Measuring connectivity in landscape networks: towards meaningful metrics and operational decision support tools

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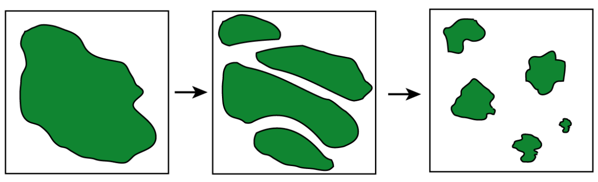
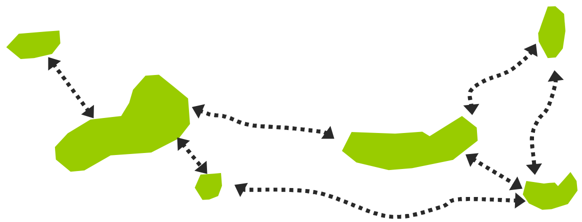
Measuring connectivity in landscape networks…

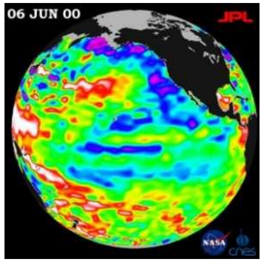
1) Which main approaches are available?
2) Should we measure only connectivity between habitat patches?
3) Is connectivity always the best conservation strategy?
4) How to model the landscape network and the connections between habitat units?
5) *Which operational tools are available?*

Landscape connectivity facilitates movement and ecological flows

- Key for the design of ecological networks, biodiversity conservation, landscape planning, climate change adaptation.
- Connectivity is functional, species-specific. Never structural?
- Positive or negative depending on the process.







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Simple spatial metrics

Easily computed with any GIS or widespread programmes for the calculation of landscape pattern metrics (e.g. Fragstats)

Many of them only consider structural connectivity or deal with functional connectivity in a very crude / primitive way.

Examples: Nearest-neighbour metrics, connectance index, patch cohesion, buffer metrics, etc.

Use:

Only for exploratory and descriptive analysis in general.

Not usable for decision making.

In some cases have suffered from particularly wide abuse.

Spatially explicit population (metapopulation) models

Biologically detailed. They consider the population dynamics resulting from birth, morality, emigration and immigration processes in individual patches.

Use:

Need to be used when the connectivity analysis requires an assessment of spatiotemporal population trends and persistence, dealing with demographic dynamics such as colonization and extinction events, demographic growth, etc.

Constrained by their data requirements. Limited to small study areas & scientific experiments (Calabrese and Fagan, 2004).

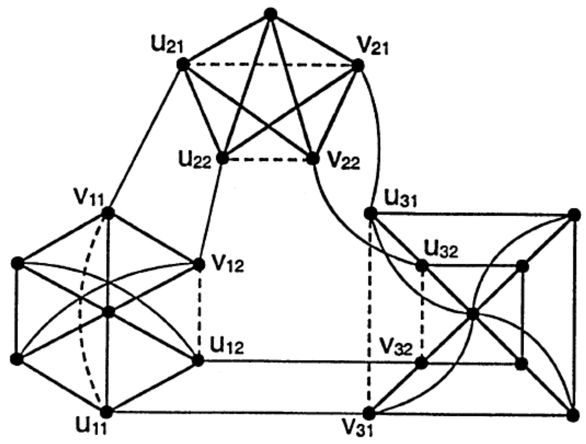
Graph-based approaches

Graph = set of nodes (habitat units) and links (connections).

Definition of nodes and links dependent on the degree of detail and the needs and objectives of the analysis.

Exponential growth as an approach to deal with landscape connectivity (Keitt, Urban, Jordan, Saura, Bodin, McRae, etc.).

Widely developed for powerful analyses of the connectivity of many types of networks (communications, internet, social, molecular, etc.).



Graph-based approaches

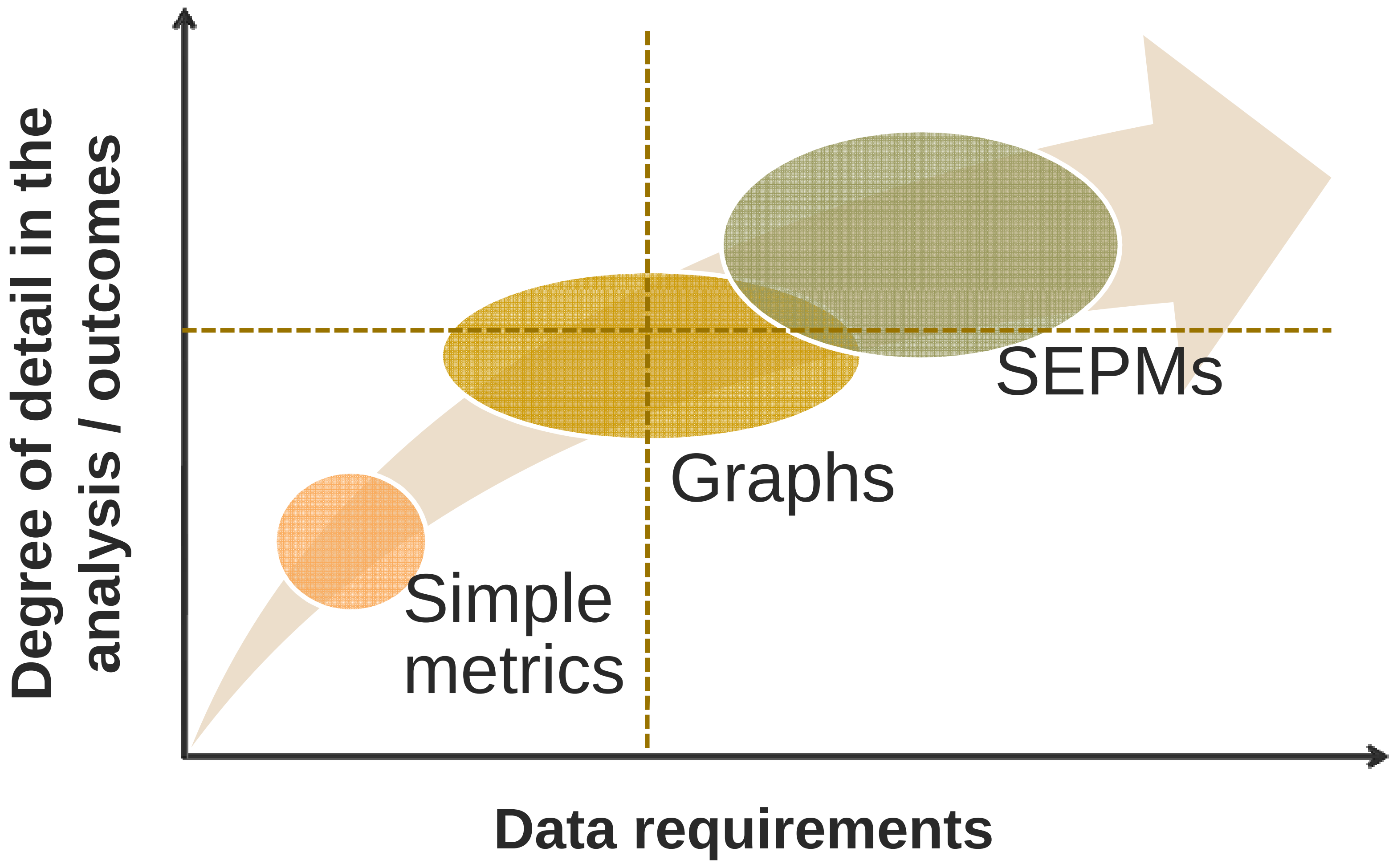
Use:

When you need: (1) a spatially explicit connectivity assessment, (2) that can estimate the value of individual patches and corridors for connectivity, (3) adaptable to different degrees of detail in the available information

When you do not need (1) tracking population dynamics and detailed biological or demographic processes, (2) or simply when such information is not available in practise.

(Some) graph metrics provide similar outcomes to SEPMs in what is required for operational planning (Minor & Urban 2007, Visconti & Elkin 2009).

Balancing data requirements with detail in the outcomes



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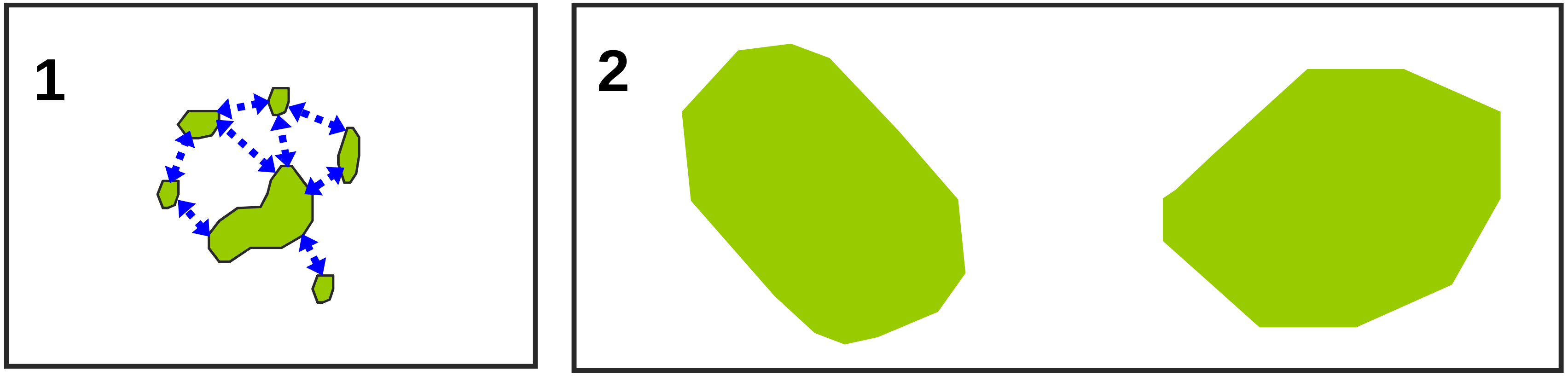
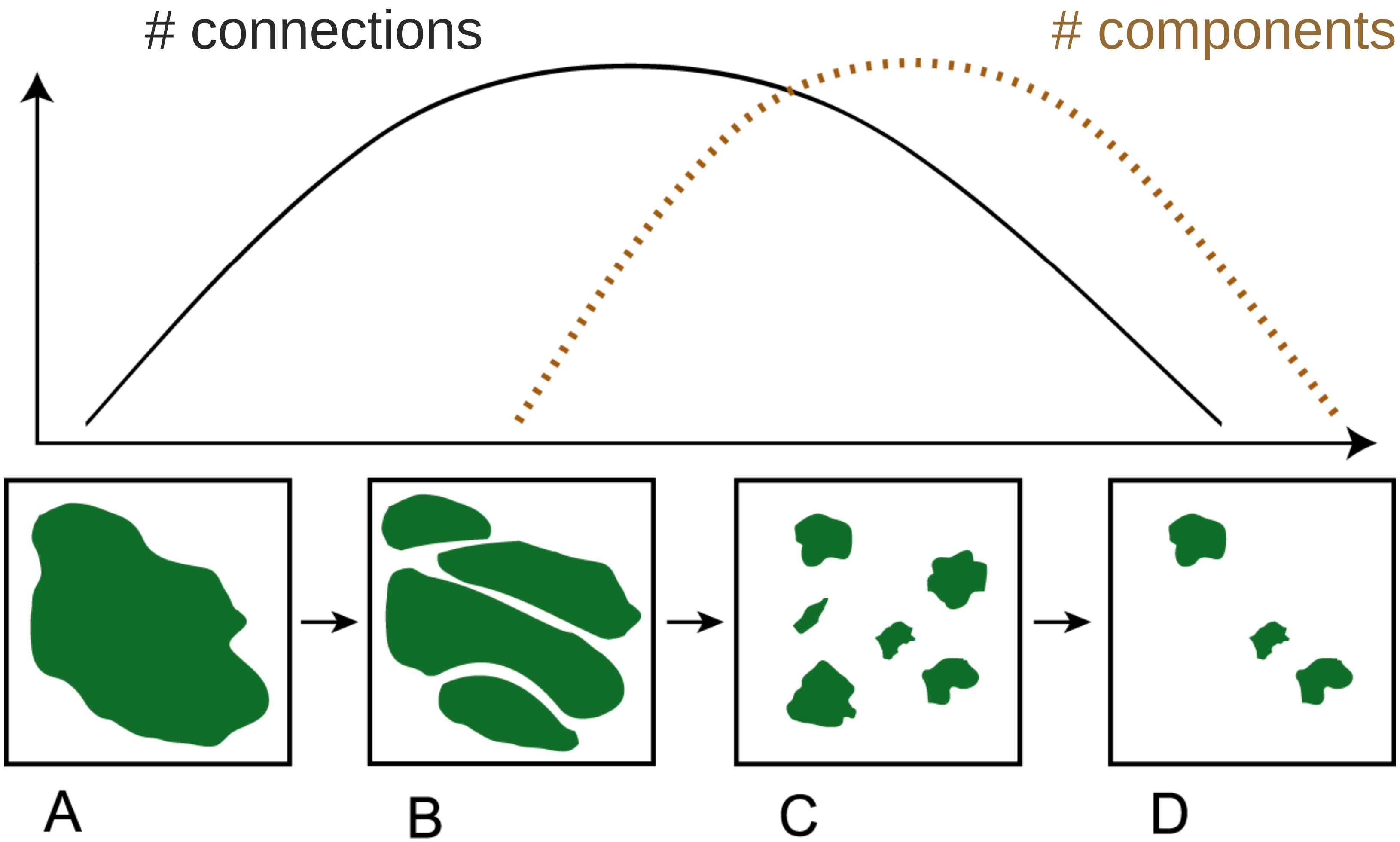
Paradoxes of only measuring connectivity between patches

- Which landscape is more connected? (1 or 2)
- Which nodes / habitat patches are more important?



- Need to measure habitat availability at the landscape scale.
- A node / patch is considered as a space where connectivity exists.
- Habitat availability metrics integrate the area within habitat patches (*intrapatch connectivity*) with the area made available by the connections between patches (*interpatch connectivity*).

Don’t trust the number of connections (or components)



NEW LANDSCAPE CONNECTIVITY METRICS

- UNWEIGHTED GRAPHS (Pascual-Hortal & Saura 2006)

Integral Index of Connectivity (IIC)

$$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \cdot a_j}{1+nl_{ij}}}{A_L^2}$$

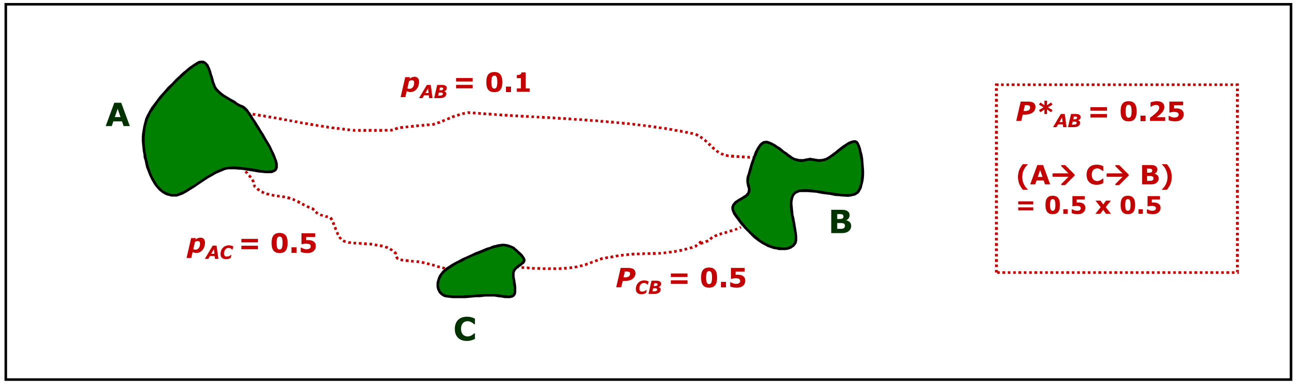
nl = topological distance (no. of links)

- WEIGHTED GRAPHS (Saura & Pascual-Hortal 2007)

Probability of Connectivity (PC)

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \cdot a_j \cdot p_{ij}^*}{A_L^{\ 2}}$$

Probability that two points randomly placed within the landscape fall into habitat areas that can be reached from each other given a set of habitat patches and links.



a_i, a_j: patch attribute (area, habitat quality, etc.)

p^*_{ij}: maximum product probability

p^*_{ij} =1 when $i=j$, $p^*_{ij} \geq p_{ij}$

A_L: maximum landscape attribute

Need to support decision making in landscape planning

?

Which habitat patches and corridors are more critical for the maintenance of overall landscape connectivity?

- **It is not just a descriptive analysis**
- **It is a decision-support analysis oriented to conservation planning**

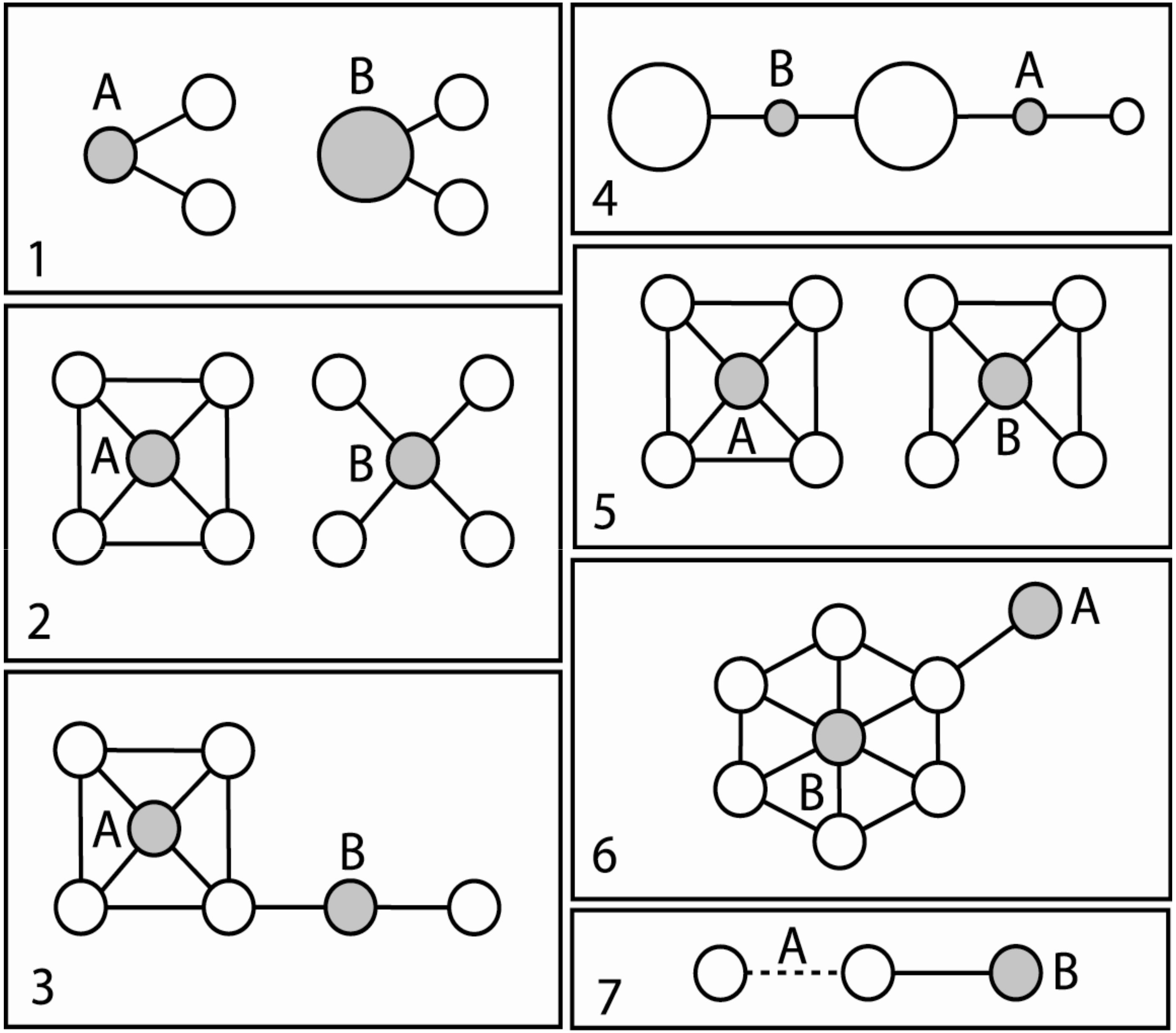
$$dPC_k = 100 \cdot \frac{PC - PC_{remove,k}}{PC}$$

→ Priority sites for conservation, restoration, forestation, etc.

IDENTIFICATION OF THE MOST IMPORTANT (CRITICAL) LANDSCAPE ELEMENTS FOR CONNECTIVITY

(INDEX PRIORITIZATION ABILITIES)

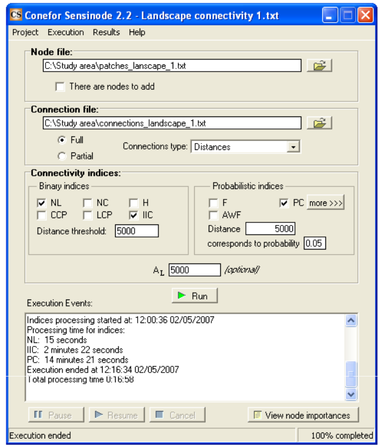
Loosing B is considered worse than A

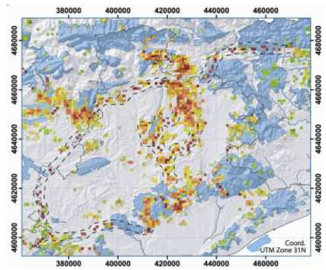


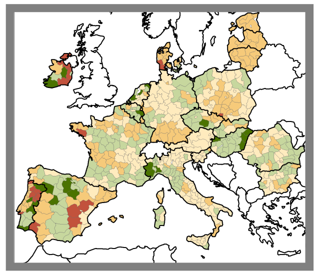
Pascual-Hortal and Saura (2006) *Landscape Ecology*

Conefor Sensinode 2.2:
graphs + habitat availability metrics

- Freeware & open source: **www.conefor.org**
- Oriented to the identification of critical areas for landscape connectivity (Saura et al.)
- User & planning oriented. GIS extensions
- Applications and case studies (2007-09):
  - o Forest and land planning in Spain
  - o Genetic diversity & connectivity in USA
  - o Forest connectivity trends in EU (EFDAC)
  - o Bird species colonization after wildfires in Spain
  - o River network connectivity for the otter in Italy
  - o More: Puerto Rico, México, China, etc.

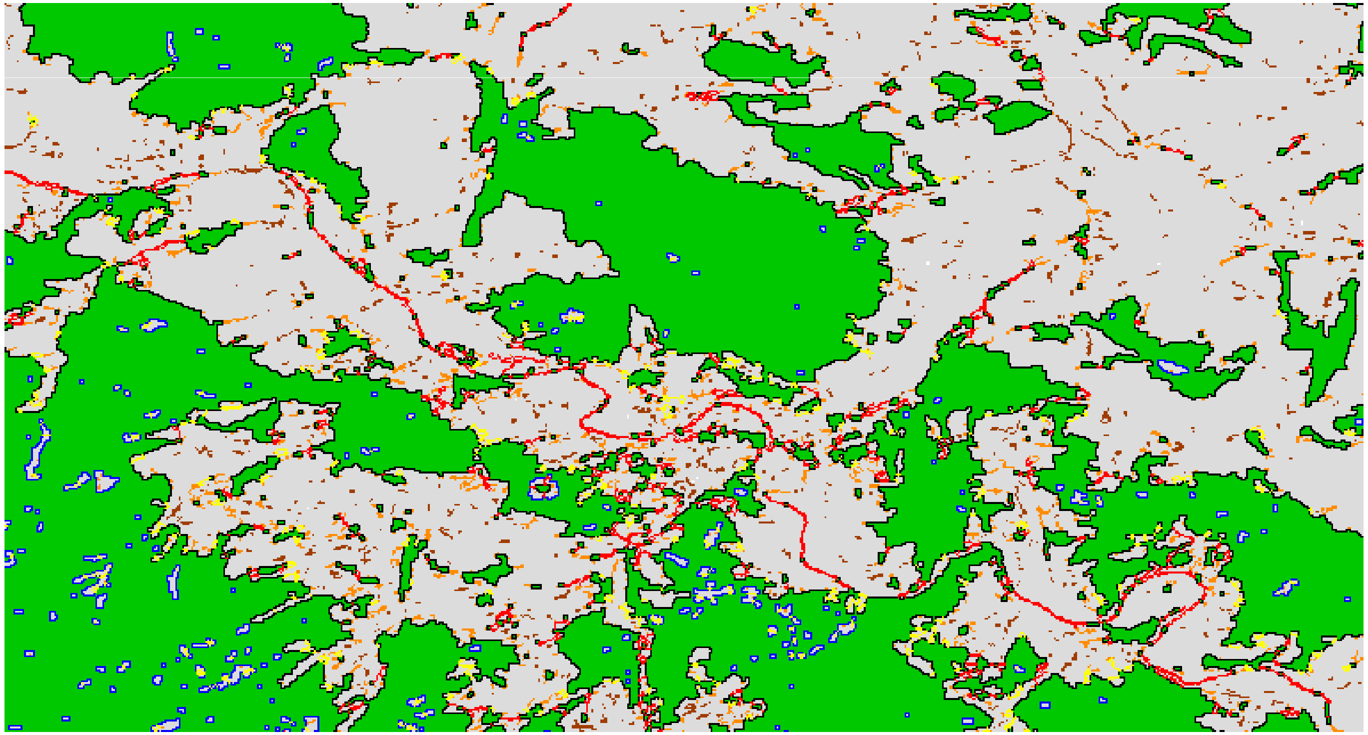






Key structural connectors

- Guidos software (Vogt et al.): MSPA bridges
- Conefor Sensinode integration: prioritization of connectors



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Selecting sites for conservation: alternatives and trade-offs

- Criterion 1: Select the best habitat sites by their intrinsic values and characteristics, independently of topology and connectivity.
- Criterion 2: Select those site that enhance most the connectivity between the rest of the sites.

- Trade off: best for 2 implies not getting the best for 1.
- Arbitrary combination of 1 & 2 in the final conservation plan?
- Is really network connectivity a key issue for planning and conservation? When?

Partitioning habitat availability metrics (PC) in three different fractions

$$dPC_k = dPCintra_k + dPCflux_k + dPCconnector_k$$

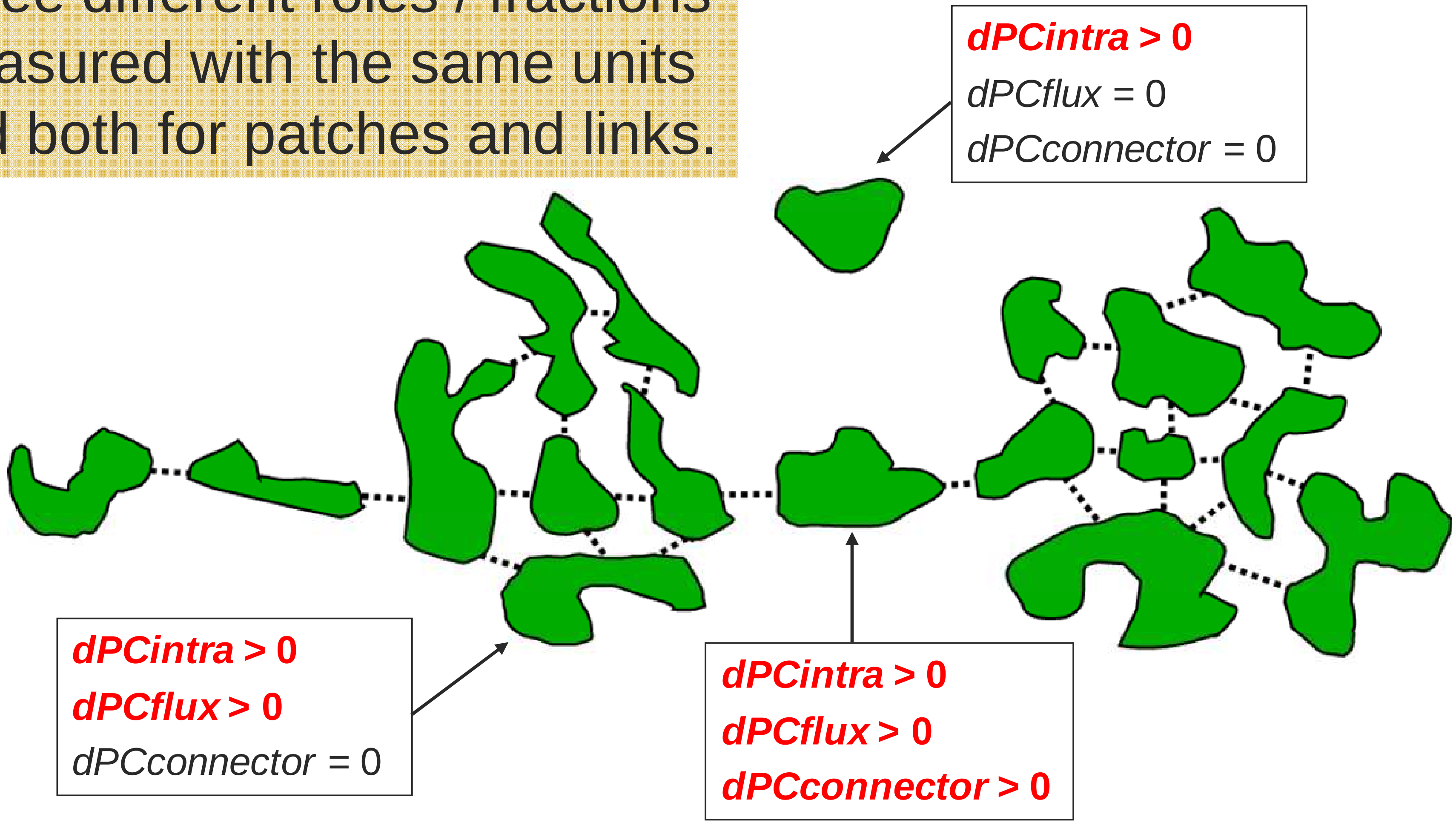
Fraction	Definition / contribution	Network topology?	Intrinsic patch attribute?
dPCintra	Available habitat area provided by patch *k* itself through the area it comprises (**intrapatch connectivity**)	No	Yes
dPCflux	**Flux** of the connections of patch *k* with all the other patches when *k* is either the starting or ending node.	Yes	Yes
dPCconnector	Contribution of *k* to the connectivity between other patches, as **connecting element / stepping stone**. Only if *k* is in optimal path between them. Depends on alternative paths after losing *k*.	Yes (patches + links)	No

Saura & Rubio 2009 *Ecography* (in press)

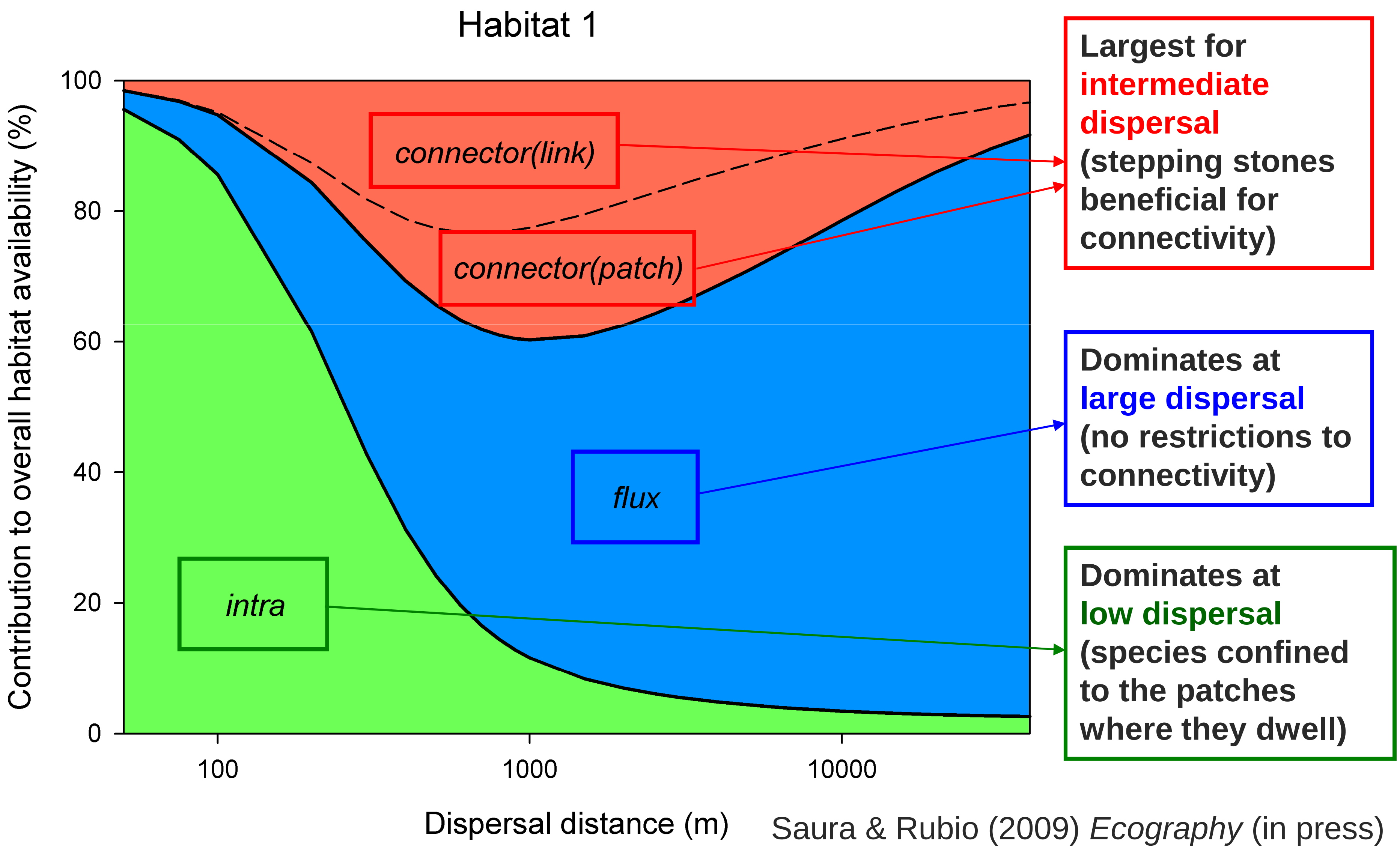
Ways in which a patch can contribute to habitat connectivity and availability

Three different roles / fractions measured with the same units and both for patches and links.

$dPC_k = dPCintra_k + dPCflux_k + dPCconnector_k$



How do the different fractions / roles contribute to overall habitat availability and connectivity?



Saura & Rubio (2009) *Ecography* (in press)

When to invest conservation efforts in connecting elements?

- Not for species with very low or large dispersal.
- Especially for species with intermediate dispersal abilities (relative to the habitat spatial pattern).

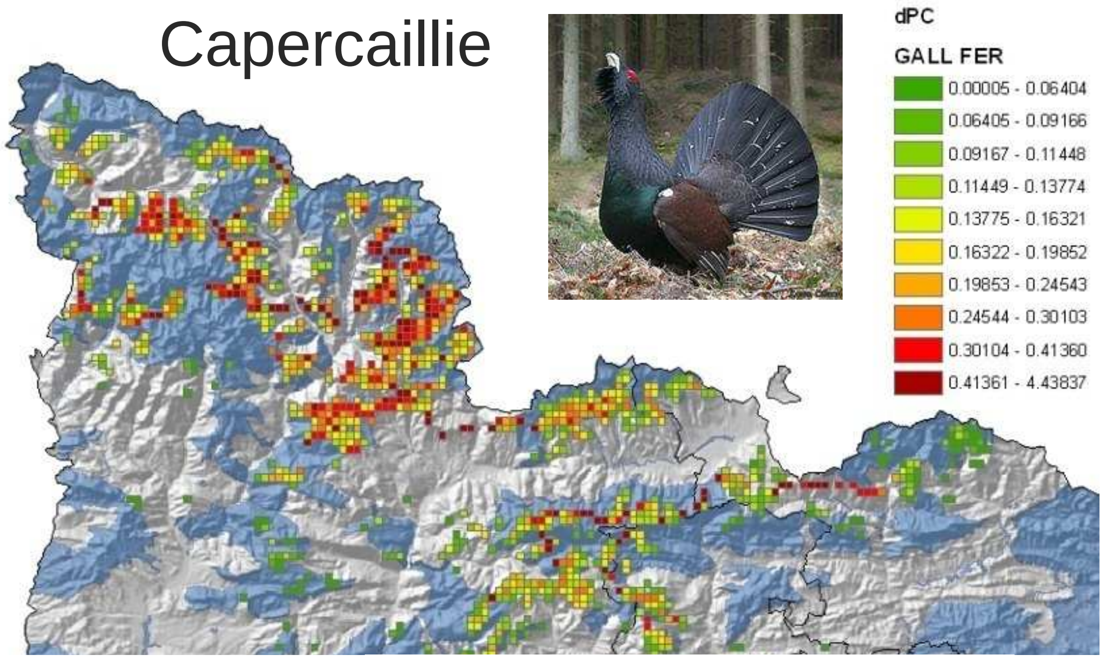
By using habitat availability metrics:

- There is no risk of overweighting connectivity considerations in the final conservation plan.
- No need to define *a priori* if conn. is important or not
- They provide a common currency / integrated analytical framework for both alternatives.

Saura & Rubio (2009) *Ecography* (in press)

Example: endangered bird species in NE Spain

Capercaillie



	Capercaillie
Habitat pattern	Fragmented
Dispersal distance (km)	2.3
Max dPC	4.44
Proportion of dPC explained by intrinsic habitat attributes	20 %

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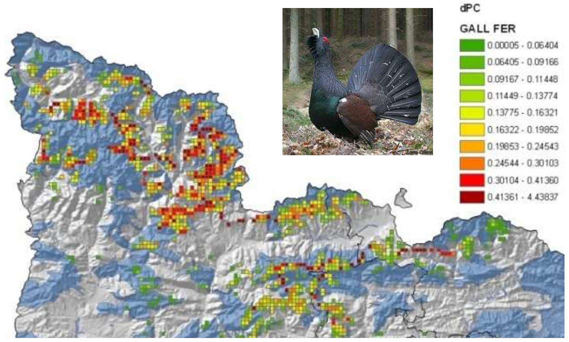
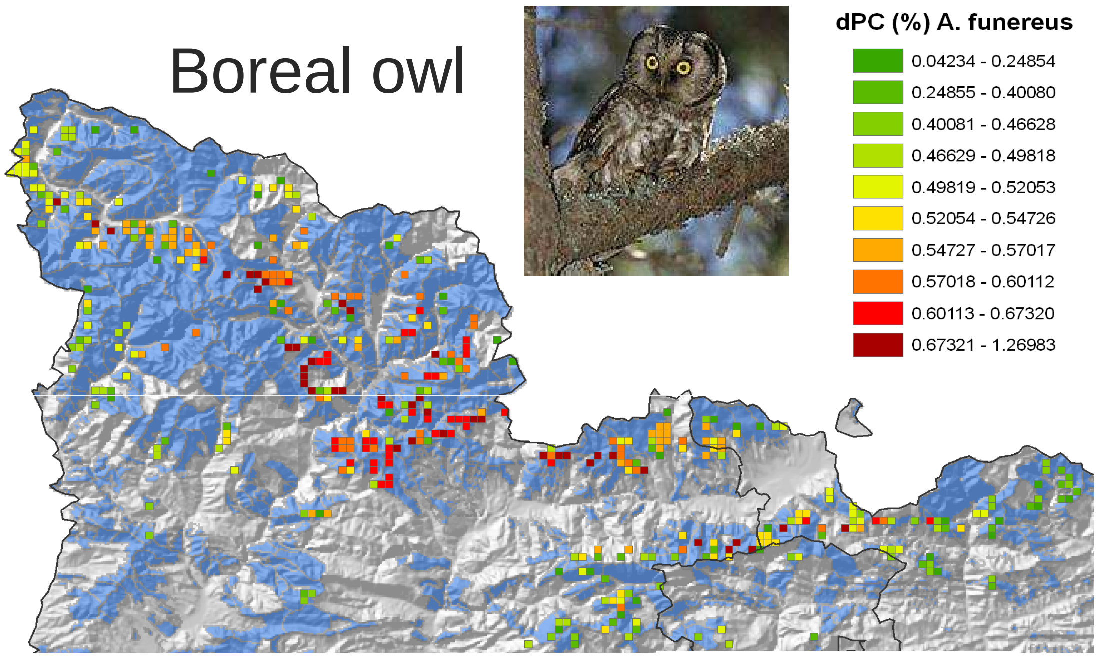
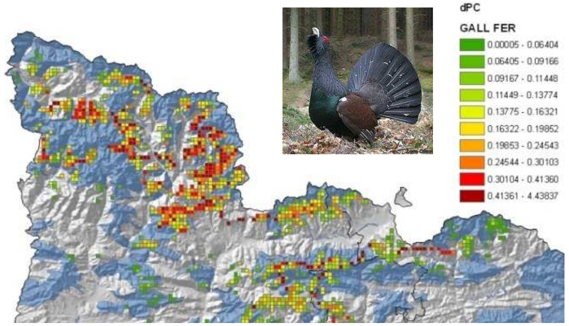
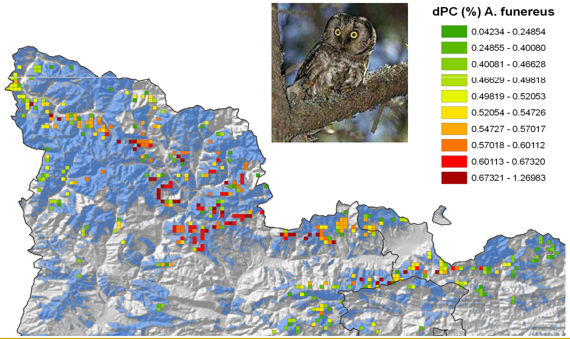


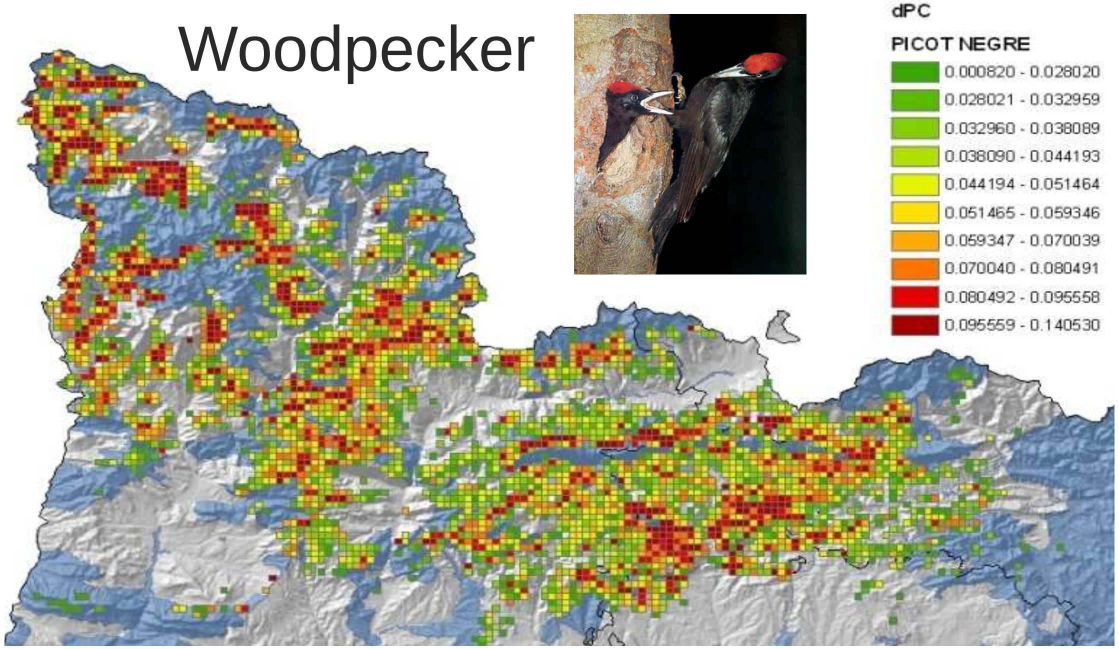


	Capercaillie	Boreal owl
Habitat pattern	Fragmented	Fragmented
Dispersal distance (km)	2.3	34.0
Max dPC	4.44	1.27
Proportion of dPC explained by intrinsic habitat attributes	20 %	75 %

Example: endangered bird species in NE Spain







	Capercaillie	Boreal owl	Woodpecker
Habitat pattern	Fragmented	Fragmented	≈ Continuous
Dispersal distance (km)	2.3	34.0	6.5
Max dPC	4.44	1.27	0.14
Proportion of dPC explained by intrinsic habitat attributes	20 %	75 %	98 %

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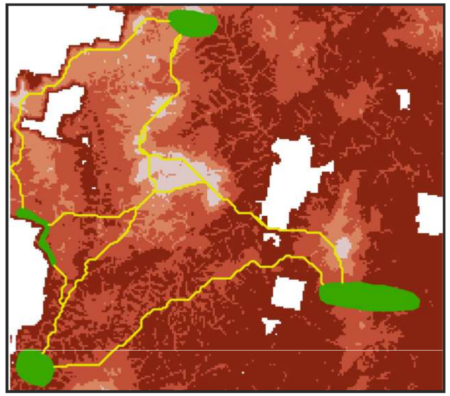
Modelling the landscape network: a balance between data requirements and operational planning

Nodes	Links / Connections
Patch area	Euclidean (straight-line) distance (intermediate landscape treated as homogeneous)
Core area	Least-cost path (effective distance)
Habitat quality / suitability	Conductances / resistances accounting for the contribution of multiple pathways (application of circuit theory: Circuitscape)
Quality-weigthed area	Radiotracking
Probability of occurence	Mark-release-recapture
Population size	Genetic similarity (long term connectivity)
Etc.	Etc.

Incorporating the matrix resistance: the popular least cost modelling

- Effective distances: resistance / friction surface + least cost analysis.
- Improvement over Euclidean distances.
- Tool: PathMatrix (Ray (2005))

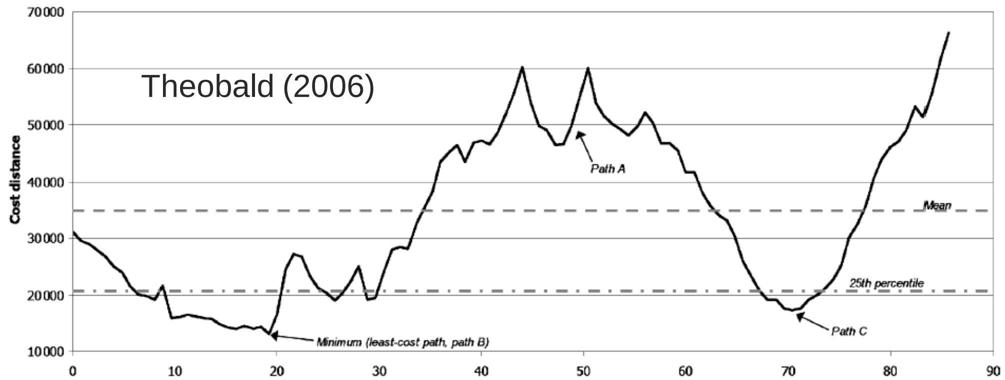


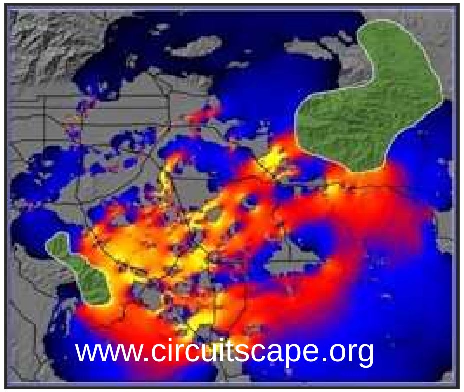
- But potential limitations:

1) A unique and optimal path identified. Rest of the matrix?
2) Arbitrary selection of friction values, lack empirical data. Errors from bad parameter estimates?
3) The least cost path is the “optimal”. But how good it is for actual species movement?
4) Computational bottlenecks

From a unique least-cost path to diffuse flows and multiple pathways

- Does an optimal path exist? Is that in fact used as such by the species? Need to account for the contribution of multiple pathways and a larger matrix proportion.
- Theobald (2006): percentiles of cost distribution.
- Circuitscape (McRae et al. 2008): application of circuit theory, more related to actual gene flow and movement of random walkers in heterogeneous landscapes.





Towards objective friction values and the landscape continuum

Which landscape model?

1) Binary: both habitat and matrix homogeneous.
2) Both habitat and matrix treated as heterogeneous.
3) Landscape continuum: habitat and matrix are not sharply separated as discrete classes.

- Habitat modelling coupled with matrix resistance modelling.
- Friction as the inverse of probability of species occurrence (Chetkiewicz et al. 2006). Needs field censuses (actual habitat use & movements recorded together) + habitat modelling.
- Every portion of the land may be habitat and permeable for movement to some degree (continuous variables).

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Some available relevant tools: summary and need for integration

- **Conefor Sensinode:** prioritizing landscape elements by their contribution to connectivity (fractions to be implemented soon)
- **PathMatrix:** connections as least cost paths
- **Circuitscape:** accounts for multiple paths to assess connection strength (circuit theory)
- **Guidos:** identification and mapping of spatial patterns and structural connectors
- **FunConn, LQGraph:** minimum spanning trees
- **Pajek, Ucinet:** generic network analysis.

Some concluding messages. To measure connectivity…

1) Think of the landscape as a network of habitat units connected by links (graphs but not only).
2) Consider both intrapatch & interpatch connectivity (habitat availability) and the different roles of landscape elements.
3) Place connectivity within a broader context of planning and conservation alternatives.
4) Be aware of the scarcity of empirical information to model the landscape network and feed your connectivity analysis: use more complex models with care and rely in adaptable approaches if possible.
5) Test and use recent tools for integrating connectivity in landscape planning and ecological network design.