# Analysing multivariate ecological data with Generalized Linear Latent Variable Models

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# Welcome! 😄

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

# 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

# Program day 2

| Topic | Duration | Who |
|---|---|---|
| - Species associations<br>- Species distribution modeling<br>- Generalized Linear Latent Variable models | 20 minutes |  |
| *Break* | 5 minutes | |
| - `gllvm` R-package (Niku et al. 2019)<br>- 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

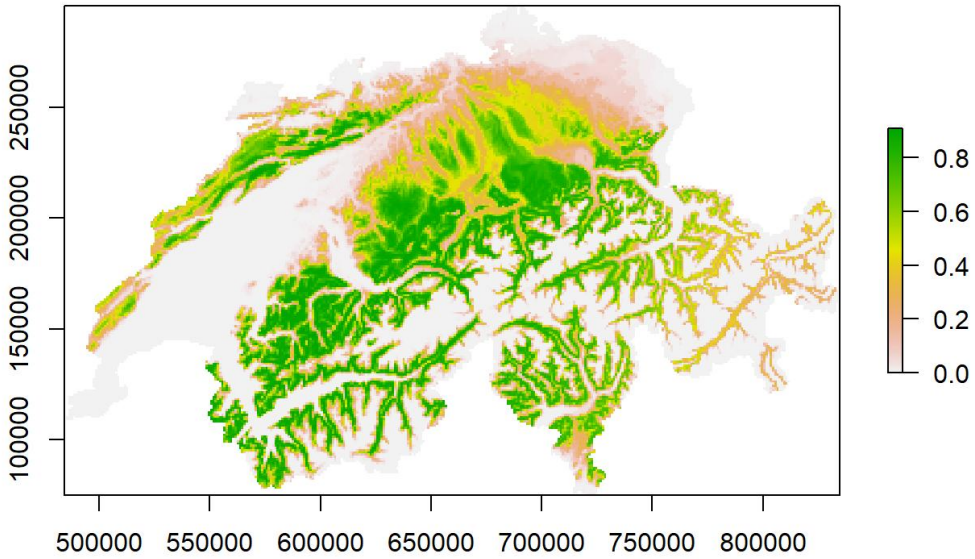
| | Predictor 1 | Predictor 2 | Predictor 3 | Predictor 4 | Predictor 5 | Predictor 6 |
|---|---|---|---|---|---|---|
| Site 1 | 2.3321 | 3.0445 | 0.0000 | 3.0445 | 4.4543 | 3.9120 |
| Site 2 | 3.0493 | 3.2581 | 1.7918 | 1.0986 | 4.5643 | 1.6094 |
| Site 3 | 2.5572 | 3.5835 | 0.0000 | 2.3979 | 4.6052 | 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

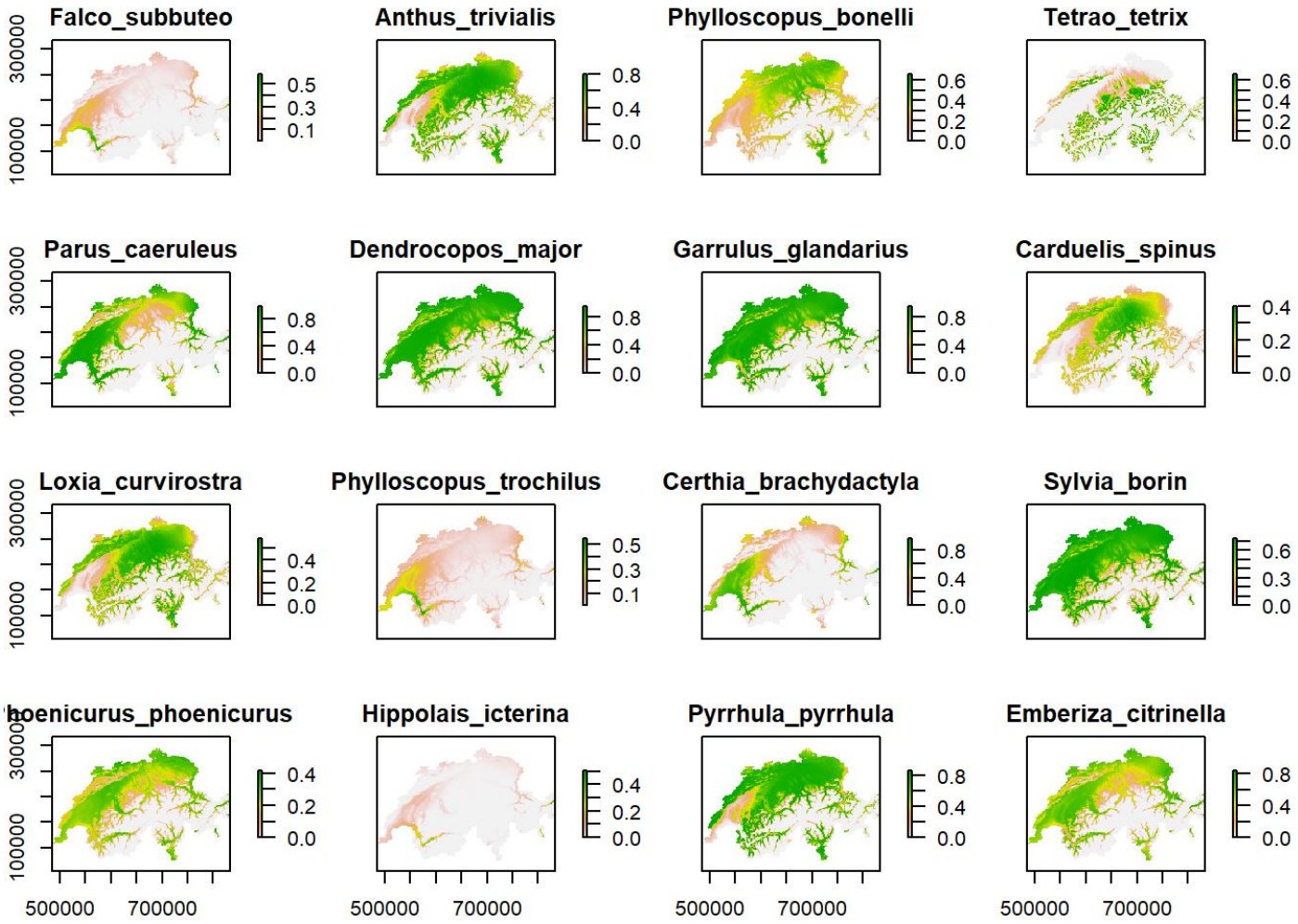
- Both data and model can be univariate or multivariate
- Multivariate data can be analysed with both multivariate and univariate models (SDM, ordination)
- Multivariable data can be used in multivariate or univariate analysis
    - Generally the same for all responses
    - (But, note that the model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

# Why analyse species distributions?

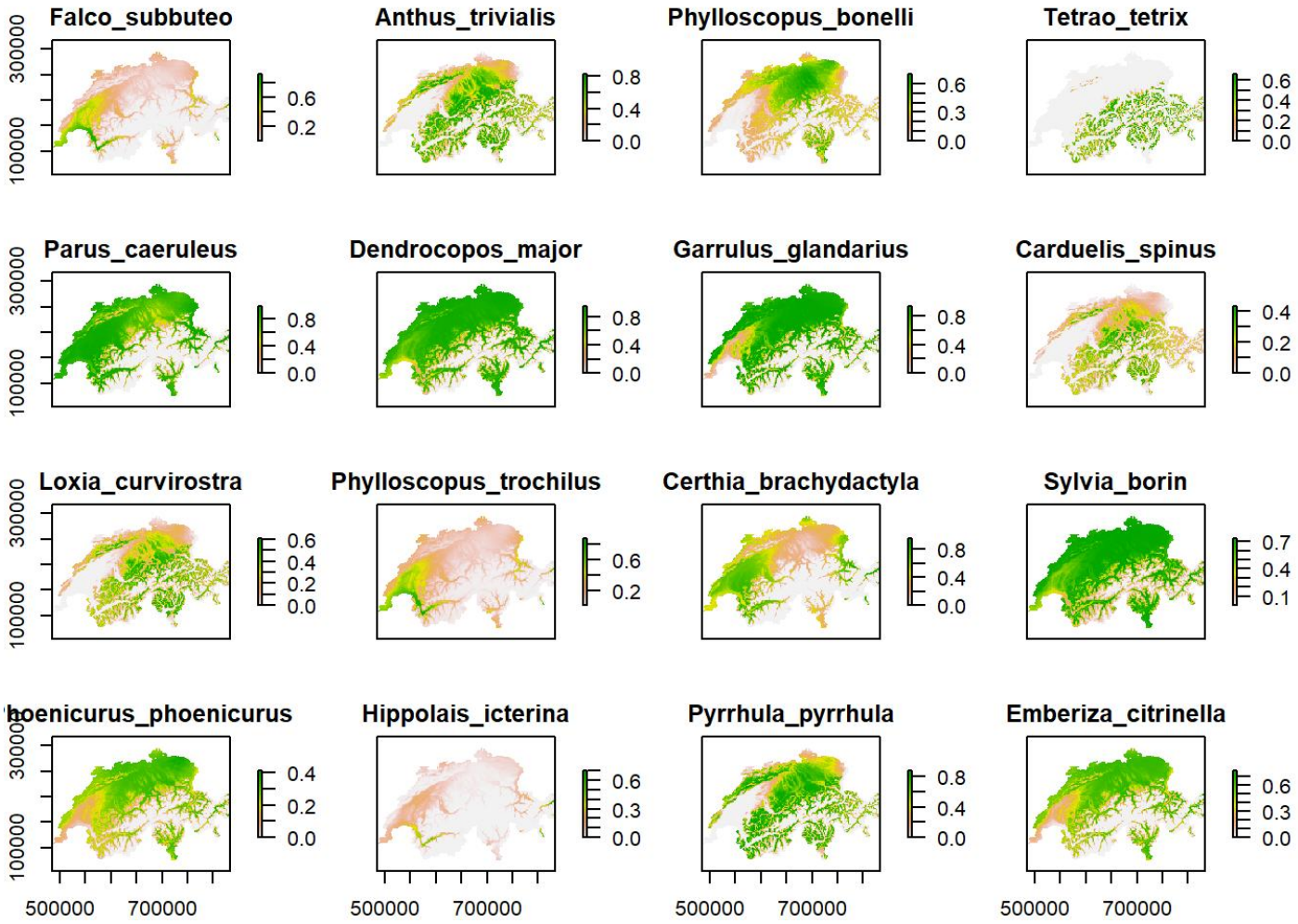
- For example:
  - Where does my species occur?
  - Where can my species occur?
  - How might that change in the future?
  - Informs us of the state of a species



# But then for more species



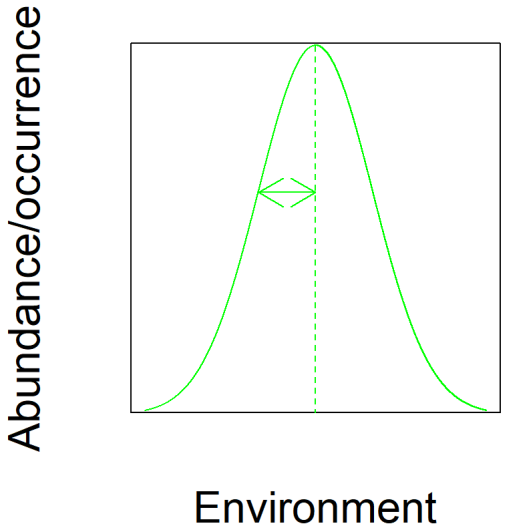
# And potentialy predict into the future



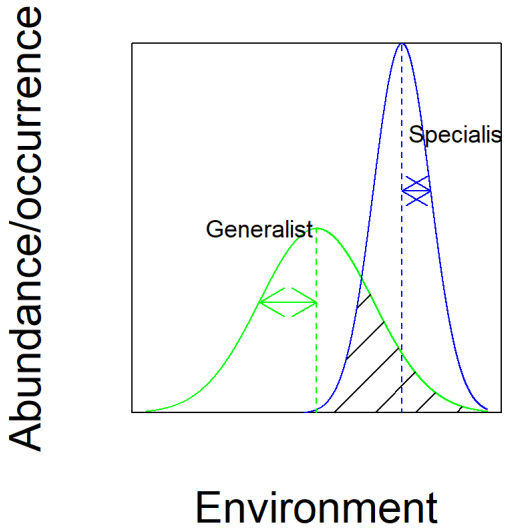
# Species associations

- 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

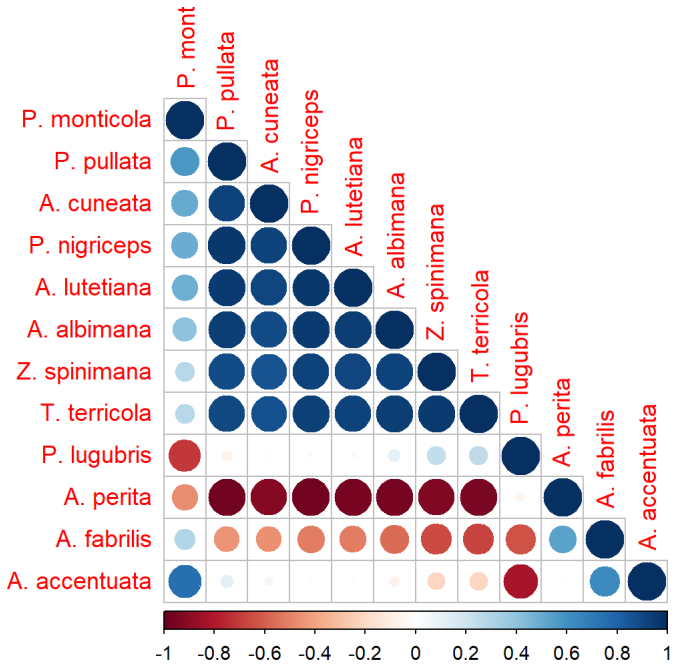



Co-occurrence pattern



# 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 (2020): Co-occurrence is not evidence of ecological interactions"

# Joint modeling

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

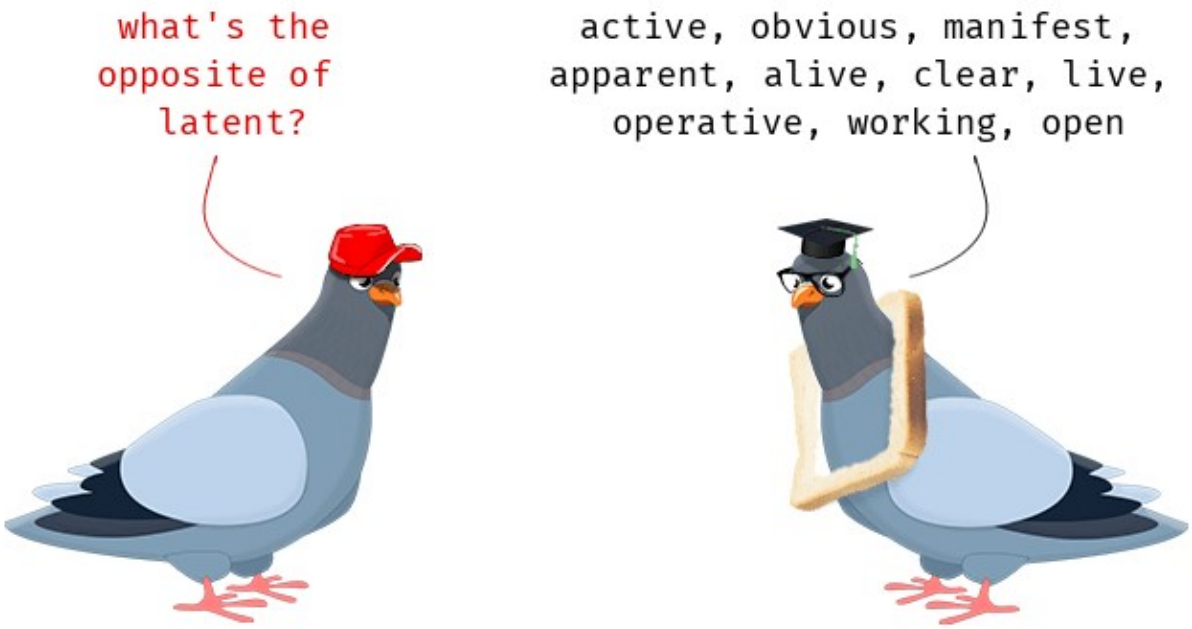
- Estimate species associations

- Concept: fit a single model for all species

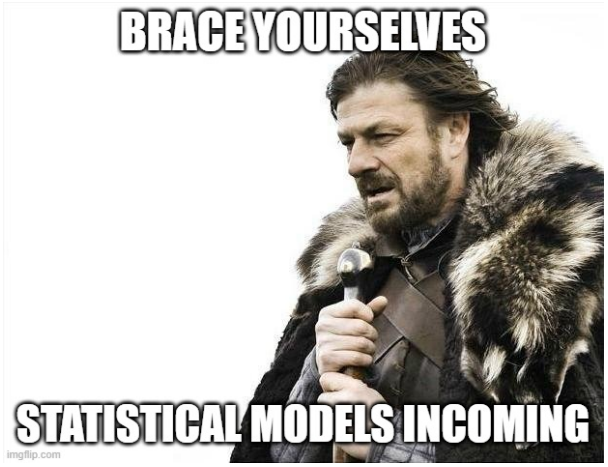
    - Faster
    - Less tedious
    - Explicitly model species co-occurrence
    - Etc.

# Patterns in our data

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



# Questions so far?



# Specifying a multivariate statistical model

- $\beta_{0j}$ intercept per species
- $X_{ik}$ site-specific covariates
- $\beta_{0j}$ species-specific coefficients

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

- Stacked SDM or glm() function
- For example: **mvabund** Wang et al. 2012
- No random-effects
- Hypothesis testing for multivariate data

# A Multivariate Mixed-effects model

- Add residual for $i = 1 \dots n$ sites and $j = 1 \dots p$ species
- Structure $\Sigma$ by species
- "Joint species distribution model" Pollock et al. 2014
- Can fit using standard mixed-effects modeling software.

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

In `lme4`:

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

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

# Model-based ordination to the rescue!

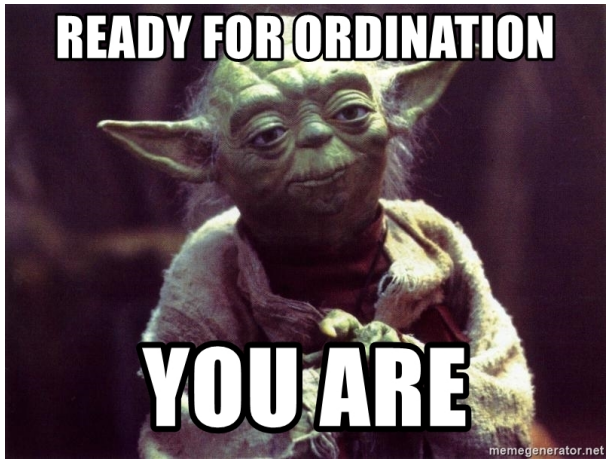
- Ordination = dimension reduction
- Represent species associations with latent variables
- So JSDM = ordination?

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

**All the benefits from regression and ordination!**

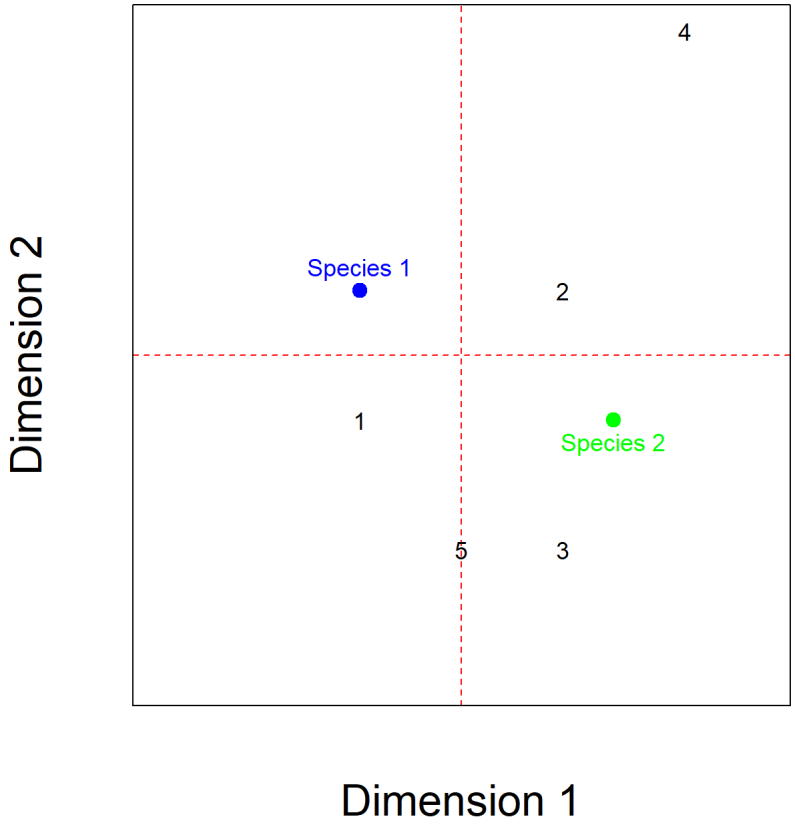
e.g.

- 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 $\Sigma$
- $\epsilon_{ij} = \boldsymbol{u}_i^\top \boldsymbol{\theta}_j$
  - 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 $\Sigma$

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

# Generalized Linear Latent Variable Models

- Still a mixed-effects model
- Low-rank approach to $\Sigma$
- $d$ 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 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**

# More complex JSDM?

e.g. spatially dependent sites
e.g. temporal replicates
e.g. including species relatedness

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## Joint species distribution modelling with the R-package HMSC

Gleb Tikhonov, Øystein H. Opedal, Nerea Abrego, Aleksi Lehikoinen, Melinda M. J. de Jonge, Jari Oksanen, Otso Ovaskainen

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