Modeling Estuary and Ocean Survival of Pacific Salmon Using a Temporally-Stratified Mark-Recapture-Recovery Approach that Accounts for Avian Predation and Age of Return

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Motivation

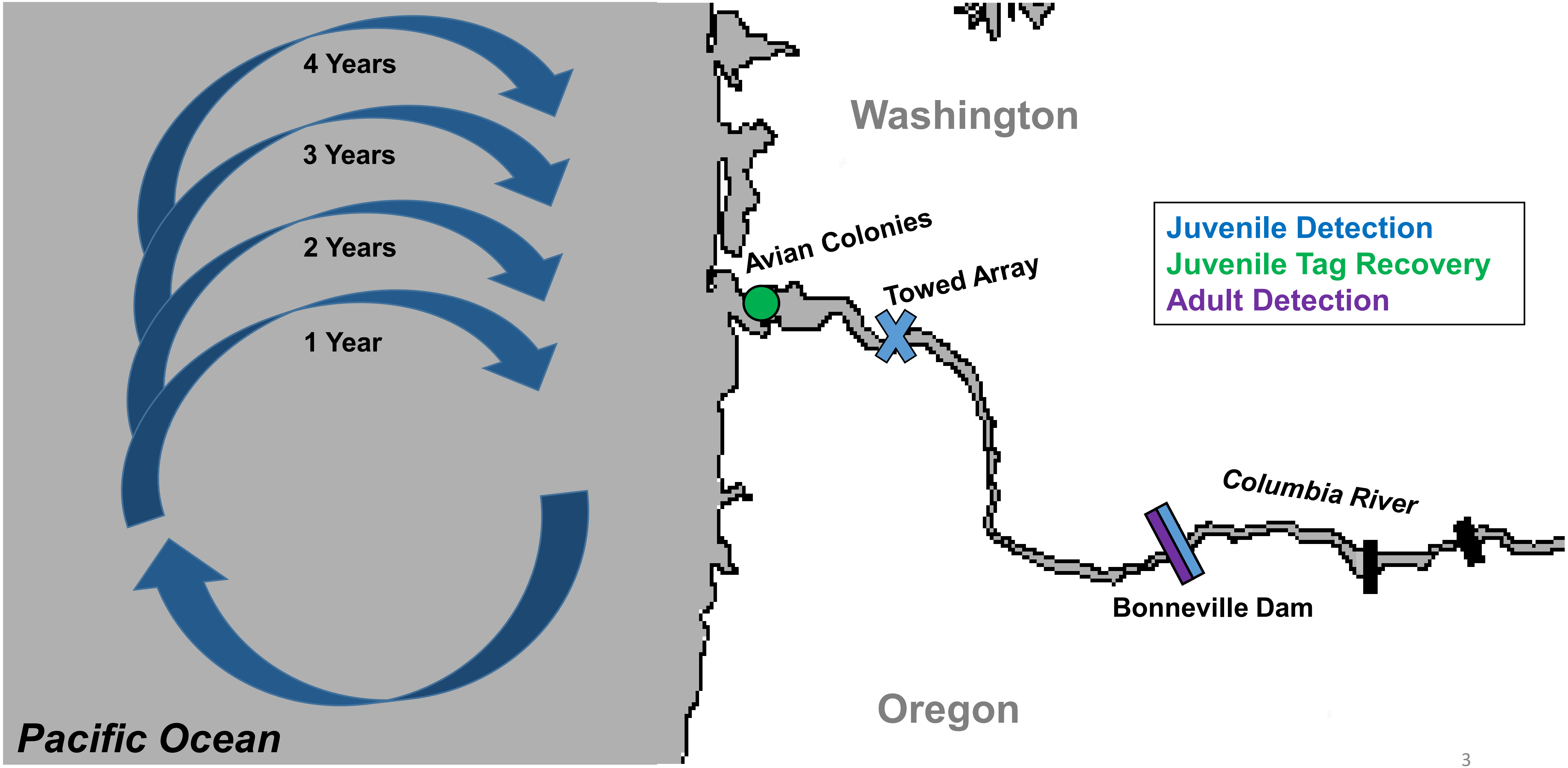
- Ocean survival of listed Pacific salmon is low and variable
- Need better understanding of factors affecting ocean survival
- Current ocean survival models to not incorporate tag recoveries from estuary avian colonies
- Need to use best available science and all available data

USGS

Grant County PUD

SkeenaWild

Salmon detection and recovery of tags



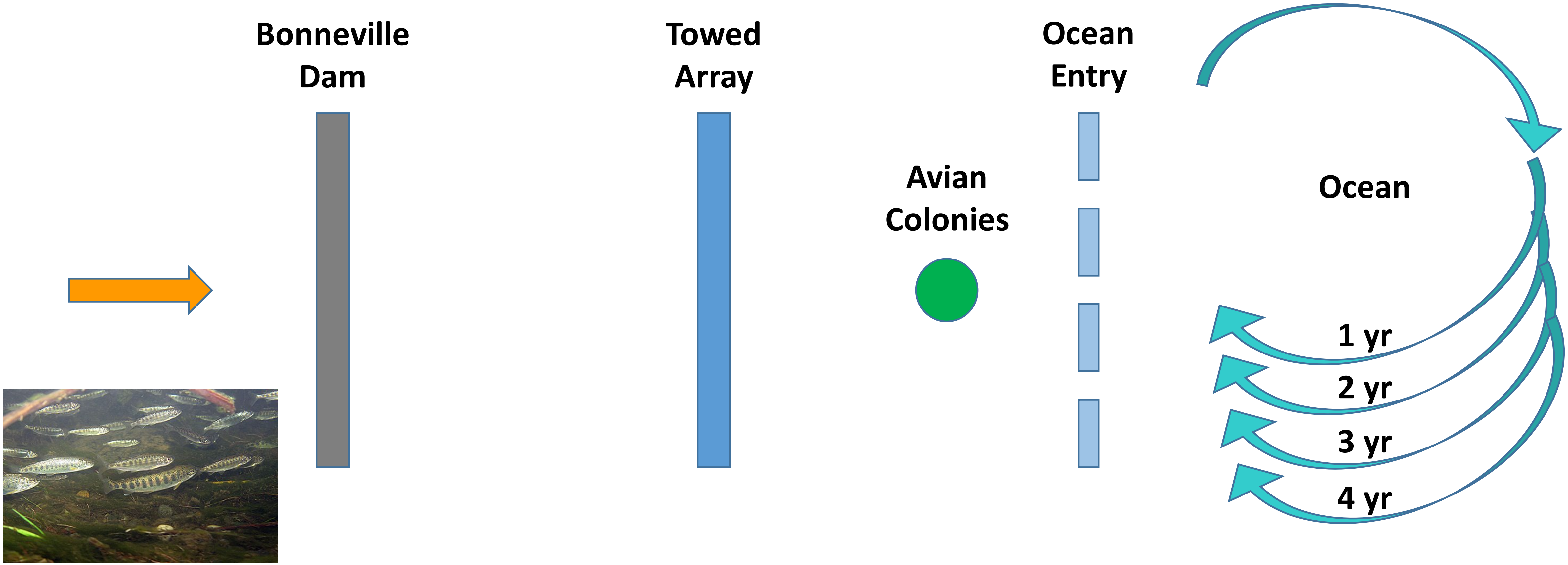
Methods - overview

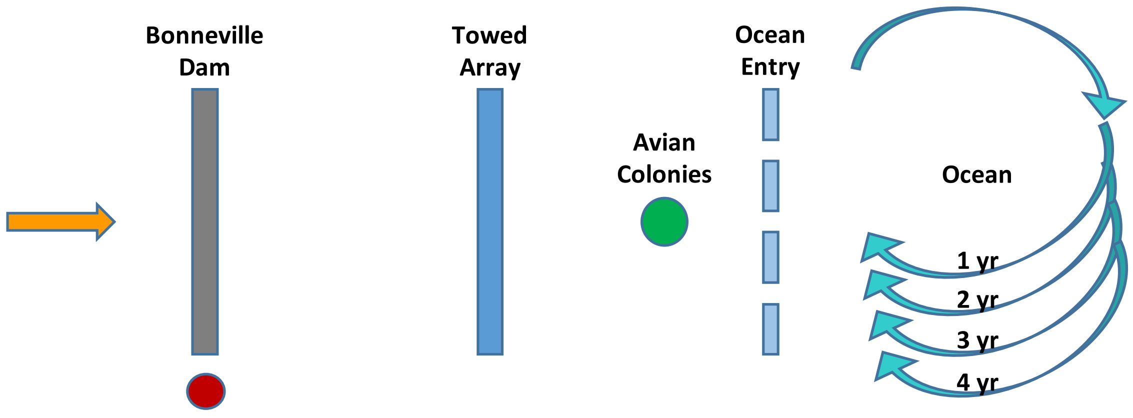
- Use mark-recapture-recovery modeling framework
- Incorporate tag recoveries from avian colonies
- Partition estuary and ocean survival
- Daily covariates related to river and ocean
- Travel time used to predict arrival timing
- Model ocean survival by age of return
- Use Bayesian statistical methods

NOAA

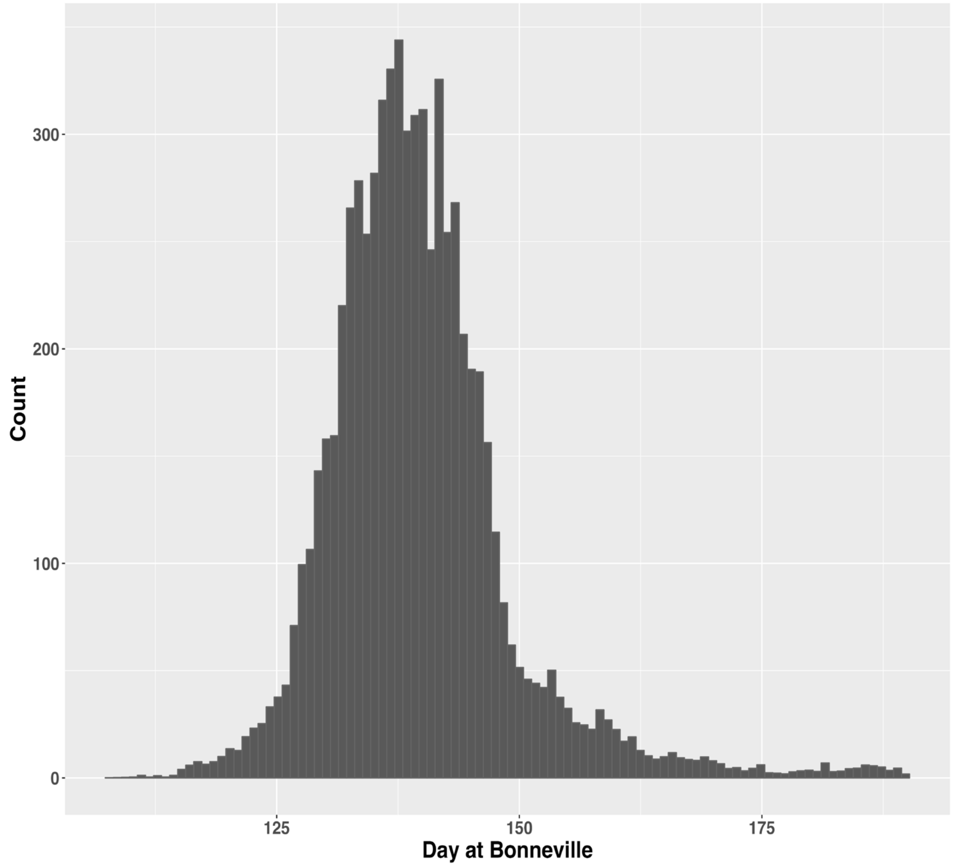
NOAA

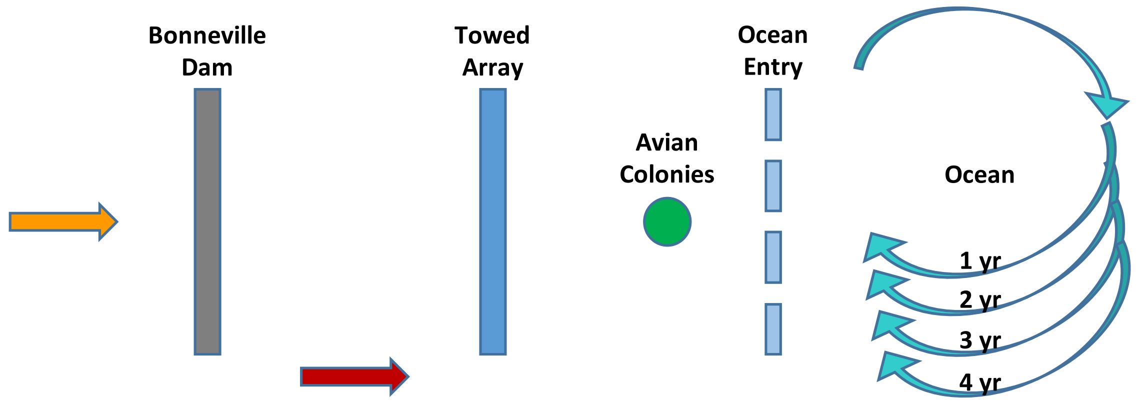
National Park Service

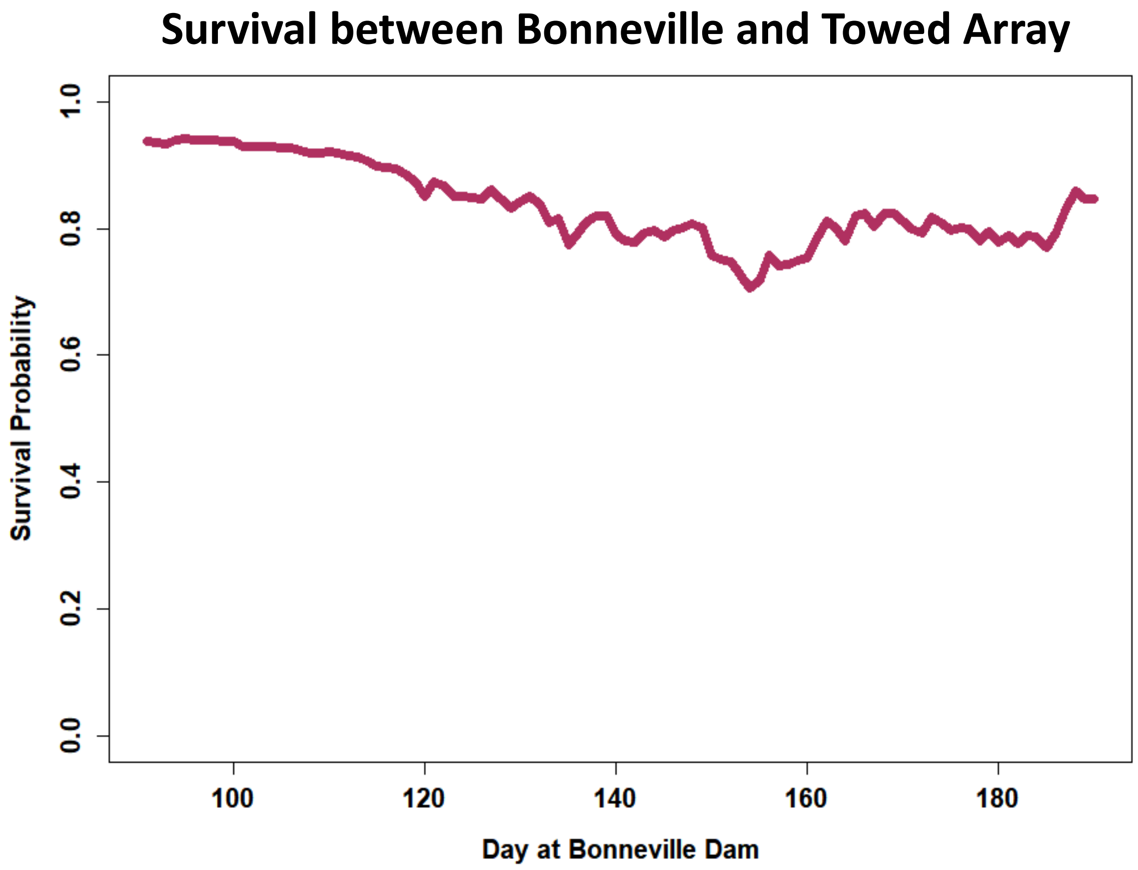

Bonneville Dam
Towed Array
Avian Colonies
Ocean Entry
Ocean
1 yr
2 yr
3 yr
4 yr



Sample of Juveniles Detected at Bonneville in Year *i*



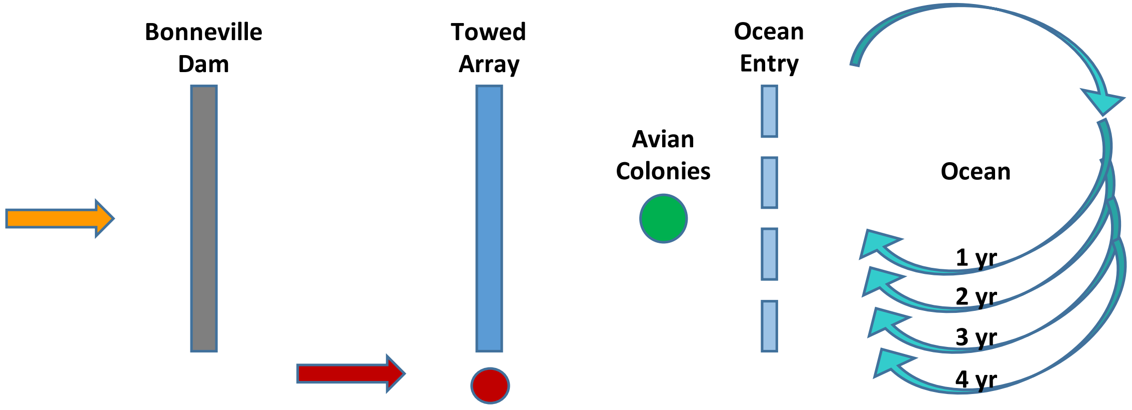


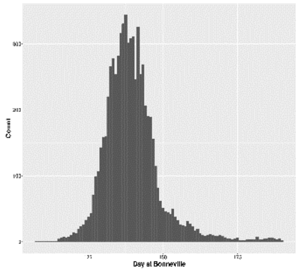


$$\text{logit}(\boldsymbol{\phi}_{1,i}) = \boldsymbol{X}_{\boldsymbol{R},\boldsymbol{i}}\boldsymbol{\beta}_{\boldsymbol{R}} + \gamma_{R1,i}$$

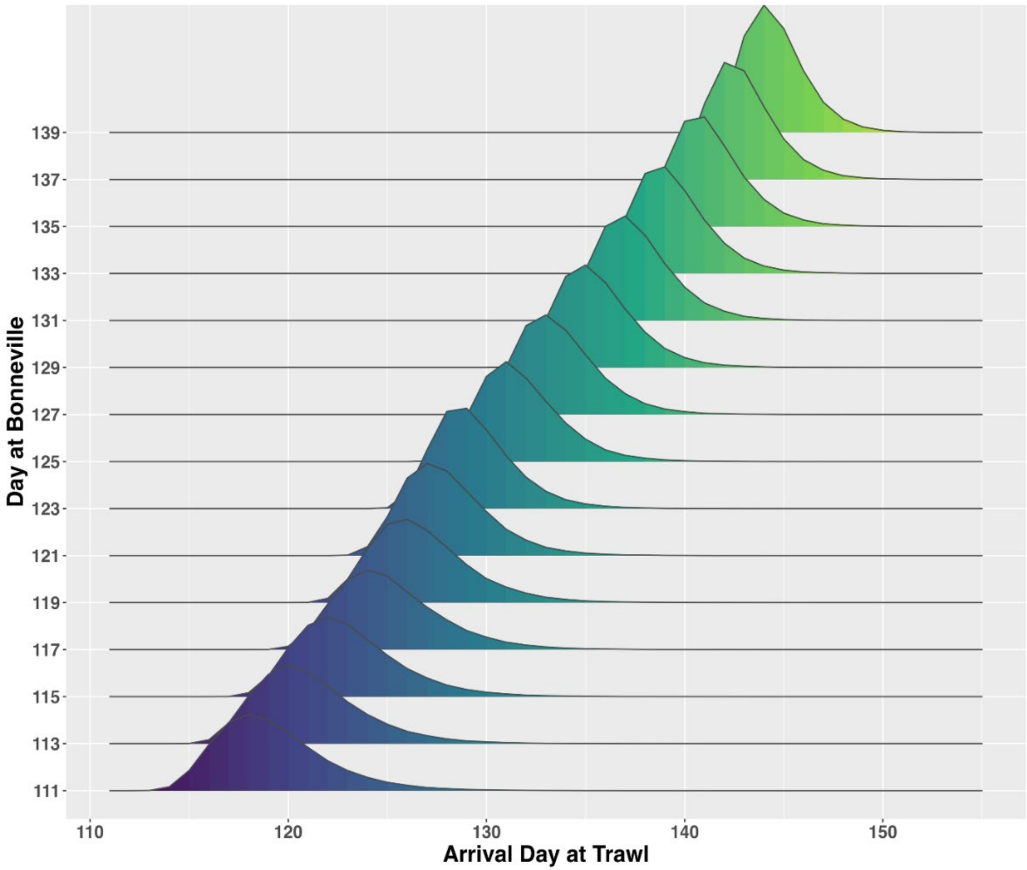
$$\boldsymbol{\beta}_{\boldsymbol{R}} \sim N(\boldsymbol{0}, \sigma_R)$$

$$\boldsymbol{\gamma}_{\boldsymbol{R1}} \sim N(\boldsymbol{0}, \sigma_{\gamma_R})$$





Arrival Probabilities at Towed Array



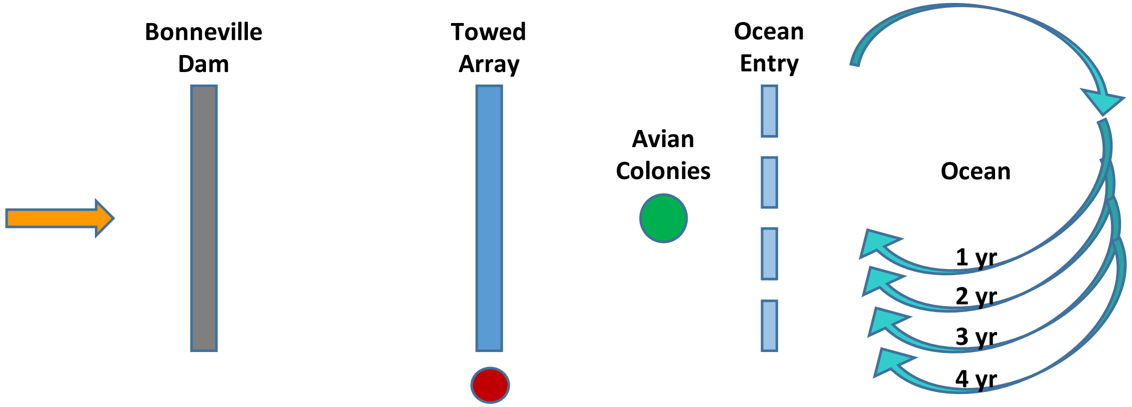
$$\boldsymbol{\mu}_{T1,i} = \boldsymbol{X}_{\boldsymbol{T},\boldsymbol{i}}\boldsymbol{\beta}_{\boldsymbol{T}} + \gamma_{T1,i}$$

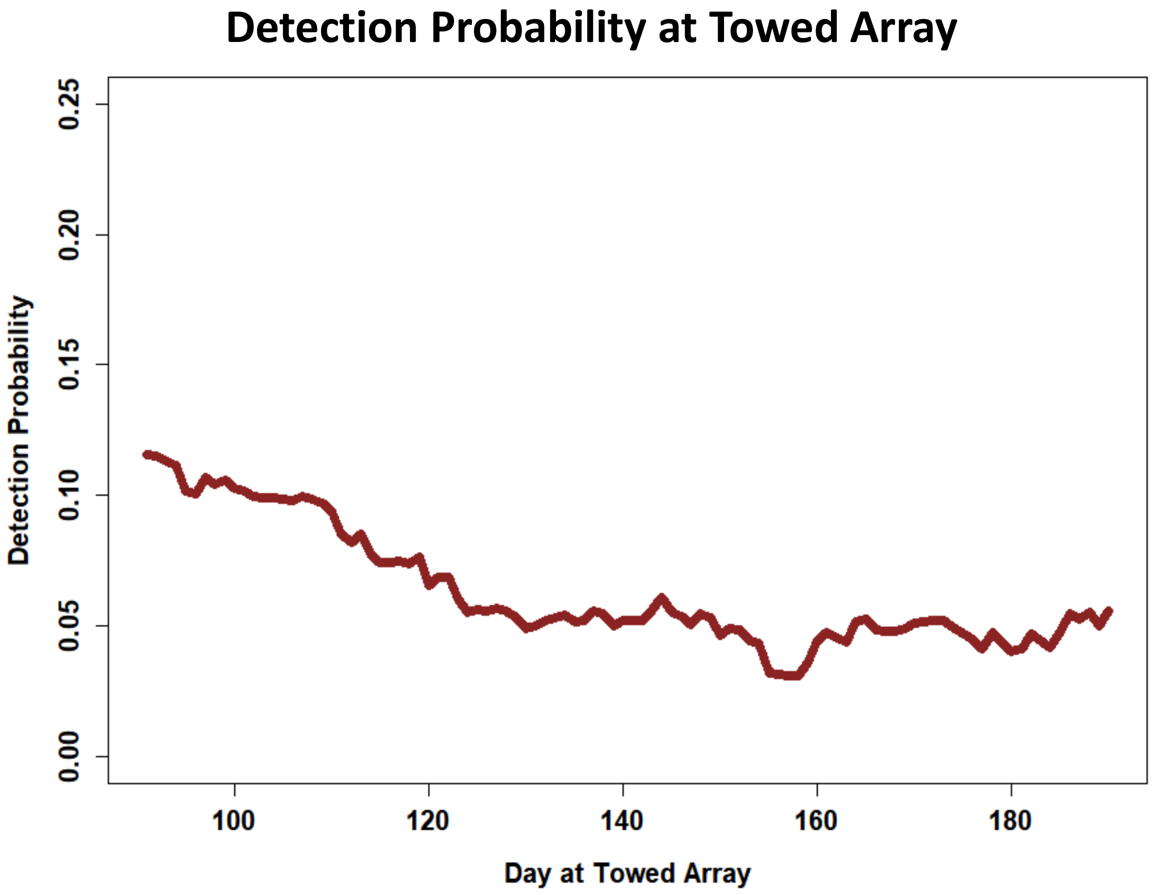
$$t_{1,i,j,k} \sim \text{discrete. lognormal}(\boldsymbol{\mu}_{T1,i}, \sigma_{T1})$$

$$\sigma_T \sim \mathrm{C}^+(\mathbf{0},\, \sigma_{\sigma_T})$$

$$\boldsymbol{\beta}_{\boldsymbol{T}} \sim N(\mathbf{0},\, \sigma_{\beta_T})$$

$$\boldsymbol{\gamma}_{\boldsymbol{T1}} \sim N(\mathbf{0},\, \sigma_{\gamma_T})$$

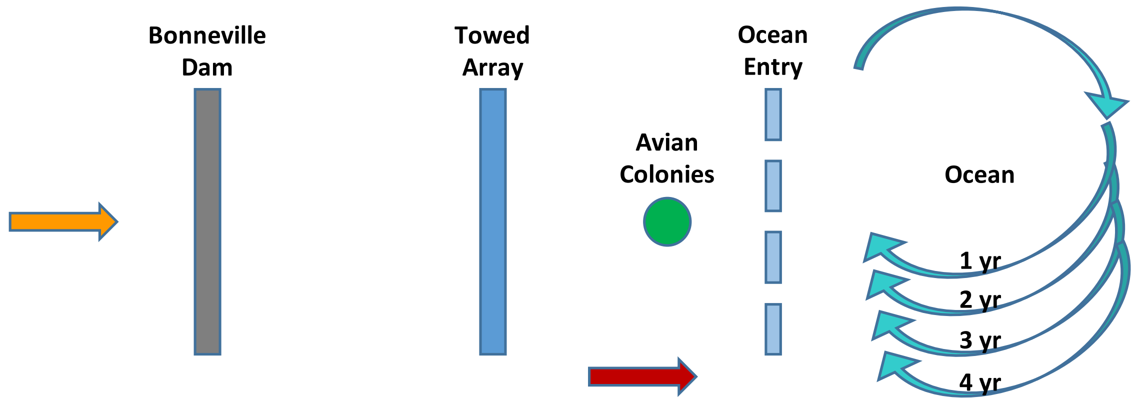




$$\mathrm{logit}(\boldsymbol{p}_i) = \boldsymbol{X}_{\boldsymbol{p},i}\boldsymbol{\beta}_{\boldsymbol{p}} + \boldsymbol{\varrho}_i$$

$$\boldsymbol{\beta}_{\boldsymbol{p}} \sim \mathrm{N}(\boldsymbol{0}, \sigma_p)$$

$$\boldsymbol{\varrho} \sim \mathrm{N}(\boldsymbol{0}, \sigma_\varrho)$$

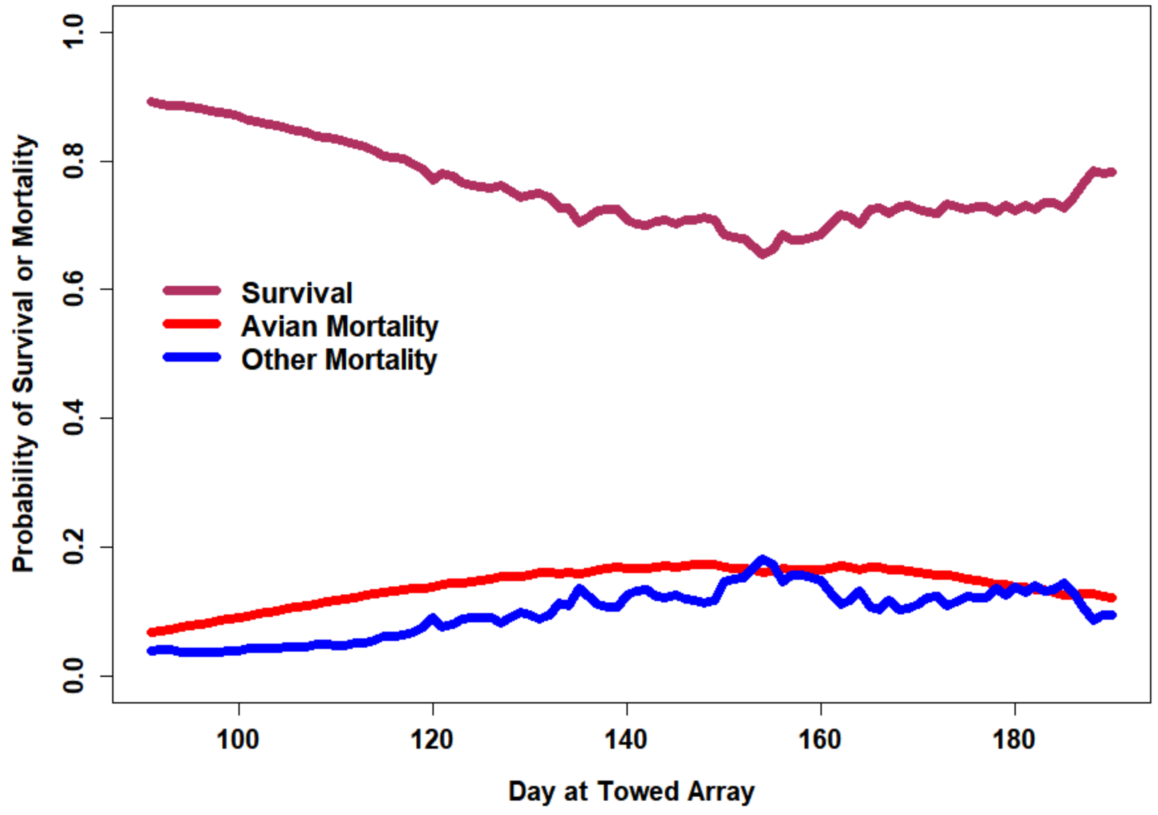


$$\boldsymbol{\eta}_{A,i} = \boldsymbol{X}_{A,i}\boldsymbol{\beta}_A + \gamma_{A,i}$$

$$\boldsymbol{\phi}_{O,i} = \text{logit}^{-1}\left(\boldsymbol{X}_{R,i}\boldsymbol{\beta}_R + \gamma_{R2,i}\right)$$

$$\boldsymbol{\eta}_{O,i} = \text{logit}(1 - \boldsymbol{\phi}_{O,i})$$

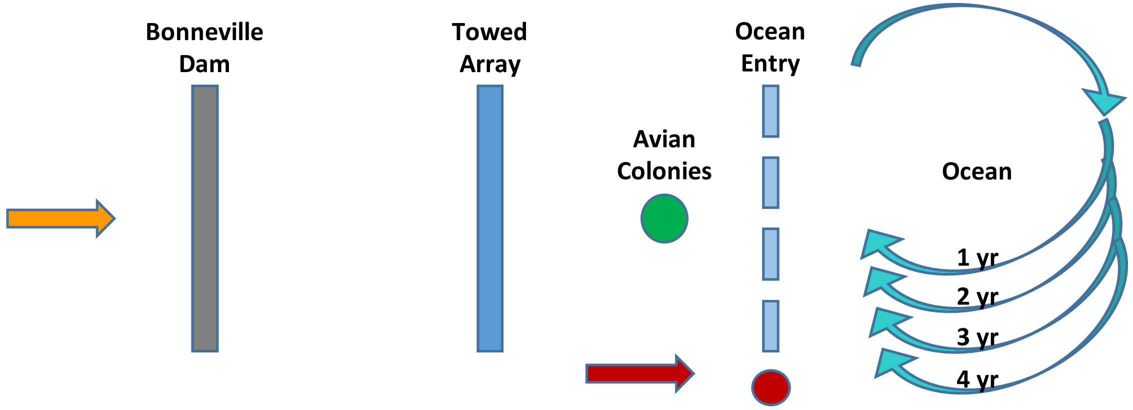
Mortality and Survival from Towed Array to Ocean



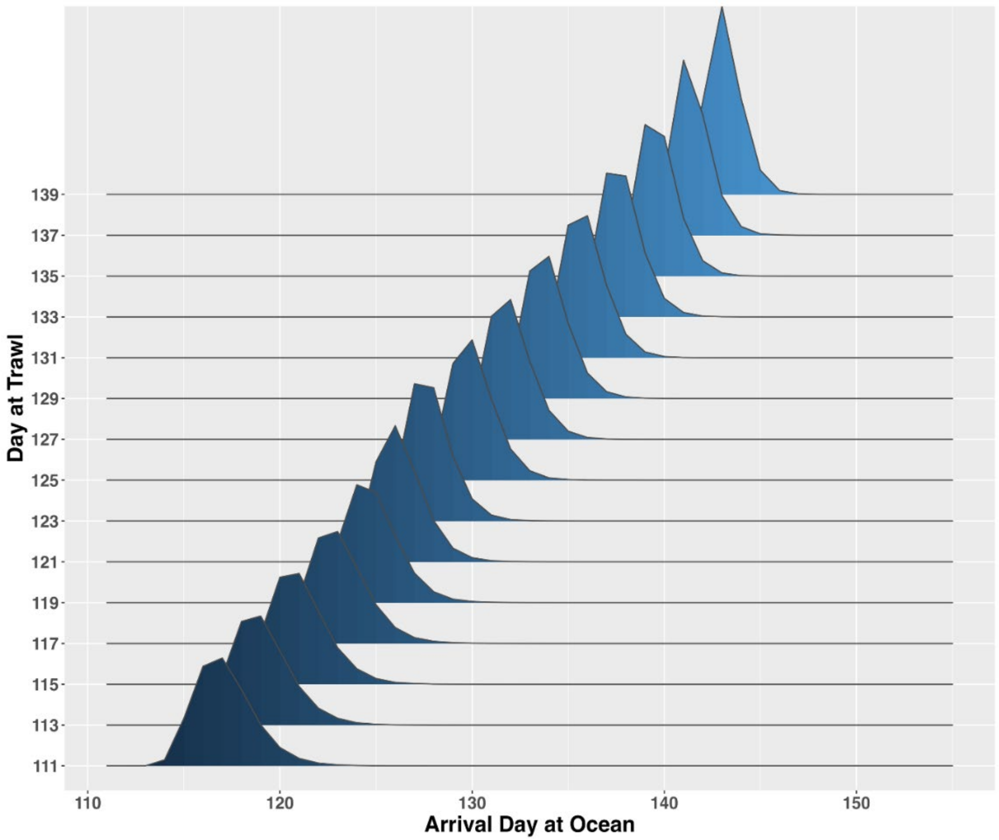
$$\boldsymbol{\theta}_{A,i} = \frac{\exp(\boldsymbol{\eta}_{A,i})}{\exp(\boldsymbol{\eta}_{A,i}) + \exp(\boldsymbol{\eta}_{O,i}) + \mathbf{1}}$$

$$\boldsymbol{\theta}_{O,i} = \frac{\exp(\boldsymbol{\eta}_{O,i})}{\exp(\boldsymbol{\eta}_{A,i}) + \exp(\boldsymbol{\eta}_{O,i}) + \mathbf{1}}$$

$$\boldsymbol{\phi}_{2,i} = \frac{\mathbf{1}}{\exp(\boldsymbol{\eta}_{A,i}) + \exp(\boldsymbol{\eta}_{O,i}) + \mathbf{1}}$$



Arrival Probabilities at Ocean



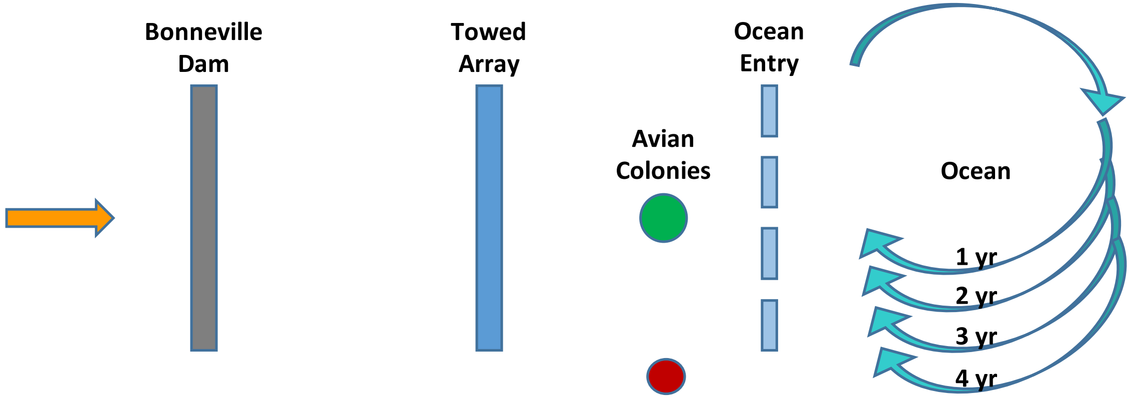
$$\boldsymbol{\mu}_{T2,i} = \boldsymbol{X}_{\boldsymbol{T},\boldsymbol{i}}\boldsymbol{\beta}_{\boldsymbol{T2}} + \gamma_{T2,i}$$

$$t_{2,i,j} \sim \text{discrete.lognormal}(\boldsymbol{\mu}_{T2,i}, \sigma_{T2})$$

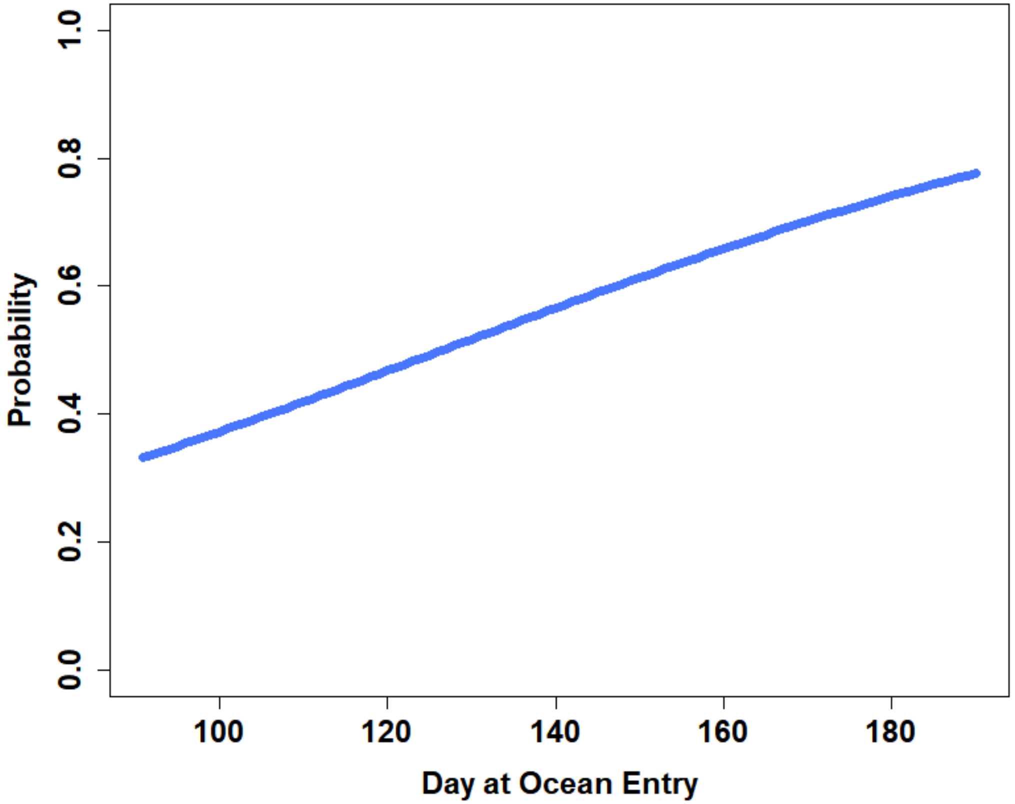
$$\sigma_{T2} \sim \mathrm{C}^{+}(\mathbf{0}, \sigma_{\sigma_{T2}})$$

$$\boldsymbol{\beta}_{\boldsymbol{T2}} \sim N(\mathbf{0}, \sigma_{\beta_T})$$

$$\boldsymbol{\gamma}_{\boldsymbol{T2}} \sim N(\mathbf{0}, \sigma_{\gamma_T})$$



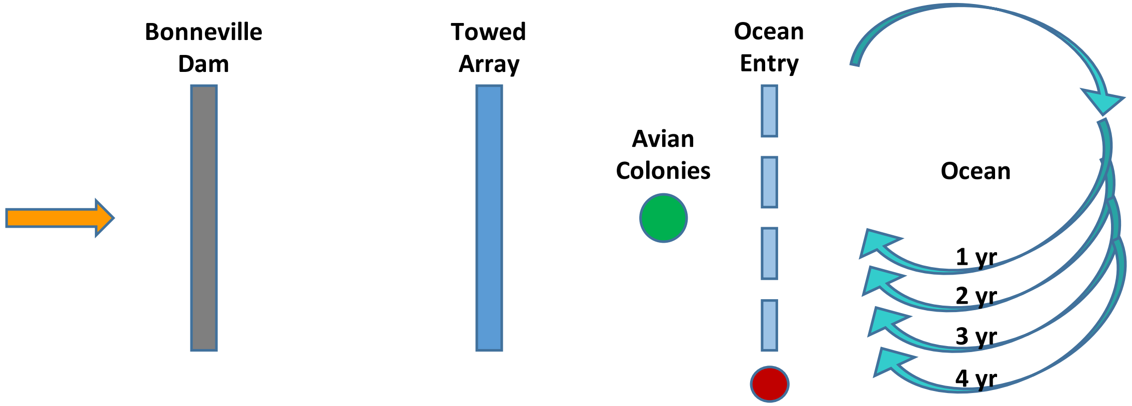
Joint Deposition and Recovery Probability



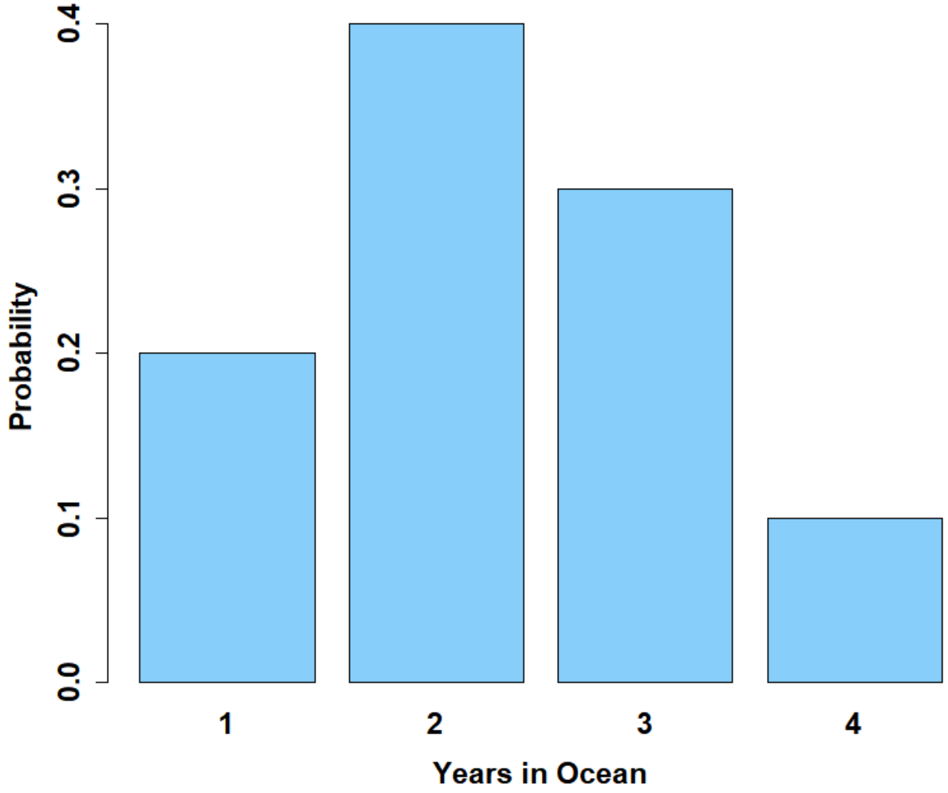
$$\text{logit}(\boldsymbol{\delta}_i) = \boldsymbol{X}_{D,i}\boldsymbol{\beta}_D$$

$$\boldsymbol{\beta}_D \sim \mathbf{MVN}(\boldsymbol{\mu}_D, \boldsymbol{\Sigma}_D)$$

$$1 - \boldsymbol{\phi}_{2,i} = \boldsymbol{\delta}_i\boldsymbol{\theta}_{2,A,i} + (1 - \boldsymbol{\delta}_i)\boldsymbol{\theta}_{2,A,i} + \boldsymbol{\theta}_{2,O,i}$$



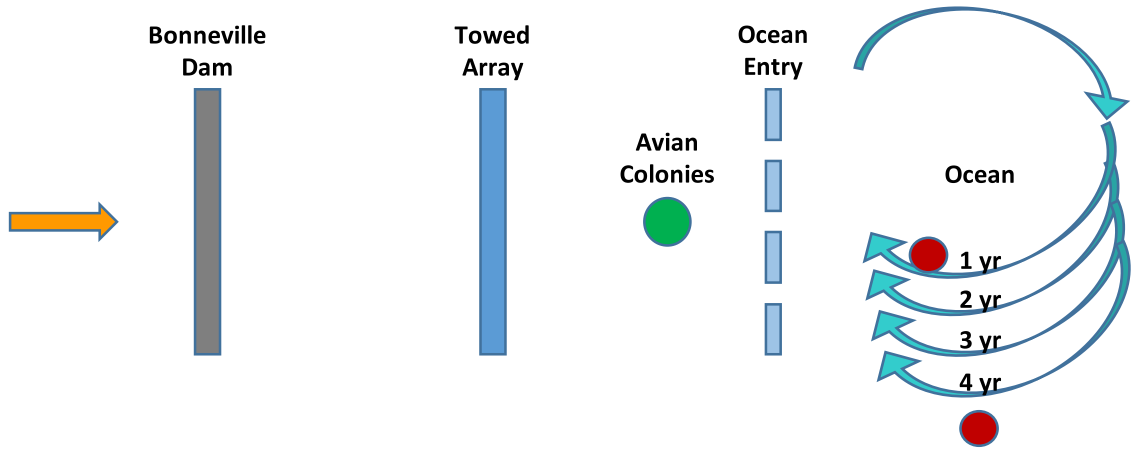
Probability of Year of Return

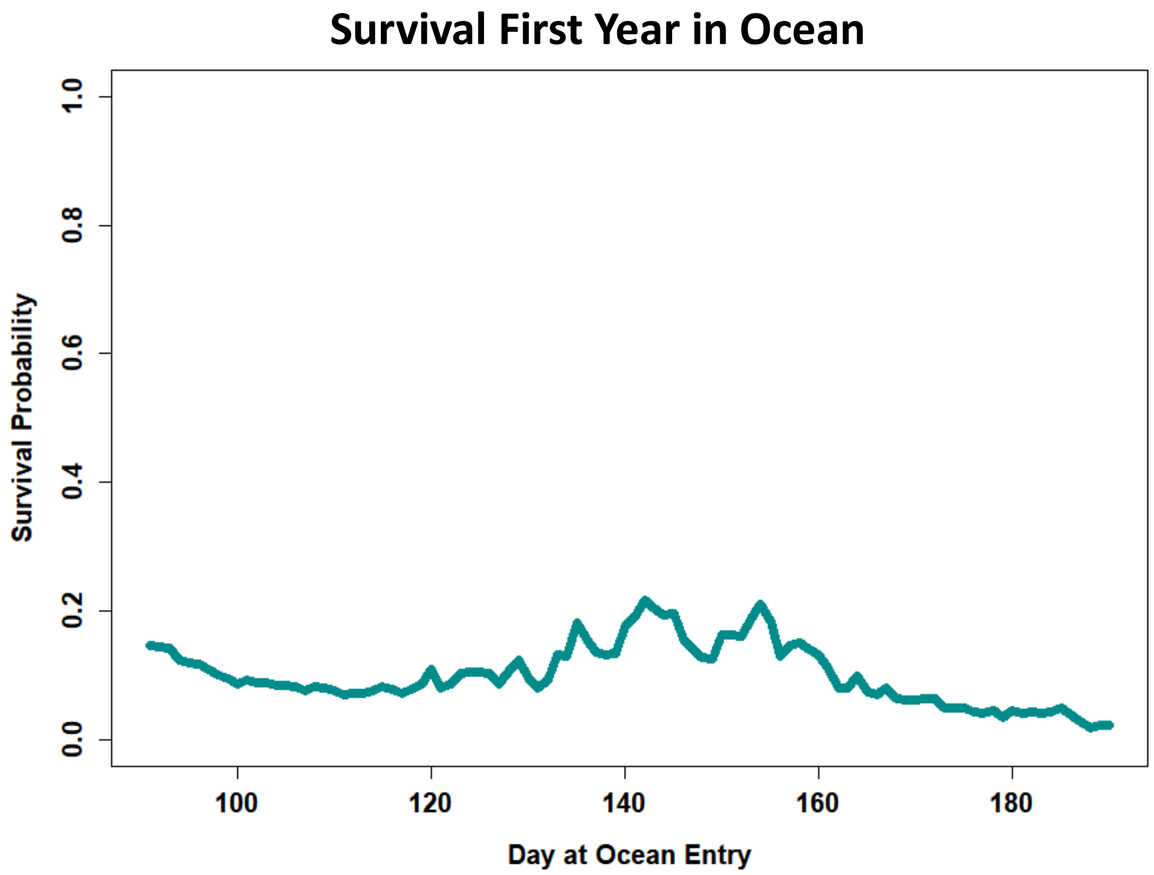


$$\boldsymbol{\pi} \sim \text{Dirichlet}(\tau \boldsymbol{\upsilon})$$

$$\boldsymbol{\upsilon} \sim \text{C}^{+}(\mathbf{0}, \sigma_{\upsilon})$$

$$\tau \sim \text{C}^{+}(0, \sigma_{\tau})$$

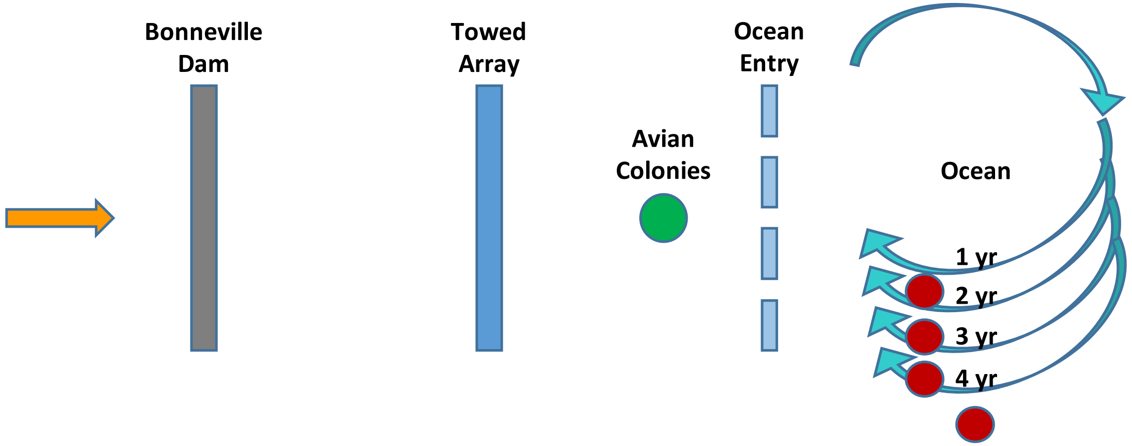


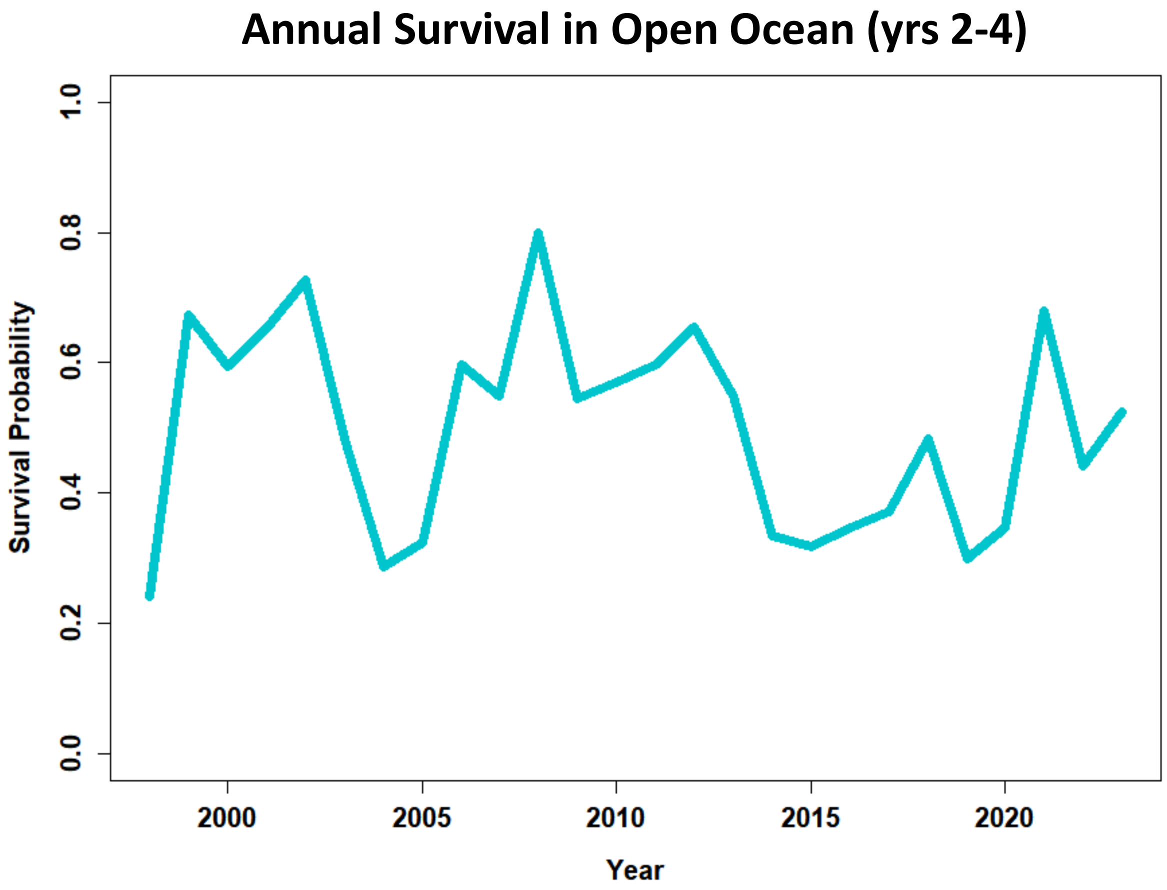


$$\text{logit}(\boldsymbol{\phi}_{31,i}) = \boldsymbol{X}_{\boldsymbol{O1,i}}\boldsymbol{\beta}_{\boldsymbol{O1}} + \gamma_{O1,i}$$

$$\boldsymbol{\beta}_{\boldsymbol{O1}} \sim N(\boldsymbol{0}, \sigma_{\boldsymbol{O1}})$$

$$\boldsymbol{\gamma}_{\boldsymbol{O1}} \sim N(\boldsymbol{0}, \sigma_{\gamma_{O1}})$$

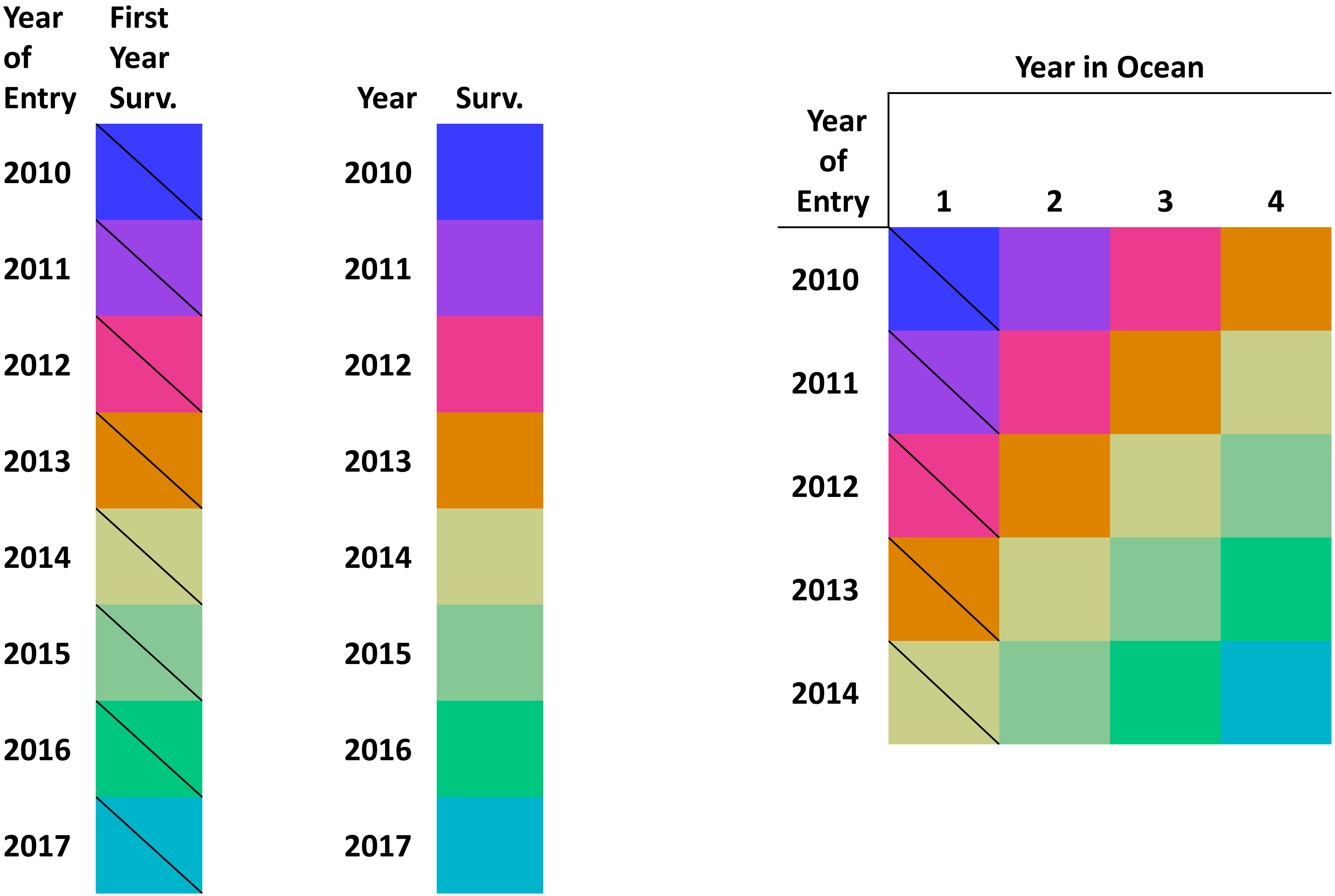




$$\text{logit}(\boldsymbol{\phi}_3) = \boldsymbol{X_O}\boldsymbol{\beta_O} + \gamma_O$$

$$\boldsymbol{\beta_O} \sim N(\mathbf{0}, \sigma_O)$$

$$\boldsymbol{\gamma_O} \sim N(\mathbf{0}, \sigma_{\gamma_O})$$


Year of Entry
First Year Surv.
2010
2011
2012
2013
2014
2015
2016
2017
Year
Surv.
2010
2011
2012
2013
2014
2015
2016
2017
Year in Ocean
Year of Entry
1
2
3
4
2010
2011
2012
2013
2014

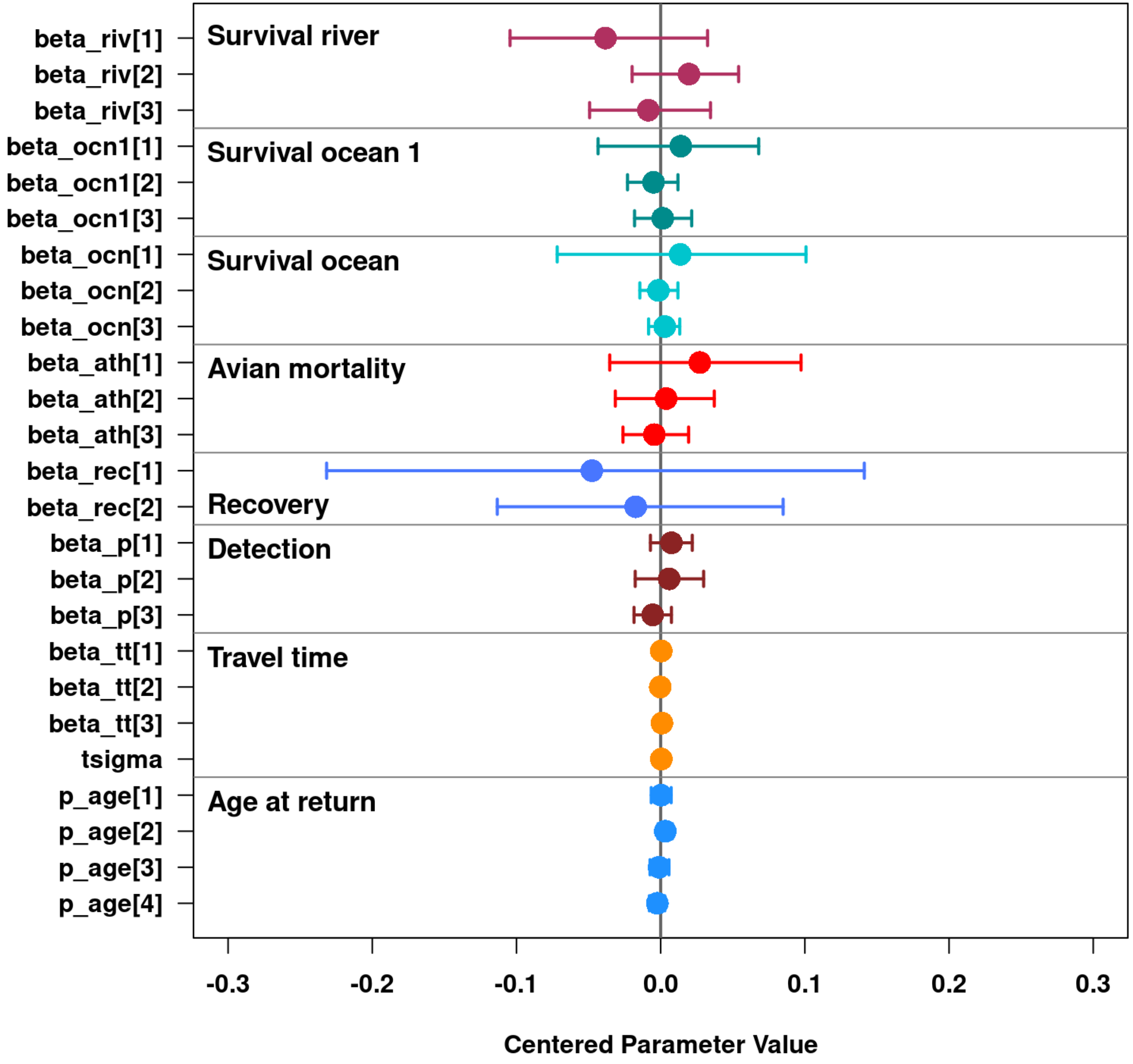
Example Data

Mig. Year	BON Day	TWX Day	Bird Island	Return
2010	111	0	1	0
2010	126	128	0	3
2010	179	0	0	0
2010	133	0	0	0
2010	117	0	0	1
2012	155	0	0	0
2018	136	141	1	0
2018	188	0	0	4
2019	212	0	1	0
…				

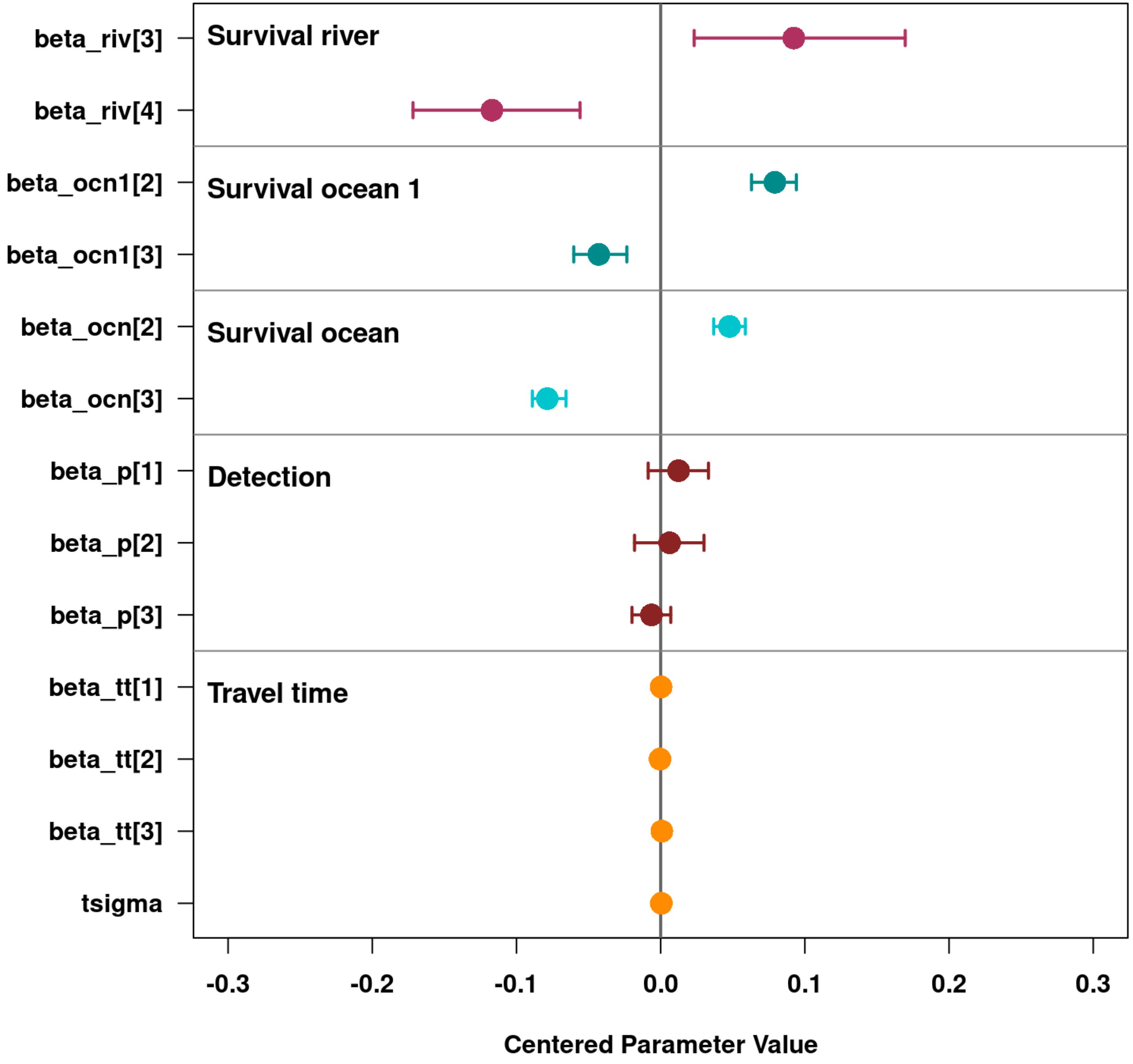
Methods – simulated data example

- Released 25k fish in each of 20 years
- One data set
- Survival, detection, avian recovery varied by year
- Fit four model types:
  - M1: Age distribution, avian recovery
  - M2: Age distribution, no avian recovery
  - M3: No age distribution, no avian recovery

Results – parameter estimates from full model



Results – parameter estimates from reduced model



Conclusions

- Method allows for partitioning of estuary and ocean survival
- Covariate effects better estimated when tag recoveries are accounted for
- Use of age of return improves parameter estimates

Future work

- Investigate benefit of recovery from harvest
- Apply models to real data
- Explore variables related to estuary and plume conditions
- Potential inclusion of factors related to age at maturity
- Include fish size and passage route history

Coastally Curious

Billie Johnson

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Questions?

Contact: jim.faulkner@noaa.gov

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