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Methods in Ecology and Evolution

APPLICATION

occupancyTuts: Occupancy modelling tutorials with RPresence

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Abstract

1. The occupancy modelling framework offers tremendous flexibility in estimating species abundance and distribution patterns while accounting for imperfect detection, and has seen rapid growth and adoption since its introduction at the beginning of the century.
2. At the same time, in an era of big data, there are increasing demands on developing quantitative skills and proficiency in young ecologists, many of whom lack the quantitative training needed to conduct research professionally.
3. We introduce *occupancyTuts*, an R package that features 28 *learnr* tutorials that teach the statistical underpinnings of several occupancy models. The tutorials include written content, instructional videos, R exercises, and quiz elements, covering a range of topics including statistical underpinnings, single- and dynamic-occupancy models, study design and several of the 'spin-off' models that extend the basic framework.
4. We plan for development of new tutorials that use *RPresence* as the analysis engine, and welcome new tutorial contributions that use other *R* packages as the analysis engine as well.

KEYWORDS
hierarchical modelling, *learnr*, occupancy modelling, *RPresence*, species distribution modelling

1 | INTRODUCTION

Understanding how species are distributed in both space and time are central questions in ecology. Abundance, distribution and species richness patterns are 'state' variables that describe an ecological system of interest (Figure 1, adapted from Kéry and Royle (2020)). These state variables are often unknown but are, for any number of reasons, of interest to ecologists.

However, the true state of an ecological system is imperfectly observed by humans because survey methods are imperfect. That is, errors can arise when conducting surveys, such as missing a species that is actually present (a false negative), or mistaking one species for another (a false positive). Such errors can lead to parameter estimates that are significantly biased, hindering progress in characterising ecological systems and informing management decisions.

Occupancy modelling is the de facto method for estimating state patterns while correcting for imperfect detection (MacKenzie et al., 2018a). The approach is part of a broader class of models in ecology known as 'hierarchical models', where the analytic approach separates the estimation of the state (abundance, distribution, or richness) from the imperfect observation of that state.

The seminal single season occupancy model (MacKenzie et al., 2002) considers monitoring a target species at *N* sites, on which the target is present on a portion of them. Monitoring is replicated at each site *T* times, generating 'encounter histories' that consist of a vector of 0's and 1's denoting nondetection and detection,

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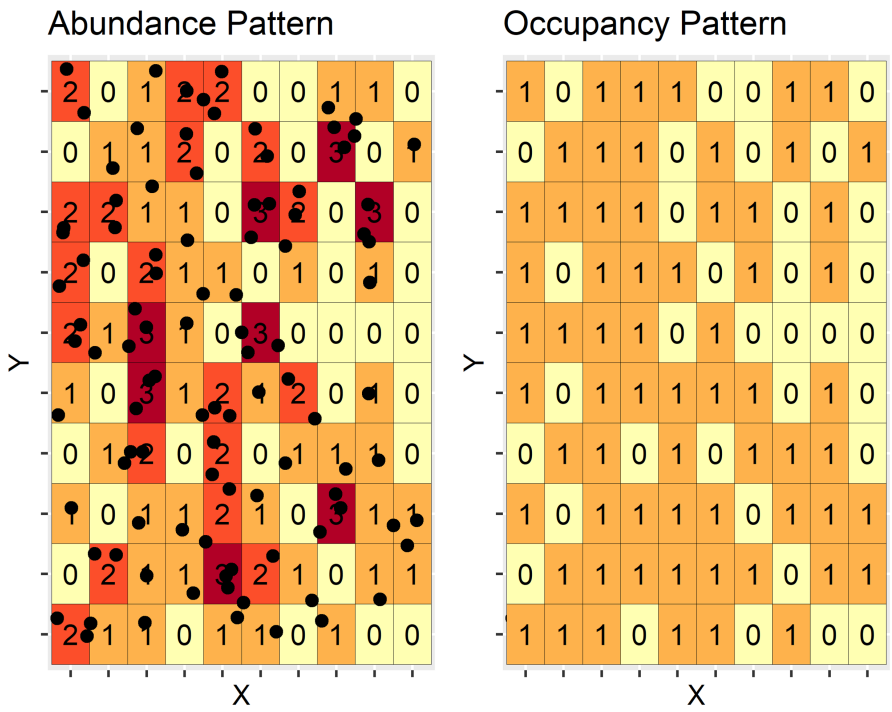

FIGURE 1 The difference between abundance and distribution, where dots represent individuals of a target species distributed in space. Imposed on this point distribution is a grid. In the left panel, the labels provide the abundance of individuals per grid cell, while the right panel's labels provide the distribution of the target species in terms of presence (1) or absence (0). The species richness state variable aggregates distribution across multiple species. Figure is adapted from Kéry and Royle (2020).

respectively, for each occasion on which the site was surveyed. For example, for a study in which three surveys are conducted at each site, a 010 history at a given site indicates that the species was not detected on the first survey, was detected on the second, and not detected on the third. From the pattern of 0's and 1's recorded in the field, the approach uses maximum likelihood or Bayesian methods to estimate the key parameters of interest: ψ (the probability of occupancy) and p_t, the probability of detecting a species on survey t given presence. Importantly, these parameters may be functions of covariates that influence occupancy and detection. As described by MacKenzie et al. (2002), the likelihood of the parameters (ψ and the vector of detection parameters, $\mathbf{p}$), given the data, is

$$L(\psi, \mathbf{p}) = \left[\psi^{n.} \prod_{t=1}^{T} p_t^{n_t} (1-p_t)^{n.-n_t}\right] \times \left[\psi \prod_{t=1}^{T} (1-p_t) + (1-\psi)\right]^{N-n.},$$

where the first term considers all sites where at least one detection was observed across surveys ($n.$), and the second term considers those sites where there were no detections ($N - n.$).

As the name implies, occupancy modelling typically focuses on uncovering species distribution patterns (presence-absence). After the influential paper by MacKenzie et al. (2002), there has been a remarkable surge in the creation and utilisation of models focused on estimating species occupancy patterns, all while accounting for imperfect detection (Bailey et al., 2014). A recent Web of Science search on the terms 'occupancy modelling' yielded >6600 peer reviewed journal articles and >7000 online resources (accessed 2023-06-27). These contributions include models that account for multiple seasons (MacKenzie et al., 2003), multiple occupancy states (MacKenzie et al., 2018b), multi-scale occupancy patterns (Nichols et al., 2008), species co-occurrence (MacKenzie et al., 2018d), and community level patterns (Dorazio & Royle, 2005; MacKenzie et al., 2018c), among others. Many extensions focus on the detection process, including species misidentification (Clement et al., 2019; Miller et al., 2011; Royle & Link, 2006), correlated detections (Hines et al., 2009), and the use of multiple survey methods (Nichols et al., 2008). An impressive span of research topics feature occupancy modelling at their core, including analysing change in bird distributions due to climate change (Clement et al., 2019) or deforestation (Ferraz et al., 2007), and mapping of dynamic species distribution patterns (Kéry et al., 2004). Additional studies use occupancy methods to estimate the prevalence of disease in animal populations (Chaudhary et al., 2020), the effect of poaching on animals of conservation concern (Moore et al., 2021) and the extinction rates of plants (Kéry, 2004). See Bailey et al. (2014) for additional examples.

One of the primary *R* packages for analysing occupancy data is *RPresence* (MacKenzie & Hines, 2023), which incorporates code from two additional software programs: (1) Program *Presence*, a Windows©-based program with a graphical user-interface (GUI) and (2) Program *GENPRES*, which generates simulated data for occupancy analysis and can be used as a design tool to determine the effort (number of sites and/or surveys) required to estimate occupancy or detection parameters with a certain level of precision (Bailey et al., 2007). *RPresence* was developed to analyse occupancy data with *R* (R Core Team, 2012) instead of the *Presence* or *GENPRES* GUIs. This package enables users to gather and edit data using *R* and run models with a function call and formulae for parameters. In other words, *R* is the 'front end' for sending analyses to *Presence or GENPRES*, which does the actual work and then returns the output to *R*.

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Additional software and *R* packages are available for occupancy analysis as well. For example, the packages *unmarked* (Fiske & Chandler, 2011), *spOccupancy* (Doser et al., 2022) and *ubms* (Kellner et al., 2021) provide tools for modelling species distribution and abundance patterns while accounting for measurement error. *RMark* (Laake, 2013) is another popular offering that uses *R* as a front end to the software *MARK* (White & Burnham, 2023), which provides tools for analysing distribution and capture-mark-recapture data.

Paired with the rapid rise in hierarchical modelling is a lack of quantitative training among early-career ecologists (Barraquand et al., 2014), potentially due to a lack of quantitative training (mathematics, statistics, and programming) at the graduate and undergraduate level (Cuddington et al., 2023). Surveys suggest that an astounding 75% of early career scientists in ecology do not feel satisfied with their understanding of models that are relevant to their own field of interest (Barraquand et al., 2014). The call for increased quantitative training has been echoed since the turn of the century (Anderson et al., 2003), growing louder as rapid developments in the sciences demand the use of advanced quantitative methods. Barraquand et al. (2014) emphasise 'With the increase in availability of advanced methods, quantitative training ought to focus on (i) understanding how these methods work and (ii) when to use them'. We suggest adding (iii) 'how to use and evaluate them' in light of recent calls to advance programming skills in students at any stage of their career (Feng et al., 2020; Juavinett, 2022).

In this article, we introduce *occupancyTuts* (Donovan et al., 2023), an R package featuring 28 *learnr* tutorials (Aden-Buie et al., 2023) that guide users through the theory and analysis of occupancy data with the package *RPresence*. The tutorials include written, instructional videos, R exercises, interactive Shiny components (Chang et al., 2022), and quiz elements that roughly accompany the book, 'Occupancy Estimation and Modeling' and the published papers that make up its foundation (MacKenzie et al., 2018a). In developing these tutorials, our aim was to provide hands-on quantitative training and show users how to run occupancy analyses in *R* on their computer.

2 | THE OCCUPANCYTUTS PACKAGE

occupancyTuts provides background and instructions for occupancy analysis with *RPresence*, which should be installed separately:

```
install.packages('RPresence', repo = 'https://eesc.usgs.gov/mbr/mbrCRAN')
```

Users should update *RPresence* to version ≥2.13.48, as well as ensure that R version 4.3.0 or higher is installed (to run the tutorials).

The canonical home of *occupancyTuts* is https://code.usgs.gov/vtcfwru/occupancyTuts/, where updated guidance on installation can be found and where users can post issues, create merge requests, and download development versions.

The current release can be installed from this site with the following code:

```
remotes::install_gitlab(
  repo = "vtcfwru/occupancyTuts@1.1.0",
  auth_token = Sys.getenv("GITLAB_PAT"),
  host = "code.usgs.gov",
  build_vignettes = FALSE,
  upgrade = "never")
```

The *occupancyTuts* package eventually will be available on the CRAN repository.

```
install.packages("occupancyTuts")
```

Once installed, *learnr*'s `available_tutorials()` function can be used to display a list of tutorials. Only the first 5 of 28 tutorials are shown below, listed alphabetically (see Data S1 for the full list of current tutorials).

```
learnr::available_tutorials(package = "occupancyTuts")[1:5,]
Available tutorials:
* occupancyTuts
  - binomial         : "occupancyTuts: Binomial Probability"
  - binomialR        : "occupancyTuts: Binomial Probability Functions in R"
  - design_matrices : "occupancyTuts: Design Matrices in RPresence"
  - eh               : "occupancyTuts: Encounter Histories"
  - gof              : "occupancyTuts: Goodness of fit test"
```

occupancyTuts includes 28 tutorials, roughly grouped into the following categories:

- Background and statistical theory—tutorials that introduce *learnr* tutorials and develop proficiency in probability mass functions (pmf) and likelihood, especially the binomial and multinomial pmf's that provide the statistical machinery behind many occupancy modelling approaches. Tutorials within this grouping include *intro*, *binomial*, *binomialR*, *multinomial* and *multinomialR*.
- Software—tutorials that introduce *RPresence* and discuss general optimisation methods for finding maximum likelihood estimates. Tutorials within this grouping include the *software* and *optimization* tutorials.
- Single season occupancy models—tutorials centered around the seminal single season occupancy paper (MacKenzie et al., 2002), how to wrangle data into encounter histories, how to include site and survey covariates into models, and how to evaluate different models with goodness of fit and model selection methods. Tutorials in this grouping include the *eh*, *wrangling*, *single_season*, *sitecovs*, *survcovs*, *spatials*, *design_matrices*, *gof* and *model_selection* tutorials.
- Single season spin-off models—tutorials that introduce extensions to the single season occupancy model, including models that consider correlated detections, false positives, unmodeled mixtures, multiple methods, or multiple occupancy states (*ss_corr_det*, *ss_false_pos*, *ss_mixture*, *ss_multi_method* and *ss_multistate* tutorials).

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- Study design—tutorials that teach how to design an occupancy study for a target species in terms of identifying the number of study sites and the number of repeat surveys needed to maximise precision (Bailey et al., 2007; MacKenzie & Royle, 2005). The primary tutorial in this grouping is the *study_design* tutorial.
- Multi-species models—tutorials that introduce models that estimate species co-occurrence (*ss_two_species*) or species richness (*ss_species_richness*).
- Multi-season (dynamic) occupancy model—tutorial that introduces the multi-season or dynamic occupancy model in which occupancy state changes through time (MacKenzie et al., 2003). This model is very popular for monitoring species status and trends while accounting for errors in detection. The primary tutorial is the *multi_season* tutorial. Extensions include models that consider false positives (*ms_false_positive*), multiple states (*ms_multi_state*) and species richness (*ms_species_richness*).

Tutorials can be accessed via the 'Tutorial' tab in RStudio by searching for tutorials with 'occupancyTuts' in the title, or can be launched via code. For example, the following code will launch the tutorial that introduces the single season occupancy model:

```
learnr::run_tutorial(
  name = "single_season",
  package = "occupancyTuts"
)
```

The `run_tutorial()` function launches the tutorial in the user's web browser, as shown in Figure 2. When launched, R is running an RShiny (Chang et al., 2022) application that 'listens' to commands or entries made within the tutorial itself, and will respond when called.

Each tutorial is divided into topics, which can be seen in the left menu. For any given tutorial, the first topic is 'Prerequisites', which identifies the preceding required tutorial and also provides a list of suggested or potential readings. The second topic typically introduces the motivation/purpose of the tutorial, and the third topic typically provides the tutorial's learning objectives. These are followed by topics that guide users through an R analysis step-by-step. For example, the 'single_season' tutorial introduces the user to the seminal single season model (MacKenzie et al., 2002) by first introducing and wrangling a built-in dataset, then introduces them to the `createPao()` function (an important input for any *RPresence* analysis), then guides them through an analysis with the `occMod()` function (the primary function in RPresence for running occupancy models) and shows them how to display results as tables and figures (Figure 2).

Each topic may contain written, instructional videos, R exercises, interactive Shiny widgets and interactive quiz elements. In an attempt to de-mystify how the field data (typically a pattern of detections and non-detections) translate into parameter estimates, many of the tutorials include videos that illustrate the nuts and bolts of the analysis in a simple spreadsheet environment. Progression can be saved, allowing users to close out when needed and returned to at a later time. Completed tutorials can be printed as a PDF for future reference.

The final topic of any tutorial is 'What's next?'. It features the `tutPrePost()` function that generates a dataframe that shows tutorial follow-ups. Follow-ups are coded as 'Optional' or 'Suggested'. For example, the code below returns the tutorials that users may be interested in after completing the data wrangling tutorial ('wrangling'):

```
occupancyTuts::tutPrePost(tut = "wrangling", type = "post")
```

Name	Priority	Description
sitecovs	Optional	Analysing occupancy data with covariates that affect site occupancy, including the analysis of null, continuous, categorical, additive, polynomial and interactive models in *RPresence*
spatials	Suggested	Working with spatial data in R, including a brief introduction to the packages *raster* and *sf*, and how to wrangle data for incorporation into occupancy models
surveycovs	Optional	Analysing occupancy data with covariates that affect detection rates, including the analysis of null, continuous, categorical, additive, polynomial and interactive models in *RPresence*

As shown, the suggested follow-up tutorial to the wrangling tutorial is the 'spatials' tutorial, while the 'sitecovs' and 'surveycovs' tutorials are optional. If *occupancyTuts* is used in a classroom or workshop, the instructor should identify the sequence of tutorials to be completed.

3 | SUMMARY AND DISCUSSION

The R package, *occupancyTuts*, provides a new entry into teaching quantitative methods to students of ecology. As an open-access contribution available to anyone with access to a computer and internet for download, *occupancyTuts* provides one option for increasing quantitative training opportunities for students that can be used in both in-person and on-line classrooms (Bachner & O'Bryrne, 2019; Touchon & McCoy, 2016), workshops (LaTourrette et al., 2021), clubs (Hagan, 2020; Johnston et al., 2019), or as an independent study. The use of *learnr* as an instructional tool builds not only background in ecology theory and statistical underpinnings, but also builds confidence in coding (Juavinett, 2022) and performance (Freeman et al., 2014).

We plan for development of new tutorials that use *RPresence* as the analysis engine. In progress tutorials can be downloaded from the master (working) branch with the following code:

```
remotes::install_gitlab(
  repo = "vtcfwru/occupancyTuts/",
  host = "code.usgs.gov",
```

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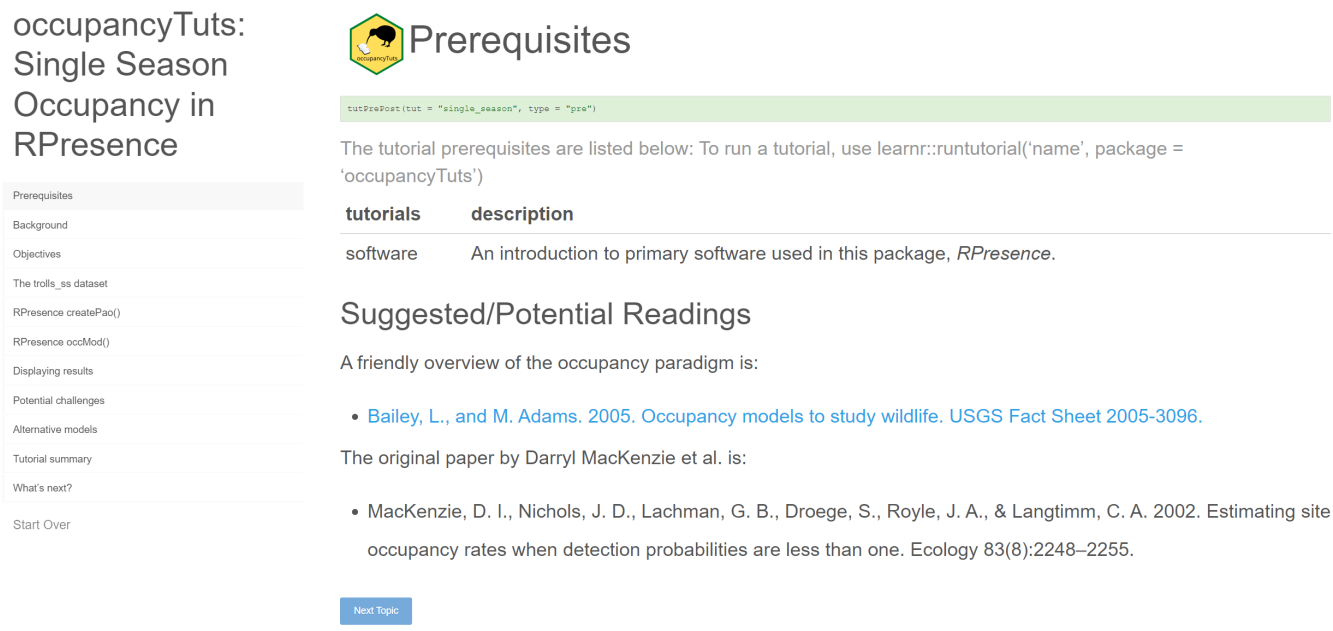

FIGURE 2 Screenshot of the 'single_season' occupancyTuts tutorial that launches in the user's web browser when called with learnr's `run_tutorial()` function. Each tutorial consists of several topics highlighted in the left menu.

```
auth_token = Sys.getenv("GITLAB_PAT"),
dependencies = TRUE)
```

The master branch can also be manually downloaded and installed from .zip files (Windows users) and tar.gz files (Mac and Linux users) from:

- https://code.usgs.gov/vtcfwru/-/archive/master/occupancyTuts-master.zip
- https://code.usgs.gov/vtcfwru/-/archive/master/occupancyTuts-master.tar.gz

We welcome new tutorial contributions that use other *R* packages as the analysis engine. Contributions can be made by contacting the authors and creating a new *learnr* tutorial that is appropriate and then posting a merge request to the canonical package repository at https://code.usgs.gov/vtcfwru/occupancyTuts. Such contributions can make use of the background content provided by *occupancyTuts* but provide alternative guidance for running models in a package of choice.

AUTHOR CONTRIBUTIONS

Therese Donovan and James Hines conceived the ideas for the *occupancyTuts* package; all authors contributed to the package itself; Therese Donovan and James Hines led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/2041-210X.14285.

DATA AVAILABILITY STATEMENT

The occupancyTuts code had been officially released by USGS and can be downloaded with the following code:

```
remotes::install_gitlab(
  repo = "vtcfwru/occupancyTuts@1.1.0",
  auth_token = Sys.getenv("GITLAB_PAT"),
  host = "code.usgs.gov",
  build_vignettes = FALSE,

  upgrade = "never")
```

The main repository is at https://code.usgs.gov/vtcfwru/occupancyTuts.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1. List of current tutorials in the R package, occupancyTuts.

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