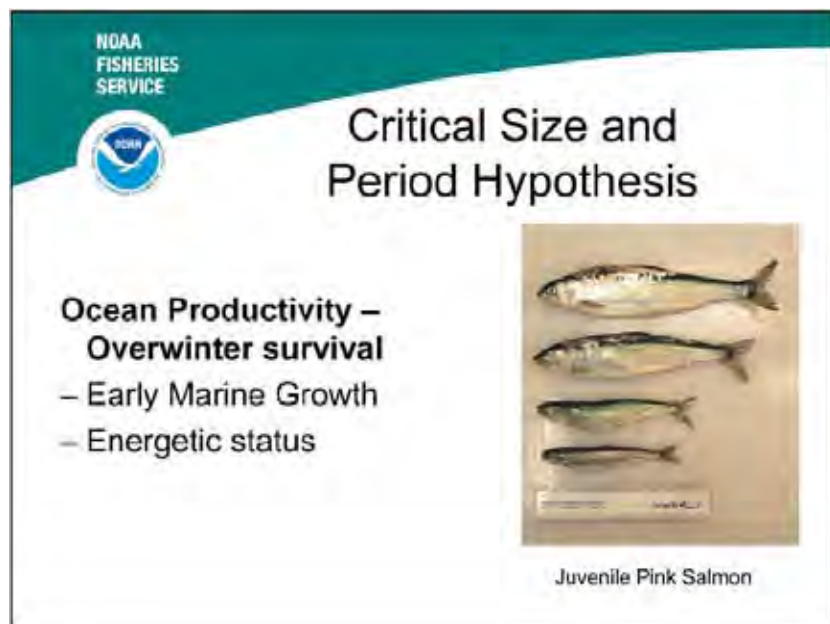


Increasing escapements of Fraser River summer-run populations including five stocks that spawn in the South Thompson watershed - Middle Shuswap, Lower Shuswap, Lower Adams, Little River and South Thompson River.

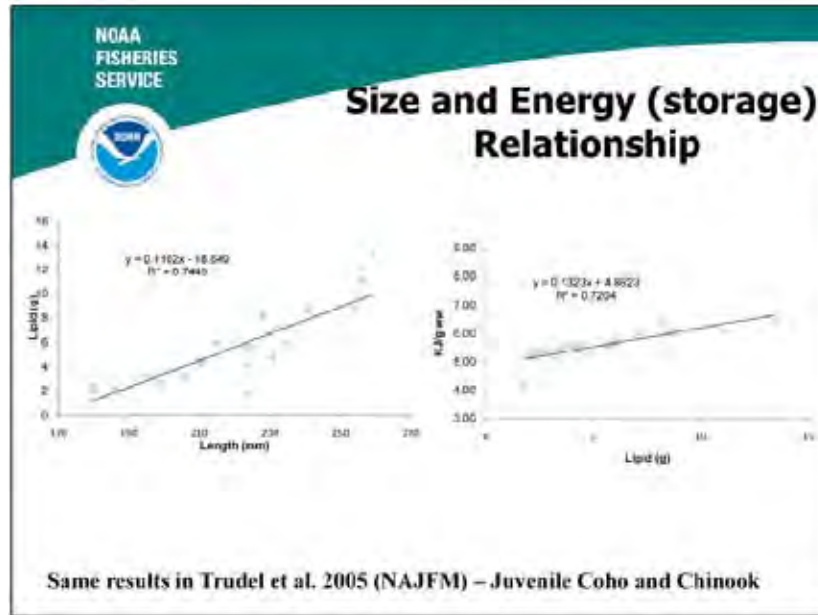
Session C: Physical oceanographic conditions; Ed Farley, NOAA



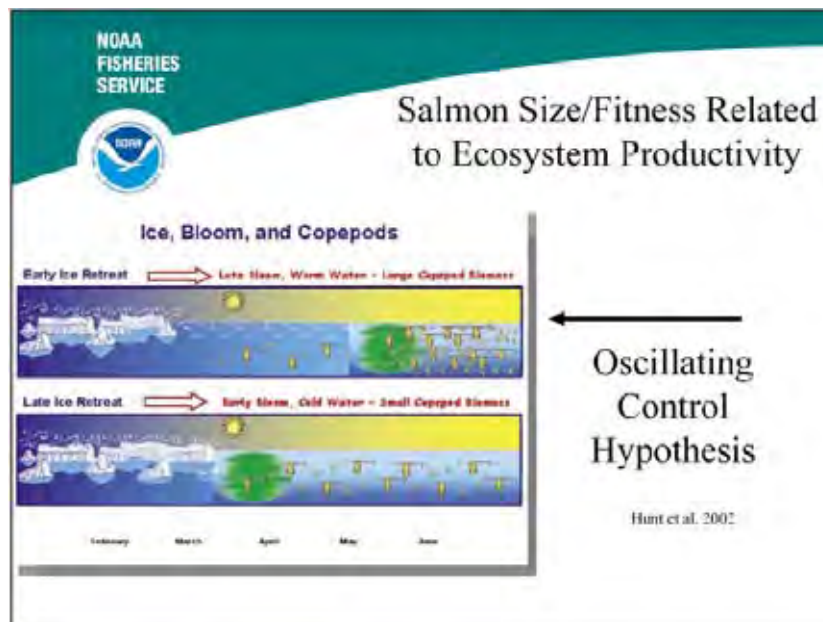
I was asked to address hypothesis: physiological and growth conditions affect marine survival in Bristol Bay juvenile sockeye salmon.



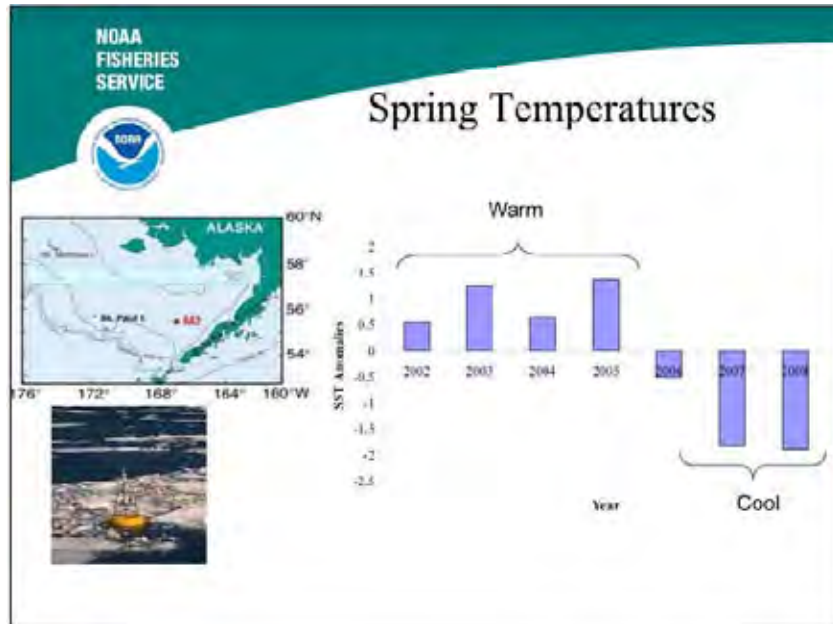
Critical size and period hypothesis – 2 stages where the first stage may occur just after juvenile salmon enter the marine environment and smaller individuals are believed to experience higher size-selective predation. The second stage is thought to occur following the first summer at sea, when smaller individuals may not have sufficient energy reserves to survive winter



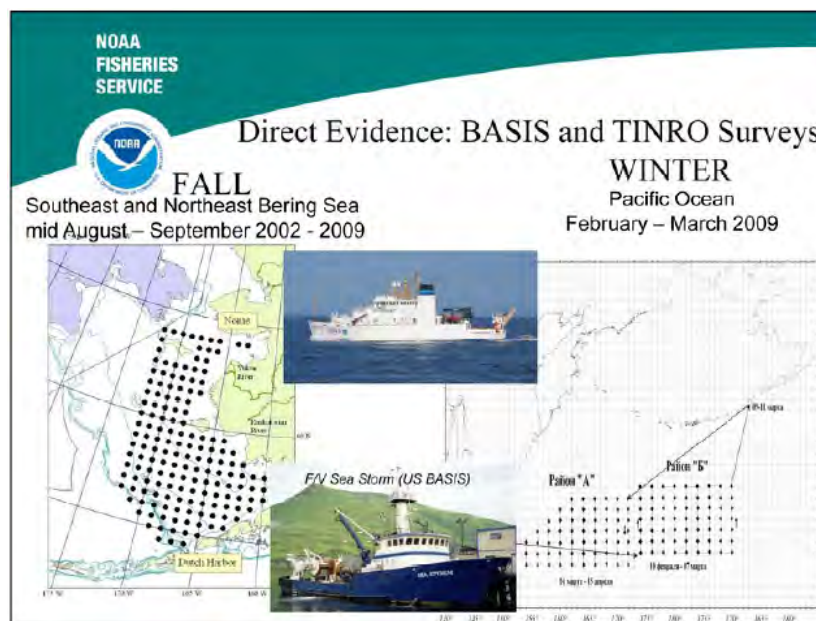
These data come from juvenile sockeye salmon captured during BASIS 2008. There is a strong relationship between the amount of lipid (or fat storage) and length of juvenile salmon. There is also a strong relationship between the amount of energy (KJ/g wet weight) and lipid in juvenile salmon. I show this relationship because we only have lipid information for a single year but have energetic status (KJ/g wet weight) back to 2003 for juvenile Bristol Bay sockeye salmon.



The Oscillating Control Hypothesis predicts that during cold regimes, zooplankton prey for larval fishes would be limited, negatively impacting recruitment of fish populations on the shelf. In contrast, warm regimes are associated with strong zooplankton productivity and higher survival of larval and juvenile fishes.



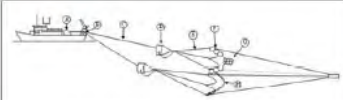
There is a strong correlation between ice extent and sea surface temperatures on the eastern Bering Shelf. Cold winters and spring SSTs are related to southward extent of sea ice leading to cold regime productivity dynamics; warm winter and spring SST lead to the opposite. Survey data that will be shown later were collected during warm (2002 to 2005) and cold (2006 to 2008) regimes and thus provide us with a means of comparing juvenile sockeye salmon fitness between cold and warm regimes.



The juvenile sockeye salmon data come from surveys conducted on the eastern Bering Sea shelf by the Alaska Fisheries Science Center during Fall (August – September) 2002 to 2008 (Figure left). The winter data come from a survey conducted in the North Pacific Ocean by scientists from the TINRO Center during Winter (February – March) 2009.


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Net Sampling



A) Trawl head	B) Top side	C) Wing 20m
D) Small 10m 3m net down 100 kg		
E) Wing 20m 3m net down 100 kg		
F) Wing 20m 3m net down 100 kg		
G) Wing 20m 3m net down 100 kg		
H) Wing 20m 3m net down 100 kg		
I) Wing 20m 3m net down 100 kg		

Mid-water trawl rigged to fish near surface to 20-m depth with a width of 60-m.




The AFSC uses a mid-water trawl rigged to fish near surface waters.

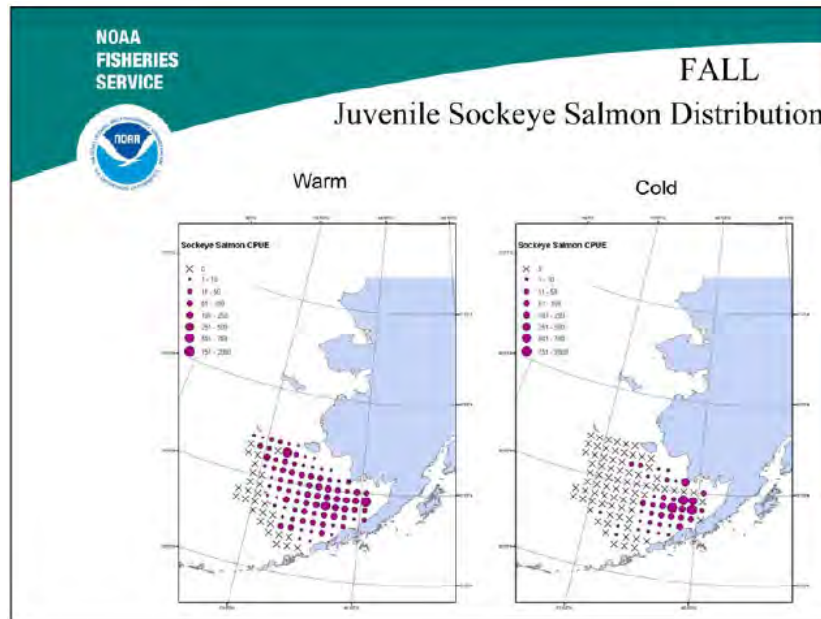
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Ecosystem Indicators

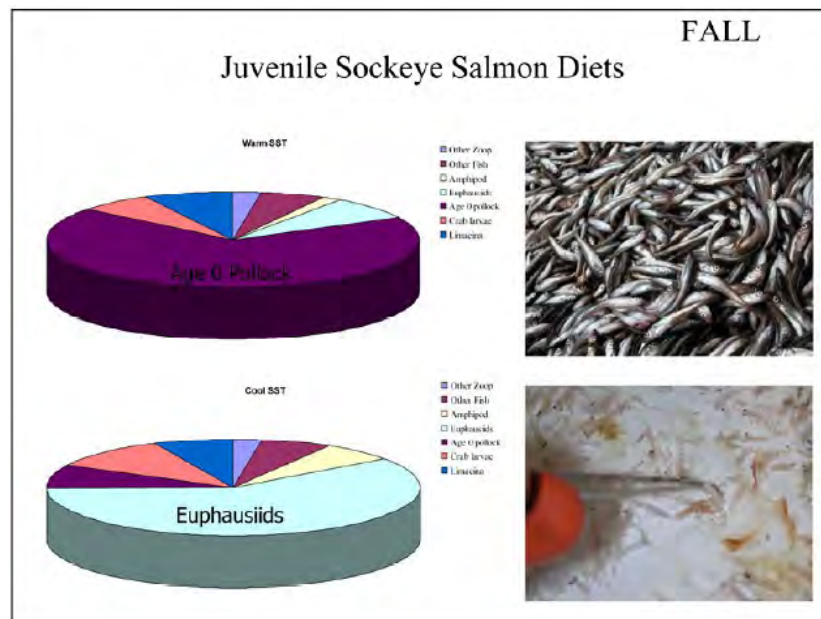
- Physical Oceanography
- Biological Oceanography
 - Zooplankton species comp and biomass
 - Phytoplankton species comp etc.
- Relative Abundance
- Fish Diet
- Size
- Energetics



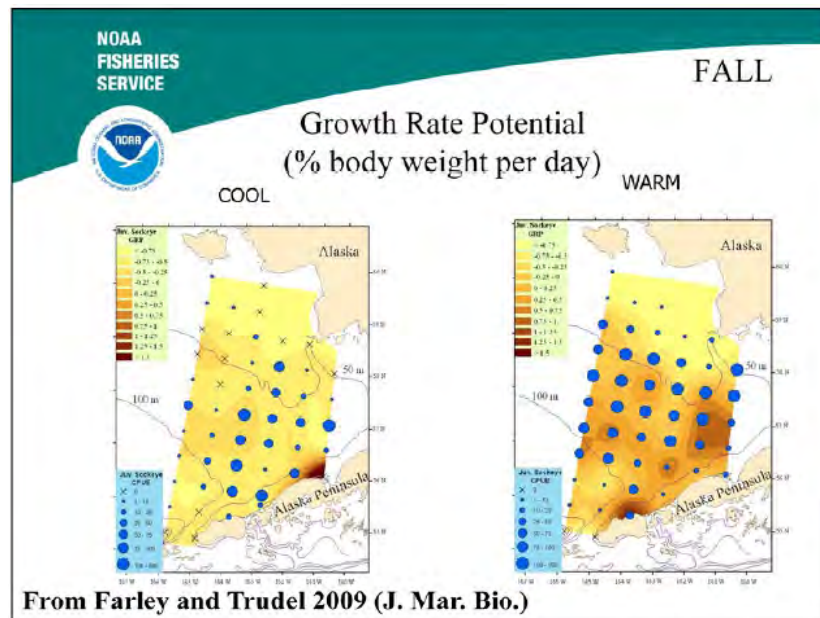
Once the net is retrieved, the catch is dumped on a sorting table, where is sorted by species and life-stage. lengths and weights are recorded, and stomach contents are removed and the composition of each prey type by weight quantified on board.



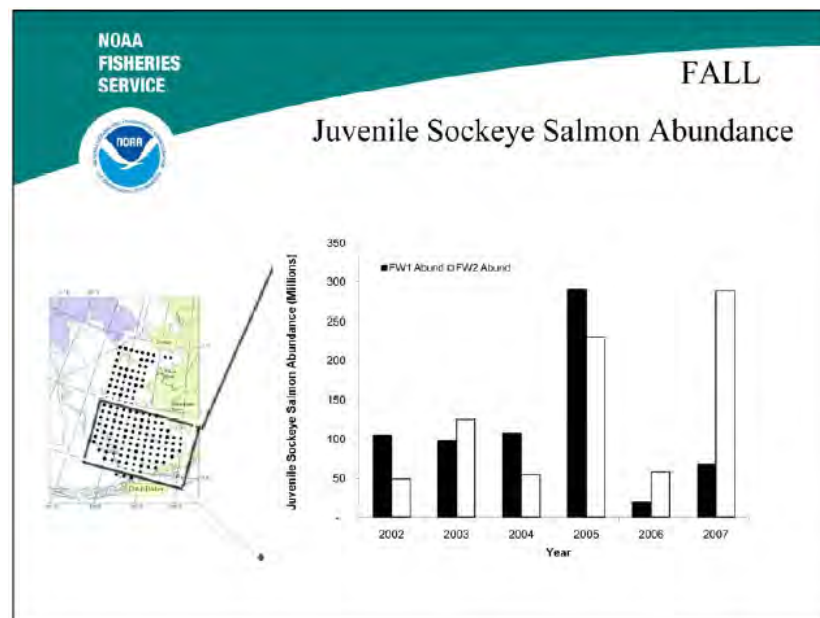
Juvenile sockeye salmon are widely distributed on the eastern Bering Sea shelf during warm years, but constricted to inner Bristol Bay during cold years. These differences in distribution can be attributed to timing of smolt migration (later lake ice break up during cold years) as well as size and growth rate (juvenile fish tended to be larger during warm years and likely grew faster - larger fish swim faster and begin to move offshore earlier in the summer).



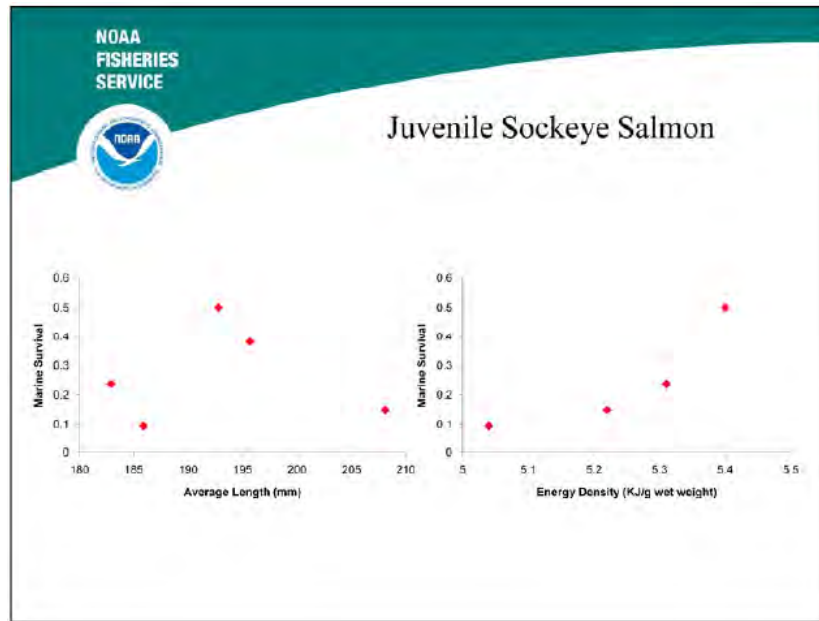
Juvenile sockeye salmon stomach contents contained mostly age 0 pollock during warm years but changed to euphausiids and other zooplankton during cold years. Implications for energetic status.



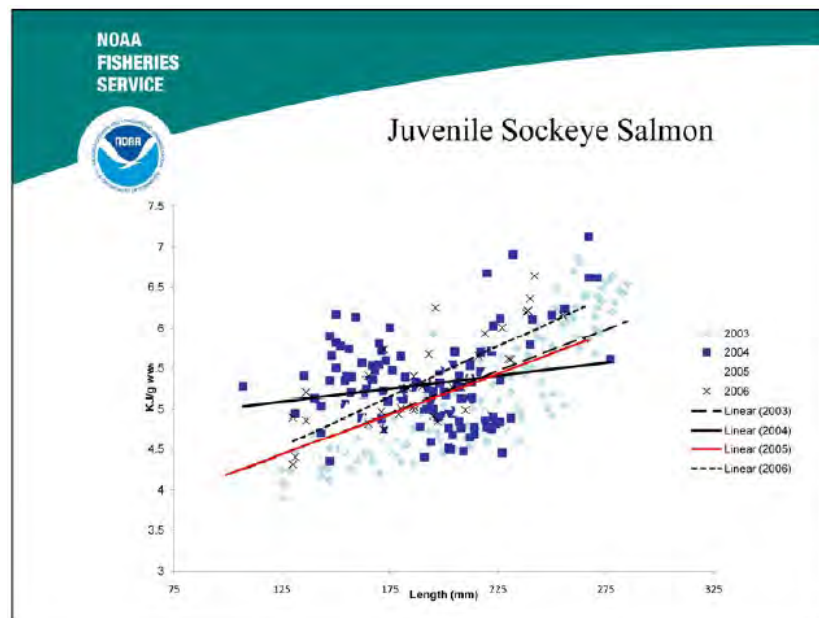
However, warm years had higher growth rate potential on the eastern Bering Sea shelf for juvenile sockeye salmon (growth rate potential is based on prey density which includes the energetic status of prey)



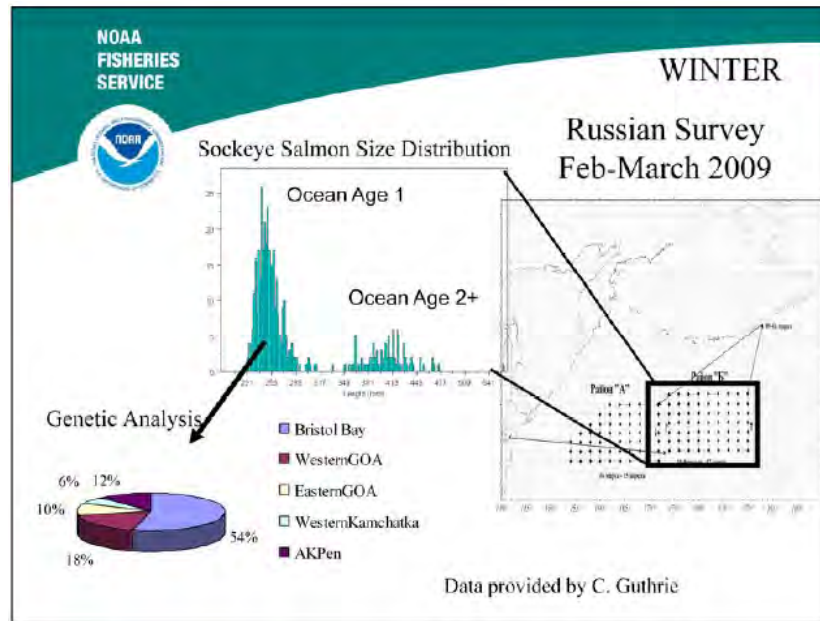
Abundance estimates based on area surveyed (km^2), area sampled by trawl (km^2), average CPUE of juvenile sockeye salmon each year and a catchability estimate of 0.3 for our trawl indicate consistent abundance from 2002 to 2004, dramatic increase in abundance during 2005 followed by a decline in 2006. Age determination was either by preferred scales or otoliths.



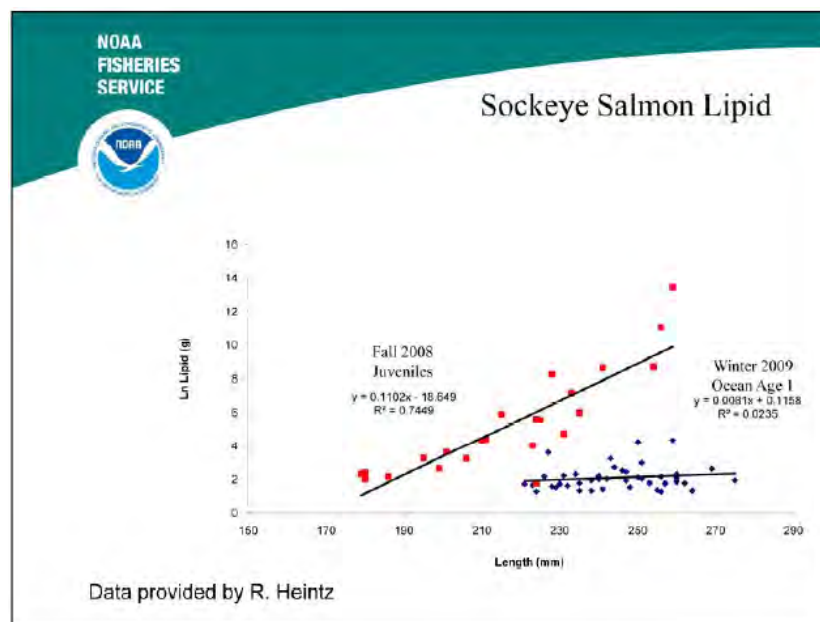
Marine survival estimates are calculated by dividing the number of adults returning to Bristol Bay during year t+2 and t+3 by the number of juveniles during year t. These data indicate that length may not always be a good predictor of marine survival; however, energy density may be a good predictor of marine survival. Average length from Farley et al. 2009.



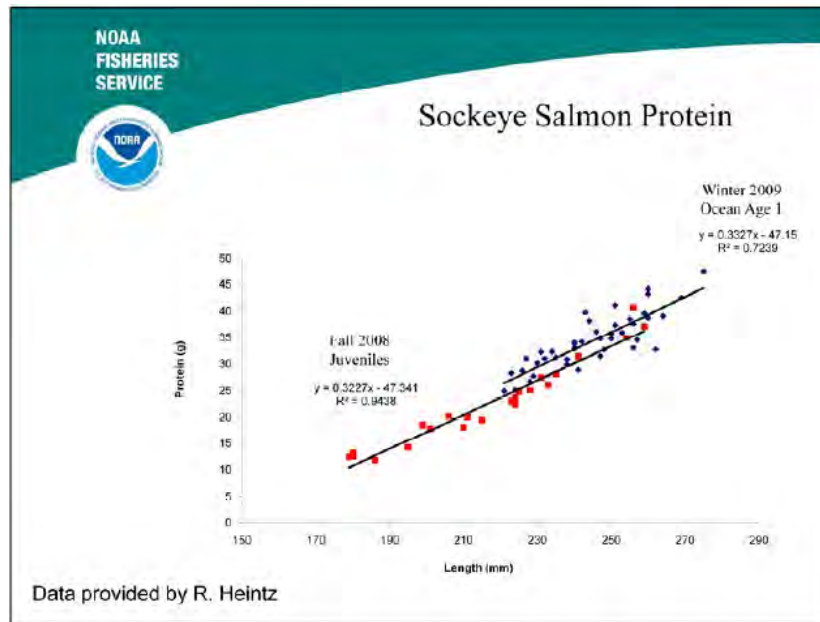
We note that the relationship between energy density and length can be different depending on the year where changes in slope or intercept are noted among years. This result is likely due to changes in ecosystem productivity where salmon fitness is likely related to type and quality of available prey.



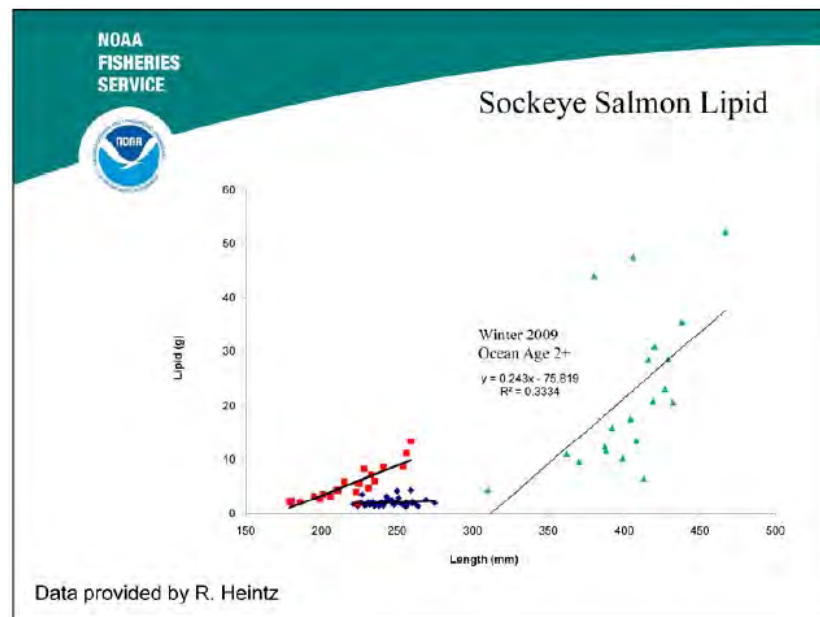
The winter survey captured all species of salmon. The length frequency of sockeye salmon suggested that many of these fish were in the size range that would be expected for ocean age 1 fish (up to 300mm). Larger/older (>300mm) fish were also collected during the survey. We did a genetic analyses of the sockeye salmon and found that approximately 70% of the ocean age 1 fish were made up of stocks from Bristol Bay and the Alaska Peninsula (AKPen). Thus, we felt that we could directly compare juvenile salmon energetic status captured during 2008 to the energetic status of the ocean age 1 fish captured during 2009.



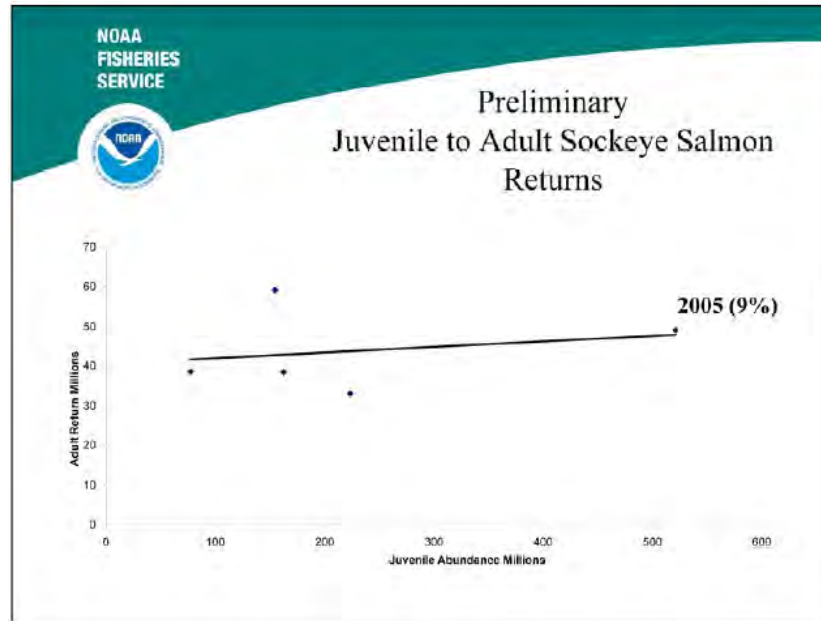
Lipid content in ocean age 1 sockeye salmon appears to be near threshold as the allometric relationship collapsed. Size range is truncated to larger fish – implies size selective mortality. Smaller fish have similar lipid to larger fish – implies that smaller fish are feeding to stay above some lipid threshold and larger fish are utilizing lipid stores perhaps to avoid predation?



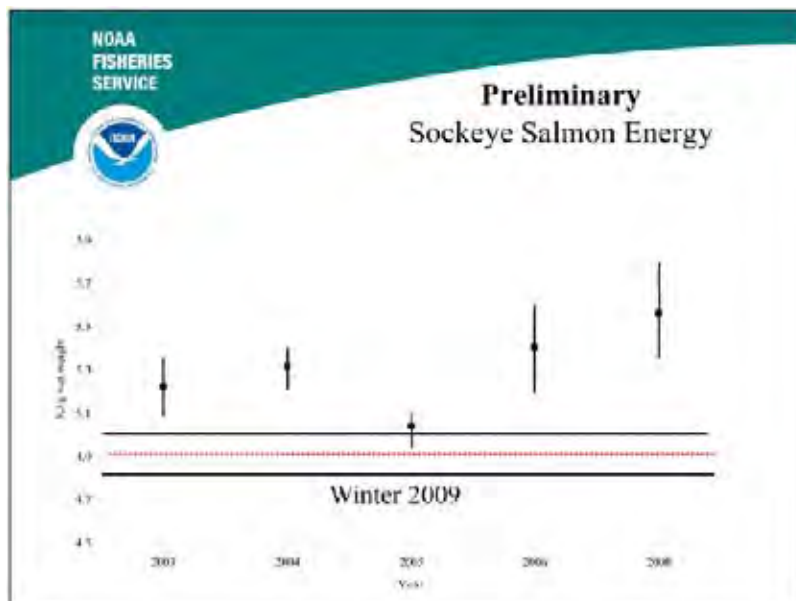
Protein or Structure has strong relationship with length and doesn't appear to drop indicating that fish are not using structure for energy but instead are using storage (lipid).



The relationship between lipid and length for older sockeye salmon indicates that these fish are not behaving the same as the smaller sockeye salmon. Why the outliers? Possibly these fish are not maturing this year, so lipid or storage is not being used for gonad development?



There are a number of studies attempting to link juvenile salmon abundance to adult returns (i.e. Orsi et al. juvenile pink salmon index related to adult pink salmon returns in southeast Alaska; Beamish juvenile sockeye salmon index related to Fraser River returns?). When we attempt relate juvenile sockeye salmon abundance to adult returns in Bristol Bay we see one possible outlier (2005) where there was only a 9% marine survival for that year.



If we use the energetic estimates for ocean age 1 sockeye salmon collected during Winter 2009 and assume that these energetic estimates are related to a threshold estimate of the surviving populations for that year and other years, then when we examine the energetic status for juvenile sockeye salmon during 2003 to 2006 and 2008 (2007 samples have not been run yet), we see that the 95% confidence intervals for 2005 overlap the 95% confidence intervals for winter energetic status. This indicates that fish collected during 2005 had low energy reserves at the end of their first summer at sea and thus would be expected to have high overwinter mortality.



Conclusions

- Recent warm cycle positive for juvenile Bristol Bay sockeye salmon.
- Energetic status after the first summer at sea may be a good predictor of marine stage survival.
- Ocean conditions (ecosystem productivity) can affect the relationship between size and energetic status.

If the Carrying Capacity (defined here as the capacity of the marine ecosystem to produce highly energetic of fit juvenile fish) of the marine ecosystem is unlimited, then we should see a positive relationship between juvenile abundance and adult returns. We show that energetic status can impact this relationship for juvenile Bristol Bay sockeye salmon indicating that carrying capacity is not unlimited, and is instead a function of ecosystem status and climate variability.

Are freshwater habitat conditions in the Fraser River watershed an important contributor to the Fraser sockeye salmon situation?

Pacific Salmon Commission Workshop to Examine the Decline in Survival of Fraser River Sockeye

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Hypothesis & Background

The following report outlines our response to the PSC request to evaluate freshwater habitat influences on recent trends in Fraser sockeye salmon returns. Here we focus only on freshwater habitat from spawning to smolt migration as the habitat conditions for migrating adults will be considered elsewhere. We have divided our analyses of the freshwater stage into two sub-hypotheses that address 1) the natal and nursery environments, and 2) the outmigration environment. Available habitat and fisheries data varies considerably both in quantity and quality influencing the degree to which these hypotheses can be addressed, and should be considered in the evaluation of our findings.

Sub-Hypothesis 1

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

Basin-Scale Analysis

Most of the total egg-adult mortality in sockeye salmon occurs in the freshwater stage of the life cycle. Bradford (1995) estimated that 58% of the total mortality occurred in the natal spawning and rearing areas, and there is additional mortality during migration from natal lakes to the ocean (Welch et al. 2009). Despite the significance of the freshwater period for population productivity, the freshwater stage is often not considered a contributor to declines in salmon stocks because there is little evidence of serial autocorrelation in freshwater survival (i.e. trends), nor large-scale spatial autocorrelation in survival that would cause populations to fluctuate synchronously at a regional scale (Bradford 1999; Rogers and Schindler 2008).

Human-induced alteration of freshwater habitats can have significant effects on salmon productivity (Table 1), and Fraser River sockeye have been impacted by activities such as the deposition of blasting spoils in the Fraser Canyon in 1912-1914 and temporary dams constructed on the Quesnel and Adams Rivers in the early 1900's (Roos 1991). Concerns over the impacts of logging on stream spawning areas led to the construction of the Weaver Creek and Nadina spawning channels in the 1960s. The impacts of road construction, removal of riparian vegetation, deforestation and other activities on stream and lake habitats have been well documented (e.g. Meehan 1991).

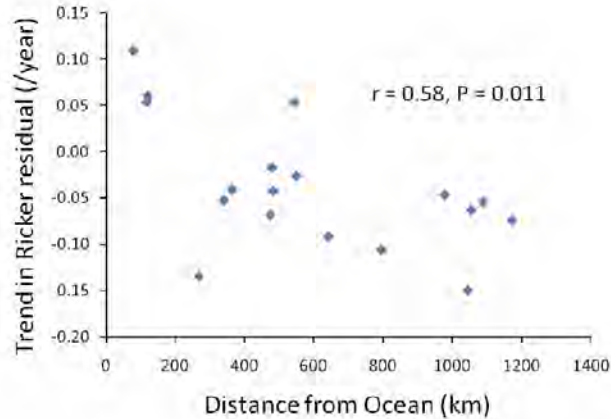
Table 1: Watershed and climatic habitat disturbance factors affecting freshwater sockeye productivity

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

To examine the role of freshwater habitats on sockeye salmon declines we hypothesized that some of the variation in the rate and severity of the decline among populations may be related to habitat conditions that are unique to that population (i.e. the natal spawning and rearing habitats). For example, if populations located in watersheds that were being heavily logged were declining at a more rapid rate than those located in parks or reserves that would support the hypothesis of changes in freshwater habitats contributing to declines in salmon productivity. This approach was successfully used to describe recent declines in Fraser River coho populations (Bradford and Irvine 2000).

For each of the populations identified by the PSC we calculated the slope of the regression of Ricker Residuals on brood year. We then developed a matrix of population and watershed characteristics to the extent that was possible in the time available. Land use statistics were obtained from the HectaresBC database (www.hectaresbc.org), although we were not always able to parse the land area most appropriate to each population using the watershed structure of the database. In addition, time series of changes in land use variables have not yet been compiled, and data for doing so may be limited. Thus our current analysis must be considered preliminary.

Using linear models, we detected a significant correlation between variation in the long-term trend in Ricker residuals (i.e. slope of regression fit to a 4-year running average of residuals) and measures of position of the natal watershed within the Fraser basin, which is most succinctly summarized by the average distance upstream from the mouth of the Fraser River to the spawning grounds for each stock ($r = -0.58$, $p = 0.11$, $n = 18$; Fig, 1). Distance from the ocean is significantly correlated to other factors reflecting watershed position, including latitude and nursery lake elevation. None of the other habitat variables used could explain additional significant variation in Ricker residual trends over this timeframe.

A) Trend in total productivity for 1984-2004 broods**B) Linear models with distance and a habitat factor**

Factor	p-value
Spawning configuration	0.63
Lake productivity	0.39
Road density	0.21
Recently logged	0.22
Stream crossings	0.28
Human land use	0.22

Figure 1: A) Relationships between the trends in total productivity (Ricker residuals) of the 18 Fraser drainage sockeye salmon populations and distance to the Pacific Ocean. Total productivity was also significantly related to other landscape variables collinear with distance (Latitude, $r = -0.58$, $p = 0.011$; Nursery Lake Elevation, $r = -0.65$, $p = 0.004$); B) Significance levels for habitat factors explored in addition to distance in our preliminary analysis.

Absence of a link between land-use and population trends is not unexpected. Sockeye salmon are likely less vulnerable to such habitat changes compared to coho salmon because sockeye often spawn in lake-buffered streams, and compensatory (and variable) mortality in the lake may mask spawning ground impacts. Moreover, lakes, with larger dilution volumes, and more varied habitat, may further buffer sockeye from land use impacts during rearing, relative to streams. However, as our analysis is preliminary, additional and more representative habitat data, and consideration of habitat effects during outmigration, may reveal underlying impacts on inter-stock productivity trends. At present, we have no evidence to support a cause-effect mechanism for the correlation between decline rates and watershed position, although a variety of factors can be hypothesized.

Nursery Lake Conditions

The productive capacity of British Columbia nursery lakes to rear juvenile sockeye salmon is limited by a variety of factors (Shortreed et al. 2001), and spatiotemporal variation in these variables can impact intra- and inter-population growth and survival (Goodlad 1974; Hume et al. 1996; Cox-Rogers et al. 2010). Synoptic information on the freshwater nursery conditions experienced by lake-rearing sockeye salmon in the Fraser drainage largely arises from seasonally-resolved (monthly; May-October), but temporally-restricted (typically 1-3 yr) limnological surveys of physical, chemical, and biological nursery ecosystem variables. Longer limnological time-series are limited, however, records for Quesnel and Chilko lakes yield some insights into multi-decadal habitat changes relative to the “*Fraser sockeye situation*”.

Seasonal mean photosynthetic rates (PR_{mean}) approximate basal food-web productivity, and have been successfully used to model productive capacities for sockeye in British Columbia (PR Model; Hume et al. 1996; Shortreed et al. 2000). Although the PR_{mean} time series are discontinuous, and recent data from Chilko Lake is limited, neither Quesnel or Chilko (unfertilized) data series demonstrate decreasing trends as would be expected if lake productive capacity was a primary control on declining total stock productivity (Fig. 2).

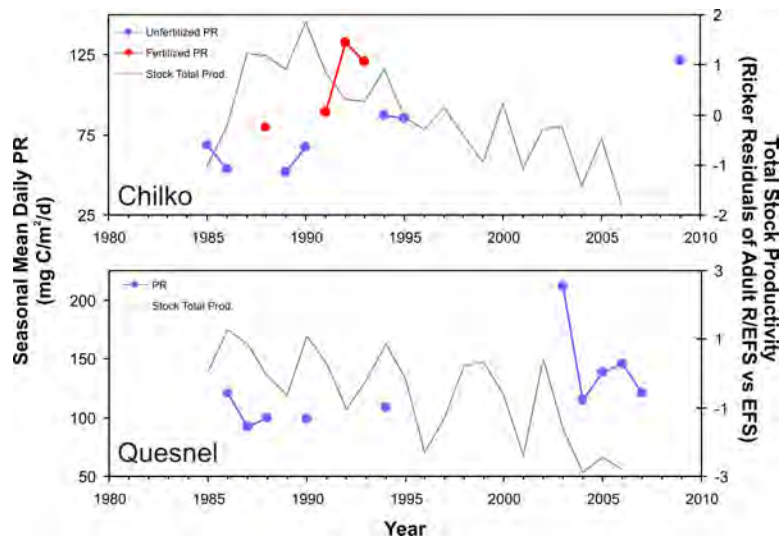


Figure 2: Time series of seasonal photosynthetic rates and stock productivity (Ricker residuals) in Chilko and Quesnel lakes (Data from Lakes Research Program and Pacific Salmon Commission)

Chilko Lake productivity appears to have increased in 2009 to levels similar to that during the artificial fertilization experiment of the early-1990's (Fig. 2). The elevated PR_{mean} may represent a food web stimulation contributing to the recent juvenile productivity index increases in Chilko Lake (i.e. Bradford et al. 2000), and studies are ongoing to determine if this is a persistent phenomenon. Quesnel Lake productivity was high in 2003 (Fig. 2)), most likely in response to the salmon-derived nutrient loading associated with the 2001-02 record escapements to the lake (Selbie and Shortreed *in prep*). While declining after 2003, Quesnel Lake PR_{mean} was significantly greater after the peak escapements than for the period before.

Fall zooplankton biomass in Quesnel Lake, which is the standing crop remaining after seasonal foraging by juvenile sockeye salmon, was expectedly lower in the years of the record escapements of 2001-02 (Fig. 3; Selbie and Shortreed, *in prep*).

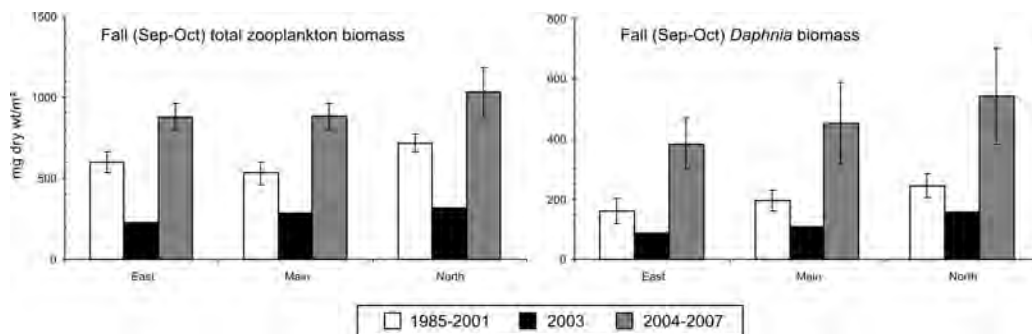


Figure 3: Mean fall (Sept.-Oct.) total zooplankton and *Daphnia* biomass in the East, Main, and North arms of Quesnel Lake. Data are averaged for the period prior to and following the lake year (2003) impacted by the record escapements in 2001 and 2002. Error bars represent 1 SE. (Selbie and Shortreed, *in prep*)

Biomass estimates for total zooplankton and *Daphnia* (the preferred food source for juvenile sockeye) following these large escapements, however, was equivalent to or even higher than those prior to 2003, indicating the persistence of quality forage in Quesnel Lake in recent years. In conjunction with the increased lake primary productivity, zooplankton abundances contrast with the hypothesis that food web productivity in the nursery lakes have been a primary control on the declines in salmon productivity.

The photosynthetic rate (PR) model (Hume et al. 1996; Shortreed et al. 2000; Cox-Rogers et al. 2010) predicts optimal sockeye salmon escapements (S_{max}) to nursery lakes that maximize the smolt biomass of these rearing ecosystems relative to productive capacity. Synoptic evidence from mean PR model predictions across the Fraser drainage indicates that while the majority of studied lakes have experienced maximum escapements below estimated productive capacity, several nursery ecosystems (Chilko, Chilliwack, Lillooet, Quesnel, Shuswap, Takla and Trembleur), which include major stocks that contributed to the 2009 poor return year, have exceeded their theoretical optimum productive capacities at least once since 1990 (Fig. 4).

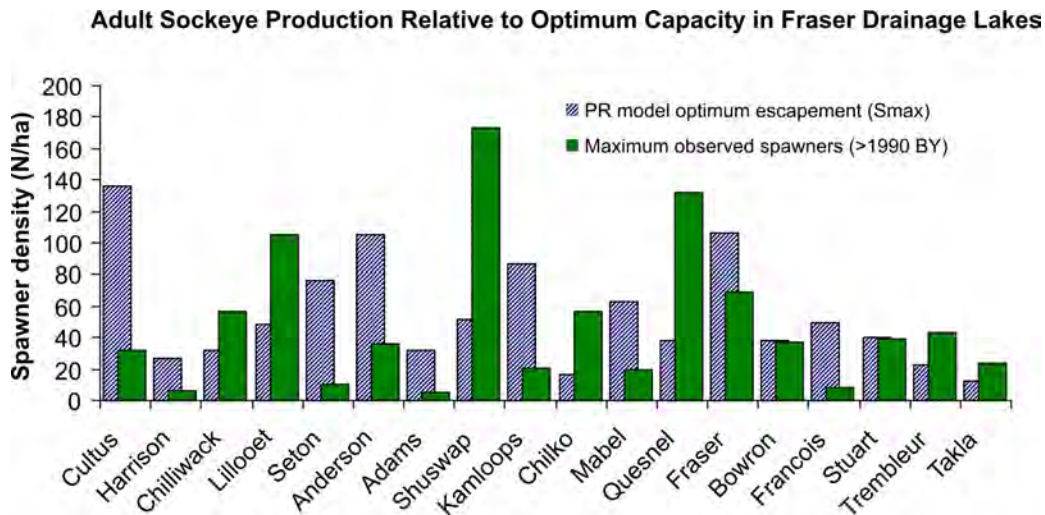


Figure 4: Maximum spawner escapements to select Fraser drainage nursery lakes relative to mean predicted optimum escapements (S_{max}) estimated by the photosynthetic rate (PR) model. Lakes are ordered by increasing distance from the Pacific Ocean (Data from Lakes Research Program and DFO Stock Assessment).

Juvenile Sockeye Productivity & Growth

We examined juvenile abundance data for sockeye populations that rear in Shuswap, Quesnel, and Chilko lakes. Time series data on the abundance and size of age-1 smolts at the Chilko River fence was available for Chilko Lake from the late 1940's. Time series data on the abundance and size of lake resident age-0 sockeye fry was available for most dominant and sub-dominant brood years from the 1970's using hydroacoustic and trawl surveys in Shuswap and Quesnel Lakes. Data from non-dominant years was not used in this analysis as the presence of kokanee at low sockeye densities could potentially influence the lake survey data. For all three lakes we also used the count of circuli to the first annulus in the otoliths of age 4₂ returning adults (indicative of growth to the first freshwater winter in surviving spawners).

We fit the Ricker model to the juvenile abundance and effective female spawner abundance (EFS) data and examined the trend in residuals. Similarly we fit a log-linear model to juvenile size and EFS data to remove the effects of density on size and examined the time series of residuals for evidence of changes in growing conditions in the nursery lakes.

Density dependent survival was observed for juveniles in all three lakes. There were no trends in the residuals over time (slopes ≈ 0 , $p \geq 0.30$). However, for 7 of 8 years since 1990 the residuals for Shuswap lake were below average. For Chilko Lake, Ricker residuals for the three recent brood years (2005-2007) are substantially above the average. These consistent deviations from the mean suggest a decrease in productivity in Shuswap Lake (unfortunately there are no recent limnological data exist to support this) or some other factor limiting survival (i.e. predation, competition, trophic restructuring), and an increase in productivity in Chilko Lake (which is supported by the 2009 limnological surveys).

Density dependent growth was observed in most but not all data sets. In Shuswap Lake, both the circuli counts ($r^2 = 0.49$, $p < 0.001$) and fall weight ($r^2 = 0.23$, $p = 0.06$) decreased with increasing EFS abundance. Circuli counts were negatively related to EFS abundance in both Quesnel ($r^2 = 0.33$, $p < 0.001$) and Chilko lakes ($r^2 =$

0.15, $p = 0.004$). However, there was no significant relationship with EFS abundance for fall fry weight in Quesnel Lake ($r^2 = 0.25$, $p = 0.09$), and smolt weight in Chilko Lake ($r^2 = 0.06$, $p = 0.06$).

For Shuswap and Chilko stocks, circuli counts, fall fry and smolt weights and their residuals from the density dependent relationships showed no temporal trend ($p > 0.10$ in all cases). We found a small but significant decrease in Quesnel Lake fall fry weight (slope = -0.05 g/yr, $r^2 = 0.56$, $p = 0.003$) and circuli count (slope = -0.09 circuli/yr, $r^2 = 0.41$, $p < 0.001$) from the 1970s to the present. Although there was a cycle year over cycle year increase in abundance in the dominant and sub-dominant cycle lines until the 2001-02 brood years, the limited evidence of density dependent growth makes it difficult to attribute the decrease in juvenile size over time entirely to spawner abundance.

Sub-Hypothesis 2

“Variation in trends in Ricker residuals for Fraser River populations is a function of changes in conditions during smolt outmigration.”

There are no survival estimates for Fraser River sockeye smolts from the time they leave their natal lakes, pass through the Fraser watershed and reach the marine environment, with the exception of the limited study of acoustically tagged Cultus Lake hatchery smolts (Welch et al. 2009), and a 2010 study at Chilko Lake. Interestingly, populations with the longest downstream smolt migrations had the greatest declines in total productivity (Fig. 1A), which is consistent with the hypothesis of increased mortality during lengthy migrations or a decrease in smolt fitness that affects survival once they reach the ocean.

Information on the timing of smolt migrations in the Fraser River are limited to records from Chilko and Cultus lakes, and from fish intercepted at the Mission pink and chum trapping program in the lower river.

Averaged over all years (Fig. 5), Chilko smolts migrate from the lake later than Cultus smolts. At Mission the smolt migration occurs over a month-long period centered on early May. However, the timing of migration of individual populations is unknown.

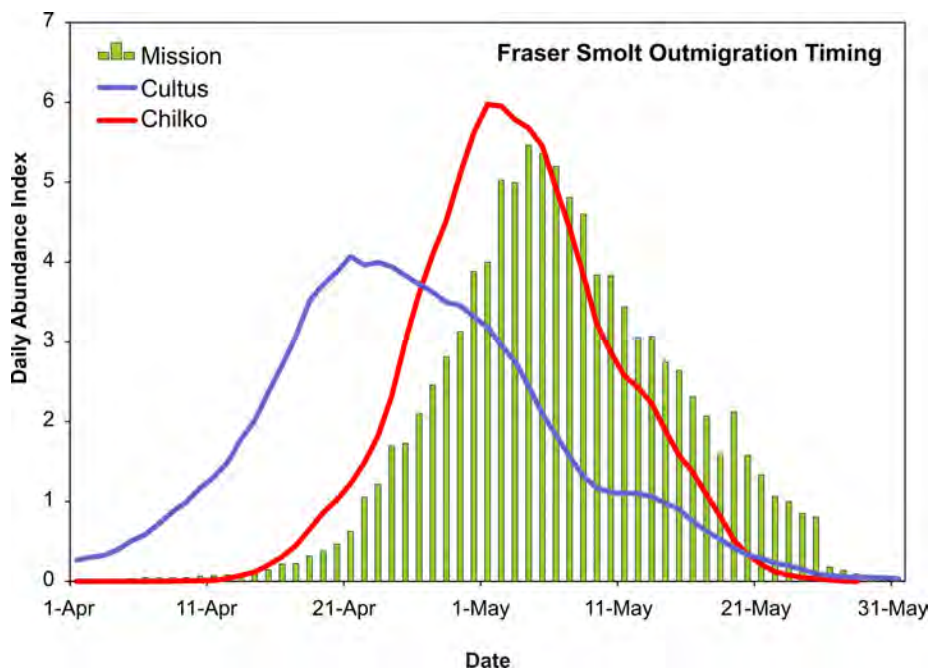


Figure 5: Available information for Fraser drainage smolt outmigration timing averaged across all years of data. Cultus and Chilko enumeration occurs at smolt fences, and the Mission estimates arise from by-catch in the downstream trap run for pink fry. Series are smoothed with a 7 day running average (data from DFO Stock Assessment and PSC).

Despite large inter-annual variability in both median date and duration of run, there has been no change in the median migration date from Chilko Lake or for captures in the Mission trap (Fig. 6). There has been a long term trend to later migration at Cultus Lake but neither the causes nor the implications of this trend are known.

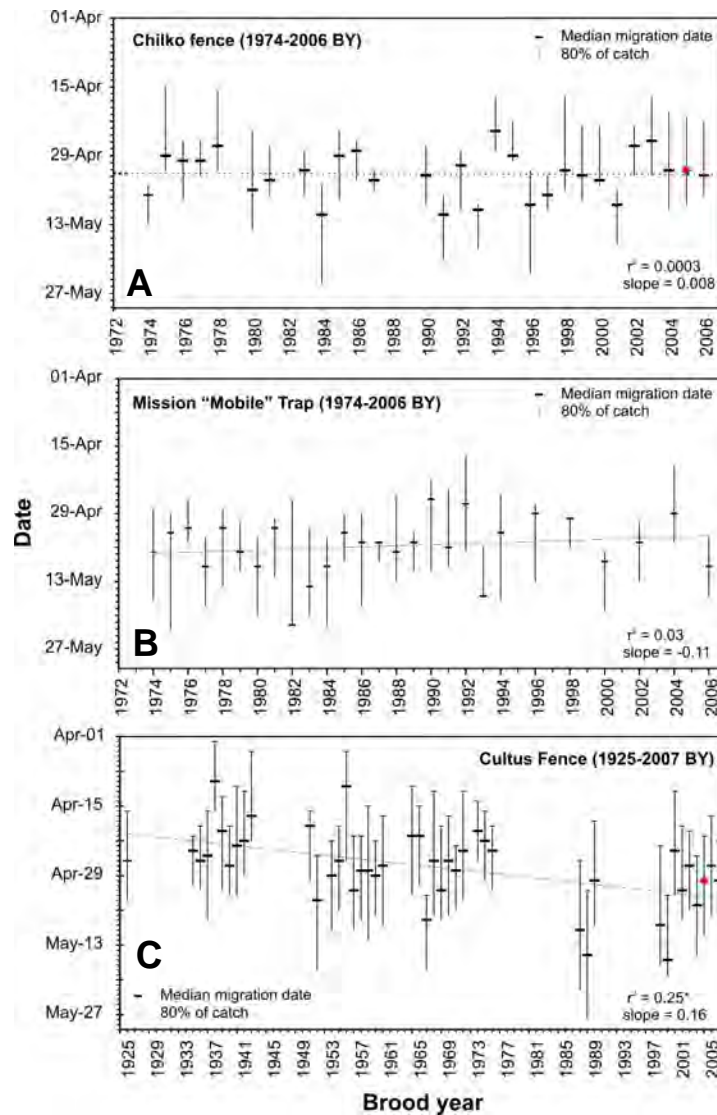


Figure 6: Timing of the smolt runs at: A) the Chilko River fence, B) the Mission "mobile" downstream trap, and C) The Cultus Lake fence. In all time series, the timing of the 2005 brood year (2009 return year) is indicated in red. Note the time series is much longer for the Cultus population (data from DFO stock assessment).

Conclusions:

We were unable to find any quantitative evidence to support the hypothesis that the declines in the productivity of Fraser sockeye salmon were related to changes in freshwater habitat conditions in the natal and nursery environments. Other than position in the basin, landscape or land use attributes of the natal watersheds were unrelated to the declines, however, our analyses are preliminary and could be further refined with better metrics of watershed condition and impacts. Estimates of lake productivity and juvenile size or survival for 3 of the major rearing lakes did not reveal any dramatic changes that would support the view that changes in those habitats are

consistent contributors to the declines, although density dependent survival occurs, and escapements have exceeded predicted optima in the last two decades.

We have only limited understanding of smolt migration stage, and no estimates of survival of juveniles for the interval between leaving the nursery lake and ocean entry. This is a major limitation in our understanding; interactions between population-specific migration timing, fish condition and ocean conditions may play a role in the variability in the rates of decline among populations.

Critical Knowledge Gaps in Freshwater

- Population-specific estimates of the timing, condition and behavior of sockeye smolts during migration from natal lakes to the Georgia Strait, including the Fraser River estuary.
- Watershed-based estimates of the degree of land-use, especially near spawning streams, and historical trends in those changes.
- Long-term monitoring of significant lakes in the watershed to evaluate human, climate and ecosystem changes that may affect sockeye production.

Future Research, Monitoring & Management Requirements

Critical Monitoring

- Expanded monitoring of smolt outmigration from the rearing lakes across populations (survival, behaviour)
- Maintain time series of freshwater productivity, nursery ecosystem structure and fry enumeration across nursery lakes with expansion to other key populations
- Maintain monitoring program for Fraser River environmental conditions with additional focus on time periods relevant for smolt outmigration

Critical Research

- Use experimental and tagging data to better understand mechanisms for, and magnitude of, freshwater outmigration mortality in sockeye smolts (e.g. UBC OTN/PCF is starting to do this). Possibilities include expanding the gear used at Mission for a better assessment of yearling migrations (may assist in chinook and coho assessments), and the use of DNA stock ID and physiological sampling to better identify stock specific factors that may affect late freshwater, estuary and early marine survival.
- Compile information on temporal changes in land use and forestry impacts and relate to changes in freshwater productivity across a range of populations (a model might be the Stuart Declines SEF Final Report submitted to the PSC)
- Merge disparate data sources available regarding environmental conditions in the spawning, incubation, and rearing environments and relate to changes in indices of freshwater productivity, fish condition, fish behaviour
- Improve our understanding of interactions between juvenile sockeye and other fish species present in rearing lakes (i.e. competition & predation)

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Session D: Freshwater conditions; Carl Walters, UBC

Hypothesis: Delayed density dependence due to Predation, food supply, and/or parasites has led to overescapement that is an important contributor to the Fraser sockeye situation

Carl Walters
Fisheries Centre, UBC

Overall recruitments and productivity (recruits/spawner, R/S) have been declining for the Fraser stock complex since the late 1980s, but fall fry (Quesnel, Late Shuswap) and smolt (Chilko, Cultus) to adult survival estimates indicate that downstream migration and marine survival rates have mainly declined since 2000, particularly in 2003-5. It appears that most of the earlier decline was due to reduced spawning and freshwater rearing survival, associated with increasing spawner abundance and hence likely due to density-dependent effects.

Even by the mid 1980s, we started to see $\ln(R/S)$ data for some stocks appeared to be better explained by including lagged density dependence effects of past spawner abundance (Larkin 1971 model) than by standard Ricker models that assume linear effects of brood year spawner abundance on $\ln(R/S)$, i.e. cyclic dominance effects (Walters and Staley 1987). More recent analyses (eg Martell et al 2008; Pestal et al. 2010 CSAP FRSSI presentation) have resulted in much stronger statistical evidence for such delayed effects, with the Larkin model clearly outperforming the Ricker model (AIC comparisons) for the major wild stocks: early Stuart, Late Stuart, Stellako, Quesnel, Chilko, Seymour, and Late Shuswap.

Both the Ricker and Larkin models overpredict recruitments during the 1950s, underpredict the peak recruitments of the 1980s, and overpredict recruitments after 2000 (Figure 1). But the Larkin model has substantially lower prediction errors after 1990, particularly if a non-standard fitting criterion (sum of squared deviations between observed and predicted recruitments) is used in the parameter estimation. The “standard” estimation approach is to assume log-normal recruitment variation, and so to seek the best fit to $\log(\text{Recruits})$. The standard approach places relatively more weight on prediction of low recruitments, leading to consistent underprediction of peak recruitments as shown in Figure 1. But as noted by Cass and Wood (1994), recruitment estimates are less reliable for low recruitments, due to errors in assignment of catch to stocks, so it is not clear that the standard $\log(\text{Recruits})$ criterion leads to correct weighting of the observations. But independent of the fitting criterion, the results in Figure 1 indicate that we can explain most of the most of the recruitment decline from 1990 to 2004 as effects of delayed density-dependence. It is also very suspicious that the two strongest negative recruitment anomalies (poor recruitments relative to predictions based on spawner abundance) prior to 2000, i.e. 1958 and 1991, both occurred shortly after recruitment peaks and influenced a number of stocks in the way that would be expected if the peak abundances had led to some widespread problem like a systemic disease outbreak; the second such event is correctly predicted by the Larkin models, but not the first one.

Delayed density dependence could be caused by predators/parasites, disease, and reduced zooplankton production. We have modeled effects of rainbow trout numerical responses (increased recruitment when juvenile trout have sockeye eggs/fry to eat in rearing streams) and

possible zooplankton depletion on the Quesnel stock, using a “risk-ratio” functional model based on the Beverton-Holt stock-recruitment equation (for derivation, see Walters and Martell 2004, Walters and Korman 1999). This model correctly predicts declining productivity up to 2004, mainly due to predator numerical response effects, then fails badly for the 2005 brood year. Walters and Martell (unpublished) found a similar good fit to a simpler food-predation model for Late Shuswap, again with predominantly predator numerical response effects. Unfortunately, time series data on actual predator changes in these systems would be needed to effectively test the models, and such data are lacking.

Piscivores like rainbow trout should cause delayed density dependent effects at lags 2-3 yr (time required for them to grow to piscivorous sizes), and the Larkin model fits do indicate such effects for Stuart, Stellako, Quesnel, and Late Shuswap. However, lag 1 yr effects are also strong in Larkin model fits for several stocks, most notably Chilko, and such rapid response effect would have to be due either to food depletion (unlikely) or diseases and parasites. Sockeye are notorious for disease problems, and disease/parasite effects could easily have delayed expression, i.e. not kill the juveniles until they are stressed by downstream migration and early ocean residence.

Except for Chilko, the Larkin model fits predict much lower optimum (MSY) spawning stocks, and substantially higher (75% vs 60-70%) optimum exploitation rates than the Ricker model. That is, models with delayed density dependence effects indicate that the adaptive management “experiment” to increase production through increased escapement was a failure, and that there has been severe overescapement since the 1980s. If marine survival improves, Larkin models indicate that the system should be managed with lower escapement and higher exploitation rates similar to those of the 1970s, and cyclic dominance should be deliberately maintained at least for Late Shuswap (dominance should also be maintained for Quesnel, but not for Chilko and late Stuart, with the best combined yield for this summer complex likely to come from policies that do not deliberately reinforce cyclic dominance).

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Figure 1. Comparison of total recruitment predictions and prediction errors for 10 wild stocks (E. Stuart, L. Stuart, Stellako, Bowron, Raft, Quesnel, Chilko, Seymour, Late Shuswap, and Birkenhead), using two alternative stock-recruitment models and model fitting criteria. Left column: prediction errors and predictions using “standard” log recruits per spawner fitting criterion. Right column: prediction errors and predictions using squared deviations of predicted from observed recruitments. Models compared are standard Ricker (no delayed density dependence) and Larkin model with parameters for delayed density effects; note delay parameter estimates vary widely among stocks. Models fitted using effective female spawners. (data from modified LaPointe spreadsheet Fraser sockeye 2010 review.xls, saved in ricker larkin comparison.xls-prediction comparison tab; available from Walters)

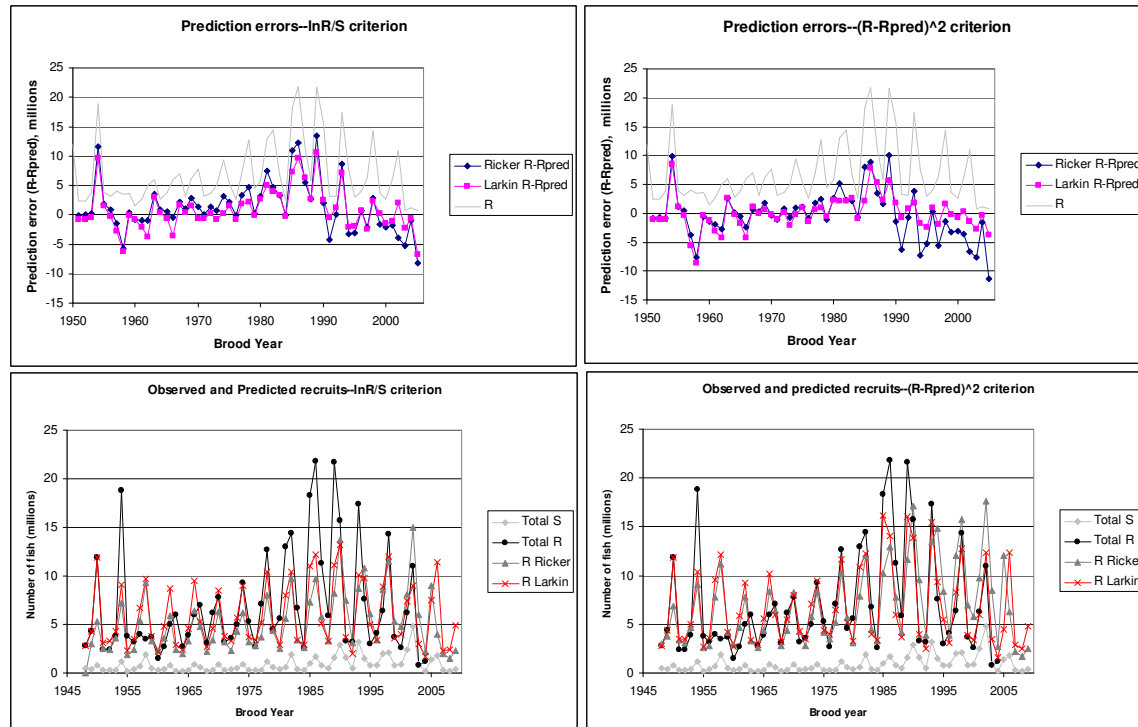
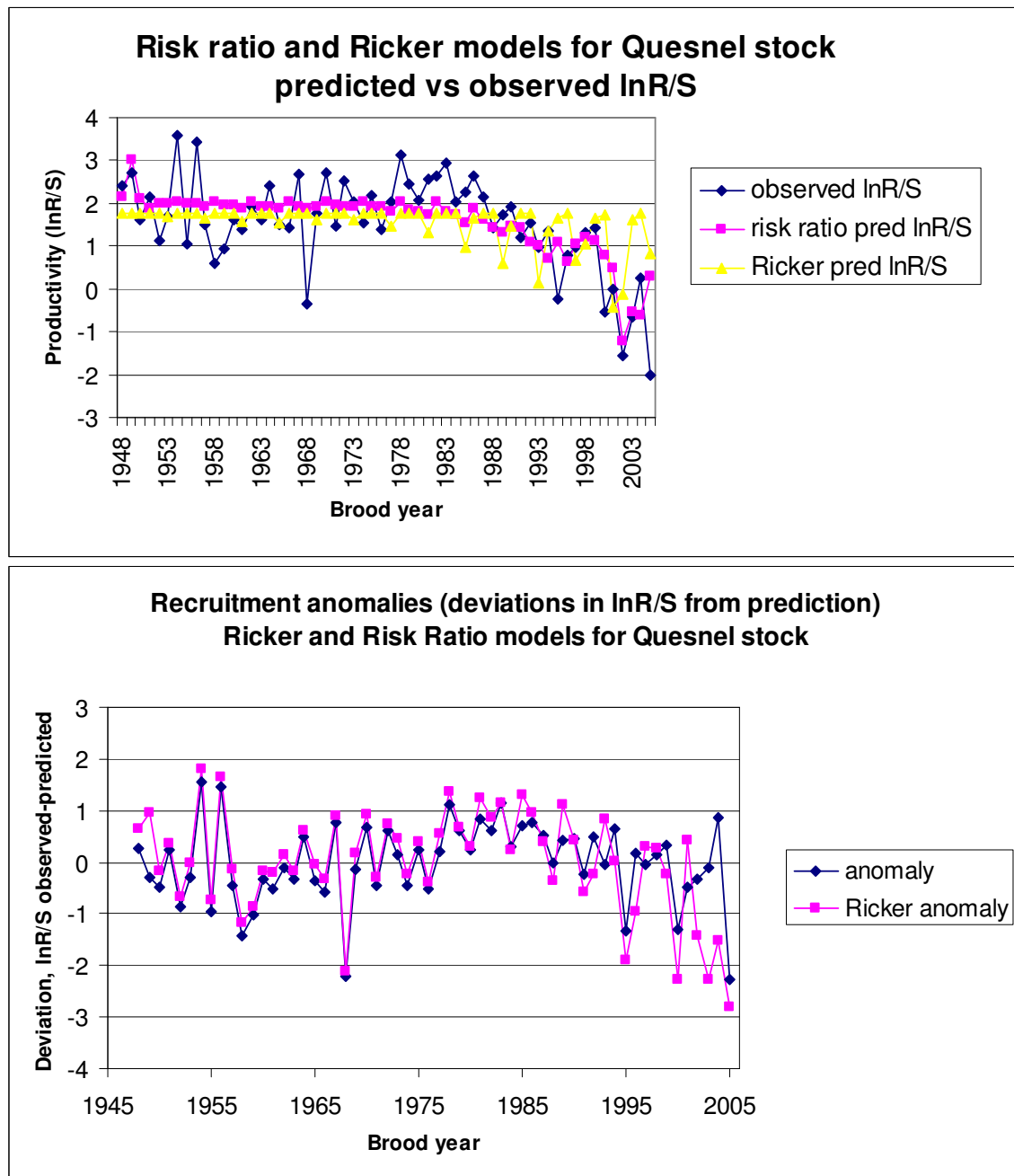


Figure 2. Comparison of Ricker model predictions of productivity ($\ln R/S$) to predictions from a functional model based on the Beverton-Holt stock recruitment equation, with terms that explicitly represent changes in zooplankton production and predation rates by rainbow trout.



Session D: Freshwater conditions; Scott Hinch. UBC

Difficult Spawning Migration Conditions and En Route Mortality, Pre-spawn mortality and Intergenerational Effects:

Hypothesis: “En-route mortality during upstream migration, plus effects on fitness of the next generation, are important contributors to the Fraser sockeye situation”

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Question 1. To what extent does adult freshwater mortality (i.e. en route and pre-spawn) explain the *overall* spatial and temporal trends of declines in spawner to spawner productivity and declines in spawner abundance

Average indices of recruits per effective female spawner (R/EFS) have remained above replacement (R/EFS > 2) since the early 1990's, for all of the 18 major Fraser sockeye stocks. However, between the 1993 – 2004 brood years, several Fraser sockeye stocks have been below total replacement (spawner-to-spawner < 1) in $\geq 50\%$ of years. We used spawner-to-spawner (S/S) trends as an index of *total* productivity as it incorporates the effects of harvest and freshwater en route mortality in overall population decline, factors not included in the traditional R/EFS. Spawner returns by brood year were calculated by subtracting total stock-specific harvest and total en route loss (scaled based on the proportion of each age-class returning in a given year) from age-specific recruitment estimates (Data source: PSC). Stocks with the lowest average S/S over the 1993 - 2004 period have, on average, the longest freshwater migration distance ($R=-0.58$; $p=0.01$); a relationship not observed in the previous 12 brood years.

En route loss estimates are influenced by natural mortality, unreported catches and escapement estimation errors (Patterson et al. 2007; Macdonald et al. 2010). Stressors contributing to increased rates of en route loss have increased from the 1990's to present across all stocks, including Shuswap and Harrison. Further, en route loss explains significant amounts of the variation in the S/S trends for some stocks. For example, >50% of the inter-annual variation in S/S for Early Stuart and Weaver can be explained by en route loss. Overall, 9 stocks had en route loss estimates >50% in at least 6 of the last 12 brood years. The decline in S/S relative to R/EFS, the spatial pattern in S/S by distance, and large stock specific en route loss estimates in recent year are all consistent with the hypothesis of a possible freshwater adult migration influence on sockeye population trends.

Question 2. Provide evidence for relating the spatial and temporal declines to freshwater adult mortality

En route (migration) mortality – The basic biological hypothesis is that thermal (and thermal-related) issues play a large role in among and within-stock variation in S/S productivity and total abundance. We know that stocks differ in their freshwater migratory distance and entry timing, both of which directly affect their thermal migratory experience. In-river thermal characteristics and migration behaviours have recently changed which has exacerbated the effect of thermal issues on migration and spawning success. Specifically, since the 1950s there has been $\sim 2^\circ\text{C}$ increase in summer water temperature ($\sim 1^\circ\text{C}$ in recent 20 years) and 8 of the last 11 years have ranked as the warmest summer temperatures on record. In addition, since 1996, Late-run sockeye

have entered the river 4-6 weeks earlier than normal and thus encounter temperatures up to 5 °C warmer than usual.

In the laboratory, we have conducted swimming and cardiac performance studies, thermal manipulation studies, disease studies, and energy manipulation studies to test and develop theories on thermal based migration mortality. We have found that optimum and critical high temperatures vary among stocks in relation to historic encountered temperatures during migration, that stocks are adapted to historic migration temperatures, and that only a narrow window exists between optimum and critical temperatures (~ 5 °C). Early Stuart and Late runs are adapted to cooler migration conditions and will perform best at these temperatures. Summer runs are adapted to higher temperatures because their river timing coincides with the peak of the thermograph occurring mid-summer. Mortality can occur quickly, in a matter of hours to days, when metabolic / cardiac collapse occurs or when fish are significantly stressed. Chronic effects related to temperature, such as disease and energy limitations, can cause mortality in days to weeks.

There are several diseases associated with different pathogens that migrating and spawning sockeye contract and that could contribute to enroute or prespawning mortality. One pathogen that has received considerable attention is the naturally occurring parasite infection - *Parvicapsula minibicornis*. It infects kidneys and gills in all Fraser sockeye and we have shown as it becomes full blown, mortality increases in lab held sockeye.

Using field data, one can examine the difference between Mission and spawning ground escapement estimates (en route losses) in relation to migratory temperature (and discharge) exposures for each stock. En route losses increase when average encountered temperatures are 18 °C and higher, and for Early Summer and Summer runs, can reach 40-50 % when average temperatures exceed 19 °C. Our group has conducted numerous telemetry studies investigating stock-specific relationships between river survival and temperature. Field information provides strong support for our lab work (and vice versa) in that adult mortality rates climb rapidly once river temperatures are 18 °C or higher. Stocks differ in their susceptibility to high temperatures with Early Stuarts and Late runs being most strongly affected. Some Summer runs also show declining survival with temperatures above 18 °C (e.g. Quesnel, Stellako) but others (e.g. Chilko) do not. Weaver Creek and Shuswap adult sockeye also showed declining survival above 18 °C. A detailed telemetry study on Weaver fish found 100% mortality at 20 °C (the upper lethal temperature for this stock as determined in lab studies), 70-90% mortality at 19 °C, and 20-50% mortality at physiological optimum temperatures. Biopsy telemetry studies focussed on Late run sockeye have found that early entering fish are maturing relatively fast but are physiologically ill-prepared for freshwater migration. The relatively high temperatures early migrants encounter compound stress and may account for the exceptionally high mortality they experience en route. These interpretations are supported by independent analyses using functional genomics by K. Miller.

In conclusion, while the spatial trends driven by stock-specific differences in en route loss are not consistent with the system-wide decline in S/S productivity, 40% of stocks show negative correlations between S/S productivity and en route loss since 1992. Further, en route mortality has been substantial in many stocks, across all run-timing groups in recent years, in particular in years when migration temperatures > 18 °C. Taken together, en route loss observations, lab experiments and field telemetry studies support the hypothesis that differences among stocks in productivity can be explained in part by how specific stocks cope with acute and chronic thermal stressors (e.g. early and late runs, and long distance migrants, cope less well).

Pre-spawning (on spawning ground) mortality (PSM) –There is a long history of information and publications on PSM. PSM can range from 0 to 90%, but extreme events are episodic and patterns are highly variable among stocks. PSM may be somewhat higher and more variable in recent years though this pattern is hard to detect. The causes of PSM are complex and multi-factorial and include disease, high stress and low energy, and time alive on spawning grounds. Most of these factors are accentuated by increasing temperature so it is not surprising that within-stock trends in PSM are correlated with migration and/or spawning ground temperatures, and that correlations with temperature improve with proximity to spawning ground. There is evidence that PSM is simply a continuation of physiological processes responsible for en route mortality. Although PSM, by definition, clearly affects effective female spawner abundance, few relationships could be uncovered between PSM and S/S productivity.

Intergenerational effects – This area of research is relatively new and involves field observations of fecundity and gamete quality, and lab experiments in which adult migrants are exposed to high temperatures or high flows to alter energy and stress levels during simulated migrations, and then using artificial fertilizations, egg, embryo, and fry characteristics are examined. Egg quality does not seem to be affected by the health of the parent (gametes from moribund and recently dead adults are highly viable and of good quality) though experiments to examine specifically how adult migrant or spawner condition affects productivity in terms of returns in the next generation have not been carried out. However, evidence is now accumulating from several telemetry and lab studies that migrating females perish at much higher rates (~ twice as high) than males when conditions are ‘stressful’ towards end of migration, creating an interesting and biologically compelling intergenerational consequence that could have ramifications to S/S productivity patterns.

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

Future research on this area should support the current research programs working on en route loss, pre-spawn mortality and intergenerational effects as well as branch out and focus on more interdisciplinary work looking at survival across different life stages and habitats. In general, more research is also needed in the area of cumulative impacts. More specific research areas that require on-going and future research include:

- Better understanding and quantification of natural mortality occurring between marine approach areas (i.e. Area 20/12) and Mission.
- Improvements to en route loss models. More specifically, being able to quantify the contributions of estimation errors and unreported catch so that models of en route loss can more explicitly account for direct estimates of mortality.
- More research examining cumulative effects in general. Both across multiple stressors and in terms of cumulative effects over life history stages and/or generations. More specifically, this could include:
 - Research into the impacts of multiple environmental stressors (e.g. temperature, flow, water quality and water chemistry)
 - Cumulative impacts of fishery interactions (e.g. discard mortality, cumulative impacts of recurring gear avoidance/encounters)
 - Cumulative effects of changes to fish health and behaviour across life stages/habitats

- How inter-annual variability in oceanographic conditions and fish condition prior to river entry affect survival and response to the freshwater environment)
 - Variation in quality and quantity of eggs successfully deposited after migration and the links to subsequent survival.
- A retooling of research to look at general patterns in explaining stock-specific vulnerability that could be applied to the more numerous CU's to align with WSP.

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

Fisheries management and habitat actions have already been applied and adopted to mitigate the effects of adult sockeye freshwater mortality. Examples include: (1) monitoring and forecasting of river temperature and discharge using pre-season (Patterson and Hague 2008), in-season (Morrison 2005), and long range forecasts (Martins et. al. In press; Hague et. al. In press); (2) application of predictive tools using environmental forecasts (e.g. Management Adjustment models – Macdonald et al. 2010) to predict harvest adjustments necessary to meet spawning escapement targets in-season; (3) general science advice regarding in-river mortality (e.g. Late run workshop – Hinch 2009); (4) evaluation of mitigation strategies e.g. Nechako water release program (Macdonald et al. 2007) and development of fish passage structures (e.g. Seton dam, Hells Gate).

Future fisheries management and habitat actions that may help reduce the effect of high en route mortality on future sustainability of Fraser sockeye include the following:

- Better predictions of in-river mortality to improve the probability of meeting escapement and harvest objectives.
 - Stock or CU specific predictions
 - Quantification of fishery interaction mortality estimates (e.g. discard mortality)
- Predictive models for pre-spawn mortality to deal with impacts of episodic events.
- Better post season estimates of en route mortality for more accurate calculation of productivity estimates.
- Quantification of intergenerational effects in relation to population productivity and abundance.
- Application of climate change modelling linked to life history models for productivity and escapement planning.
- Development of best practices for different fisheries for reducing indirect fishery induced mortality.
- Habitat protection of migration corridors and potential thermal refugia.
- Habitat mitigation projects to improve fish passage conditions.

For Publications see:

<http://faculty.forestry.ubc.ca/hinch/index.html>

<http://www.pac.dfo-mpo.gc.ca/science/habitat/frw-rfo/index-eng.htm>

Session E: Other factors affecting Fraser sockeye; Phil Mundy, NOAA

Workshop on the Decline of Fraser River sockeye

**Vancouver Island Conference Centre
101 Gordon St., Nanaimo, BC, V9R 5J8**

June 15 – 17, 2010

Hypothesis: Unreported catch outside of the Pacific Salmon Treaty area is an important contributor to the Fraser sockeye situation

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Summary of Recommendations

Illegal, Unregulated and Unreported Fishing

High Seas Drift Net Fishing

NPAFC: Reject, data unavailable

U.S. NOAA OLE: Reject, data available

Regulated non-PST fisheries

Bycatch in U.S. non-treaty federal fisheries

Fishery Observer Reports: Reject, data available

Coded Wire Tags: Reject, data available

The hypothesis that unreported catch outside of the Pacific Salmon Treaty area is an important contributor to the Fraser sockeye situation is not tenable. Sockeye are not reported in illegal fisheries inside the US EEZ. Outside the EEZ, high seas drift net fishing HSDN targeting salmon including sockeye are thought to be declining but the amount of salmon caught in HSDN salmon fishing is unknown. Sockeye salmon are relatively uncommon in bycatches of directed legal fisheries in non-PST areas. The absence of coded wire tagged sockeye from hatcheries in Alaska in fishery observer samples, and the absence of coded wire tag recoveries from the limited number of Fraser sockeye that have been tagged in federal fisheries, lends credence to the absence of sockeye in bycatch of legal fisheries.

Please note the answers to the four questions are on the last page.

Illegal, Unregulated and Unreported Fishing, IUUF

IUUF: North Pacific Anadromous Fish Convention

Data on enforcement under the Convention for the Conservation of Anadromous Stocks in the North Pacific Ocean are not publicly available. Enforcement effort is dependent on annually determined levels of funding by individual member nations, hence levels of enforcement effort may vary annually. For example in the years 1999 – 2008 annual enforcement effort in person-hours for a single Convention law enforcement entity varied from 125 to 1648, averaged 481.7 and annual effort was highly variable (S.D. 477.6). Similarly total annual law enforcement vessel and aircraft operating hours for a different single law enforcement entity 1999-2008 ranged from 109 hours to 2443 hours with an average of 1007.0 hours and S.D. of 771.9. Catch of HSDN vessels per hundred patrol vessel hours (CPUE) for this one agency ranged from a low of zero to a high of 0.42 from 1999 – 2008. Average CPUE was 0.22 and the S.D. was 0.17. The agency had zero vessel patrol hours in three of the ten years, so $N = 7$.

Total law enforcement vessel and air hours by all members in the convention areas is roughly twice the amount for the single entity used as an example above, based on publicly released information. For example in 2009 the NPAFC reported in its publicly available annual report that members' patrolled convention waters for 188 vessel days and 279 air hours without sighting (or presumably apprehending) any HSDN vessels, so HSDN CPUE in 2009 was zero. The number of years with zero, or near zero CPUE, and the lack of sightings of HSDN vessels in 2009 is the foundation for the current conventional wisdom that HSDN harvest of salmon is on the decline. Nonetheless depending on the locality and time of year, HSDN vessels are capable of removing enough Fraser sockeye to be responsible for the current situation. The issue is moot however because it is not known how many salmon have been or are being taken in HSDN fishing, so the likelihood that HSDN fishing in the convention areas is an important contributor to the Fraser sockeye situation cannot be evaluated. The matter should not be examined further in the current inquiry.

IUUF: U.S. NOAA Office of Law Enforcement (OLE) Alaska

Data on enforcement activities in the U.S. federal EEZ in Alaska are freely available on request and in web published quarterly reports so they will not be reproduced here. Annual levels of active enforcement including patrol and investigation typically exceed 10,000 person hours. Infractions involving IUUF for salmon are relatively rare, and advances in technology are making vessels that may be fishing illegally easier to detect.

OLE has an important law enforcement advantage in the Alaskan EEZ not yet available in Convention waters. The law enforcement advantage in the U.S EEZ is the increasing proportion of the fishing fleet that is participating in the vessel monitoring system (VMS). VMS permits relatively inexpensive shore based tracking of the exact location of each VMS equipped vessel at all times. It provides an advantage because legally permitted vessels, which transmit with VMS can be readily distinguished from vessels that may be fishing illegally. Vessel Monitoring Systems (VMS) are required on all vessels permitted for directed federal fisheries for pollock, Pacific cod, and Atka mackerel. In federal fisheries in the Aleutians all vessels are required to

have VMS. In the Gulf of Alaska all vessels fishing non-pelagic trawl and dredge gear are required to have VMS. Requiring smaller fishing vessels to carry VMS is somewhat controversial due to the added expense imposed. As larger proportions of the fishing fleet are required to carry VMS, detection of illegal fishing becomes easier.

Based on the data available from OLE, IUUF in federally regulated non-treaty waters of Alaska is unlikely to have contributed to the situation of low productivity with which the workshop is concerned.

Bycatch in Regulated Non-PST Fishing Sockeye in Federal Fisheries bycatch

The majority of the salmon bycatch occurs in the Bering Sea fisheries. Bycatch of salmon other than Chinook is mostly chum salmon. Note that the figures for 2005 refer only to the first quarter of 2005, which is a time of year when non-Chinook bycatches are minimal.

Table 3-2 Bycatch of salmon species comprising the 'other salmon' management category, 2001-2005, in numbers of fish

Year	Sockeye	Coho	Pink	Chum	Total	% Chum
2001	178	584	12	51,152	51,926	98.5
2002	1	143	45	66,975	67,164	99.7
2003	24	111	106	139,421	139,662	99.8
2004	13	135	135	363,019	363,302	99.9
2005*	0	222	2	658	882	74.6
Total	216	1,195	300	621,225	622,936	99.7

*catch data through March 2005

Source: NOAA Fisheries Catch Accounting (note these data are preliminary)

Even if all of the few sockeye reported from among the bycatches originated in the Fraser River there are not enough to be of interest in the evaluation of the situation at hand. Coded wire tag releases and recoveries were examined to as a means to confirm the low incidence of sockeye in the fishery observer reports.

Evidence from coded wire tags

Federal fisheries in Alaska are sampled for fish bearing coded wire tags by fishery observers deployed on fishing vessels. Although sockeye from hatchery programs in Alaska are routinely coded wire tagged, no CWT sockeye (any stock) have ever been recovered by fishery observers in the Bering Sea Aleutian Islands or Gulf of Alaska fisheries. There have been 4 recoveries of CWT sockeye from Japanese (2) and US (2) high seas research (1996-98). The 2 US trawl research recoveries were in the area of the GOA trawl fishery; both fish were 2 year olds (total age) originating from PWS. The 2 Japanese recoveries were far off the coast of BC, with 1 fish originating from PWS and 1 from SE AK.

In the Pacific States Marine Fisheries Commission database there are records of release for only 276,794 sockeye from the Fraser River basin. These releases were in 1989 - 1992. Out of those 276,794 released, only 780 (0.3%) were ever recovered, all in PST area fisheries. There were

754 recovered on the spawning grounds, 26 (0.009%) in ocean fisheries distributed as follows: 3 in BC ocean sport, 1 in BC troll, and 22 in net fisheries (17 SE AK, 4 BC, 1 WA).

The lack of tag recovery data substantially confirms the low incidence of sockeye in bycatch reported by observers.

Conclusion: The hypothesis that unreported catch outside of the Pacific Salmon Treaty area is an important contributor to the Fraser sockeye situation is inconsistent with all of the available data.

Answers to the Four Questions

Q1. To what extent does the specific hypothesis (or hypotheses) about Fraser River sockeye salmon stocks that you have been asked to address explain the spatial and temporal trends of: (1) adult recruits, (2) adult recruits per effective female spawner, and/or (3) residuals from Ricker models fit to $\log_e(\text{recruits per effective female spawner})$?

A1. It does not explain these spatial or temporal trends at all.

2. What direct or indirect evidence is there to support (or not support) the hypothesis you have been asked to address?

Please see materials above for the data used. Changes in fisheries gear or seasons could change patterns of non-PST fishing mortality for Fraser sockeye. Fishing is a source of direct mortality.

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

Implementation of a Vessel Monitoring System requirement for fishing vessels of all nations within the NPAFC Convention area.

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

The mechanism is completely under the control of management given sufficient law enforcement and implementation of VMS technologies on fishing vessels.

Session E: Other factors affecting Fraser sockeye; Greg Ruggerone, Natural Resources Consultants Inc.

Competition Between Fraser Sockeye Salmon and Pink Salmon

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Introduction

Recent studies of Bristol Bay sockeye salmon indicate strong competition with Russian pink salmon, which have a distinct alternating-year pattern of abundance (Ruggerone et al. 2003, 2005, 2007; Ruggerone and Nielsen 2005, 2009). Competition with Russian pink salmon led to reduced growth, reduced smolt survival, and approximately 91 million fewer Bristol Bay sockeye salmon during 1977-1997.

The objective of this investigation was to test the hypothesis that interactions with pink salmon may adversely affect the growth, survival, and age-at-maturation of Fraser River sockeye salmon. Analyses relied, in part, on the natural experimental control in which adult pink salmon abundance is high during odd- versus even-numbered years. Pink salmon abundance in the North Pacific Ocean has doubled since the early 1970s. During 1990-2005, approximately 160 million pink salmon per year returned to North America and 365 million pink salmon per year returned to all regions of the North Pacific (Ruggerone et al. 2010).

Methods

Fraser sockeye salmon data were provided by the Pacific Salmon Commission (PSC). Total productivity was defined as the residual from the Ricker recruitment curve ($\ln R/S$) for each of 18 stocks, i.e., adult return per spawner after removing density-dependent effects of parent spawners. Productivity estimates included all age groups of sockeye salmon. Analyses relied upon mean productivity of 16 sockeye salmon stocks. Harrison and Shuswap sockeye salmon were analyzed separately because the productivity of those stocks was reportedly different from the other 16 stocks. Some analyses relied upon differenced values (e.g., value in year Y minus the value in the previous year, etc.) to remove the long-term trend and to highlight alternating-year patterns that were associated with pink salmon. Findings are preliminary.

Alternating-year Patterns in Sockeye Salmon Productivity

- Differenced productivity from odd-year broods was significantly less than that of even-year broods, 1979-2005 (**Fig. 1**). Mean productivity of the 2003 and 2005 broods, which returned primarily in 2007 and 2009, were exceptionally low but productivity from the 2004 brood was not.
- Lower total productivity from odd-year broods was observed in 14 of 18 stocks (**Fig. 1**). The four “outlier” stocks having higher productivity from odd-year broods, on average, were Harrison, Shuswap, Chilko, and Quesnel.

- Odd-year broods produced smolts (mostly age-1) that entered the ocean during odd-numbered years when relatively few Fraser pink salmon were present. Therefore, it appears that the alternating-year productivity pattern of the 14 stocks was not directly related to interactions with juvenile pink salmon migrating from the Fraser River. Instead, an interaction with pink salmon may have occurred in the ocean and/or during the homeward migration (see below).
- Odd-year broods produced juvenile sockeye salmon having significantly lower productivity in freshwater (spawners to fry or smolts) and lower post-freshwater productivity, based on the 8 stocks for which data were available.

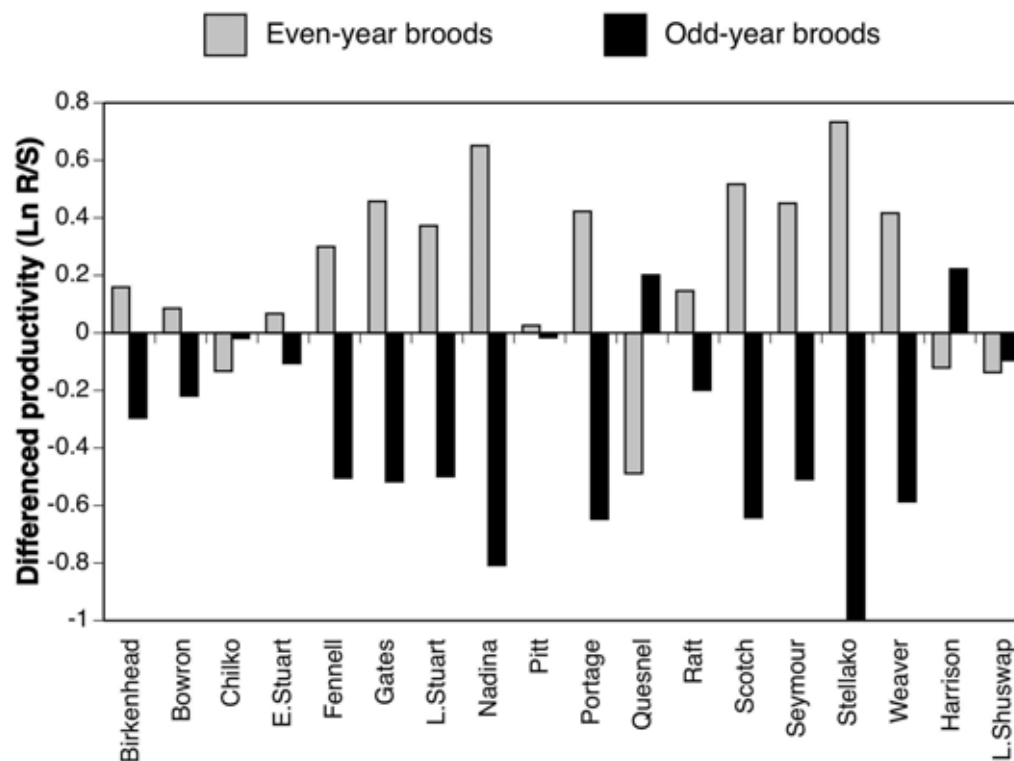


Fig. 1. Mean differenced productivity of 18 Fraser sockeye salmon stocks during odd- versus even-year broods, 1979-2005. Productivity from even-year broods was significantly greater than productivity from odd-year broods. Harrison and Shuswap sockeye salmon are shown but excluded from the statistical analysis.

Sockeye Length-at-Age

- Differenced mean length of age-1.2 sockeye salmon from Chilko, Weaver, Stellako, and early Stuart stocks (stocks with complete time series) were significantly smaller during odd- versus even-numbered years of return, 1953-2009. This observation, coupled with the fact that age-1 sockeye smolts produced by odd-year broods encounter very few pink salmon in the Strait of Georgia, suggests that the primary interaction occurred during late marine life rather than early marine life. Reduced adult length might have influenced lower freshwater productivity from odd-year broods (see above).

Sockeye Age-at-Maturation

- Mean age-at-maturation of 16 stocks was significantly delayed among odd- versus even-year broods, 1979-2004 (2005 brood is incomplete). This pattern held for Harrison but not Shuswap sockeye.
- The mean proportion of age-5 sockeye salmon (16 stocks) produced by a brood increased significantly with greater pink salmon abundance returning four years after the sockeye brood year during 1961-2004 (pink salmon stocks: Fraser, Southeast Alaska and Prince William Sound). Variability explained by pink salmon was 48%.
- Mean total productivity of Fraser sockeye salmon was inversely related to mean proportion of age-5 sockeye in the brood return, 1961-2004. Approximately 32% of the variability in productivity was explained by proportion of age-5 salmon, suggesting that delayed maturation contributed to the overall decline in Fraser sockeye salmon. Productivity of Shuswap and Harrison sockeye salmon was not associated with age composition.

Do Adult Pink Salmon Consume Sockeye Smolts?

- Total sockeye productivity was not negatively correlated with adult pink salmon that returned during the year of sockeye smolt migration. Thus, adult pink salmon do not appear to significantly predate on sockeye salmon smolts entering the ocean.

Effects of Pink Salmon on Sockeye Productivity and Abundance

- Mean total productivity of 16 sockeye stocks was inversely correlated with abundance of adult pink salmon from key populations in North America ($r = -0.57$) and inversely correlated with these stocks plus Russian pink salmon ($r = -0.67$), which have been exceptionally abundant (**Fig. 2**).
- Assuming average spawner abundance during 1979-2005, the estimated “loss” of sockeye salmon from odd- versus even-year broods was approximately 611,000 sockeye salmon per year (avg. 26% reduction per stock) for all stocks, excluding Harrison and Shuswap. Return per spawner was 2.4 lower, on average. Excluding Quesnel, which tended to produce greater returns from odd-numbered broods, the loss per year increased to 1.38 million sockeye salmon per year.

Conclusion

- Pink salmon in the North Pacific influenced productivity, length-at-age, and age-at-maturation of Fraser sockeye salmon. The “pink salmon effect” was consistent with exceptionally low productivity from the 2003 and 2005 broods (adult returns in 2007 & 2009), but additional factors likely contributed to the recent decline.

References: Available on request.

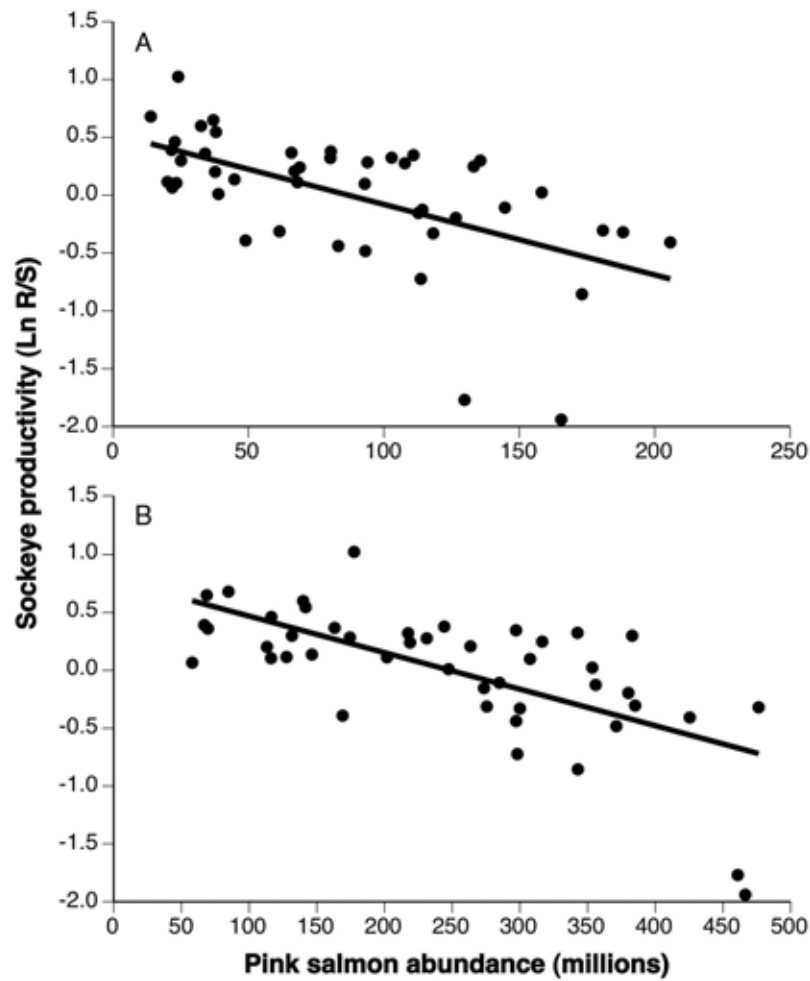


Fig. 2. Relationship between mean total productivity of 16 Fraser sockeye stocks (brood years 1961-2005) and A) abundance of pink salmon returning to the Fraser River, Southeast Alaska and Prince William Sound during the year of adult sockeye return, i.e., brood year plus 4 years, and B) abundance of pink salmon returning to the aforementioned areas plus Russia. The 2003 and 2005 broods remain outliers.