Use of Bayesian Hierarchical Models for Multi-Year Ecological Studies

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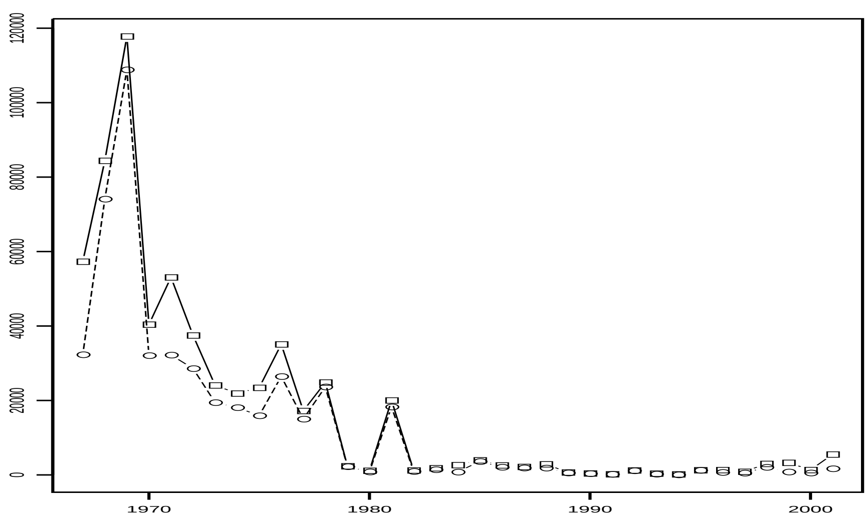
MOTIVATION

Throughout the Sacramento-San Joaquin River Systems *native* chinook salmon population levels are far below historical levels.

For example, the winter-run chinook salmon was one of the first Pacific salmon stocks declared endangered under the Endangered Species Act.



Management agencies, including USFWS, want to know the role of certain factors, e.g., flow, in terms of salmon survival.

To quantify the effects of some of these factors on salmon survival, release-recovery experiments have been conducted for many years.

STUDY DESIGN

1. Mark and tag: Hatchery-reared *juvenile* salmon.

2. Release: “pair” of locations, one location often serving as a control location.

3. Freshwater Recovery: within a few weeks at one or two downstream locations by trawling.

4. Ocean Recovery: over 1 to 3 year period.

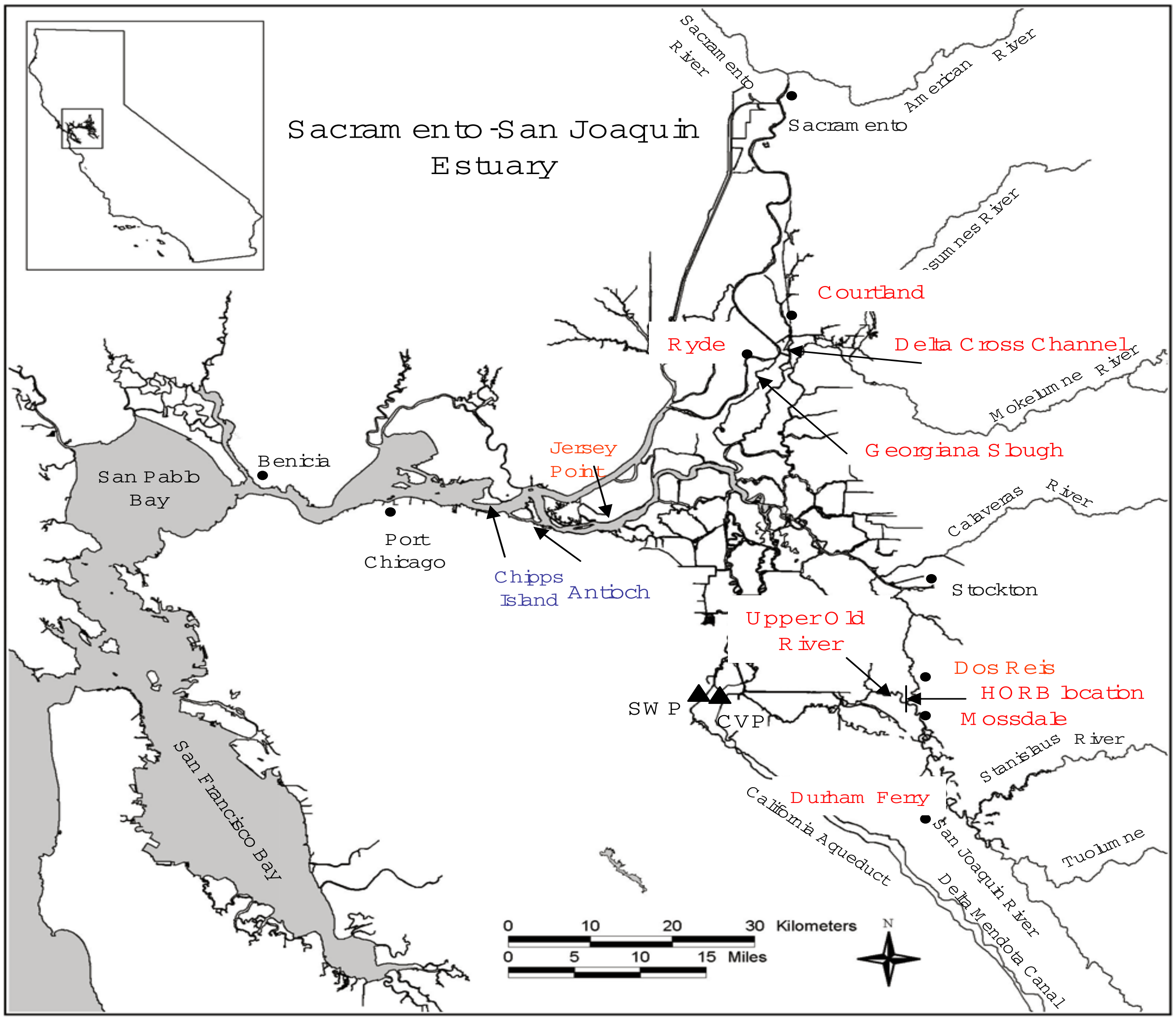
Notation for release and recovery data:

$$R_{i,t} = \text{Number released at location } i \text{ in ``year'' } t$$

$$y_{i \to j,t} = \text{Number recovered at location } j \text{ from } R_{i,t}$$

For example, a 1994 paired release from Ryde (control) and Georgiana Slough (trt):

Release Site	R	$y_{i \to \text{Chipps Is.}}$	$y_{i \to \text{Ocean}}$
Ryde	34,560	37	292
Georg.Sl	33,668	5	80



CWT release sites in the Sacramento-San Joaquin Estuary, California.

SIMPLE STUDY

Effect of Exports on Relative Survival of Georgiana Slough compared to Ryde releases

1994-2006: 15 paired releases.

Previous analysis approach: Two Stage

1. Estimate relative survival rate, θ:

$$\widehat{\theta} = \frac{y_{GS \rightarrow Chipps}/R_{GS}}{y_{Ryde \rightarrow Chipps}/R_{Ryde}}$$

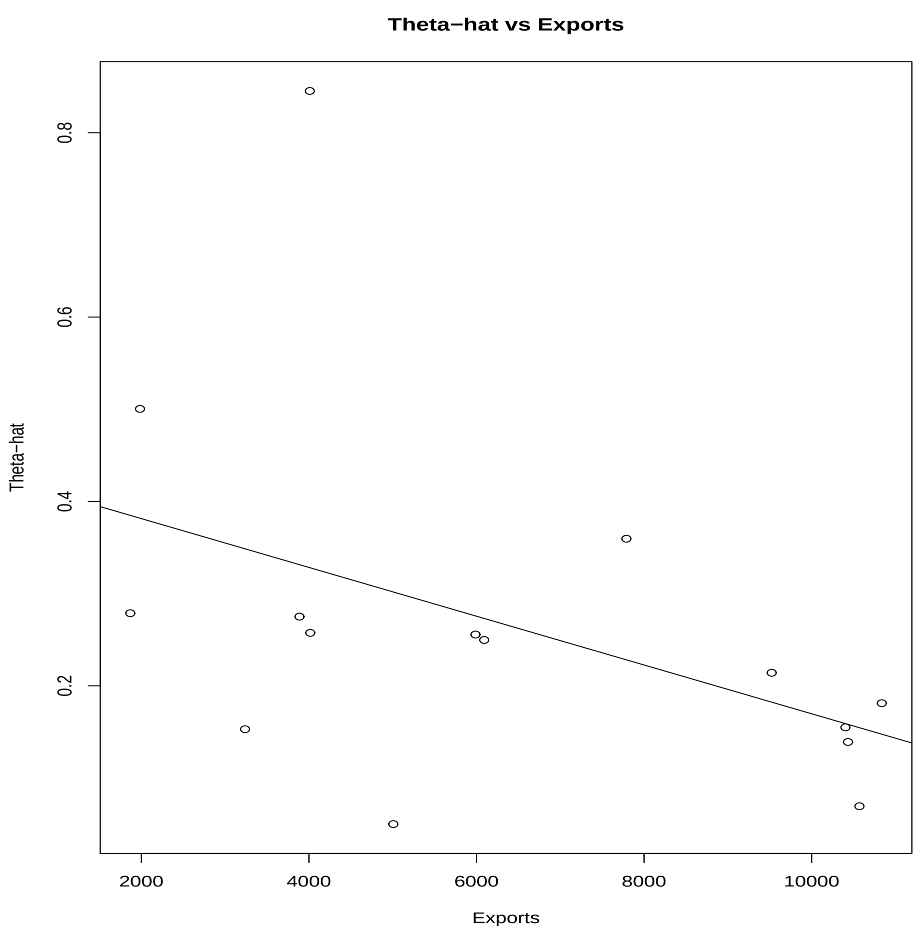
2. Regress $\widehat{\theta}$ against Exports

$$\widehat{\theta} = \beta_0 + \beta_1 Exports + \epsilon$$

β_1 of primary interest.

Previous analysis results

```
Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
scale(exports.gs) -0.08693    0.04864  -1.787   0.0973 .

Residual standard error: 0.182 on 13 df
Multiple R-Squared: 0.1972
```



Comments re: previous analysis

1. Analysis of ocean recoveries proceeded similarly, but done *separately*.

2. Sampling variation in $\widehat{\theta}$ is not accounted for.

3. Between year variation not accounted for, e.g., $\theta_t \sim$ Dist'n(μ_θ).

New Analysis: BAYESIAN HIERARCHICAL MODEL (BHM)

Level 1: Recoveries $|S_{i \rightarrow j,t}, p_{j,t}$

$$y_{i \rightarrow FW,t}, y_{i \rightarrow Oc} \sim \text{Multinomial}\left(R_i, S_{i \rightarrow Chipps,t} p_{Chipps,t}, S_{i \rightarrow Chipps,t}(1 - p_{Chipps,t})\pi_{Oc,t}\right)$$

Level 2: Parameters as random effects

$$\begin{aligned} logit(S_{i \rightarrow j,t}) &\sim \text{Normal}\left(\beta_0 + \beta_1 Exports, \sigma^2_{S_{i \rightarrow j}}\right) \\ logit(p_{j,t}) &\sim \text{Normal}\left(\mu_{p_j}, \sigma^2_{p_j}\right) \end{aligned}$$

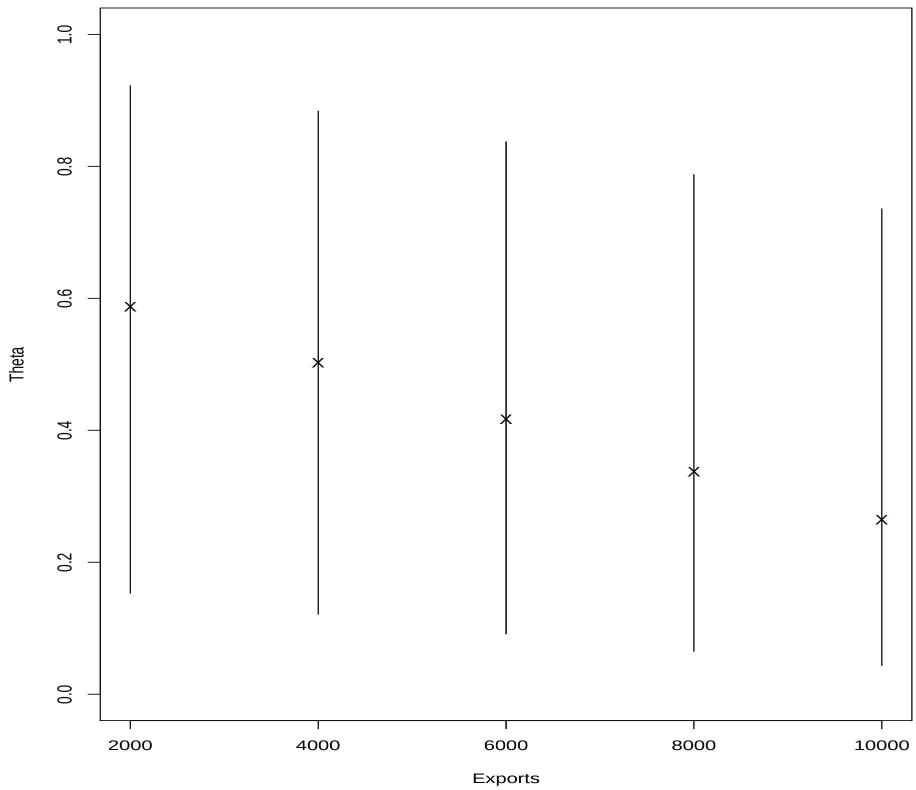
Level 3: Priors for hyperparameters

$$\beta_1 \sim \text{Normal}(\mu_1, \sigma^2_r) \ldots$$

WinBUGS code:

```
model {

    #Priors for the Parameters in the logistic models
    b0         ~ dnorm(0, 1.0E-6)
    b1         ~ dnorm(0, 1.0E-6) ...

   for(i in 1:n) {

      # random effects
      eps.theta[i]   ~ dnorm(0.0, tau.theta) ...

      logit(theta[i])  <- b0 + b1*exports[i] + eps.theta[i] ..

      p13[i]         <- theta[i] * rc[i]
      p14[i]         <- theta[i] * ro[i] ....

      #Two trinomial distributions for the recoveries
      y13[i]      ~ dbin(p13[i], R1[i])
      condR1[i]  <- R1[i]-y13[i]
      y14[i]      ~ dbin(condp14[i], condR1[i])  ...
   }
}
```

RESULTS



Two-Stage	Est	Std Err	t
(FW only)	-0.087	0.049	-1.79
(FW+Oc)	-0.124	0.052	-2.38

HBM	Mean	Std Dev	0.025	0.975
Posterior	-0.57	0.27	-1.12	-0.04

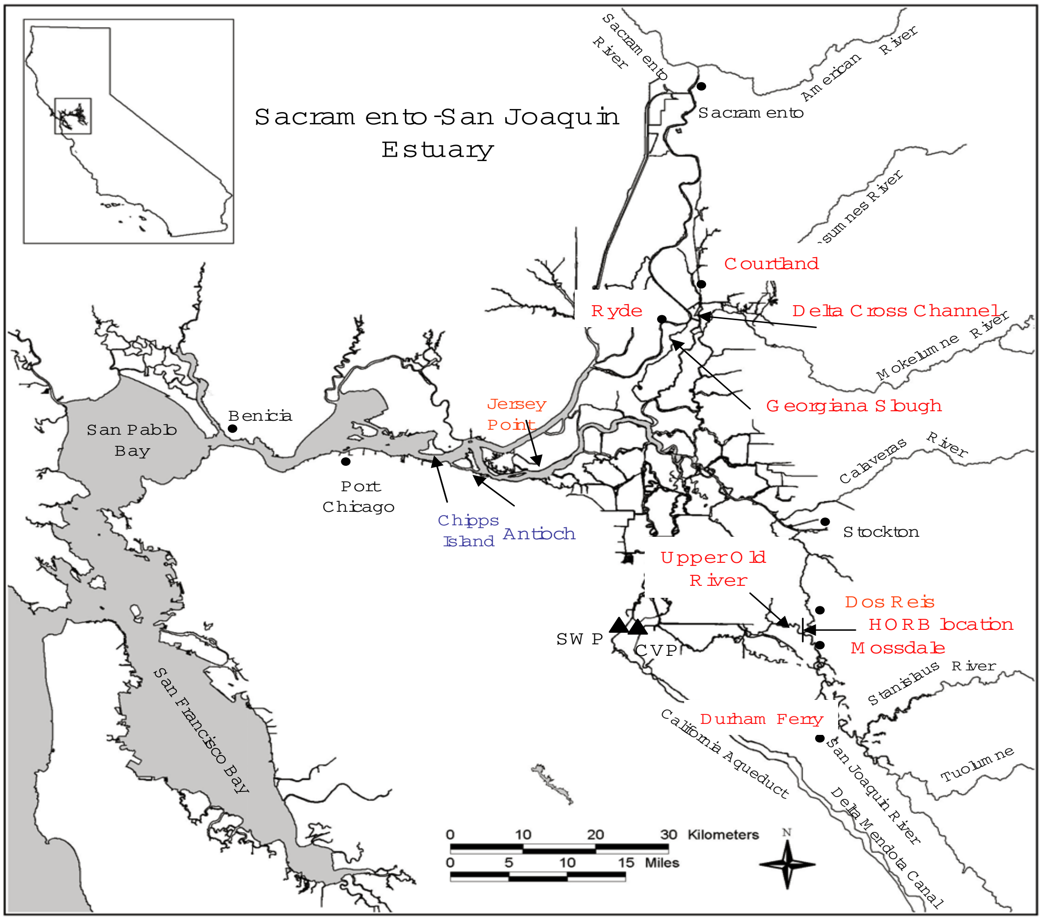
COMPLEX STUDY

San Joaquin salmon: 31 release “sets” during 1989-2006

Objective: Study effects of exports, flow, and a barrier to entering Old River (passing pumps)

Releases: up to 4 different locations

Recoveries: up to 3 locations—Antioch (FW), Chipps Island (FW), Ocean



CWT release sites in the Sacramento-San Joaquin Estuary, California.

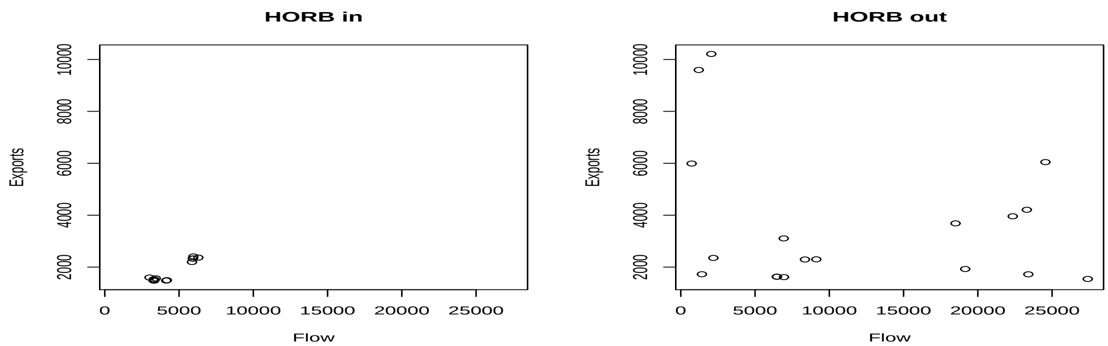
Complications of complex study

- Unbalanced release strategy
- Unbalanced recovery strategy
- Unbalanced combinations of flow, exports, and barrier placement
- Factors of interest vary by *release section*

Unbalanced release and recovery design

	DF	MD	DR	JP	Ant	CI	Oc	# obs'ns
1989			R	R		X	X	4
1990a			R	R		X	X	4
1990b			R	R		X	X	4
1991			R	R		X	X	4
1994a		R		R		X	X	4
1994b		R		R		X	X	4
1995a		R	R	R		X	X	6
1995b		R	R			X	X	4
1995c		R	R			X	X	4
1996a		R		R		X	X	4
1996b		R	R	R		X	X	6
1996c			R	R		X	X	4
1997a		R	R	R		X	X	6
1997b			R	R		X	X	4
1997c			R	R		X	X	4
1998a		R	R	R		X	X	6
1998b		R	R	R		X	X	6
1999		R	R	R		X	X	6
2000a	R	R		R	X	X	X	9
2000b	R	R		R	X	X	X	9
2001a	R	R		R	X	X	X	9
2001b	R	R		R	X	X	X	9
2002a	R	R		R	X	X	X	9
2002b	R	R		R	X	X	X	9
2003a	R	R		R	X	X	X	9
2003b	R	R		R	X	X	X	9
2004	R	R		R	X	X	X	9
2005a	R		R	R	X	X	X*	6
2005b	R		R	R	X	X	X*	6
2006a		R	R	R	X	X	X*	6
2006b		R		R	X	X	X*	4

Lack of balance in covariate design space



HBM: survival by stream section, "borrowing of strength" between release sets

Level 1:

$$y_{DF\to A}, y_{DF\to CI}, y_{DF\to Oc} | \Theta \sim$$
$$\text{Mn}(R_{DF},$$
$$S_{DF\to MD}\theta_{MD\to DR}\theta_{DR\to JP}r_{JP\to A}, \text{ Antioch}$$
$$S_{DF\to MD}\theta_{MD\to DR}\theta_{DR\to JP}r_{JP\to CI}, \text{ Chipps Is}$$
$$S_{DF\to MD}\theta_{MD\to DR}\theta_{DR\to JP}r_{JP\to Oc}) \text{ Ocean}$$

...

Level 2:

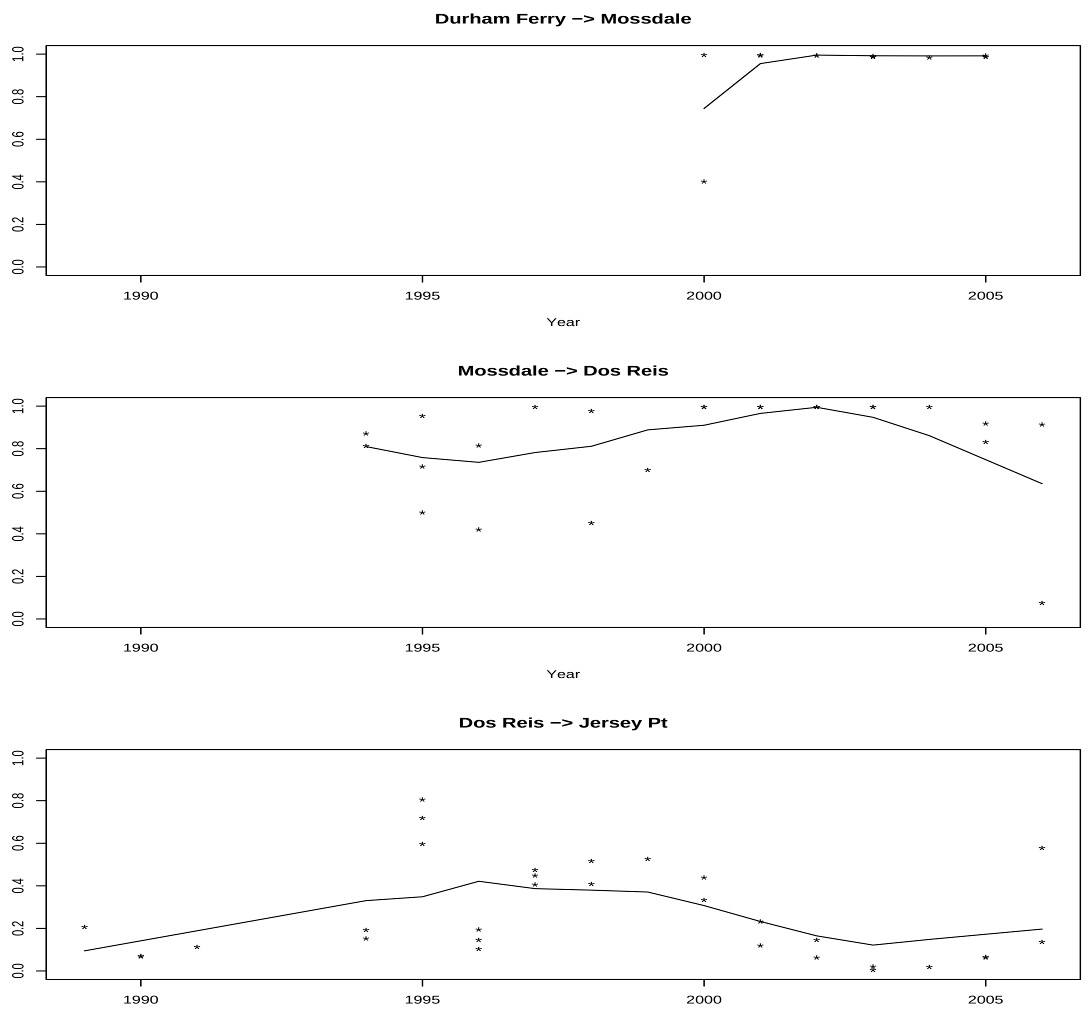
$$logit(S_{DF\to MD}) \sim$$
$$\text{Normal}\left(\beta_0 + \beta_1 Flow_{DF}, \sigma^2_{S_{DF\to MD}}\right)$$

$$logit(\theta_{MD\to DR}) \sim$$
$$\text{Normal}(\gamma_0 + \gamma_1 Flow_{MD} +$$
$$\gamma_2 HORB + \gamma_3 Exports_{MD} * (1 - HORB), \sigma^2_{\theta_{MD\to DR}})$$

$$logit(\theta_{DR\to JP}) \sim$$
$$\text{Normal}\left(\xi_0 + \xi_1 Flow_{DR} + \xi_2 HORB + \xi_3 Exports_{DR}, \sigma^2_{\theta_{DR\to JP}}\right)$$

HBM RESULTS for COMPLEX STUDY

Reach-specific survival estimates



More Results for Complex Study:

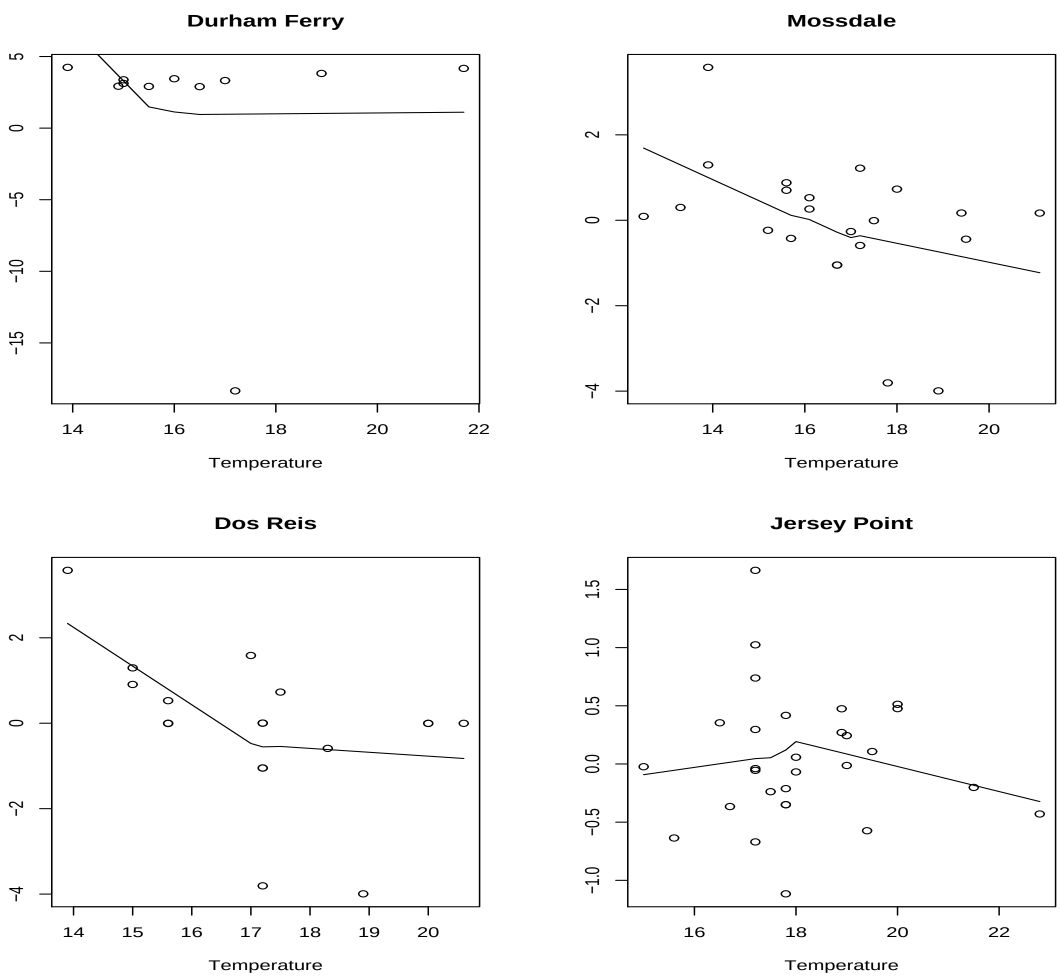
- Barrier is very beneficial to survival

- Without barrier, exports have adverse effect on survival

- Increasing flows helps survival in the longest stretch (between Dos Reis and Jersey Pt)

Analysis of random effects

Can also study release-specific random effects for relationships with other “unpaired” factors, like temperature.



CONCLUSIONS

- BHMs able to capture environmental and sampling variability

- BHMs allow "sharing" of information between years

- For these models, `WinBUGS` was adequate, and much simpler than likelihood analysis

Interesting Problems to Pursue:

- Ocean recoveries have extra-binomial variation

- Potential dependencies between fish, schooling

- Sample size determination: number of years vs. number of fish