EXECUTIVE SUMMARY:

Project 9: Effects of climate change on Fraser River sockeye salmon

- We present an assessment of the possible contribution of climate change to the recent decline in abundance and productivity of Fraser River sockeye salmon. Our assessment was based on a review of the literature evaluating the effects of climate-related variables (i.e. climate variables and other physical variables influenced by climate) on the biology and ecology of sockeye salmon across all life stages.

- A total of 1799 documents were found in our search for primary (n=1519) and grey (n=280) literature. Of this total, only 114 documents (89 and 25 from the primary and grey literature, respectively) remained after the removal of duplicates, conference abstracts and documents that did not attempt to link a climate-related variable to sockeye salmon biology or ecology. Fraser River sockeye salmon were included in the dataset of 64 (56.1%) publications. The earliest publication resulting from our literature search appeared in the late 1930s. In the subsequent three decades, only a few publications on the effects of climate-related variables on sockeye salmon appeared in the literature and virtually all of them dealt with freshwater life stages. It was not until the 1970s that the number of publications started to increase considerably until the current decade. The great majority of publications dealing with marine life stages only started to appear in the 1980s and their numbers have been growing ever since, though they still lag behind those dealing with freshwater life stages.

- We synthesized the current state of knowledge on the effects of climate-related variables on survival (estimated by the authors either indirectly using productivity indices or directly through direct observation or the analysis of tagging data) on the life stages of sockeye salmon. Based on our synthesis, we made a qualitative assessment of the likelihood that life-stage-specific survival of Fraser River sockeye salmon has been undergoing a trend in the past 20 years due to the recent trends in climate, particularly in temperature (warming of 0.5 oC and 1.0 oC in marine and freshwater environments, respectively, over the past two decades). For each life stage, we rated potential climate-driven trends in survival as very likely, likely, possible and unlikely to have occurred. In general, these ratings were defined so that more weight of evidence was given to findings obtained from field studies.

- Our assessment concluded that: survival of eggs has possibly increased (but not in all stocks); survival of alevins has unlikely changed; survival of fry in lakes has possibly decreased; survival of smolts and postsmolts has likely decreased; survival of immatures in the ocean has possibly decreased; survival of returning adults has very likely decreased (but not in all stocks); once on the spawning grounds, survival to spawn has possibly decreased (but not in all stocks).

- Our qualitative assessment suggests that the survival of all life stages of Fraser River sockeye salmon, with the possible exception of eggs and alevins, may be declining due to trends in temperature (and the factors that correlate with temperature) in both marine and freshwater environments over the past 20 years. However, where data exist at the stock-level for some life history stages (e.g. eggs, alevin, adult migrants), the picture is

complicated by stock-specific patterns indicating that the survival of some stocks may have been less impacted than that of others or not impacted at all.

- Although the recent warming may not have resulted in large declines in survival of individual life stages, the cumulative impacts of climate change on survival across life stages could have been substantial. Overall, the weight of the evidence suggests that climate change may have adversely affected survival of Fraser River sockeye salmon and hence has been a possible contributor to the observed declining trend in abundance and productivity over the past 20 years. It also seems that inter-annual variability in climate conditions have contributed to the extreme variation in the abundance of returning adults that were observed in 2009 (much lower than average) and 2010 (much higher than average), as the years that those cohorts went to sea were characterized by unusually warm (2007) and cool (2008) sea surface temperatures, respectively.

- Recent analyses of the potential effects of future climate change on Fraser River sockeye salmon all point to reduced survival and lower productivity if the climate continues to warm. Although there is some potential for tolerance to warm temperatures to evolve in Pacific salmon, further evolutionary change may already be restricted in populations that have historically experienced high temperatures, such as Summer-run Fraser River sockeye salmon. Phenological (i.e. timing of events such as seaward migration and return migration) changes are likely to be one of the major responses of Pacific salmon to climate change. Several adaptation strategies to lessen the ecological, economic and social impacts of climate change effects on Pacific salmon have been recently proposed.

Adult mortality during river migration and on spawning grounds

- The primary purposes of this section are to: review the major environmental factors responsible for adult sockeye salmon mortality during Fraser River migrations (termed 'en route mortality') and for premature mortality on spawning grounds (termed 'pre-spawn mortality'), review the early migration/high mortality Late-run sockeye salmon phenomenon, describe interannual and within-year among stock patterns in adult mortality, and provide a mechanistic understanding for several of these patterns.

- River entry timing and abundance of adult sockeye salmon has been quantitatively assessed since 1977 by the Pacific Salmon Commission (PSC) just upstream of the Fraser River mouth near Mission, B.C., using various forms of hydroacoustic methods linked with stock ID sampling. Fisheries and Oceans Canada (DFO) and the PSC refer to the differences in estimates of stock-specific abundance obtained from the Mission site and those obtained from spawning grounds (after accounting for reported in-river harvest upstream of Mission) as 'escapement discrepancies' which are used to assess en route loss, the percentages of each run that cannot be accounted for during the migration, which is an indirect assessment of migration (en route) mortality.

- Generally, en route loss begins to be reported in 1992 for Early Stuart, Early summer, and Summer-runs, but not until 1996 for Late-runs. Relative to total catch and spawning ground escapement, levels of en route loss have been increasing, with recent years having some of the relative highest levels. In several years, en route loss is the dominant component of the fate of the Early Stuart and Late-run timing groups, and, since 1996,

en route loss of at least 30% has been observed for at least one run-timing group in each year.

- Eight out of 11 stocks had more than half of years between 1996 and 2008 when en route loss within those stocks exceeded 50%. There is clearly an effect of run timing on this pattern. The earlier runs (e.g. Early Stuart, Scotch, Seymour, Fennell, Gates and Nadina) and the later runs (Harrison, Portage and Weaver) have the most years with high en route loss. Summer-runs (e.g. Quesnel and Chilko) have experienced few if any years with large (> 50%) en route loss. There is good evidence that the among-stock patterns in en route loss are indicative of stock-specific abilities to cope with warming rivers and high river temperatures.

- Changing thermal conditions have been one of the largest environmental challenges that migrating adult Fraser River sockeye salmon have had to deal with over the past 20 years: 1) the Fraser River has experienced ~ 2.5 oC warming in the summer compared to 60 years ago, with average summer temperatures warming ~ 1 ºC in the most recent 20 years; 2) there have been several recent years with extreme temperatures during mid-summer (water temperatures in 13 of the last 20 summers have been the warmest on record); and 3) since 1996, segments of all Late-run sockeye salmon stocks have been entering the Fraser River 3-6 weeks earlier than normal – they now encounter temperatures up to 5 ºC warmer than they historically did and are spending longer in freshwater because spawning migration dates have not changed. Therefore Late-run fish have been exposed to freshwater diseases and parasites for much longer periods of time, with disease development being accelerated by higher than normal river temperatures (due to earlier river entry and climate warming), and greater degree day accumulation.

- Over the past decade there have been numerous field telemetry investigations examining en route mortality and the body of evidence indicates that en route mortality is stock-specific with Summer-runs having the greatest thermal tolerance, relative to earlier and later runs, supporting the among-stock patterns in en route loss. Laboratory investigations suggest that Fraser River sockeye salmon stocks vary in both their optimum and critical high temperatures in a manner that reflects local adaptation to temperatures experienced during their historic migration - stocks appear to be physiologically fine-tuned to function best at the river migration temperatures they historically encountered. Summer-run stocks have the highest critical temperatures and the largest aerobic and cardiac scopes of all groups of sockeye salmon. Earlier migrating Late-runs are particularly poorly adept at dealing with the relatively high temperatures and prolonged exposure to freshwater diseases.

- Pre-spawn mortality is highly variable among stocks, run-timing groups and years over the 70-year data series. With the exception of 12 years, pre-spawn mortality has not exceeded 30% at the run-timing group level; only in four years did pre-spawn mortality of a run-timing group exceed 40%. Across all run-timing groups over the entire 70-year period, pre-spawn mortality averaged ~ 10%. There is no clear indication that pre-spawn mortality, at the run-timing level, has been increasing over the recent few decades in concordance with run-timing trends in increasing en route mortality, with the possible exception of the past 25-year trend in Late-run pre-spawn mortality, which shows high variability but a general increase.

- Spawning abundance has declined in Early Stuart and several Late-run stocks during a time period when en route loss became a significant component of the total fate of adult migrants in those groups of fish. Spawning abundance has not declined dramatically in most stocks partly because of reductions in harvest associated with management adjustments made to compensate for en route mortality. Therefore, spawning abundance could have been a great deal higher (or allocations to fisheries greater) in recent years if it were not for en route loss.

- En route loss may be a critical factor contributing to decreasing trends in spawning abundance for some Fraser River sockeye salmon stocks, in particular, those that do not cope well with warming rivers. En route and pre-spawn mortality in adult sockeye salmon are significant factors that reduce the number of effective female spawners, and thus may pose a threat to the long-term viability of the populations that are particularly affected.

Recommendations

We recommend the following research directions:

- Telemetry approaches and direct experimentation are needed to better understand sockeye salmon marine survival: An understanding of the mechanisms through which climate-related variables affect sockeye salmon in the marine environment should be sought with the application of electronic tagging technologies and exposing tagged fish to varying temperature, salinity, pH, or parasites.

- Field-based research is needed on early life stages in freshwater: Much of the past work in freshwater has been conducted in the laboratory; little is known on how temperature influences biology and ecology (e.g. interaction with prey and predators) of the early life stages of sockeye salmon in streams and lakes. Future research efforts should also be directed at the effects of increased stream flows on egg survival since higher levels of rainfall during the time of incubation are expected to occur with climate change.

- Improvements are needed in-season and post-season estimates of spawning migration mortality: Fisheries management needs better ways to predict en route and pre-spawn mortality prior to fish entering the Fraser River. Also needed are improvements to en route loss models (e.g. quantify the contributions of estimation errors and unreported catch).

- Tagging programs are needed for direct and accurate estimates of survival: Accurate estimates of survival from tagged fish are required for efficient monitoring of stocks and analyses of viability using life-cycle models. Telemetry programs as well as programs using other tagging approaches (e.g. Petersen discs, PIT or anchor tags) are needed for this purpose and should be coupled with capture-mark-recapture methods of data analysis.

- Additional stocks need to be examined: Only a few major stocks have been intensively studied to date in terms of en route mortality, but adult sockeye salmon from different stocks vary substantially in their life history, energy use and allocation, thermal tolerance, and habitats used. A multi-stock approach to research could provide valuable

information on the mechanisms through which climate-related variables will sockeye salmon on the watershed level scale.

- Better assess the extent and consequences of gender differences in survival of migrating adult sockeye salmon: Future research should look into the extent and physiological basis of survival differences between sexes and investigate the consequences of female-specific survival for the viability of Fraser River sockeye salmon, particularly under future climate warming.

- Assess impacts of fisheries capture and release/escape on en route and pre-spawn mortality: Managers need to know how release or escape of captured fish affects en route loss and escapement. In an era of warming rivers we expect higher stress-related mortality after release/escape but these levels are largely unknown for Fraser River sockeye salmon and most Pacific salmon.

- Cumulative impacts, carry-over and intergenerational effects: There has been little research examining cumulative impacts, both across multiple stressors (e.g. fisheries capture, temperature, pollutants) or life history stages (i.e. carry-over effects), and/or among generations (i.e. intergenerational effects). These information gaps are critical to fill to begin to understand current trends in sockeye salmon productivity and abundance.

- Climate change modelling: Needed are the development of life-cycle models in order to quantify the impact of climate warming on future trends in Fraser River sockeye salmon productivity and abundance. More stock-specific information on the susceptibility to climate change is needed for this purpose. Research aimed at understanding how sockeye salmon will adapt to climate change through genetic and non-genetic mechanisms will also be needed.