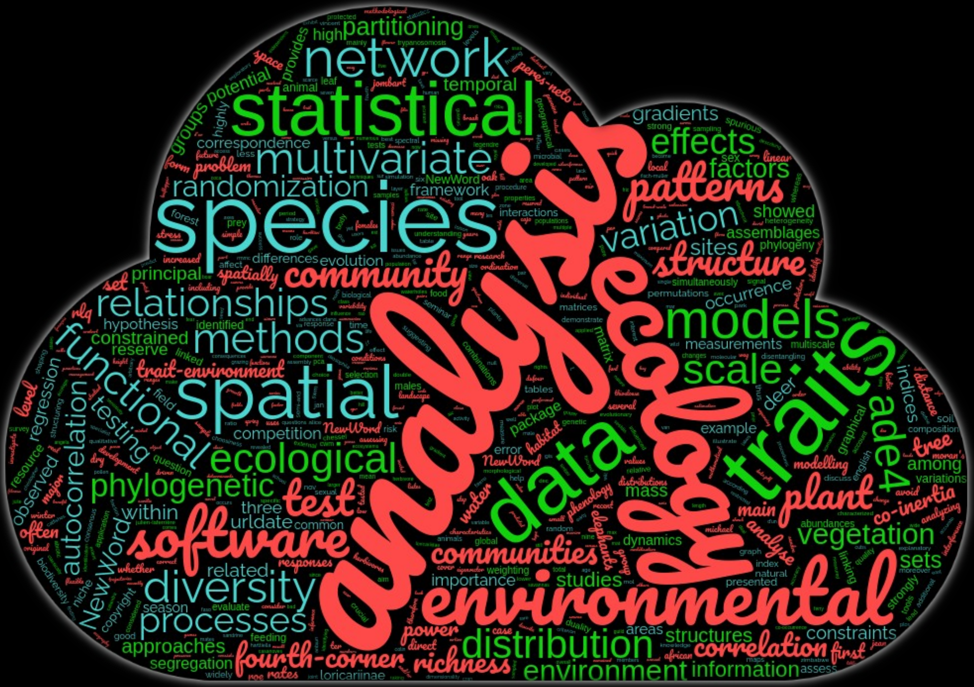
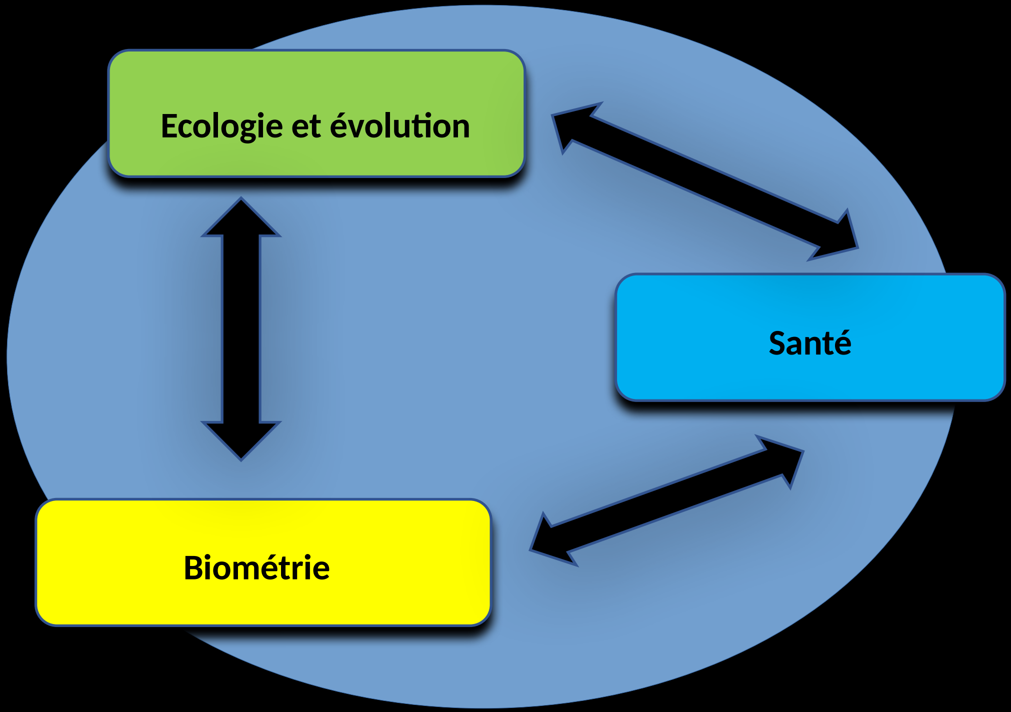
Analyse des structures spatiales multivariées
- le package adespatial -

Stéphane Dray

INED - 2026

LBBE


analysis
ecology
environmental
species
statistical
traits
spatial
network
multivariate
models
data
software
diversity
community
relationships
methods
ecological
phylogenetic
functional
processes
patterns
effects
scale
distribution
randomization
variation
structure
plant
test
communities
partitioning
correlation
fourth-corner
richness
vegetation
factors
ade4
autocorrelation


Ecologie et évolution
Santé
Biométrie

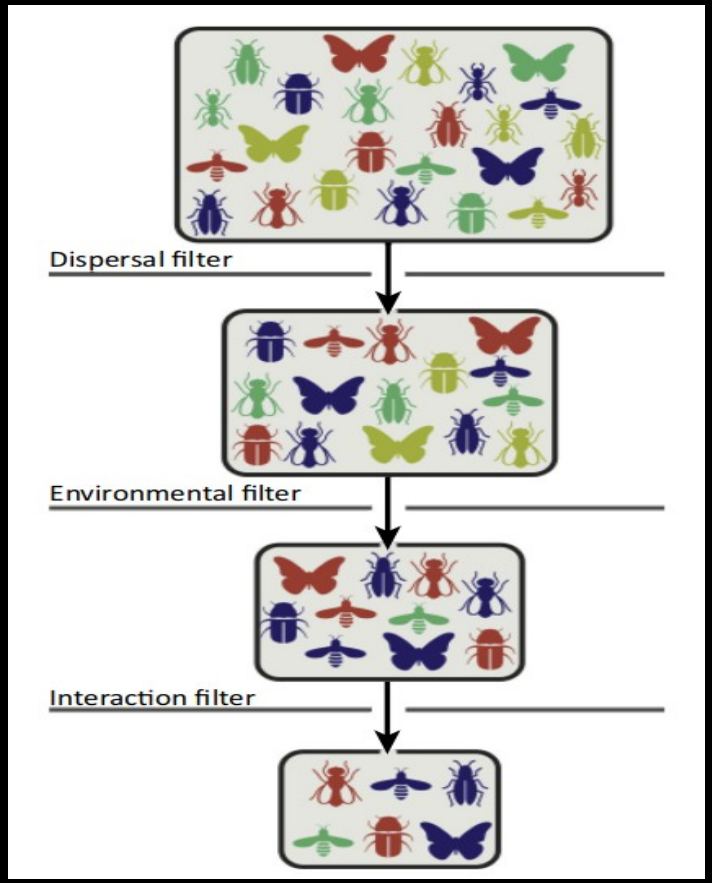
Communautés écologiques

Gewin (2006) PLoS Biology

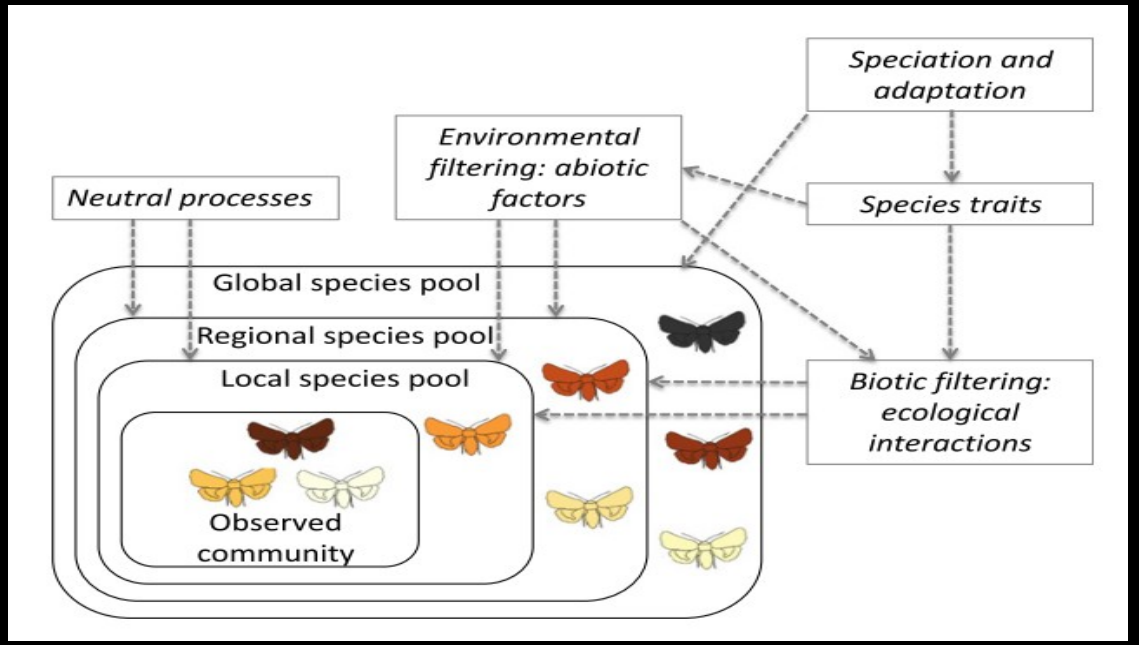
Écologie des communautés

- Décrire les communautés (assemblage d’espèces)
- Étudier les variations de composition (dans l’espace et le temps)
- Identifier les facteurs/processus sous-jacents

De nombreux processus

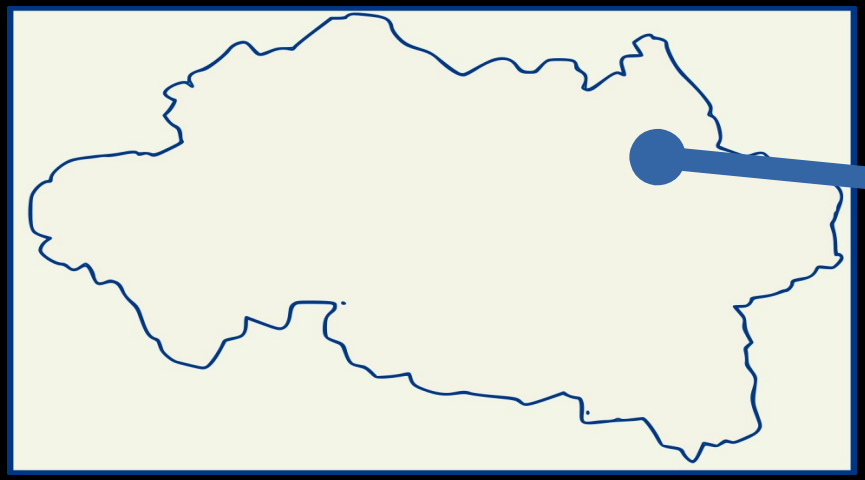


Cadotte and Tucker (2017) Trends in Ecology & Evolution

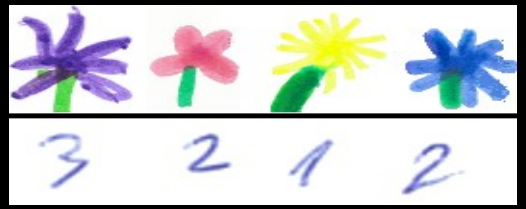


Ovaskainen et al (2017) Ecology Letters

Une communauté

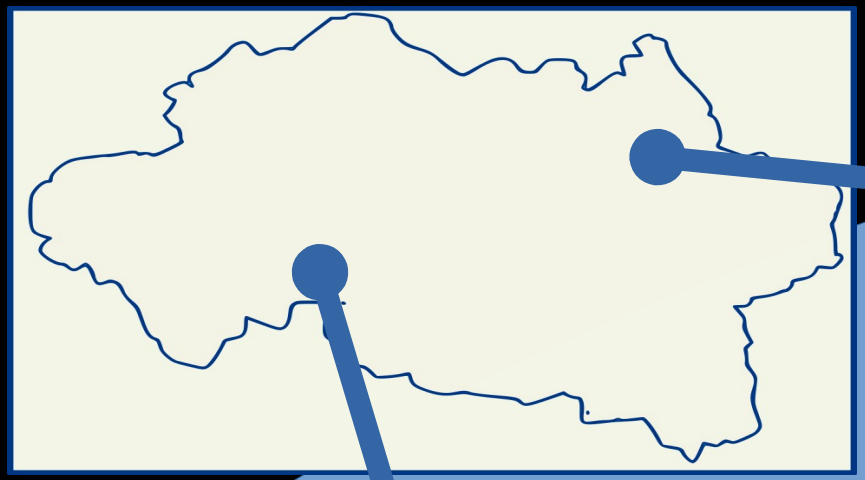


Un vecteur :



Diversité α

Deux communautés

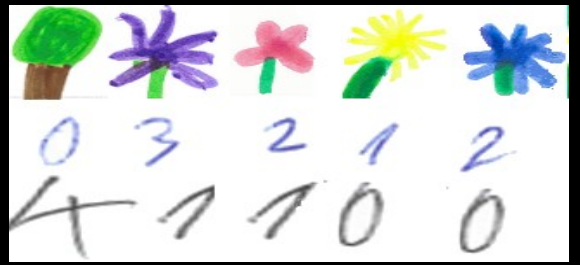


Diversité α_1

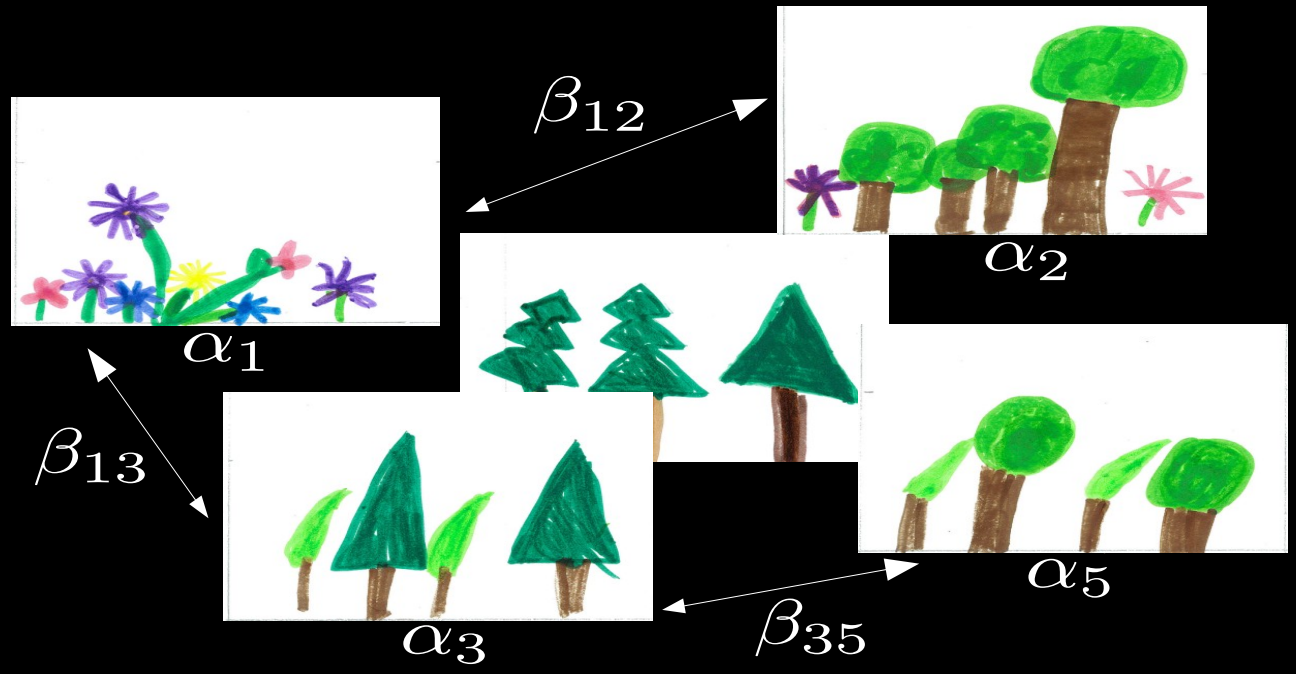
Diversité β_{12}

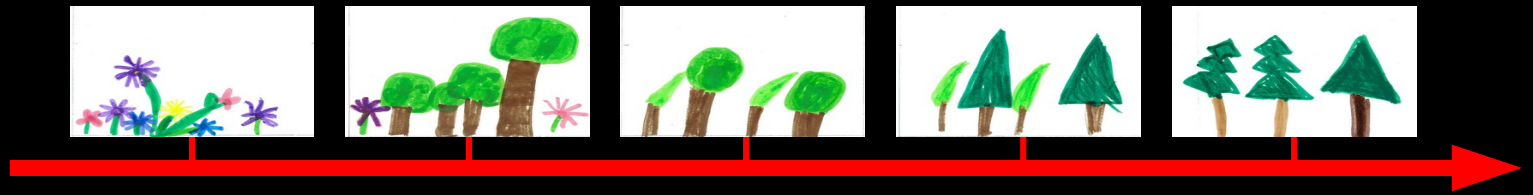
Diversité α_2

Diversité γ

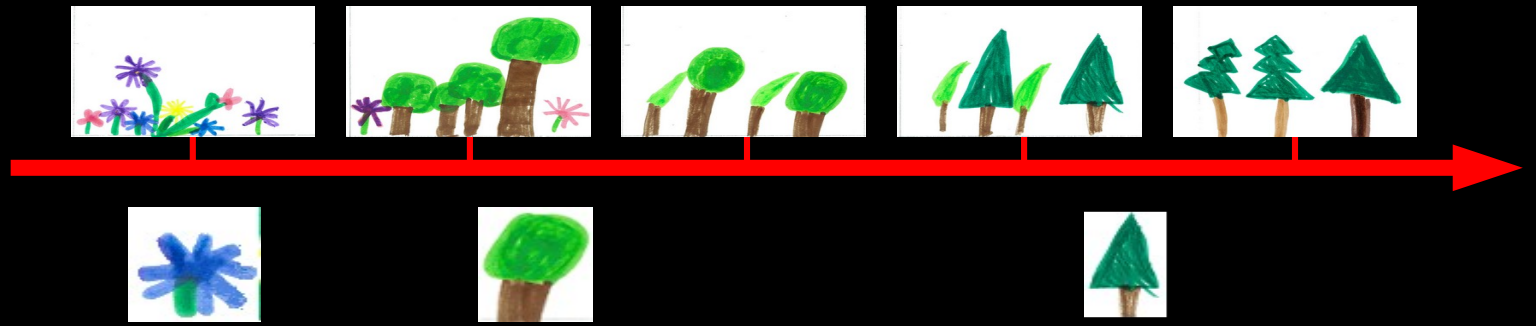


Ordination des communautés



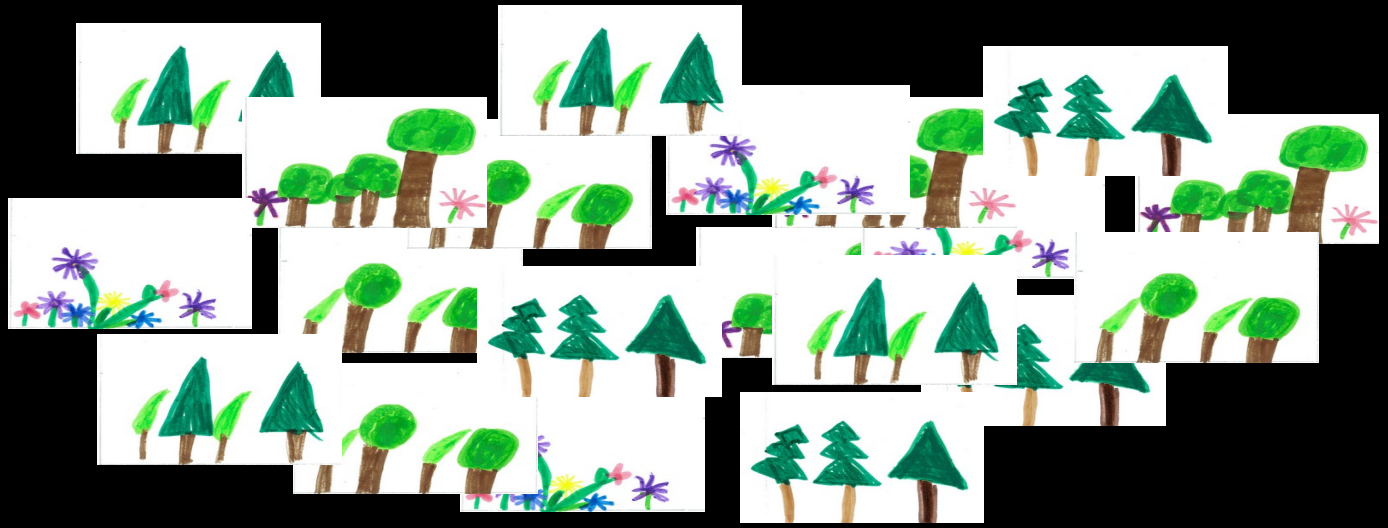


Ordination simultanée

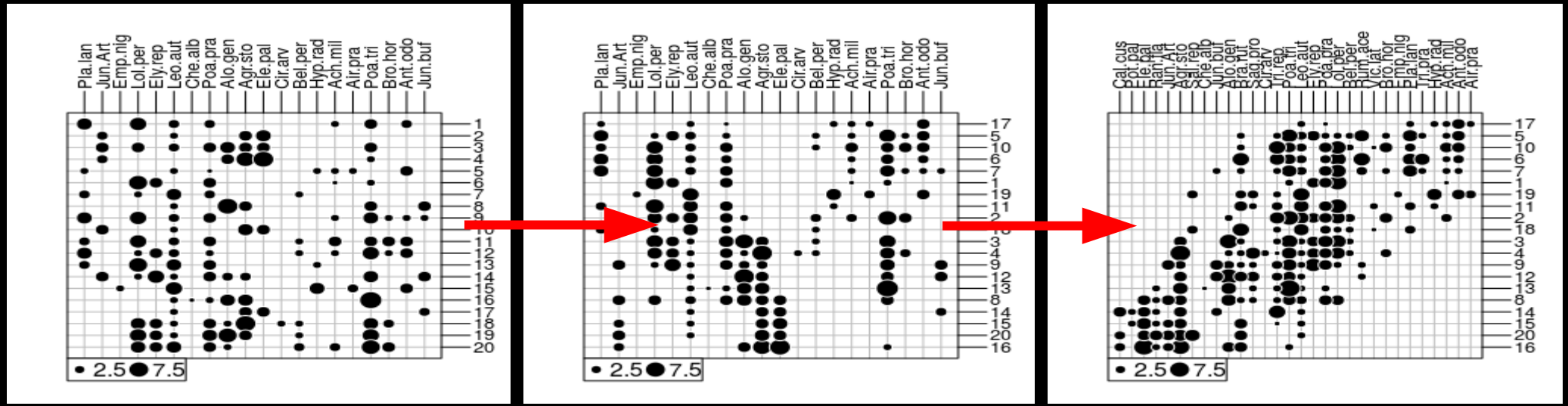


Moyenne pondérée
(*weighted averaging*)

Un casse-tête

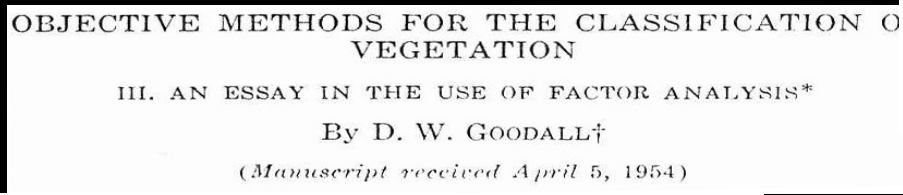


Ordonner un tableau



Besoin de méthodes objectives permettant d'ordonner les sites et les espèces et d'identifier les principaux axes de variation de diversité.

D'une question écologique à une problématique méthodologique

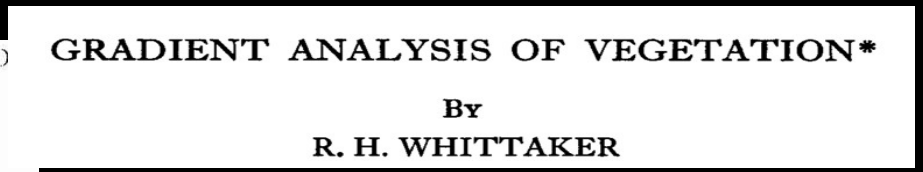


OBJECTIVE METHODS FOR THE CLASSIFICATION O
VEGETATION

III. AN ESSAY IN THE USE OF FACTOR ANALYSIS*

By D. W. GOODALL†

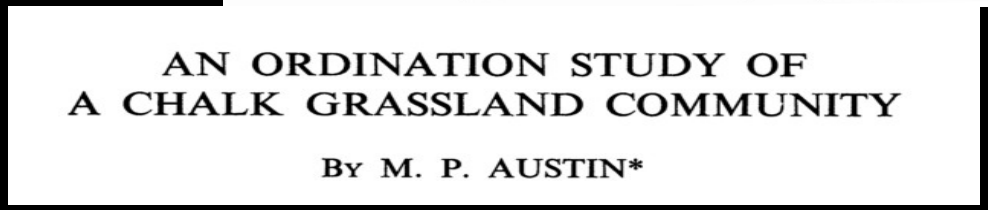
(*Manuscript received April 5, 1954*)



GRADIENT ANALYSIS OF VEGETATION*

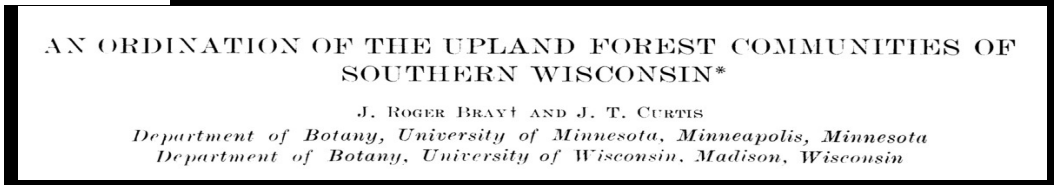
By

R. H. WHITTAKER



AN ORDINATION STUDY OF
A CHALK GRASSLAND COMMUNITY

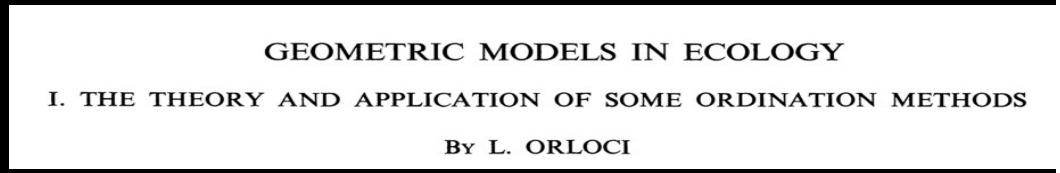
By M. P. AUSTIN*



AN ORDINATION OF THE UPLAND FOREST COMMUNITIES OF SOUTHERN WISCONSIN*

J. ROGER BRAY† AND J. T. CURTIS

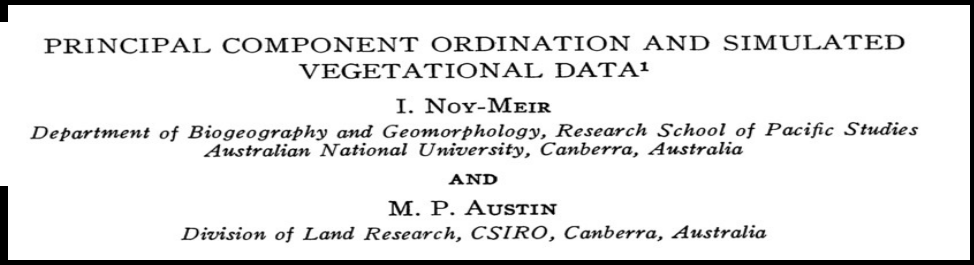
Department of Botany, University of Minnesota, Minneapolis, Minnesota
Department of Botany, University of Wisconsin, Madison, Wisconsin



GEOMETRIC MODELS IN ECOLOGY

I. THE THEORY AND APPLICATION OF SOME ORDINATION METHODS

By L. ORLOCI



PRINCIPAL COMPONENT ORDINATION AND SIMULATED VEGETATIONAL DATA[1]

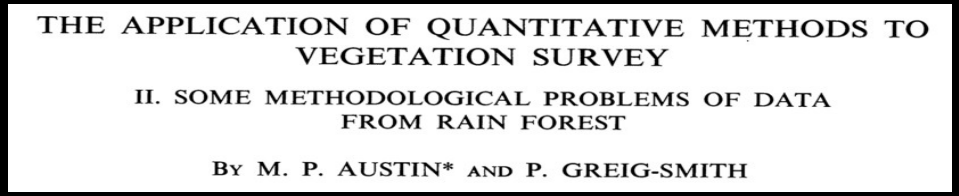
I. NOY-MEIR

Department of Biogeography and Geomorphology, Research School of Pacific Studies
Australian National University, Canberra, Australia

AND

M. P. AUSTIN

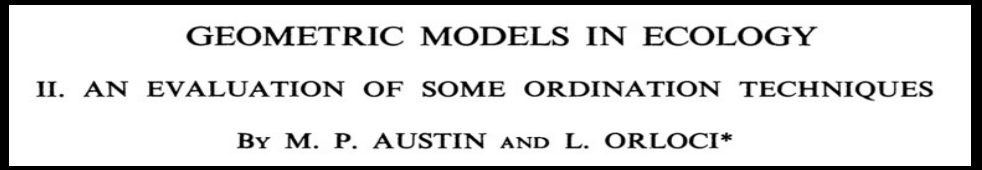
Division of Land Research, CSIRO, Canberra, Australia



THE APPLICATION OF QUANTITATIVE METHODS TO VEGETATION SURVEY

II. SOME METHODOLOGICAL PROBLEMS OF DATA FROM RAIN FOREST

By M. P. AUSTIN* AND P. GREIG-SMITH



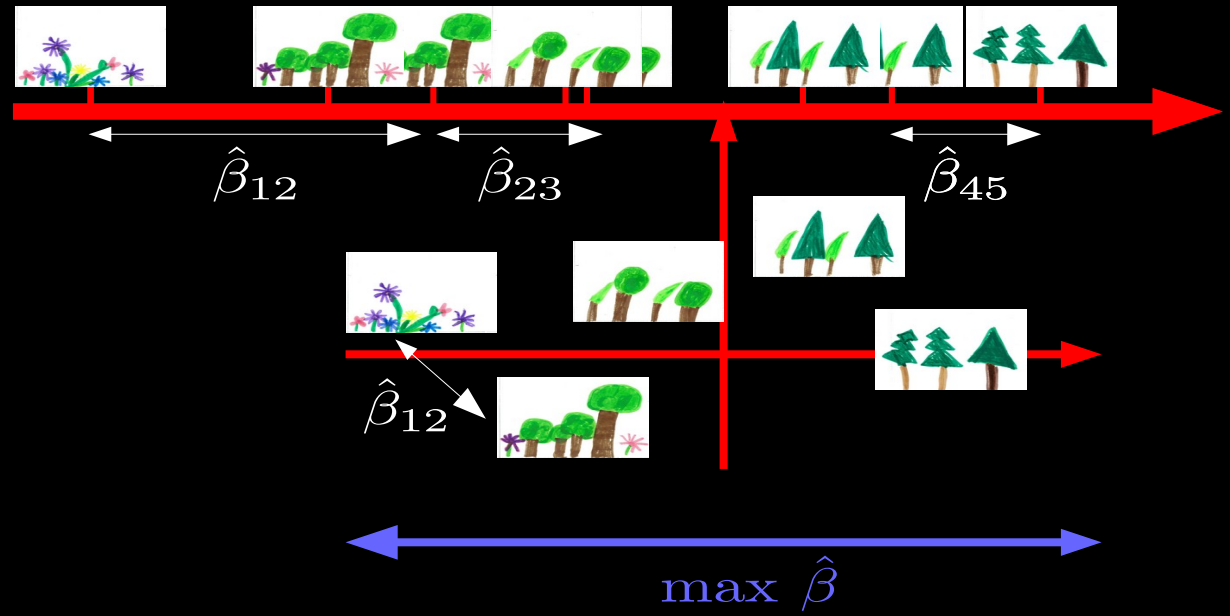
GEOMETRIC MODELS IN ECOLOGY

II. AN EVALUATION OF SOME ORDINATION TECHNIQUES

By M. P. AUSTIN AND L. ORLOCI*

L'ordination des tableaux écologiques

- Scoring
- Multi-dimensionnel
- Maximise la diversité



Analyses multivariées

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ACP (1954)

AN ORDINATION OF THE UPLAND FOREST COMMUNITIES OF SOUTHERN WISCONSIN*

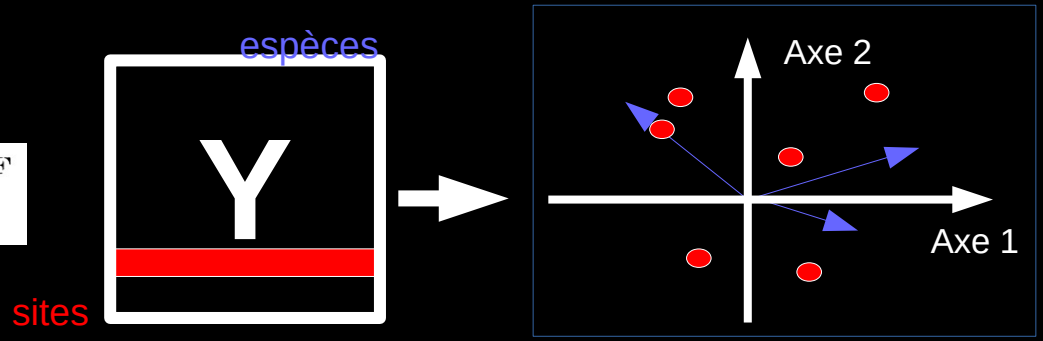
J. ROGER BRAY† AND J. T. CURTIS

PCoA (1957)

RECIPROCAL AVERAGING: AN EIGENVECTOR METHOD OF ORDINATION

BY M. O. HILL*

AFC (1973)



Réconcilier statistiques et écologie

« *A major purpose is* ***interpretation*** *[…] and not simply the representation of numerical relationships among samples or species in a hyperspace with a limited number of axes.* »

Patrons ↔ Facteurs / Processus

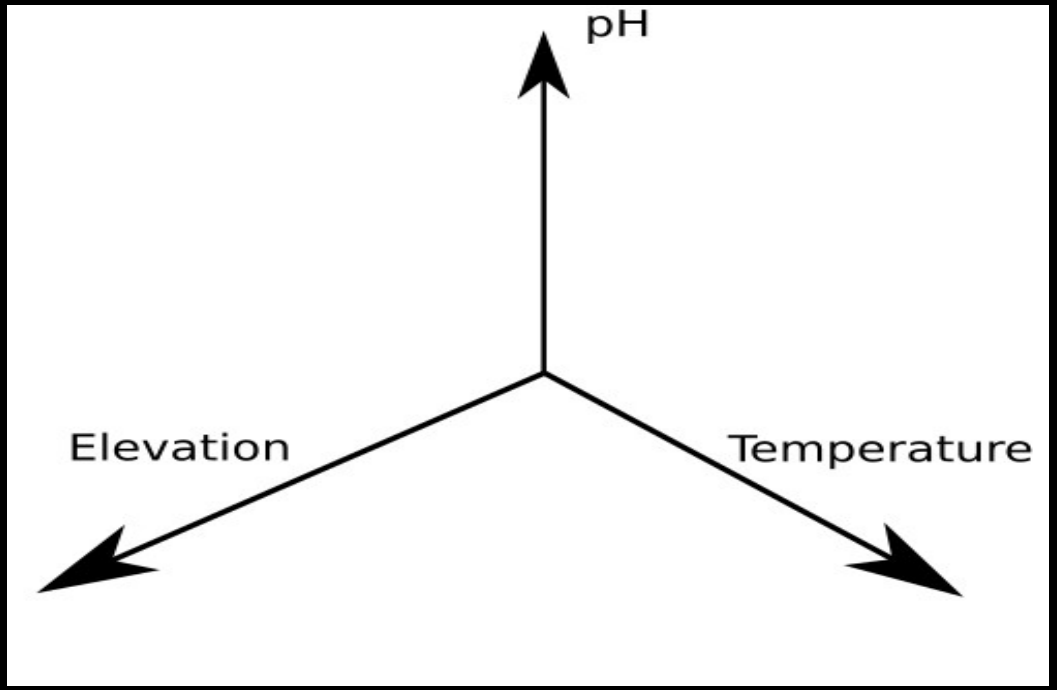
Gauch & Wentworth (1976) Vegetatio

Réconcilier statistiques et écologie

« *A major purpose is* ***interpretation of community relationships to environment,*** *and not simply the representation of numerical relationships among samples or species in a hyperspace with a limited number of axes.* »

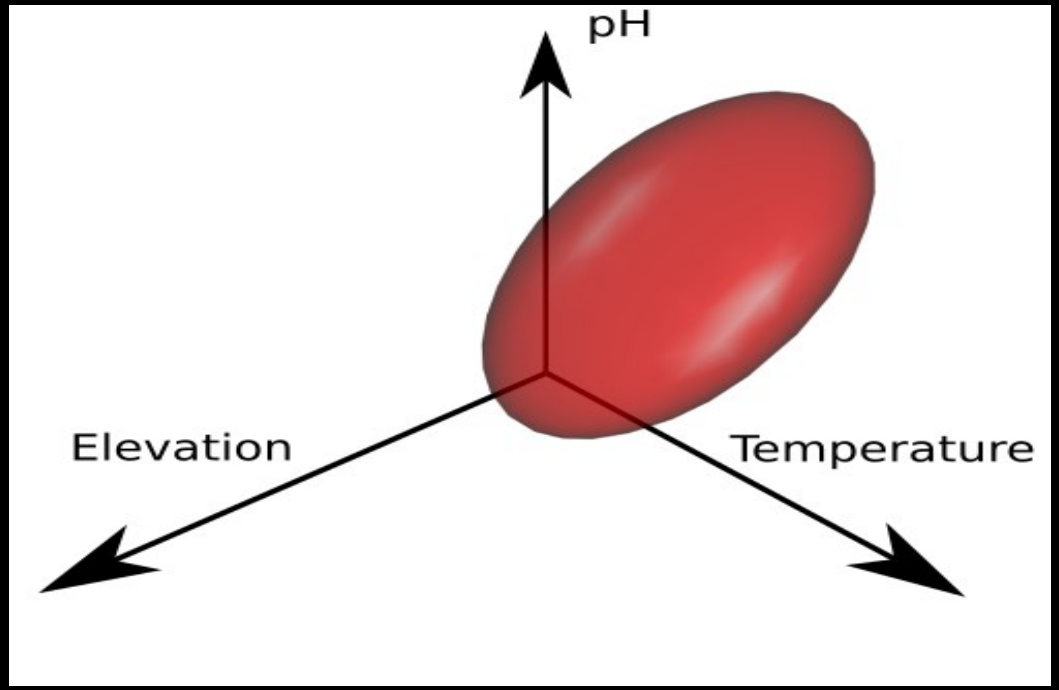
Gauch & Wentworth (1976) Vegetatio

La théorie de la niche



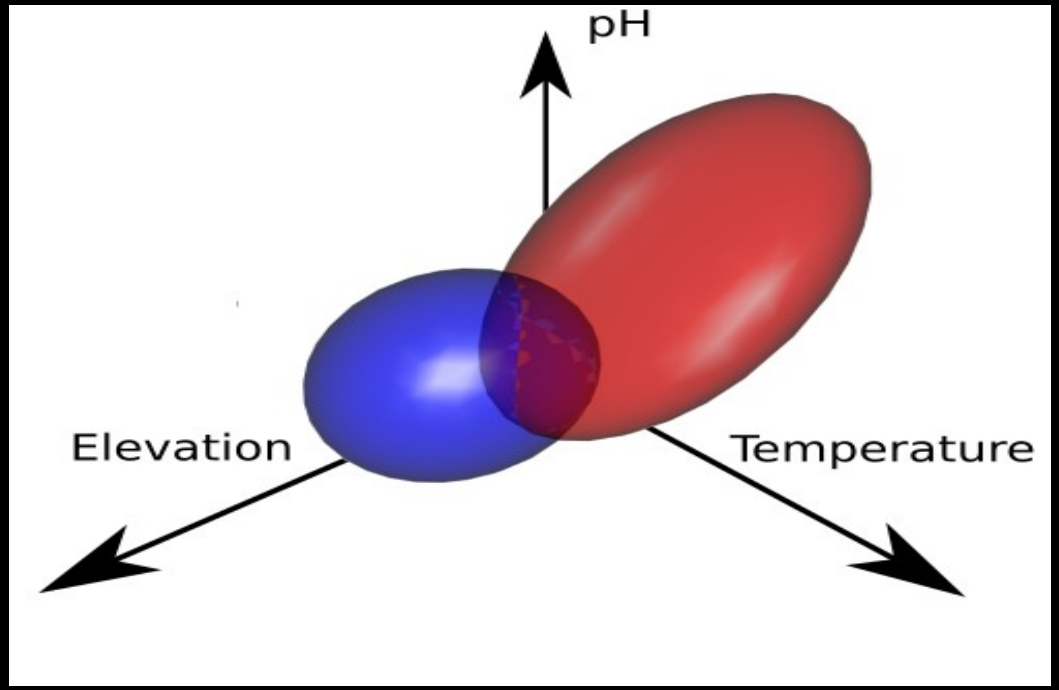
Hutchinson (1957) Population studies:

La théorie de la niche



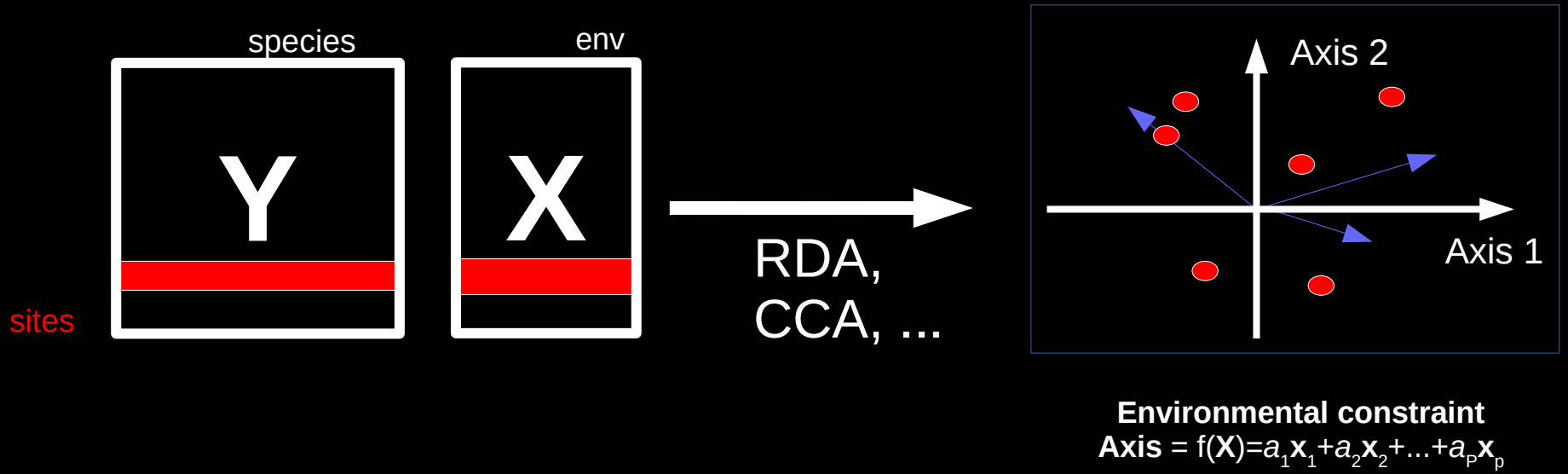
Hutchinson (1957) Population studies: animal ecology and demography

La théorie de la niche



Hutchinson (1957) Population studies: animal ecology and demography

Couplage de tableaux



Environmental constraint
Axis = f(**X**)=$a_1\mathbf{x}_1+a_2\mathbf{x}_2+...+a_P\mathbf{x}_p$

ter Braak (1986) Ecology ; ter Braak (1987) Vegetatio

Ordination directe

- Redundancy Analysis (Rao 1964)
- Canonical Correspondence Analysis (ter Braak 1986)

$$Y = XB + R = F + R$$

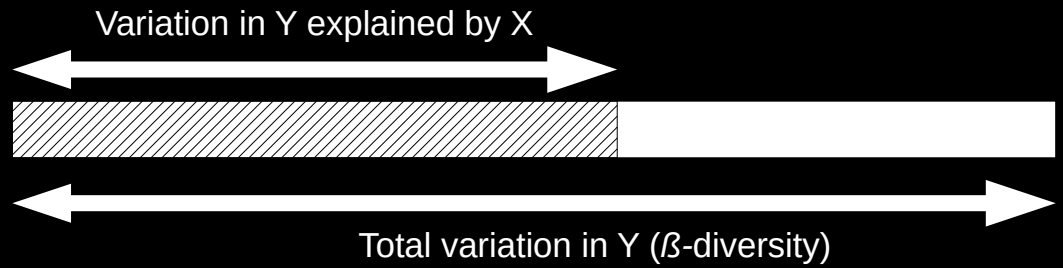
Ordination directe

- Redundancy Analysis (Rao 1964)
- Canonical Correspondence Analysis (ter Braak 1986)

$$\mathbf{Y = XB + R = F + R}$$

- Variation partitioning (Borcard et al 1992)

$R^2_{Y/X}$:



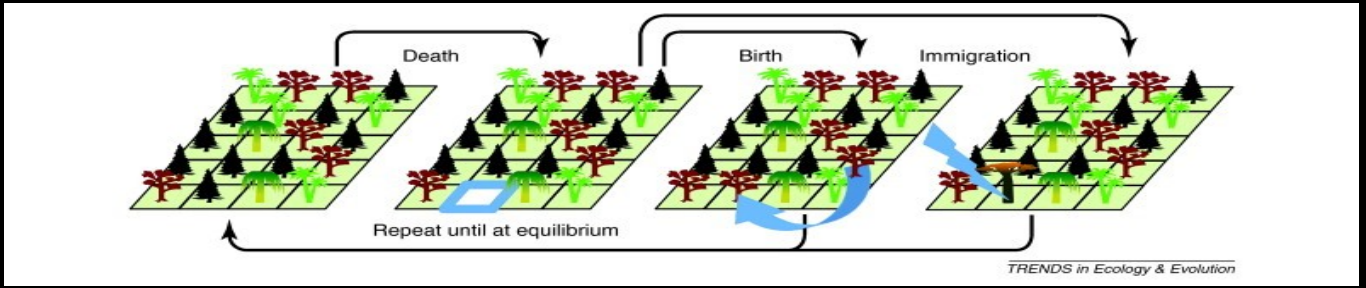
La fin de l’histoire ?

- Variables environnementale non mesurées
- Influence d’autres processus écologiques

La fin de l’histoire ?

- Variables environnementale non mesurées
- Influence d’autres processus écologiques

Species are equivalent, only stochastic events



Hubbell (2001)

Rosindell et al. (2011) TREE

La fin de l’histoire ?

- Variables environnementale non mesurées
- Influence d’autres processus écologiques
- Études expérimentales ou long-terme difficiles

Structures spatiales

- Variables environnementale non mesurées
- Influence d’autres processus écologiques
- Structures spatiales comme signature de variables non mesurées ou de processus inconnus


Ecology, 90(1), 2009, pp. 46–56

Beyond description: the active and effective way to infer processes from spatial patterns

ELIOT J. B. MCINTIRE[1,4] AND ALEX FAJARDO[2,3]

McIntire & Fajardo (2009) Ecology

Analyses Spatiales Multivariées

- Comment intégrer l’information spatiale dans une analyse ?
- Quelles méthodes pour faire parler les structures spatiales multivariées ?
- Quand les structures spatiales posent un problème ?

Dray et al (2012) Ecological Mongraphs

2008

SEDAR

Spatial Ecological Data Analysis with R" Workshop

2012

REVIEWS

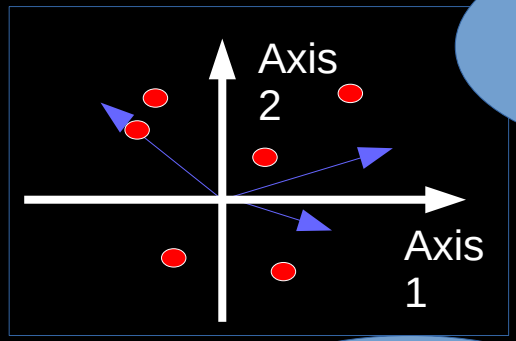
Ecological Monographs, 82(3), 2012, pp. 257–275

Community ecology in the age of multivariate multiscale spatial analysis

S. Dray,[1,16] R. Pélissier,[2,3] P. Couteron,[2] M.-J. Fortin,[4] P. Legendre,[5] P. R. Peres-Neto,[6] E. Bellier,[7,8] R. Bivand,[9] F. G. Blanchet,[10] M. De Cáceres,[11] A.-B. Dufour,[1] E. Heegaard,[12] T. Jombart,[1,13] F. Munoz,[2] J. Oksanen,[14] J. Thioulouse,[1] and H. H. Wagner[15]

2015

`adespatial` 0.0-1 on CRAN

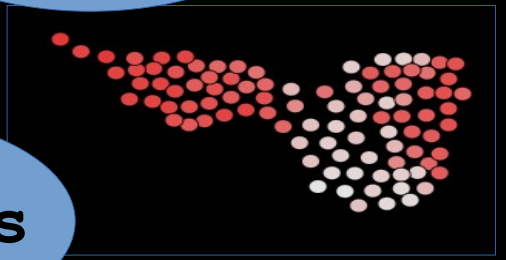


ade4

sp

adespatial

spdep



adegraphics

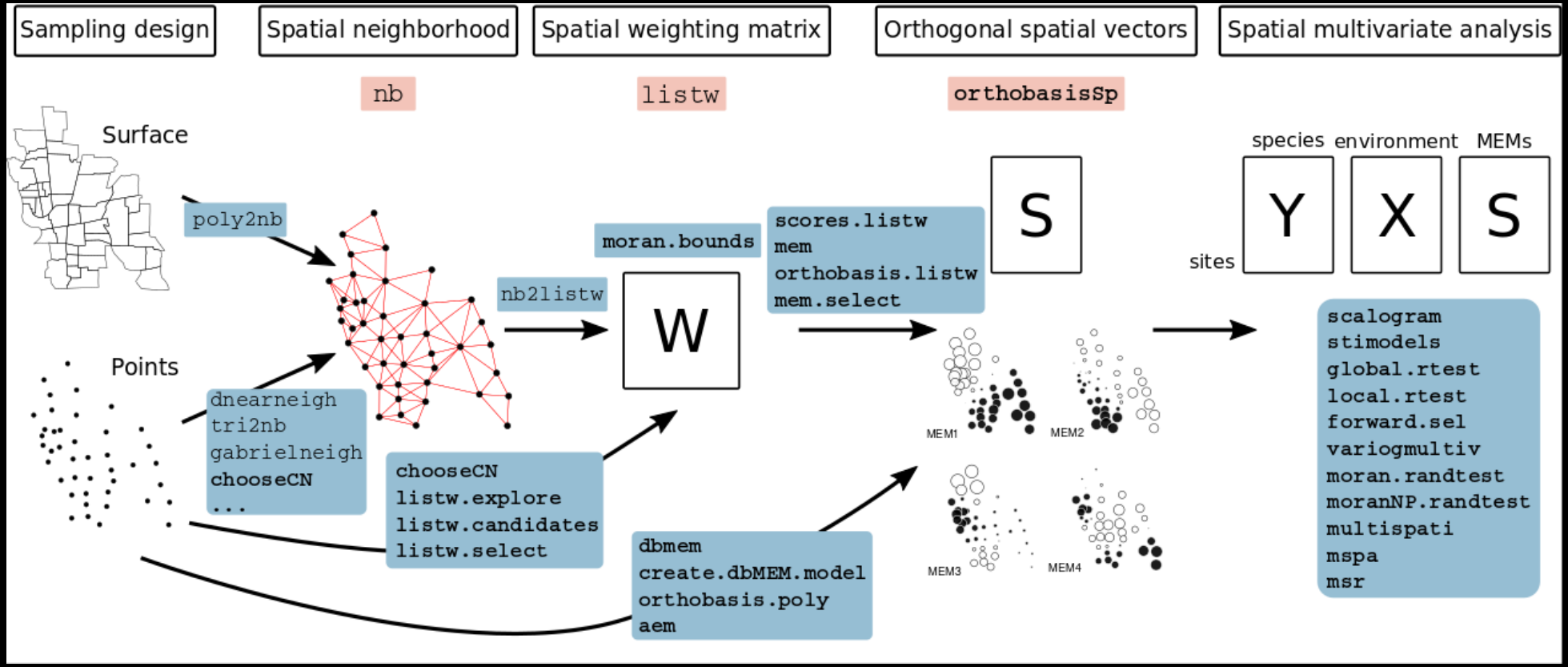
maptools

vegan

multivarié

spatial

adespatial:


Sampling design
Spatial neighborhood
Spatial weighting matrix
Orthogonal spatial vectors
Spatial multivariate analysis
nb
listw
orthobasisSp
Surface
Points
poly2nb
dnearneigh
tri2nb
gabrielneigh
chooseCN
...
nb2listw
moran.bounds
W
chooseCN
listw.explore
listw.candidates
listw.select
dbmem
create.dbMEM.model
orthobasis.poly
aem
scores.listw
mem
orthobasis.listw
mem.select
S
MEM1
MEM2
MEM3
MEM4
species
environment
MEMs
sites
Y
X
S
scalogram
stimodels
global.rtest
local.rtest
forward.sel
variogmultiv
moran.randtest
moranNP.randtest
multispati
mspa
msr

Analyses Spatiales Multivariées

- Comment intégrer l’information spatiale dans une analyse ?
- Quelles méthodes pour faire parler les structures spatiales multivariées ?
- Quand les structures spatiales posent un problème ?

Comment intégrer l’information spatiale?

- Cartographie (Goodall, 1954)
- Distances (Mantel, 1967)
- Poids spatiaux (Moran, 1954)
- Prédicteurs spatiaux (variables):
    - Polynômes des coordonnées (Gittins, 1968)
    - PCNM (Borcard & Legendre, 2002)
    - MEM (Dray et al, 2006)
    - AEM (Blanchet et al, 2008)

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Espace comme graphe (matrice de poids spatiaux)

ECOLOGICAL MODELLING 196 (2006) 483–493

available at www.sciencedirect.com

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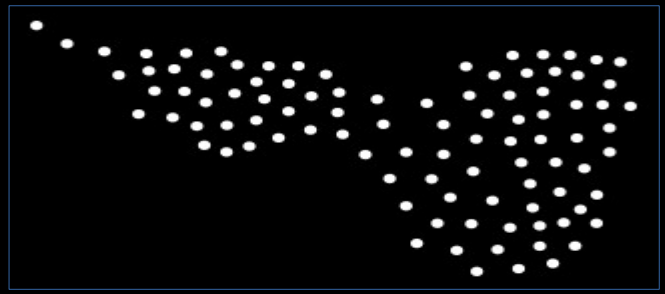
journal homepage: www.elsevier.com/locate/ecolmodel

ELSEVIER

Spatial modelling: a comprehensive framework for principal coordinate analysis of neighbour matrices (PCNM)

Stéphane Dray[a,b,*], *Pierre Legendre*[a], *Pedro R. Peres-Neto*[a,c]



Dray et al (2006) Ecological Modelling

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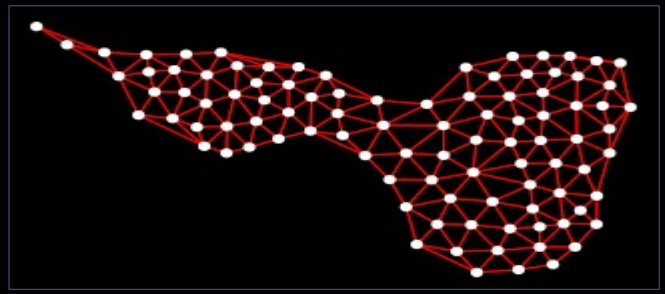

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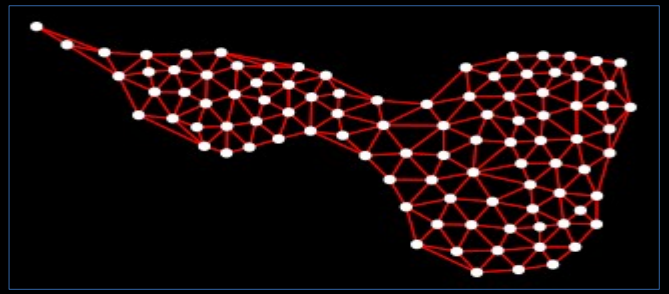
Stéphane Dray[a,b,*], *Pierre Legendre*[a], *Pedro R. Peres-Neto*[a,c]

$$\mathbf{W} = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ 1 & 0 & \cdots & 1 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 1 & \cdots & 0 \end{bmatrix}$$



Dray et al (2006) Ecological Modelling

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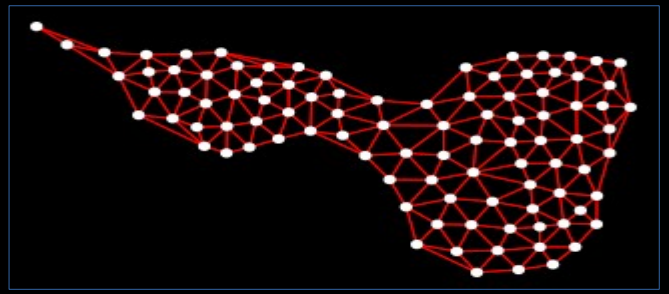
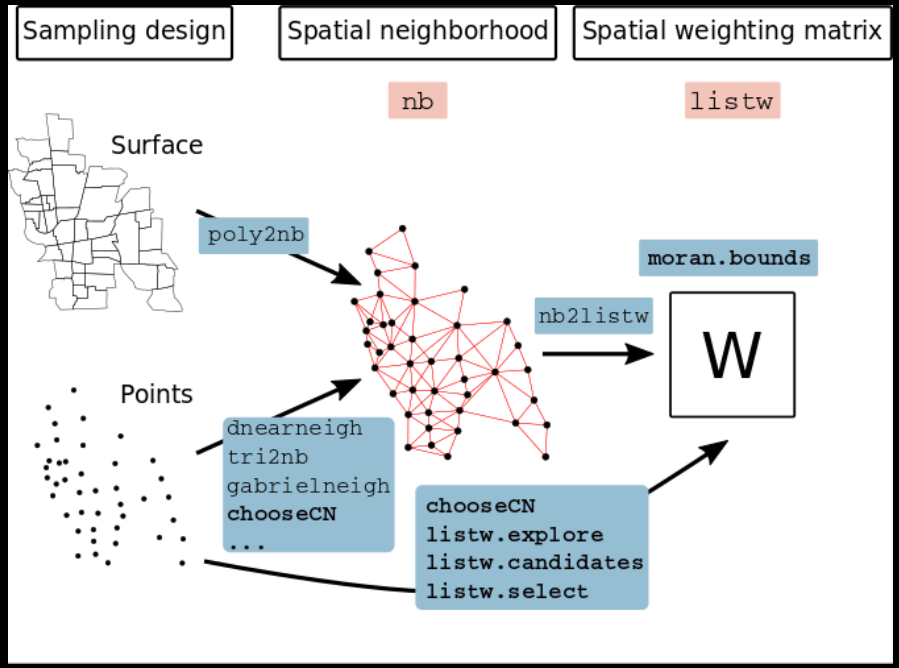


$$\mathbf{W} = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ 1 & 0 & \cdots & 1 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 1 & \cdots & 0 \end{bmatrix}$$

$$MC(\mathbf{x}) = \frac{n}{\mathbf{1}_n^\top \mathbf{W} \mathbf{1}_n} \frac{\mathbf{x}^\top \mathbf{HWHz}}{\mathbf{z}^\top \mathbf{HHz}} = \frac{n \sum_{i,j} w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i,j} w_{ij} \sum_i (x_i - \bar{x})^2}$$

Dray et al (2006) Ecological Modelling

De l ‘échantillonnage aux poids spatiaux



Disentangling good from bad practices in the selection of spatial or phylogenetic eigenvectors

David Bauman, Thomas Drouet, Stéphane Dray and Jason Vleminckx

Optimizing the choice of a spatial weighting matrix in eigenvector-based methods

David Bauman,[1,4] Thomas Drouet,[1] Marie-Josée Fortin,[2] and Stéphane Dray[3]

Bauman et al (2018) Ecography
Bauman et al (2018) Ecology

listw.explore

Generate R code to create a spatial weighting matrix

nb options

Sp object or coordinates: xyir

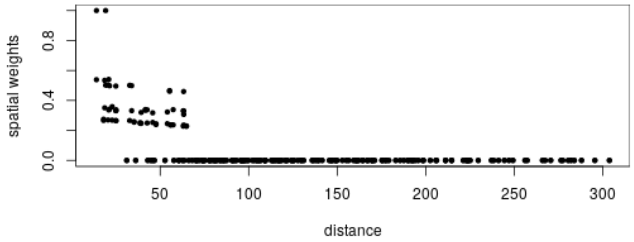
Graph type: Gabriel

listw options

Standardization style: W

General weights: 1 - d/max(d)

Spatial weights



R code (copy & paste in the R console):

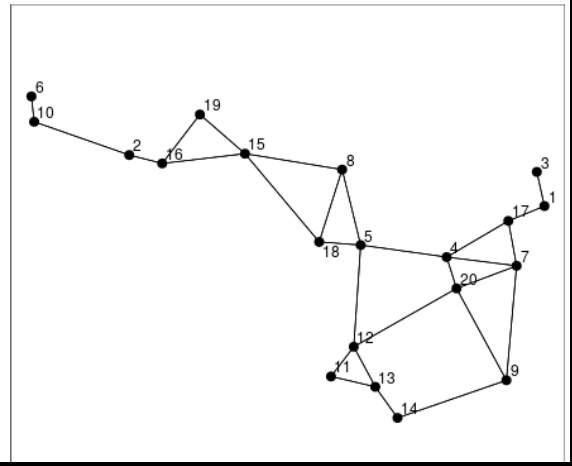
```
library(adespatial);library(sp);library(spdep)
nb <- chooseCN(coordinates(xyir), type = 2, plot.nb = FALSE)
distnb <- nbdists(nb, xyir)
fdist <- lapply(distnb, function(x) 1 - x/max(dist(xyir)))
lw <- nb2listw(nb, style = 'W', glist = fdist, zero.policy =
```

☑ Display summary

```
Neighbour list object:
Number of regions: 20
Number of nonzero links: 56
Percentage nonzero weights: 14
Average number of links: 2.8
Link number distribution:

1 2 3 4
```

Connectivity



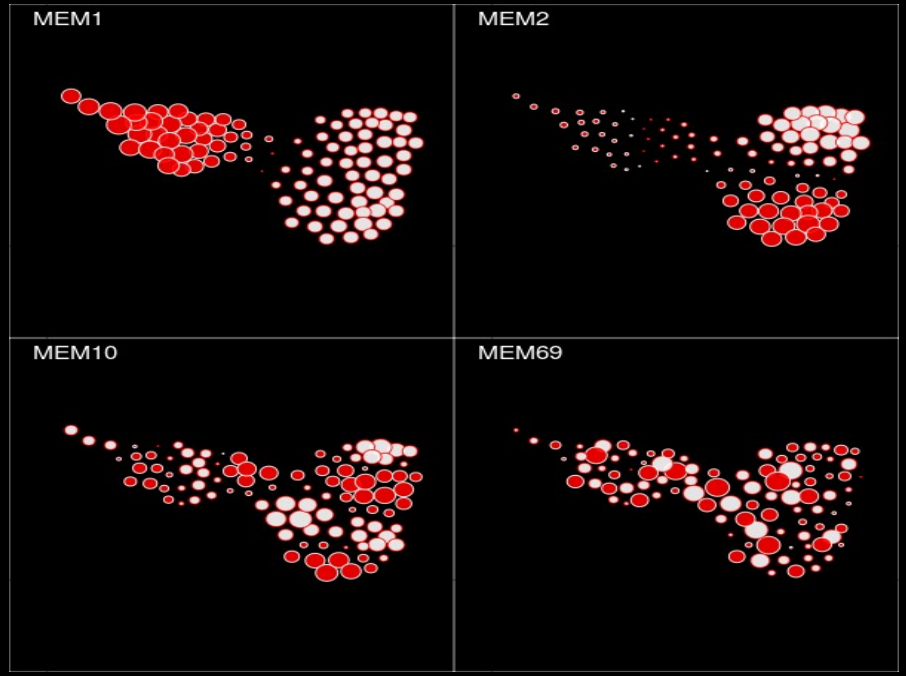
Moran's Eigenvector Maps

$$\mathbf{HWHV} = \mathbf{V}\Lambda$$

Eigenvectors are orthogonal and maximize Moran's coefficient :

$$MC(\mathbf{v}_i) = \lambda_i$$

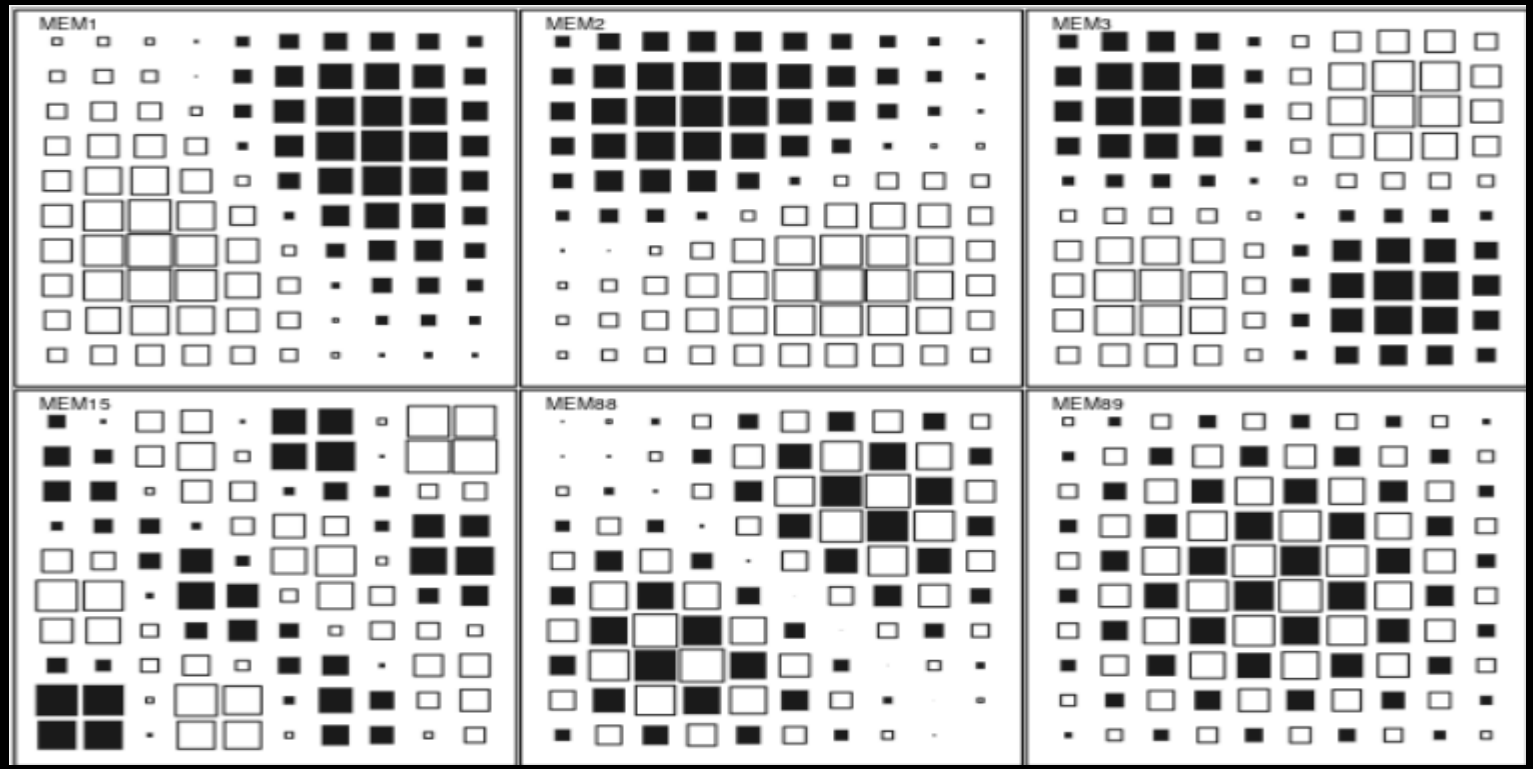
```
mymem <- mem(mylistw)
plot(mymem[,c(1,2,10,69], xy)
```



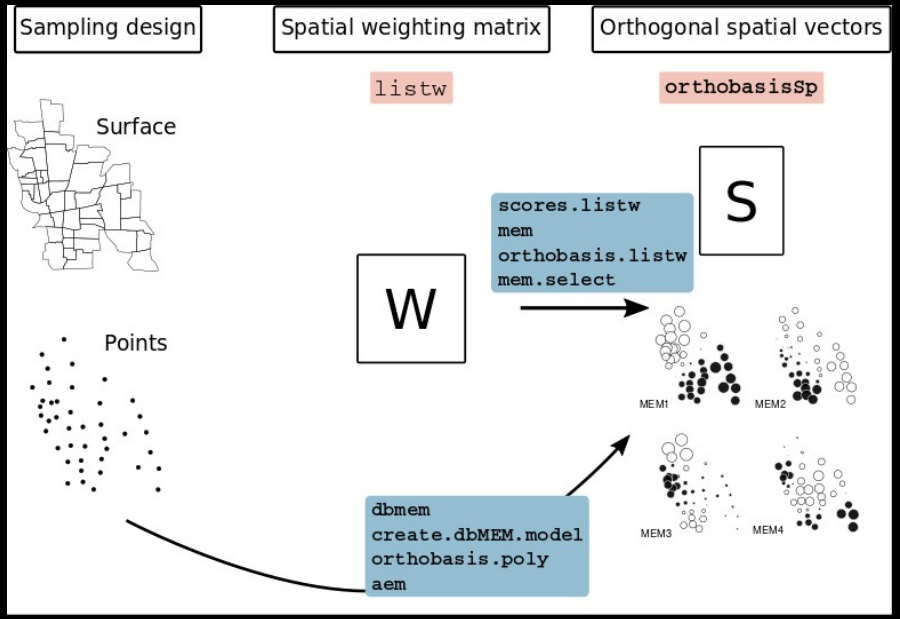
Dray et al (2006) Ecological Modelling

Moran's Eigenvector Maps

Échantillonnage régulier 2D



Des matrices de poids aux prédicteurs spatiaux



`orthobasisSp`

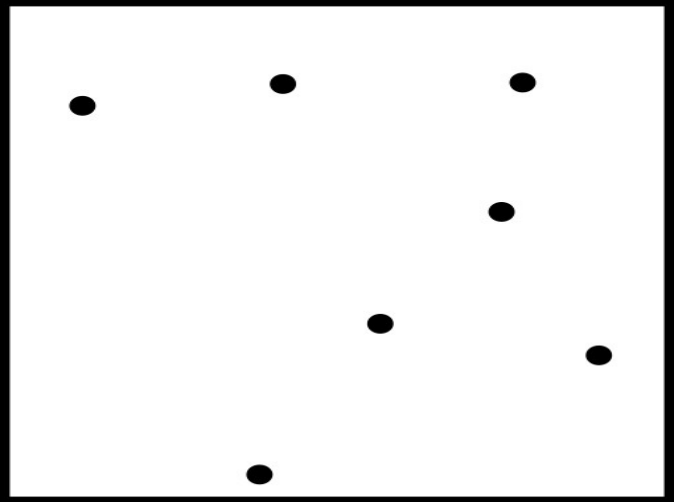
- **`plot, summary, print`** methods
- inherits from **`data.frame`**

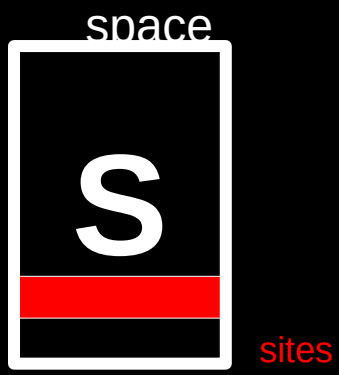
Analyses Spatiales Multivariées

- Comment intégrer l’information spatiale dans une analyse ?
- Quelles méthodes pour faire parler les structures spatiales multivariées ?
- Quand les structures spatiales posent un problème ?

Dray et al (2012) Ecological Mongraphs

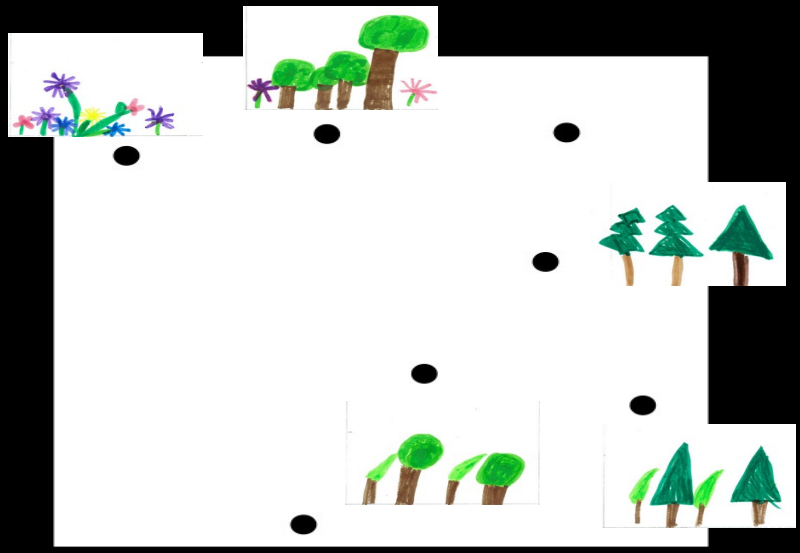
Information spatiale

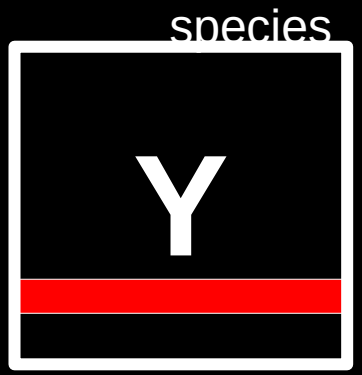


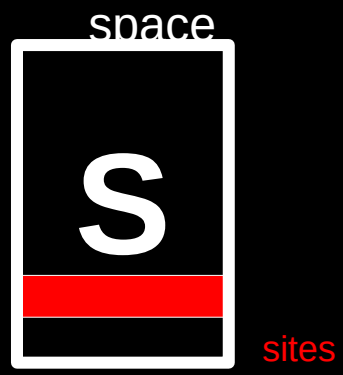


- Poids spatiaux
- MEM
- Distances

Comment la composition varie dans l’espace ?

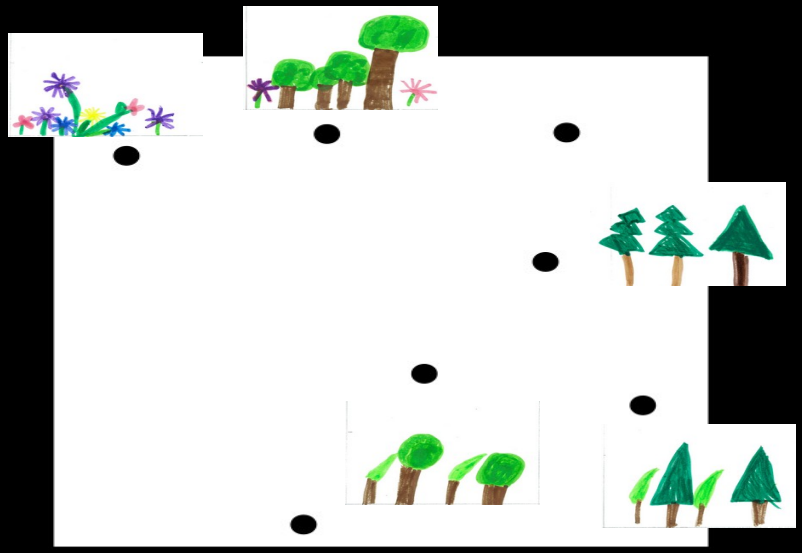


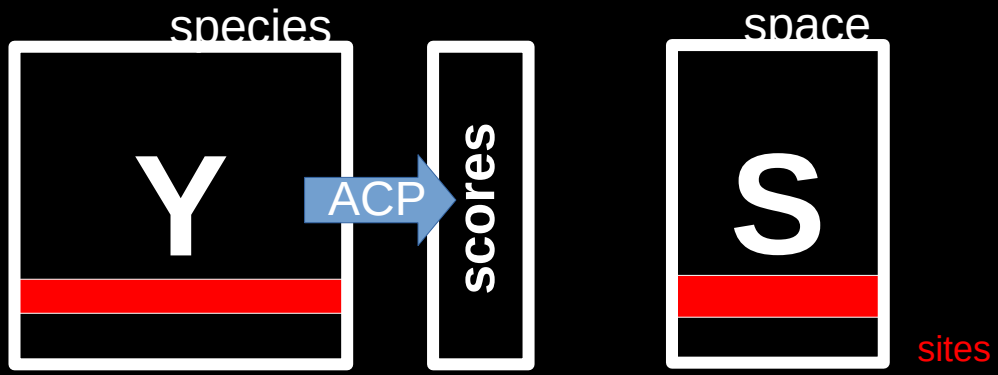




- Poids spatiaux
- MEM
- Distances

Comment la composition varie dans l'espace ?
Approche indirecte

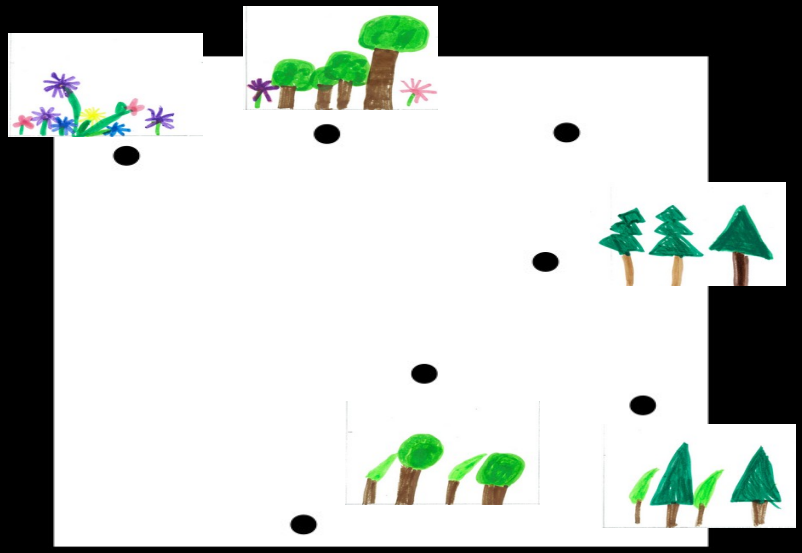


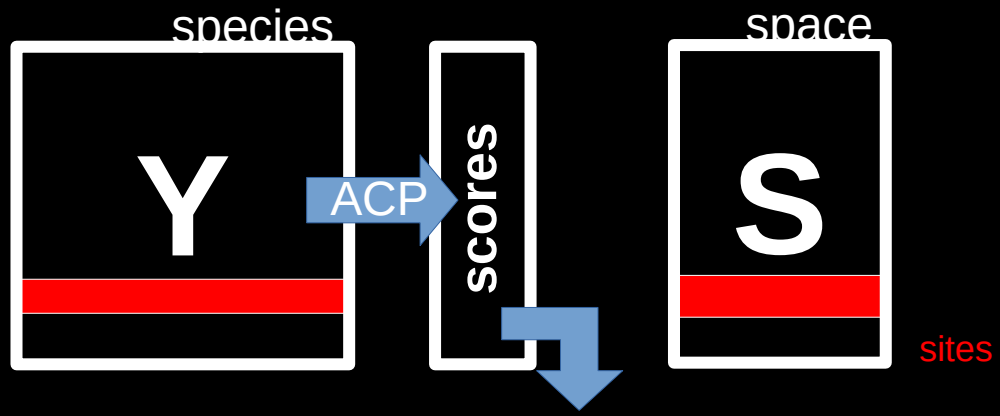


- Poids spatiaux
- MEM
- Distances

Comment la composition varie dans l'espace ?

Approche indirecte





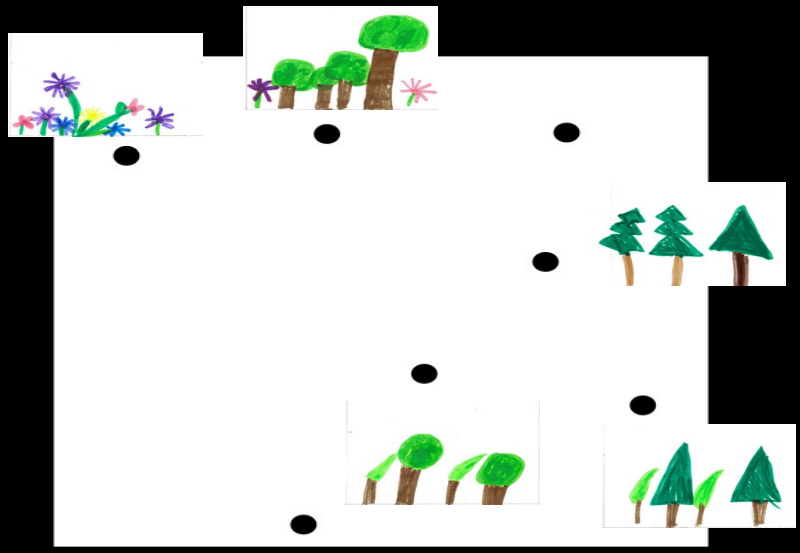
Indice de Moran ⟵ Poids spatiaux

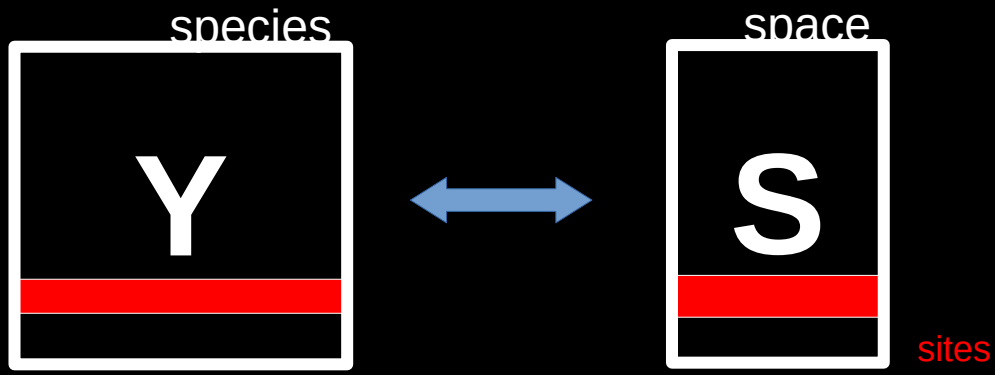
Régression ⟵ MEM

Test de Mantel ⟵ Distances

Comment la composition varie dans l'espace ?

Approche directe



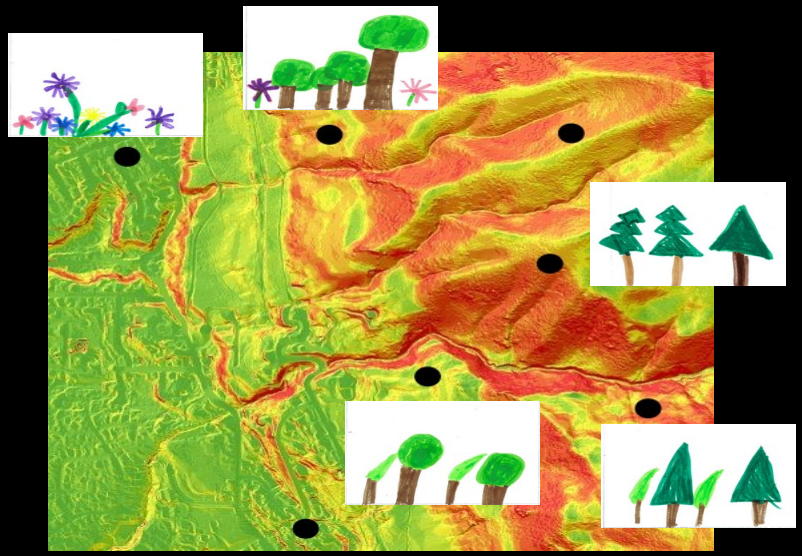


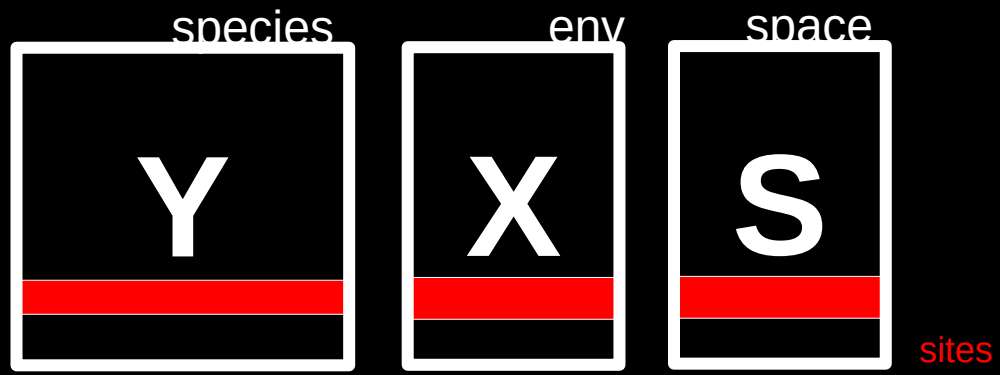
Multispati ⟵ Poids spatiaux

RDA / MSPA ⟵ MEM

Test de Mantel ⟵ Distances

Pourquoi la composition varie dans l'espace ?



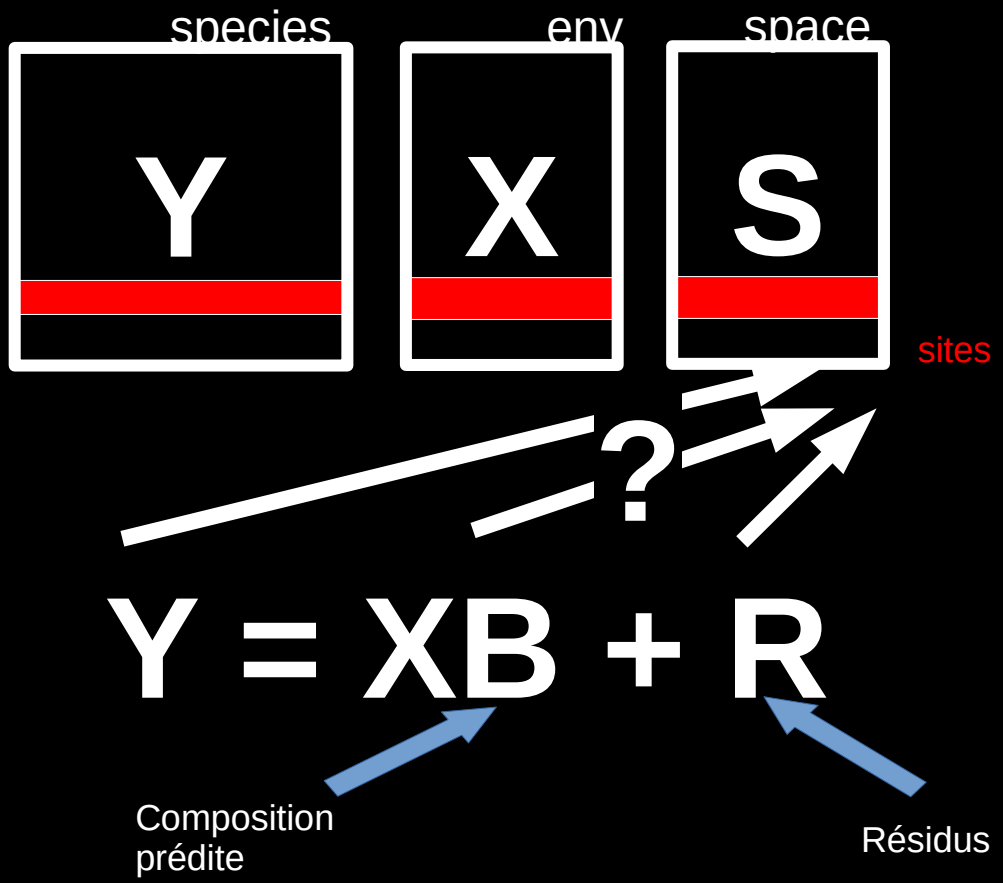


$$Y = XB + R$$

Composition prédite

Résidus

Pourquoi la composition varie dans l’espace ?



La présence et la nature des structures spatiales observées, prédites et résiduelle peut être étudiée ou prise en compte.

Structures spatiales comme proxy

Résidus (autocorrélés)

$$Y = XB + R$$

$$= XB_S + XB_{NS} + R_S + R_{NS}$$

Proxy de processus ou variables non mesurées

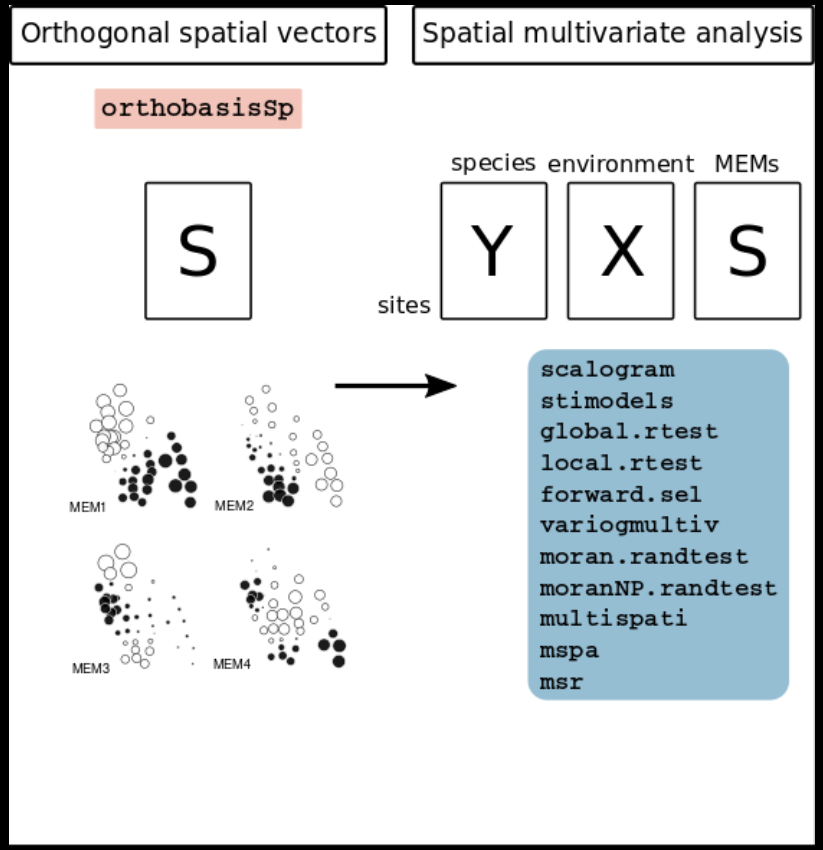
Résidus indépendants

Structures spatiales comme proxy

$$Y = XB + R$$
$$= XB_S + XB_{NS} + R_S + R_{NS}$$

- Structures spatiales liées à l'environnement (Y~X ↔ S) : XB_S
- Structures spatiales liées à d'autres facteurs (Y|X ↔ S) : R_S
- Quelles échelles ?

Méthodes spatiales multi-échelles et/ou multivariées



Méthodes spatiales multivariées

- Multivariate autocorrelation:
  `global.rtest(Y, mylistw)`

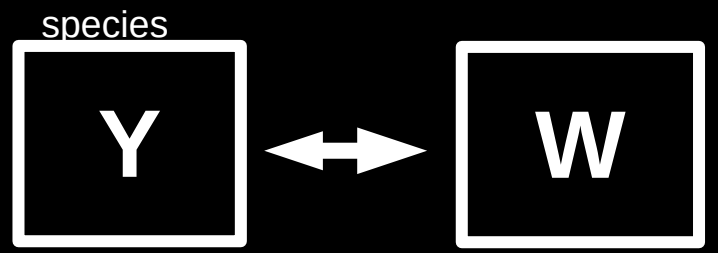
  Jombart et al (2008) Heredity

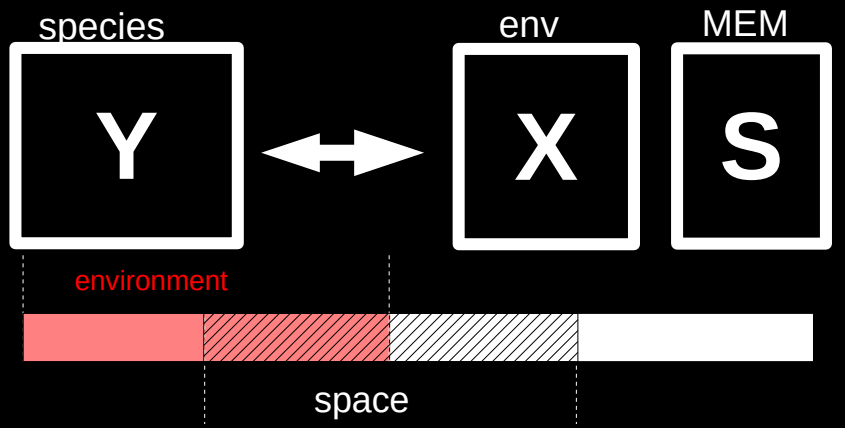
- Spatial multivariate analysis:
  `multispati(mypca, mylistw)`

  Dray et al (2008) Journal of Vegetation Science

- Constrained ordination/Variation partitioning:
  `pcaiv(mypca, mymem)`
  `varipart(Y, X, mymem)`

  Dray et al (2012) Ecological Monographs





Méthodes multi-échelles

- Moran's Index: **`moran.randtest(x, mylistw)`**

- Positive/Negative decomposition: **`moranNP.randtest(x, mylistw)`**

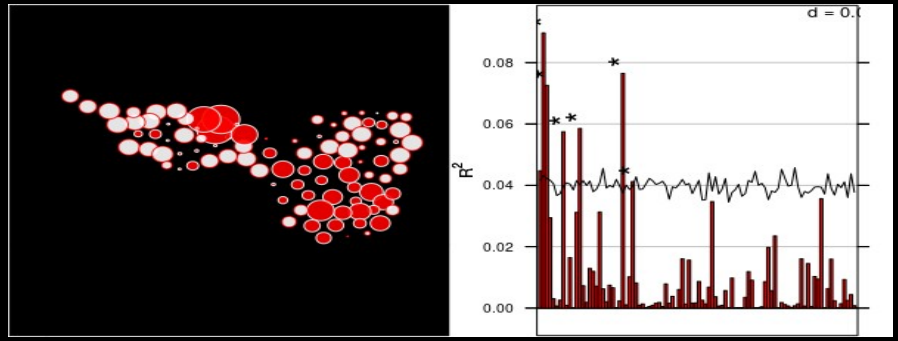
$$MC(\mathbf{x}) = \sum_{i=1}^{n-1} \lambda_i cor^2(\mathbf{x}, \mathbf{v}_i)$$

Dray (2011) Geographical Analysis

- Multiscale decomposition:

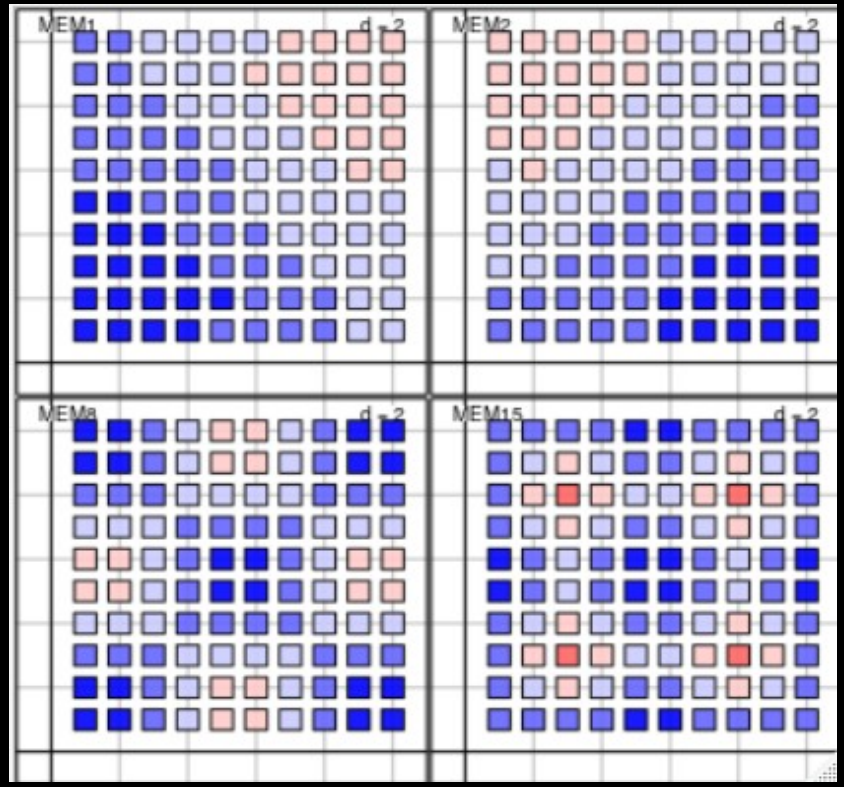
`scalogram(x, mymem)`
`mspa(mypca, mymem)`

$$\sum_{i=1}^{n-1} cor^2(\mathbf{x}, \mathbf{v}_i) = 1$$

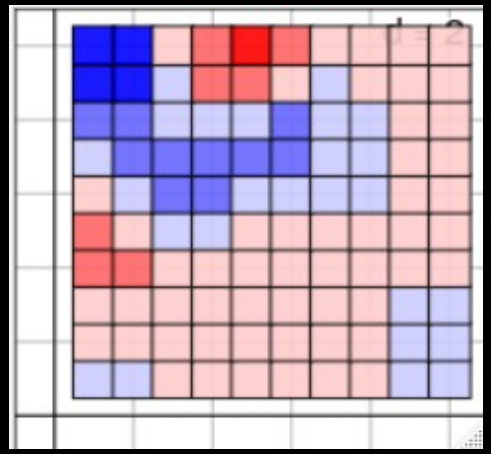


Dray et al (2012) Ecological Monographs
Jombart, Dufour & Dray (2009) Ecography

Décomposition des structures



Prédicteurs spatiaux (MEM)



Variable spatiale latente

Analyses Spatiales Multivariées

- Comment intégrer l’information spatiale dans une analyse ?
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- Quand les structures spatiales posent un problème ?

Les deux visages de l’autocorrélation

Proxies de processus non mesurés

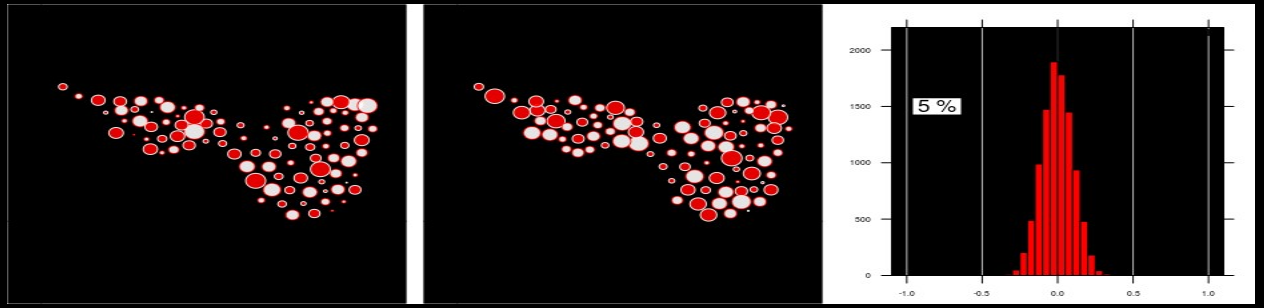
Les deux visages de l’autocorrélation

Proxies de processus non mesurés

Observations non-indépendantes

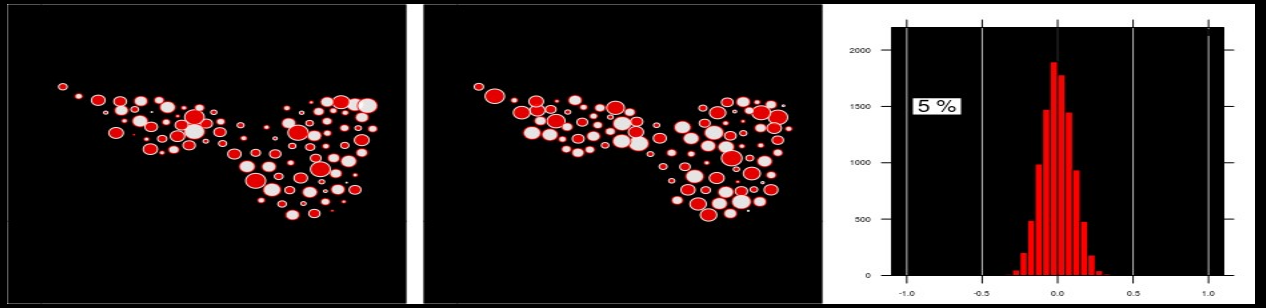
Inférence et autocorrélation spatiale

- Pas de structure

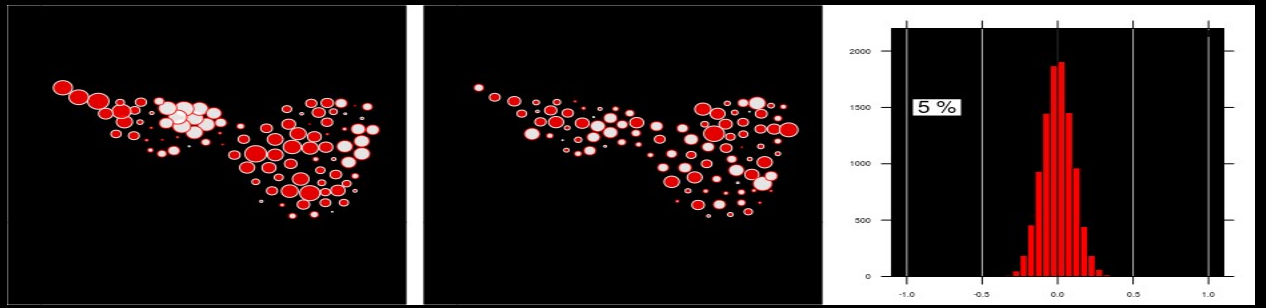


Inférence et autocorrélation spatiale

- Pas de structure

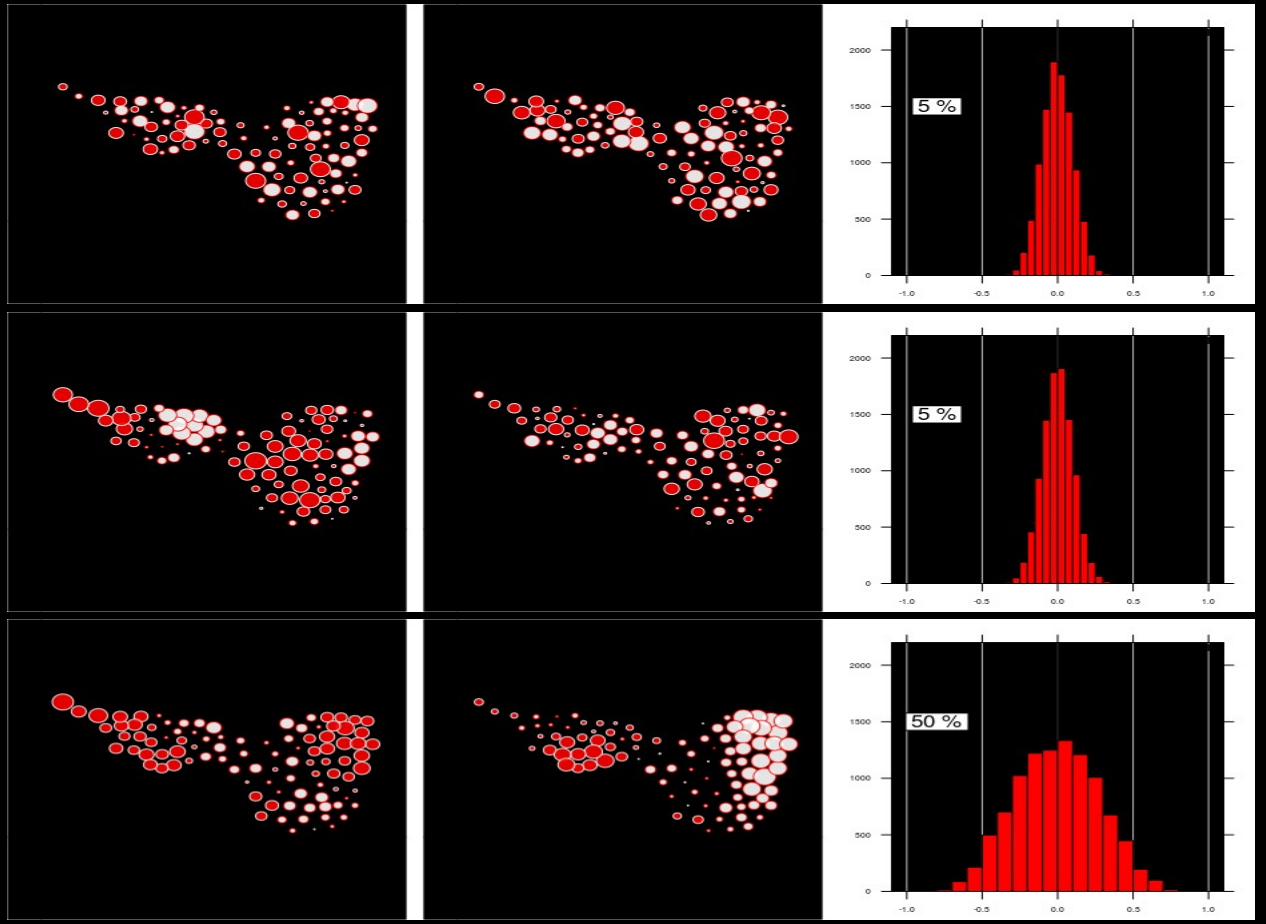


- Une structure spatiale



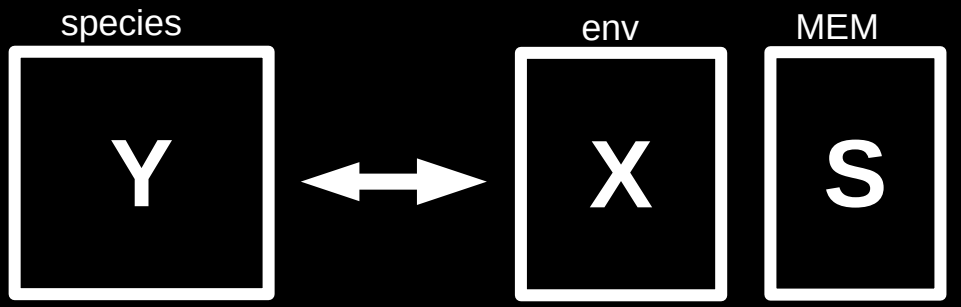
Inférence et autocorrélation spatiale

- Pas de structure
- Une structure spatiale
- Deux structures spatiales indépendantes



Conséquences en multivarié

- **X** and **Y** independent
  X and **Y** spatially structured



Conséquences en multivarié

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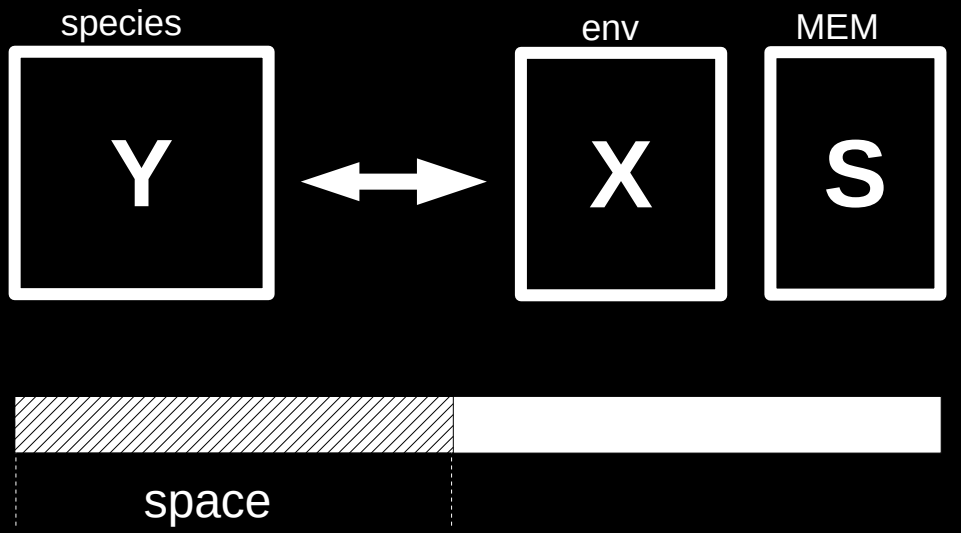
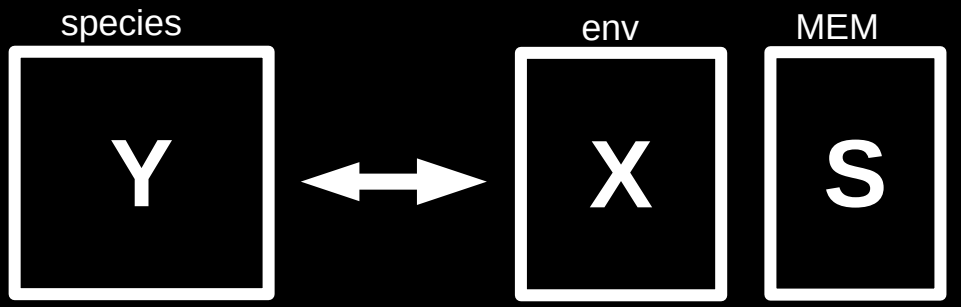


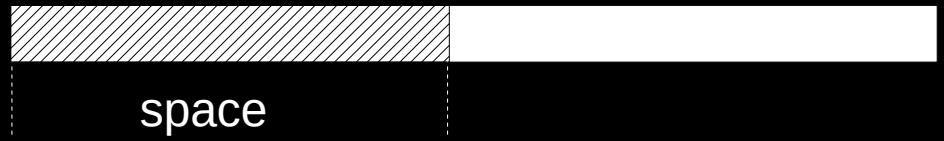
- In theory

Conséquences en multivarié

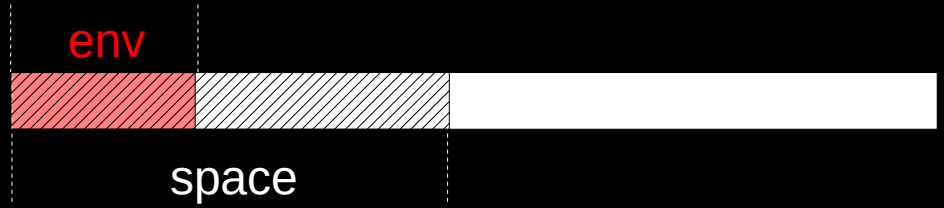
- **X** and **Y** independent
  X and **Y** spatially structured



- In theory

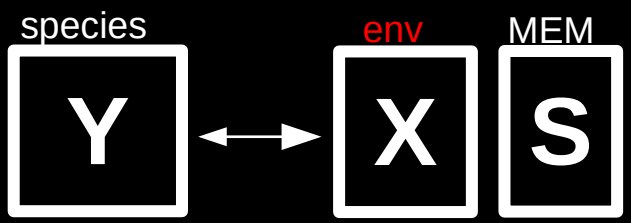


- In practice

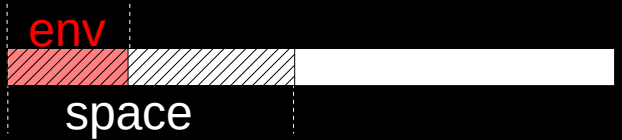


Modèles nuls contraints

- Observed data



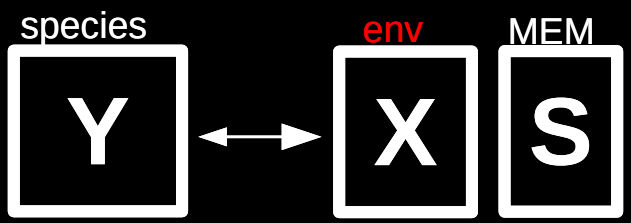
Obs :



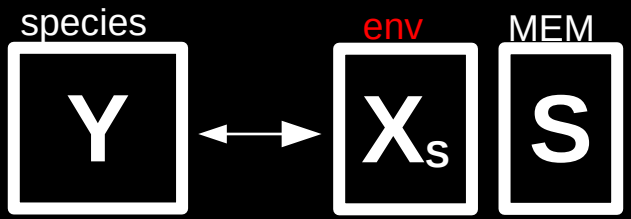
Clappe et al (2018) Ecology

Modèles nuls contraints

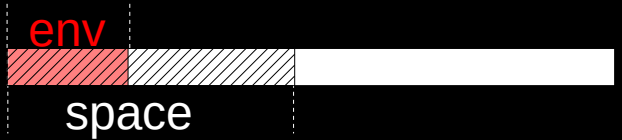
- Observed data



- Simulated data



Obs :



Clappe et al (2018) Ecology

Modèles nuls contraints

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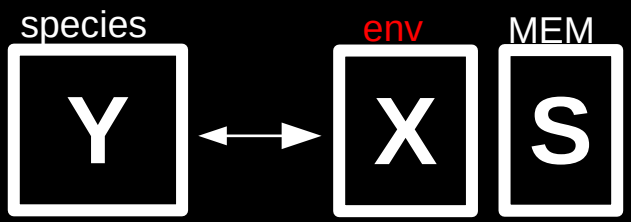
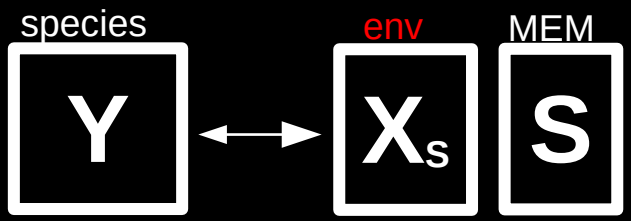
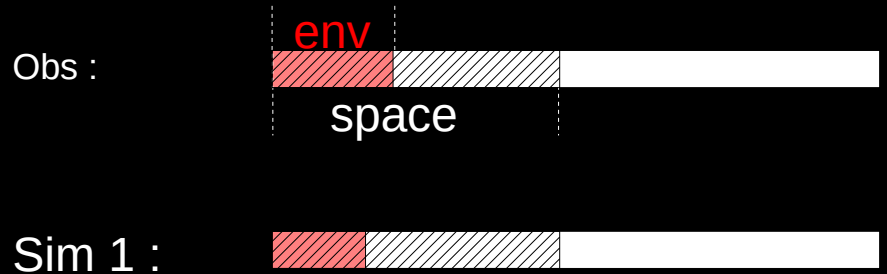


- Simulated data

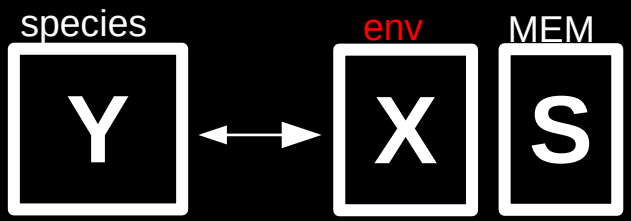




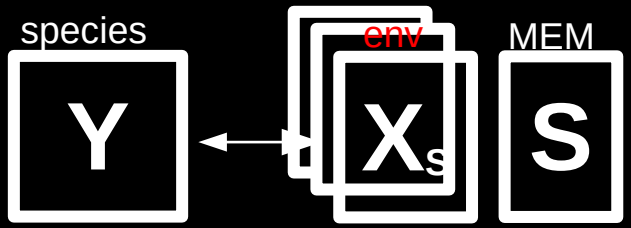
Clappe et al (2018) Ecology

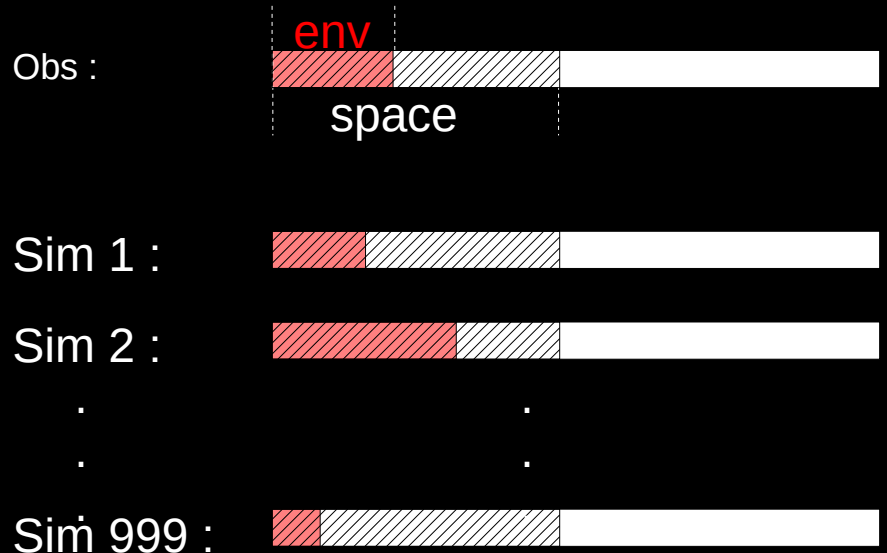
Modèles nuls contraints

- Observed data



- Simulated data

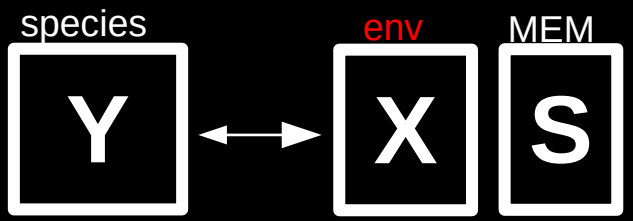




Clappe et al (2018) Ecology

Modèles nuls contraints

- Observed data



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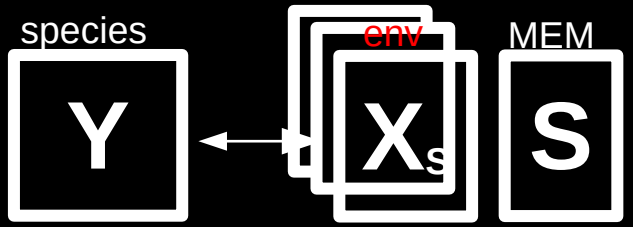
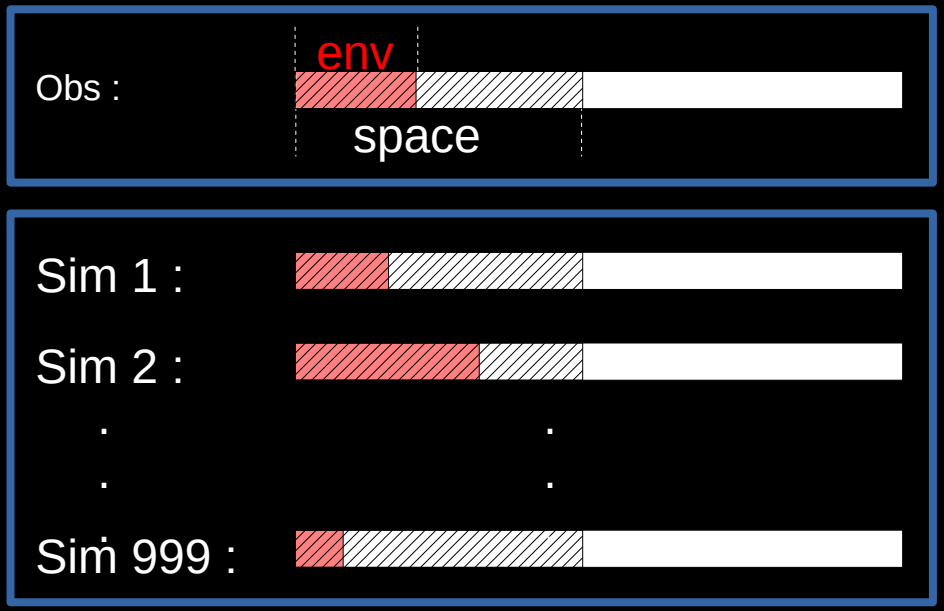


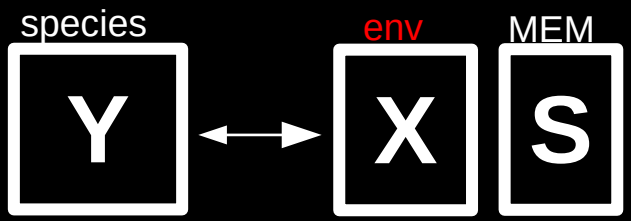
- Comparison



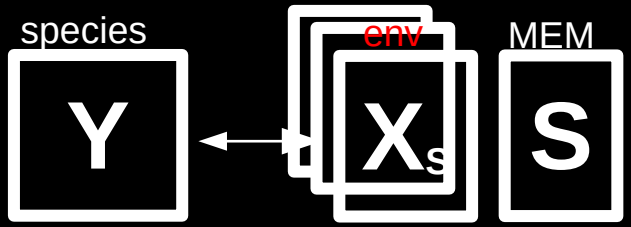
Clappe et al (2018) Ecology

Modèles nuls contraints

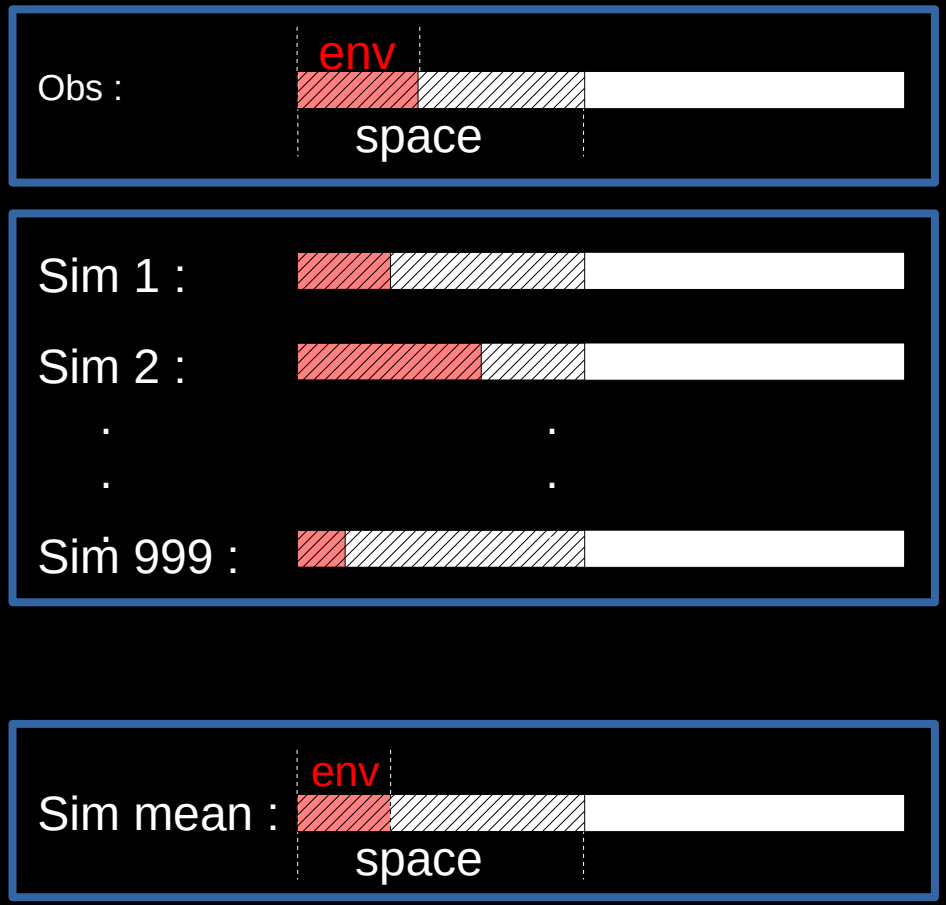
- Observed data



- Simulated data



- Comparison



Clappe et al (2018) Ecology

Moran spectral randomization

Moran's coefficient decomposition :

$$MC(\mathbf{x}) = \sum_{i=1}^{n-1} \lambda_i cor^2(\mathbf{x}, \mathbf{v}_i)$$

Variable decomposition:

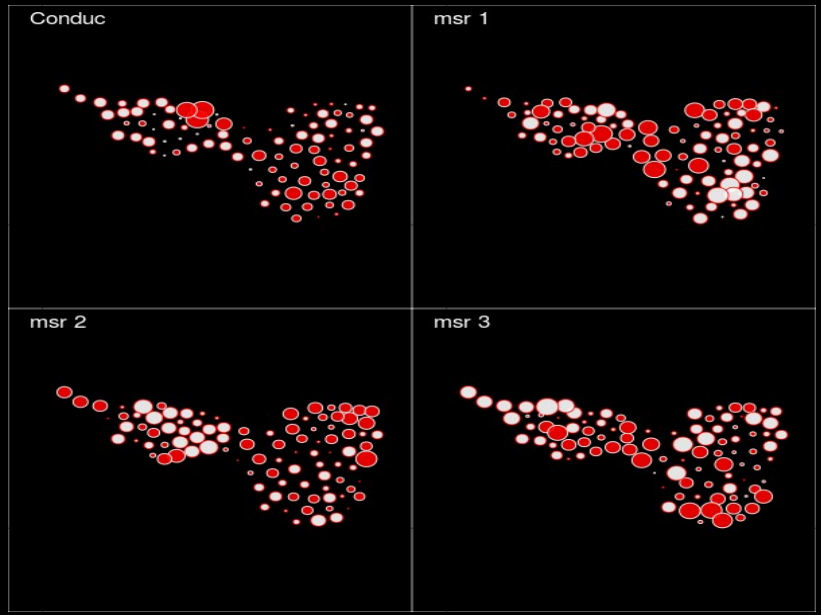
$$\mathbf{x} = \bar{x} + s(\mathbf{x}) \sum_{i=1}^{n-1} cor(\mathbf{x}, \mathbf{v}_i)\mathbf{v}_i$$

Random replicates:

$$\mathbf{x}_{sim} = \bar{x} + s(\mathbf{x}) \sum_{i=1}^{n-1} a_i \mathbf{v}_i$$

$$\text{with } a_i = \pm cor(\mathbf{x}, \mathbf{v}_i)$$

`msr(X, mymem)`



Wagner & Dray (2015) Methods in Ecology and Evolution

Conclusions

- Différents moyen d’intégrer l’information spatiale et multivariée
- Espace comme signature de processus non-mesurés

$$(Y \mid X) \leftrightarrow S$$

- Ou comme paramètre de nuisance en inférence

$$(Y \sim X) \mid S$$

GitHub

https://github.com/sdray/adespatial

Vignette

```
vignette("tutorial", package = "adespatial")
```