Ecological dynamics of a salmon parasite

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Domestic animals: Novel reservoirs

Most examples are terrestrial:
- African buffalo, cattle, rinderpest (Hudson et al. 2002 *Ecology of Infectious Diseases*, Oxford)
- American buffalo, cattle, brucellosis (Dobson & Meagher 1996 *Ecology*)
- African wild dogs, domestic dogs, rabies (Kat et al. 1996 *Proc Roy Soc Lond B*)
- Lion, domestic dogs, canine distemper virus (Roelke-Parker et al 1996 *Nature*)
Understanding disease emergence

Transmission of disease from farmed to wild salmon would expose out-migrating juveniles to the disease very early in their life cycle--at a few weeks of age, when they are vulnerable.
**Historical Context**

- In 2001 locals and fishers reported infestation of juvenile salmon by sea lice in the Broughton Archipelago.
- Observers traced infestations to salmon farms.
- Department of Fisheries and Oceans discounted this link, describing sea lice as naturally occurring.
- There was a great deal of public interest and media coverage.
- A local biologist and environmentalist, Alexandra Morton, started studying the phenomenon and collecting data.
- Sea lice inserted themselves into the contentious intersection of biology and politics.

S. Bocking *Science, salmon and sea lice: Constructing practice and place in an environmental controversy* 2012 *J. History of Biology*
Outline

- Lice on farm salmon
- Lice on juvenile wild salmon
- Higher mortality in wild salmon
- Fewer salmon returning to spawn
Outline

- Connecting salmon farms to infections in juvenile wild pink and chum salmon
  - Spatial footprint of farm parasites on wild pink and chum
  - Reduced survival of parasitized juvenile wild pink and chum
  - Diminished spawning returns for pink but not chum
  - Trophic complexities may explain differences
• Connecting salmon farms to infections in juvenile wild pink and chum salmon

• **Spatial footprint of farm parasites on wild pink and chum**
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Lice on wild and farmed fish

Peacock, Krkosek, Proboszcz, Orr and Lewis 2013 *Ecol Appl*
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Fieldwork – 2003

Krkosek, Morton, Volpe,
Trans. Am. Fish. Soc. 2005
Data – First Glance

![Graph showing mean number of lice per salmon along migration route.](image)

- **Copepodids**
- **Chalimi**
- **Motiles**

Position along migration route (km)

![Map of migration routes.](image)

- Wakeman R
- Kingcome R
- Klinaklini R
- Ahnuhati R
- Ahta R
- Kakweiken R
- Kingcome Inlet
- Tribune Channel
- Gilford Island
- Glendale R
- Knight Inlet

![Life cycle stages.](image)

- **Nauplius 1,2**
- **Copepodid**
- **Chalimus 1-4**
- **Preadult 1,2 & Adults**

**Types:**

- Female
- Male

(larvae, motiles)
Results

- Fitted a model with advection diffusion for larvae with stage structure plus advection for later stages.
- Both natural and farm sources of lice identified but natural sources are marginal.
- Louse footprint of a farm exceeds ambient levels for 30 km and peaks at 73 times ambient levels.
- Colonizing lice population subsequently grows and spreads in the wild salmon populations.
Origins of lice

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Mortality Experiments
“Camp Sea Lice”
Mortality Experiments

Multiple farms

Predictions for spatial survival

- Louse-induced mortality rates $\alpha_1, \alpha_2$ estimated from experiments
- Lice transmission is spatial but host survival is temporal
- Use the chain rule to map time to space via migration velocity
  \[- \frac{dg}{dx} = v^{-1} \cdot \frac{dg}{dt} \]

\[
\begin{align*}
\frac{dP_{1,1}}{dx} &= \frac{p_c \beta}{\nu} L(x - \lambda_i) - \frac{1}{\nu} (n\mu_1 + \alpha_1) P_{1,1} \\
\frac{dP_{1,2}}{dx} &= \frac{n\mu_1}{\nu} P_{1,1} - \frac{1}{\nu} (n\mu_1 + \alpha_1) P_{1,2} \\
&\vdots \\
\frac{dP_{1,n}}{dx} &= \frac{n\mu_1}{\nu} P_{1,n-1} - \frac{1}{\nu} (n\mu_1 + \alpha_1) P_{1,n} \\
\frac{dP_2}{dx} &= \frac{n\mu_1}{\nu} P_{1,n} - \frac{\sigma}{\nu} P_2
\end{align*}
\]

Salmon survival

\[
\frac{dN}{dx} = -\frac{1}{\nu} \left[ \alpha_1 \sum_{i=1}^{n} P_{1,i}(x) + p\alpha_2 P_2(x) \right] N
\]

Pink Salmon

Chum Salmon

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Testing population level impacts

Hierarchical models of stock-recruit dynamics

Latitude

Longitude

Salmon farm
Testing for Population Impacts – Pink Salmon

- Exposed populations with no known farm lice
- Exposed populations with known farm lice
- Unexposed populations
Stochastic Ricker equation:

\[ n_i(t) = n_i(t-2) \exp[r - bn_i(t-2) + Z(0, \sigma^2)] \]

Stock-recruitment model (S spawners R recruits):

\[ R_i(t) = S_i(t-2) \exp[r - bS_i(t-2) + Z(0, \sigma^2)] \]

Log transformed model:

\[
\log\left[ \frac{R_i(t)}{S_i(t-2)} \right] = r - bS_i(t-2) + Z(0, \sigma^2)
\]

Hierarchical model:

\( r \) includes random effects for year, river, management area

\( b \) includes random effects for river

Dennis and Taper, 1994, *Ecol Monogr*
Results – Pink Salmon

Krkošek, Ford, Morton· Lele, Myers and Lewis
Science, 2007
Include sea lice $L$ mortality in Ricker equation:

$$R_i(t) = S_i(t-2) \exp[r - bS_i(t-2) - aL(t-1) + Z(0, \sigma^2)]$$

with

- $r = r^*$ (maximum reproductive rate)
- $b$ = estimated in previous analysis
- $a$ = to be estimated

Results:
- Annual mortality commonly exceeds 80%
- Parameter estimates agree:
  - $a = 0.9$ (0.5-1.3 95% Credible Interval)
  - $a = \alpha T = 1.3$ (from Krkosek et al. 2006)
- Pink salmon extinction/persistence threshold:
  - $L_c = r^*/a = 1.3$ motile lice per fish
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Predator mediated mortality?

Krkosek et. al. *Ecol Appl* 2011
Lice alter behaviour

- One infected and 29 uninfected fish
- Photos every 6 minutes for 1.5 hrs = 30 photos per trial
- Image analysis shows high louse load means
  - Nearest neighbour distances increase
  - Fish more likely to be in peripheral rather than central positions (using minimum convex polygons)
  - Fish more likely to be in back of school rather than front (by calculating axes of movement)
Lice alter predation risk

Before

After

Total Lice

Fork Length (mm)

Krkosek et. al. *Ecol Appl* 2011
Parasite mediated predation

\[ \frac{(\gamma + p\theta)N}{1 + (\gamma + p\theta)T_h N} \]

Increasing louse abundance

Juvenile salmon abundance

Juvenile salmon mortality rate per predator

Krkosek et. al. *Ecol Appl* 2011
Do predators increase mortality or provide an ecosystem service?

Predators add significantly to mortality from lice because infected fish are consumed rapidly. Predators do not add significantly to mortality from lice because preferential consumption of heavily infected fish mean that fish would have died from infection anyway.
Pinks preferred to chum (Hargreaves and Lebrasseur. CJFAS 1980 a, b)

Infection increased susceptibility to consumption (Krkosek, Connors et al. *Ecol App.* 2011)

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In conclusion...

- Sea lice are an emerging disease on juvenile wild salmon due to proximity to migration corridors and timing of infections.
- We have been able to measure the spatial footprint of infection from salmon farms and have replicated this many times.
- Parasite impact can be modelled and measured at the level of infection, individual mortality, population dynamics and trophic interactions.
- The parasitism appears to shift predator dynamics by coho away from chum onto pink salmon.
Role of science in policy

• This work lead to scientific debates published in Science, PNAS and Reviews in Fisheries Science.

• One key issue is the nature of acceptable scientific evidence in a system where it is difficult to make replicable experiments (correlation does not prove causation).

• It also led to over 500 news articles, meetings with policy makers, evidence at a judicial commission etc.

• Recently researchers and the broader community (academics, Department of Fisheries and Oceans, environmental groups, aquaculture industry, tourism, First Nations) appear to be coming closer to a consensus on the impacts of aquaculture on wild salmon.
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