Hierarchical Models in Population Ecology
What are they and why should we use them?

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Topics of Discussion
- Introduction to hierarchical models
  - What is a hierarchy?
  - What is a statistical model?
  - What is a hierarchical model?
  - What is NOT a hierarchical model?
- Hierarchical models in population ecology
  - Brief primer to population ecology
  - Process-only models
  - Process + observation model
  - Hyperparameter models
- Why should we use hierarchical models?
  - Scope and scale of inference
  - Correct accounting of variance
  - Borrowing strength
- Areas of active development
  - Integrated population models
  - Spatial capture-recapture models
- Hierarchical modeling resources

Introduction to Hierarchical Models
What is a hierarchy?

Definition: hierarchy (noun) – A series of ordered groupings of people or things within a system.

Definition: classification (noun) – the arrangement of entities in a hierarchical series of nested classes, in which similar or related classes at one hierarchical level are combined comprehensively into more inclusive classes at the next higher level.

Hierarchies in population ecology:

- **Metacommunity**: distribution of communities
- **Community**: distribution of metapopulations
- **Metapopulation**: distribution of populations
- **Population**: distribution of individuals

How different factors affect different hierarchical levels
Introduction to Hierarchical Models

What is a hierarchy?

Distribution and abundance of ovenbirds:

- Occurrence dependent on patch size
- Conditional on occurrence

- Local density dependent on habitat quality

High | Medium | Low
---|---|---
0.5 x 0.5 | + | - | +
1.0 x 1.0 | + | + | +
2.0 x 2.0 | + | + | +

Introduction to Hierarchical Models

What is a hierarchy?

Hierarchies in population ecology:

- Number of recruits as outcome of a series of processes

Surviving adults → Fertilized eggs → Hatched eggs → Surviving tadpoles
**Introduction to Hierarchical Models**

*What is a statistical model?*

**Definition:**

A formal description of a number generating process comprised of a deterministic and a stochastic component, expressed algebraically, and based on probability distributions (i.e., parametric).

"Parametric statistical modeling means describing a caricature of the ‘machine’ that plausibly could have produced the numbers we observe."

**Kery 2010**

**Linear regression example:**

\[ y_i = \beta_0 + \beta_1 x_i + \epsilon_i \]

- **Deterministic**
- **Stochastic**

**Introduction to Hierarchical Models**

*The Hierarchical Model*

**Definition:**

A series of [parametric] models, ordered by their conditional probability structure.

*Royle et al. 2013*

**Example:** SPECIES OCCURRENCE MODEL

- **State process:**
  \[ z \sim \text{Bernoulli}(\nu) \]

- **Observation process:**
  \[ y_i | z = \text{Bernoulli}(z \cdot p) \]

where \( y_i \) = observed presence at site \( i \),
\( z \) = true occurrence status at site \( i \) and \( p \) = detection probability.

**NOT Hierarchical Models**

- "Step-down" or "Stepwise" model selection
  - The ad hoc process of holding model structure constant for some parameters, while investigating structures for others.

**Example:** Cormack-Jolly-Seber model

*Model parameters:* \( \phi \) (apparent survival) and \( p \) (detection probability)

1) Hold \( \phi \) constant, test alternative structures for \( p \)
2) Hold best structure for \( p \) constant, test \( \phi \)

*NOT RECOMMENDED*

*Doherty et al. 2012*
Introduction to Hierarchical Models

Multi-stage analyses (i.e., statistics on statistics)

- The process of using estimates from an initial analysis as input data for a secondary analysis

Example: Evaluate habitat effects on local abundance ($N$)

A WELL KNOWN "NO NO" in STATISTICS

Bayesian inference

- A statistical inference paradigm based on Bayes theorem that uses probability to describe all unknown quantities

**Bayesian hierarchical modeling:**

The fitting of hierarchical models using Bayesian methods

Hierarchical models can also be fit using frequentist methods
Hierarchical Models in Population Ecology

Population ecology
- Abundance and distribution of individuals and species
- Dynamics of populations, metapopulations, communities, etc.
- Factors affecting abundance, distribution, and dynamics

How do we use hierarchical models in the study of population ecology?
- Match structure of the statistical model to the structure of our conceptual model of ecological processes

Frog recruits revisited: # of recruits (R) into adult class

- E ~ Poisson(λ)
- FE | E ~ Binomial(E, f)
- T | FE ~ Binomial(FE, h)
- R | T ~ Binomial(T, m)
Hierarchical Models in Population Ecology
How do we use hierarchical models in the study of population ecology?

- Match structure of the statistical model to the structure of our conceptual model of ecological processes

Frog recruits revisited: # of recruits ($R$) into adult class

- Incorporate conditional observation process into model structure to account for imperfect detection

Example: CORMACK-JOLLY-SEBER MODEL

- Impose additional structure via hyper-parameters

Example: CORMACK-JOLLY-SEBER MODEL
Why Should We Use Hierarchical Models?

- **Scope and Scale of Inference**
  - Extend inference beyond levels under study
  - Generalize to population from which sample units were drawn
  - Need to know means and variances of global processes
  - Scale-dependent inference
  - Evaluate factors affecting different levels of ecological processes
    - Distribution and abundance of ovenbirds

- **Correct accounting of variance**
  - Random effects allow partitioning of process and sampling variances
  - Critical for population projection models used in population viability analyses
  - Avoids variance-accounting problems with multi-stage analyses
    - Violation of constant sampling variance assumption
  - Allows modeling covariances among different parameters
    - Temporal covariance between survival and recruitment
Why Use Hierarchical Models?

- **Borrowing strength**
  - Fixed effects can result in imprecise or extreme group-specific estimates for small samples
  - By constraining parameters by a common distribution (random effects), individual estimates are pulled toward the global mean (e.g., shrinkage)
  - Individual estimates “borrow strength from the ensemble”
  - Assumption of exchangeability must hold

Areas of Active Development

- **Integrated Population Models**
  - Integrate data from multiple sources to model individual demographic processes
    - *Capture-recapture and known-fate data for survival*
  - Integrate data from multiple demographic processes to model population dynamics
    - *Capture-recapture, reproduction, known-fate, and band-return data*
  - Extend population models to metapopulation and community models
    - *Shared information among multiple populations or similar species*
Areas of Active Development
Spatial Capture-Recapture Models

- Explicit modeling of territoriality
  - Spatial interactions among individuals
- Extending models to accommodate gregarious species
  - Non-independence of individual activity centers
- Development of explicit movement models
  - Dispersion, transience, and migration

Hierarchical Modeling Resources


Hierarchical Modeling Resources


LITERATURE CITED


PHOTO CREDITS


Ø http://www.uri.edu/cels/nrs/paton/LH_wood_frog.html

Ø http://www.uri.edu/cels/nrs/paton/photo_wofr2.htm