Estimating wolf occupancy with R

Olivier Gimenez

Lecture 1

Introduction

Occupancy to map species distribution

Occupancy: proportion of an area occupied by a species

- Species range dynamics
- Habitat preferences
- Metapopulation dynamics
- …

0	0	1	0	0
0	1	0	0	0
0	1	1	0	0
0	0	1	0	0
1	0	1	0	0
0	1	0	0	0
0	0	0	0	1
0	0	0	0	1

10/40 = 0.25

Levins 1967, McKenzie *et al*. 2003, 2006

Issue of detectability < 1

0	0	1	0	0
0	1	0	0	0
0	1	1	0	0
0	0	1	0	0
1	0	1	0	0
0	1	0	0	0
0	0	0	0	1
0	0	0	0	1

True occupancy = 25%

Issue of detectability < 1

0	0	1	0	0
0	1	0	0	0
0	1	1	0	0
0	0	1	0	0
1	0	1	0	0
0	1	0	0	0
0	0	0	0	1
0	0	0	0	1

True occupancy = 25%

0	0	1	0	0
0	1	0	0	0
0	1	1	0	0
0	0	1	0	0
1	0	1	0	0
0	1	0	0	0
0	0	0	0	1
0	0	0	0	1

Species detected in 6 occupied sites

Occupancy underestimation

0	0	1	0	0
0	1	0	0	0
0	1	1	0	0
0	0	1	0	0
1	0	1	0	0
0	1	0	0	0
0	0	0	0	1
0	0	0	0	1

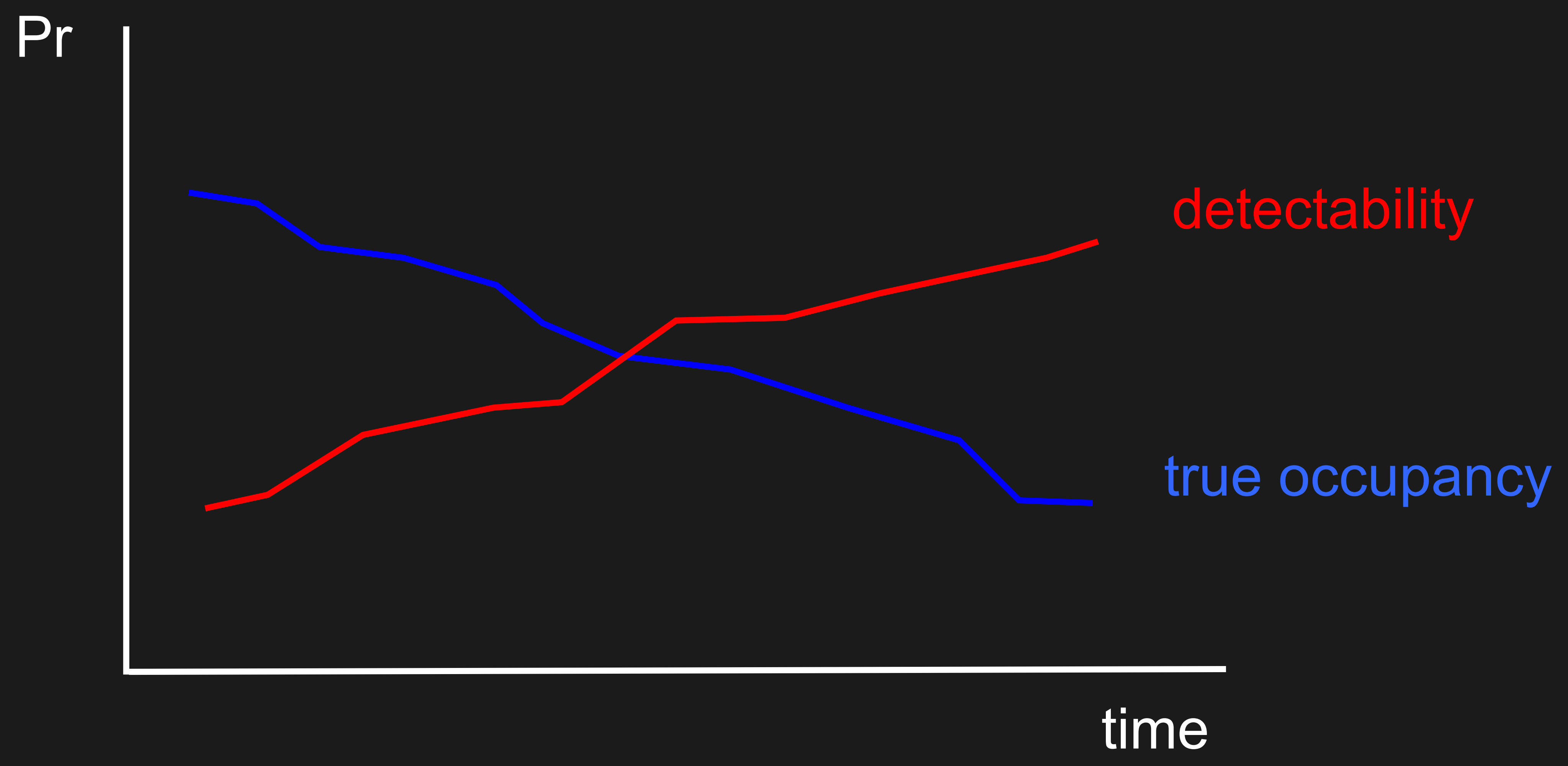
True occupancy = 25%

0	0	1	0	0
0	1	0	0	0
0	1	1	0	0
0	0	1	0	0
1	0	1	0	0
0	1	0	0	0
0	0	0	0	1
0	0	0	0	1

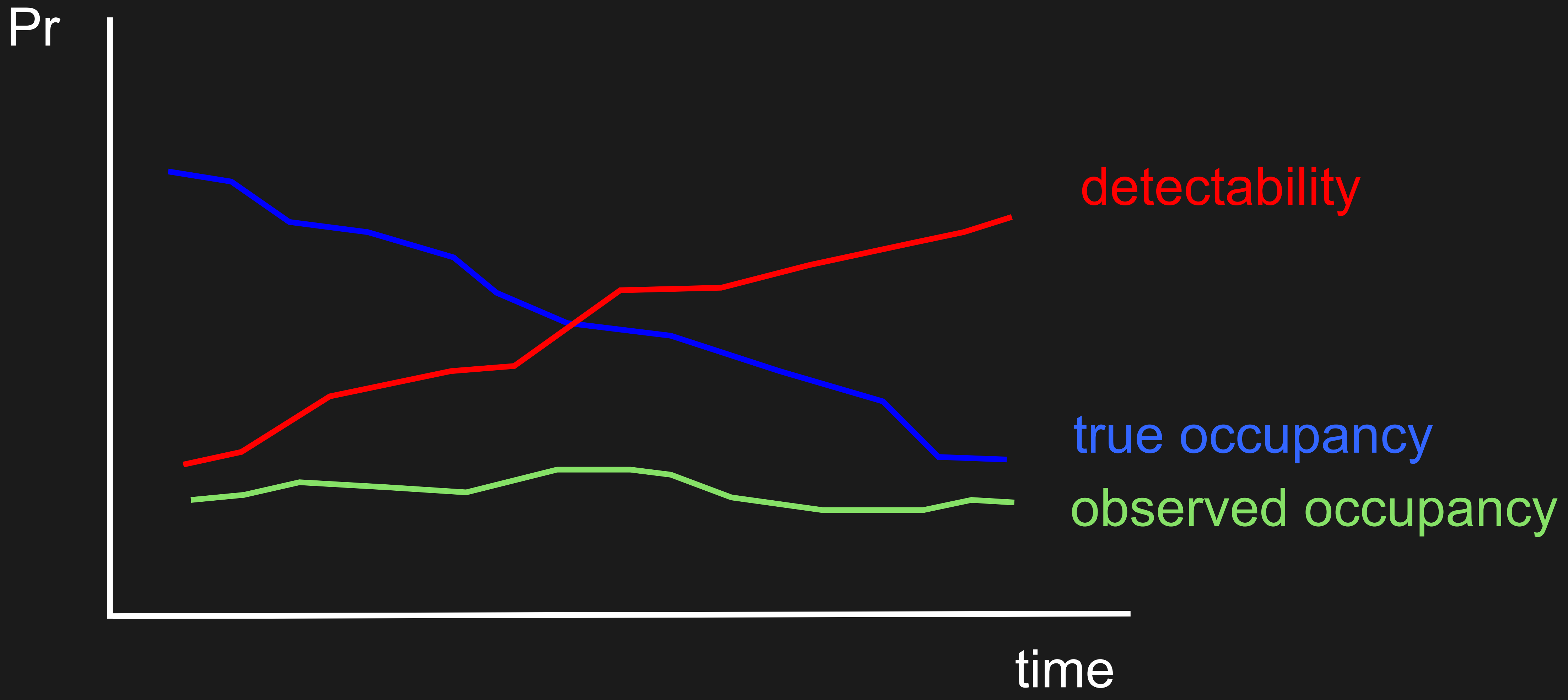
Species detected in 6 occupied sites

Naive occupancy estimate = 6/40 = 15%

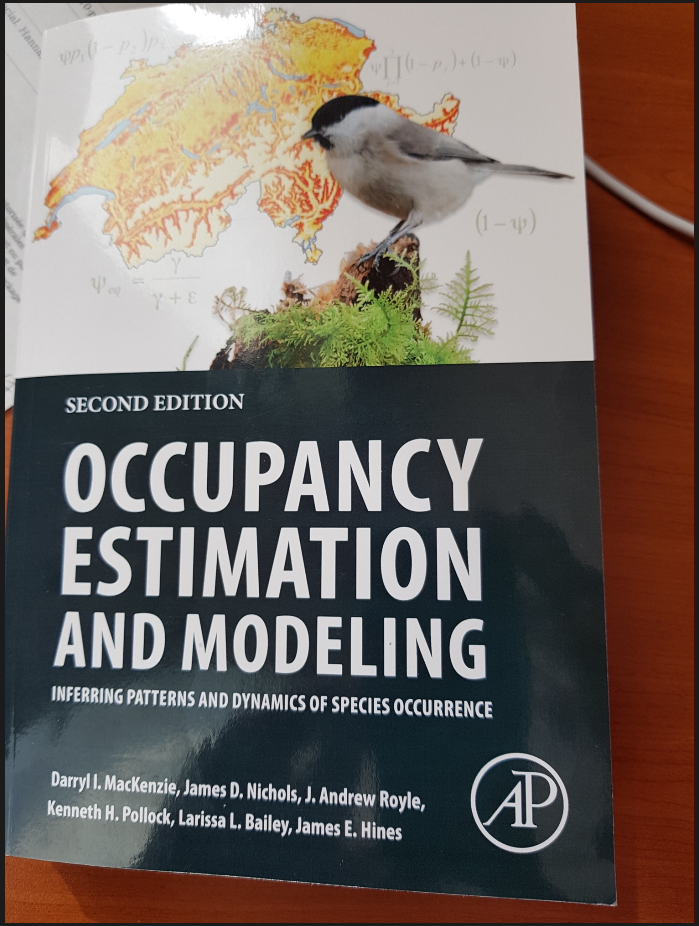
Issue of detectability < 1



Bias in occupancy trends



Occupancy models



ECOGRAPHY
A JOURNAL OF SPACE AND TIME IN ECOLOGY

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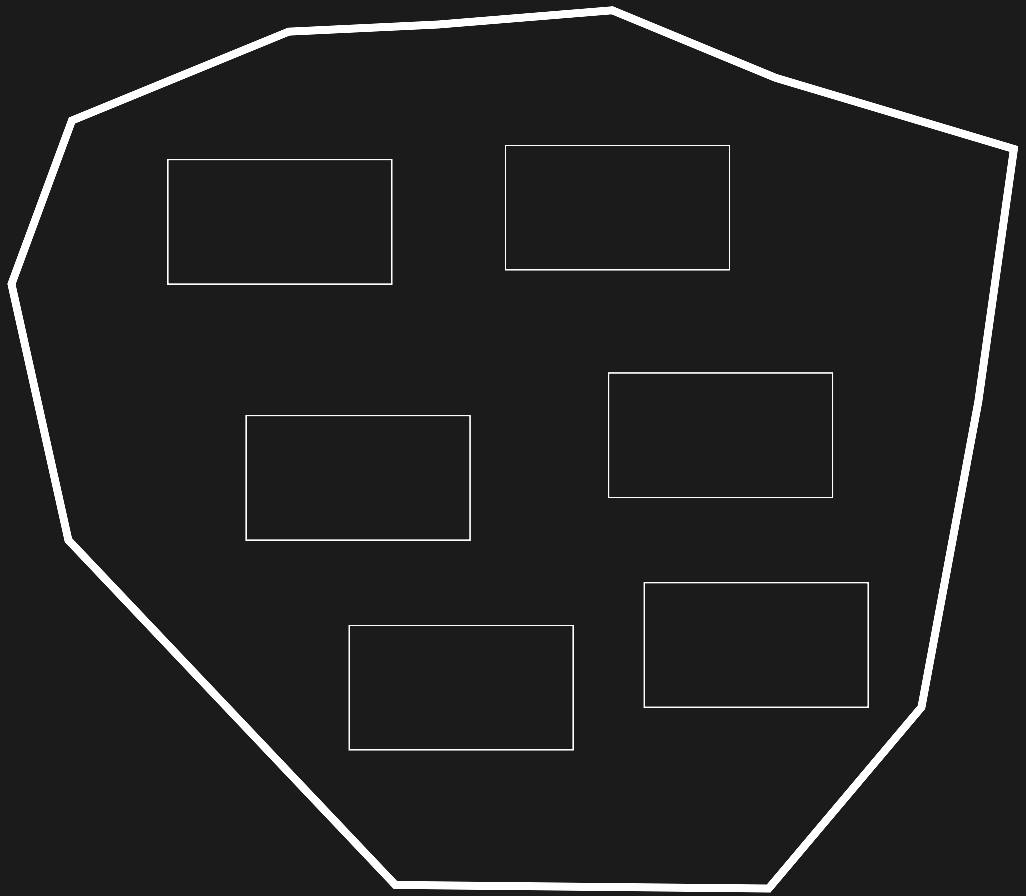
Modelling of species distributions, range dynamics and communities under imperfect detection: advances, challenges and opportunities

Gurutzeta Guillera-Arroita

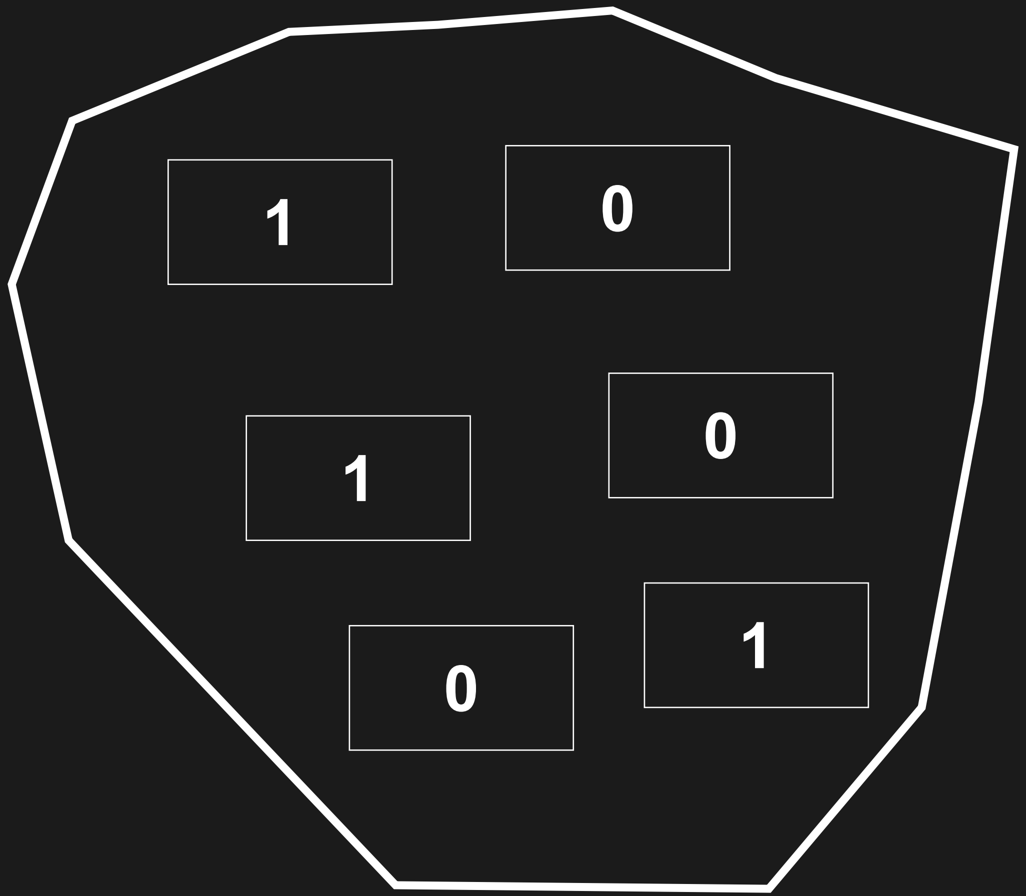
First published: 20 June 2016 | https://doi.org/10.1111/ecog.02445 | Citations: 134

Occupancy protocol



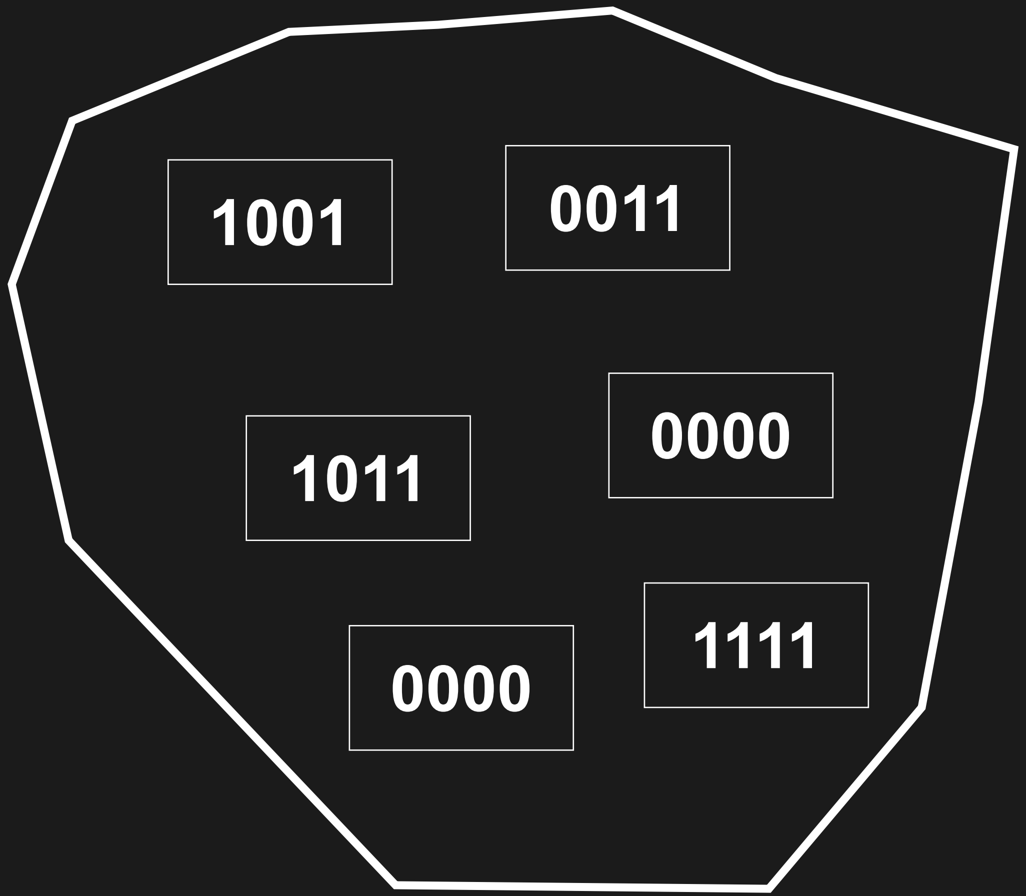
- Several sampling units surveyed

Occupancy protocol



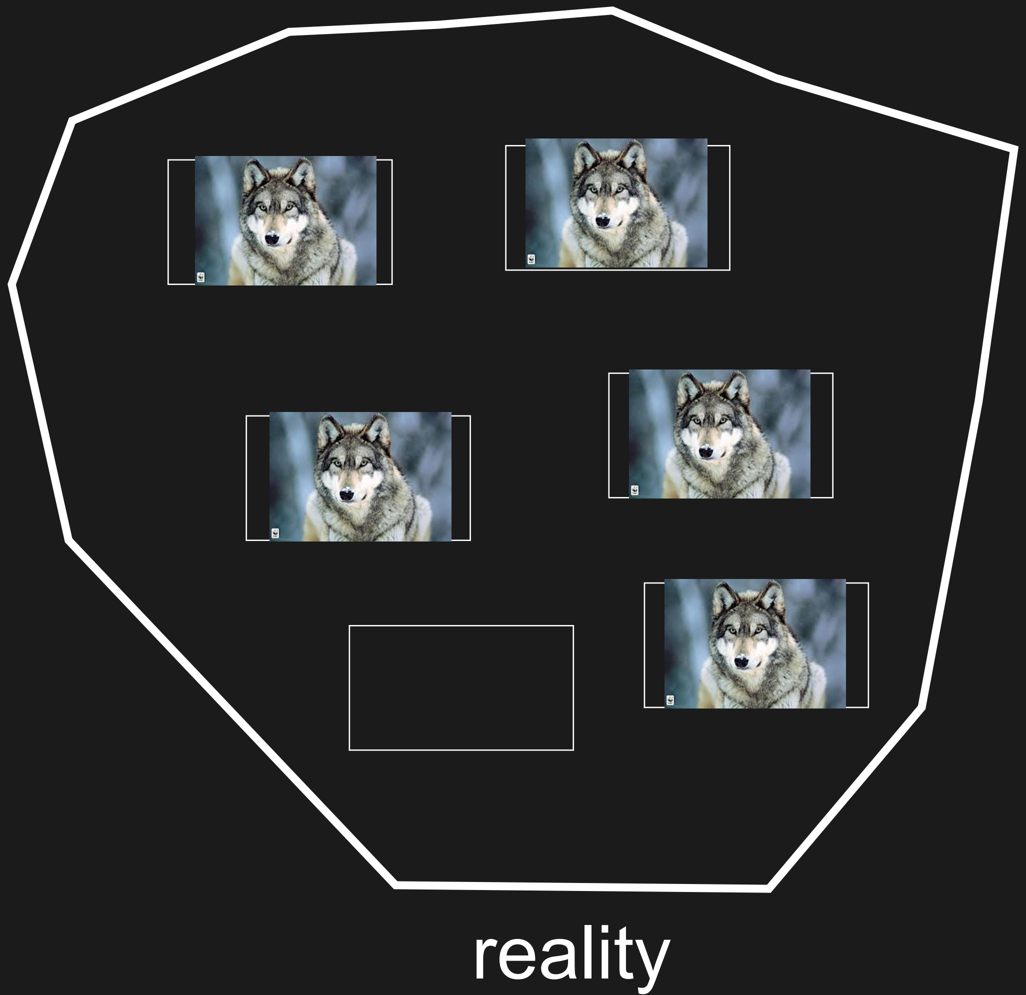
- Several sampling units surveyed
- Collection of detection/non-detection

Occupancy protocol



- Several sampling units surveyed
- Collection of detection/non-detection
- Replicate surveys in each unit

True or false absence?



True or false absence?

True or false absence?

reality

observation

True or false absence?

reality

observation

Lecture 2

Static aka single-season occupancy models

Single-season occupancy model likelihood

$\psi_1 =$ prob. a site is initially occupied - **occupancy**

p = prob. species is detected (given presence) – **detection**

Single-season occupancy model likelihood

$\psi_1 =$ prob. a site is initially occupied - **occupancy**

p = prob. species is detected (given presence) – **detection**

Assuming closure, and independence of surveys:

Pr(1001) = $?$

Single-season occupancy model likelihood

$\psi_1 =$ prob. a site is initially occupied - **occupancy**

p = prob. species is detected (given presence) – **detection**

Assuming closure, and independence of surveys:

Pr(1001) = ψ_1 p (1 – p) (1 – p) p

Single-season occupancy model likelihood

$\psi_1 =$ prob. a site is initially occupied - **occupancy**

p = prob. species is detected (given presence) – **detection**

Assuming closure, and independence of surveys:

Pr(0000) = $?$

Single-season occupancy model likelihood

$\psi_1 =$ prob. a site is initially occupied - **occupancy**

p = prob. species is detected (given presence) – **detection**

Assuming closure, and independence of surveys:

$\Pr(0000) = \psi_1\,(1 - p)\,(1 - p)\,(1 - p)\,(1 - p) + (1 - \psi_1)$

Single-season occupancy model

Initial states

$$\begin{array}{cc} U & O \\ \end{array}$$
$$\begin{pmatrix} 1-\psi_1 & \psi_1 \end{pmatrix}$$

O = occupied; U = unoccupied

ψ_1 = occupancy, p = detection

Single-season occupancy model

Initial states

$$\begin{array}{cc} U & O \\ (\,1-\psi_1 & \psi_1\,) \end{array}$$

State process

$$\begin{array}{ccc} & \begin{array}{cc} U & O \end{array} & \text{t+1} \\ \text{t} & \begin{array}{c} U \\ O \end{array} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & \end{array}$$

Markov model

O = occupied; U = unoccupied

ψ_1 = occupancy, p = detection

Single-season occupancy model

Initial states

$$\begin{array}{cc} U & O \\ (1-\psi_1 & \psi_1) \end{array}$$

State process

$$\begin{array}{ccc} & U & O \quad \textbf{t+1} \\ \textbf{t} \quad \begin{array}{c} U \\ O \end{array} & \multicolumn{2}{c}{\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}} \end{array}$$

Markov model

Observation process

$$\begin{array}{ccc} & 0 & 1 \quad \textbf{t} \\ \textbf{t} \quad \begin{array}{c} U \\ O \end{array} & \multicolumn{2}{c}{\begin{pmatrix} 1 & 0 \\ 1-p & p \end{pmatrix}} \end{array}$$

hidden

O = occupied; U = unoccupied

ψ_1 = occupancy, p = detection

Key occupancy model assumptions

- Independent detections
- No unmodelled heterogeneity
- No false positives

Live demo

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Mapping and explaining wolf recolonization in France using dynamic occupancy models and opportunistic data

Julie Louvrier, Christophe Duchamp, Valentin Lauret, Eric Marboutin, Sarah Cubaynes, Rémi Choquet, Christian Miquel, Olivier Gimenez

Covariates

blabla

blabla

Lecture 3

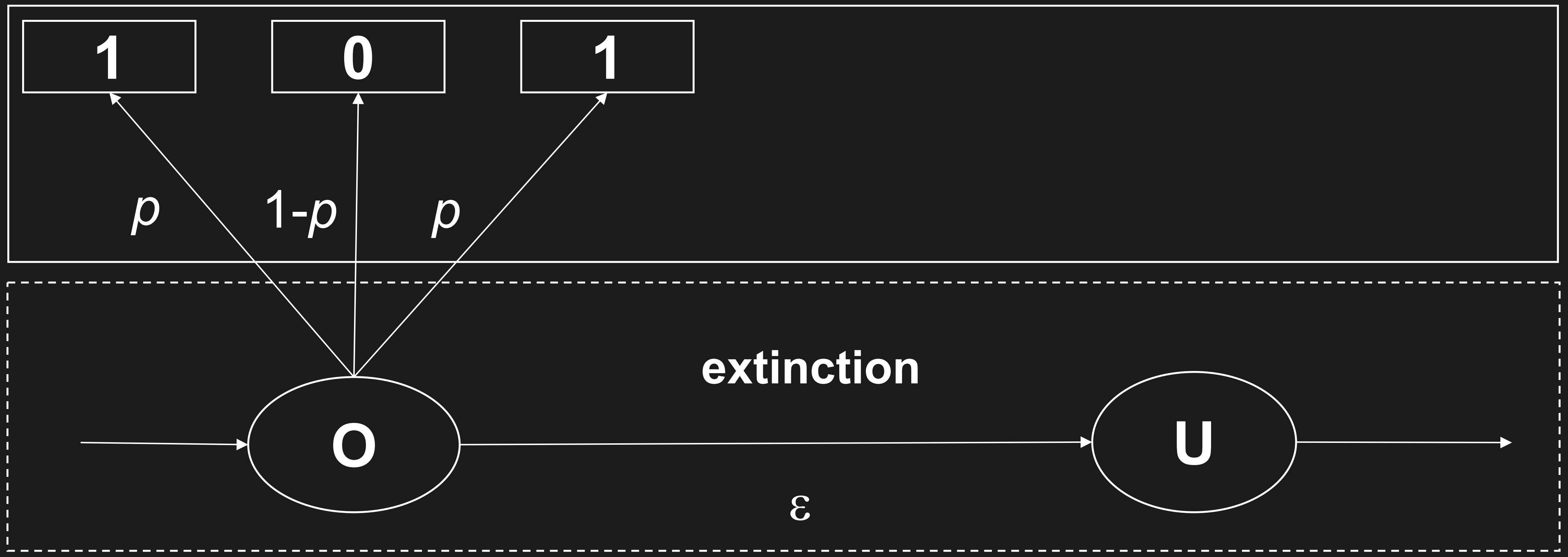
Dynamic aka multiple-season occupancy models

Dynamic (multi-season) occupancy models

O = occupied; U = unoccupied

Dynamic (multi-season) occupancy models

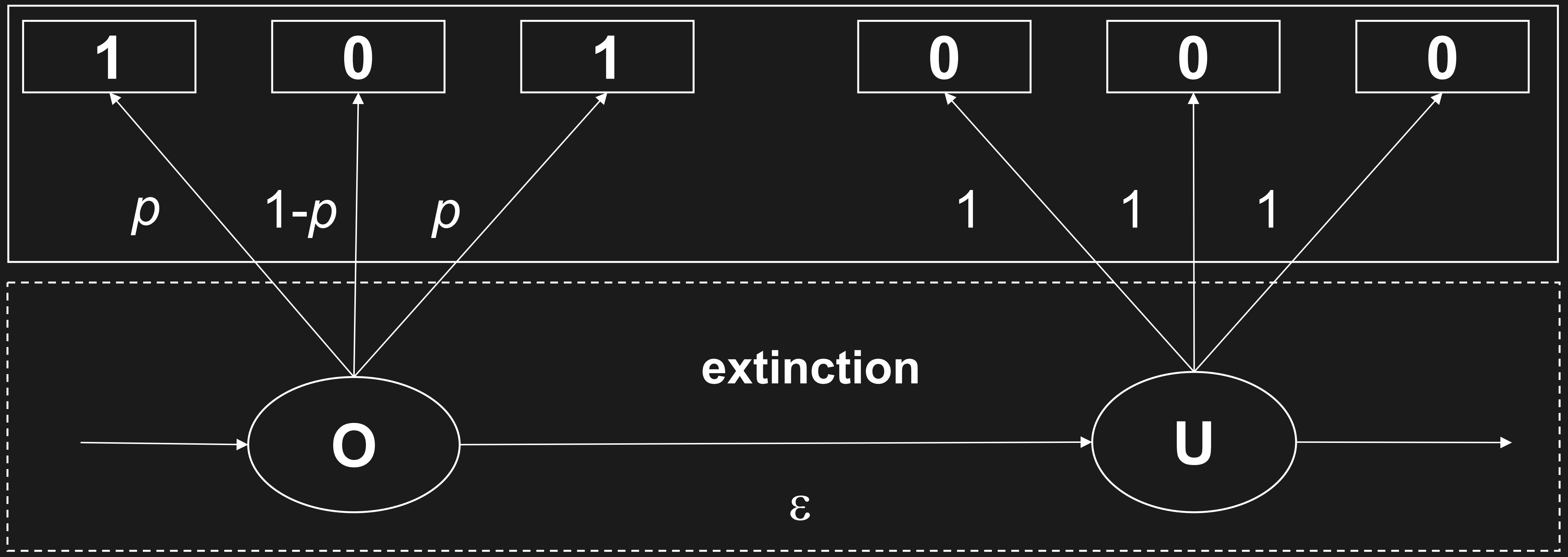
1 = species detected; 0 = species undetected



O = occupied; U = unoccupied

Dynamic (multi-season) occupancy models

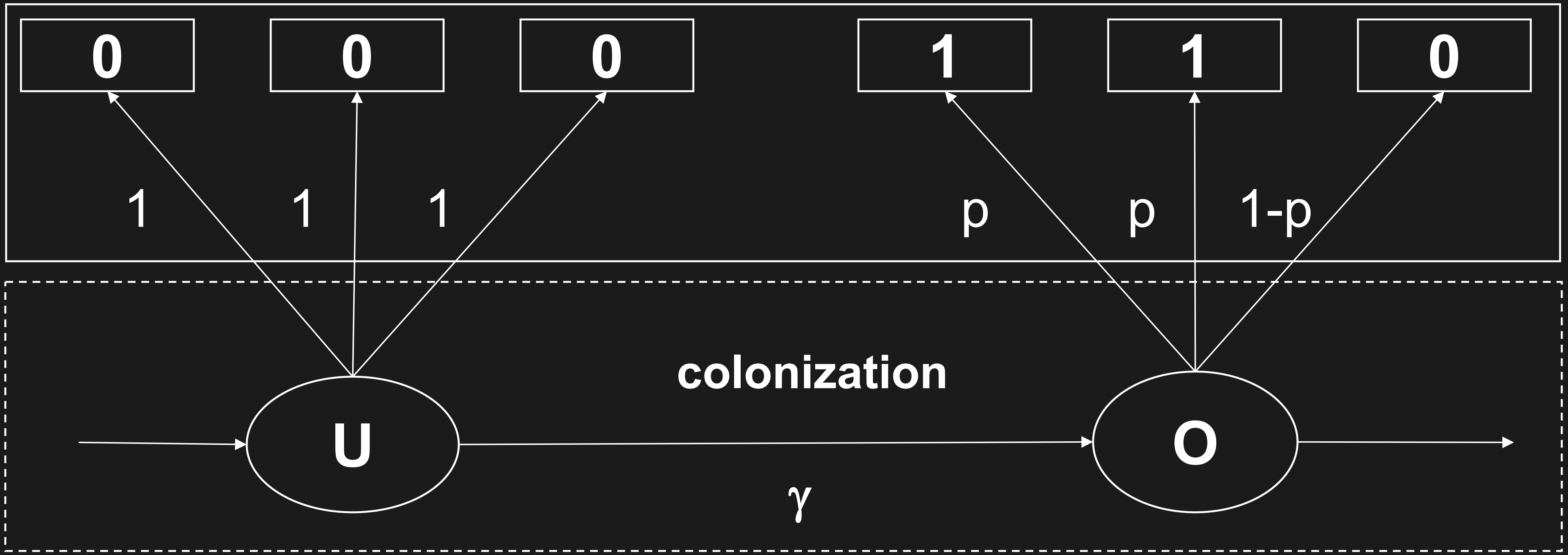
1 = species detected; 0 = species undetected



O = occupied; U = unoccupied

Dynamic (multi-season) occupancy models

1 = species detected; 0 = species undetected



O = occupied; U = unoccupied

Dynamic (multi-season) occupancy models

ψ_1 = prob. a site is occupied - **occupancy**

p = prob. species is detected (given presence) – **detection**

γ = prob. unoccupied site becomes occupied – **colonisation**

ε = prob. occupied site becomes unoccupied – **extinction**

Dynamic occupancy model likelihood

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

Pr(110 000) = ?

Dynamic occupancy model likelihood

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

Pr(110 000) =

Three replicated surveys or secondary occasions
Closure assumption

Dynamic occupancy model likelihood

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

$\Pr(110\ 000) = \psi_1\, p\, p\, (1 - p)$

Three replicated surveys or secondary occasions
Closure assumption

Dynamic occupancy model likelihood

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

$$\Pr(110\ 000) = \psi_1\, p\, p\, (1 - p)\ [\ \varepsilon + (1 - \varepsilon)\ \ldots\ ]$$

Dynamic occupancy model likelihood

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

$$\Pr(110\ 000) = \psi_1\, p\, p\, (1 - p)\, [\, \varepsilon + (1 - \varepsilon)\, (1 - p)\, (1 - p)\, (1 - p)\,]$$

Dynamic occupancy model likelihood

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

Pr(000 010) = ?

Dynamic occupancy model likelihood

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

$$\Pr(000\ 010) = [\ \psi_1\ (1 - p)\ (1 - p)\ (1 - p)\ (1 - \varepsilon) + (1 - \psi_1)\ \gamma\ ]$$

Dynamic occupancy model likelihood

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

$$\Pr(000\ 010) = [\ \psi_1 (1 - p)(1 - p)(1 - p)(1 - \varepsilon) + (1 - \psi_1)\gamma\ ] \\ \times (1 - p)\, p\, (1 - p)$$

Derived parameters

ψ_1 = **occupancy**

p = **detection**

γ = **colonisation**

ε = **extinction**

- Season-specific occupancy:

$$\psi_{t+1} = \psi_t (1 - \varepsilon_t) + (1 - \psi_t) \gamma_t$$

- Rate of change in occupancy:

$$\lambda_t = \psi_{t+1} / \psi_t$$

Dynamic occupancy model

Initial states	State process	Observation process
$\begin{array}{cc} U & O \\ \big(1-\psi_1 & \psi_1 \big) \end{array}$	$\begin{array}{c c} & \begin{array}{cc} U & O \end{array} \\ \begin{array}{c} U \\ O \end{array} & \begin{pmatrix} 1-\gamma & \gamma \\ \epsilon & 1-\epsilon \end{pmatrix} \end{array}$	$\begin{array}{c c} & \begin{array}{cc} 0 & 1 \end{array} \\ \begin{array}{c} U \\ O \end{array} & \begin{pmatrix} 1 & 0 \\ 1-p & p \end{pmatrix} \end{array}$
	Markov model	hidden

Single-season is a particular case of multi-season

No colonization ($\gamma = 0$) and no extinction ($\varepsilon = 0$)

Initial states

$$\begin{array}{cc} U & O \\ \end{array}$$
$$\begin{pmatrix} 1-\psi_1 & \psi_1 \end{pmatrix}$$

State process

$$\begin{array}{c|cc} & U & O \\ \hline U & 1 & 0 \\ O & 0 & 1 \end{array}$$

Observation process

$$\begin{array}{c|cc} & 0 & 1 \\ \hline U & 1 & 0 \\ O & 1-p & p \end{array}$$

Live demo

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Lecture 4

Occupancy models with species misidentification

Estimating wolf occupancy with R

Species misidentification

OPEN ACCESS Freely available online 2013 PLOS ONE

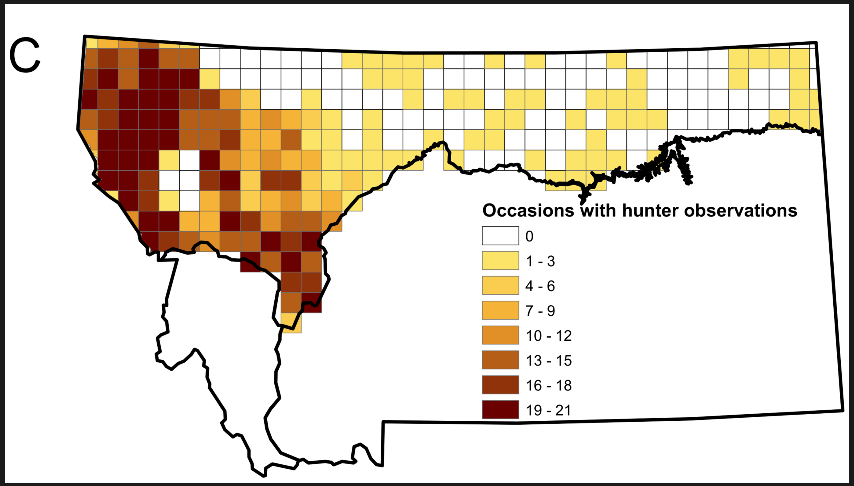
Determining Occurrence Dynamics when False Positives Occur: Estimating the Range Dynamics of Wolves from Public Survey Data

David A. W. Miller[1,2*], James D. Nichols[1], Justin A. Gude[3], Lindsey N. Rich[4], Kevin M. Podruzny[3], James E. Hines[1], Michael S. Mitchell[4]

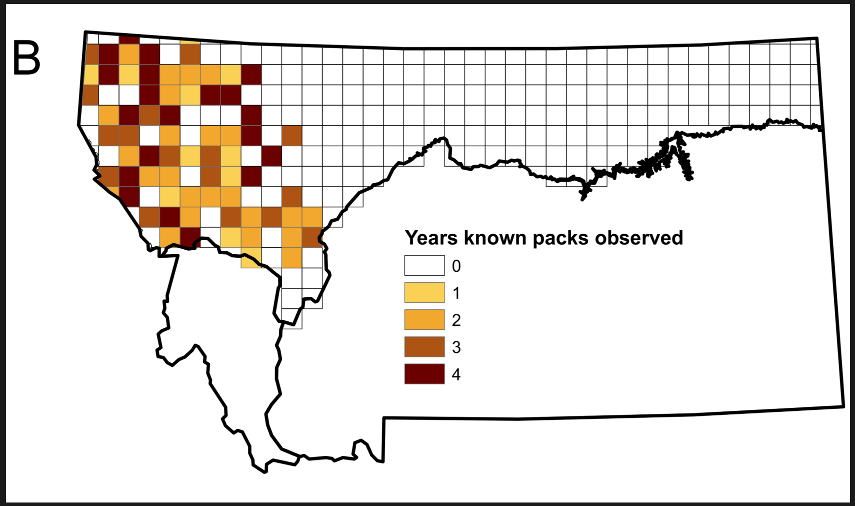
- How to account for false positives due to species misidentification?

Data

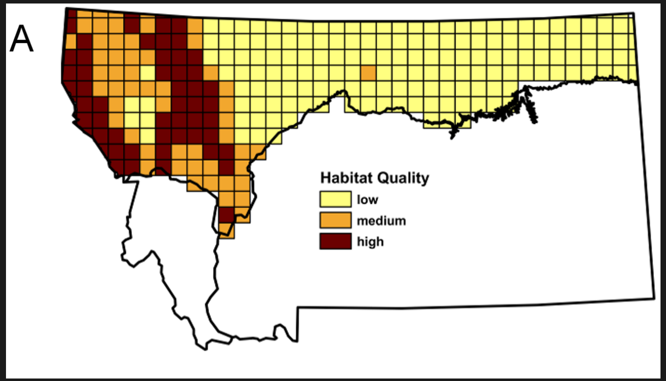
Observations by hunters (phone interviews);
uncertainty in species identification



Telemetry;
no doubt about species



Habitat quality



Reminder: static occupancy model

Initial states

$$\begin{array}{cc} U & O \\ \end{array}$$
$$\begin{pmatrix} 1-\psi_1 & \psi_1 \end{pmatrix}$$

State process

$$\begin{array}{c|c} & \begin{array}{cc} U & O \end{array} \\ \begin{array}{c} U \\ O \end{array} & \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \end{array}$$

Observation process

$$\begin{array}{c|c} & \begin{array}{cc} 0 & 1 \end{array} \\ \begin{array}{c} U \\ O \end{array} & \begin{pmatrix} 1 & 0 \\ 1-p & p \end{pmatrix} \end{array}$$

Model allowing for false positives

Observation process

0

1

2

Uncertain detection

Detection with no doubt about the species

Model allowing for false positives

Observation process

$$\begin{array}{cccc} & 0 & 1 & 2 \\ U & \big(1 - p_{10} & p_{10} & 0 \big) \end{array}$$

p_{10} = probability of false positive detection

Model allowing for false positives

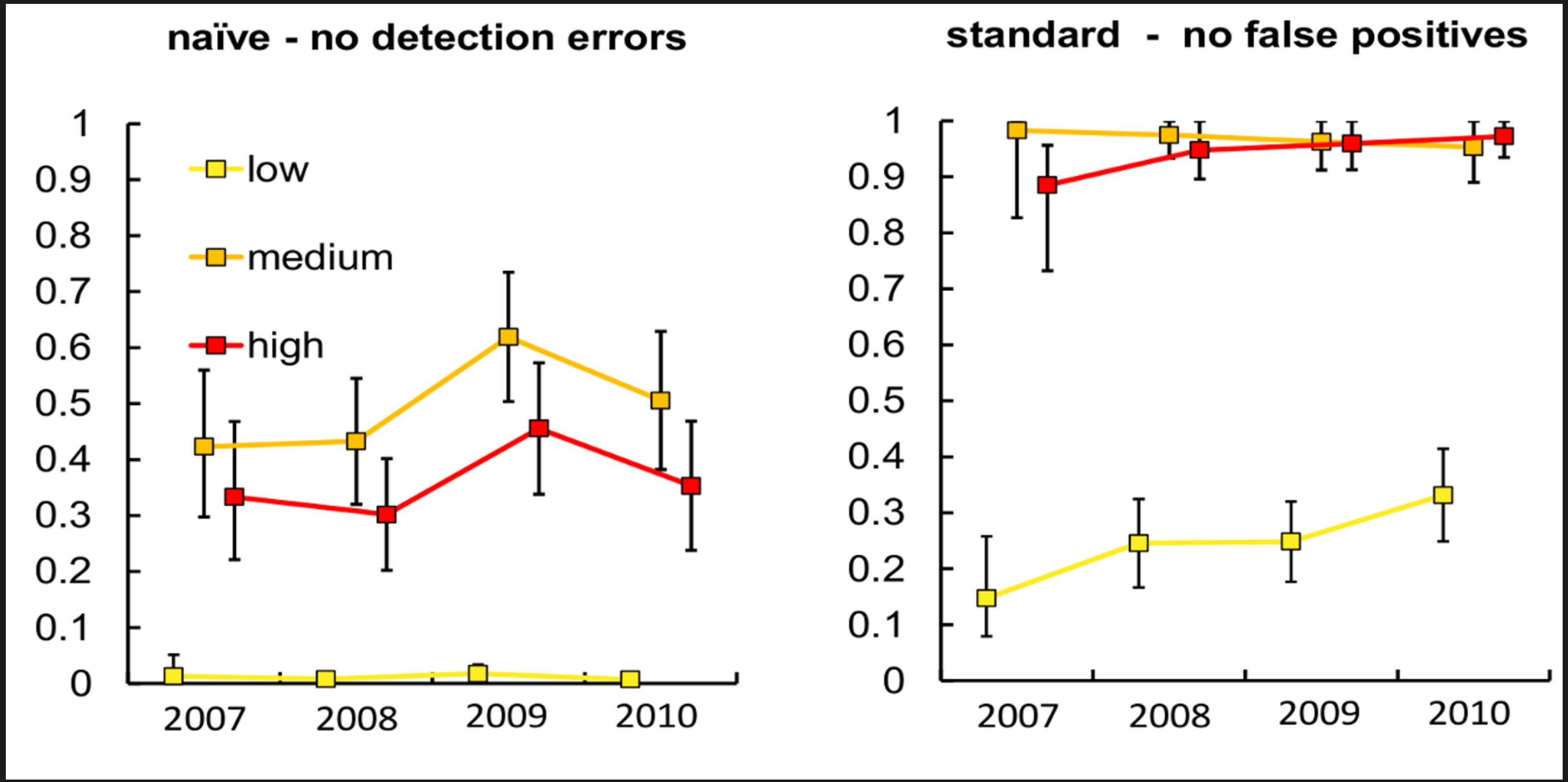
Observation process

$$
\begin{array}{cccc}
 & 0 & 1 & 2 \\
\begin{array}{c} U \\ O \end{array} & \multicolumn{3}{c}{\left(\begin{array}{ccc} 1 - p_{10} & p_{10} & 0 \\ 1 - p_{11} & (1 - b)p_{11} & bp_{11} \end{array}\right)}
\end{array}
$$

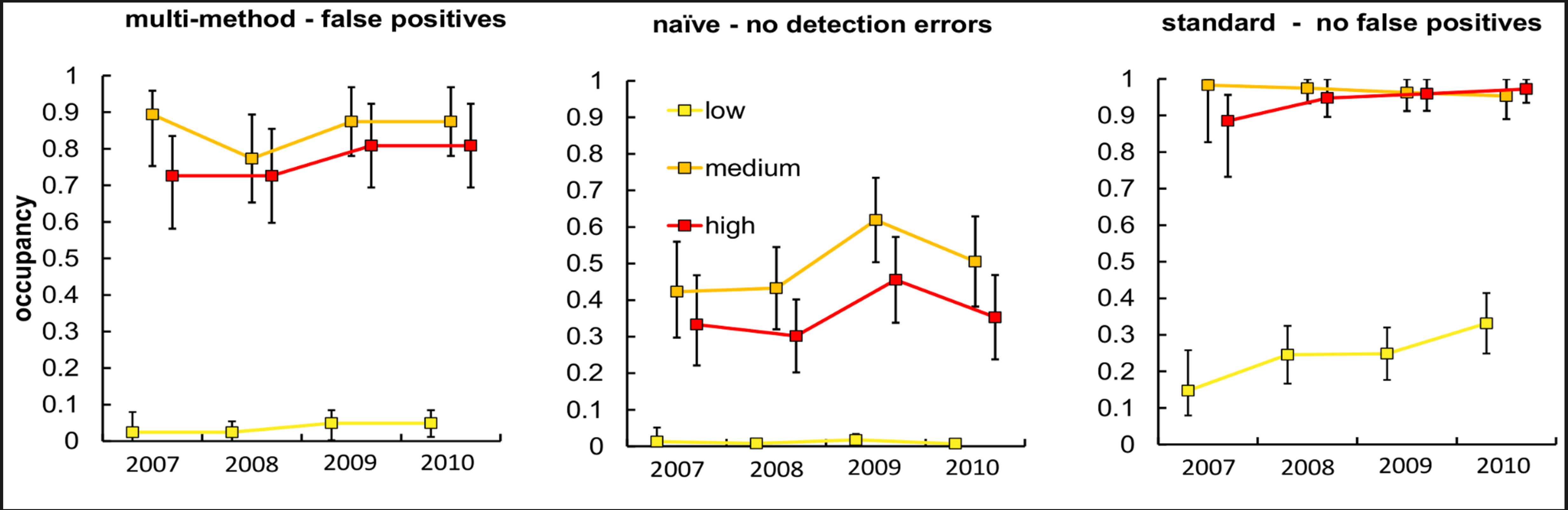
p_{11} = probability of detection

b = probability that a detection is classified as unambiguous

Estimates of occupancy for gray wolves in northern Montana from 2007–2010



Estimates of occupancy for gray wolves in northern Montana from 2007–2010



Live demo

Lecture 5

Estimating co-occurrence of interacting species

Rationale

- Several (say 2) different species on a site
- Interactions affect occupancy probabilities
- Detection of a species affected by presence of another one: blurred interactions
- Examples: predation, mutualism, competition, …
- Occupancy of a species when other species is present?

States

U = site unoccupied
A = site occupied by species A only
B = site occupied by species B only
AB = site occupied by both species

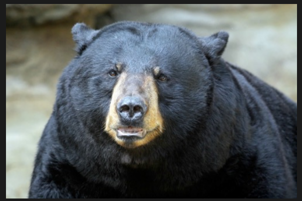
State process

ψ^{A} = prob. a site is occupied by species A

ψ^{B} = prob. a site is occupied by species B

ψ^{AB} = prob. a site is occupied by species A and B

Venn diagram



Occupied by species A only

$\psi^{A} - \psi^{AB}$

Occupied by both species

ψ^{AB}

Occupied by species B only

$\psi^{B} - \psi^{AB}$

Site unoccupied with prob.: $1 - \psi^{A} - \psi^{B} + \psi^{AB}$

Events

0 = species undetected
1 = A detected
2 = B detected
3 = both species detected

Observation process

p^A = prob. detecting species A given only species A is present

p^B = prob. detecting species B given only species B is present

r^{AB} = prob. detecting both species A and B when both present

r^{Ab} = prob. detecting species A but not B when both present

r^{aB} = prob. detecting species B but not A when both present

r^{ab} = prob. detecting neither species when both present

Initial states

Initial states

$$\begin{array}{cccc} \text{U} & \text{A} & \text{B} & \text{AB} \\ \end{array}$$
$$\begin{bmatrix} 1-\Sigma & \psi^{A}-\psi^{AB} & \psi^{B}-\psi^{AB} & \psi^{AB} \end{bmatrix}$$

State process

State process

$$
\begin{array}{c c}
 & \begin{array}{cccc} U & A & B & AB \end{array} \\
\begin{array}{c} U \\ A \\ B \\ AB \end{array} & \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{array}
$$

Observation process

Observation process

$$\begin{array}{c|c}
 & \begin{matrix} 0 & 1 & 2 & 3 \end{matrix} \\
\begin{matrix} \text{U} \\ \text{A} \\ \text{B} \\ \text{AB} \end{matrix} & \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1-p^{A} & p^{A} & 0 & 0 \\ 1-p^{B} & 0 & p^{B} & 0 \\ 1-\Sigma & r^{Ab} & r^{aB} & r^{AB} \end{bmatrix}
\end{array}$$

Quantifying interactions

Interaction estimated by: $\eta = \psi^{AB} / (\psi^{A} \psi^{B})$

$\eta < 1$ – avoidance (less frequent than expected)

$\eta > 1$ – convergence (more frequent than expected)

$\eta = 1$ – independence ($\psi^{AB} = \psi^{A} \psi^{B}$)

Alternative parameterization

- Introduce conditional probabilities

$$\psi^{A|B} = \text{prob. a site is occupied by A given presence of B}$$

$$\psi^{A|\overline{B}} = \text{prob. a site is occupied by A given absence of B}$$

$$\psi^{B} = \text{prob. a site is occupied by B}$$

Initial states

Initial states, in 2 steps

$$\begin{array}{cc} \text{no-B} & \text{B} \\ \left[\begin{matrix} 1-\psi^{B} \end{matrix}\right. & \left.\begin{matrix} \psi^{B} \end{matrix}\right] \end{array}$$

$$\begin{array}{cccc} \text{U} & \text{A} & \text{B} & \text{AB} \end{array}$$

$$\begin{bmatrix} 1-\psi^{A|\overline{B}} & \psi^{A|\overline{B}} & 0 & 0 \\ 0 & 0 & 1-\psi^{A|B} & \psi^{A|B} \end{bmatrix}$$

Testing interactions

- A and B independent?

Compare:

model in which $\psi^{A|B} \neq \psi^{A|\overline{B}}$ vs.

model in which $\psi^{A|B} = \psi^{A|\overline{B}}$

Live demo

Lecture 6

Conclusions

Conclusions

1. We covered several occupancy models
   - Single-season, dynamic models
   - False-positives
   - Species interactions

Conclusions

1. We covered several occupancy models
   - Single-season, dynamic models
   - False-positives
   - Species interactions

2. Implementation in R using package *unmarked*

We did not cover…

- How to choose sites? Occasions?
  - site selection
  - allocation of effort
  - design comparisons
  - survey timing

Journal of Applied Ecology 2005
42, 1105–1114

METHODOLOGICAL INSIGHTS

Designing occupancy studies: general advice and allocating survey effort

DARRYL I. MACKENZIE* and J. ANDREW ROYLE†
**Proteus Wildlife Research Consultants, PO Box 5193, Dunedin, New Zealand; †US Geological Survey, Patuxent Wildlife Research Center, 12100 Beech Forest Road, Laurel, MD 20708–4017, USA*

Assessing the Fit of Site-Occupancy Models

Darryl I. MacKenzie and Larissa L. Bailey

Journal of Agricultural, Biological, and Environmental Statistics, Volume 9, Number 3, Pages 300–318
DOI: 10.1198/108571104X3361

- Goodness-of-fit testing
- A few other models…
  - habitat and species occurrence dynamics, multistate, heterogeneity, …