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Workshop to assess population dynamics of cyclic Fraser River sockeye and implications for management

Compte rendu de l'atelier d'évaluation de la dynamique des populations de saumon rouge du fleuve Fraser à dominance cyclique et la gestion de celles-ci

February 7-8, 2006
University of British Columbia
Vancouver, BC

7 et 8 février 2006
Université de la Colombie-Britannique
Vancouver, C.-B.

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Summary

A workshop was held at the University of British Columbia Feb 7-8 2006 to review hypotheses, models and management implications for cyclic populations of Fraser River sockeye. The workshop was hosted by Fisheries and Oceans Canada and was attended by 31 experts from BC, Washington State and Alaska. The workshop was part of the Fraser River Sockeye Spawning Initiative (FRSSI) to develop harvest rules for managing Fraser river sockeye. This FRSSI is also the pilot implementation project for Canada's Wild Salmon Policy. Day-1 focused on alternative stock-recruitment models/hypotheses for modelling the population dynamics of sockeye. Day-2 evaluated management implications for cyclic populations. Workshop participants reached consensus on several long-standing issues related to population dynamics modelling and implications for the management of sockeye salmon.

Sommaire

Un atelier a été tenu à l'Université de la Colombie-Britannique le 7 et le 8 février 2006 pour examiner les hypothèses et les modèles liés aux populations à dominance cyclique de saumon rouge du fleuve Fraser ainsi que la gestion de celles-ci. L'atelier a été organisé par Pêches et Océans Canada, et 31 spécialistes provenant de la C.-B., de l'État de Washington et de l'Alaska y ont participé. Cet atelier s'inscrivait dans le cadre du projet de reproduction du saumon rouge du fleuve Fraser (PRSRFF) dont le but est d'élaborer des règles relatives à la pêche pour gérer le saumon rouge du fleuve Fraser. Le PRSRFF constitue également le projet pilote de mise en œuvre de la Politique canadienne concernant le saumon sauvage. Le jour 1 de l'atelier a été axé sur les modèles/hypothèses de rechange concernant le stock et le recrutement utilisés pour modéliser la dynamique des populations de saumon rouge. Au cours du jour 2, on a évalué la gestion des populations à dominance cyclique. Les participants à l'atelier sont parvenus à un consensus sur plusieurs enjeux de longue date concernant la modélisation de la dynamique des populations ainsi que la gestion du saumon rouge.

Introduction

Fisheries and Oceans Canada (DFO) has undertaken a multi-year initiative to develop and implement harvest control rules for the management of Fraser sockeye. The *Spawning Initiative* uses alternative assumptions about population dynamics models and clearly specified management objectives to determine optimal harvest control rules that specify variable target exploitation rates for a range of abundances. This deviates from the historical escapement-based policies of the last several decades.

In the past four years, DFO has been engaging stakeholders and client groups through a series of workshops, and collectively substantial progress has been made developing a stakeholder-driven management approach. One critical issue that has polarized participants' views on management alternatives is how to deal with populations that exhibit cyclic patterns in abundance. Despite more than 50 years of study, there has been no scientific consensus on the mechanisms that cause cycles or on assessing the full suite of model structures that could be used to capture these dynamics. Recent work at Simon Fraser University, The University of British Columbia and elsewhere, however, has made progress on this front.

DFO hosted a workshop February 7-8 2006 to facilitate a scientific debate of alternative hypotheses for Fraser sockeye population dynamics and implications for resource management in the next steps of the *Spawning Initiative*. The meeting agenda is provided in Appendix 1. Scientific experts and participants with additional experiential knowledge from BC, Washington and Alaska attended the meeting (Appendix 2). The workshop format consisted of several presentations and open discussion on the population dynamics and implications for management. Consensus among participants on key issues discussed at the workshop is reported in the conclusions of these proceedings.

Purpose of the workshop

The workshop addressed the four topics reflected in the questions below:

1. **Hypotheses -** Given the patterns observed in total abundance and escapement of Fraser River sockeye, what hypotheses can explain the observed patterns of recruitment (e.g., random variation, cycle line interactions, genetic effects, ecosystem interactions, depensatory mortality, depensatory fishing, etc...)? Can any of these hypotheses be rejected with current data given the weight of evidence?

2. **Stocks -** Which stocks/populations clearly demonstrate cyclic patterns? For those stocks where the possibility of cyclic dominance cannot be rejected,

can the potential for cyclic dominance be expressed as a range of probabilities (e.g. >80% probability that the stock is cyclical)?

3. **Models -** For those stocks that appear to be cyclical, which stock-recruitment model best describes the current pattern of recruitment? Are the data that are currently available adequate to characterize the production dynamics of these stocks?

4. **Implications -** Given uncertainty about the population dynamics and the management system (i.e. implementation error), how should we manage? What are the implications of managing based on the incorrect assumption about the population dynamics? What types of adaptive management or experimentation would have a high probability of detecting the causes of cyclic dominance (i.e., of rejecting hypotheses)? What types of research would elucidate the mechanisms initiating and maintaining cyclic dominance? How many years of data would be required? What is the value/cost of experimentation/research to determine the answer?

Presentation summaries and discussion points

1. Cycle-line interaction as a mechanism for cyclic dominance in Fraser River sockeye. Jim Woodey, Mike Lapointe and Jeremy Hume

- Interactions between brood year and prior cycle-line abundances of Quesnel Lake sockeye spawners and/or juveniles were found in analyses of recruitment rate and of first year lacustrine growth as measured from adult scales.

- In addition to a significant effect of parental spawner abundance, spawner abundances one, two and, at times, three years earlier yielded significant effects when added sequentially as variables in multiple regressions. At times, these lag effects were of similar magnitude as the brood year effect.

- Cycle-line interactions in Quesnel Lake sockeye appear to be initiated by the large numbers of juveniles produced by dominant line broods every fourth year. Weight growth of subdominant and first offcycle line juveniles appeared inhibited despite expected compensatory effects due to lower density.

- Information from *in situ* acoustic surveys and trawl net catches of juvenile sockeye showed that dominant line juveniles were more abundant and larger in body size at a given parent spawner density than following year subdominant line juveniles when sampled in the summer (August).

- Depletion of *Daphnia*, the preferred food organism, by large dominant line juvenile populations in summer and fall samples appeared to carry over into the spring of the following year when subdominant line juveniles entered the lake. This may have led to lower juvenile growth on the latter line and, presumably, to higher spring-early summer mortality rates.

- Subdominant line juveniles had higher instantaneous body growth rates from summer to fall surveys, but did not recover from the retarded early growth and, presumably due to size-mediated survival rate, abundance remained lower than expected.

- Regression analyses showed significant one-year lag effects on juvenile abundance and fall mean weight. These findings strongly implicate the retardation of juvenile growth on cycle lines following the dominant line broods as the mechanism behind cyclic dominance in Quesnel Lake sockeye.

- We speculate that piscivorous fish and birds exert a size-mediated predation mortality on the juvenile sockeye populations, overcoming the compensatory survival that would be expected if cycle-line interaction was absent.

- Regressions between recruitment rate ($\log_e$ R/EFS) and scale circuli count produced a two-step spawner-recruit model, the Juvenile Growth Model, that provided a means of predicting recruitment rate under various assumptions of adult spawner escapement.

Participant discussion points:

- Differences in parameter estimates for the Ricker model for all years versus cycle line are due to leverage of single data points and are caused by time series bias.

- What is the difference in spring (e.g. plus) growth between sub-dominant and dominant cycle lines for Quesnel? Is there evidence to suggest smolts on sub-dominant cycle line leave rearing areas later to make up growth?
    - No direct evidence for Quesnel. Haven't observed this at Chilko. This may occur in the Shuswap as the lake is warmer and food supply is not as depleted.

- The issue is not whether cycle line interactions occur given there is strong evidence for cycles.
    - The key question is the determination of which dynamics predict higher yield (e.g. cyclic or non-cyclic). This question is related to model fitting (e.g. which model will predict the higher production). However, the evidence here is much weaker.

- How good are the spawner escapement estimates? What is the potential for errors in this variable?
    - Different assessment programs are used depending on forecast abundance: Mark recapture program for escapement >25,000 spawners and visual programs for smaller escapements.
    - Measurement errors are likely larger for smaller spawner abundance

2. Simulation of the Juvenile Growth Model (JGM) for cyclical stocks of Fraser River sockeye salmon. Carrie A. Holt and Randall M. Peterman

- Models that are used to evaluate management options for Fraser River sockeye salmon should adequately reflect observed cyclic dominance patterns, preferably by representing the underlying mechanisms.

- Using Monte Carlo simulations, we compared the performance of a new, more mechanistically based stochastic stock-recruitment model, the Juvenile Growth model (JGM), to that of the Ricker and Larkin models for two sockeye stocks of the Fraser River, Quesnel Lake and Late Shuswap.

- The JGM, which includes empirically estimated cycle-line interactions, related spawner abundances in two or more brood years to the freshwater growth of juvenile sockeye salmon, which in turn affected their survival rate in fresh and salt water.

- Our formulation of the JGM also included an environmental covariate, the PDO index. We measured performance of each model in terms of its propensity to emulate the observed cyclic dominance pattern and reflect the historically observed range of abundances.

- In simulations of Quesnel Lake sockeye that used mean historical exploitation rates with random implementation error, the JGM and Larkin models produced cyclic-dominant recruitment patterns in 28% to 48% of the trials, which was more often than the widely used Ricker model (13%). Thus, models that assumed interactions among cycle lines performed better than the Ricker model. However, no model produced cyclic-dominant patterns close to the historically observed level (100%), suggesting that other factors, such as temporal patterns in historical exploitation rates, may also be important.

- Although the JGM emulated cyclic-dominant patterns for Late Shuswap sockeye in 51% to 58% of the cases, its simulated mean annual recruitment was unreasonably large. The Ricker and Larkin models performed even more poorly for Late Shuswap sockeye, especially at low exploitation rates, suggesting that none of these models adequately represented the population dynamics of this stock.

Participant discussion points:

- JGM and Larkin models are structurally similar, so what caused the differential model results? Was it due to differences in parameter estimates?
    - PDO was included in the JGM model in the parameter estimation and forward simulation, but not in the Larkin model.

3. The mystery of cyclic dominance in sockeye salmon. Carl Walters

- A retrospective analysis evaluated optimal MSY policies by calculating what would have been the optimal sequence of spawner abundance given observed residual patterns in recruitment.

- Stock-recruitment models that did not account for cycle interactions were not optimal for the Bristol Bay Kvichak River and Quesnel Lake sockeye.

- For fixed escapement policies, it is important to account for changes in the carrying capacity parameter (e.g. Naknek and Wood systems in Alaska).

- For exploitation rate policies, it is important to know the productivity parameter (e.g. intercept for fit of Log_e (R/S) vs. S). This parameter may differ between cycle lines for Quesnel.

- Higher potential yields could have been obtained in the period 1950's – 1970's because escapements were below "optimum" for maximizing yield. Exploitation rates were likely close to "optimal".

- Dynamic programming results:
    - With zero uncertainty about the system, the optimal harvest rule is a fixed escapement strategy.
    - Uncertainty about the size of the population shifts the harvest rule towards a fixed exploitation rate rule.
    - Increased weighting on economic objectives also shifts the result towards a fixed exploitation rate objective.
    - Reconstructions of Fraser sockeye abundance suggests past abundance may not have been much larger than those recently observed, suggesting little support for further increases to escapement.

- When plotted on log scale, off-cycle lines are rapidly increasing in abundance in all Fraser populations (except Adams). In other words, cyclic dominance is breaking down and may not be the natural state of affairs for these populations. So, is cyclic dominance an intrinsic natural phenomenon given that it may break down as exploitation rates decline?

- Evidence indicates that cyclic dynamics may not be a natural phenomenon. Cascading of 5 year old fish from dominate to sub-dominate to off-cycle lines may be proximate cause of building abundance on other cycle lines and breakdown of cyclic dominance.

- Recovering populations like Quesnel have had reduced exploitation rates on at least some off-cycle years. Adams is an exception, but this population has had consistently higher exploitation rates on off-cycle Adams years due to fisheries targeting Weaver (e.g. depensatory fishing hypothesis) until late 1990's.

- In Alaska, the Kvichak population may have been forced out of a cyclic regime by an experimental program of higher escapements on off-cycles in 1980-90's. This has resulted in lower yield relative to historical cyclic period.

- Declines in recruits/spawner have occurred in Kvichak and Quesnel where cycles are breaking down, but not in Shuswap where cycles are persisting.

- Issues associated with stabilizing spawning abundance at a high level:
    - progressive depletion of food organisms leading to reduced growth and hence reduced survival of sockeye.
    - numerical responses of pathogens and predators leading directly to reduced survival.

- Output from an ecological model that incorporates foraging risk into Larkin type interaction model (risk ratio mortality dynamics) closely matched observed data. This may be driven more by historical exploitation rates and/or age structure of population.

- Most alternative model approaches that have been proposed (e.g. JGM) are variations of the Larkin model. Larkin model formulations are most useful for capturing different interactions between cycles.

- Can yield be increased by switching from a constant escapement to a cyclic escapement policy?
    - Simple models with estimated delay effects suggests yield is maximized with cyclic escapement if there are strong cycle line interaction parameters (e.g. Quesnel).
    - If cycle line interaction is weak then constant escapement across all cycle lines maximizes yield (e.g. Adams).

<u>Recommendations:</u>

- Manage Fraser sockeye based on a fixed exploitation rate strategy for a number of practical reasons (e.g. difficulty to correctly estimate the "optimal" escapement target given parameter uncertainty).

- Specifically, for the large summer runs with cyclic populations (Late Stuart and Quesnel), manage with a fixed exploitation rate, but be careful not to drive the populations back into cycles given probable loss of yields.

- Stop fishing late runs on off-cycle years and harvest Weaver sockeye with a terminal fishery (this provides rebuilding for Cultus and Adams). This policy combination leads to gains for all players given stability of harvest. Loss of short-term harvest will be confined to Weaver only.

- Cyclic policies are only better for Kvichak and Quesnel, but this conclusion is only in single population context. They may not be optimal when considering mixed population context.

Participant discussion points:

- There is concern about measurement errors on off-cycle Adams years and possibility that exploitation rates are overestimated on these cycle lines (e.g. small population bias tends to over-allocate recruits and visual estimation of spawners also tends to underestimate abundance)
    - Avoid the problem by using exploitation rates from Weaver.
    - If exploitation rates used in simulations differed substantially from those used, then simulation model trajectories would diverge from observed trajectories of S-R data. This suggests that the exploitation rates used were appropriate.

- Optimal escapements for cyclic populations are lower (by 1/2 or less) based on Larkin type models relative to Ricker model.

- The effect of alternative harvest policy objectives other than the MSY objective need to be assessed.

4. Cyclic Dominance in Bristol Bay sockeye system. Brandon Chasco

- In the past, target escapement policies were ten million spawners on peak years and two million on off-peak cycles. Recent experiments were designed to equalize escapements on all years.

- Stocks have a complex age structure: 4_2, 5_2, 5_3, and 6_3.

- Kvichak had dominant 5 year cycle but peak cycle years declining recently.

- How has the fixed escapement policy worked?
    - Large runs and short migration period (three weeks) actually results in a proportional exploitation rate, so essentially there has been a

fixed exploitation rate historically even though a fixed escapement policy is the official policy.

5. Beyond Brood Tables: Sockeye stock assessment methods using life history Models. Bob Lessard

- The standard paradigm for the management of Bristol Bay sockeye salmon is to calculate maximum sustainable harvests by fitting spawner and recruit data to mathematical models, such as Ricker curves, and to establish a range of escapement targets around the optimum spawning stock that maximizes the long-term yield.

- This method assumes, among other things, that there is no depensatory mortality at low densities and that there are no systematic changes in productivity over the time period analyzed.

- The method aggregates mortality across all stages of life history. Two notable Bristol Bay stocks are the Kvichak and Egegik runs. The Kvichak is a cyclic dominant run that has been declining since the early 90's. Ricker analyses of spawner-recruit data indicate that recruits per spawner are at their lowest at low densities, confounding the inherent assumptions of density dependence.

- Efforts to increase returns from off-cycle years with lower exploitation rates in those years have failed. During this same period of time the Egegik stock increased.

- A Ricker analysis of Egegik brood data indicates no density dependence, and there are indications that a systematic increase in ocean survival has occurred. We have developed a model of sockeye life history that explicitly captures smolt migration rates, spawning migration rates, and mortality rates (both density dependent and independent).

- We use this model to examine density dependent effects within and between cohorts, as well as interaction effects between stocks. The model estimates parameters that maximize the likelihood of the observed spawners, smolts and recruits.

- Policy optimization subroutines are developed to examine the effects of different harvest policies under different assumptions of biological interactions.

- We use the model to examine the benefits of managing with constant harvest rates versus fixed escapement target. We compare these policies in cases where there is no assumed systematic change in productivity to cases where systematic changes are detected by the model and reflected in parameter estimates. Results indicate that a systematic increase in ocean survival of Egegik fish occurred in the early 1980's, coincident with a decrease in ocean survival of Kvichak sockeye, suggesting a possible interaction between the stocks or just conditions favourable to one but not the other.

- Optimization of long-term yields suggests that the Kvichak was under-escaped for much of it's past history. This is reflected in both the constant exploitation rate policies and fixed escapement policies. It is consistent with analyses of spawner recruit data of both stocks, which indicates that the stocks are not limited in productivity at higher densities. This is inconsistent with broadly accepted principles of density dependence.

- The model will be further developed to incorporate between-cohort interaction effects in fry survival rates to further isolate the stage of life history where strong density dependence should be evident. This effect can then be separated from the confounding effects of systematic changes in survival at other stages of life history, which would be reflected in the optimal constant exploitation rates and fixed escapement policies that are derived from the model.

- Climate effects on freshwater and marine survival rates will also be incorporated to provide a sensitivity of harvest policies to climate change effects.

Participant discussion points:

- It is important to determine where in the life history the density dependent dynamics occur (e.g. need to look at data on zooplankton, predators, etc.) to improve model structure. The model needs to explore the structure of the interactions between cycle lines.

- There was a suggestion to test simulation model using Fraser sockeye data given the simpler age class.

- Have we learned anything from the Kvichak experiment to equalize cycle line abundance that would inform us about what might happen in the Fraser?
    - It is difficult to assess the impact of the experiment to increase off-peak line escapement given confounding caused by changes in survival that occurred concurrently, data issues and uncertainty about how well the strategy was implemented.
    - Although the stated management policy was a fixed escapement strategy to rebuild off-peak lines for Kvichak sockeye, it may not have been implemented (exploitation rates have resembled a fixed proportional removal more akin to a fixed exploitation rate)

- Are there other Alaskan populations that had changes in escapement policy similar to Kvichak?
    - There is little evidence of change in the management policies for other populations.
    - There are also problems with mis-allocation of catch between Egegik and Kvichak.

6. Choosing harvest rules for Fraser River sockeye: the Fraser River sockeye spawning initiative. Al Cass

- The Modelling approach uses stock-recruitment parameter estimates and specified management objectives to estimate an “optimal” harvest rule.

- Population dynamics include the Ricker model, Ricker cycle line aggregate model and a Larkin model.

- Parameters estimates for the Ricker cycle aggregate model were based on aggregated data for dominant and subdominant years and similarly for aggregated for the low abundance years thereby assuming complete independence in the productivity and capacity of high and low abundance years.

- Parameter uncertainty for each model is captured with Bayesian statistics.

- A Multi-attribute objective function is used to construct management objective that attempts to maximize catch and applies penalties for years with low overall catch or low population-specific spawner abundance.

- Model output is a harvest rule specifying target exploitation rates at different abundances of returning adults.

- The shape of harvest rule can encompass fixed exploitation rate strategies and rules that represent fixed escapement strategies.

Participant discussion points:

- Suggestion that utilities should not be additive as was done in the analysis. Literature suggests that <u>log</u> of terms in utility function better reflects actual importance to people (e.g. increment of catch when catch is low is much more important compared with additional increment of catch when catch is already high)
    - Preliminary check of log utility function did not appear to dramatically alter results.

- Questions to participants:
    - What S-R model should be used for populations that don't appear to be cyclic? (Is it appropriate to use a Larkin model for all populations?)
    - How can decision makers be informed about model results and implications of policy rules?
        - Need to query stakeholders about what is the most appropriate harvest rule for every "normal" year (fishermen may opt for a fixed exploitation rate rule). But, then need to indicate to stakeholders that this harvest rule will also need to incorporate contingencies to protect the population at low abundance.
    - What happens when one of the populations in a mixed-stock fishery becomes too low?
        - This will be a major problem for Fraser sockeye.
        - Is weak population management going to drive management? No optimization is available to solve this problem. It will be a trade-off problem. For example, probability of recovering an individual population plotted against expected catch from aggregate of populations.

- Retrospective analyses conducted by Carl Walters to estimate "optimal" exploitation rates for Early Stuart, Mid-summer and Late stock aggregates to assess how an omniscient manager would we have managed differently given the historical recruitment pattern and MSY objective resulted in the following:
    - Model assumes three aggregates can be harvested discretely (e.g. different exploitation rates can be applied to different stock groups without error)
    - Early Stuart would have shut down periodically
    - Summer would not have shut down very often, with exploitation rates stable
    - Lates would shut down regularly to rebuild the off-cycle lines
    - Population sizes:
        - Cyclic pattern maintained only in Quesnel (consistent with single stock analysis suggesting yield could be maximized with cycles in the Quesnel system).
        - Cyclic patterns damped out in other populations.
        - Late Shuswap cyclic pattern removed by building off-cycle lines.

Participant discussion points on management implications

1. **Given uncertainty about the population dynamics and the management system (i.e. implementation error), how should we manage?**

A) fixed exploitation rate policy

- A fixed exploitation rate strategy is close to the "optimal" strategy for maximizing the log utility of catch (e.g. additional increment of catch when catch is low is much more important compared with additional increment of catch when catch is already high).

- This policy is not sensitive to different S-R model formulations because optimal exploitation rates are a function of the intercept (a) parameter.

- In the mixed stock case for an MSY objective and where stocks have conflicting exploitation rate objectives then optimization indicates the average exploitation rate is "optimal", not the exploitation rate for the weakest population. This conclusion is based on the objective of maximizing average annual catch.

- Estimates of optimal exploitation rates are better determined than optimal escapement levels, so managers should manage to exploitation rate targets and let the population move to the "optimal" spawning population abundance on its own. This will also allow spawner abundance to passively move to the "optimal" level, but also allow greater fluctuations in spawners to learn about the S-R dynamics (e.g. more contrast in spawner abundance compared with fixed escapement strategy).

- What should the harvest rule look like at low abundance?

    - There was agreement that a simple, three parameter "hockey stick" model is a good candidate harvest control rule. The hockey stock model imposes a fixed exploitation rate across a wide range of run sizes and a contingency plan to reduce exploitation to zero if conservation conditions are not met.

    - Given uncertainty in in-season run size, there are still risks of not meeting objectives due to errors in the implementation of the harvest control rule (i.e. the deviations between the target and the realized exploitation rate).

B) Fixed escapement policy

- This type of policy is not recommended for most salmon populations.

- This policy is "optimal" only for single stocks where spawner capacity is clearly understood, stock size is known at the time of harvest and implementation error is small. Given the inherent uncertainty in the dynamics, there is little opportunity to learn from a fixed escapement policy.

2. Should we use the Larkin model for all Fraser sockeye populations (where the Ricker model is a special case with interaction parameters equal to zero)? (e.g. the probability of cycles in the population will be determined by parameter distributions of the interaction terms and the exploitation rate).

- The choice of S-R model is important if a fixed escapement policy (not recommended) is contemplated where different models suggest very different values for "optimal" escapement.

- The choice of model is less important if the recommended fixed exploitation rate policy is implemented.

- The mixture of stocks included in the aggregate may have a larger influence on the shape of the harvest rule than the choice of the S-R model.

Conclusions

There was consensus among participants on the following points:

- Some stocks clearly display a pronounced 4-year cycle in population abundance. Evidence based on recent ecological modeling indicates delayed-density interactions are a biological reality. Although the precise mechanisms are not known, high densities of juvenile sockeye appear capable of over-cropping zooplankton in rearing lakes. The evidence shows that the effect can carry-over into succeeding years resulting in reduced juvenile body growth in low abundance years and increased vulnerability to size-mediated predation of sockeye by in-lake predators.

- There is high uncertainty in the degree of delayed-density interaction. Some lakes have shown a 2-year (high-low) periodicity with high interaction between two adjacent years (i.e. Chilko and Nadina sockeye). Other lake systems (Shuswap, Quesnel and Stuart lake populations) show a 4-year pattern (dominant-subdominant-low-low) with carry-over into the third and fourth year following the dominant cycle.

- High fishing pressure is a prerequisite of population cycles. Reduced exploitation rates have resulted in the break-down of cycles in some lakes (i.e. Quesnel Lake, Bowron Lake and cyclic Bristol Bay sockeye). One explanation for recovery of low abundance years is the filling in of low-cycles by age-5 recruits from preceding dominant brood lines when fishing is relaxed.

- Statistical models (Larkin multiple regression model) are the best models for assessing the delayed-density effects compared to ecological models that incorporate fish growth and predation terms given the uncertainty in the data.

- Participants agreed that the Ricker cycle aggregate model used in the Fraser sockeye spawning initiative that assumes complete independence of high and low cycle years should not be used to estimate harvest control rules.

- A particularly important conclusion for the resource management of Fraser sockeye is that the maintenance of cycles is not necessary and is difficult to implement in mixed-stock fisheries. Cycles will persist under high exploitation (i.e. Adams) and break-down when fishing pressure is reduced (i.e. Quesnel).

- Participants agreed that a fixed-exploitation policy is superior over a wide range of populations, objectives and conditions compared a fixed escapement policies. It is robust to uncertainty about whether population dynamics are cyclic or non-cyclic and to uncertainty in habitat capacity estimates. There is, however, a need to develop a contingency plan at low abundances to reduce exploitation rates and avoid conservation risks.

- Meeting participants concluded that a fixed escapement policy is only superior in very limited management situations. It is only "optimal" for single-stock management where habitat capacity estimates are well know, the population size is known at the time of harvest and implementation error is small.

- Given the strong evidence for delayed-density ecological processes in sockeye rearing lakes, meeting participants endorsed the need for research and monitoring programs to better understand the ecosystem of freshwater rearing systems.

- Biological interactions between different stocks may need to be assessed to determine if management actions that increase one population have biological effects on other comigrating populations. For Late run Fraser sockeye, models indicate that it is worth giving up harvest on Weaver to rebuild off-cycles in Adams and stabilize escapement across cycle lines.

Appendix 1. Agenda

Day 1 – Alternative stock-recruit models

9:00 Introduction of issue and workshop objective

- Brian Riddell

9:30 Presentations and discussion of models

Cycle-line interaction as a mechanism for cyclic dominance
- Jim Woodey

10:15 – 10:30 Break

10:30 Presentations and discussion of models (continued)

Simulation of the Juvenile Growth Model (JGM) for cyclical stocks
- Carrie Holt

The mystery of cyclic dominance in sockeye salmon
- Carl Walters

12:00 – 13:00 Lunch

13:00 - 14:30 Discussion

- Hypotheses
- Stocks
- Models

14:30 – 14:45 Break

14:45 – 16:00 Conclusions

Day 2 – Management Implications

9:00 – 9:30 Review of Day 1 (Jeff Grout)

9:30 Presentations on management implications

Bristol Bay sockeye
- Brandon Chasco
- Bob Lessard

10:15-10:30 Break

10:30 Presentations on management implications (continued)

The Fraser Sockeye Spawning Initiative
- Al Cass

12:00 – 13:00	Lunch
13:00 – 14:30	Discussion on management implications
14:30 – 14:45	Break
14:45 – 16:00	Conclusions

Appendix 2. Meeting Participants

Allan MacDonald (Chair)
Jeff Grout (Rapporteur)
Jim Woodey
Carl Walters
Al Cass
Carrie Holt
Brian Riddell
Randall Peterman
Elan Park
Les Jantz
Amy Seiders
Marla Maxwell
Mike Staley
Jim Cave
Gary Graves
Timber Whitehouse
Jeremy Hume
Mike Lapointe
Josh Korman
Ron Goruk
Nathan Taylor
Karl English
Ann-Marie Huang
Bob Lessard
Brandon Chasco
Dave Robichaud
Michael Folkes
Ian Guthrie
Jim Cave
Ken Wilson