Spatial occupancy models with the spOccupancy R package

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Overview

- Overview of occupancy modeling and spatial modeling
- spOccupancy functionality
- spOccupancy syntax and example: single-species and multi-species spatial occupancy models
- Q&A

Motivation

- Species distribution modeling
  - Where do species occur and how does this change over time?
  - What drives species distributions?
- Two key complexities when modeling species distributions
  - Imperfect detection
  - Spatial autocorrelation

Imperfect Detection

How do we account for imperfect detection?

- Occupancy modeling
- Basic idea: perform multiple surveys (i.e., visits) at each site
- Multiple visits give information on detection probability
- Allows us to separately estimate occupancy probability from detection probability

Detection-nondetection matrix

Site	Survey 1	Survey 2	Survey 3	Survey 4
1	1	0	0	1
2	0	0	0	0
3	1	1	0	NA
4	1	NA	0	NA
5	0	1	1	1
6	0	0	0	1

Occupancy model: what is it?

- Two distinct sub-models
  - Model occupancy probability as a function of site-level covariates
  - Model detection probability as a function of site and/or survey-level covariates
    - Can only detect a species if it truly occupies a site
    - Detection probability is modeled "conditional" on true occupancy

Single-species occupancy model

$j = 1, \dots, J$ (site)

$k = 1, \dots, K_j$ (replicate)

Occupancy (ecological) sub-model

$$z_j \sim \text{Bernoulli}(\psi_j)$$
$$\text{logit}(\psi_j) = \beta_1 + \beta_2 \cdot X_{2,j} + \cdots + \beta_r \cdot X_{r,j}$$

Detection (observation) sub-model

$$y_{j,k} \sim \text{Bernoulli}(p_{j,k} \cdot z_j)$$
$$\text{logit}(p_{j,k}) = \alpha_1 + \alpha_2 \cdot V_{2,j,k} + \cdots + \alpha_r \cdot V_{r,j,k}$$

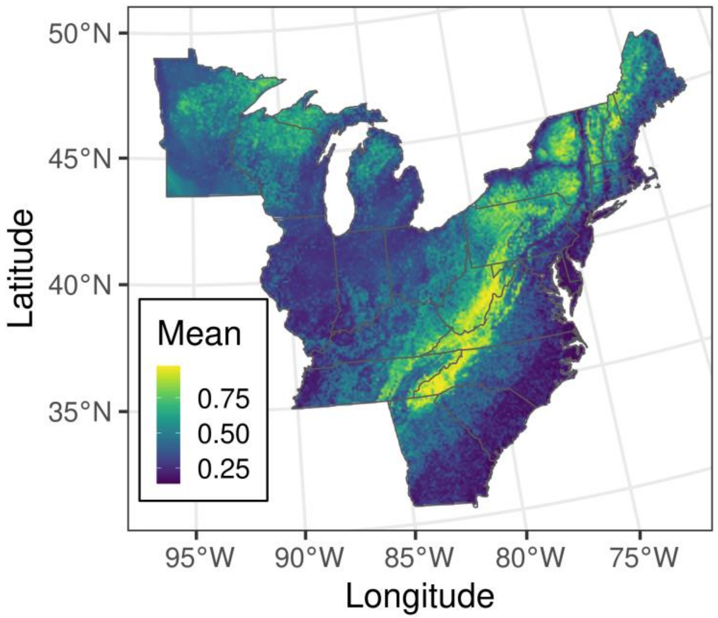
Multi-species occupancy models

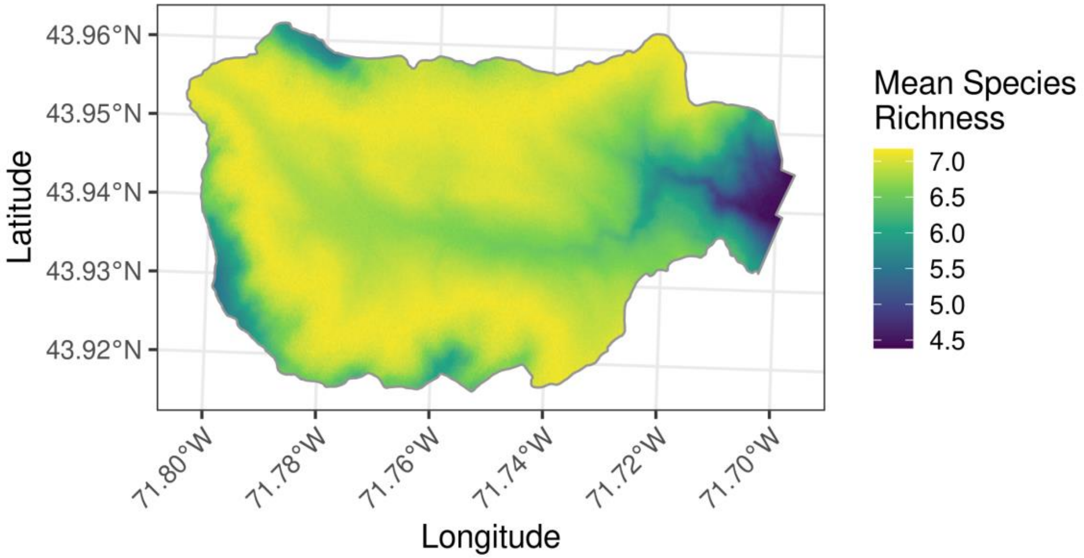
- Two flavors in spOccupancy:
  - Dorazio-Royle multi-species (community) occupancy models
    - Spatial and non-spatial
  - Joint species distribution models with imperfect detection
    - Spatial and non-spatial
    - Account for species correlations using factor modeling (Doser, Finley, Banerjee 2022)

Site	Survey 1	Survey 2	Survey 3	Survey 4
1	1	0	0	1
2	0	0	0	0
3	1	1	0	NA
4	1	NA	0	NA
5	0	1	1	1
6	0	0	0	1

Spatial autocorrelation

- Things closer together in space tend to be more similar than things further apart
- What leads to spatial autocorrelation in species distributions?
  - Environmental drivers, habitat requirements
  - Biotic factors (dispersal, conspecific attraction)
- Initial approach: attempt to explain spatial variation in species distributions with covariates (e.g., forest cover, temperature, elevation)





Residual spatial autocorrelation

- Spatial correlation in data *after* including spatial covariates
- Often arises from missing/unavailable covariates
- Can lead to bias if unaddressed
- Account for using spatial random effects
  - Each site has a local adjustment in occupancy probability
  - The local adjustments are given a spatial structure
  - Estimated parameters: spatial variance and spatial decay
  - Caution: spatial confounding (Hanks et al. 2015)

Single-species spatial occupancy model

$$j = 1, \ldots, J \text{ (site)}$$
$$k = 1, \ldots, K_j \text{ (replicate)}$$

Occupancy (ecological) sub-model

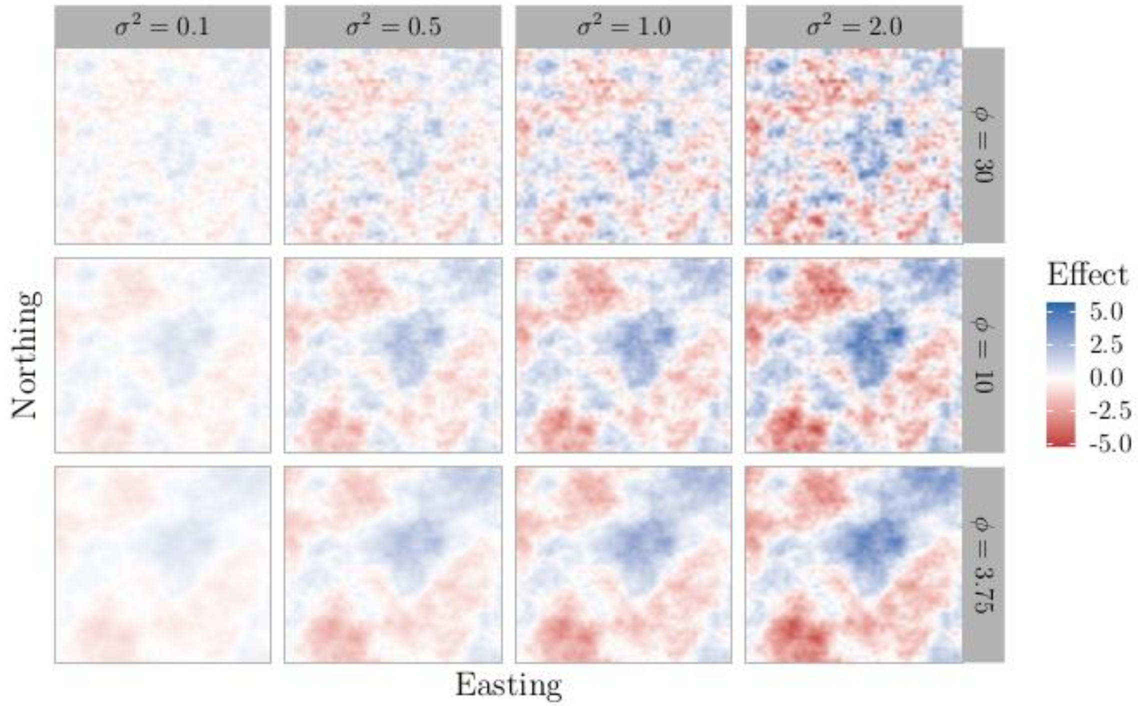
$$z_j \sim \text{Bernoulli}(\psi_j)$$
$$\text{logit}(\psi_j) = \beta_1 + \beta_2 \cdot X_{2,j} + \cdots + \beta_r \cdot X_{r,j} + \text{w}_j$$
$$\text{w}_j \sim \text{Normal}(0, \boldsymbol{\Sigma})$$

Detection (observation) sub-model

$$y_{j,k} \sim \text{Bernoulli}(p_{j,k} \cdot z_j)$$
$$\text{logit}(p_{j,k}) = \alpha_1 + \alpha_2 \cdot V_{2,j,k} + \cdots + \alpha_r \cdot V_{r,j,k}$$

Gaussian processes

- "Gold standard" for modeling spatial data
- Spatial correlation function determines structure
- Downside: computationally intensive for big data
- Alternative: Nearest Neighbor Gaussian Processes (Datta et al. 2016, Doser et al. 2022)



spOccupancy

- Designed to fit a variety of Bayesian occupancy models
- Efficiently accommodates spatial autocorrelation
- Workflow completely in R using standard model syntax (no Bayesian programming languages necessary)
- Key functionality:
  - Single-species models
  - Multi-species models with options to account for species correlations
  - Data integration
  - Multi-season (spatio-temporal) models

Why Bayesian for occupancy modeling?

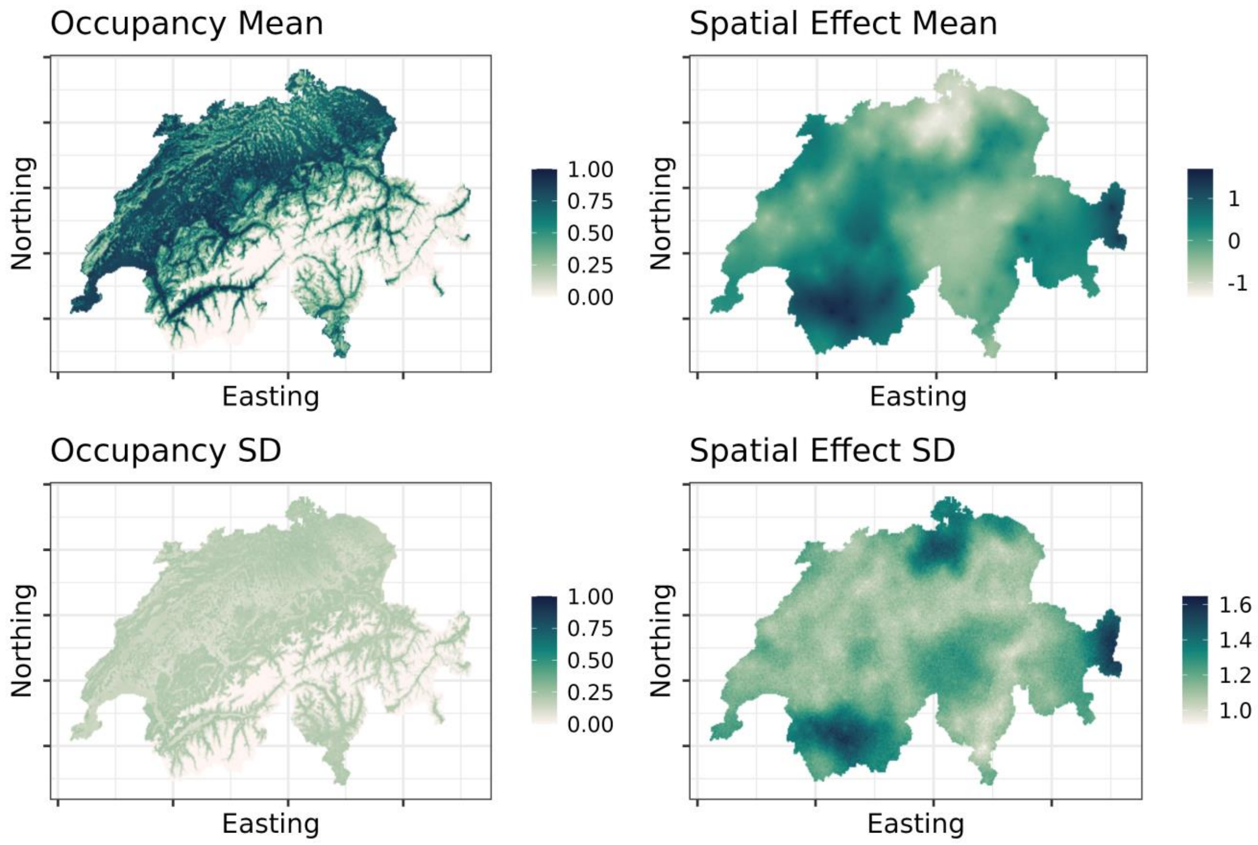
- Interpretation
- More flexible to accommodate spatial autocorrelation
- Easy to extend to multi-species frameworks/integrate multiple data sources
- Fully propagate uncertainty in all estimates (and derived quantities)

spOccupancy workflow

1. Data simulation/prep
2. Model fitting
3. Model validation
4. Model comparison
5. Posterior summaries
6. Prediction

Example dataset: Swiss MHB Survey

- Data from the Switzerland Breeding Bird Survey in 2014
- 266 survey locations distributed throughout Switzerland
- Single species (European Goldfinch) and multi-species models (20 species)



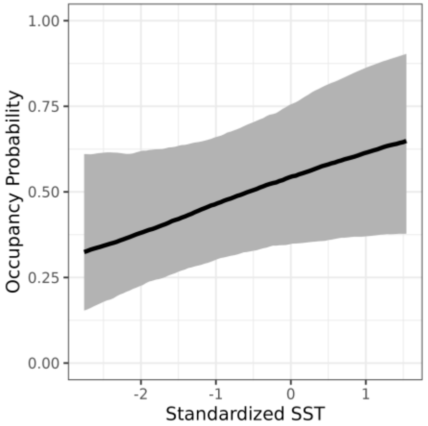
Additional examples

Single-species and multi-species occupancy models



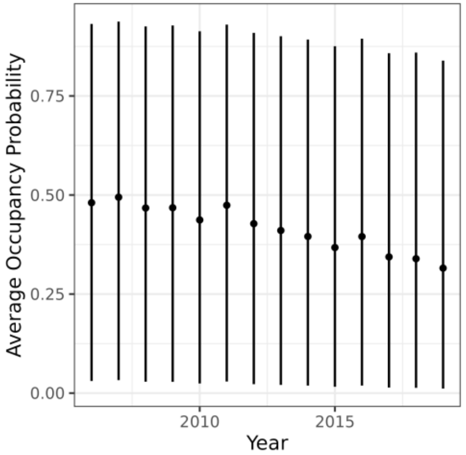
Amphibian community from Ribeiro Jr et al (2018) Eco Apps

Integrated occupancy model



Bottlenose dolphin data from Lauret et al. (2021) Ecology

Multi-season occupancy model



Eastern wood pewee data from Doser et al. (2021) Eco Apps

Coming soon...

- Spatially-varying coefficient occupancy models
- Multi-species spatio-temporal occupancy models
- Multi-species integrated occupancy models

spOccupancy

spOccupancy 0.4.0 Reference Articles Changelog Search for

Articles

Fit occupancy models

Introduction to spOccupancy
Learn how to get started with the core spOccupancy functionality

Formatting data for use in spOccupancy
Learn how to format raw data to fit occupancy models in spOccupancy

Joint species distribution models with imperfect detection in spOccupancy
Learn how to account for species correlations within multi-species occupancy models

Multi-season occupancy models for assessing species trends and spatio-temporal occurrence patterns (PDF)

Multi-season occupancy models for assessing species trends and spatio-temporal occurrence patterns
Learn how to fit multi-season occupancy models in spOccupancy

Fitting occupancy models with random intercepts in spOccupancy
Learn how to include random effects in spOccupancy

MCMC sampler details

MCMC samplers for models fit in spOccupancy (PDF)

MCMC samplers for joint species distribution models in spOccupancy (PDF)

On this page
- Fit occupancy models
- MCMC sampler details

- Package website
  - https://www.jeffdoser.com/files/spoccupancy-web/
- GitHub development page
  - https://github.com/doserjef/spOccupancy/
- MEE intro paper
- arXiv preprint
- @jeffdoser18
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Methods in Ecology and Evolution BRITISH ECOLOGICAL SOCIETY

APPLICATION

spOccupancy: An R package for single-species, multi-species, and integrated spatial occupancy models

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Joint species distribution models with imperfect detection for high-dimensional spatial data arXiv

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Thank you!