Open net pen salmon farming, infectious disease, and the ecology of coastal ecosystems

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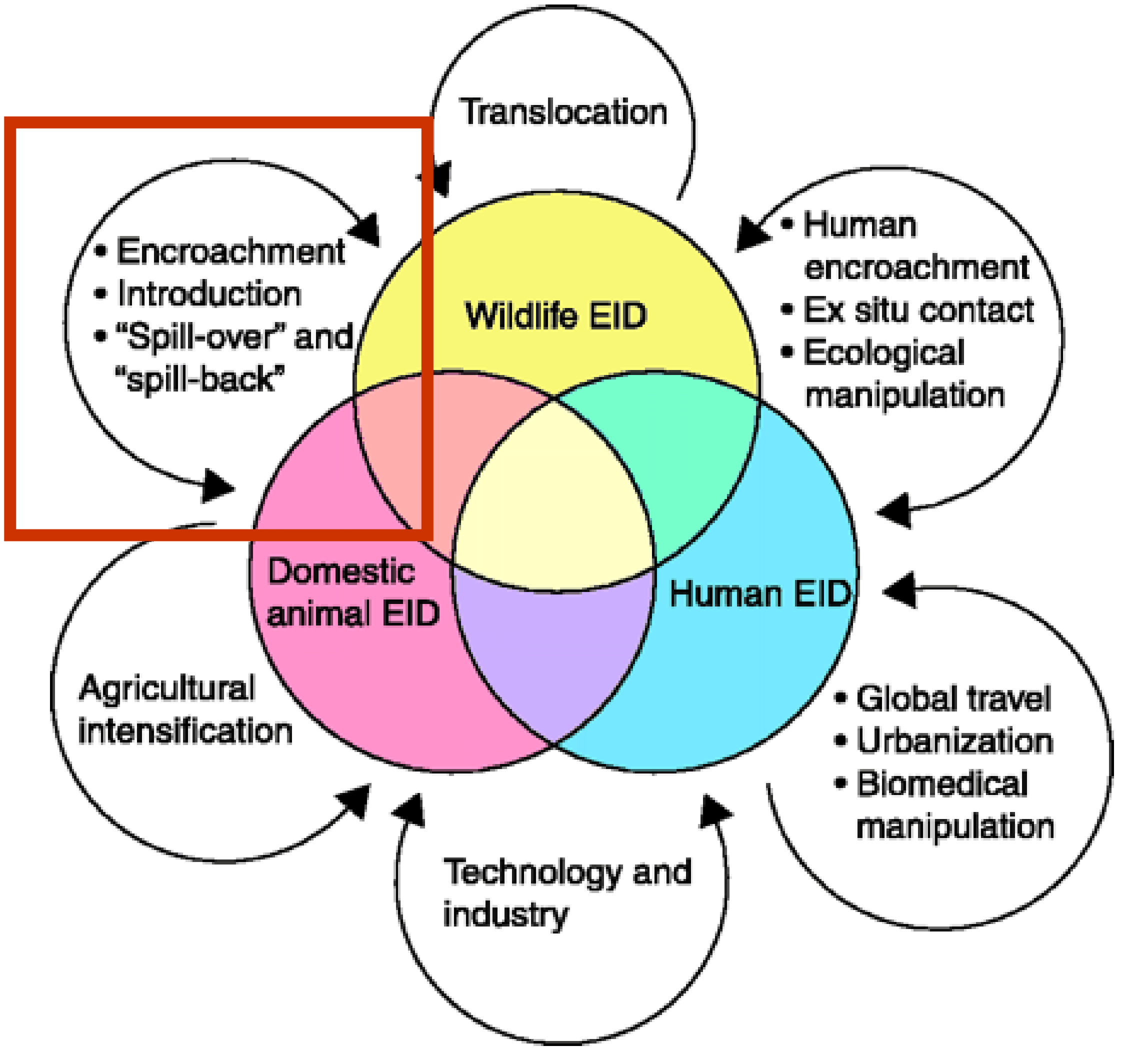
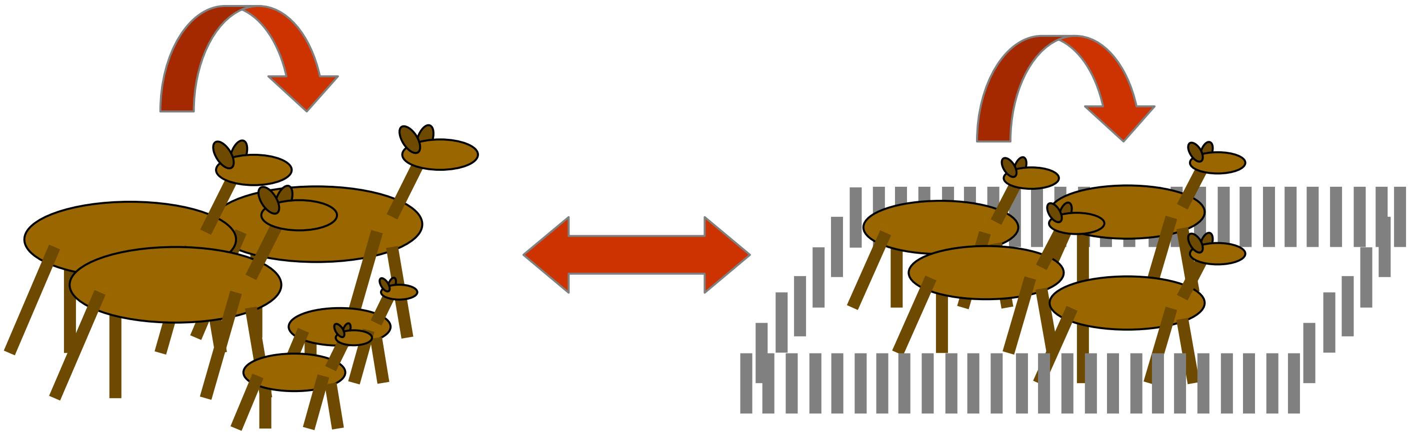
Understanding disease emergence



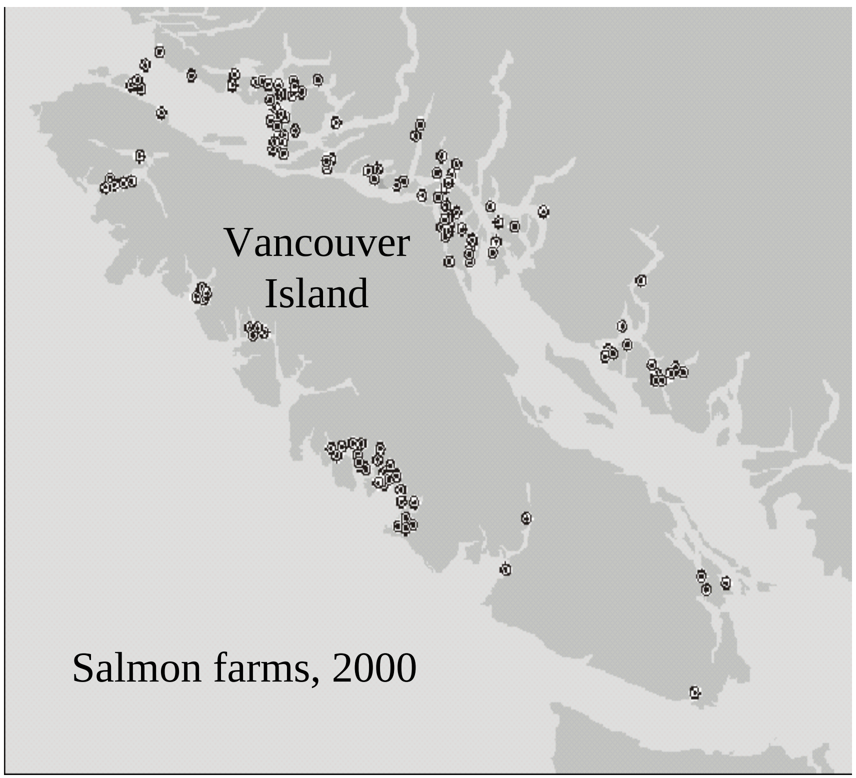
Daszak et al. (2000) *Science*, 287: 443-449.

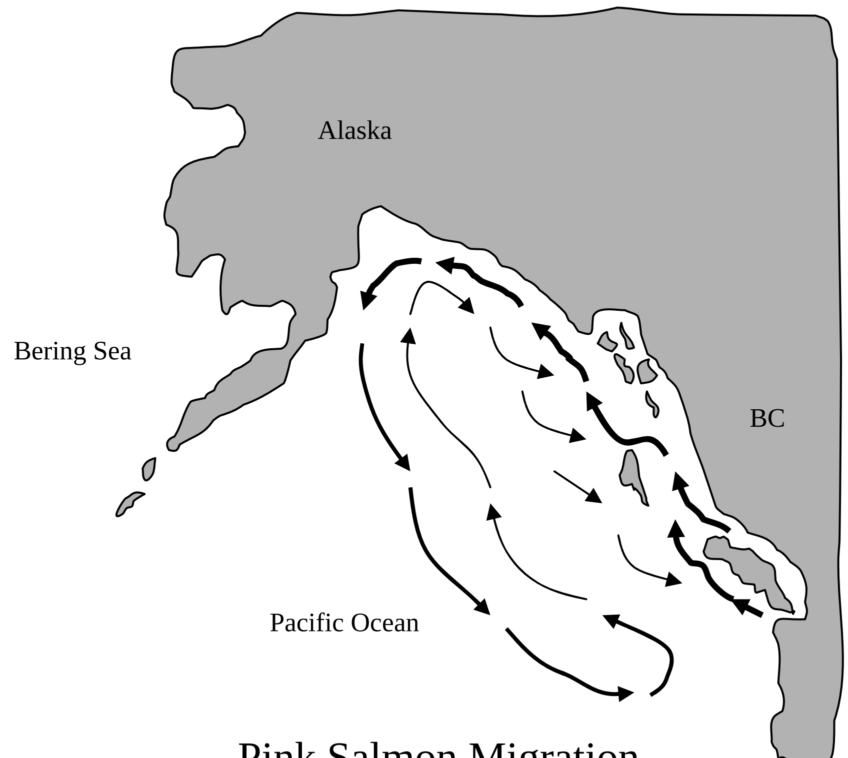
Domestic animals: novel pathogen reservoirs



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*)

Salmon farms along wild salmon migration routes





Pink Salmon Migration

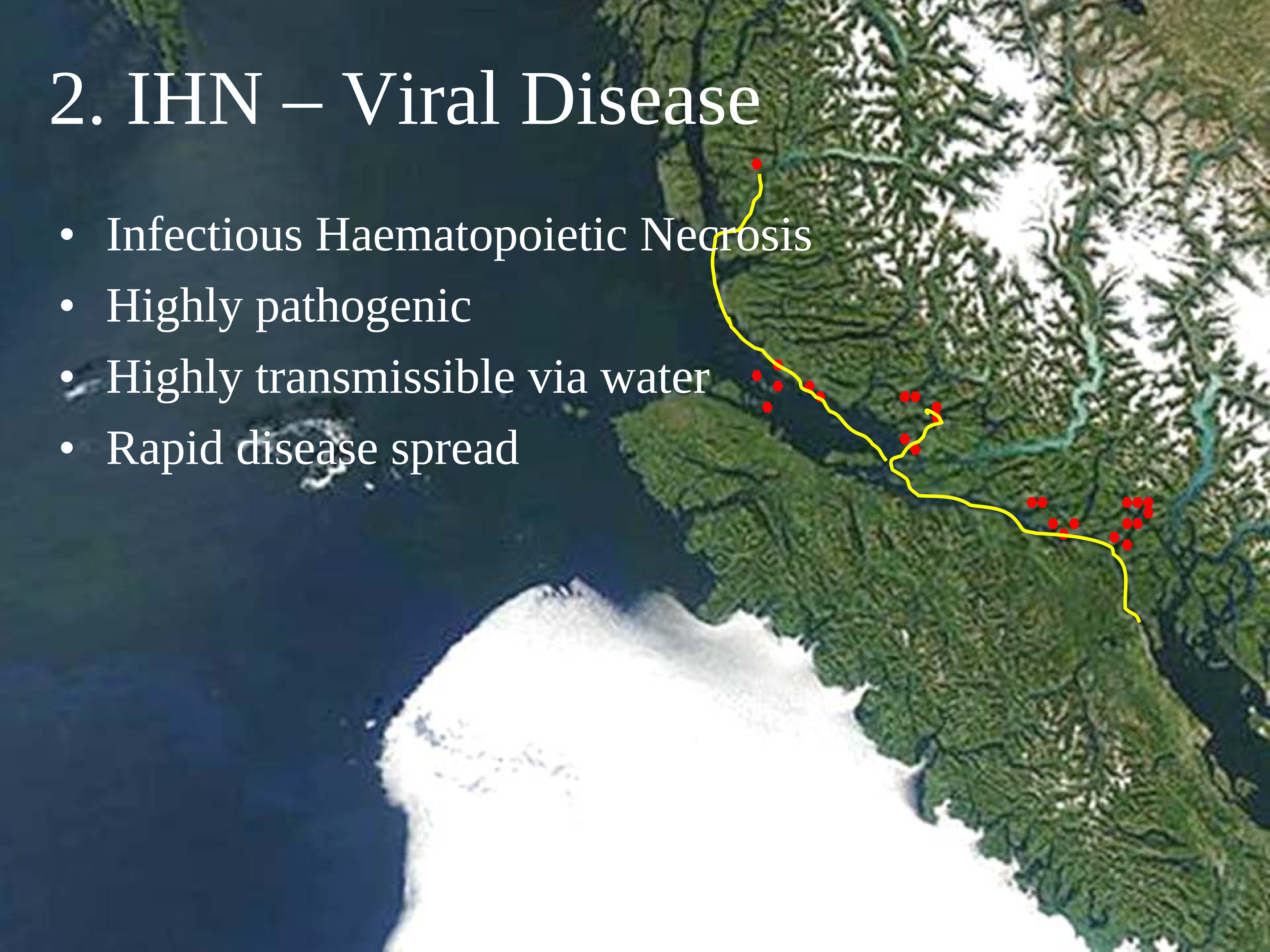
Groot & Margolis 1991

1. Furunculosis – Bacterial Disease

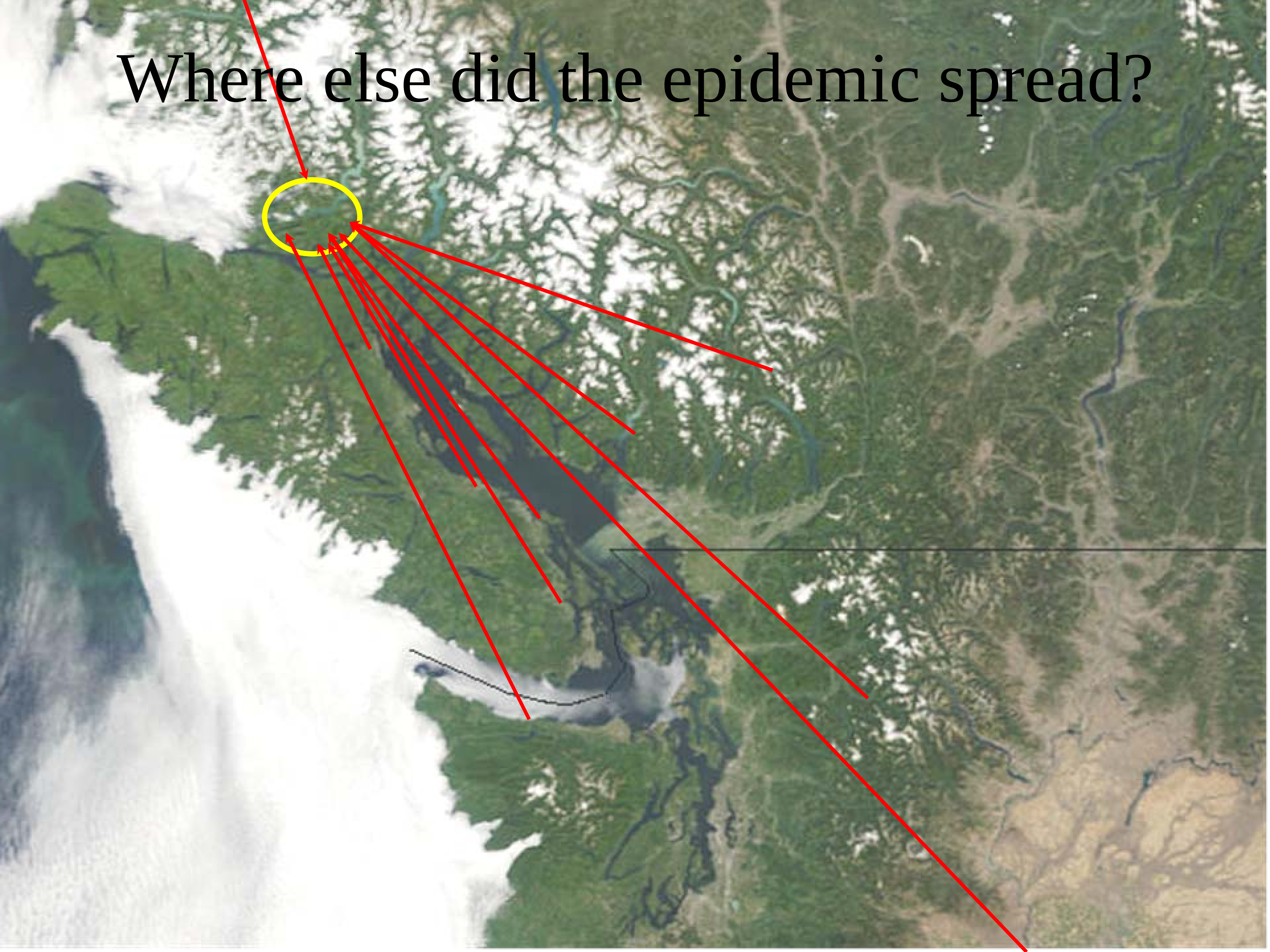
- Infectious disease caused by *Aeromonas salmonicida*
- Disease spread in the Broughton Archipelago
  - 1991 – Furunculosis outbreak in Brougthon Atlantic salmon precedes outbreak in hatchery resulting in 28% mortality
  - 1993 – Outbreak of antibiotic resistant Furunculosis strain in Atlantic salmon precedes outbreak of same strain in hatchery

2. IHN – Viral Disease

- Infectious Haematopoietic Necrosis
- Highly pathogenic
- Highly transmissible via water
- Rapid disease spread



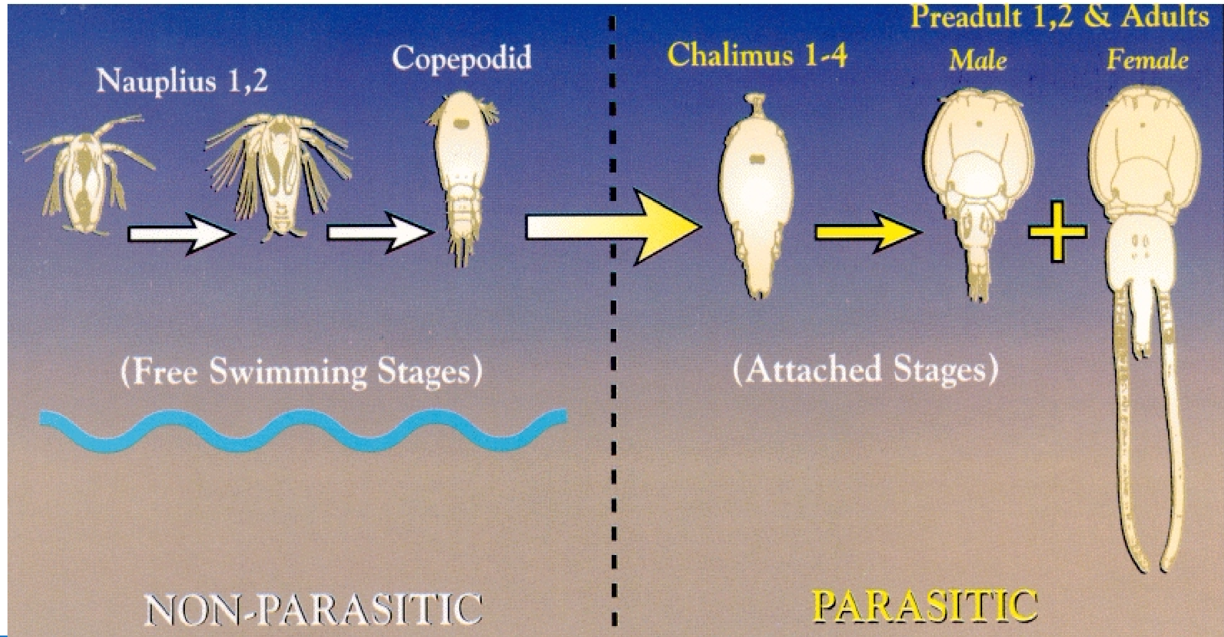
Where else did the epidemic spread?



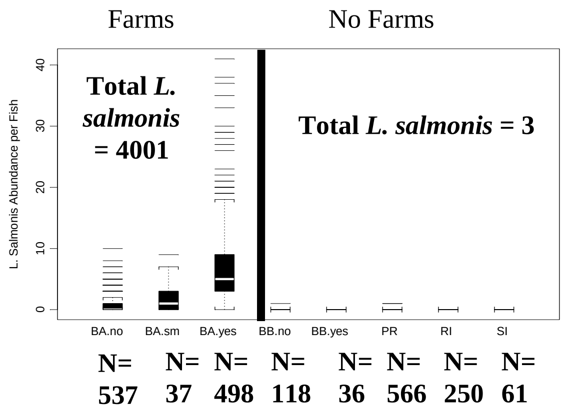
Salmon lice – Crustacean parasites

(*Lepeophtheirus salmonis*)

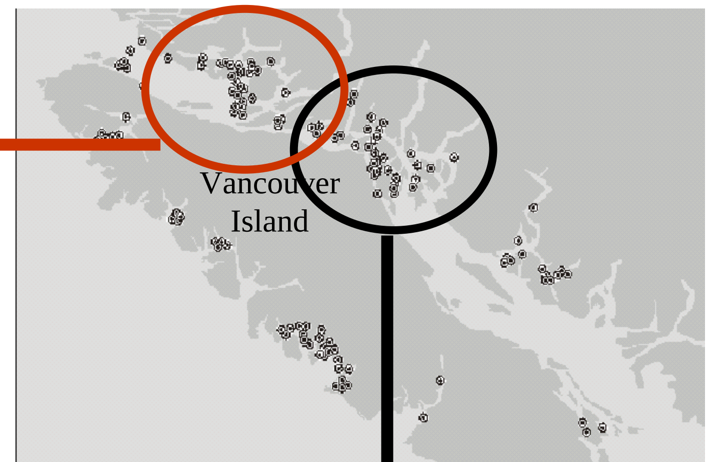
- Native parasite
- Common on farm salmon
- Common on wild adults
- Rare on wild juveniles
  < 5% prevalence

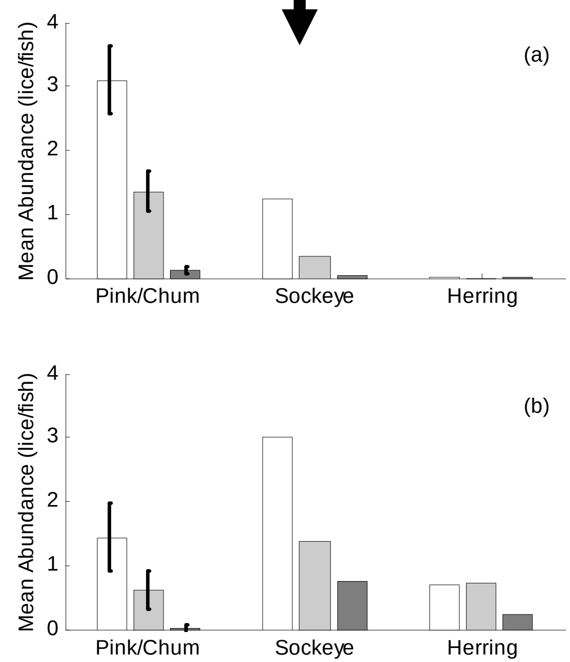


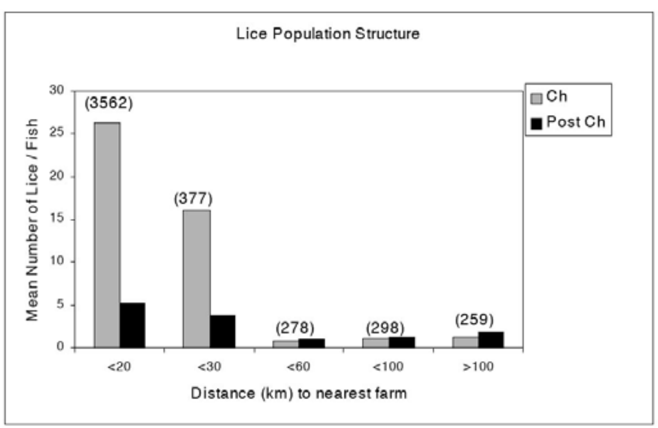
Farms associated with sea lice infestations



Morton *et al.* (2004) *Can. J. Fish. Aquat. Sci.*

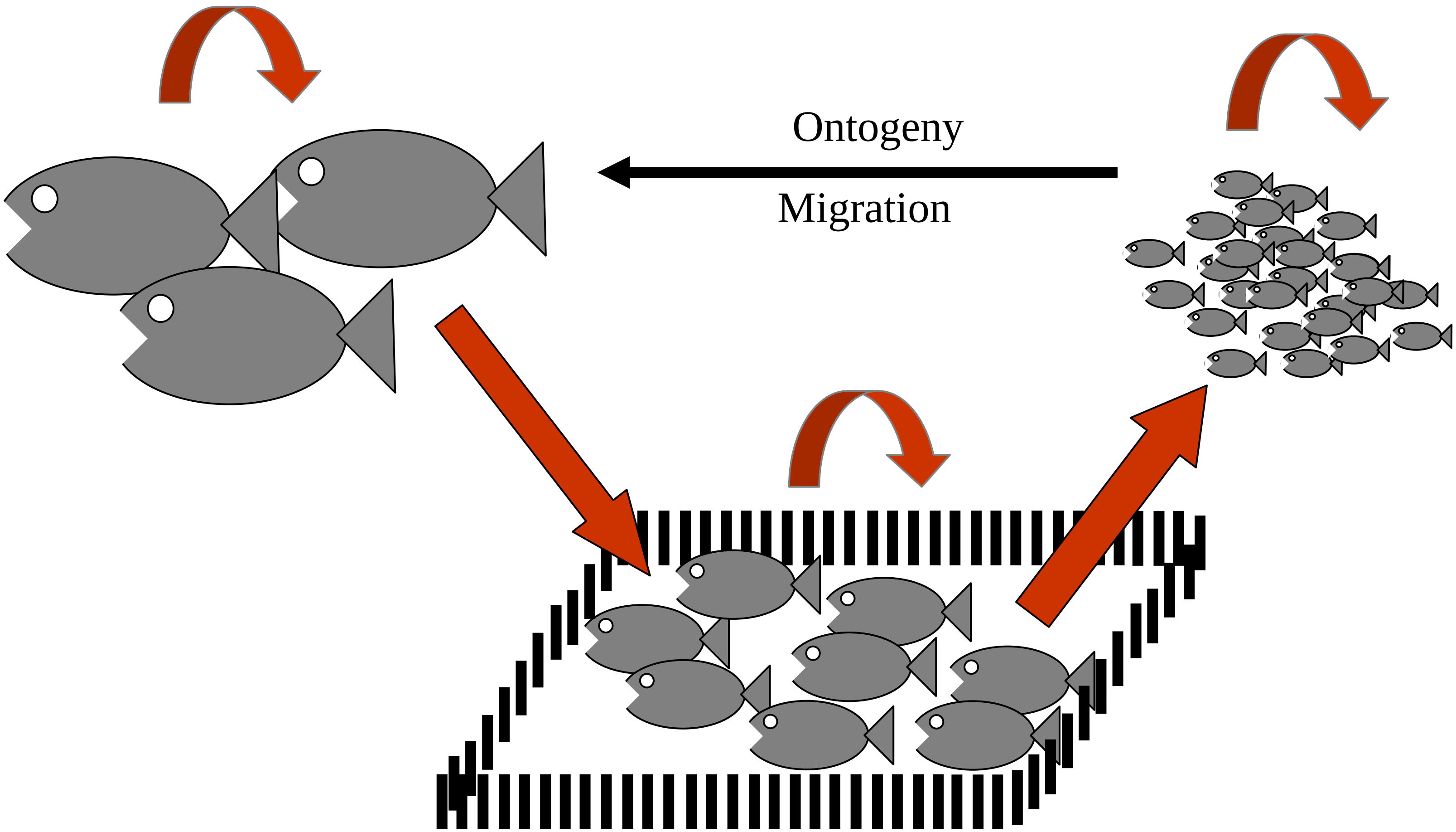






Gargan, P.G., O. Tully, & W.R. Poole, 2002.

Net pen aquaculture can undermine transmission barriers

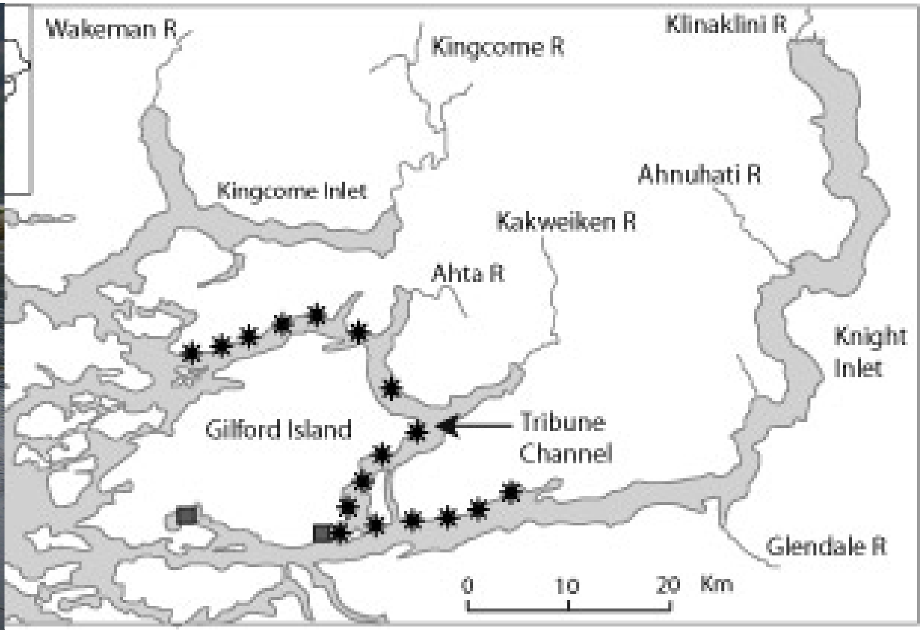


Opportunities for novel transmission pathways and novel dynamics

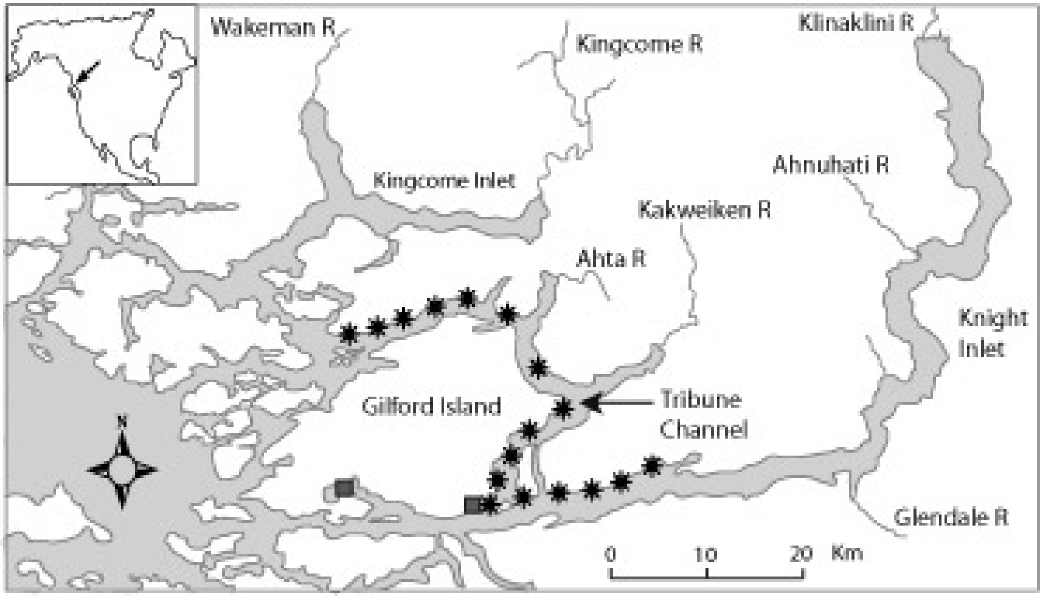
Understanding sea lice impacts

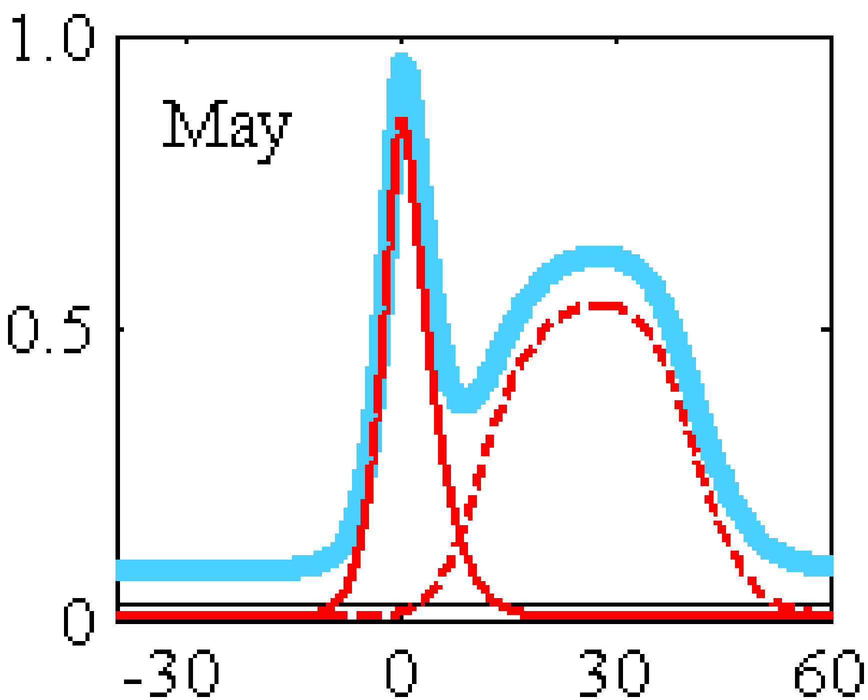
- Do sea lice spread from farm to wild salmon?
- How many juvenile salmon die from lice?
- Do lice threaten wild salmon populations?

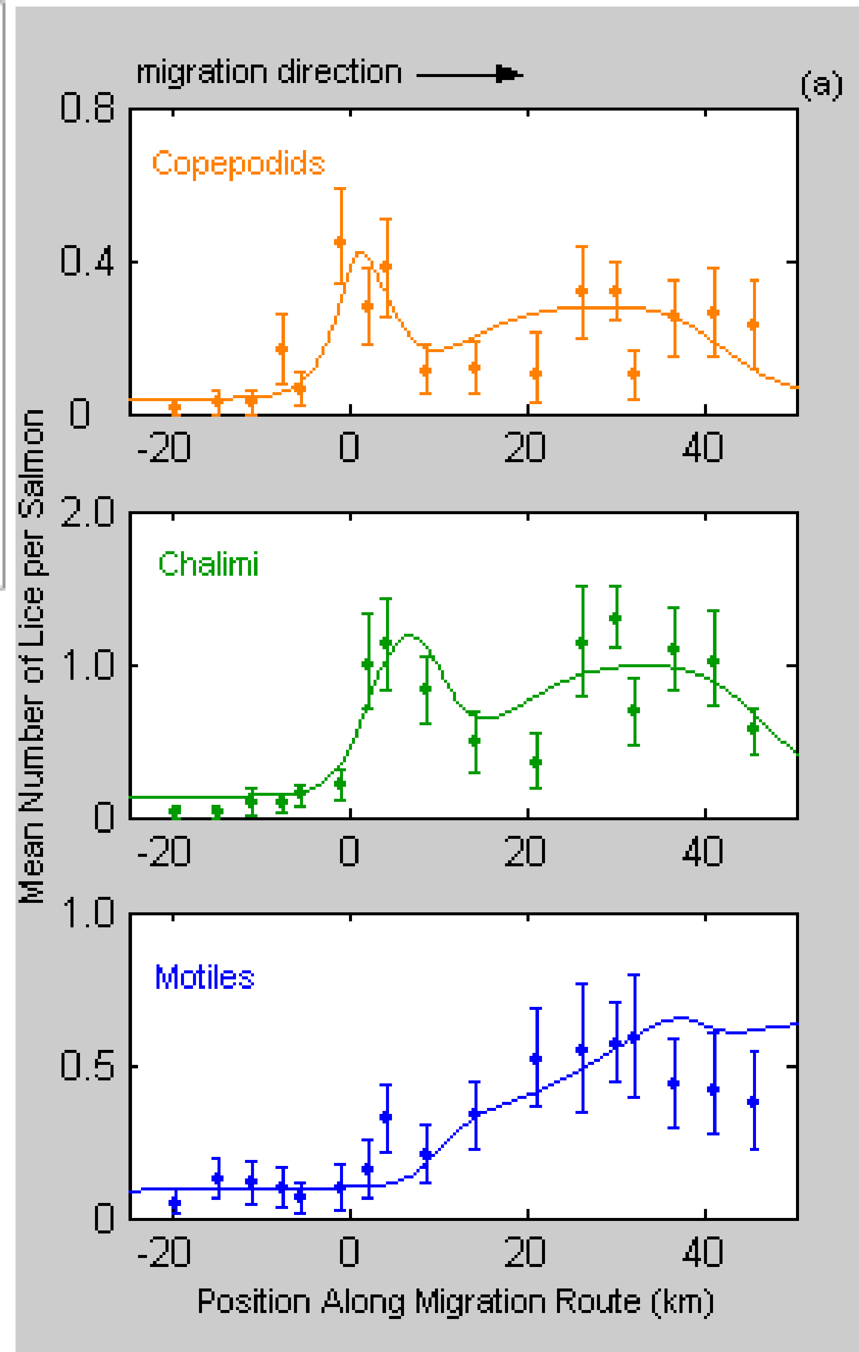
Fieldwork: Counting lice on juvenile salmon



Krkosek, Morton, Volpe. *Trans Am Fish Soc, 2005*


Wakeman R
Kingcome R
Klinaklini R
Kingcome Inlet
Ahnuhati R
Kakweiken R
Ahta R
Knight Inlet
Gilford Island
Tribune Channel
Glendale R
N
0
10
20
Km


May
1.0
0.5
0
-30
0
30
60


migration direction
(a)
Copepodids
Chalimi
Motiles
Mean Number of Lice per Salmon
Position Along Migration Route (km)
0.8
0.4
0
2.0
1.0
0
1.0
0.5
0
-20
0
20
40

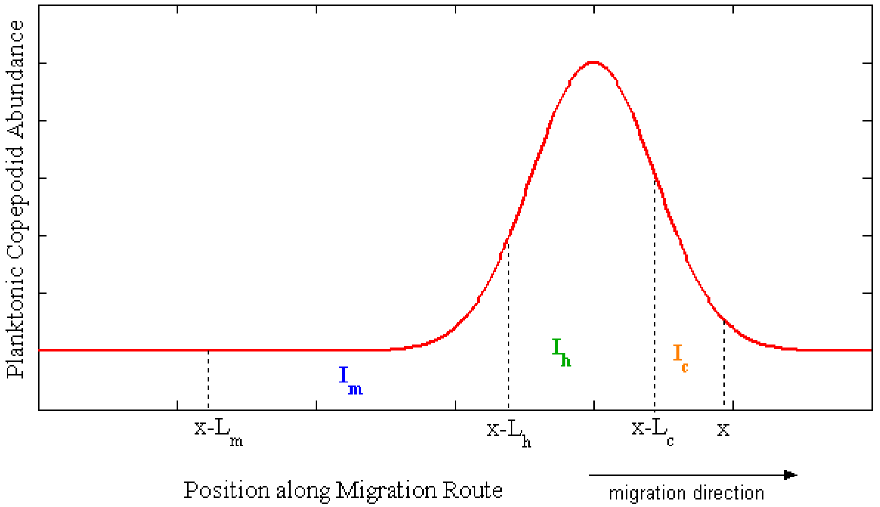
Infection Dynamics

Life-history stage	Time duration	Spatial displacement
Copepodids	T_c	$L_c = vT_c$
↓ Chalimi	T_h	$L_h = v(T_c + T_h)$
↓ Motiles	T_m	$L_m = v(T_c + T_h + T_m)$

Copepodids: $$C(x) = \frac{\beta}{v}\int_{x-\lambda_c}^{x} L(u)du$$

Chalimi: $$H(x) = \frac{s_c\beta}{v}\int_{x-\lambda_h}^{x-\lambda_c} L(u)du$$

Motiles: $$M(x) = \frac{s_c s_h\beta}{v}\int_{x-\lambda_m}^{x-\lambda_h} L(u)du,$$



Secondary infections

Motile lice can reproduce and disperse

Assume time scale of 2 parasite generations

$$L_2(x) = \varphi\int_{-\infty}^{\infty} M(y)k_L(x-y)dy$$

Fitting the transmission model

- Probabilistic model of infection events and parasite development
  - Infection by copepodids occurs as a Poisson process with spatially variable rate parameter
  - Infection by later developmental stages occurs as a Poisson-binomial process with variable rate parameter

$$\begin{aligned} \mathrm{P}\{N_h = k\} &= \sum_{n=k}^{\infty} \left[\binom{n}{k} (s_c)^k (1 - s_c)^{n-k} \left(\frac{[I_h(x)]^n}{n!} \mathrm{e}^{-\mathrm{I_h}(x)} \right) \right] \\ &= \frac{1}{k!} \left[s_c I_h(x) \right]^k \mathrm{e}^{-\mathrm{s_c} I_h(x)}, \end{aligned}$$

where

$$I_h(x) = \beta \frac{1}{v} \int_{x-\lambda_h}^{x-\lambda_c} L(u)\, du$$

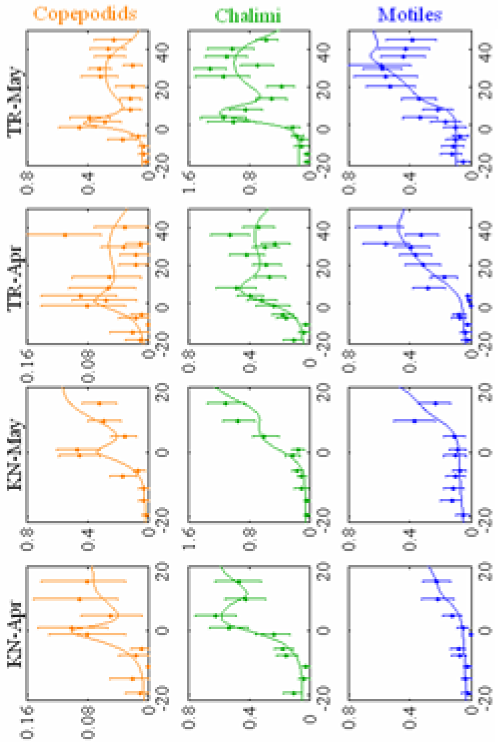
gives the likelihood

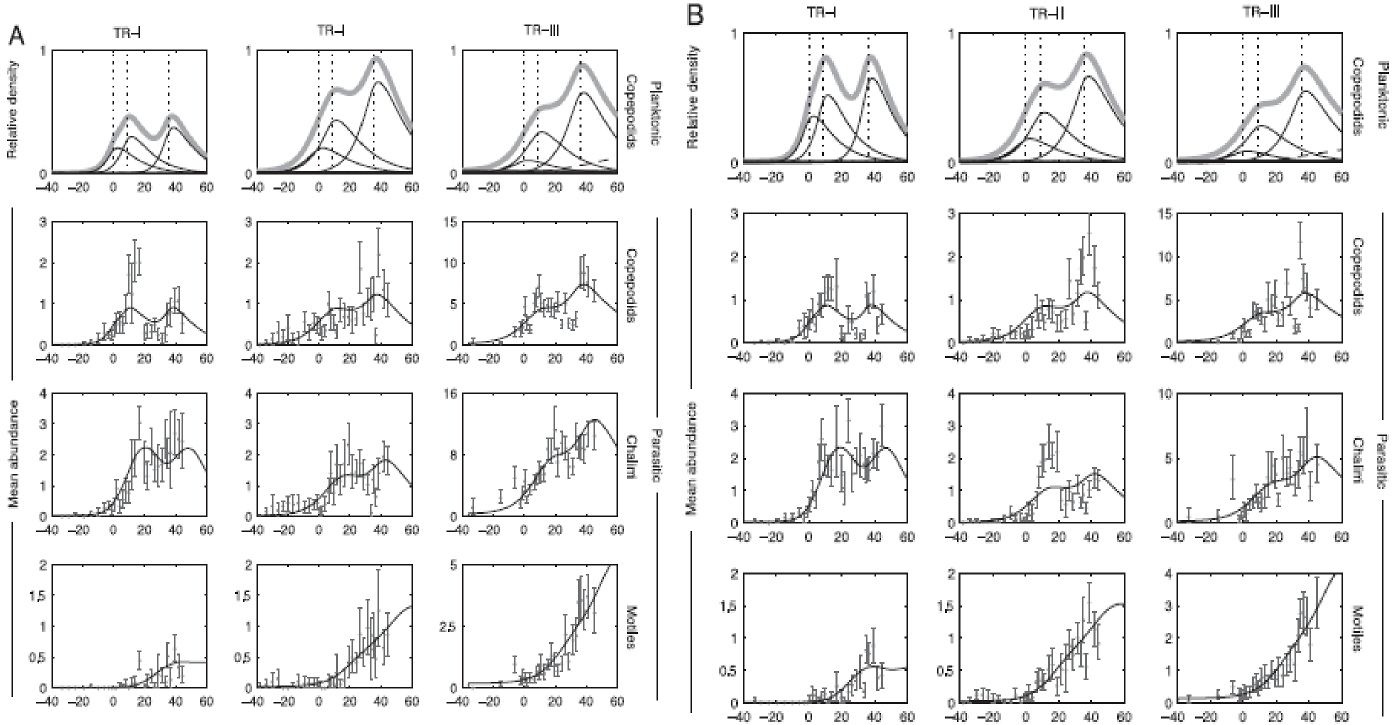
Sample set

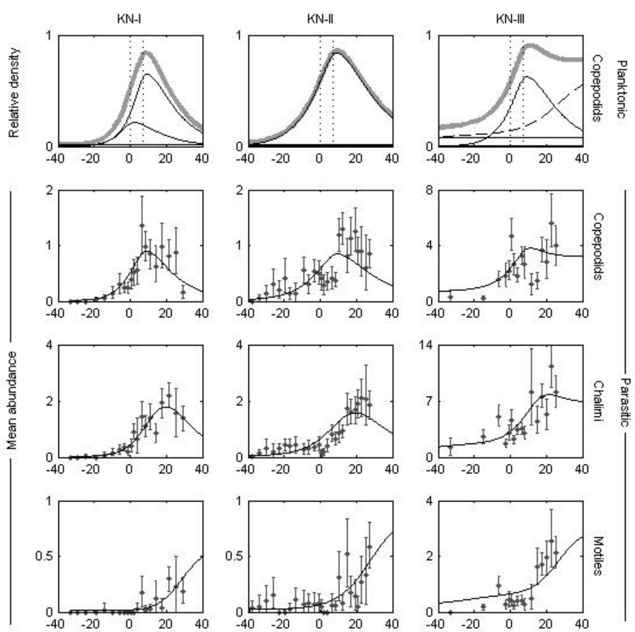
Individual fish

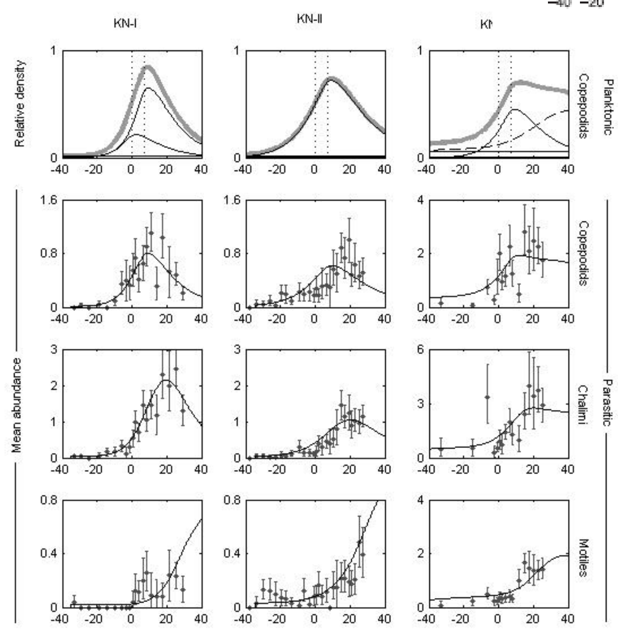
Louse stage

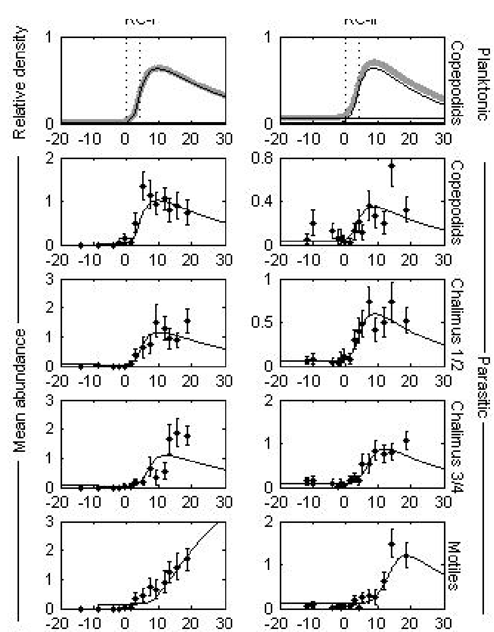
$$L\left[\text{data} \mid \text{model}\right] = \prod_i \prod_j \prod_k P\left\{ y_{i,j,k} \mid \text{model} \right\}$$


Copepodids
Chalimi
Motiles
TR-May
TR-Apr
KN-May
KN-Apr


A
B
TR-I
TR-II
TR-III
Relative density
Mean abundance
Planktonic
Copepodids
Parasitic
Chalimi
Motiles


KN-I
KN-II
KN-III
Relative density
Mean abundance
Planktonic
Copepodids
Parasitic
Chalimi
Motiles

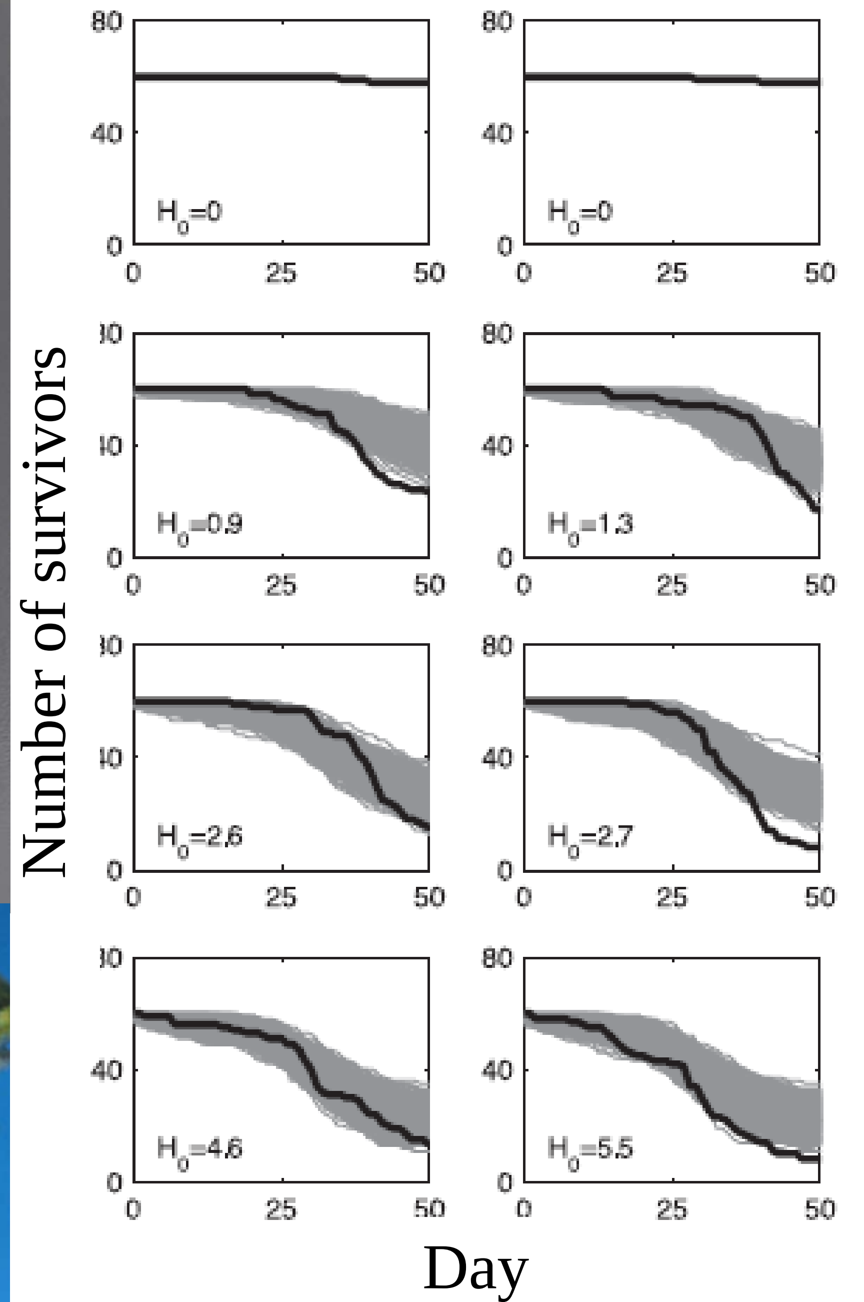

KN-I
KN-II
Relative density
Mean abundance
Planktonic
Copepodids
Parasitic
Chalimi
Motiles


Relative density
Mean abundance
Planktonic
Copepodids
Parasitic
Chalimus 1/2
Chalimus 3/4
Motiles

Understanding sea lice impacts

- Do sea lice spread from farm to wild salmon?
  - YES, for 30 - 80 km
- How many juvenile salmon die from lice?
- Do lice threaten wild salmon populations?

Infection and Survival



Survival Analysis

- $Q(t)$ – probability a host survives to time t
- $f(t)$ – probability density function of mortality events

$$f(t) = \frac{d}{dt}\left[1 - Q(t)\right] \qquad Q(t) = \exp\left[-H_0 \int_0^t \Lambda(\tau)\,d\tau\right]$$

- The likelihood function $\prod_i f(\tau_i) \prod_j Q(\tau_j)$
- Lice transmission is spatial but host survival is temporal
- Use the chain rule to map time to space via migration velocity
  - $dg/dx = dg/dt \cdot dt/dx = v^{-1} \cdot dg/dt$

Sea lice dynamics

$$\frac{dP_{1,1}}{dx} = \frac{p_c \beta}{v} L(x - \lambda_h) - \frac{1}{v}(n\mu_1 + \alpha_1) P_{1,1}$$

$$\frac{dP_{1,2}}{dx} = \frac{n\mu_1}{v} P_{1,1} - \frac{1}{v}(n\mu_1 + \alpha_1) P_{1,2}$$

$$\vdots$$

$$\frac{dP_{1,n}}{dx} = \frac{n\mu_1}{v} P_{1,n-1} - \frac{1}{v}(n\mu_1 + \alpha_1) P_{1,n}$$

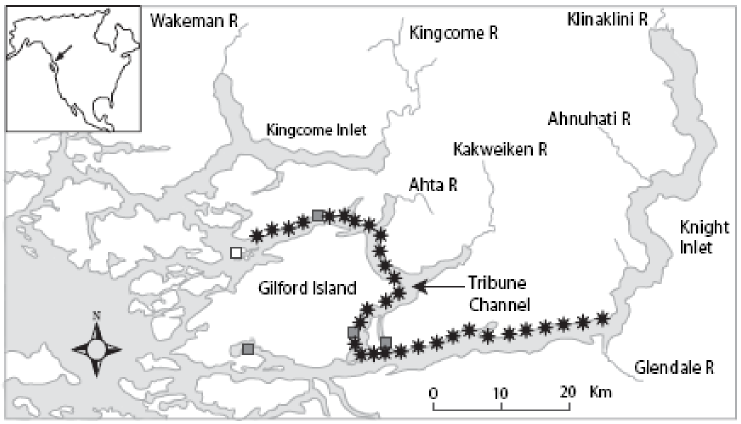
$$\frac{dP_2}{dx} = \frac{n\mu_1}{v} P_{1,n} - \frac{\sigma}{v} P_2$$

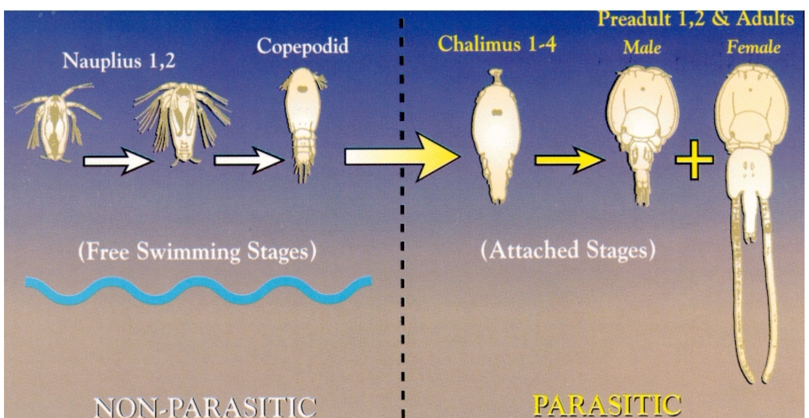
Salmon survival

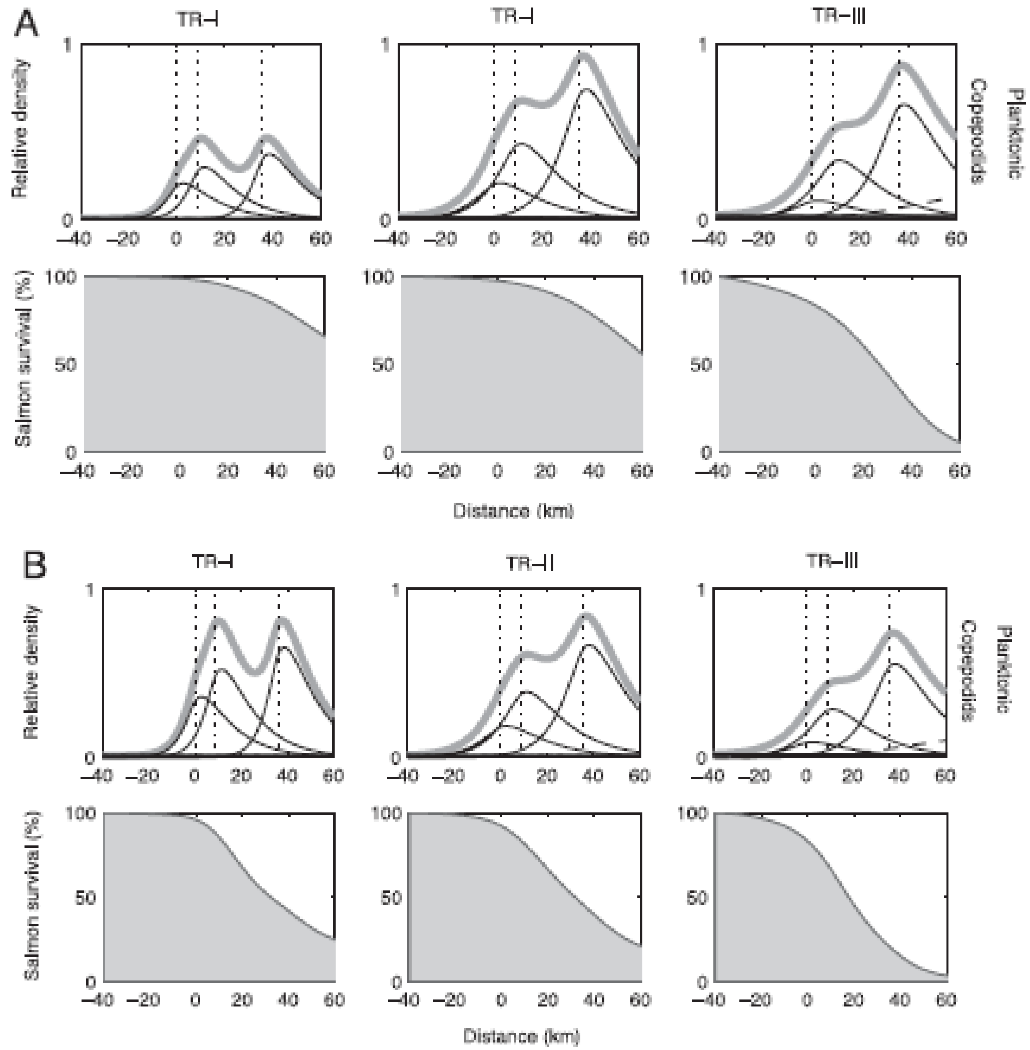
$$\frac{dN}{dx} = -\frac{1}{v}\left[\alpha_1 \sum_{i=1}^{n} P_{1,i}(x) + p\alpha_2 P_2(x)\right] N$$

Farm lice and wild salmon survival

Krkosek, Lewis, Morton, Frazer, Volpe, *Proc Natl Adac Sci USA*, 2006





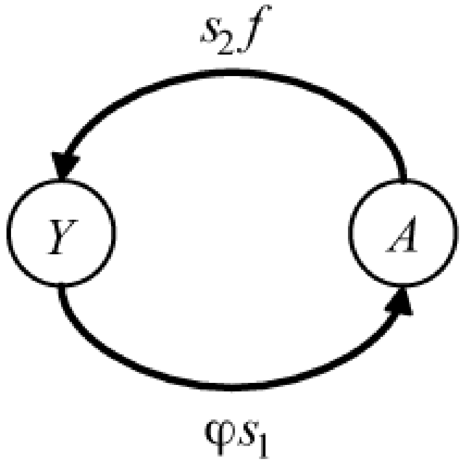


Understanding sea lice impacts

- Do sea lice spread from farm to wild salmon?
  – YES, for 30 - 80 km
- How many juvenile salmon die from lice?
  – 9-95% of juvenile salmon are killed by lice.
- Do lice threaten wild salmon populations?

Predicting population impacts

Krkosek, Gottesfeld, Proctor, Rolston, Carr-Harris, Lewis, *Proc Roy Soc Lond B*, 2007



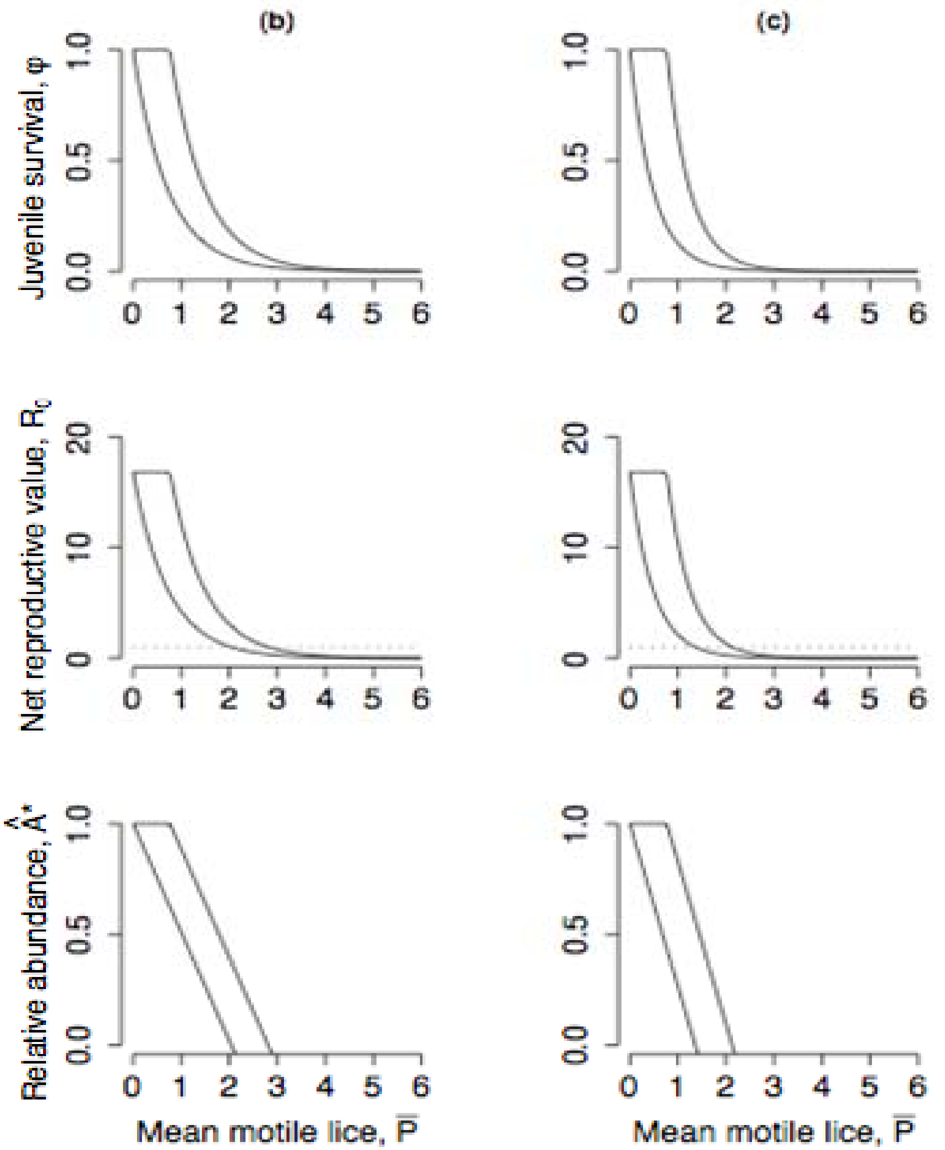
$$\varphi = \exp\left[-\int_0^T \Phi(t)\,dt\right]$$

Non-compensatory mortality

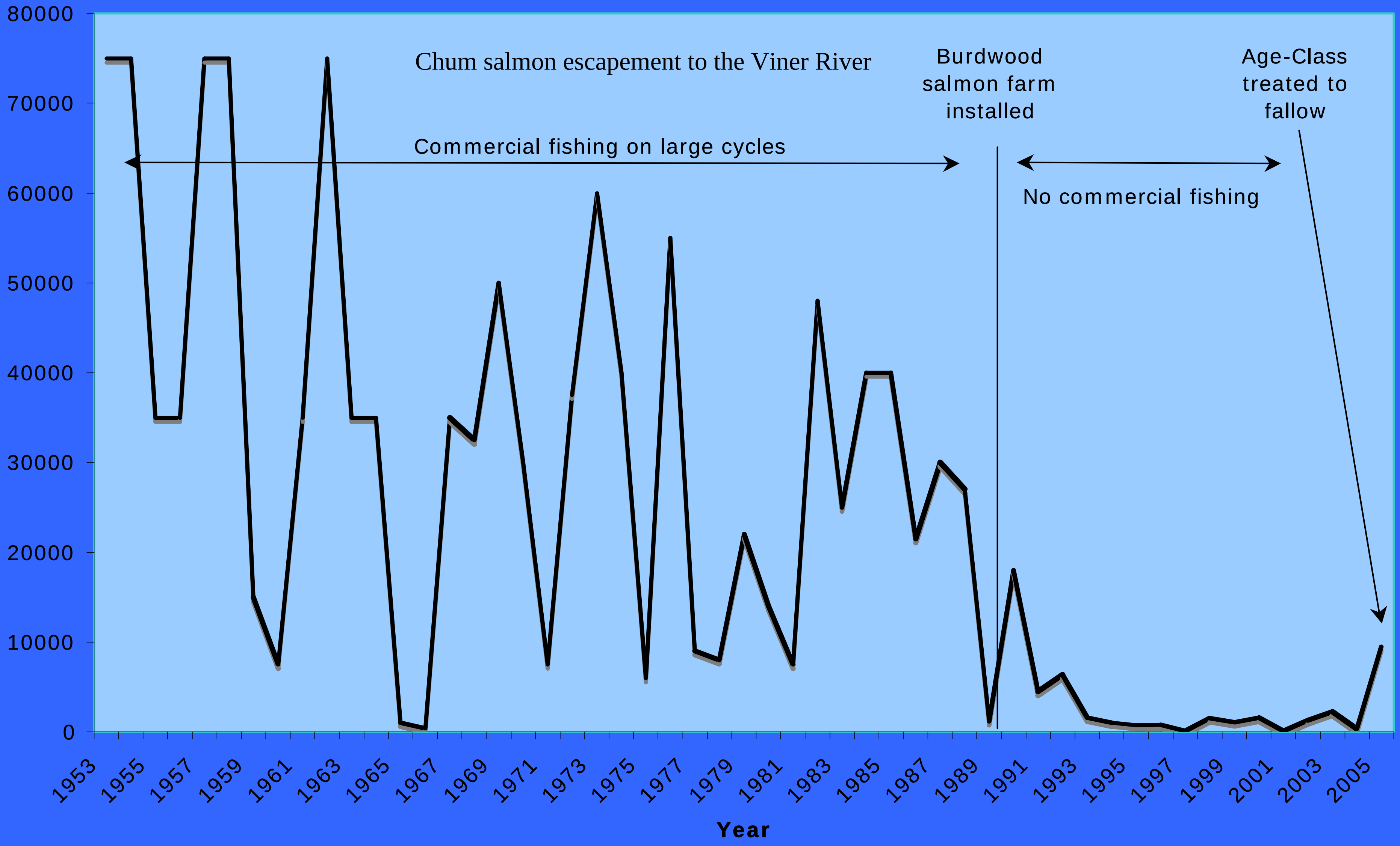
$$\Phi_1(t) = \alpha \overline{P}(t)$$

Compensatory mortality

$$\Phi_2(t) = \begin{cases} 0 & \text{, if } \alpha\overline{P}(t) < \mu(t) \\ \left(\alpha\overline{P}(t) - \mu(t)\right) & \text{, if } \alpha\overline{P}(t) > \mu(t) \end{cases}$$



The case of the Viner Chums

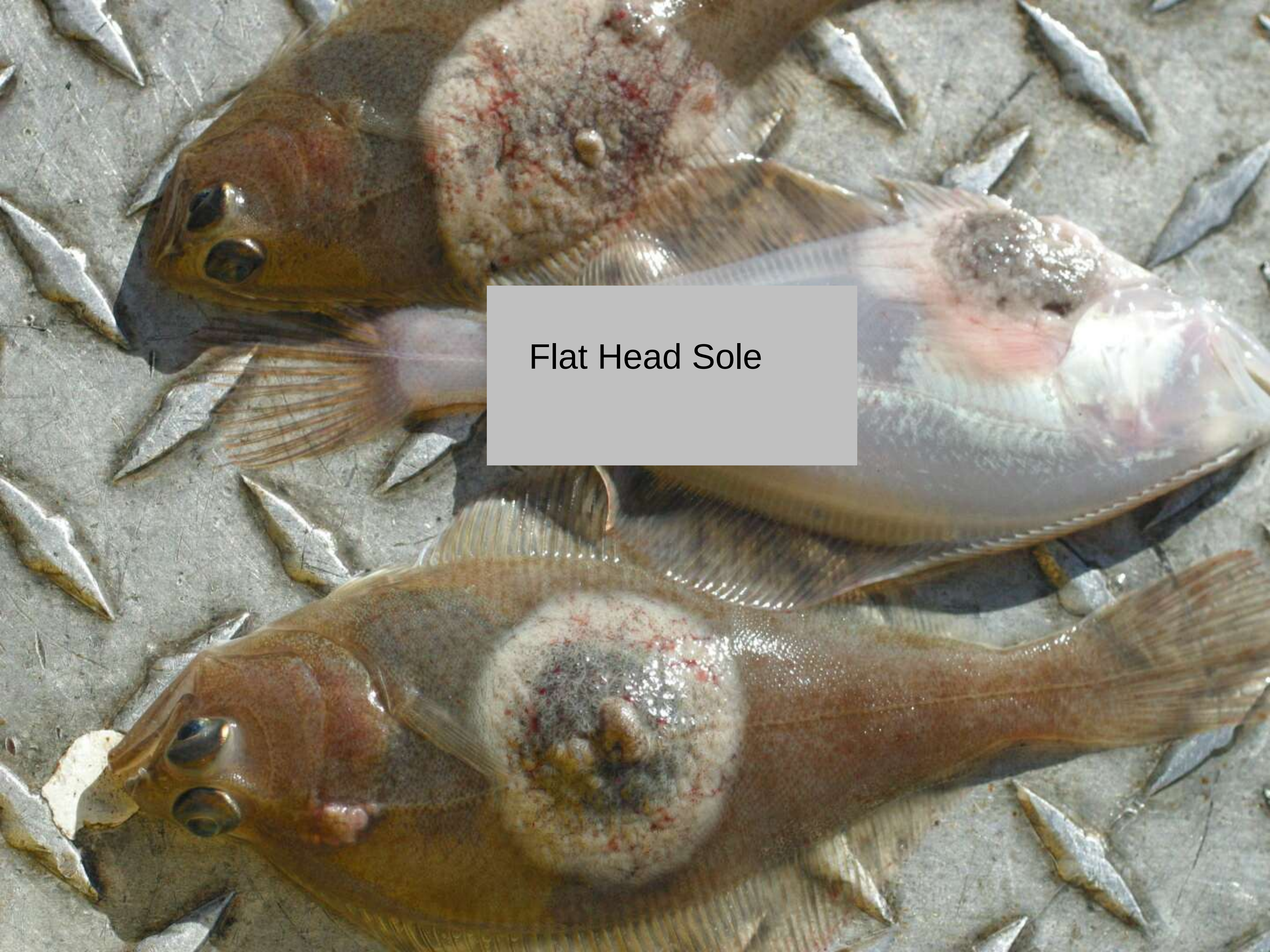


Understanding sea lice impacts

- Do sea lice spread from farm to wild salmon?
  - YES, for 30 - 80 km

- How many juvenile salmon die from lice?
  - 9-95% of juvenile salmon are killed by lice.

- Do lice threaten wild salmon populations?
  - Probably, but thorough analysis not yet complete


Flat Head Sole


Rock Sole


Turbot

Conclusions

1. Myriad disease interactions between wild and farm fish
2. Disease dynamics and impacts are unpredictable and poorly understood
3. Scientific capacity is just beginning to detect, study, understand, and manage disease interactions.



The ocean is an open system

Funding Sources

Natural Science and Engineering Research Council (29%)
Pacific Salmon Forum (20%)
National Research Council - MITACS (19%)

68%

National Geographic Society Research and Exploration Grant (4%)

University of Alberta Fellowships (5%)

77%

David Suzuki Foundation (13%)
The Canadian Sablefish Association (4%)
BC Wilderness Tourism Association (3%),
Finest at Sea (2%)

MITACS
Funding Partners

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