Analysing multivariate ecological data with Generalized Linear Latent Variable Models

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Exercise material and package installation

https://github.com/BertvanderVeen/BES2020GLLVMworkshop

Questions

In zoom chat to **Bob** or

On twitter: #**GLLVMs**, @**vdVeenB** or @**J__Niku** or @**samperrinNTNU** or @**BobOHara**
On github: https://github.com/BertvanderVeen/BES2020GLLVMworkshop/discussions

Welcome! 😄

	Who	Affiliation	Expertise
	Bert van der Veen PhD candidate	Norwegian insitiute of Bioeconomy research & Norwegian univeristy of Science and Technology	- Statistical ecology - Ordination - Species distribution modeling
	Jenni Niku Postdoc	University of Jyväskylä	- Statistical ecology - Species distribution modeling
	Sam Perrin PhD candidate	Norwegian university of Science and Technology	- Fresh water ecology - Invasion ecology - Species distribution modeling
	Robert Brian O'Hara Professor	Norwegian University of Science and Technology	- Statistical ecology - Species distribution modeling - Data integration

Program day 2

Topic	Duration	Who
- Species associations - Species distribution modeling - Generalized Linear Latent Variable models	20 minutes	
Break	5 minutes	
- `gllvm` R-package (Niku et al. 2019) - How to: species distributions with GLLVMs	20 minutes	
- Exercise: break out	10 minutes	
Break	5 minutes	
- Some ecology	20 minutes	
- Exercise: break out	15 minutes	
- Discuss results exercise		

Gathering data

We go out, register species at multiple sites

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Gathering data

We go out, register species at multiple sites

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"Multivariate"

- What does multivariate mean?
- Multivariate: multiple **responses**
- E.g. counts of species at sites

	Species 1	Species 2	Species 3	Species 4	Species 5
Site 1	25	10	0	0	0
Site 2	0	2	0	0	0
Site 3	15	20	2	2	0
Site 4	2	6	0	1	0
Site 5	1	20	0	2	0

"Multivariable"

- Multiple **predictors**
- E.g. measurements of the environment

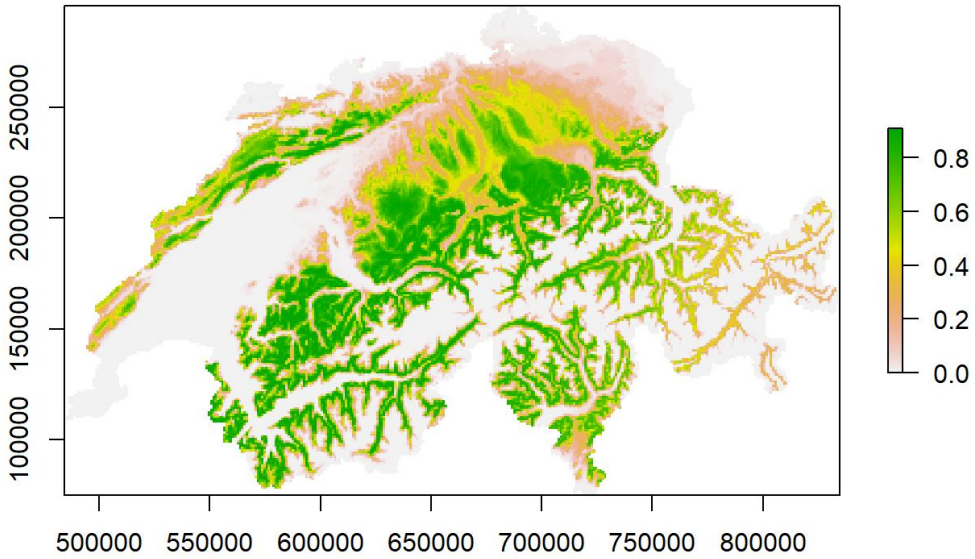
	Predictor 1	Predictor 2	Predictor 3	Predictor 4	Predictor 5	Predictor 6
Site 1	2.3321	3.0445	0.0000	3.0445	4.4543	3.9120
Site 2	3.0493	3.2581	1.7918	1.0986	4.5643	1.6094
Site 3	2.5572	3.5835	0.0000	2.3979	4.6052	3.6889
Site 4	2.6741	4.5109	0.0000	2.3979	4.6151	2.9957
Site 5	3.0155	2.3979	0.0000	0.0000	4.6151	2.3026
Site 6	3.3810	3.4340	3.4340	2.3979	3.4340	0.6931

To clarify

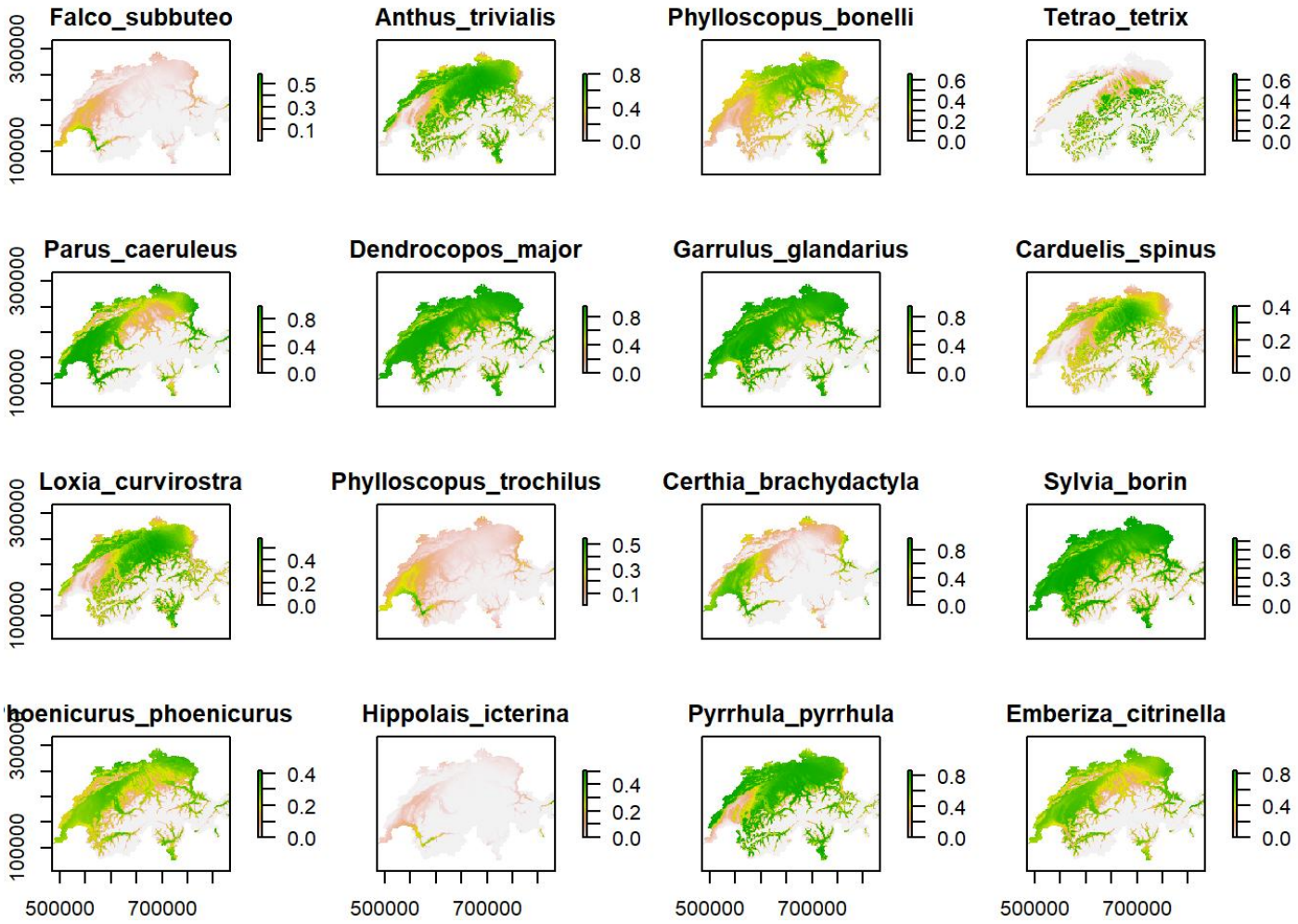
- Both data and model can be univariate or multivariate
- Multivariate data can be analysed with both multivariate and univariate models (SDM, ordination)
- Multivariable data can be used in multivariate or univariate analysis
    - Generally the same for all responses
    - (But, note that the model can of course set terms to zero)

Why analyse species distributions?

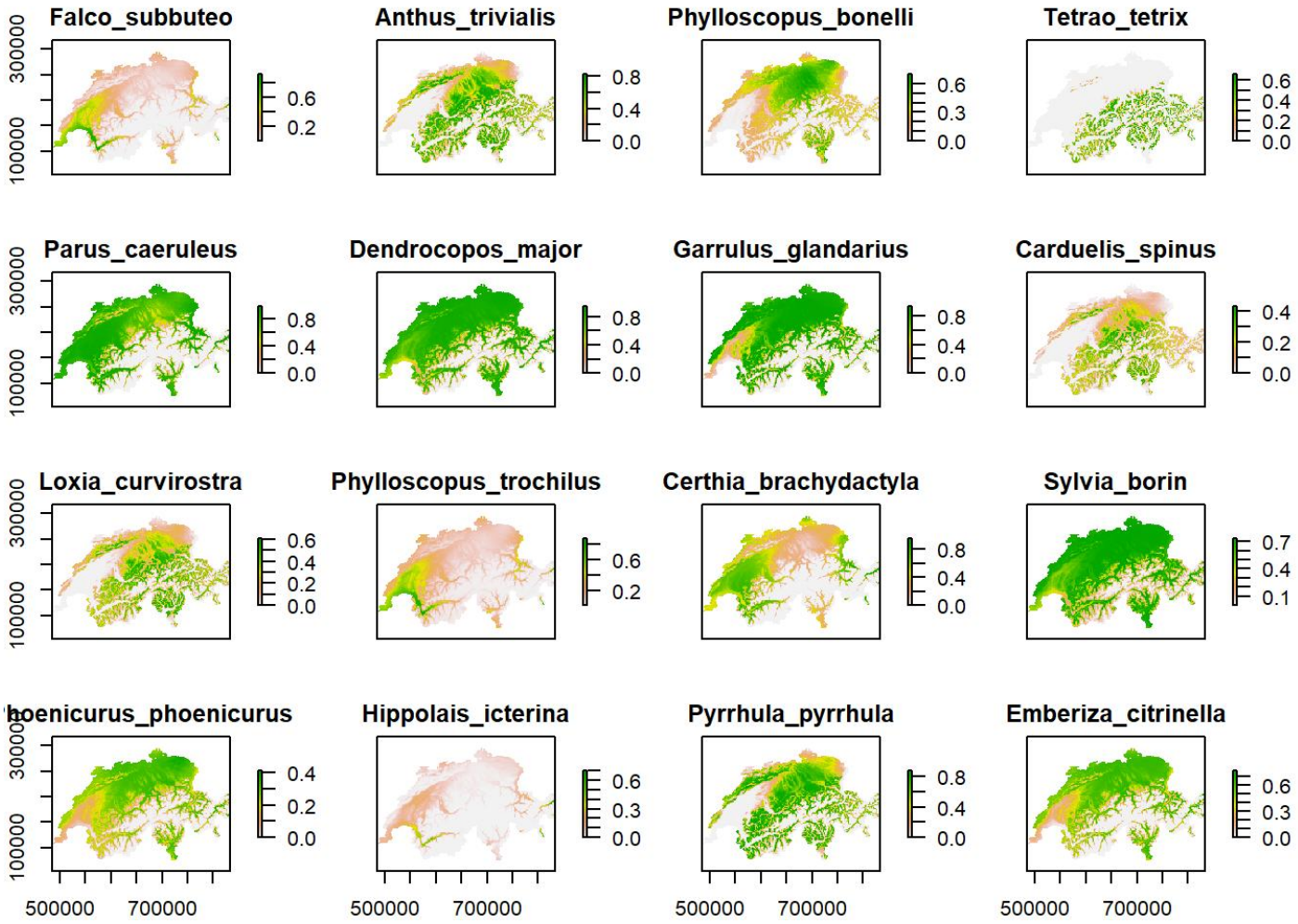
- For example:
  - Where does my species occur?
  - Where can my species occur?
  - How might that change in the future?
  - Informs us of the state of a species



But then for more species



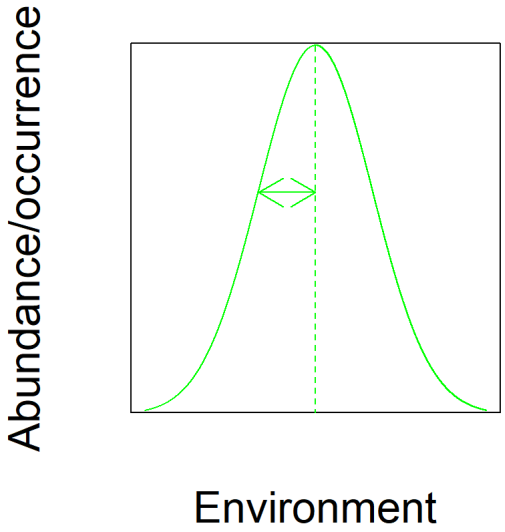
And potentialy predict into the future



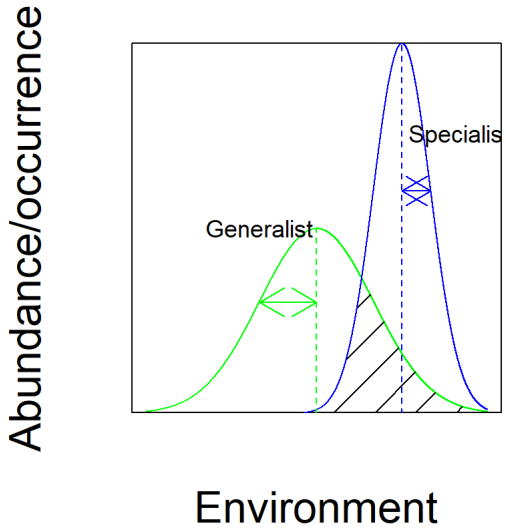
Species associations

- Our data contains information on where **multiple species** occur at the same time!
  - Similar environmental preferences
  - Similar history in the environment
  - Might result in **Interactions**
- Multiple species form a **community**

Occurrence pattern

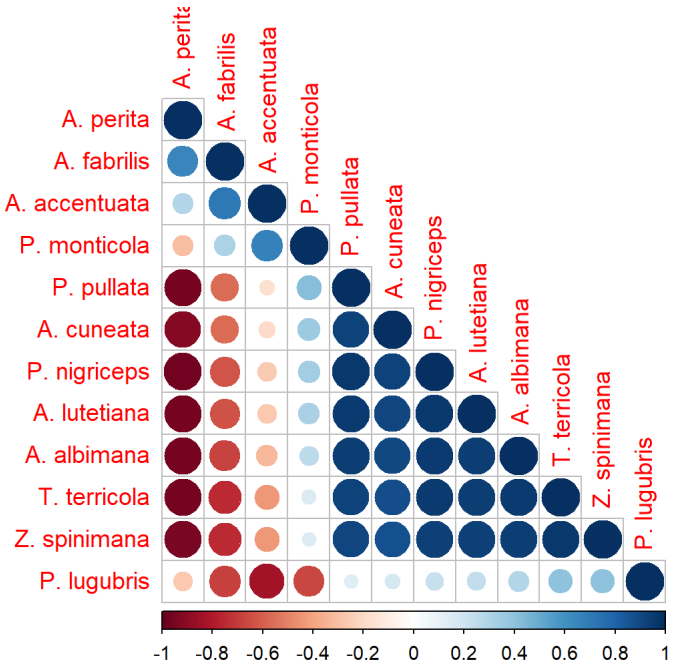


Co-occurrence pattern



Co-occurrence

- Occurrence data can tell use about where multiple species occur
- How species are "associated"
- Statistically: correlation
- So we are looking for patterns in our data



Analysing co-occurrence patterns

- Community ecology has been doing it for a hundred years
- e.g. Forbes (1907) or Goodall (1954)
- Ordination: Principal Component Analysis (PCA), Correspondence analysis (CA), NMDS
- Niche overlap
- Some discussion in Blanchet et al. (2020): Co-occurrence is not evidence of ecological interactions"

Joint modeling

- Account for correlation between taxa
- "borrow" information from other species

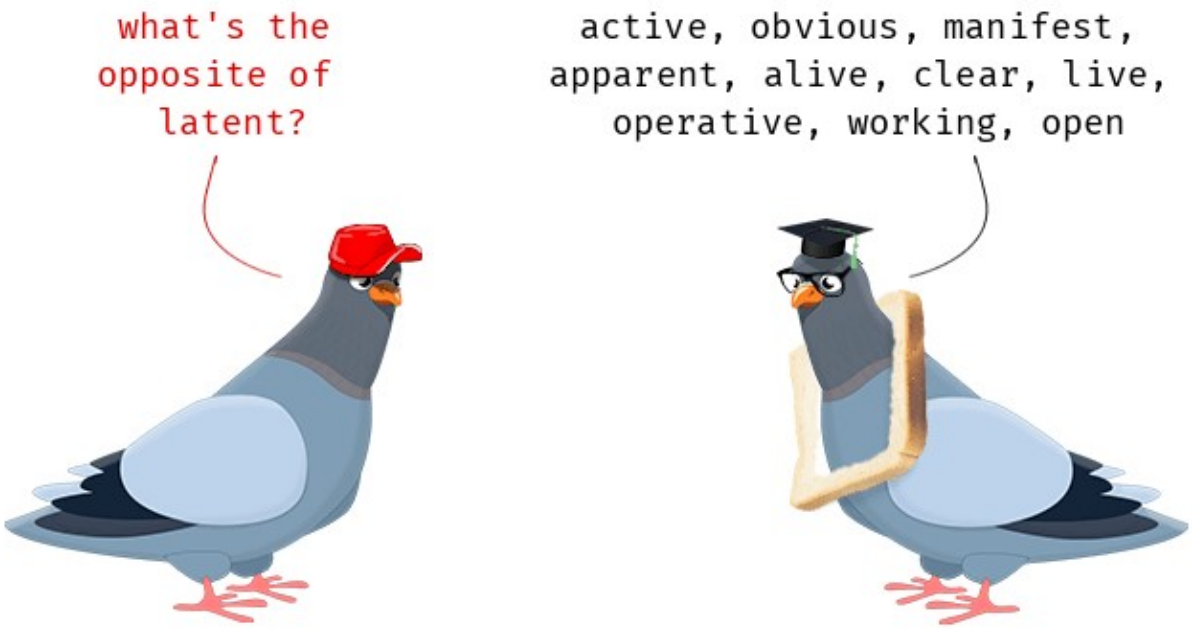
- Estimate species associations

- Concept: fit a single model for all species

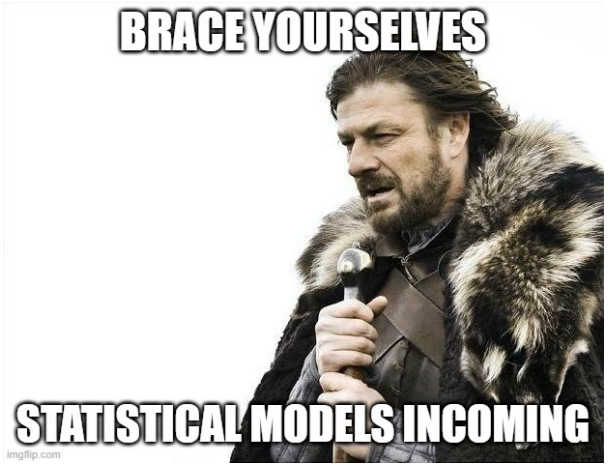
    - Faster
    - Less tedious
    - Explicitly model species co-occurrence
    - Etc.

Patterns in our data

Can be **observed** (covariates) or **latent**



Questions so far?



Specifying a multivariate statistical model

- β_{0j} intercept per species
- X_{ik} site-specific covariates
- $\boldsymbol{\beta_j}$ species-specific slopes

$$g(\mathbf{E}(y_{ij})) = \beta_{0j} + \boldsymbol{X}_i^\top \boldsymbol{\beta}_j \tag{2}$$

- Stacked SDM or `glm(.)` function

A Multivariate Mixed-effects model

- Add residual for $i = 1 \dots n$ sites and $j = 1 \dots p$ species
- Structure Σ by species
- "Joint species distribution model" Pollock et al. 2014

$$g(\mathrm{E}(y_{ij})) = \beta_{0j} + \boldsymbol{X}_i^\top \boldsymbol{\beta}_j + \epsilon_{ij}, \qquad \boldsymbol{\epsilon}_i \sim \mathcal{N}(0, \Sigma) \tag{3}$$

- Can be fit using standard mixed-effects modeling software.

In `lme4`:

```
glmer(abundance~species+x:species+
(0+species|sites),family="poisson",data=data)
```

- Σ has $p(p+1)/2$ parameters (which increases quadratically with # species)

Model-based ordination to the rescue!

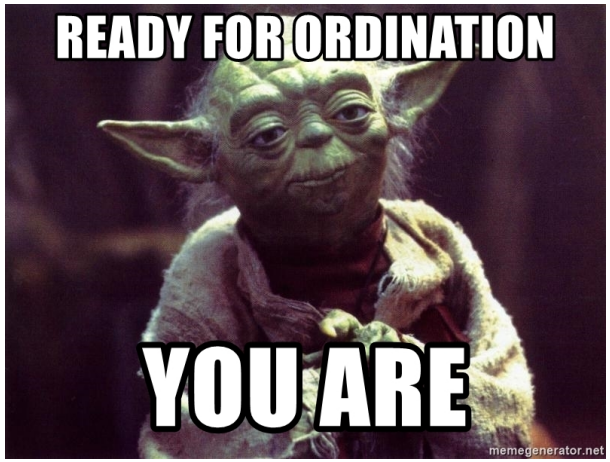
- Ordination = dimension reduction
- Represent species associations with latent variables
- So JSDM = ordination? Yes! (for GLLVMs)

- "Model-based approaches to unconstrained ordination" Hui et al. 2015

All the benefits from regression and ordination!

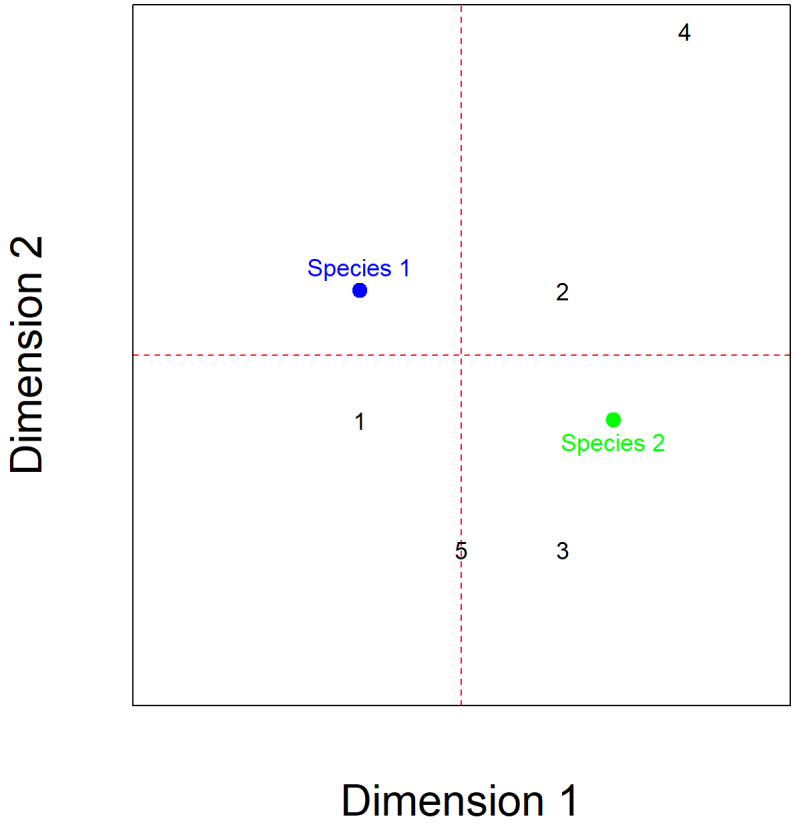
e.g.

- Procrustus analysis
- Biplots
- Model-selection
- Residual diagnostics
- Appropriate mean-variance relationships
- Hypothesis testing
- etc.



Ordination: visual inspection

- Most common tool is the biplot Gabriel 1971
- Distance between species indicates dissimilarity
- Distance between sites indicates dissimilarity
- What is a latent variable?



Ecological gradients

1) Ecological gradient: gradual change in the environment

- e.g. temperature

2) Complex gradient: change in several ecological gradients

- e.g. soil moisture and acidity on an elevation gradient
- Can be represented as a single factor, covariate, predictor, latent variable, ordination axis

Ecological gradients

"Few major complex ecological gradients normally account for most of the variation in species composition." **(Halvorsen, 2012)**

In essence:

Community structure is generally low-dimensional.

Generalized Linear Latent Variable Models

- GLLVM for short
- Add factor analytic structure to Σ
- $\epsilon_{ij} = \boldsymbol{u}_i^\top \boldsymbol{\theta}_j$
  - i.e. $\boldsymbol{\epsilon}_i \sim \mathcal{N}(0, \boldsymbol{\theta}_j \boldsymbol{\theta}_j^\top)$
- Faster and fewer parameters:
  - Number of parameter doesn't grow so fast
  - More latent variables, better estimation of Σ

$$\Sigma = \begin{bmatrix} \theta_{11} & 0 & 0 \\ \theta_{12} & \theta_{22} & 0 \\ \vdots & \ddots & \vdots \\ \theta_{1j} & \cdots & \theta_{dj} \end{bmatrix} \begin{bmatrix} \theta_{11} & \theta_{12} & \cdots & \theta_{1j} \\ 0 & \theta_{22} & \ddots & \vdots \\ 0 & 0 & \cdots & \theta_{dj} \end{bmatrix} \tag{4}$$

Generalized Linear Latent Variable Models

- Still a mixed-effects model
- $\boldsymbol{d}$ latent variables treated as random-effect
- Produces ordination
  - "site scores" : $\boldsymbol{u}_i$
  - "species scores" or "loadings": $\boldsymbol{\theta}_j$
  - No varimax

$$g(\mathrm{E}(y_{ij})) = \beta_{0j} + \boldsymbol{X}_i^\top \boldsymbol{\beta}_j + \boldsymbol{u}_i^\top \boldsymbol{\theta}_j, \qquad \boldsymbol{u}_i \sim \mathcal{N}(0, \boldsymbol{I}) \tag{5}$$

Compared to SDMs

- Multivariate GLM is a GLLVM without latent variables
  - (so the kind of same for a GAM)
- Multivariate GLMM is a GLLVM if the covariance matrix is of reduced rank

- **GLLVMs are a flexible approach to estimate species distributions**
- **That can readily be extended**

gllvm R-package

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gllvm: Fast analysis of multivariate abundance data with generalized linear latent variable models in R

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