An integrated, life-cycle modeling approach to investigate cumulative effects on Fraser River sockeye salmon dynamics

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LIBER ERO FELLOWSHIP PROGRAM
Cumulative effects

- Fish farms
- Overfishing
- Warm water
- Deforestation

Grahame Arnould
The Georgia Straight
Objectives

• Develop a mechanistic framework to assess cumulative effects on Fraser River sockeye salmon dynamics

• Generate results and tools to understand how cumulative effects and management actions will influence the future sustainability of Fraser River sockeye salmon
Life-cycle graph

females only, some stages ignored, annual time step (Oct 1)
Matrix model

\[
\begin{pmatrix}
n_1 \\
n_2 \\
n_3 \\
n_{4i} \\
n_{4s} \\
n_5 \\
\end{pmatrix}_t = \begin{pmatrix}
0 & 0 & 0 & 0 & F_{14s} & F_{15} \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & P_{32} & 0 & 0 & 0 & 0 \\
0 & 0 & P_{4i3} & 0 & 0 & 0 \\
0 & 0 & 0 & P_{4s3} & 0 & 0 \\
0 & 0 & 0 & 0 & P_{54i} & 0 \\
\end{pmatrix} \begin{pmatrix}
n_1 \\
n_2 \\
n_3 \\
n_{4i} \\
n_{4s} \\
n_5 \\
\end{pmatrix}_{t-1}
\]

\[
n_t = A_{t-1} n_{t-1}
\]
Piecemeal modeling

- fecundity
- smolt survival
- fry survival
- immature survival
- adult survival
- age/stage structured model
- abundances (some ages/stages)
Integrated modeling

- Fecundity
- Smolt survival
- Adult survival
- Age/stage structured model
- Fry survival
- Immature survival
- Abundances (some ages/stages)
Data in a PostgreSQL database
Preliminary analysis of Chilko Lake sockeye data
Chilko data

- Abundance
  - Spawners
  - Fall-fry
  - Outmigrating smolts
- Fecundity $\sim$ Length
  - Length $\sim$ Age + PDO + Salmon Abundance
- Spawning success
- Survival of upriver migrants $\sim$ Fraser temperature
- Survival of outmigrating smolts

Model fitted using Bayesian approach
Retrospective analyses

Growth rate ($\lambda$):

- Rate of change in TOTAL population size between consecutive years

Asymptotic dynamics:

- Population is at its stable age/stage structure
- $\lambda$ depends only on transition rates

Transient dynamics:

- Population is not at its stable age/stage structure
- $\lambda$ depends on transition rates AND age/stage structure
Asymptotic $\lambda$: mild fluctuations in growth, below replacement level in only 6 years
Realized $\lambda$: extreme fluctuations in growth, below replacement level in 28 years

$\lambda_{\text{asymptotic}}$ and $\lambda_{\text{realized}}$
Retrospective analysis

Contribution of $\theta_i$ to $\text{Var}(\lambda_{\text{realized}})$

$$\chi_{\theta_i} \approx \sum_j \text{cov}(\theta_{i,t}, \theta_{j,t}) \left( \frac{\partial \lambda_{\text{realised},t}}{\partial \theta_{i,t}} \frac{\partial \lambda_{\text{realised},t}}{\partial \theta_{j,t}} \right)_{\theta_{ij}}$$

Koons et al. (2016)
**Transition rate contributions:** mainly attributed to variation in transition rate *spawner (a4) to fall-fry*
Population structure contributions: mainly attributed to variation in age-4 spawner abundance.
Geometric mean of $\lambda$: Which demographic parameters contributed the most to the difference between 1970-1989 and 1990-2009?
Retrospective analysis

Contribution of $\theta_i$ to difference in log $\lambda_g$ between two periods

\[ \chi_{\theta_i} \approx \Delta \log \mu_i \times e_{\mu_i}^A + \Delta \log \sigma_i \times e_{\sigma_i}^A \]

\[ + \Delta \log \mu_i \times e_{\mu_i}^\hat{n} + \Delta \log \sigma_i \times e_{\sigma_i}^\hat{n} \]

*direct* contribution of transition rate

*indirect* contribution of transition rate (channeled via population structure)

Koons et al. (2016)
Transition rate \textit{spawner (a4) to fall-fry} made the largest contribution to differences in log $\lambda_g$ between periods.
Declining trend in fecundity (# of eggs)

Year

Fecundity

age 4

age 5
length effect on fecundity

PDO (mean) effect on length

PDO (SD) effect on length

Salmon abundance effect on length
Elasticity analysis estimates the proportional change in the population growth rate for a proportional change in a vital rate (i.e. survival, growth or reproduction). It can be used to pinpoint those parts of an organism’s life history that should be the focus of management effort, or those that contribute most to fitness.”
Analysis of mean matrix for 2008-2012 indicates growth would be more sensitive to changes in spawner (a4) to fall-fry
Ongoing and Next Steps

• Expand the model to include other CUs
  o 18 conservation units
  o Hierarchical modeling approach

• Detailed retrospective and prospective analysis
  o Contribution of lower level parameters (vital rates and effect of factors/stressors)

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