

# Exploration of Overcompensation and the Spawning Abundance Producing Maximum Sustainable Yield for Upper Cook Inlet Sockeye Salmon Stocks

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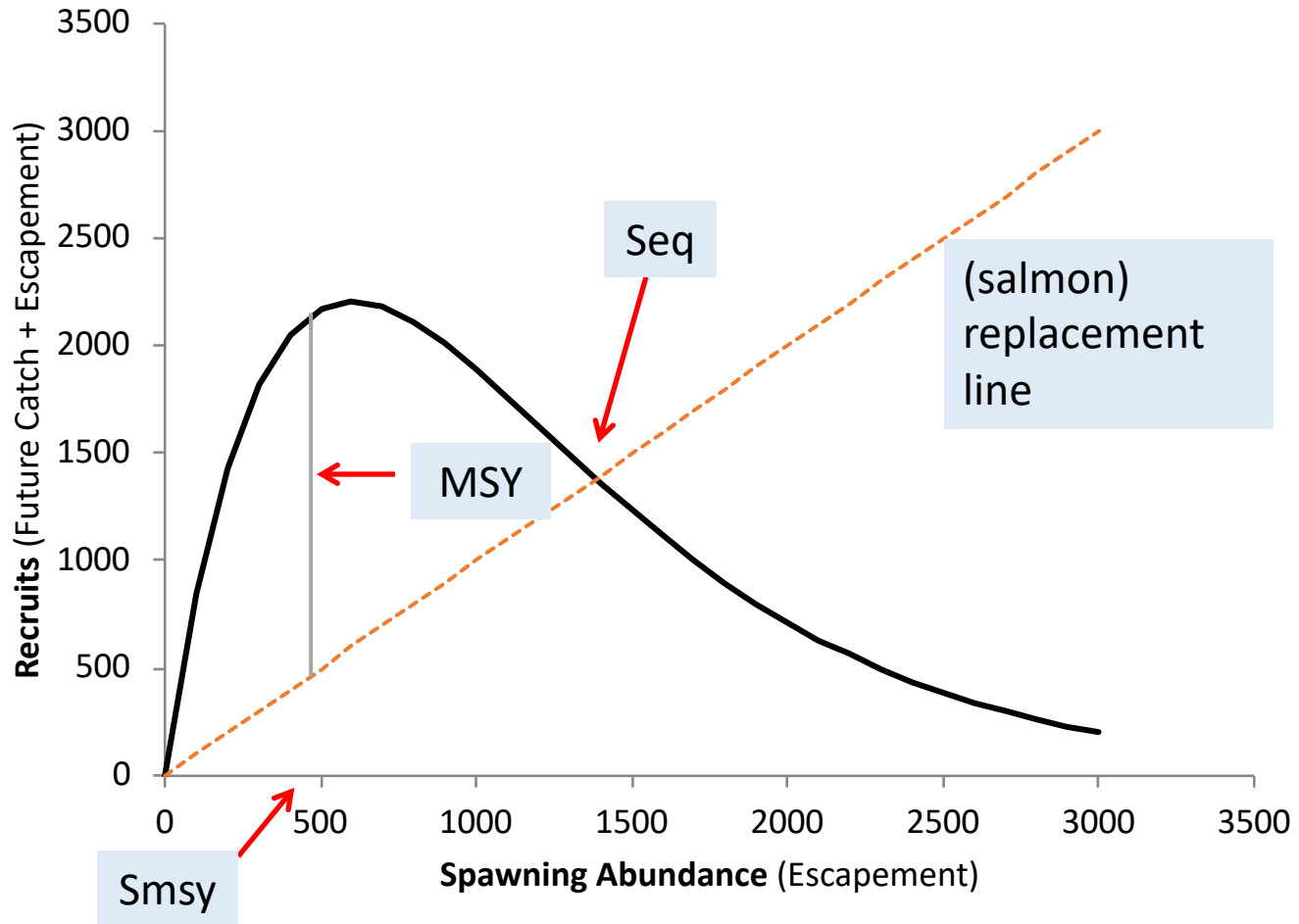
# Corrections

- $\max(\Delta WAIC)$  for Kenai River late-run sockeye
  - 4.27 not 3.31
- Description of Autoregressive Ricker model
  - Original text
    - “...maximum productivity is equal to  $\alpha$  and not  $\ln(\alpha)$ .”
  - Corrected text
    - “...maximum productivity is equal to  $\alpha$  and not  $\exp(\alpha)$ .”

# Background and Purpose

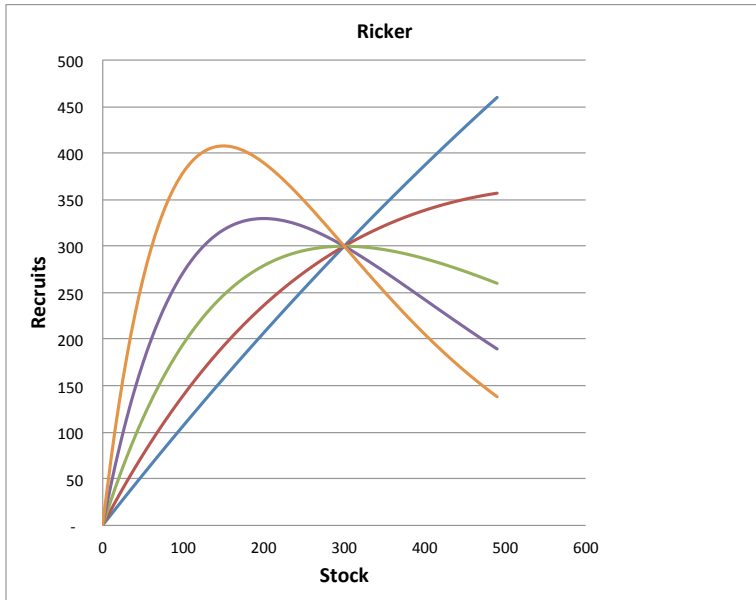
- Focus
  - Kenai River late-run sockeye salmon
  - Kasilof River sockeye salmon
- Identify spawning abundance expected to produce maximum sustainable yield (Smsy)
  - Compare alternative stock-recruitment models
  - Quantify evidence for a “preferred” model
  - Simulate potential yield across a range of spawning abundances
- Implications of surplus escapement
  - Quantify evidence for overcompensation

# MSY and Smsy

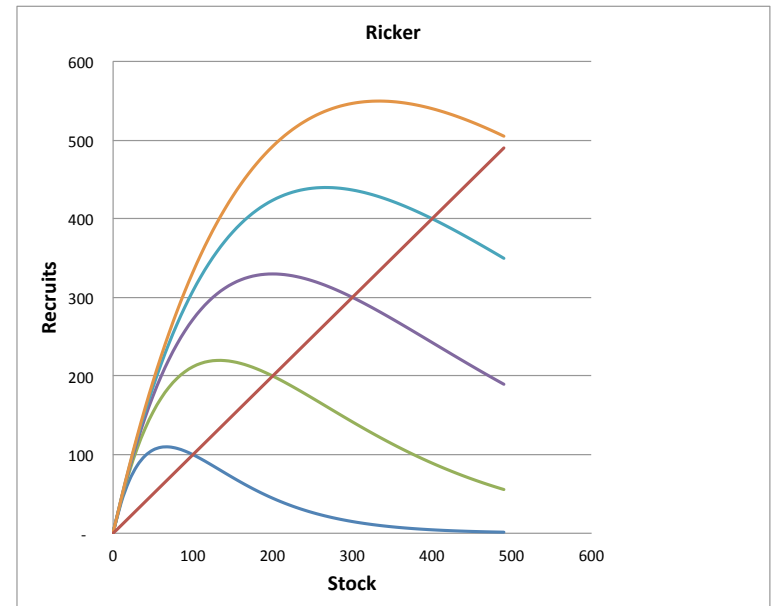


# Models: Standard Ricker

## Changing $\alpha$



## Changing $\beta$



Name	Equation	Priors
Ricker	$R_t = S_t e^{\alpha(1-S_t/\beta)+\varepsilon_t}$	$\alpha \sim \ln(\text{Uniform}(1e-3, 20))$ $\beta \sim \text{Uniform}(1, 1e7)$ $\sigma \sim \text{Normal}(0, 1)[1e-3, 2]$

# Models: Brood Year Interaction Ricker

- Mechanisms for delayed density dependence
  - Delayed-embryo mortality hypothesis (Hunter 1959)
  - Delayed-parasitism hypothesis (Ricker and Smith 1975)
  - Delayed-predation hypothesis (Ricker 1950)
  - Delayed-food availability (Koenings and Kyle 1997)
- Delayed density dependence as main effects:

Name	Equation	Priors
Brood Year Interaction Ricker (main effects)	$R_t = S_t e^{\alpha - \beta_1 S_t - \beta_2 S_{t-1} + \varepsilon_t}$	$\alpha \sim \ln(\text{Uniform}(1e - 3, 20))$ $\beta_{1,2} \sim \text{Uniform}(0, 1e - 3)$ $\sigma \sim \text{Normal}(0, 1)[1e - 3, 2]$

# Models: Brood Year Interaction Ricker

- Mechanisms for delayed density dependence
  - Delayed-embryo mortality hypothesis (Hunter 1959)
  - Delayed-parasitism hypothesis (Ricker and Smith 1975)
  - Delayed-predation hypothesis (Ricker 1950)
  - Delayed-food availability (Koenings and Kyle 1997)
- Delayed density dependence as interaction term:

Name	Equation	Priors
<b>Brood Year Interaction Ricker (interaction term)</b>	$R_t = S_t e^{\alpha + \gamma S_t S_{t-1} + \varepsilon_t}$	$\alpha \sim \ln(\text{Uniform}(1e - 3, 20))$ $\gamma \sim \text{Normal}(0, 1e - 2)$ $\sigma \sim \text{Normal}(0, 1)[1e - 3, 2]$

# Models: Autoregressive Ricker

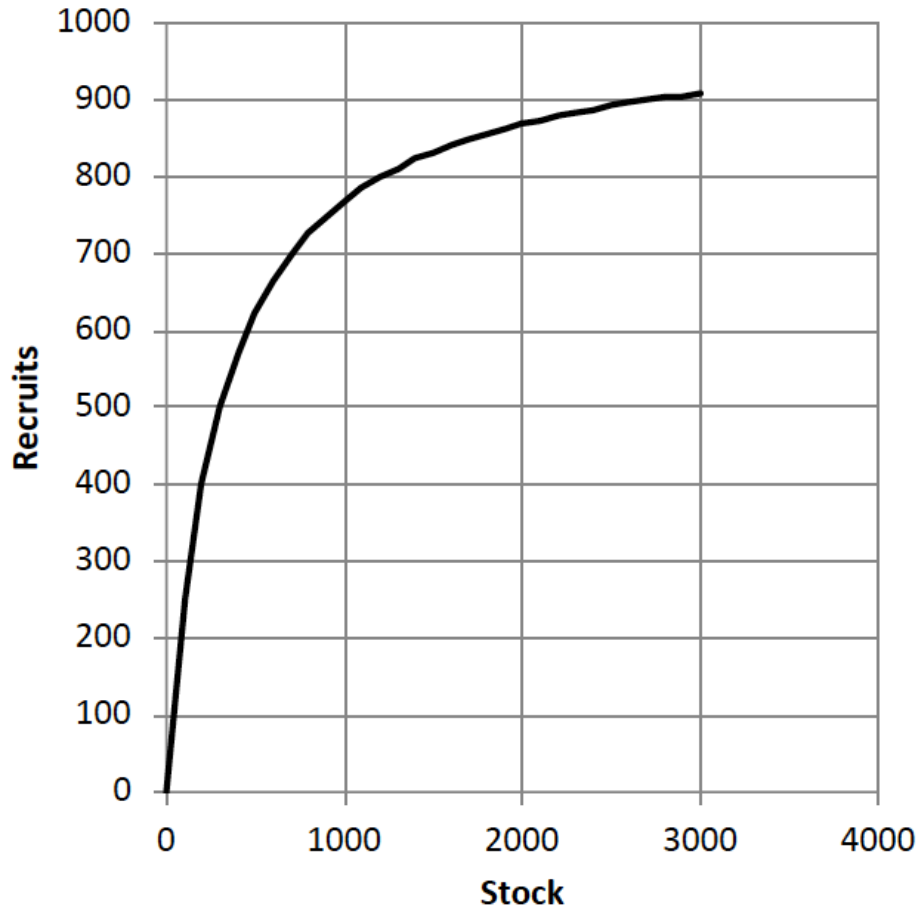
- Residuals are correlated among brood years

Name	Equation	Priors
Autoregressive Ricker	$R_t = \alpha S_t e^{-\beta S_t + \phi v_{t-1} + \varepsilon_t}$ $v_{t-1} = \ln(R_{t-1}) - \ln(S_{t-1}) - \ln(\alpha) + \beta S_{t-1}$	$\alpha \sim \text{Uniform}(1e - 3, 20)$ $\beta \sim \text{Uniform}(0, 1)$ $\phi \sim \text{Normal}(0, \sqrt{10})$ $v_0 \sim \text{Normal}\left(0, \frac{\sigma^2}{1 - \phi^2}\right)$ $\sigma \sim \text{Normal}(0, 1)[1e - 3, 2]$



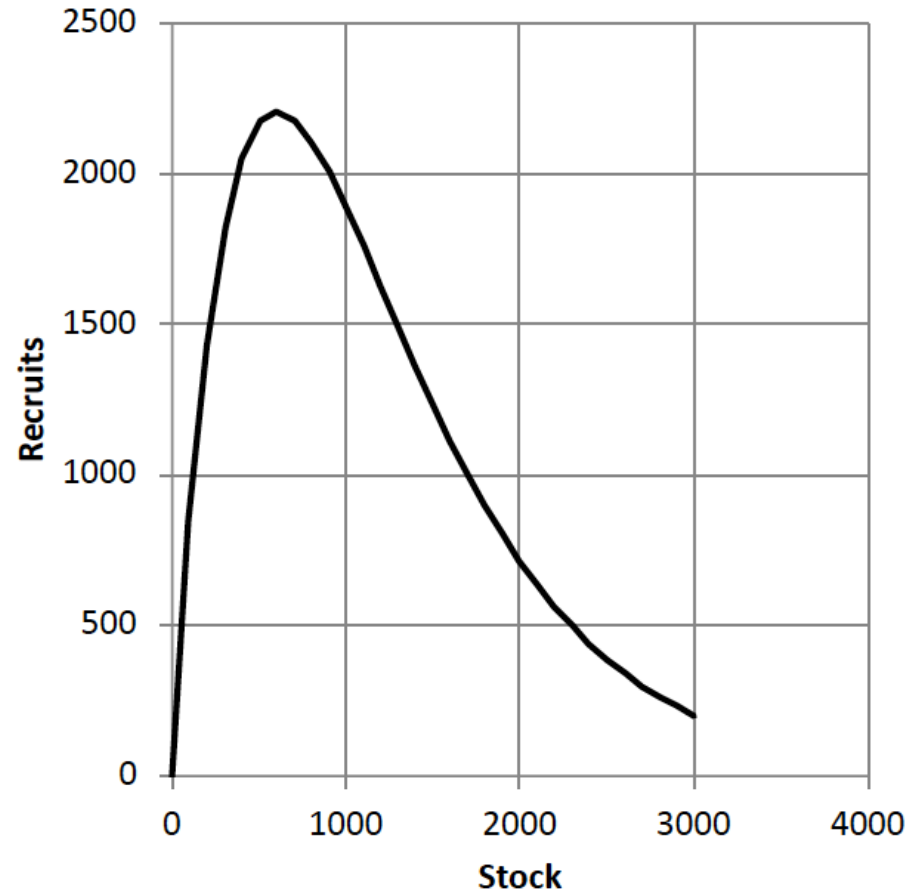
# Compensation vs. Overcompensation

## Beverton-Holt



R/S (rec. rate) declines with increasing S

## Ricker



Recruitment (number) begins to decline

# Models: Ricker Beverton-Holt Mixture

- Represents SR relationship as a mixture of two functional forms
  - **Ricker: Allows for *overcompensation***
  - **Beverton-Holt: Allows for *compensation* but not *overcompensation***
- Jumps between alternative models during estimation
  - **Estimates occupancy probability**

Name	Equation	Priors
<b>Ricker Beverton- Holt Mixture</b>	$R_t = \left[ \delta (S_t e^{\alpha_R (1 - S_t / \beta_R)}) + (1 - \delta) \left( \frac{\alpha_B S_t}{1 + \frac{\alpha_B S_t}{\beta_B}} \right) \right] e^{\varepsilon_t}$	$\alpha_R \sim \ln(\text{Uniform}(1e - 3, 20))$ $\alpha_B \sim \text{Uniform}(1e - 3, 20)$ $\beta_R \sim \text{Normal}(0, (1e7)^2) [0, ]$ $\beta_B \sim \text{Normal}(0, (1e7)^2) [0, ]$ $\sigma_R \sim \text{Normal}(0, 1) [1e - 3, 2]$ $\sigma_B \sim \text{Normal}(0, 1) [1e - 3, 2]$ $\delta \sim \text{Bernoulli}(p = 0.5)$

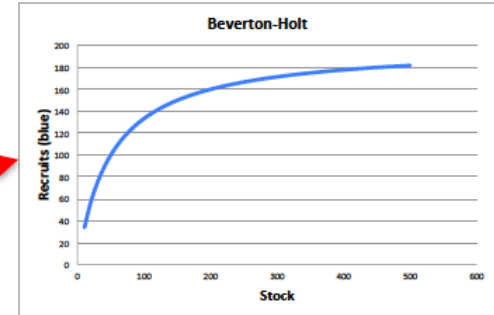
# Models: Deriso-Schnute

- Beverton-Holt and Ricker all *special cases*

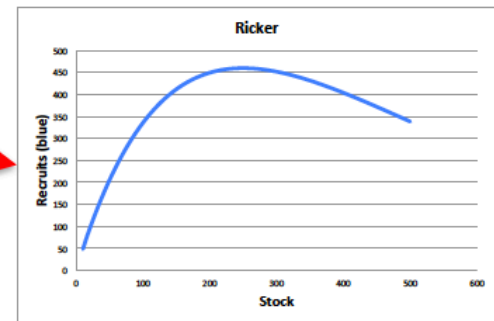
$$R_t = \alpha S_t (1 - \beta c S_t)^{1/c}$$

If  $c = -1$   
 $c \rightarrow 0$  then

$$R_t = \frac{\alpha S_t}{1 + \beta S_t}$$



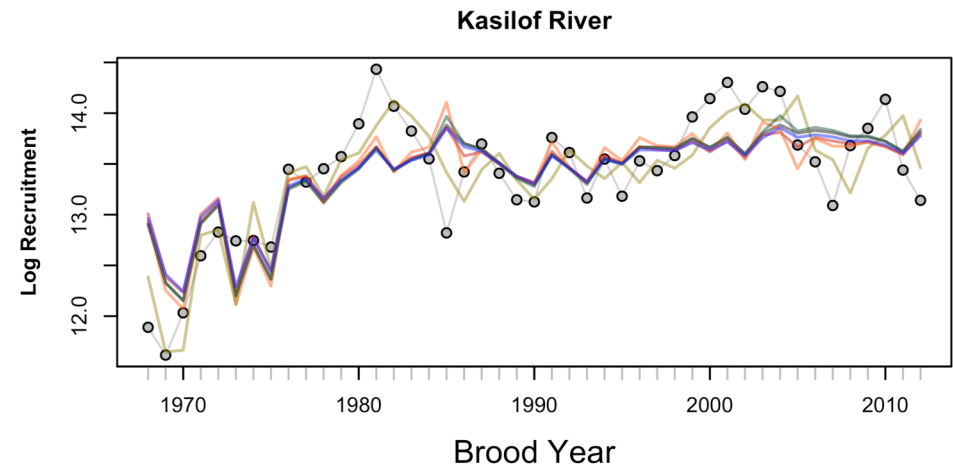
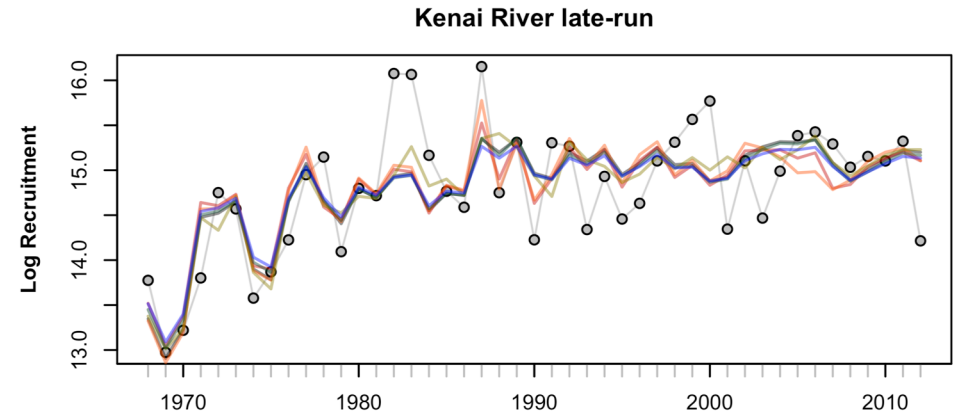
$$R_t = \alpha S_t e^{-\beta S_t}$$



Name	Equation	Priors
Deriso-Schnute	$R_t = \alpha S_t (1 - c\beta S_t)^{\frac{1}{c}} e^{\epsilon_t}$	$\alpha \sim \text{Uniform}(1e - 3, 20)$ $\beta \sim \text{Uniform}(0, 1)$ $c \sim \text{Uniform}(-1, 0)$ $\sigma \sim \text{Normal}(0, 1)[1e - 3, 2]$

# Results: Model Fit and WAIC

- Multiple models provide **similar** fits to the data
- WAIC Model selection
  - Kenai: BYI Ricker, ...
  - Kasilof: AR Ricker



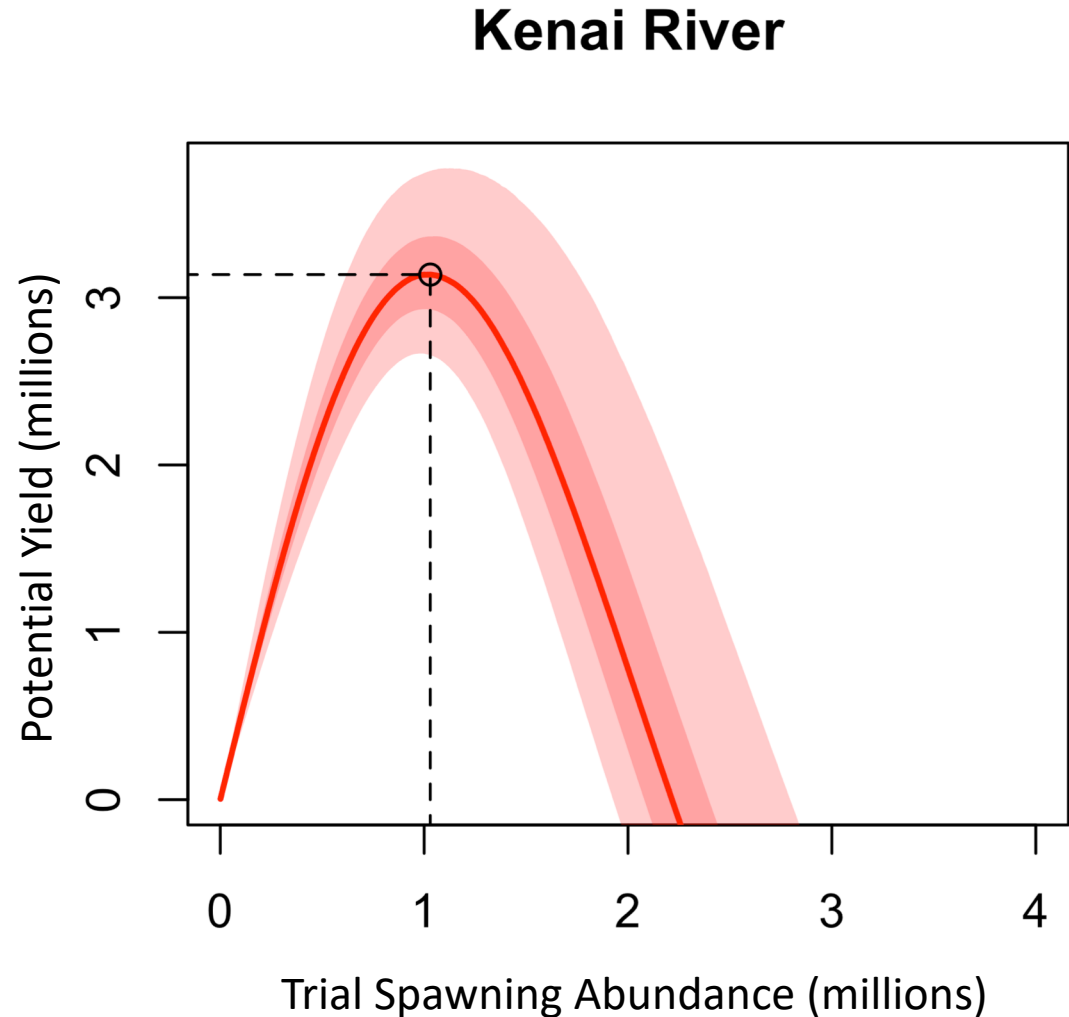
Model Type

- Ricker
- Brood Year Interaction Ricker (main effects)
- Brood-year Interaction Ricker (interaction term)
- Autoregressive Ricker
- Ricker Beverton-Holt Mixture
- Deriso-Schnute

Model	Kenai River		Kasilof	
	WAIC	dWAIC	WAIC	dWAIC
Basic Ricker	67.06	3.31	55.80	20.70
Brood Year Interaction (main effects)	66.04	2.30	56.38	21.28
Brood Year Interaction (interaction term)	<b>63.75</b>	<b>0.00</b>	56.37	21.27
Autoregressive Ricker	68.02	4.27	<b>35.10</b>	<b>0.00</b>
Ricker Beverton-Holt Mixture	66.41	2.66	56.58	21.48
Deriso-Schnute	66.55	2.80	55.34	20.24

# Results: Kenai River Late-Run

- Brood Year Interaction Ricker (interaction term)
  - Smsy: 1.03 million sockeye
  - MSY: 3.14 million sockeye

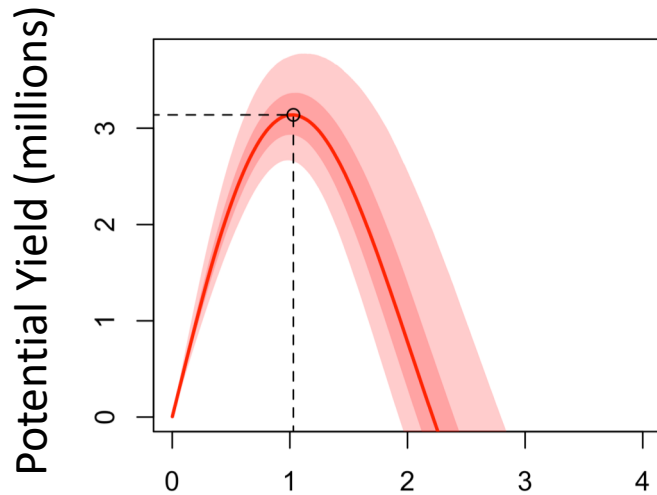


# Results: Kenai River Late-Run

- Potential yield across “preferred” management models

**Brood Year  
Interaction Ricker  
(interaction term)**

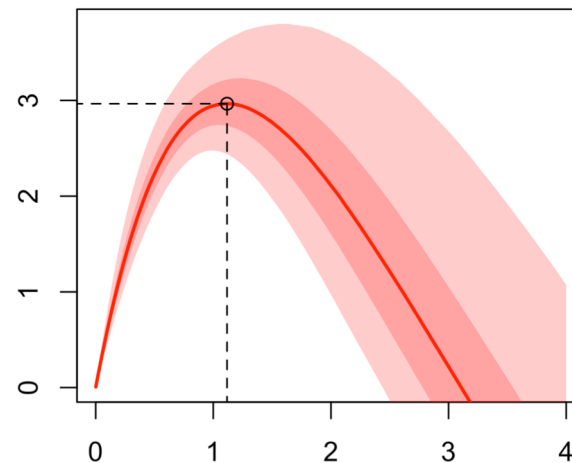
Kenai River



$\Delta WAIC = 0$

**Brood Year  
Interaction Ricker  
(main effects)**

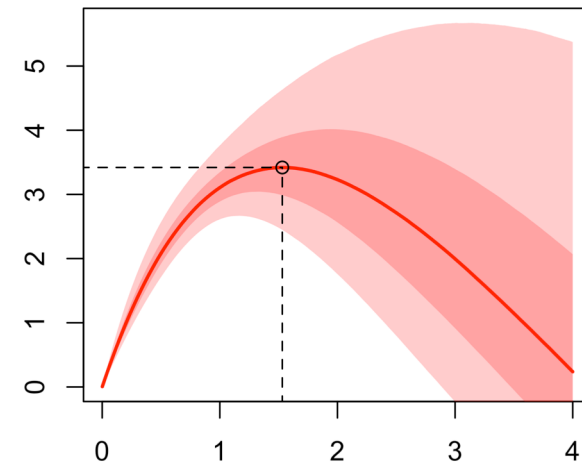
Kenai River



$\Delta WAIC = 2.30$

**Basic Ricker**

Kenai River

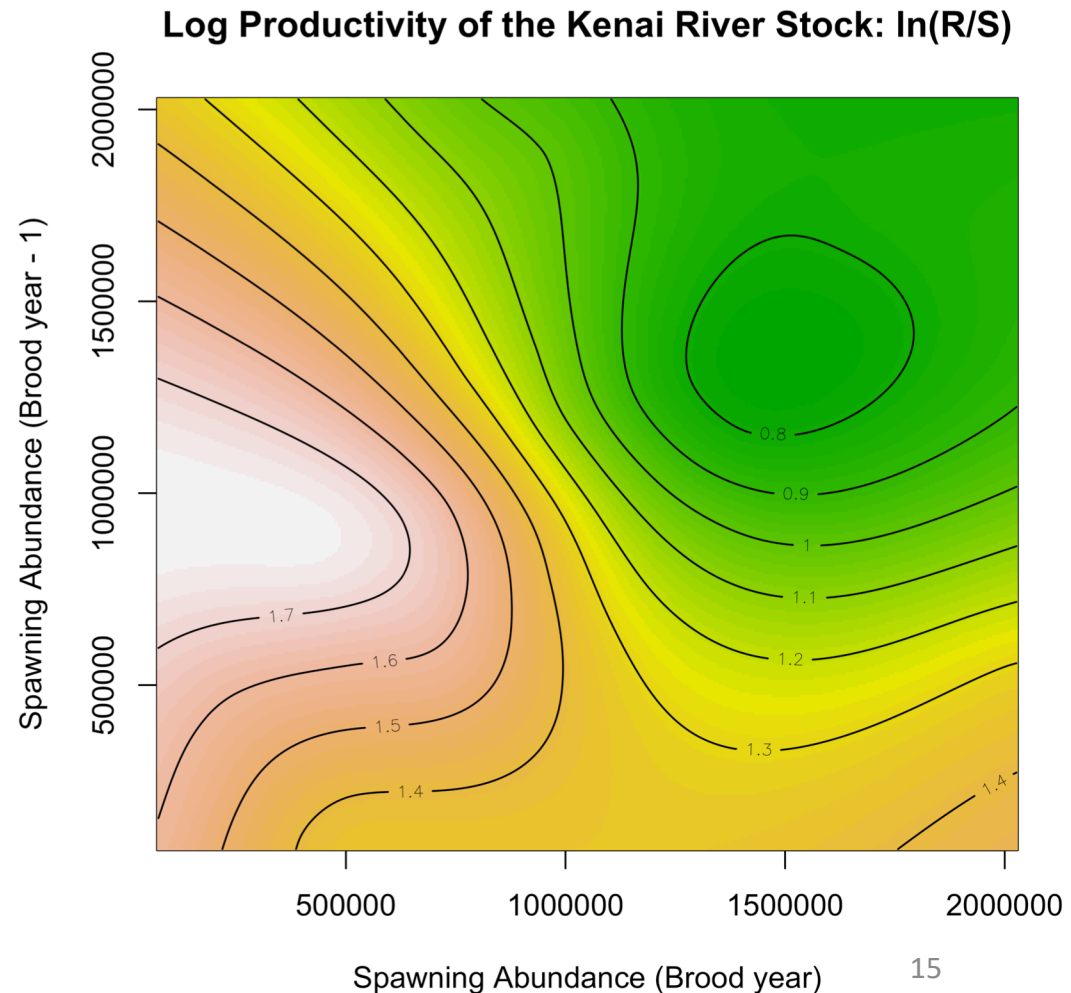


$\Delta WAIC = 3.31$

# Meaning of Interaction Term

- Kenai River
  - Visualize interaction effect with GAM

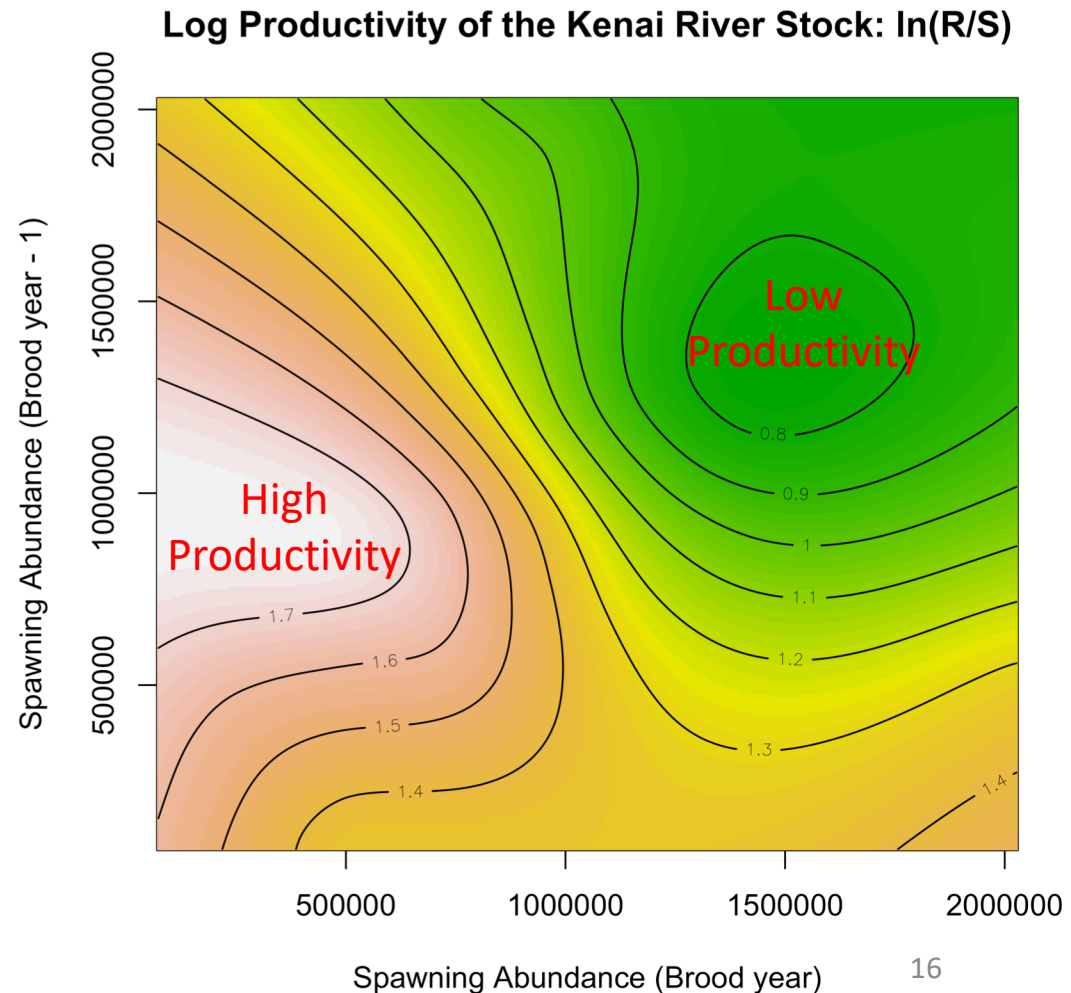
$$\ln\left(\frac{R_t}{S_t}\right) \sim \alpha + f(S_t, S_{t-1})$$



# Meaning of Interaction Term

- Kenai River
  - Visualize interaction effect with GAM

$$\ln\left(\frac{R_t}{S_t}\right) \sim \alpha + f(S_t, S_{t-1}) + \varepsilon_t$$



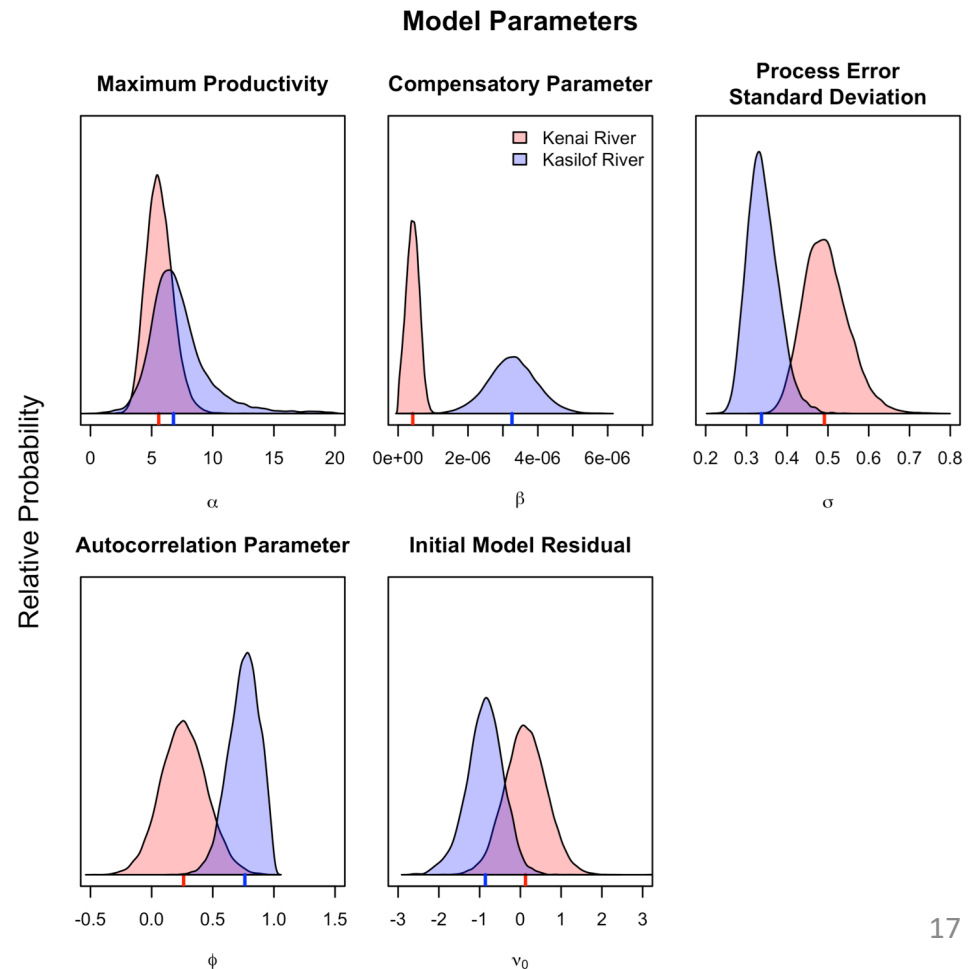


# Results: Kasilof River

- Autoregressive Ricker parameter estimates

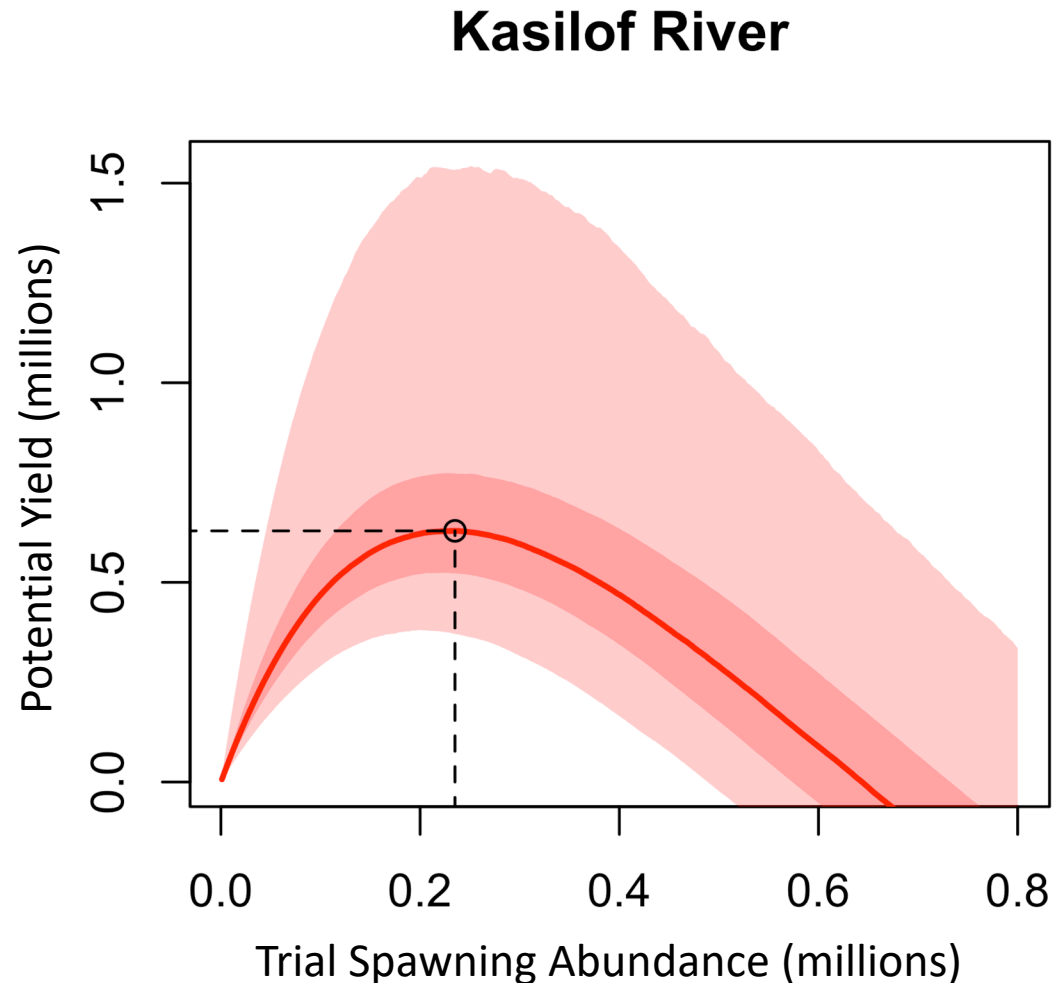
$$R_t = \alpha S_t e^{-\beta S_t + \phi v_{t-1} + \varepsilon_t}$$

$$v_{t-1} = \ln(R_{t-1}) - \ln(S_{t-1}) - \ln(\alpha) + \beta S_{t-1}$$



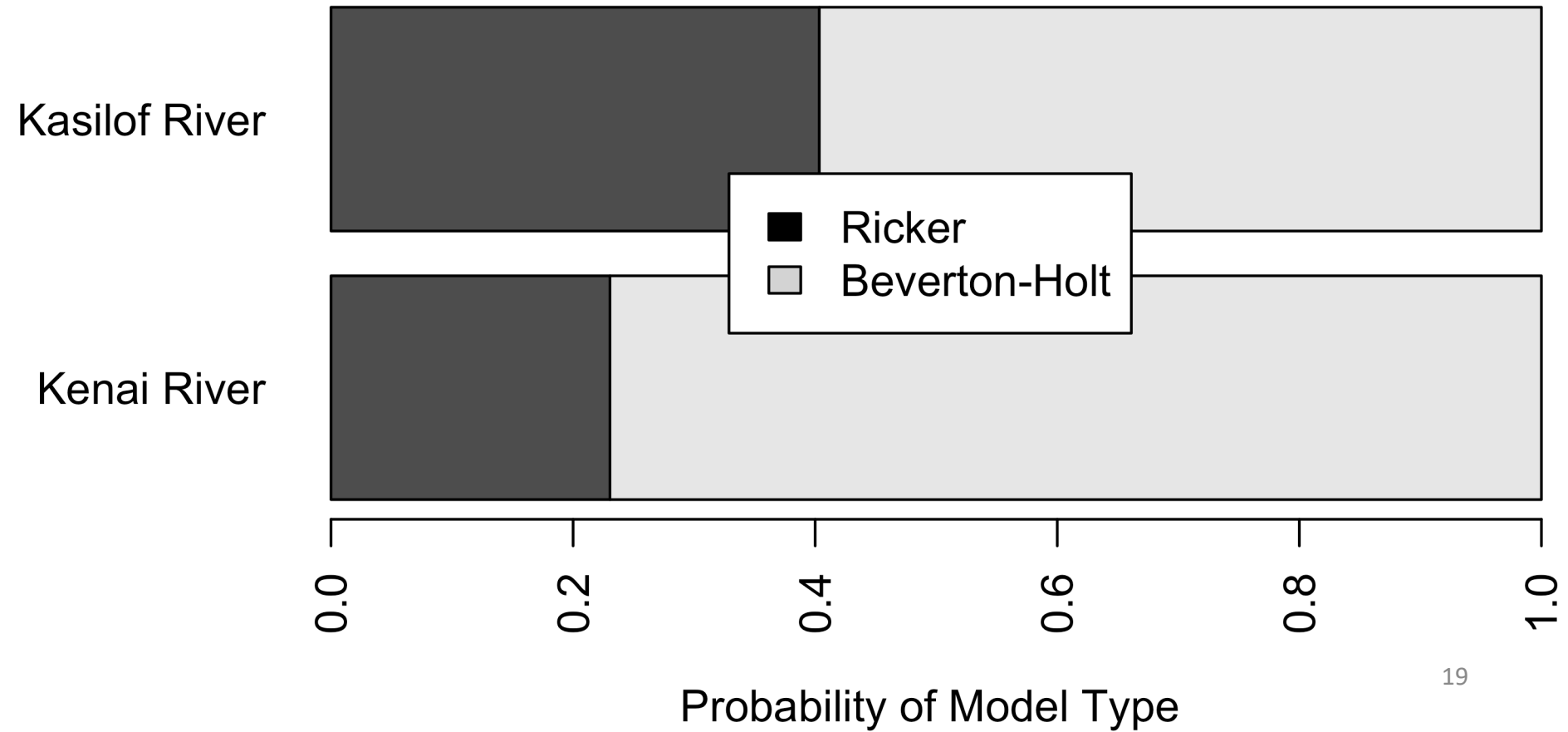
# Results: Kasilof River

- Autoregressive Ricker
  - Smsy: 235 thousand sockeye
  - MSY: 629 thousand sockeye



# Results: Overcompensation

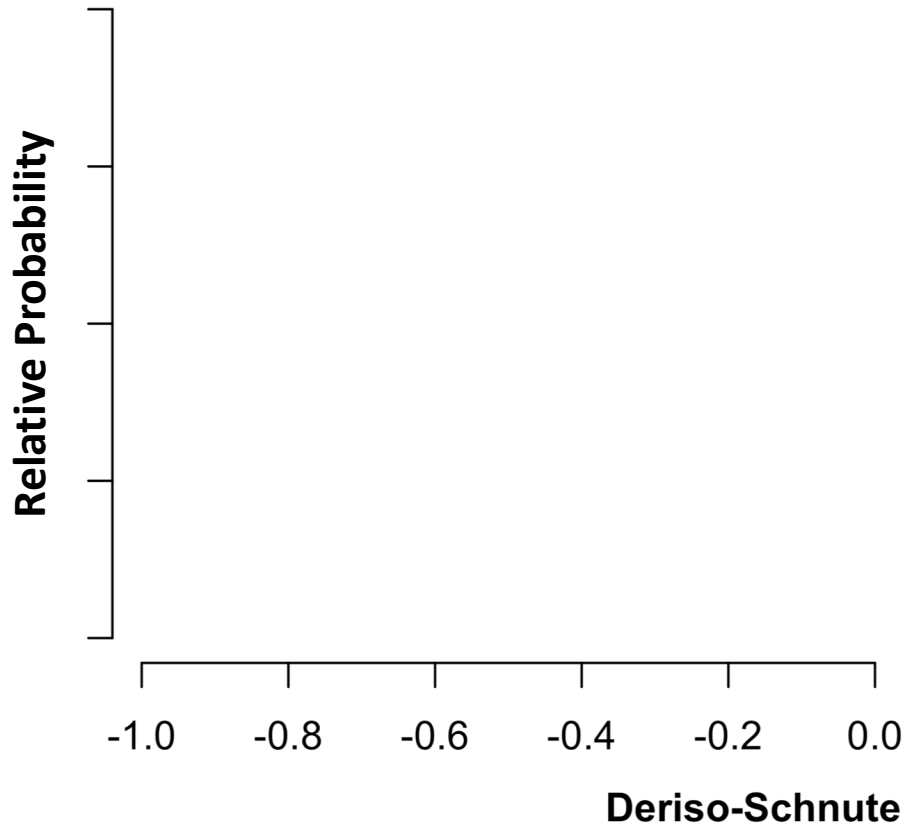
- Model: Ricker Beverton-Holt Mixture



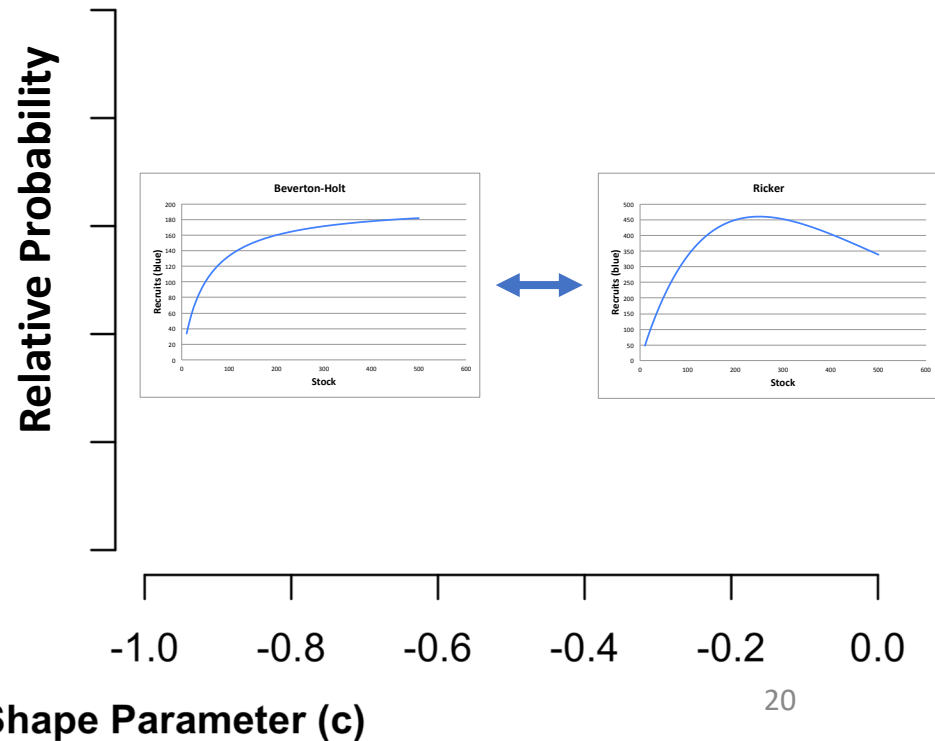
# Results: Overcompensation

- Model: Deriso-Schnute

### Kenai River



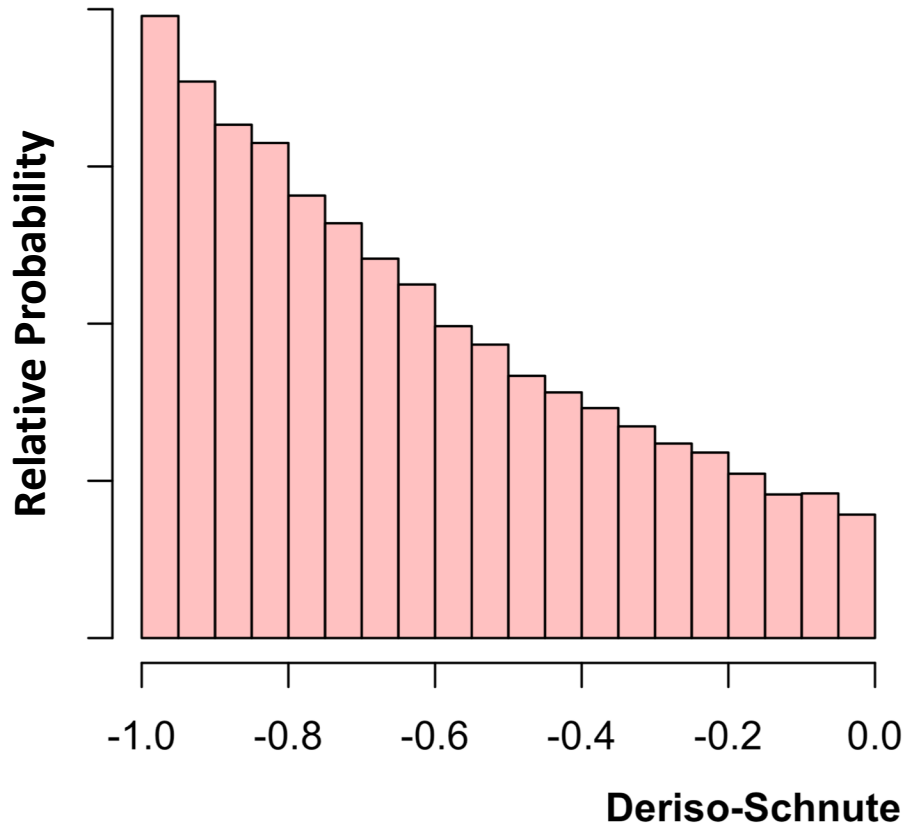
### Kasilof River



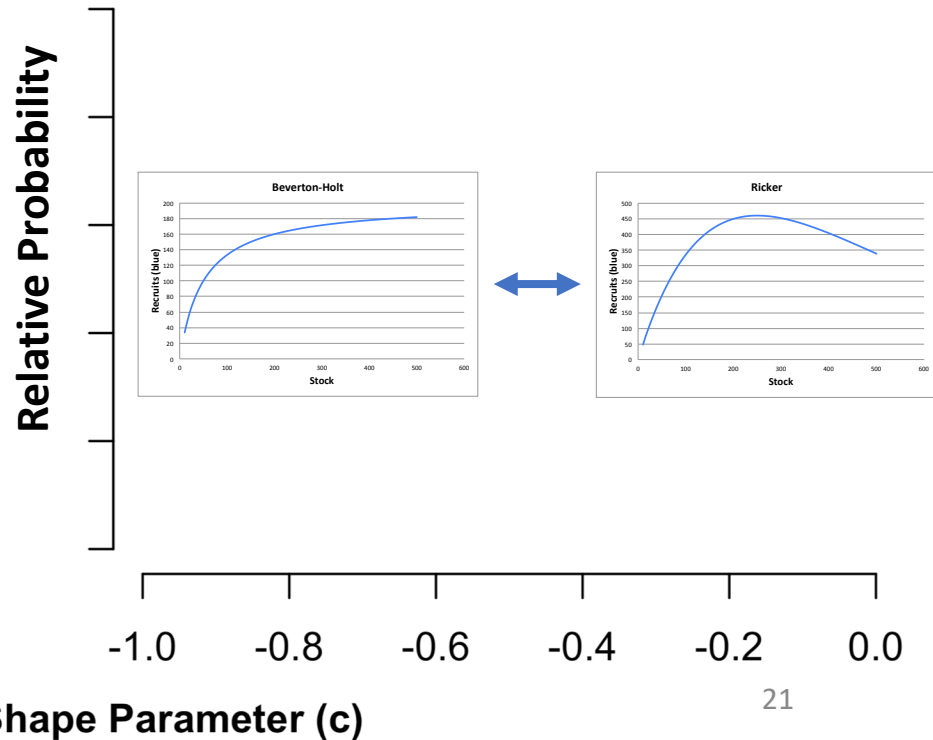
# Results: Overcompensation

- Model: Deriso-Schnute

### Kenai River



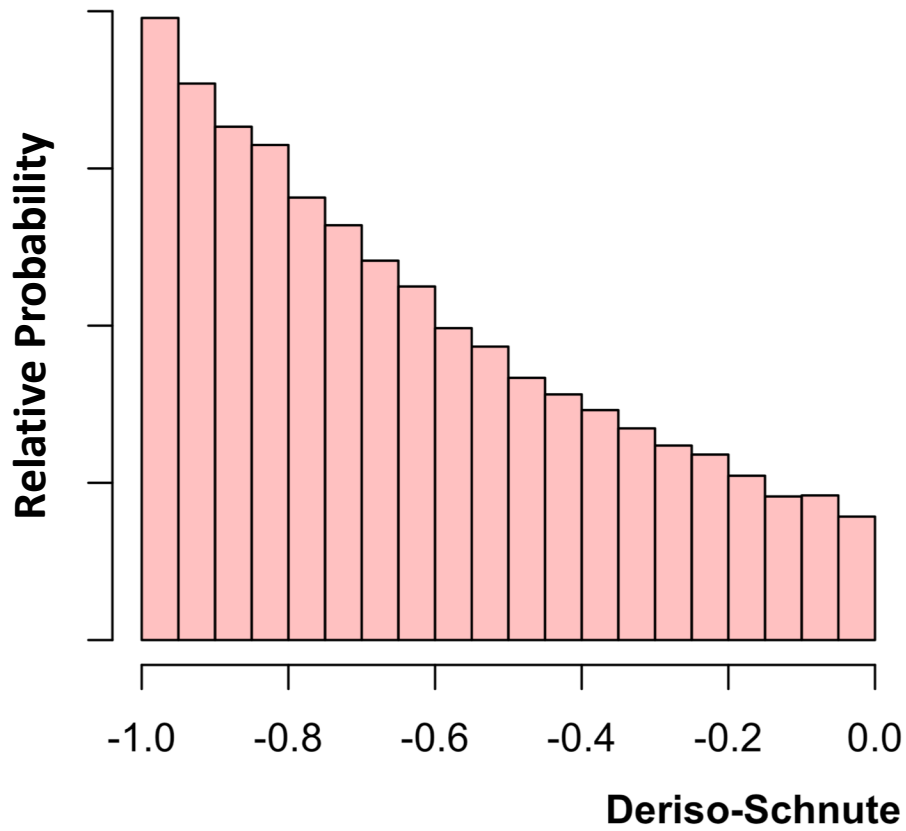
### Kasilof River



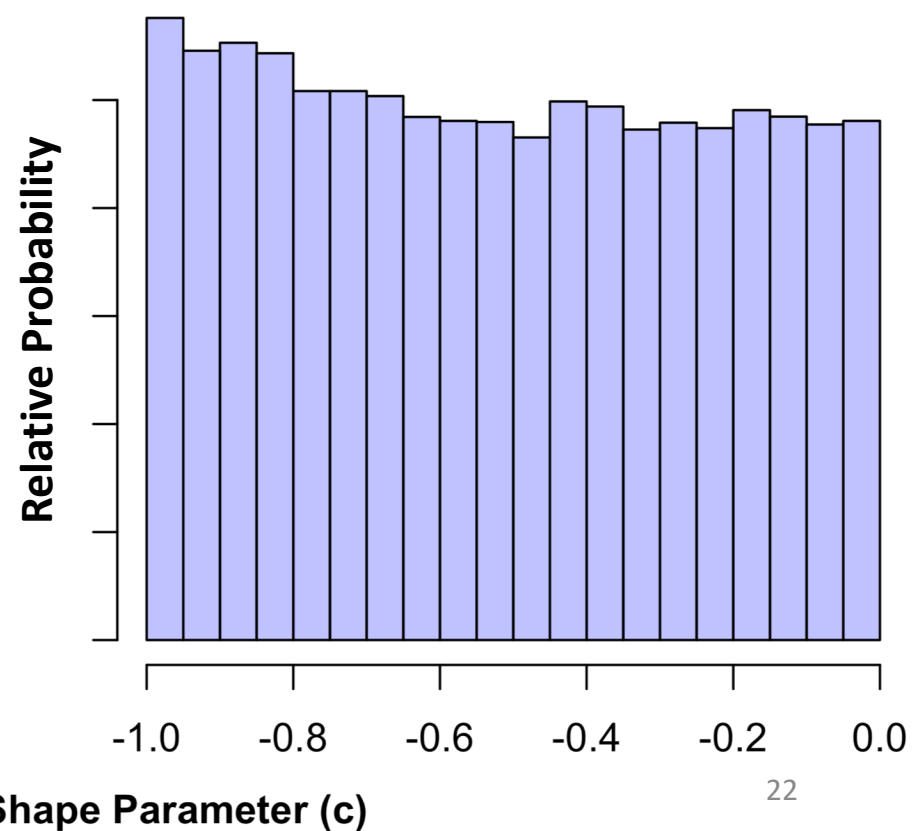
# Results: Overcompensation

- Model: Deriso-Schnute

## Kenai River



## Kasilof River



# Conclusions

- WAIC model selection agrees with findings by Erickson et. al (2017)
  - Kenai River – Brood Year Interaction Ricker (interaction term)
    - Several models exhibit similar WAIC
  - Kasilof River – Autoregressive Ricker
- Reference Points
  - Kenai River – Smsy: 1.03 (million), MSY: 3.14 (million)
  - Kasilof River – Smsy: 235 (thousand) , MSY 629 (thousand)
- Overcompensation
  - Both the Ricker Beverton-Holt Mixture and Deriso-Schnute models provide *minimal* support for Ricker-type recruitment dynamics
    - Indicating limited evidence for overcompensation
  - Exception: Kasilof River Deriso-Schnute – Only *marginally* higher probability of BH
  - While a preference for Ricker would not *definitively* indicate overcompensation
    - Greater support for BH *suggests* limited evidence for overcompensation across range of observed spawning abundances (escapements)

# Smsy and MSY Estimates

- Smsy (millions of salmon)

Smsy	Basic Ricker	Brood Year Interaction (main effects)	Brood Year Interaction (interaction term)	Autoregressive Ricker	Ricker Beverton-Holt Mixture	Deriso-Schnute
Kenai	1.53	1.12	<b>1.03</b>	1.66	1.78	1.38
Kasilof	0.37	0.30	0.28	<b>0.24</b>	0.48	0.35

- MSY (millions of Salmon)

**\*Lowest WAIC**

MSY	Basic Ricker	Brood Year Interaction (main effects)	Brood Year Interaction (interaction term)	Autoregressive Ricker	Ricker Beverton-Holt Mixture	Deriso-Schnute
Kenai	3.42	2.97	<b>3.14</b>	3.55	3.18	3.04
Kasilof	0.72	0.67	0.70	<b>0.63</b>	0.74	0.68