# Assessing Inter-population Variation in Survival Using Mark-Recapture Data

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# Mark-recapture data & survival in the wild

- Survival in the wild with detectability less than 1
- Collecting and modelling mark-recapture data
- Investigating factors explaining variation in survival – biological scenarios
- Flexible regression-like framework

# Modelling mark-recapture data

- A particular encounter history: 1 0 1

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- Survival probability $\phi_t$

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$$\overbrace{1 \quad 0}^{\phi_1} \overbrace{\quad 0 \quad 1}^{\phi_2}$$

$$\uparrow \qquad \uparrow$$

$$1 - p_2 \qquad p_3$$

- Survival probability $\phi_t$
- Detection probability $p_t$

# Modelling mark-recapture data

- A particular encounter history: 1 0 1

$$\overbrace{1 \quad 0}^{\phi_1} \overbrace{\quad 0 \quad 1}^{\phi_2}$$

$$\uparrow \qquad \uparrow$$

$$1 - p_2 \qquad p_3$$

$$\Pr(101) = \phi_1 (1 - p_2) \phi_2 p_3$$

- Survival probability $\phi_t$
- Detection probability $p_t$

# A flexible framework

- We use the following relationship:

$$\text{logit}(\phi) = \beta_0 + \beta_1 x + \varepsilon$$

  - Forces survival estimates to be within [0,1]
  - Possibly incorporates random effects ε
    - Copes with unexplained variance

      (*Barry et al. 2002 – Biometrics; Royle 2008 - Biometrics*)
    - Allows temporal autocorrelation to be incorporated (*Johnson & Hoeting 2003 – Biometrics*)
  - Extends to nonparametric modelling via P-splines

# Demography over large geographical scales?

- What if we have several (unconnected) populations?
  - Are survival time series synchronized?
  - Role of environmental covariates – Moran effect?
- Multi-population studies and spatial modelling of demographic parameters

# Needs for new developments

- Standard tools in time series analyses of count data and presence/absence data (Bjørnstad et al. 1999, Koenig 1999, Liebhold et al. 2004)

- But Bjørnstad et al. (1999) noted that « *the mechanisms behind spatio-temporal dynamics are interpreted most easily through studies of local demographic rates because determinants of these dynamics ultimately exert their influence via local demographic rates* »

# Synchrony in survival using ad-hoc methods

- Consider 3 patterns of inter-annual variation
  - M1: time * site
  - M2: time + site
  - M3: site
- 'Analysis of deviance' exercise
  - NUM = Dev(M2)-Dev(M3) represents deviance with inter-annual variation shared by the 2 sites
  - DEN = Dev(M1)-Dev(M3) represents deviance with total inter-annual variation in the 2 sites
  - DEN / NUM = fraction of the total inter-annual deviance explained by a common inter-annual pattern of variation

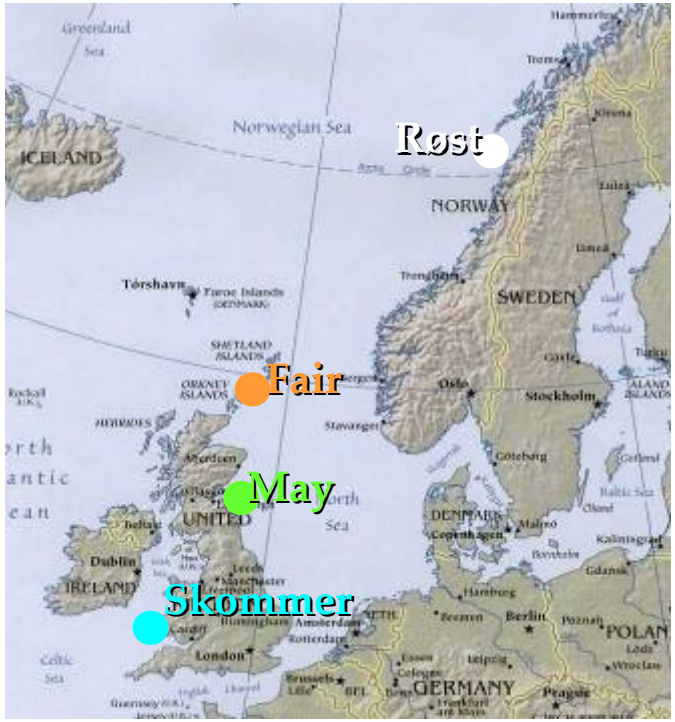
# Synchrony in survival using ad-hoc methods

- Consider 3 patterns of inter-annual variation
- 'Analysis of deviance' exercise

- Process and sampling variabilities are not explicitly separated
  - How to quantify process covariance in survival time series?
  - How to assess the role of environmental covariates in synchrony / asynchrony?

# Motivating data set

- Survival of adult Atlantic puffin (*Fratercula arctica*) in the eastern Atlantic




**Joint work with V. Grosbois, B.J.T. Morgan, M. Harris, T. Anker-Nilssen, R.H. McCleery, D.N. Shaw**

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# Spatial modelling

- Spatial modelling of demographic parameters: multi-population studies
  - Are survival rates synchronized?
  - Role of environmental covariates – Moran effect?

# New statistical model

- *Random effects* for handling spatial effects

$$\text{logit}(\phi_{is}) = f_s(x_{is}) + \delta_i + \varepsilon_{is}$$

  - $\phi_{is}$ *is the survival probability between occasions i and i+1 in site s*
  - $x_{is}$ is the value of the covariate measured at the *i*th sampling occasion in site *s*
  - $f_s$ is a smooth function for site *s*

# New statistical model

- *Random effects* for handling spatial effects

$$\text{logit}(\phi_{is}) = f_s(x_{is}) + \delta_i + \varepsilon_{is}$$

  - $\delta_i$ is a random effect for year *i* shared across sites: $\delta_i \sim N(0,\sigma^2_\delta)$
  - $\varepsilon_{is}$ is a site-specific random effect for year *i*: $\varepsilon_{is} \sim N(0,\sigma^2_\varepsilon)$

# New statistical model

- *Random effects* for handling spatial effects

$$\text{logit}(\phi_{is}) = f_s(x_{is}) + \delta_i + \varepsilon_{is}$$

  - $\sigma^2_\delta$ is the process variance shared among colonies: *shared variance*
  - $\sigma^2_\varepsilon$ is the process variance independent across colonies: *unshared variance*
  - $\sigma^2_\delta + \sigma^2_\varepsilon$ is the total process variance

# Property 1

- Pattern of inter-annual variation in survival probabilities is correlated between two distinct sites *s* and *s′*, and this correlation is the same for all possible pairs of sites:

$$\mathrm{cov}(\mathrm{logit}(\phi_{is}), \mathrm{logit}(\phi_{is'})) = \sigma_\delta^2$$

# Property 2

- No temporal autocorrelation in survival between two occasions *i* and *j*, whatever the sites (different or not):

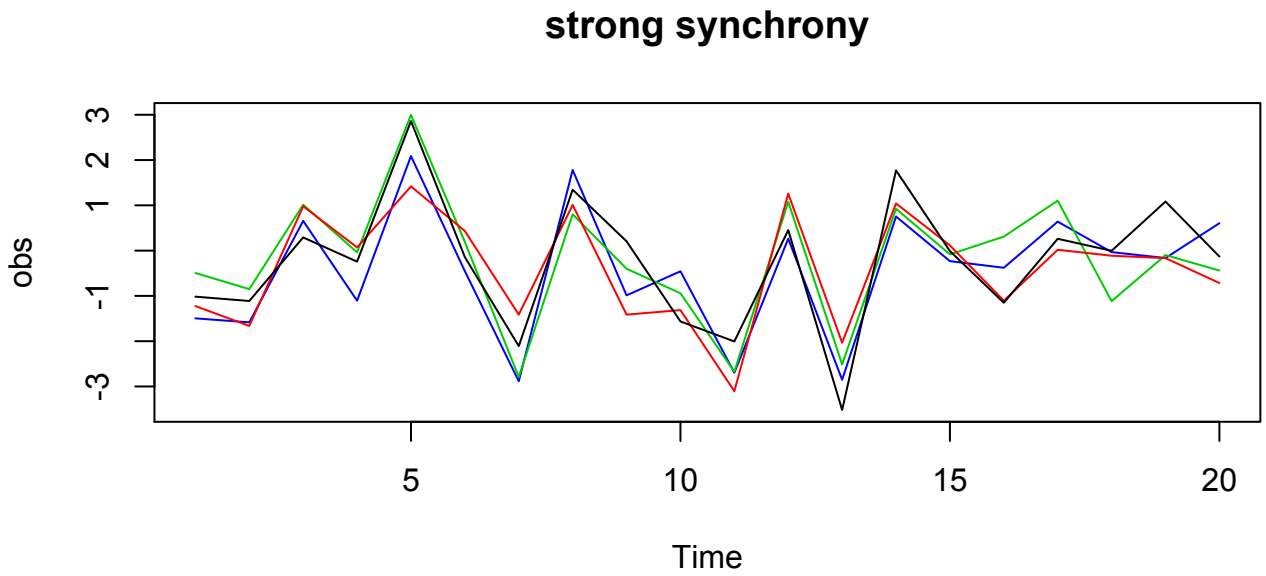
$$\mathrm{cov}(\mathrm{logit}(\phi_{is}), \mathrm{logit}(\phi_{js'})) = 0$$

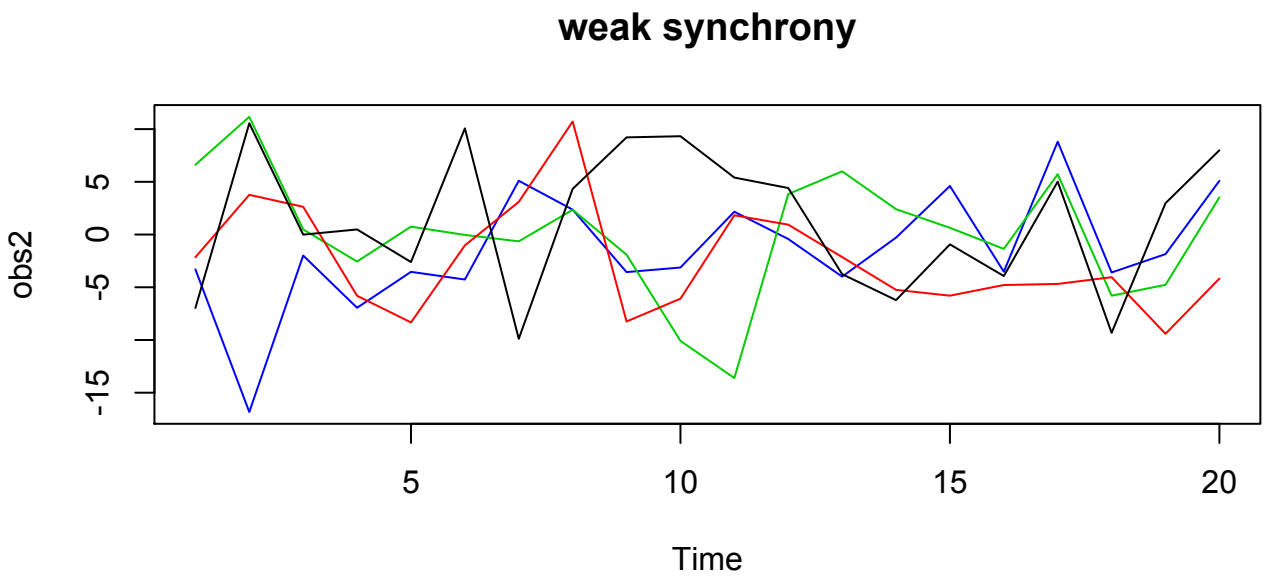
# Quantifying synchrony

- We aim to evaluating the relative contribution of each of these components to the total variation $\sigma^2_\varepsilon + \sigma^2_\delta$
- $\sigma^2_\delta >> \sigma^2_\varepsilon$ => synchrony across sites in inter-annual variation in survival probability
- Quantify the degree of spatial synchrony by calculating the intra-class correlation

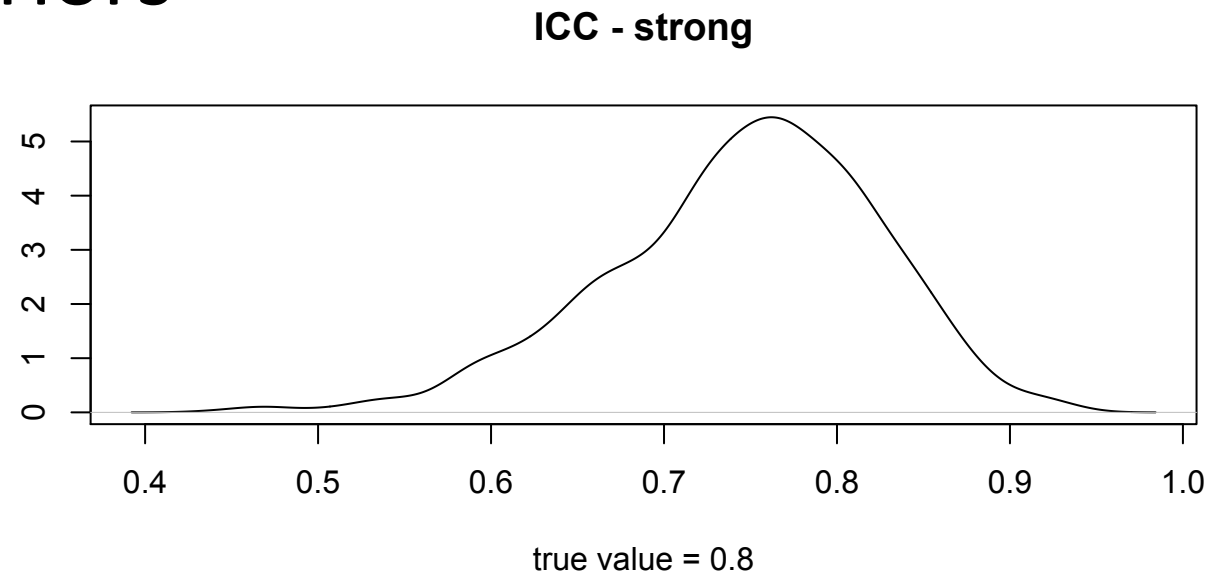
$$\mathrm{ICC} = \frac{\sigma_\delta^2}{\sigma_\delta^2 + \sigma_\epsilon^2}$$

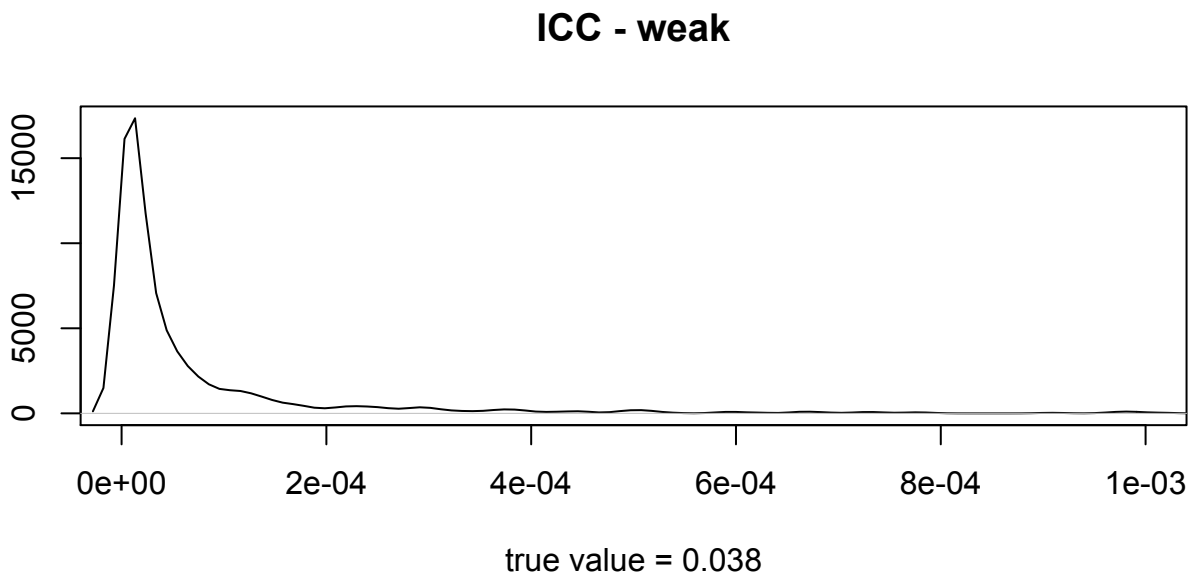
# Simulated data



# ICC posteriors

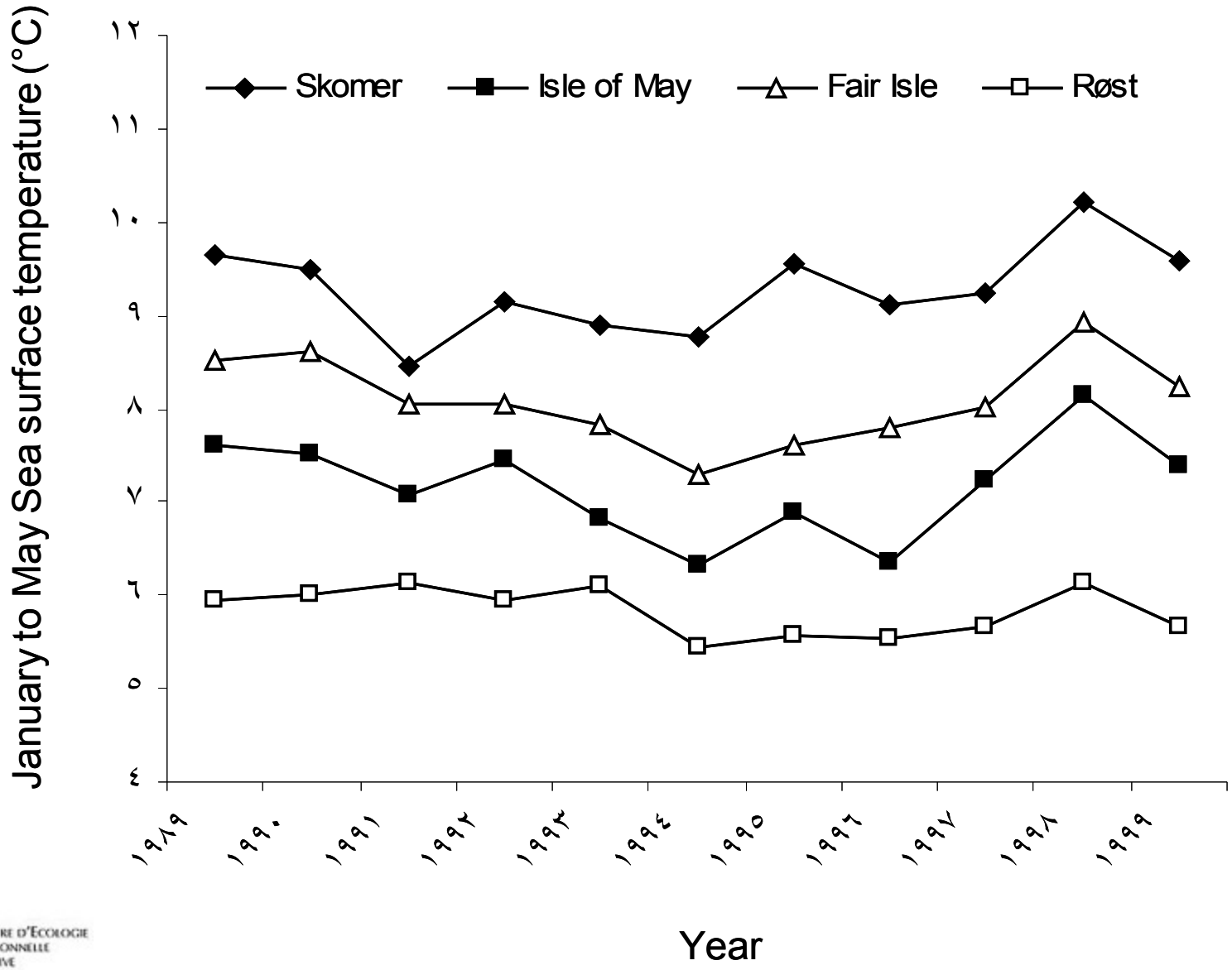


# Contribution of the covariable in generating synchrony

- We consider models with and without the covariate
- $\sigma^2_\delta$(*res*) and $\sigma^2_\delta$(*total*) shared variance in model *with* and *without* covariate
- $\sigma^2_\varepsilon$(*res*) and $\sigma^2_\varepsilon$(*total*) unshared variance in model *with* and *without* covariate
- Contribution to **shared** process variance is: $\mathbf{1 - \sigma^2_\delta(\mathit{res})/\sigma^2_\delta(\mathit{total})}$
- Contribution to **unshared** process variance is: $\mathbf{1 - \sigma^2_\varepsilon(\mathit{res})/\sigma^2_\varepsilon(\mathit{total})}$

# Results: SST was positively correlated among colonies (Harris et al. 2005)

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# Results: spatial synchrony

- There is spatial synchrony in survival time series since ICC = 67% in model

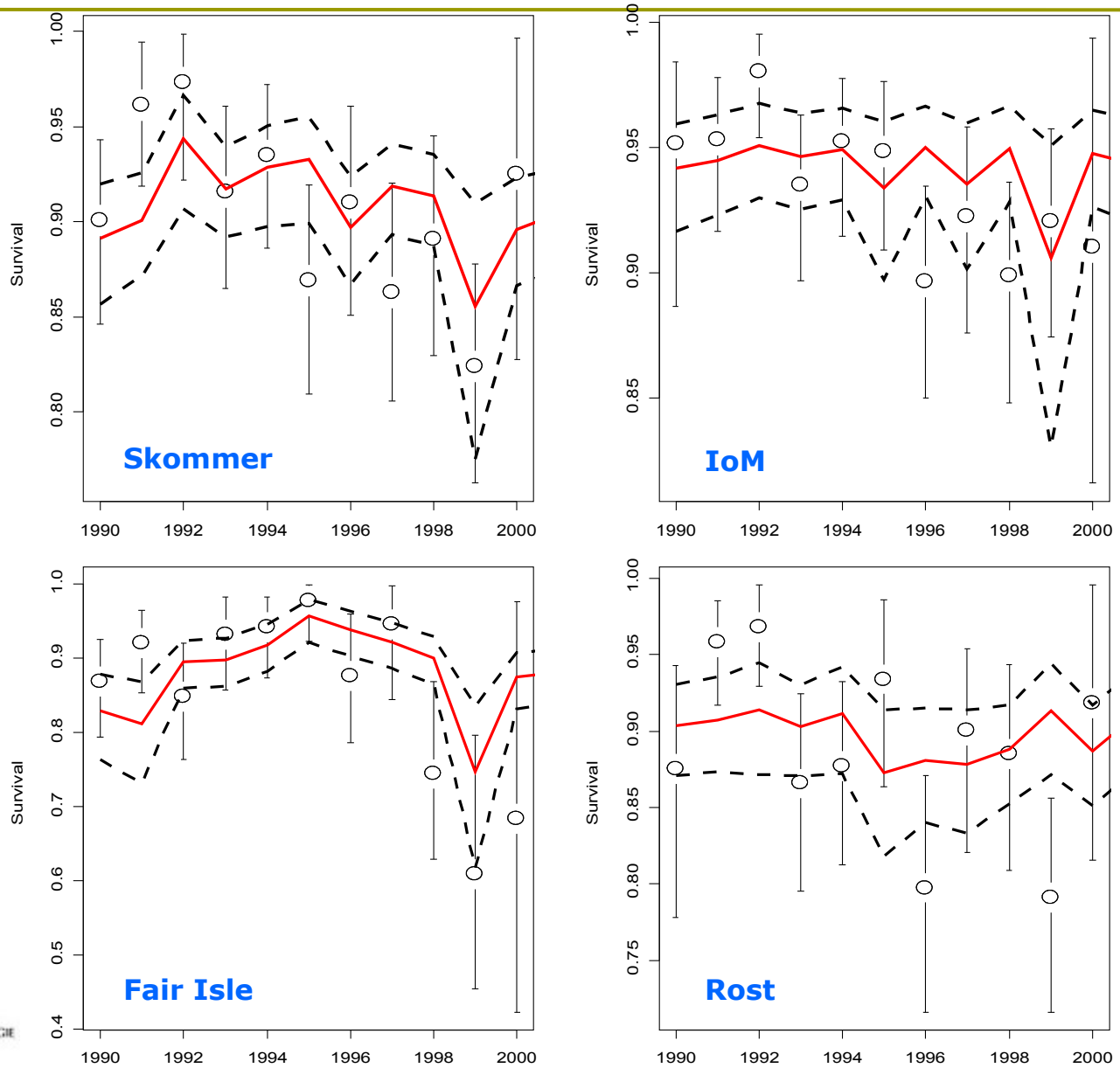
$$\text{logit}(\phi_{is}) = f_s(x_{is}) + \delta_i + \varepsilon_{is}$$

- But not totally explained by SST since ICC = 67% in model without SST...

$$\text{logit}(\phi_{is}) = \mu_s + \delta_i + \varepsilon_{is}$$

- In addition to SST, other environmental factors synchronize temporal variation in survival accross colonies

# Results: annual variations in survival

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# Results: contribution of SST in generating synchrony

- $1 - \sigma^2_\delta(res)/\sigma^2_\delta(total) = 39\%$

-> SST acted as a synchronizing agent

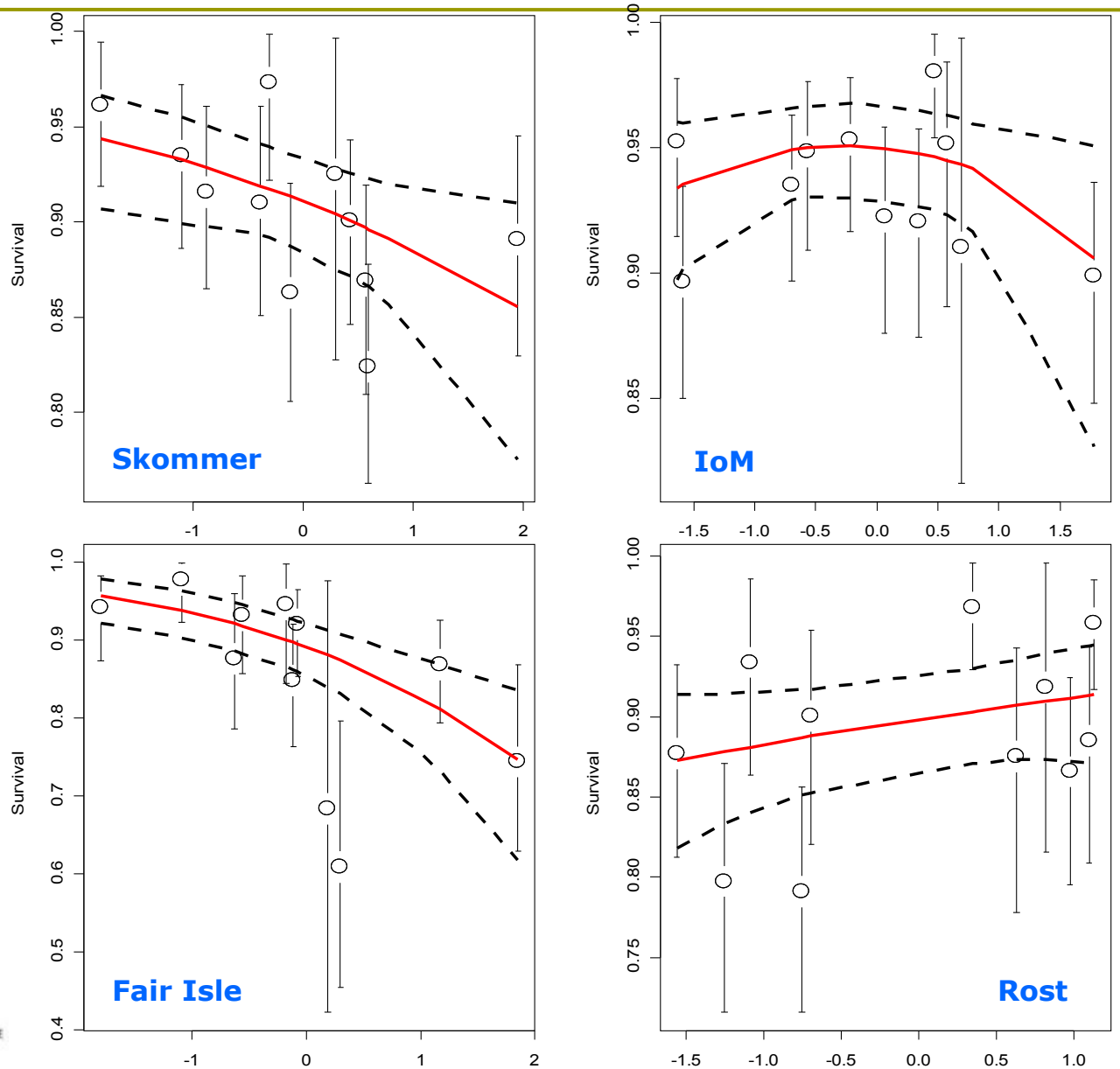
- $1 - \sigma^2_\varepsilon(res)/\sigma^2_\varepsilon(total) = 40\%$

-> SST acted also as a desynchronizing agent

- Unexpected result given positive correlations in SST among colonies

- What are the relationships between survival and SST in each site?

# Results: survival vs. local SST

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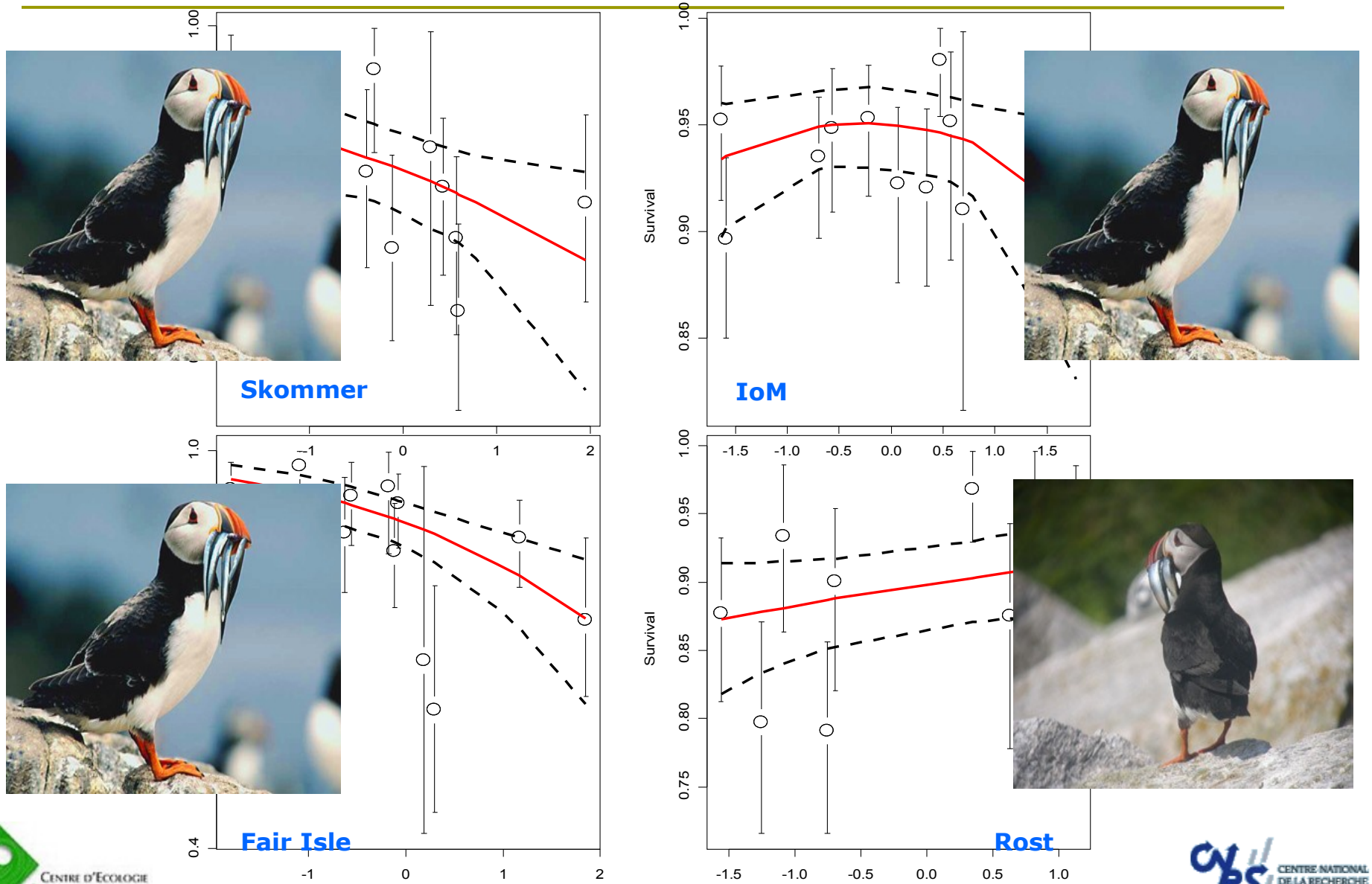
# Biological interpretation

- Local SST influences food chain with geographical specificities
- The forage fish compartment is dominated in the northernmost colony (Røst) by a species (*herring*) which cohort strength increases with increasing SST while in the three other colonies (Isle of May, Fair Isle and Skommer) by a species (*sandeel*) which cohort strength decreases with increasing SST

# Results: survival vs. local SST



# Conclusions: Multi-population survival modelling

- Benefits of a mixed-modeling approach
  - Spatial dependence easily accounted for
  - Quantify the amount of synchrony
  - Contribution of factors generating synchrony

- Limits
  - Oversimplification: 1 parameter to account for spatial dependence

- (Exciting!) perspectives

# 1. Path analysis of mark-recapture data

Sea Surface Temperature January (t-1) to May (t-1)

Effect of local sea surface temperature on survival

Annual survival summer (t) to summer (t+1)

Harris et al. (2005) Marine Ecology Progress Series 297: 283-296

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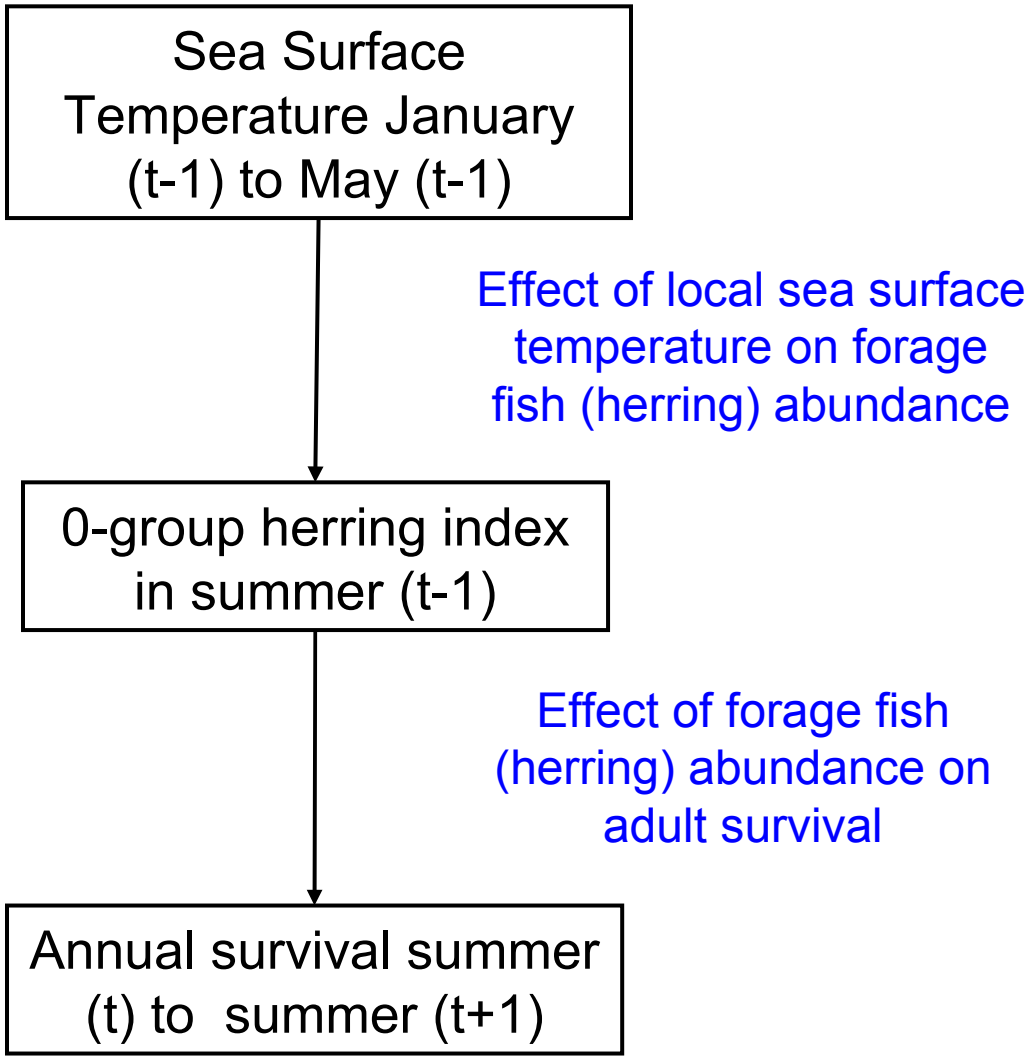
# Scenario possibly explaining the effect of SST on survival

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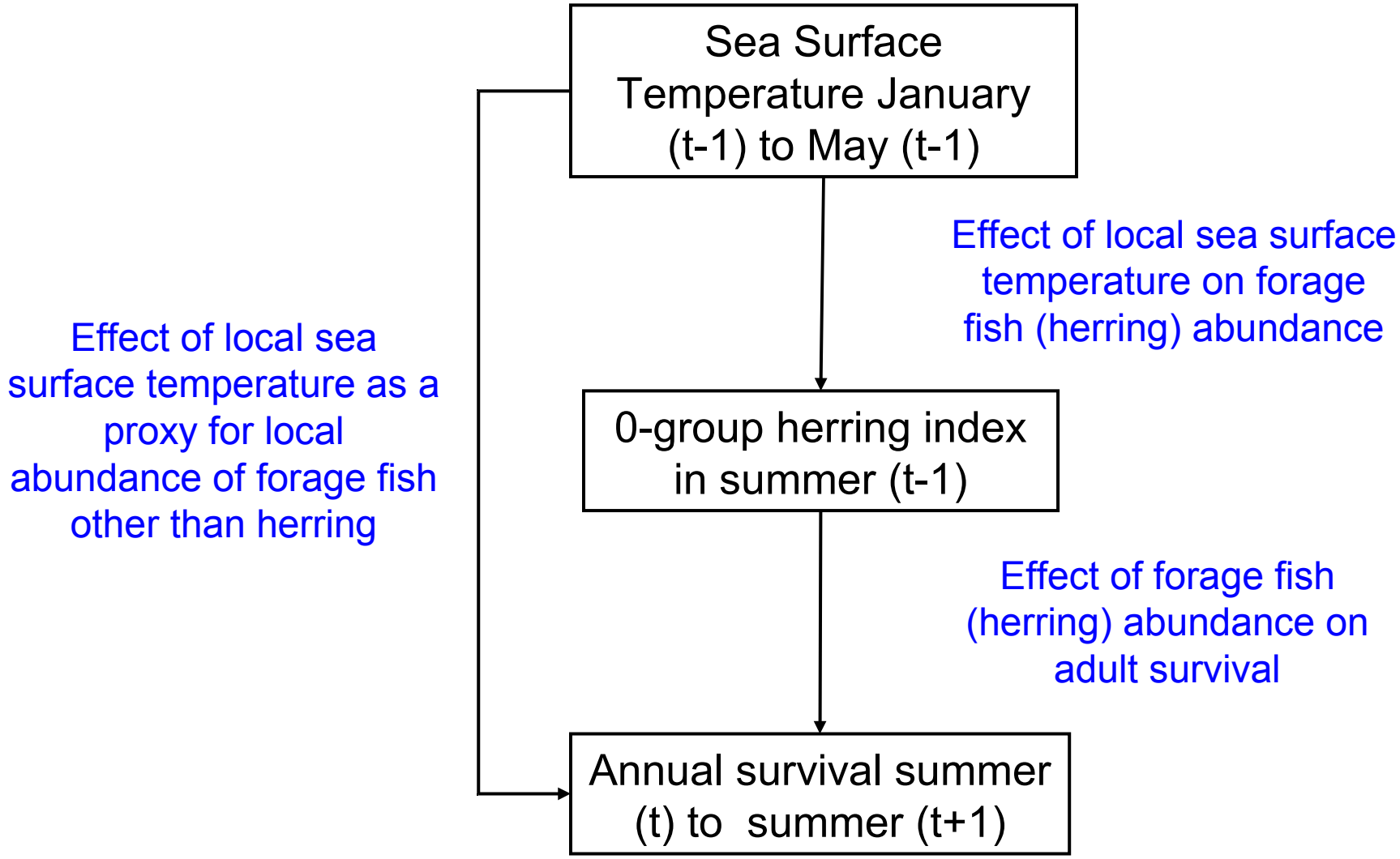


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# Disentangling direct vs. indirect effects using a path analysis mark-recapture model

Sea Surface Temperature $SST_{t-1}$

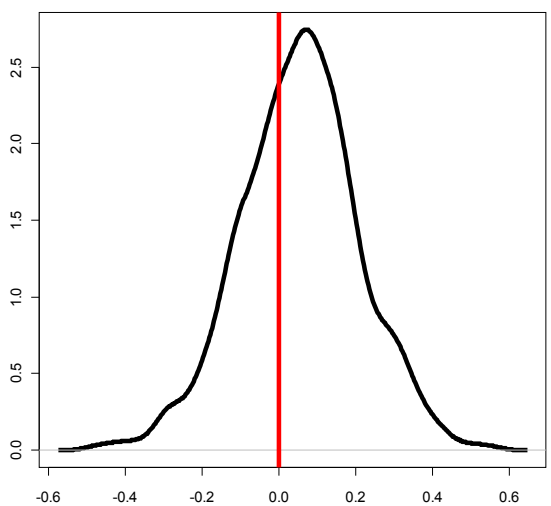
DIRECT EFFECT

$\theta_3 = 0.06\,[-0.27, 0.36]$

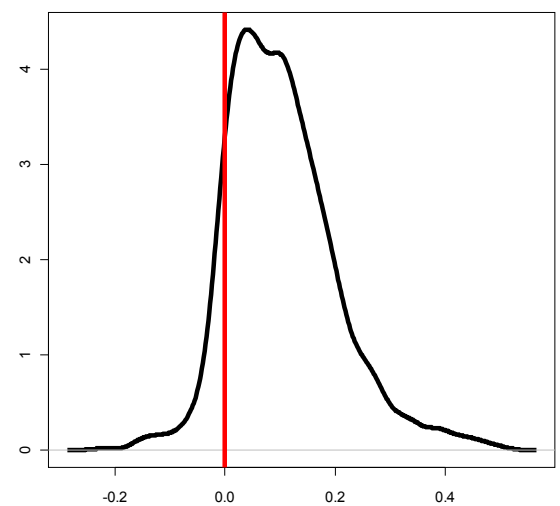
Food $R_{t-1}$

INDIRECT EFFECT

$\theta_2 \cdot \theta_5 = 0.14\,[-0.02, 0.28]$




Survival $\phi_t$



# Disentangling direct vs. indirect effects using a path analysis mark-recapture model

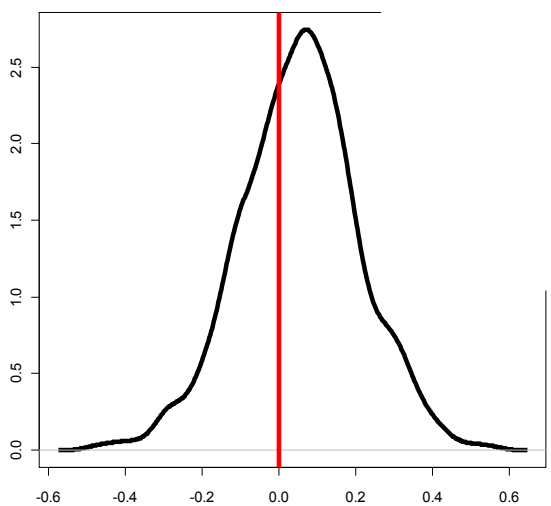
DIRECT EFFI

$\theta_3 = 0.06[-0.2$

# Make it spatial?

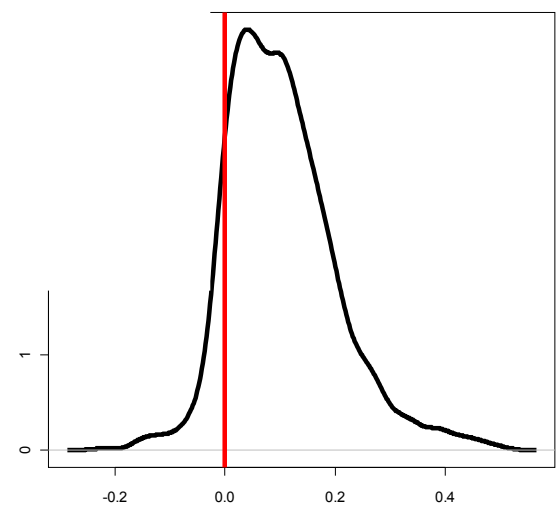
ECT EFFECT

$14[-0.02, 0.28]$




Survival

$\phi_t$

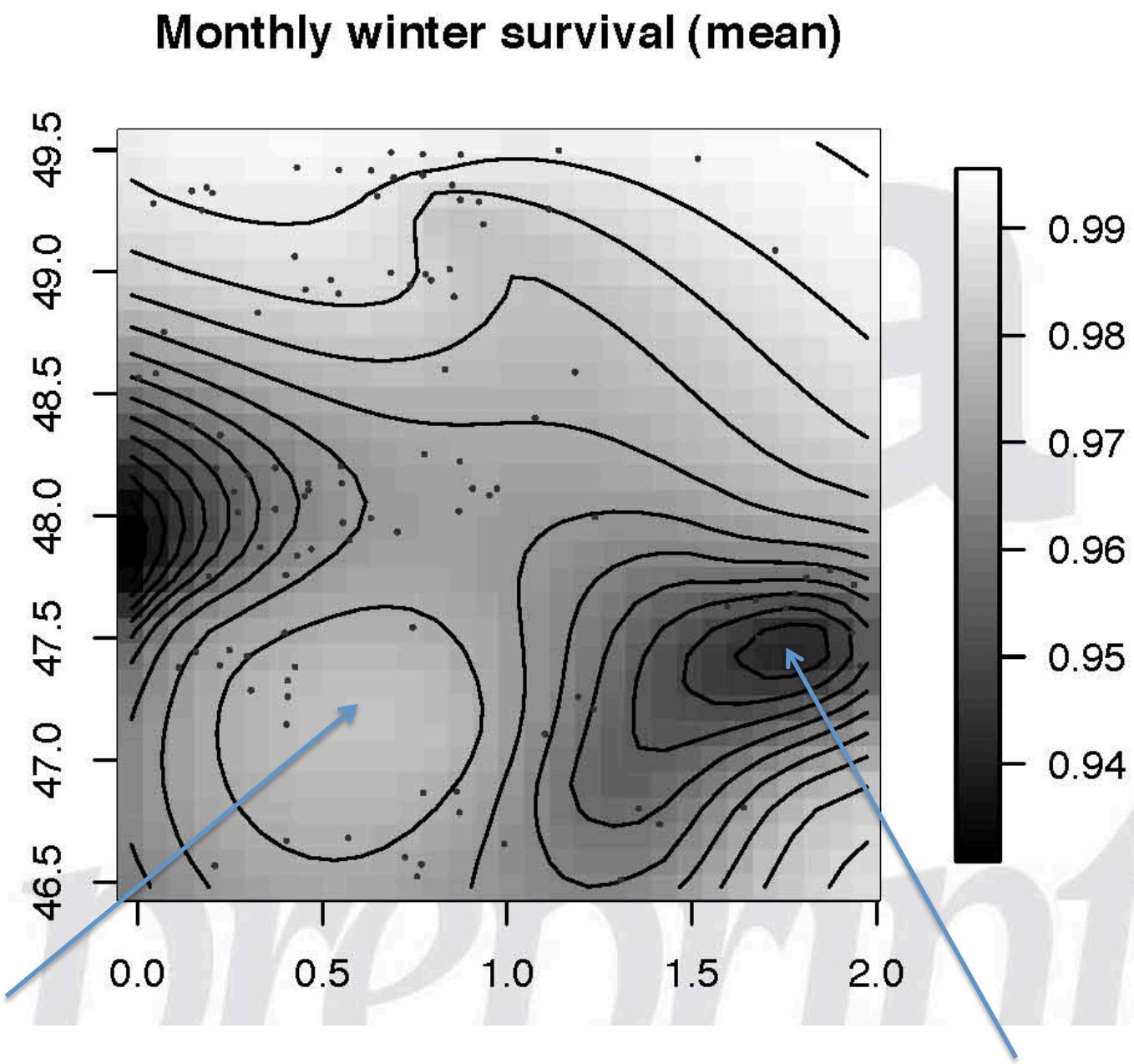


# 2. Spatially-explicit mark-recapture models

- Incorporate inter-site distances
- If (many) more sites, survival mapping
  - Exponential, CAR
  - Bivariate smoothing

# Modélisation spatiale & survie

- Bécasse des bois, espèce chassée
- Données de reprise sur > 5000 individus
- Centre et Ouest de la France
- Estimer survie dans l'espace
- Gestion de la chasse?
- Survie fonction des coordonnées de bagages via splines bivariées (modèles mixtes de CR)
- Péron et al. (in press). Nonparametric spatial regression of survival probability: visualization of population sinks in Eurasian Woodcock. *Ecology*




Parc régional de Loire Anjou Touraine

Sologne

Thank you for your attention

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# Model selection

| Model | *DIC* | pD | $\Delta DIC$ |
|---|---|---|---|
| $f(SST)+\delta+\varepsilon$ | 8403.01 | 129.89 | 28.75 |
| $f(SST)+\varepsilon$ | 8405.44 | 134.68 | 31.18 |
| $f(SST)+\delta$ | 8387.05 | 105.00 | 12.79 |
| $f(SST)$ | 8403.73 | 96.56 | 29.47 |
| $\alpha+\delta+\varepsilon$ | 8419.38 | 145.74 | 45.12 |
| $\alpha+\varepsilon$ | 8408.82 | 139.68 | 34.56 |
| $\alpha+\delta$ | 8388.06 | 96.45 | 13.80 |
| $\alpha$ | 8455.31 | 91.13 | 81.05 |
| $parametric+\delta+\varepsilon$ | 8389.12 | 119.26 | 14.86 |
| $parametric+\varepsilon$ | 8396.92 | 127.83 | 22.66 |
| **$parametric+\delta$** | **8374.26** | **96.08** | **0** |
| *parametric* | 8405.13 | 90.23 | 30.87 |

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# Likelihood of a standard mark-recapture model

Example

| | | |
|---|---|---|
| 1111 | 10; | $\phi^3 p^3$ |
| 1110 | 11; | $\phi^2 p^2 (1-\phi p)$ |
| 1011 | 2; | $\phi^3 p^2 (1-p)$ |
| 1101 | 3; | ..... |
| 1100 | 50; | ..... |
| 1010 | 3; | |
| 1001 | 1; | |
| 1000 | 120; | |
| 0111 | 10; | |
| 0110 | 18; | |
| 0101 | 4; | |
| 0100 | 172; | |
| 0011 | 24; | |
| 0010 | 76; | |

$$L = \prod_{\omega} \Pr(\omega)^{n_\omega} = \left(\phi^3 p^3\right)^{10} \times \left[\phi^2 p^2 (1-\phi p)\right]^{11} \times \ldots$$

$$\log(L) = 10 \cdot \log\left(\phi^3 p^3\right) + 11 \cdot \log\left(\phi^2 p^2 (1-\phi p)\right) + \ldots$$

(Lebreton et al. 1992)