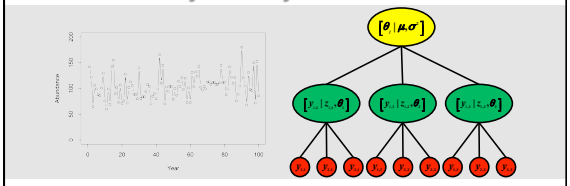
Hierarchical Models in Population Ecology

What are they and why should we use them?



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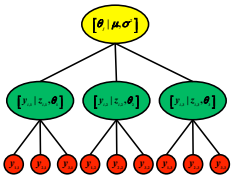
2 May, 2014 10:15 AM Room 160 PBB

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
  - *Hyper-parameter* 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



Introduction to Hierarchical Models
What is a hierarchy?

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

Royle et al. 2013

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***

Mayr and Bock 2002

Introduction to Hierarchical Models
What is a hierarchy?

- Hierarchies in population ecology:

ECOLOGICAL SCALES OF ORGANIZATION

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:

Introduction to Hierarchical Models

What is a hierarchy?

Distribution and abundance of ovenbirds:

Occurrence dependent on patch size

Conditional on occurrence

	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?

Distribution and abundance of ovenbirds:

Occurrence dependent on patch size

Conditional on occurrence

Local density dependent on habitat quality

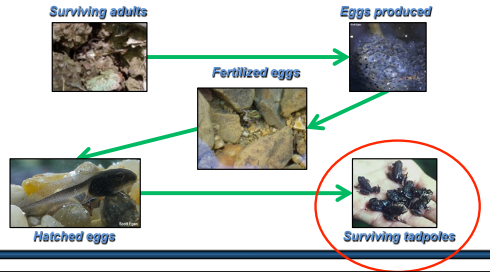
	High	Medium	Low
0.5 x 0.5	0	0	0
1.0 x 1.0	6	4	2
2.0 x 2.0	24	16	8

Introduction to Hierarchical Models

What is a hierarchy?

➢Hierarchies in population ecology:

NUMBER OF RECRUITS AS OUTCOME OF A SERIES OF PROCESSES



Introduction to Hierarchical Models
What is a statistical model?

Definition: ***statistical model*** (noun) – 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"

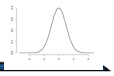
Kery 2010

Linear regression example:

$y_i = \alpha + \beta_1 x_1 + ... + \beta_n x_n + \varepsilon_i$

where $E[Y] = \alpha + \beta_1 x_1 + ... + \beta_n x_n$ ← Deterministic

and $\varepsilon_i \sim \text{Normal}(0, \sigma^2)$ ← Stochastic



Introduction to Hierarchical Models
The Hierarchical Model

Definition: ***hierarchical model*** (noun) – A series of [parametric] models, ordered by their ***conditional*** probability structure

Royle et al. 2013

aka: state-space, multi-level, random-effects, GLMM, nested

Example: *SPECIES OCCURRENCE MODEL*

$z_i \sim \text{Bernoulli}(\psi)$ — State process

$y_i \mid z_i \sim \text{Bernoulli}(z_i \times p)$ — Observation process

Observation is ***CONDITIONAL*** on true state

where y_i = observed presence at site *i*,

z_i = true occurence status at site *i*

and p = detection probability

Introduction to Hierarchical Models
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: ϕ (apparent survival) and p (detection probability)

1) Hold ϕ constant, test alternative structures for p

2) Hold best structure for p constant, test ϕ

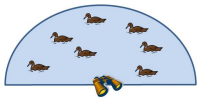
NOT RECOMMENDED

Doherty et al. 2012

Introduction to Hierarchical Models
NOT 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*)



Obtain estimate *N-hat*

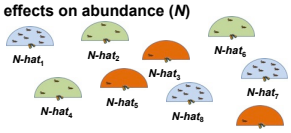
Introduction to Hierarchical Models
NOT Hierarchical Models

- 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 abundance (*N*)

1) Estimate abundances from encounter data
2) Test for relationship between *N* estimates and habitat variables

A WELL KNOWN "NO NO" in STATISTICS



Linear regression of *N - hat*:

$N\text{-}hat_i = \alpha + \beta_1 x_1 + ... + \beta_x x_x + \varepsilon_i$

where $x_1 ... x_x$ are habitat variables

Introduction to Hierarchical Models
NOT Hierarchical Models

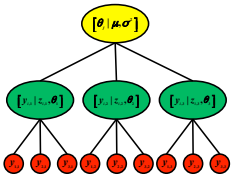
- Bayesian inference
  - A statistical inference paradigm based on Bayes theorem that uses probability to describe all unknown quantities

Bayesian hierarchical modeling:

The fitting of hierarchical models using Bayesian methods

Hierarchical models can also be fit using frequentist methods

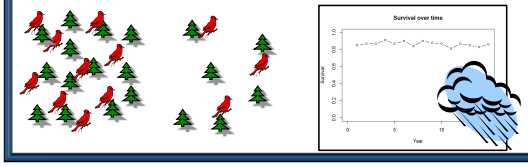
Hierarchical Models in Population Ecology



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

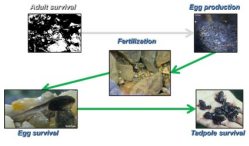


Hierarchical Models in Population Ecology

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



$$E_i \sim \text{Poisson}(\lambda_i)$$

$$FE_i \mid E_i \sim \text{Binomial}(E_i, f_i)$$

$$T_i \mid FE_i \sim \text{Binomial}(FE_i, h_i)$$

$$R_i \mid T_i \sim \text{Binomial}(T_i, m_i)$$

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

$E_i \sim \text{Poisson}(\lambda_i)$ $\quad \log(\lambda_i) = \alpha + \beta_1 x + \varepsilon_{\lambda,i}$ *e.g., female body mass, pathologies, etc*

$FE_i \mid E_i \sim \text{Binomial}(E_i, f_i)$ $\quad \text{logit}(f_i) = \alpha + \beta_2 x + \varepsilon_{f,i}$ *e.g., male body mass, pathologies, etc*

$T_i \mid FE_i \sim \text{Binomial}(FE_i, h_i)$ $\quad \text{logit}(h_i) = \alpha + \beta_3 x + \varepsilon_{h,i}$ *e.g., predator density, temp, etc*

$R_i \mid T_i \sim \text{Binomial}(T_i, m_i)$ $\quad \text{logit}(m_i) = \alpha + \beta_4 x + \varepsilon_{m,i}$ *e.g., predator density, temp, etc*

Hierarchical Models in Population Ecology

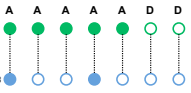
How do we use hierarchical models in the study of population ecology?

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

Example: *CORMACK-JOLLY-SEBER MODEL*

$z_i \sim \text{Bernoulli}(\phi)$ *State process*

$y_i \mid z_i \sim \text{Bernoulli}(z_i \times p)$ *Observation process*



where z_i = true alive status for individual i,
y_i = observed alive status for individual i,
and p = detection probability

Observation is ***CONDITIONAL*** on true state

Hierarchical Models in Population Ecology

How do we use hierarchical models in the study of population ecology?

- Impose additional structure via hyper-parameters

Example: *CORMACK-JOLLY-SEBER MODEL*

Individual covariates and random effects

$$\text{logit}(\phi_i) \sim \text{Normal}(\alpha + \beta x_i, \sigma^2)$$
$$z_i \sim \text{Bernoulli}(\phi_i)$$
$$y_i \mid z_i \sim \text{Bernoulli}(z_i \times p)$$

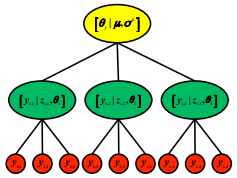
Evolutionary processes on fitness

Temporal covariate and random effects

$$\text{logit}(\phi_i) \sim \text{Normal}(\alpha + \beta x_i, \sigma^2)$$
$$z_i \sim \text{Bernoulli}(\phi_i)$$
$$y_i \mid z_i \sim \text{Bernoulli}(z_i \times p)$$

Environmental processes on fitness

Why Should We Use Hierarchical Models?



Why 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 known means and variances of global processes*
- Scale-dependent inference
  - Evaluate factors affecting different levels of ecological processes
    - ✓ *Distribution and abundance of ovenbirds*

Why Use Hierarchical Models?

Correct accounting of variance

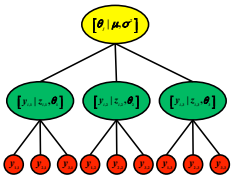
- Random effects allow partitioning of process and sampling variances
  - *Critical for population projection models used in population viability analyses*
- Avoids variance-accounting problems with multi-stage analyses
  - *Violation of constant sampling variance assumption*
- Allows modeling covariances 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



Areas of Active Development

Integrated Population Models

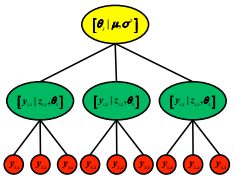
- Integrate data from multiple sources to model individual demographic processes
  - *Capture-recapture and known-fate data for survival*
- Integrate data from multiple demographic processes to model population dynamics
  - *Capture-recapture, reproduction, known-fate, and band-return data*
- Extend 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
  - *Dispersal, transience, and migration*

Hierarchical Modeling Resources



Hierarchical Modeling Resources

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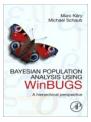

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