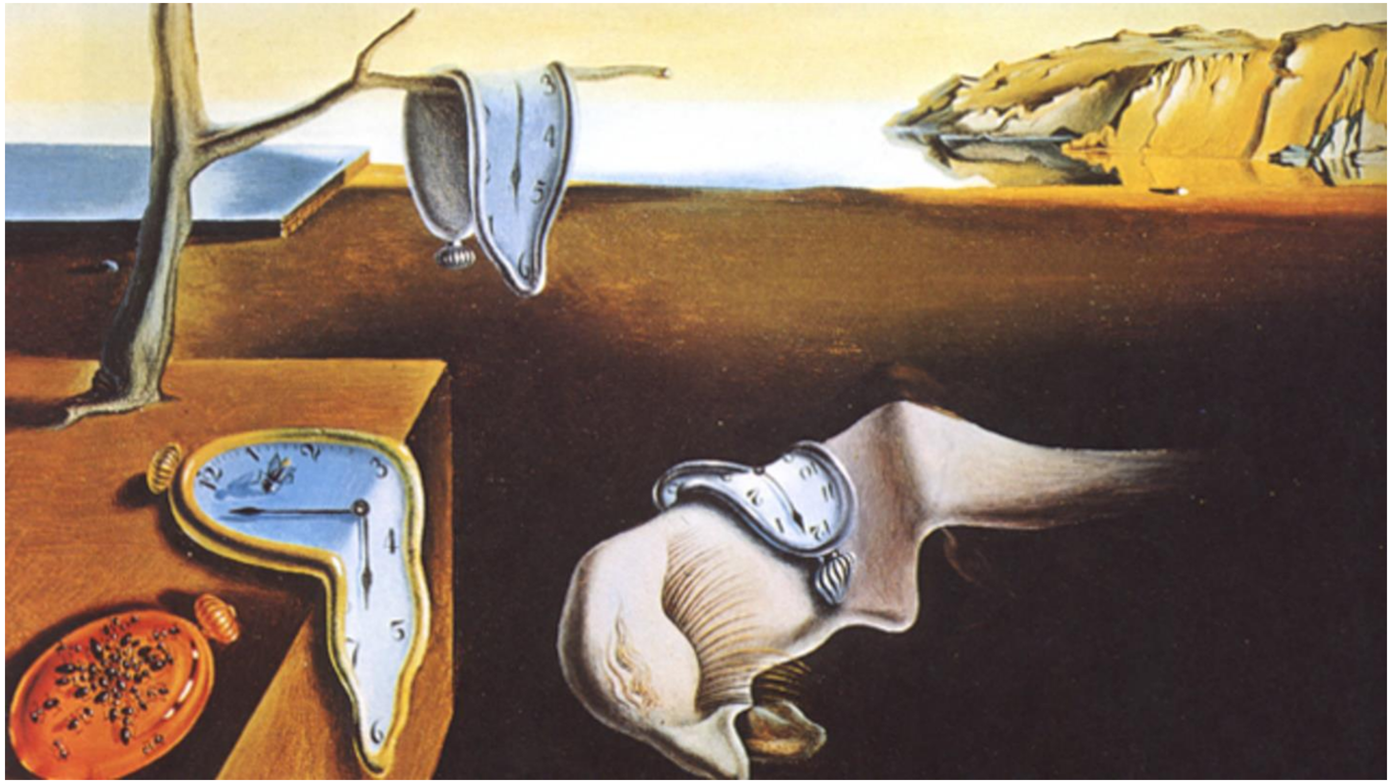
Biodiversity patterns across space and time



Federico Riva, PhD

McGill, BIOL 310 February 9th, 2022

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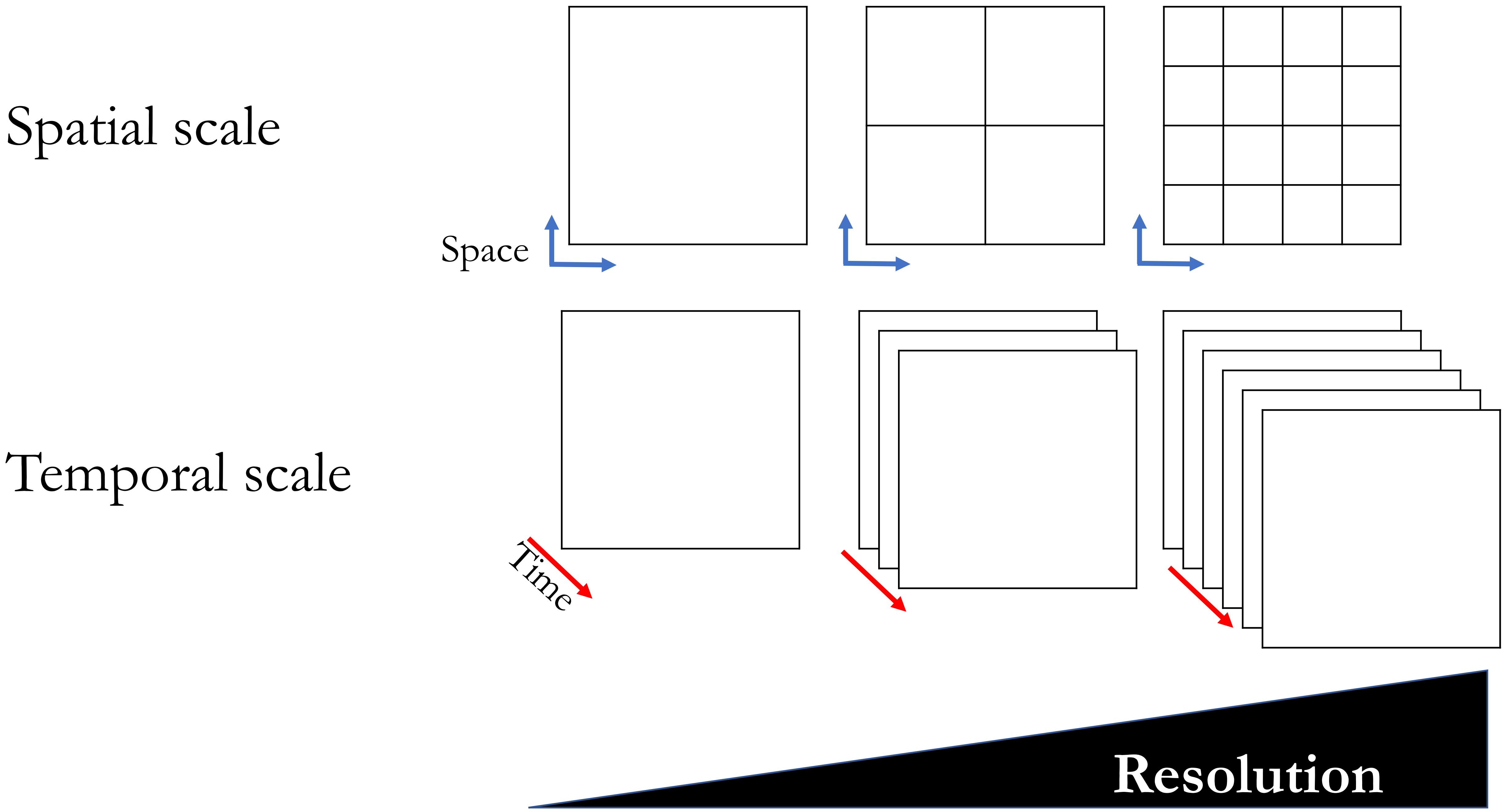
Summary

- Defining scales
- The complexity of natural systems motivates attention to scales
- Scaling in ecology and conservation
    - History of research on scales
    - Theory developed to understand biodiversity across scales
    - The role of scaling in solving long-standing debates
    - Applied implications
- Conclusions
    - How to deal with scales in your own work
    - R workshop

"In ecology, scale usually refers to the spatial and temporal dimensions of a pattern or process"

Cumming et al. 2006: https://www.ecologyandsociety.org/vol11/iss1/art14/.


Spatial scale
Space
Temporal scale
Time
Resolution

Today, my goal is convincing you that the spatial and temporal scales of your analysis are crucial to interpreting your findings

Complexity in ecology:
why we need scales to begin with

Trends in Ecology & Evolution

CellPress REVIEWS

Opinion

Protecting Biodiversity (in All Its Complexity): New Models and Methods

ECOGRAPHY

Forum

Future restoration should enhance ecological complexity and emergent properties at multiple scales

nature ecology & evolution

ARTICLES

https://doi.org/10.1038/s41559-021-01644-4

Check for updates

Ecological network complexity scales with area

PNAS Proceedings of the National Academy of Sciences of the United States of America

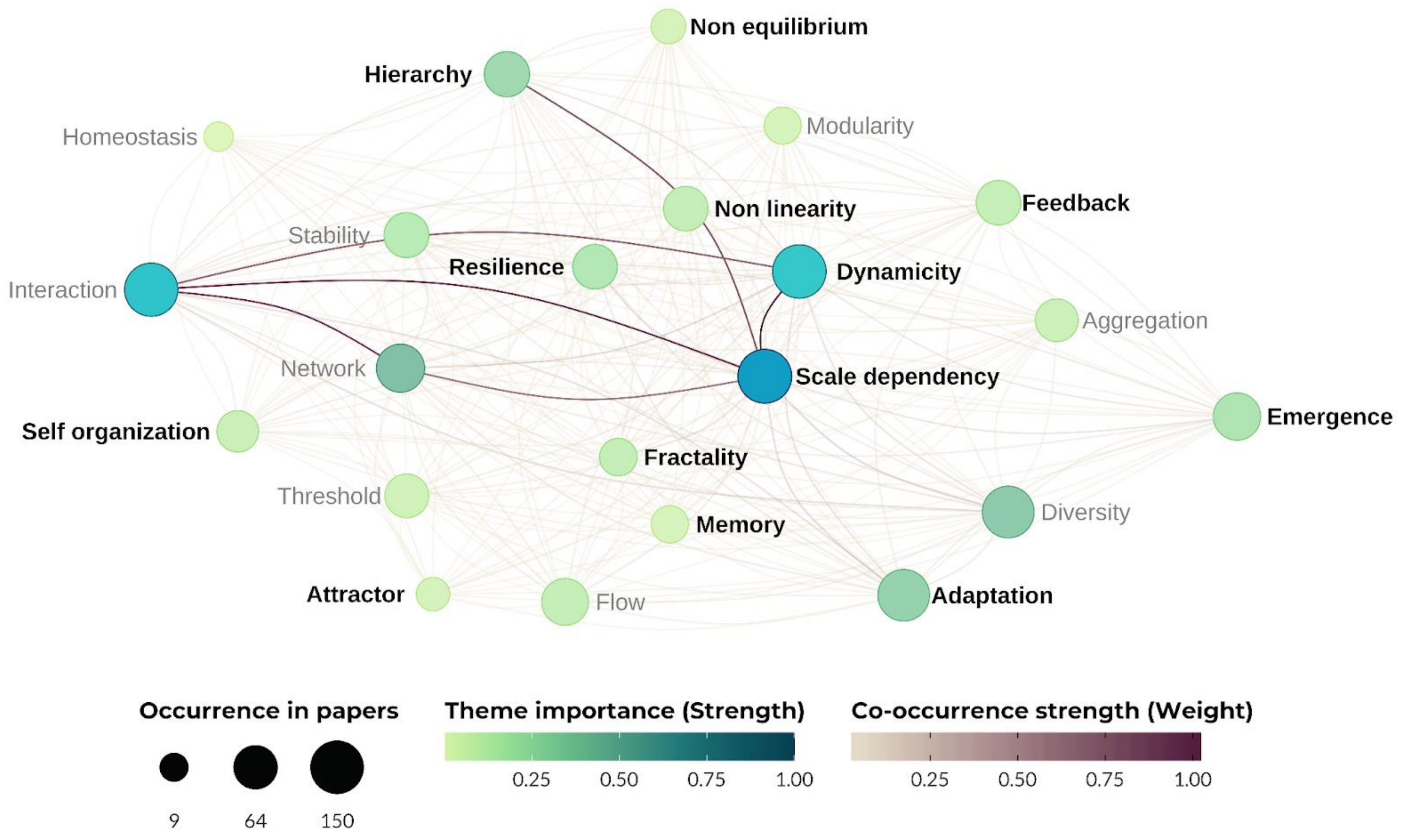
Key

Home Articles Front Matter News Podcasts

RESEARCH ARTICLE

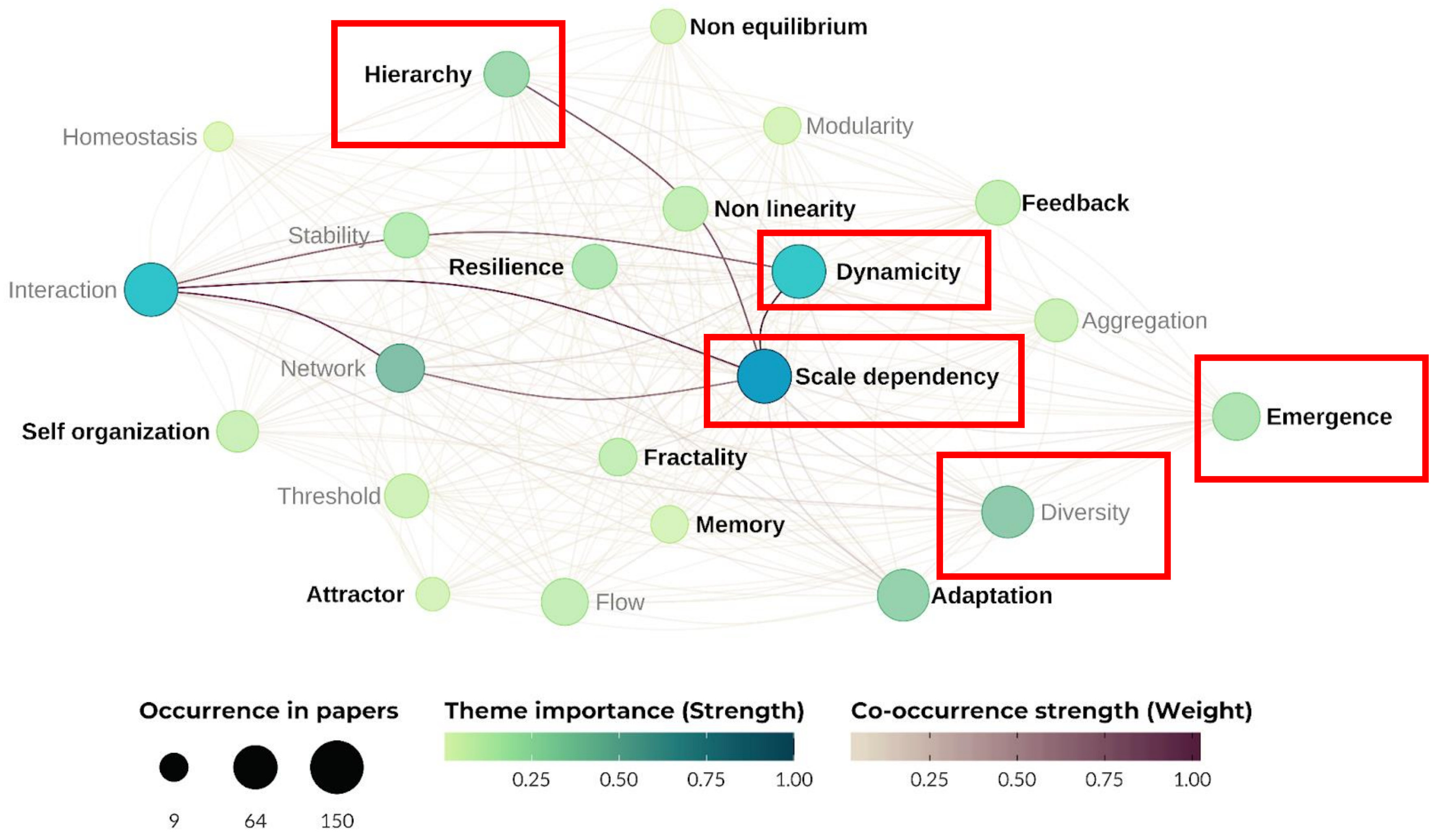
Multiscale structural complexity of natural patterns

Natural systems are prototypical complex adaptive systems



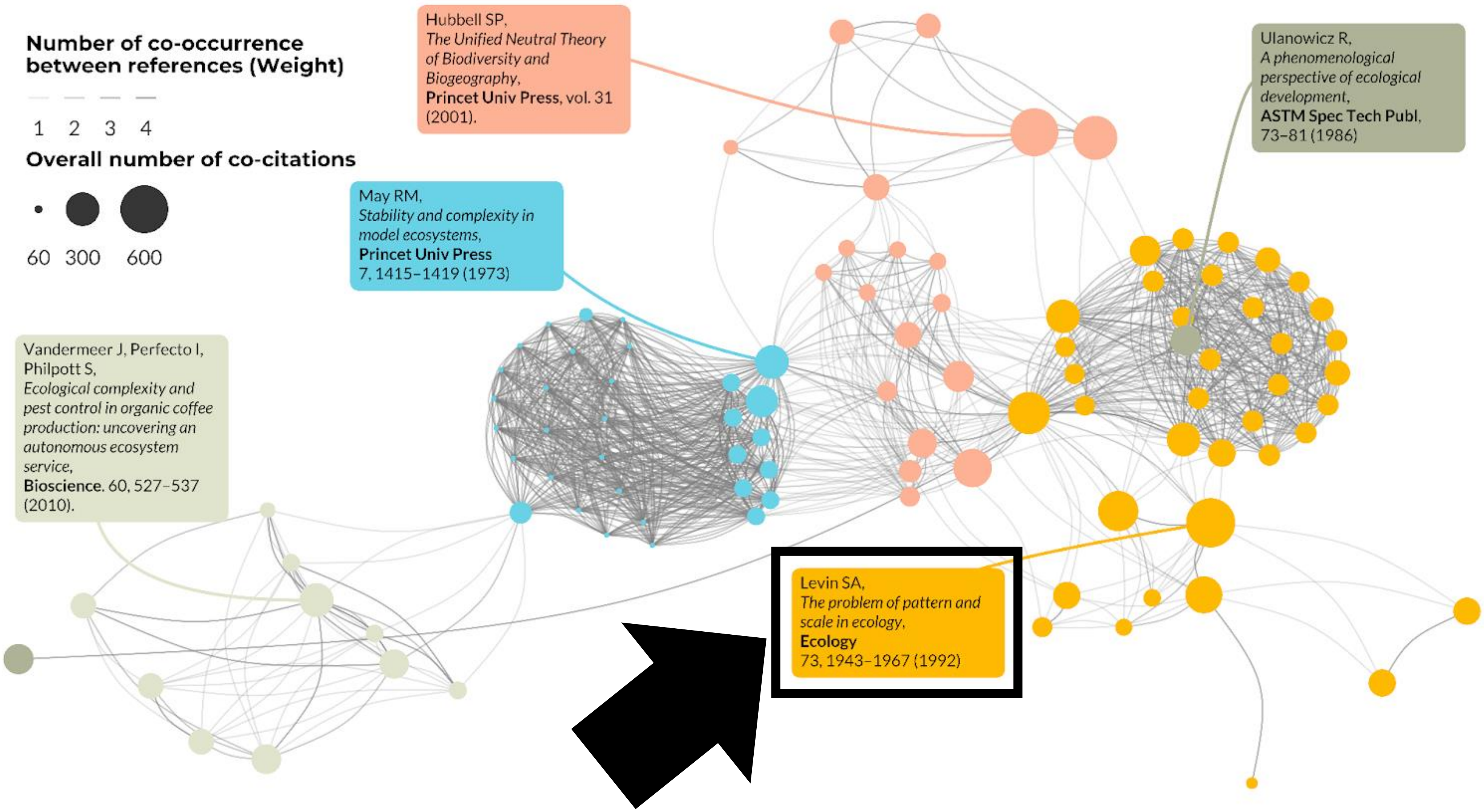
Riva*, Graco-Roza*, Daskalova, Hudgins, Lewthwaite, Newman, Ryo, Mammola (in prep)

Natural systems are prototypical complex adaptive systems



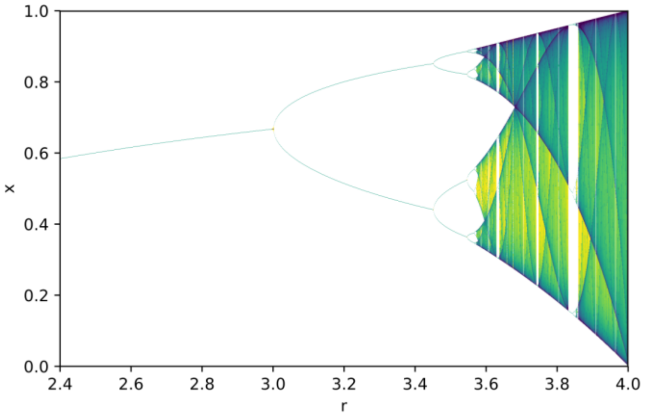
Riva*, Graco-Roza*, Daskalova, Hudgins, Lewthwaite, Newman, Ryo, Mammola (in prep)

How do we deal with this complexity?



Riva*, Graco-Roza*, Daskalova, Hudgins, Lewthwaite, Newman, Ryo, Mammola (in prep)

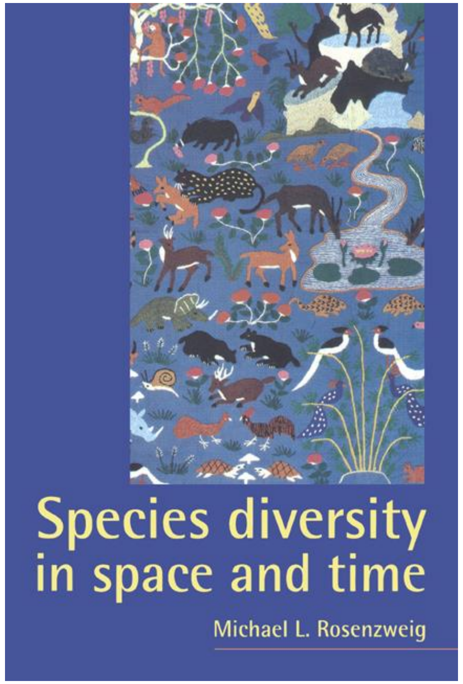
Hard theory



$$x_{n+1} = rx_n\left(1 - x_n\right)$$

May 1976
Rosen 2000
Kuhn 1970
…

Macroecology



Rosenzweig 1995
Hubbell 2001
Brown 1995
…

Scaling

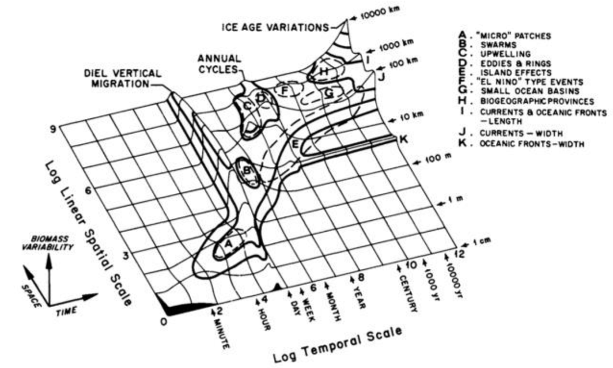


FIG. 3. Stommel diagram of spatial and temporal scales of zooplankton biomass variability (from Haury et al. 1978).

Levin 1992
Allen and Starr 1982
Wu 1995
…

Natural systems span multiple, interconnected levels of biological organization and change dynamically through time

Focusing on meaningful scales simplifies this complexity, resulting in tractable scenarios

Growing awareness of the importance of scales

Wiens 1989 – Space

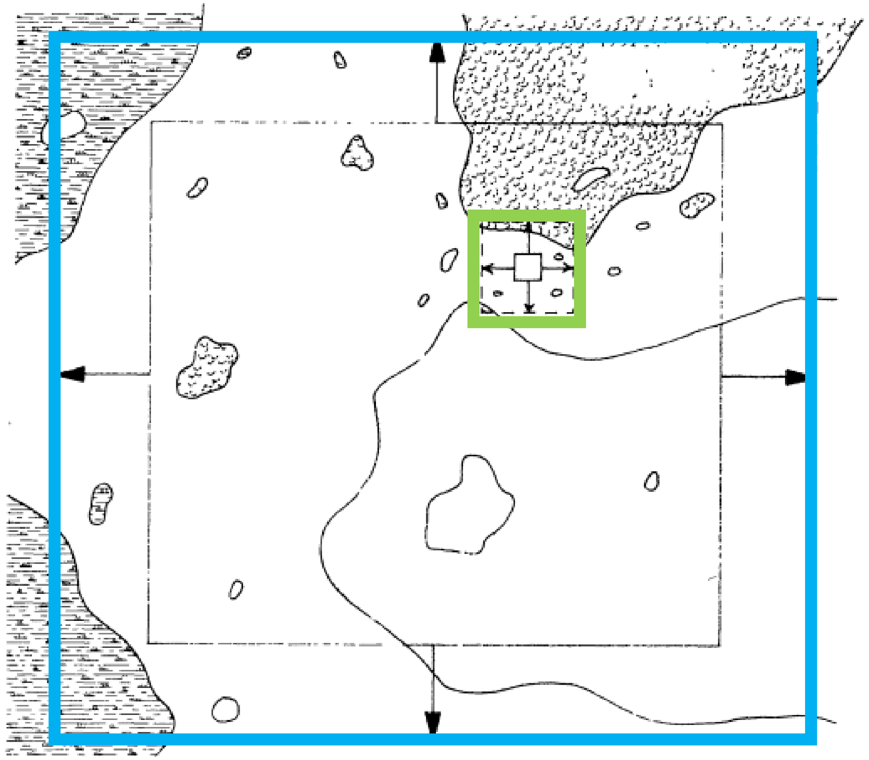


Fig. 1. The effects of changing the grain and extent of a study in a patchy landscape. As the extent of the study is increased (large squares), landscape elements that were not present in the original study area are encountered. As the grain of samples is correspondingly increased (small squares), small patches that initially could be differentiated are now included within samples and the differences among them are averaged out.

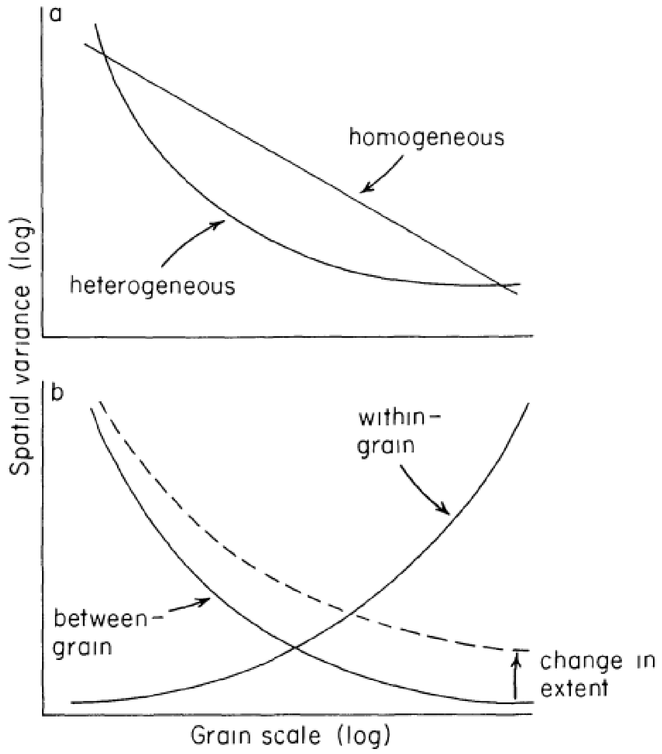


Fig. 2. (a) As the grain of samples becomes larger, spatial variance in the study system as a whole decreases, albeit differently for homogeneous and heterogeneous areas. This is related to the within- and between-grain (sample) components of variation. (b) With increasing grain scale, less of the variance is due to differences between samples and more of the overall variation is included within samples (and therefore averaged away). An increase in the extent of the investigation may increase the beween-grain component of variance by adding new patch types to the landscape surveyed (Fig. 1), but within-grain variance is not noticeably affected.

Grain vs. extent

https://esajournals.onlinelibrary.wiley.com/doi/pdfdirect/10.2307/1941447

Levin 1992 – Space and time

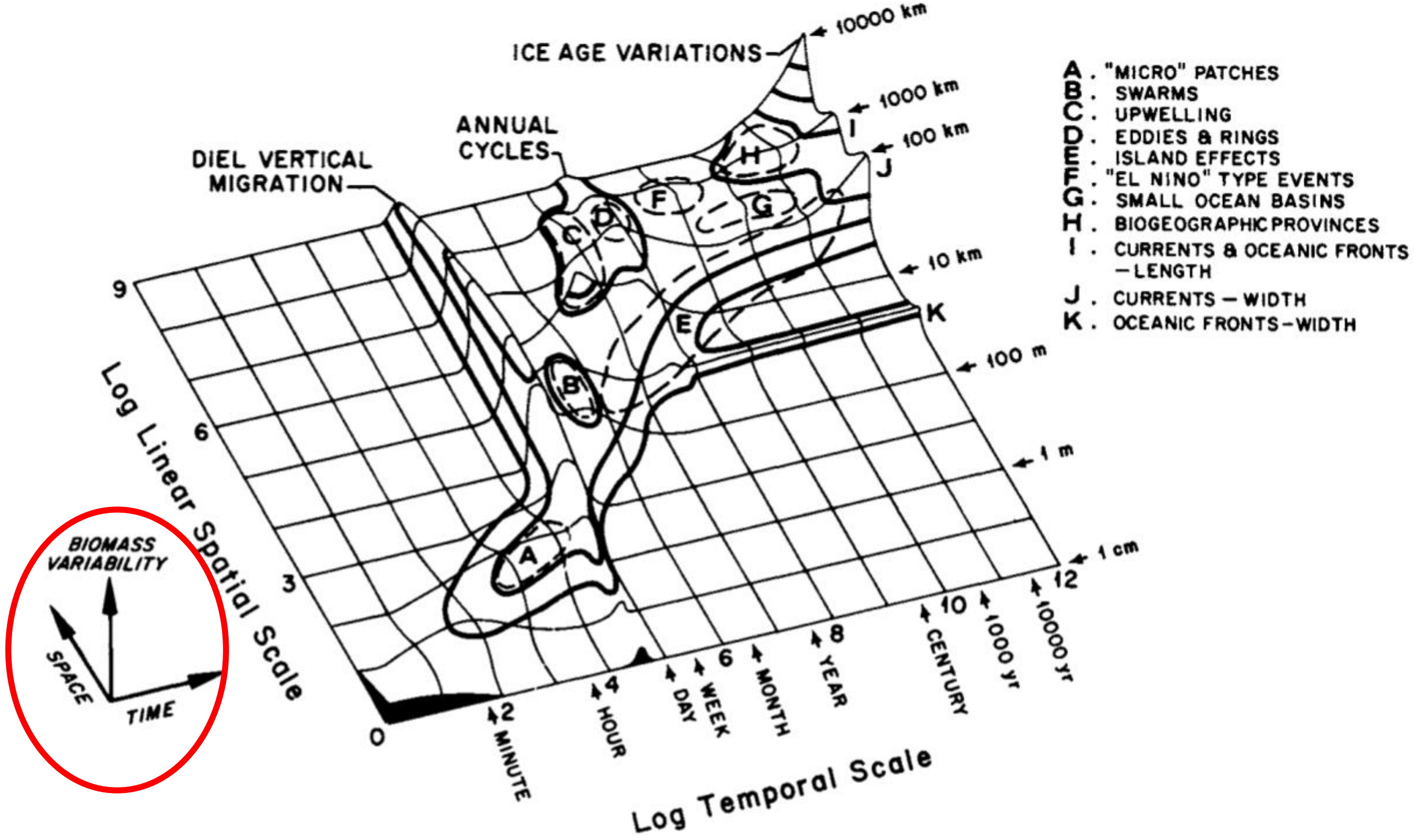
THE PROBLEM OF PATTERN AND SCALE IN ECOLOGY

THE ROBERT H. MACARTHUR AWARD LECTURE
Presented August 1989
Toronto, Ontario, Canada

by

SIMON A. LEVIN
Department of Ecology and Evolutionary Biology, Princeton University, Princeton, New Jersey 08544-1003 USA, and
Section of Ecology and Systematics, Cornell University, Ithaca, New York 14853-2701 USA

Simon A. Levin
MacArthur Award Recipient



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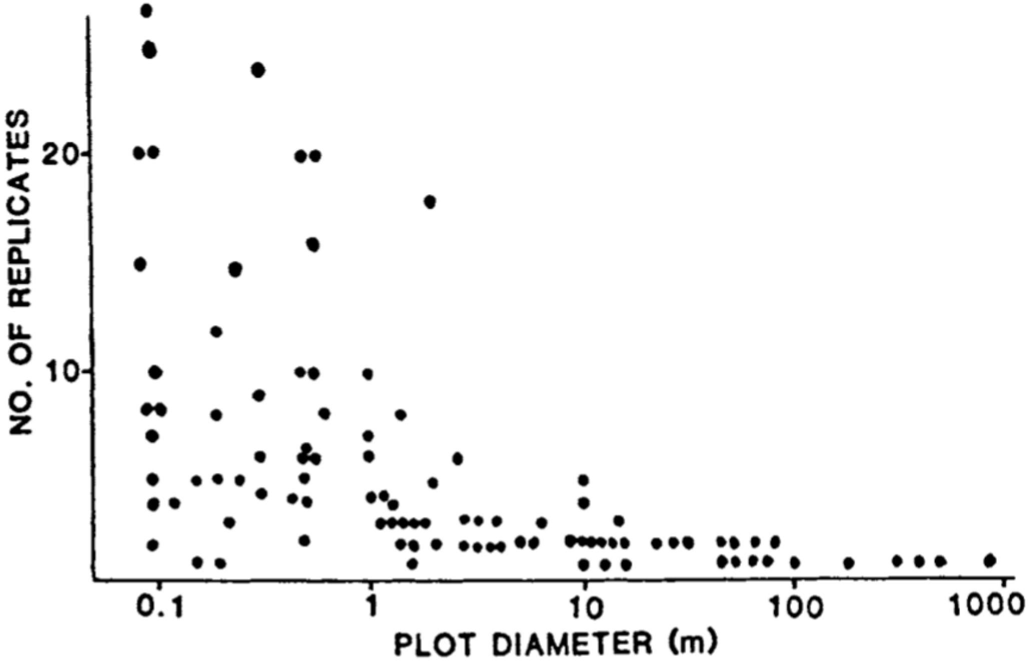
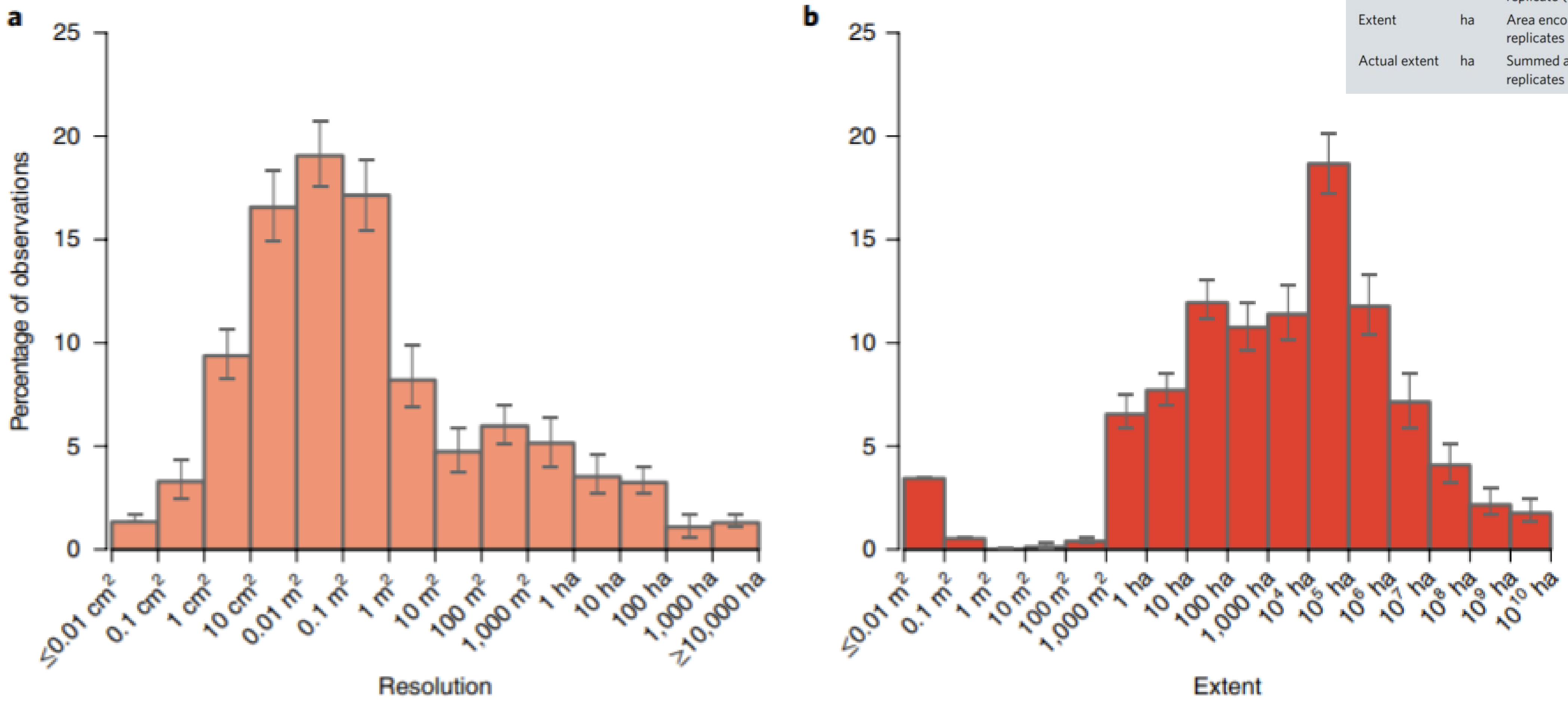


FIG. 14. Size and number of replicates in experimental community ecology. Each point is taken from a different paper published in *Ecology*. Every paper from January 1980 to August 1986 was included if it involved experimental manipulation of resources or populations "in order to learn about community dynamics or community properties" (from Kareiva and Anderson 1988).

https://esajournals.onlinelibrary.wiley.com/doi/pdfdirect/10.2307/1941447

Estes et al. (2018) – after 30+ years, our perspective is still very biased towards short studies, small spatial resolutions

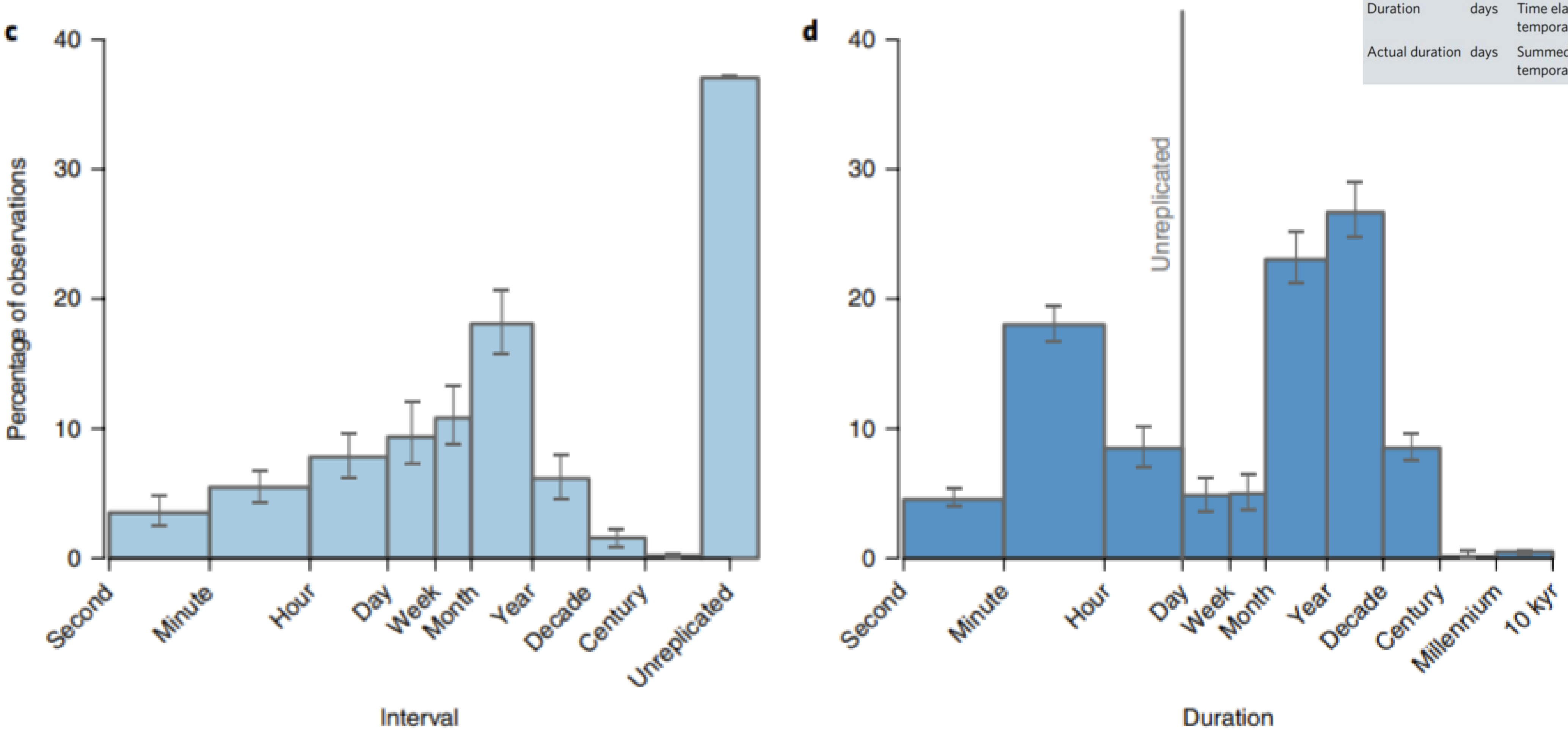
Resolution	m^2	Area of an individual spatial replicate (for example, plot)
Extent	ha	Area encompassed by all spatial replicates
Actual extent	ha	Summed area of all spatial replicates



https://www.nature.com/articles/s41559-018-0524-4

Estes et al. (2018) – after 30+ years, our perspective is still very biased towards short studies, small spatial resolutions

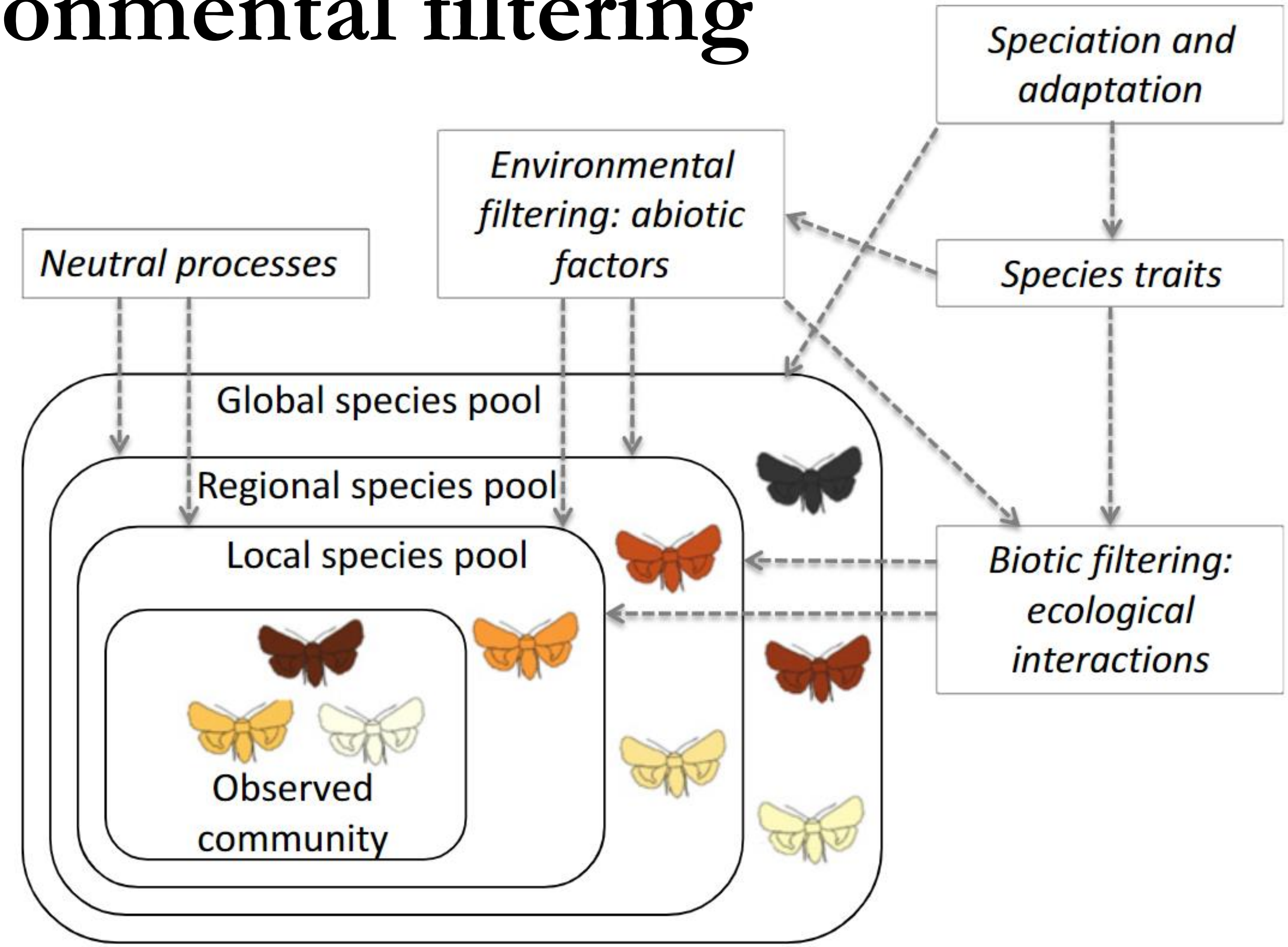
Interval	days	Time elapsed between successive temporal replicates
Duration	days	Time elapsed between first and last temporal replicates
Actual duration	days	Summed observational time of all temporal replicates



https://www.nature.com/articles/s41559-018-0524-4

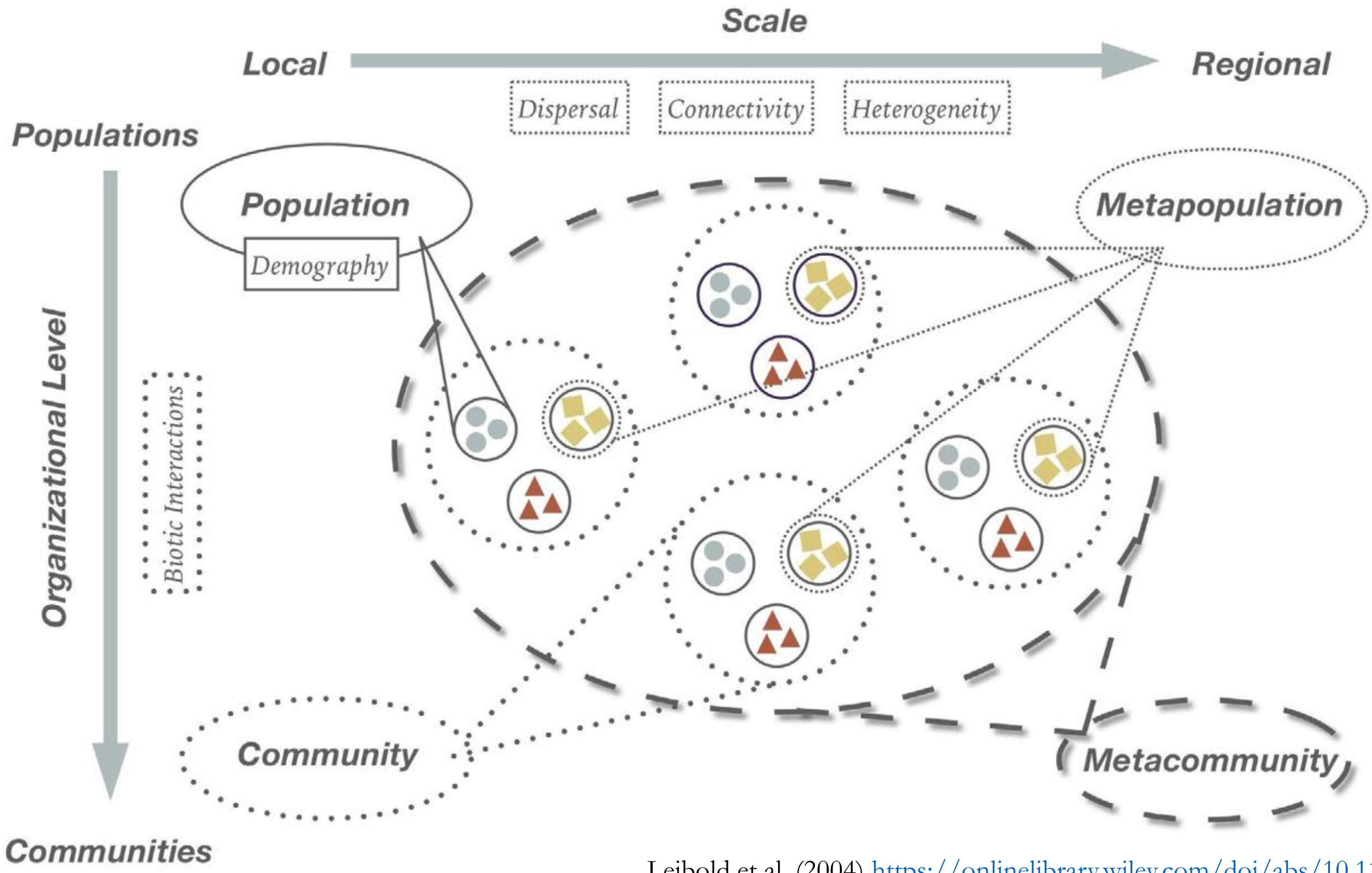
Theoretical paradigms that incorporate scaling in the study of biodiversity

Environmental filtering



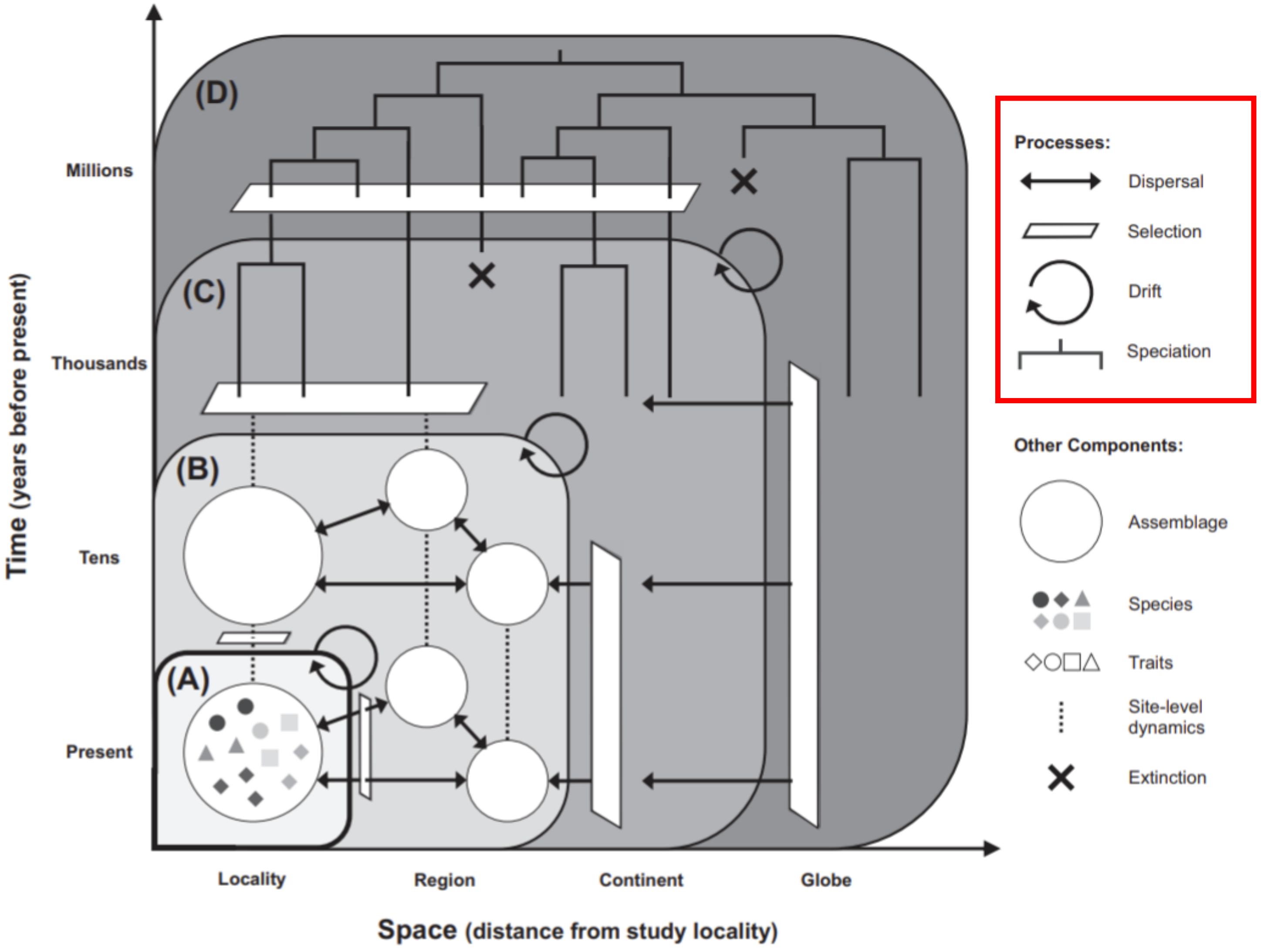
Ovaskainen et al. (2017) https://onlinelibrary.wiley.com/doi/10.1111/ele.12757
Kraft et al. (2015) https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2435.12345

Metacommunity theory



Leibold et al. (2004) https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1461-0248.2004.00608.x
Chase et al. (2020) https://nyaspubs.onlinelibrary.wiley.com/doi/10.1111/nyas.14378

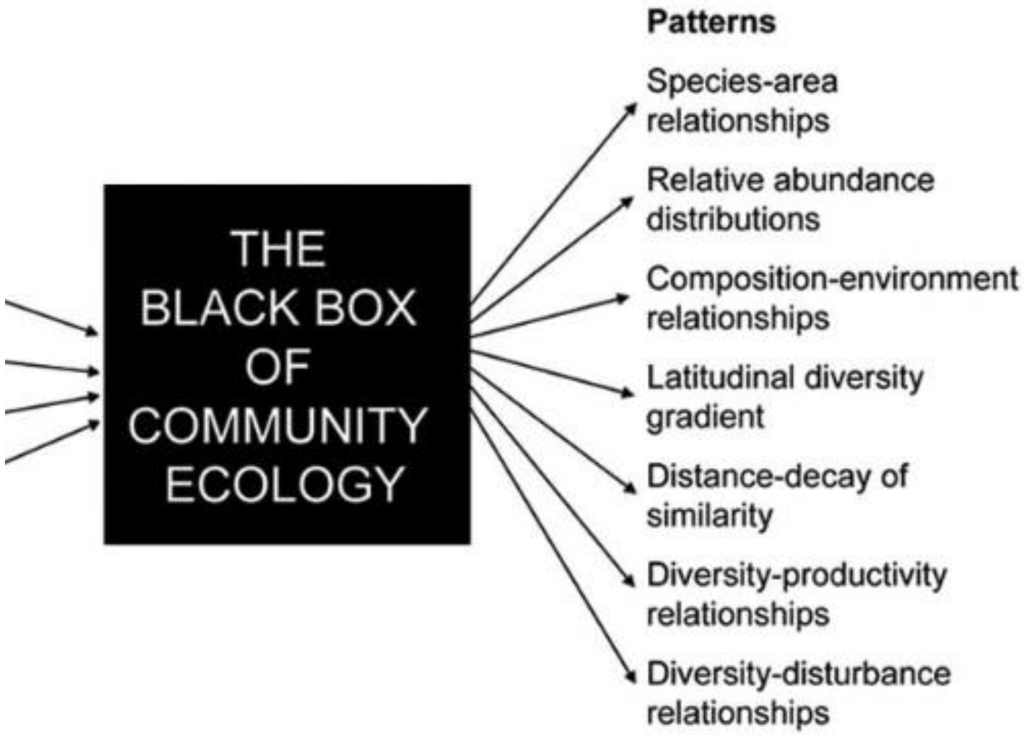
The Theory of Ecological Communities



Vellend (2010) https://www.researchgate.net/publication/44689600_Conceptual_Synthesis_in_Community_Ecology
Rapacciuolo and Blois (2019) https://onlinelibrary.wiley.com/doi/pdf/10.1111/ecog.04616

Population genetics
- Selection
- Drift
- Mutation
- Gene flow

Community ecology
- Selection
- Drift
- Speciation
- Dispersal

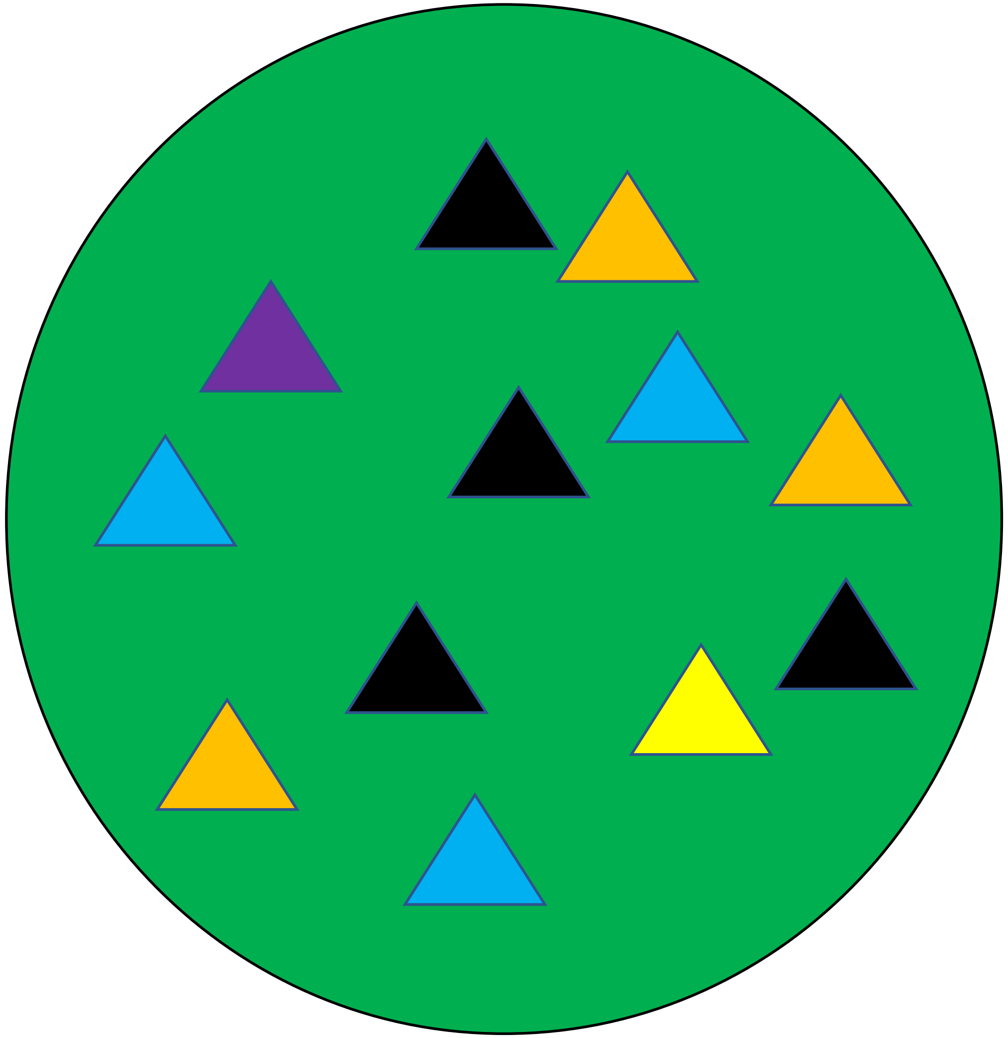


Vellend (2010) https://www.researchgate.net/publication/44689600_Conceptual_Synthesis_in_Community_Ecology

More or less explicitly, most theoretical paradigms developed to address biodiversity patterns have to tackle the concept of spatial and temporal scales

Yes, but

The concept of ecological community



N species
at a site s,
at time t

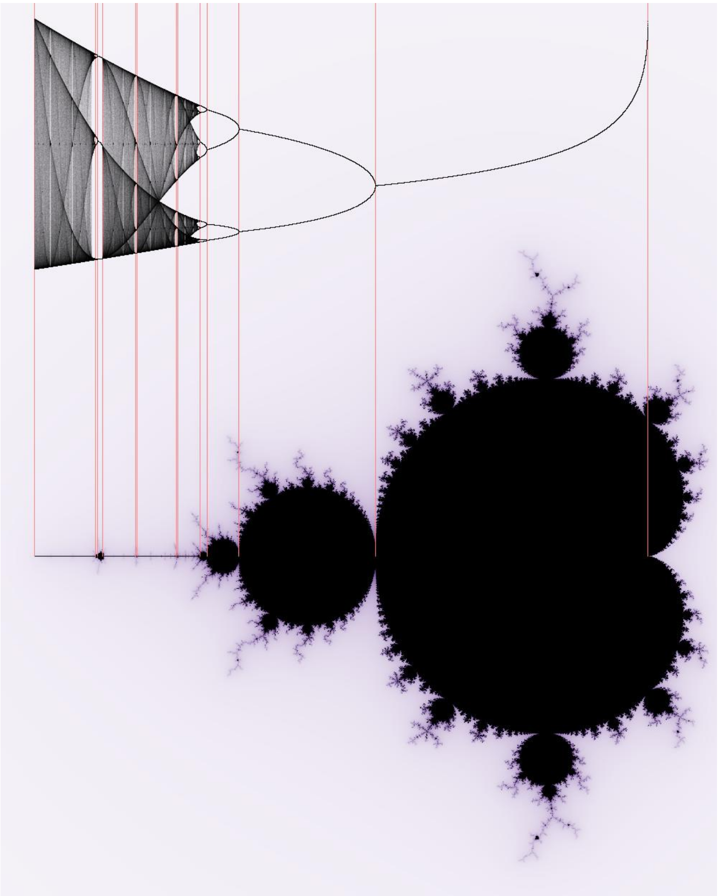
Disintegration of the ecological community

ABSTRACT: In this essay, I argue that the seemingly indestructible concept of the community as a local, interacting assemblage of species has hindered progress toward understanding species richness at local to regional scales. I suggest that the distributions of species within a region reveal more about the processes that generate diversity patterns than does the co-occurrence of species at any given point. The local community is an epiphenomenon that has relatively little explanatory power in ecology and evolutionary biology. Local coexistence cannot provide insight into the ecogeographic distributions of species within a region, from which local assemblages of species derive, nor can local communities be used to test hypotheses concerning the origin, maintenance, and regulation of species richness, either locally or regionally. Ecologists are moving toward a community concept based on interactions between populations over a continuum of spatial and temporal scales within entire regions, including the population and evolutionary processes that produce new species.

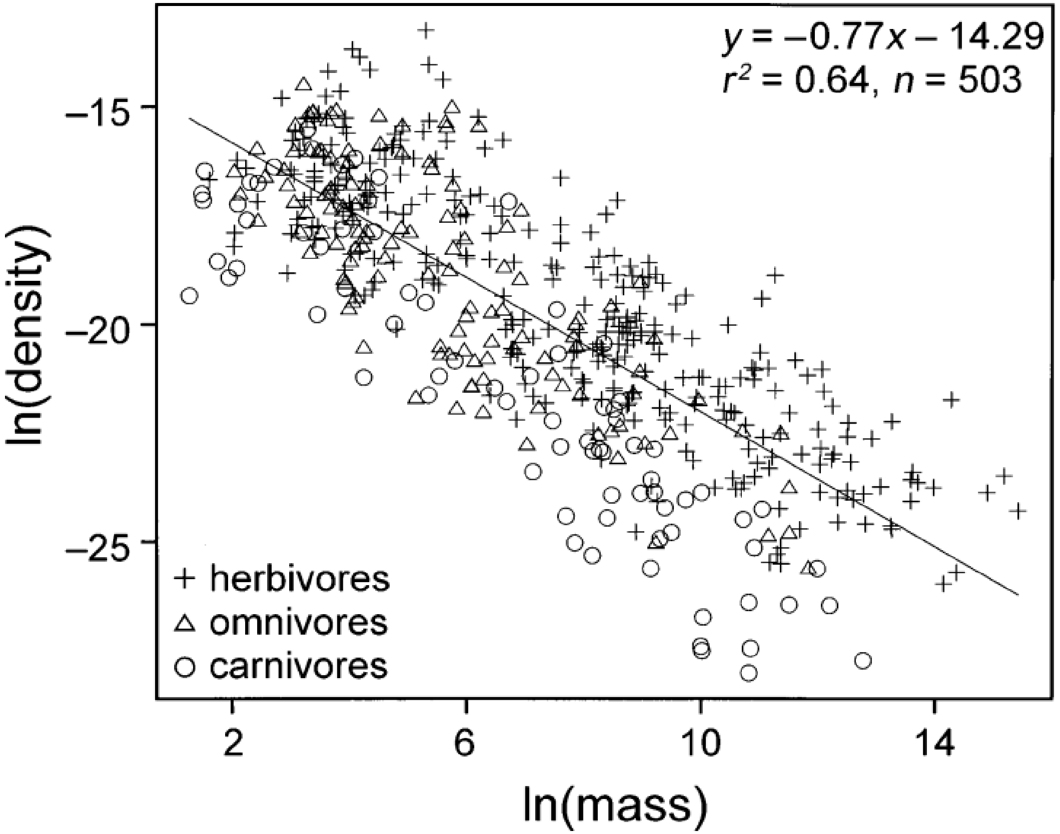
Ricklefs (2008) https://www.zoology.ubc.ca/bdg/pdfs_bdg/2020spring/Ricklefs_2008.pdf

Also, some processes do not change with scales

E.g., fractals (self-similarity across different scales) and metabolic constraints



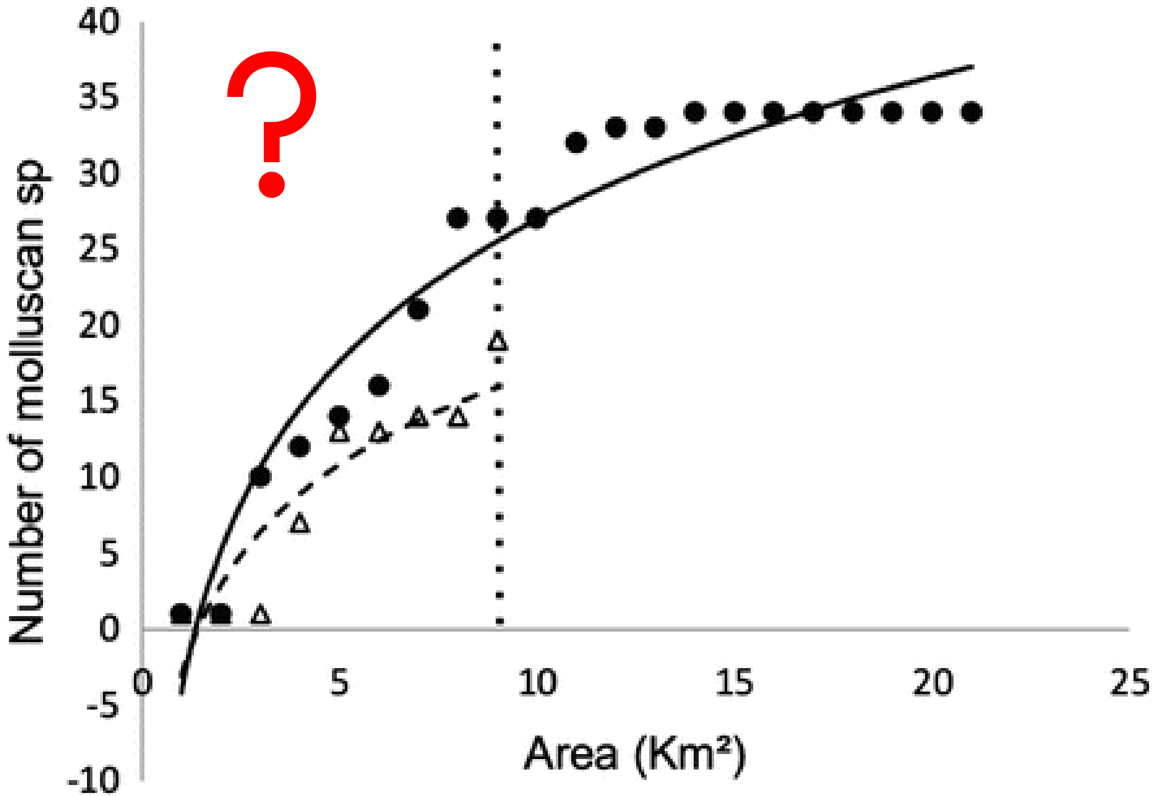
https://commons.wikimedia.org/wiki/File:Verhulst-Mandelbrot-Bifurcation.jpg

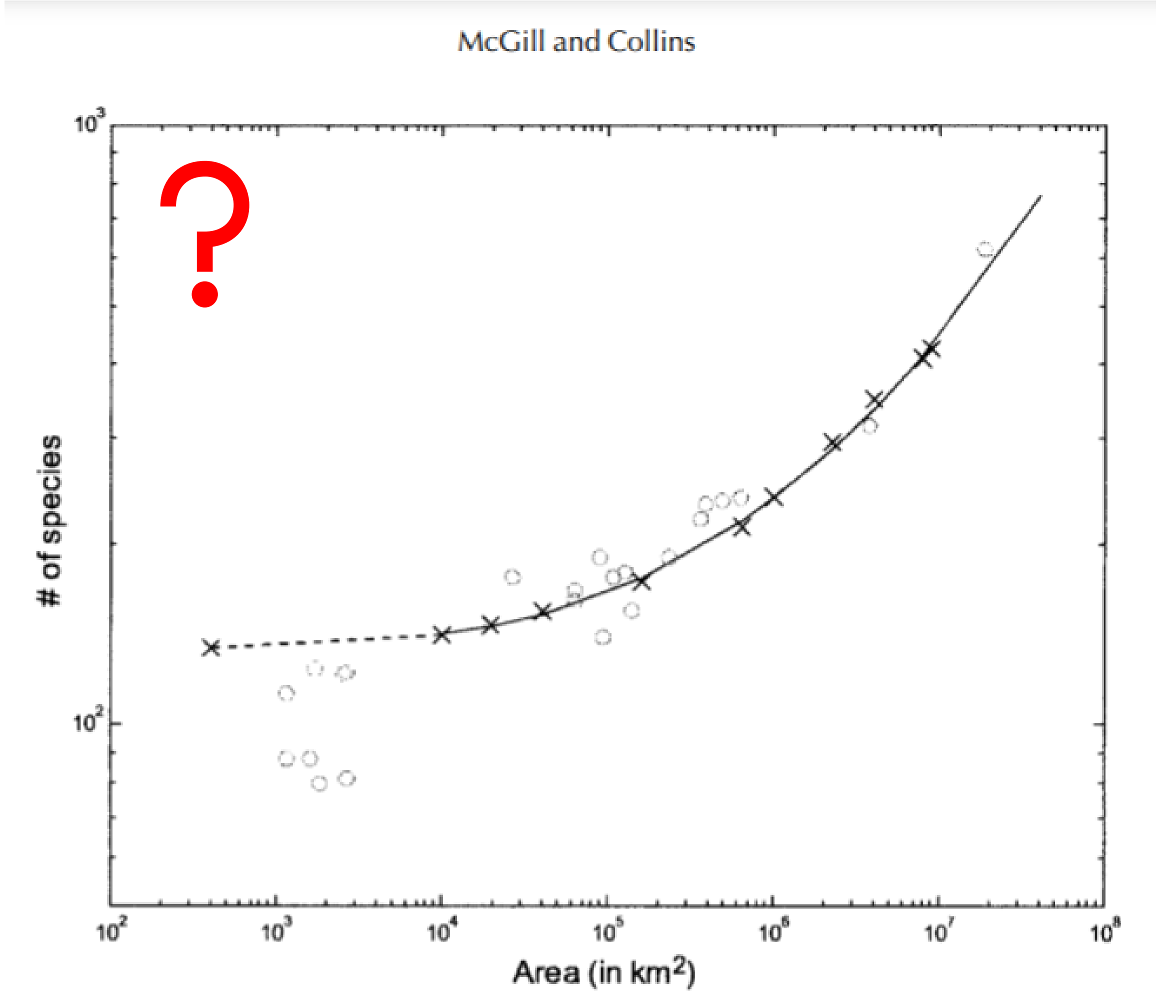


Brown et al. (2004) https://www.esa.org/history/Awards/papers/Brown_JH_MA.pdf
Halley et al. (2004) https://pdodds.w3.uvm.edu/files/papers/others/everything/halley2004a.pdf

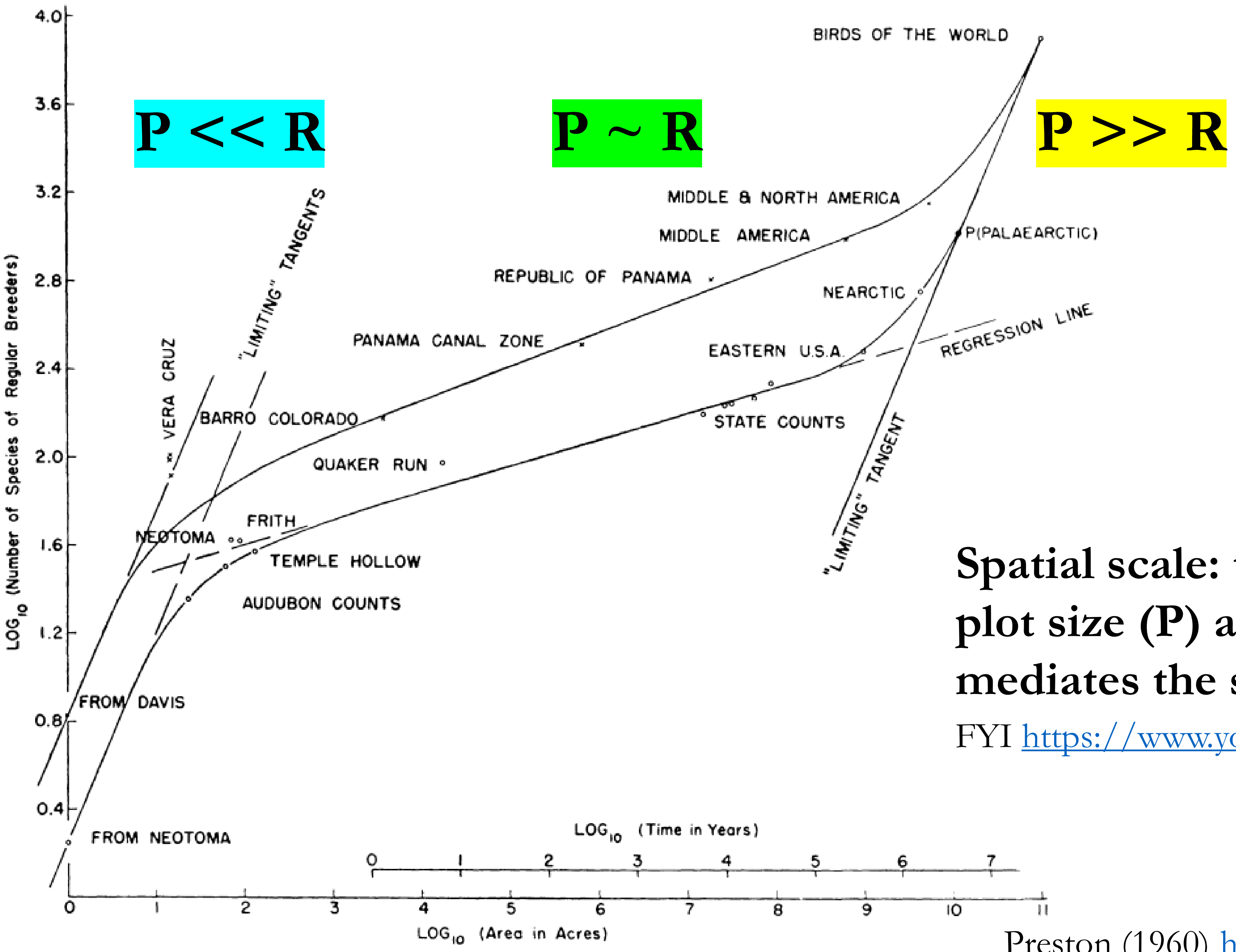
Scales as a mediator of contrasting perspectives

Species-area relationship





Pruden and Leighton (2018) https://link.springer.com/chapter/10.1007/978-3-319-73795-9_7
McGill and Collins (2003) https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.499.9375&rep=rep1&type=pdf



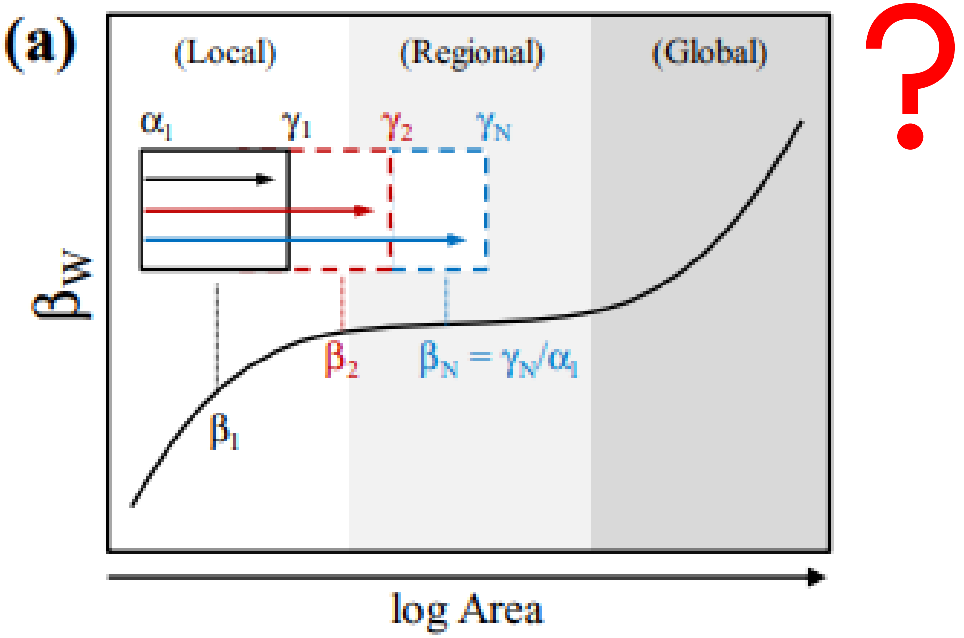
Spatial scale: the relationship between plot size (P) and the range of species (R) mediates the species-area relationship

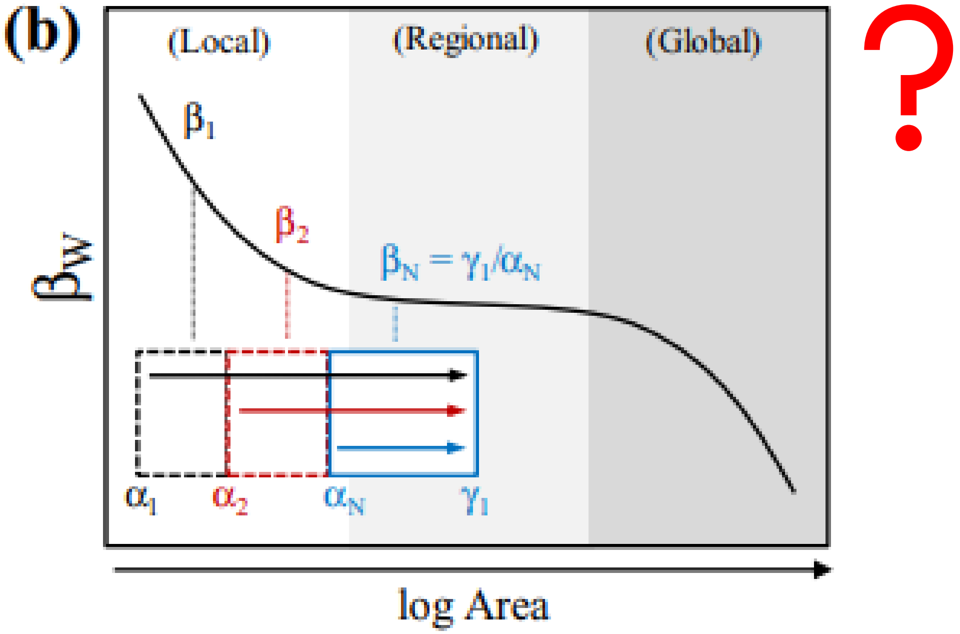
FYI https://www.youtube.com/watch?v=YfbKYKPUzdo

Preston (1960) https://www.jstor.org/stable/1931793

Beta diversity (species turnover)

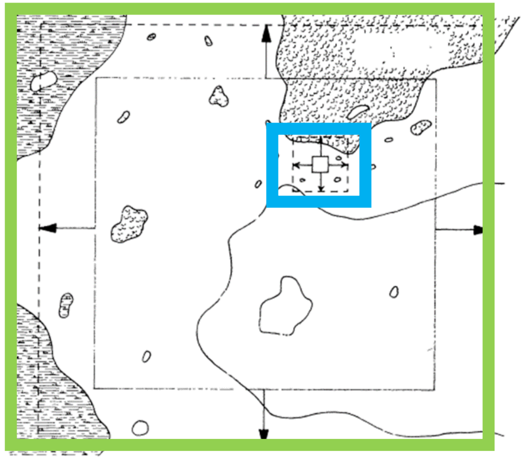
Whittaker's multiplicative beta: Alpha*Beta = Gamma ← → Beta = Gamma/Alpha
Alpha = species in a community
Gamma = species in a region





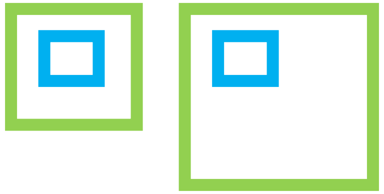
Whittaker (1962) https://esajournals.onlinelibrary.wiley.com/doi/10.2307/1943563
Barton et al. (2013) https://onlinelibrary.wiley.com/doi/pdfdirect/10.1111/geb.12031

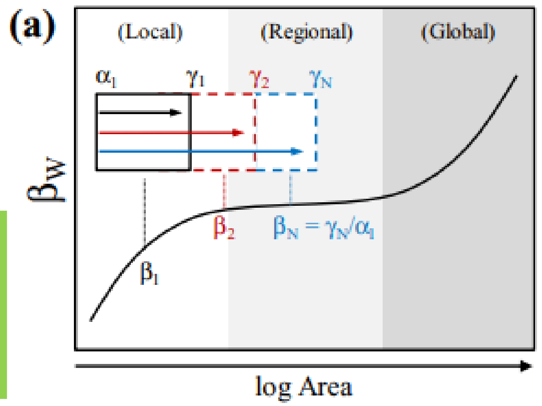
Wiens 1989 – grain vs extent



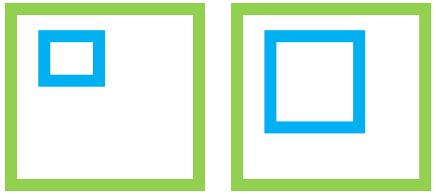
Whittaker's beta diversity
(multiplicative partitioning)

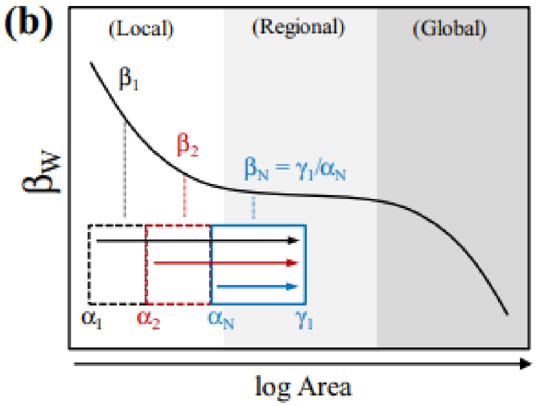
Fixed grain, varying extent





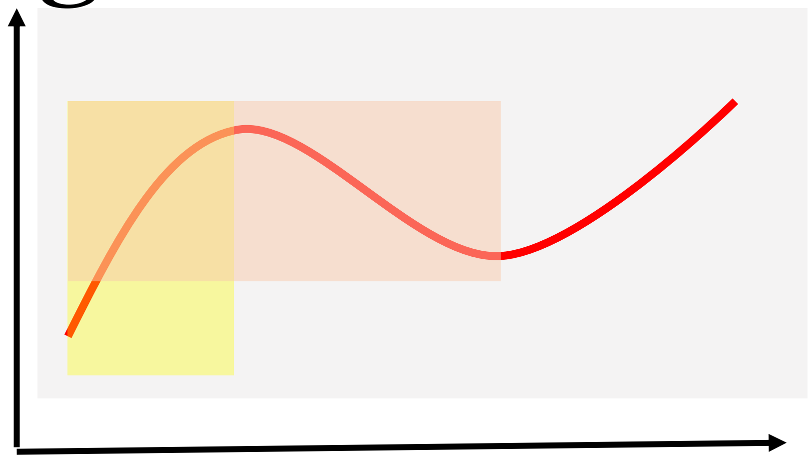
Varying grain, fixed extent

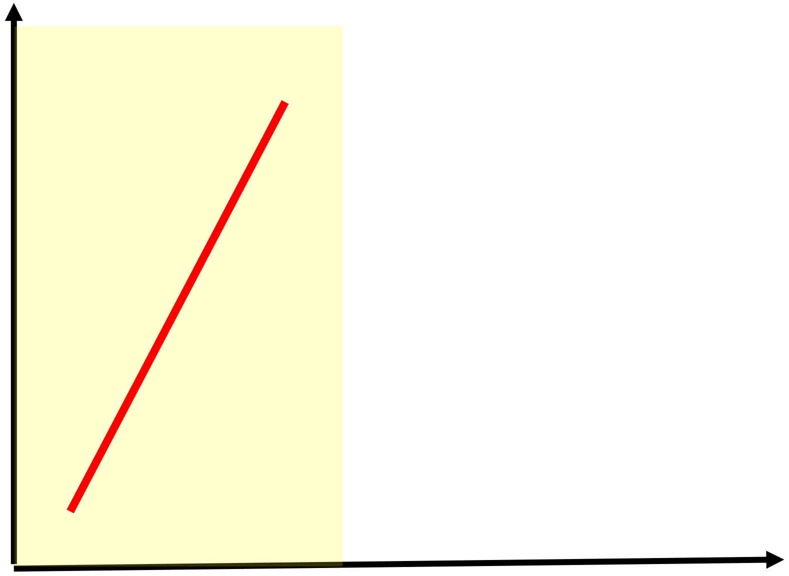


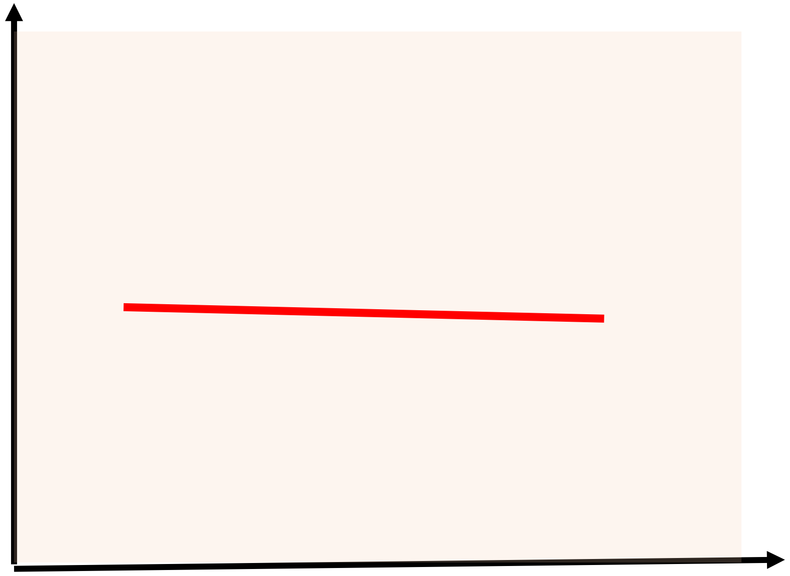


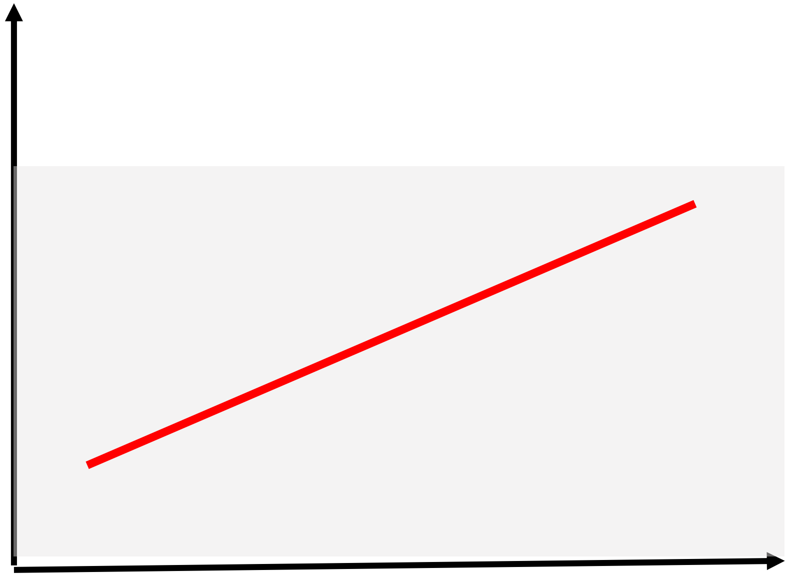
Barton et al. (2013) https://onlinelibrary.wiley.com/doi/pdfdirect/10.1111/geb.12031

Biodiversity change in time









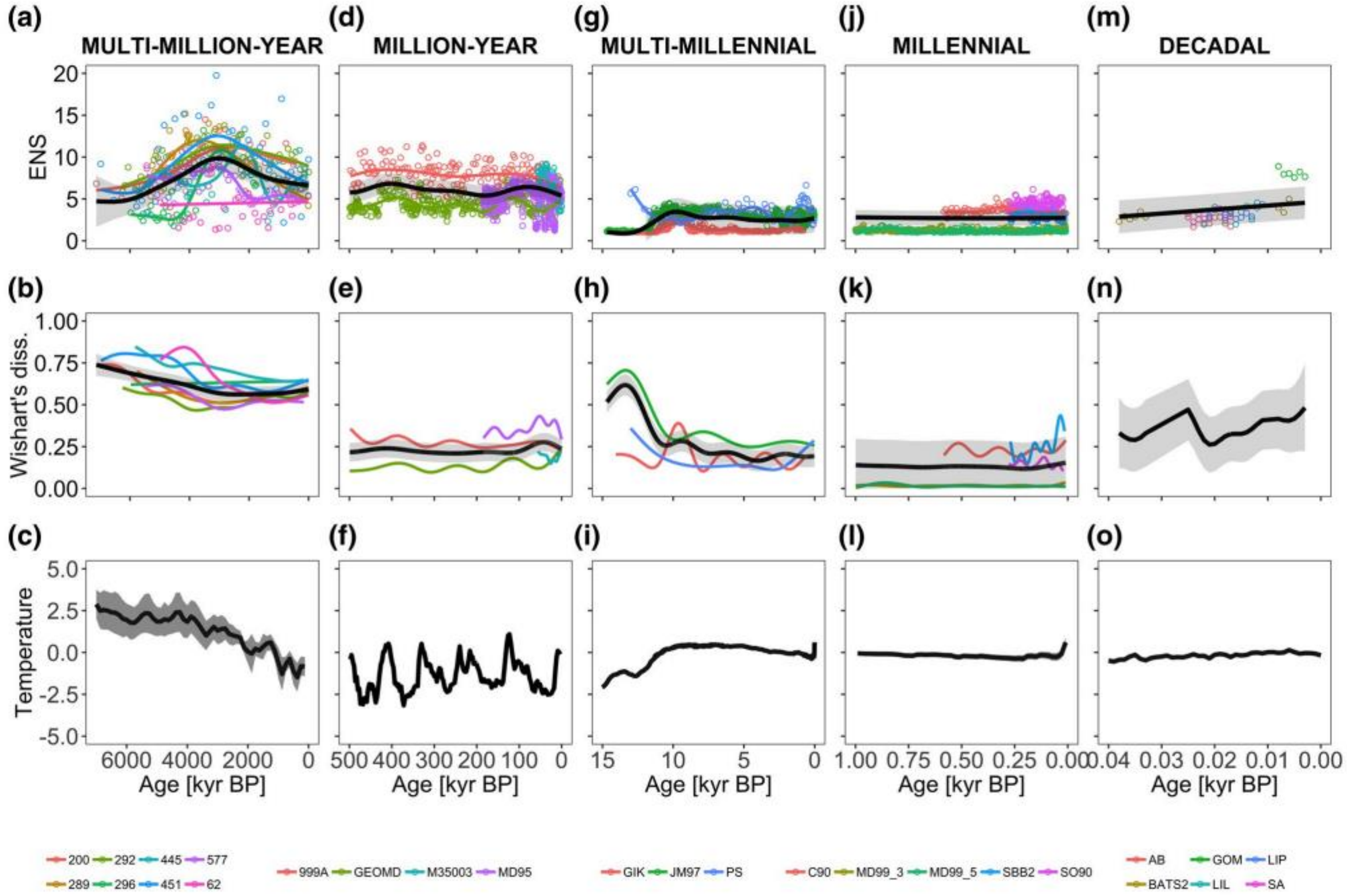
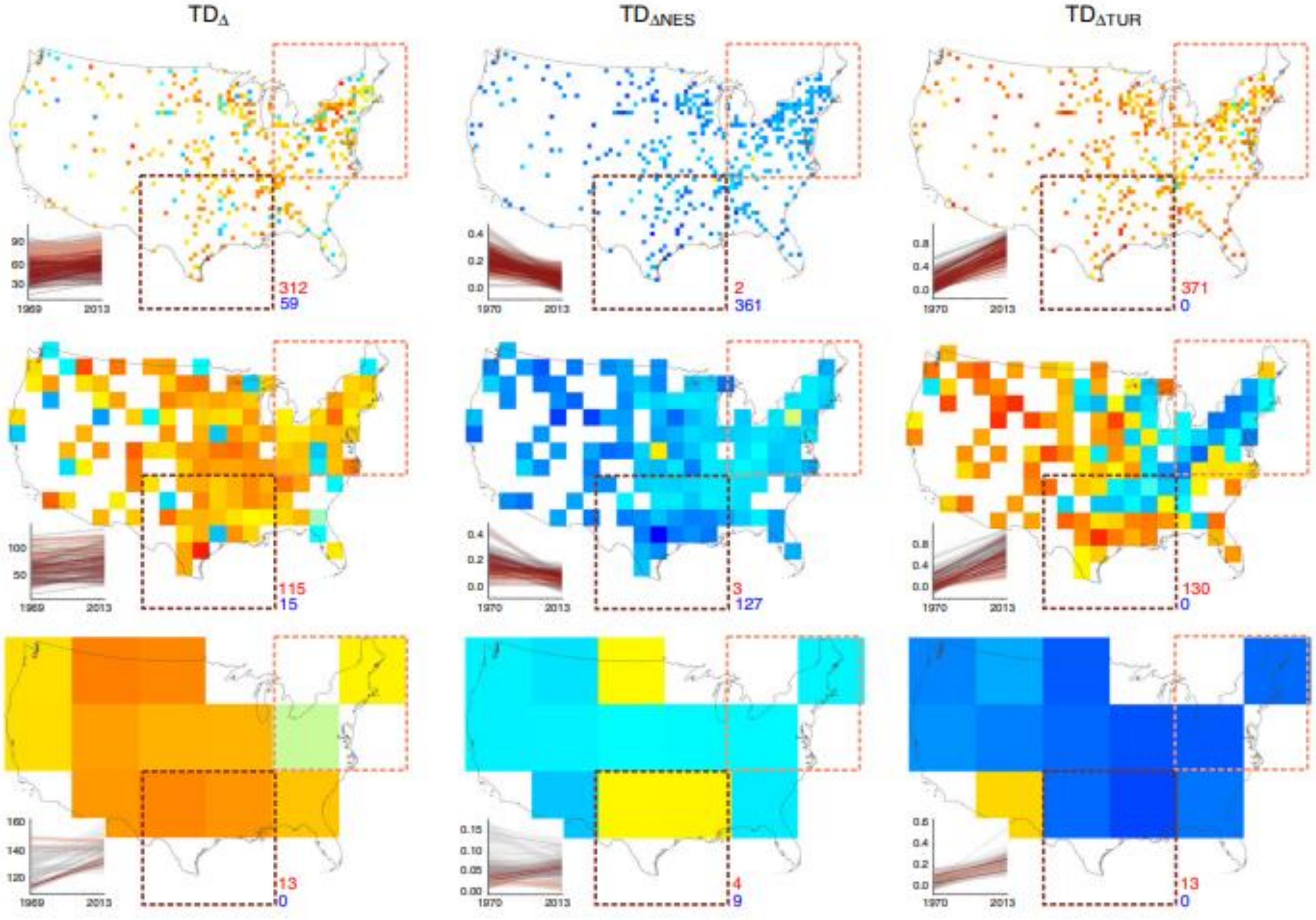


FIGURE 5 Temporal trends of foraminifera biodiversity over different time periods (as in Figure 2) as effective number of species (upper panels) and Wishart's dissimilarity (mid panels) in relation to temperature (bottom panels). Colours represent different sites, which are listed in the Supporting Information Appendix S1: Table S1. Black solid lines are general trends (± 95% confidence intervals) calculated using generalized additive models (GAMs) [Colour figure can be viewed at wileyonlinelibrary.com]

Lewandowska et al. (2020) https://onlinelibrary.wiley.com/doi/pdf/10.1111/geb.13078

Trends in biodiversity change with spatial scales

… Scales shown, from top to bottom, are 50 km, 200 km, 800 km. Fitted positive and negative slopes indicate increases and declines in taxonomic diversity (TDΔ, left panel), temporal nestedness of taxonomic diversity (TDΔNES, middle panel), and temporal turnover of taxonomic diversity (TDΔTUR, right panel). Red and blue numbers indicate the number of grid cells for which these trends were positive and negative, respectively. Insets show the fitted slopes between the respective measure of change (y-axis) and time (x-axis; calendar year) for the cell inside the brown (brown lines) or beige (beige lines) quadratic regions.



Jarzyna and Jetz (2018) https://www.nature.com/articles/s41467-018-04889-z.pdf

Temporal cycles affect diversity and abundance estimated

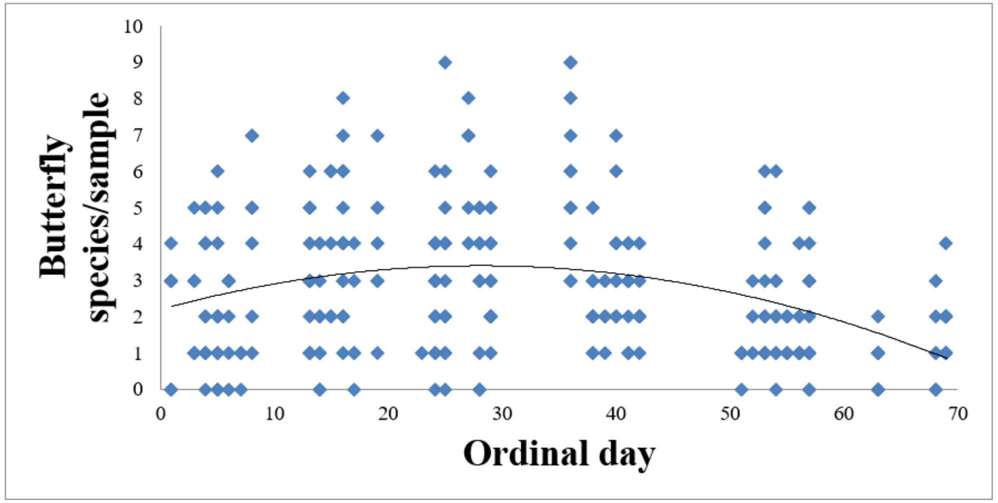


Figure 6: Number of butterfly species observed per sample (n = 275) between June 14th (ordinal day = 1) and August 24th (ordinal day = 69). Diversity of butterflies peaks around the second week of July. A quadratic function is fitted to represent the unimodal diversity trend.

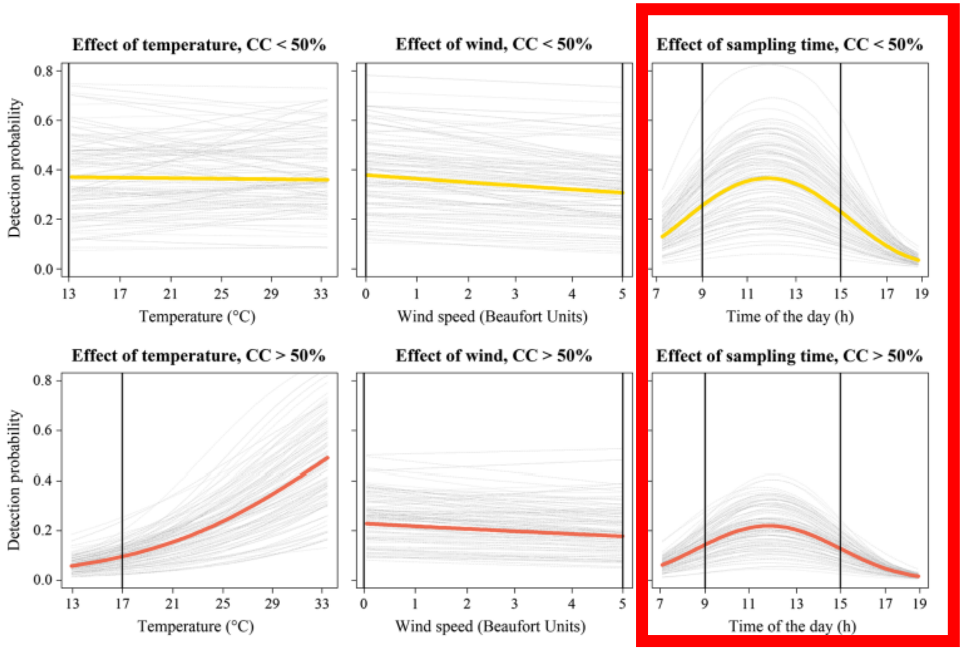
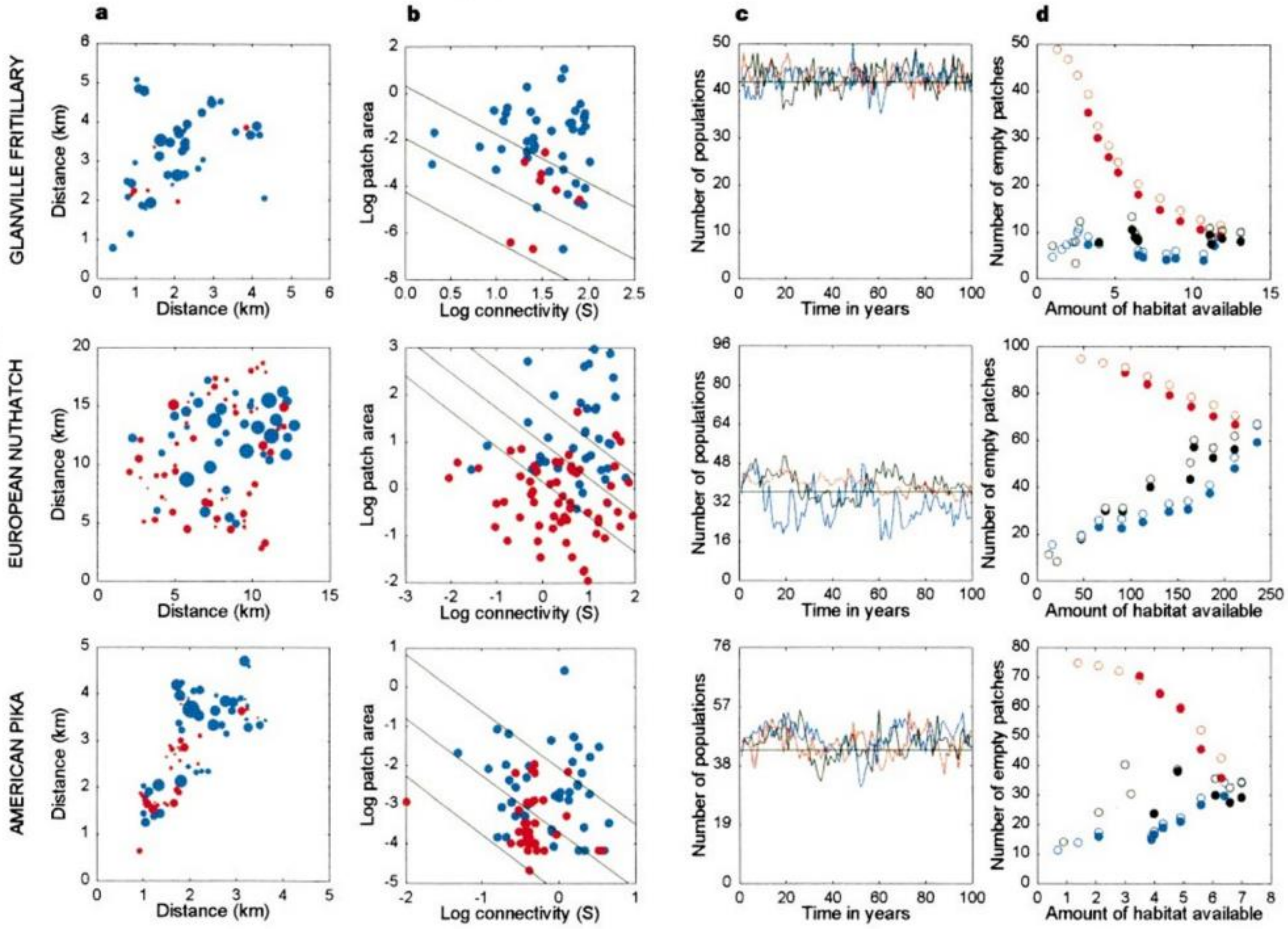


Fig. 3. Trends in detectability with temperature, hour of samples, and wind speed at cloud cover (CC) >50% (top row, in gold) and <50% (bottom row, in red). Predictions are calculated holding the other covariates at their average value (i.e., temperature ~ 24°C, wind speed ~ 1 BU, time of the day ~ noon). Black vertical lines represent the sampling criteria recommended for PW for monitoring schemes (i.e., temperature >13°C with cloud cover <50% and >17°C when cloud cover >50%; wind speed <5 BU; sampling hour between 9:00 and 15:00).

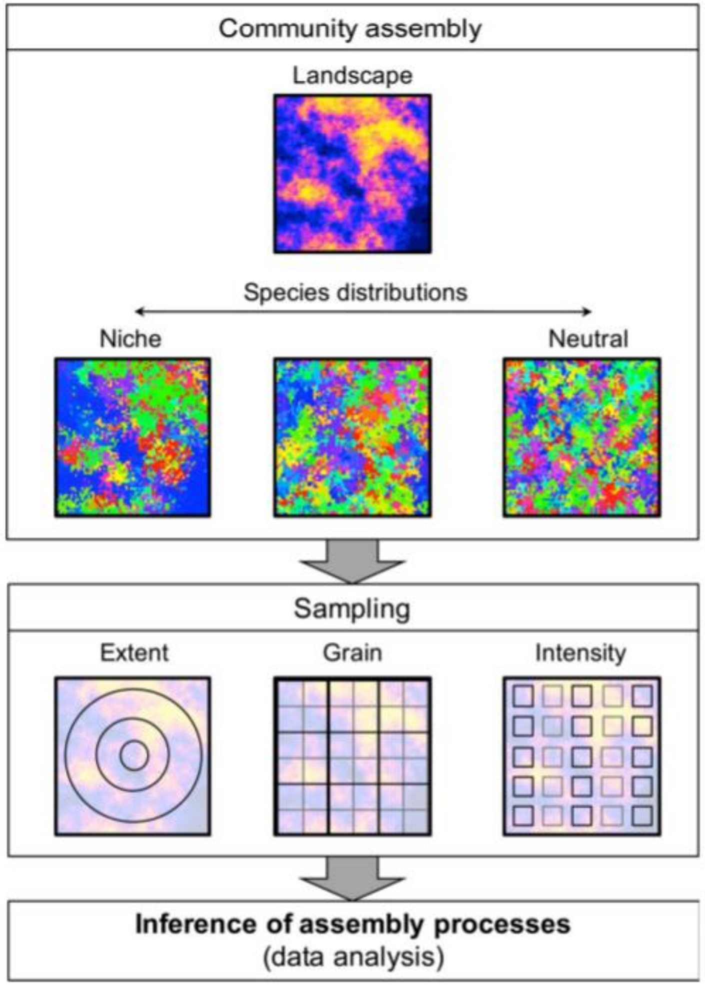
Riva et al. (2018) https://www.ace-lab.ca/assets_b/Riva%20et%20al.%20%282018%29%20Biological%20Conservation.pdf
Riva et al. (2020) https://esajournals.onlinelibrary.wiley.com/doi/pdf/10.1002/ecs2.3101

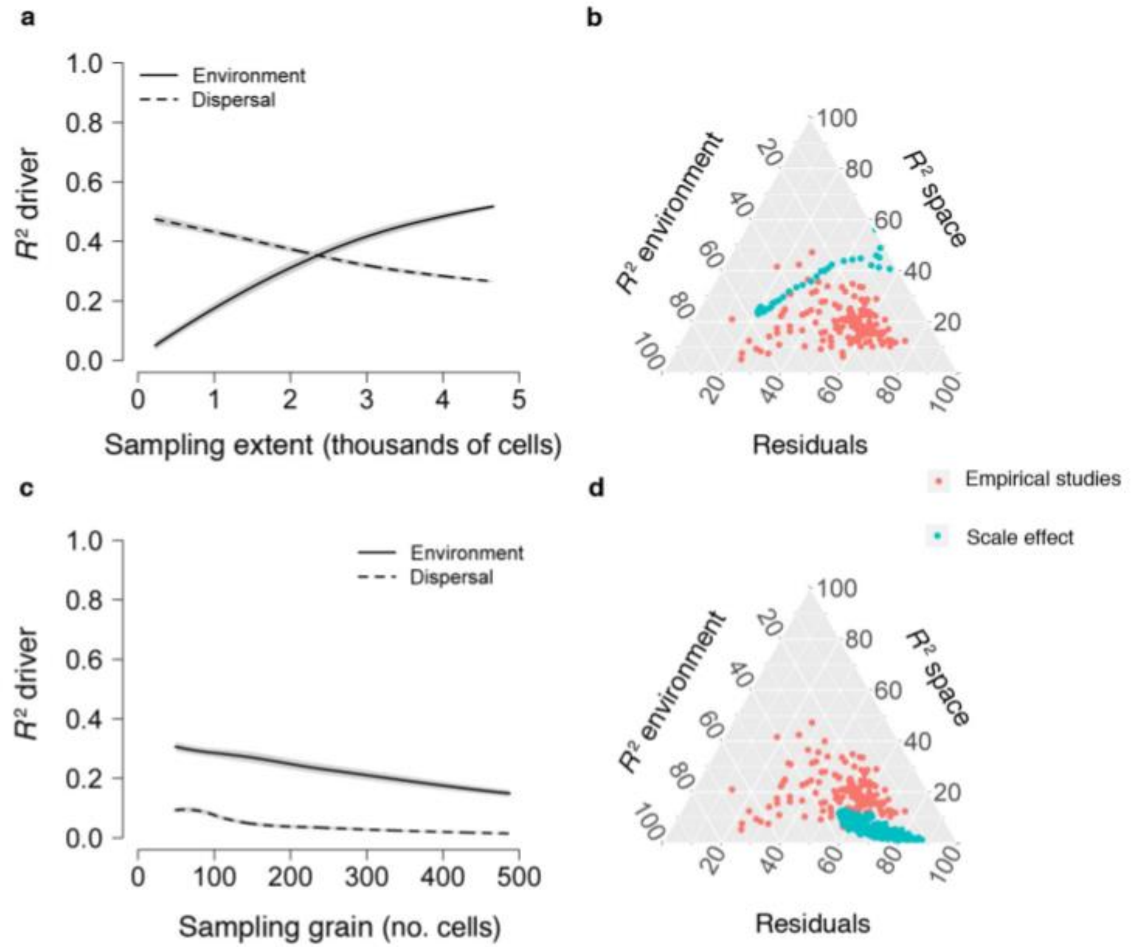
Metacommunity dynamics



Hanski (2002) https://www.nature.com/articles/23876.pdf

Assembly processes in metacommunities





Viana and Chase (2019) https://www.idiv.de/uploads/tx_znmidivpublications/Viana_2019_SpatialScale.pdf

Productivity-diversity relationship

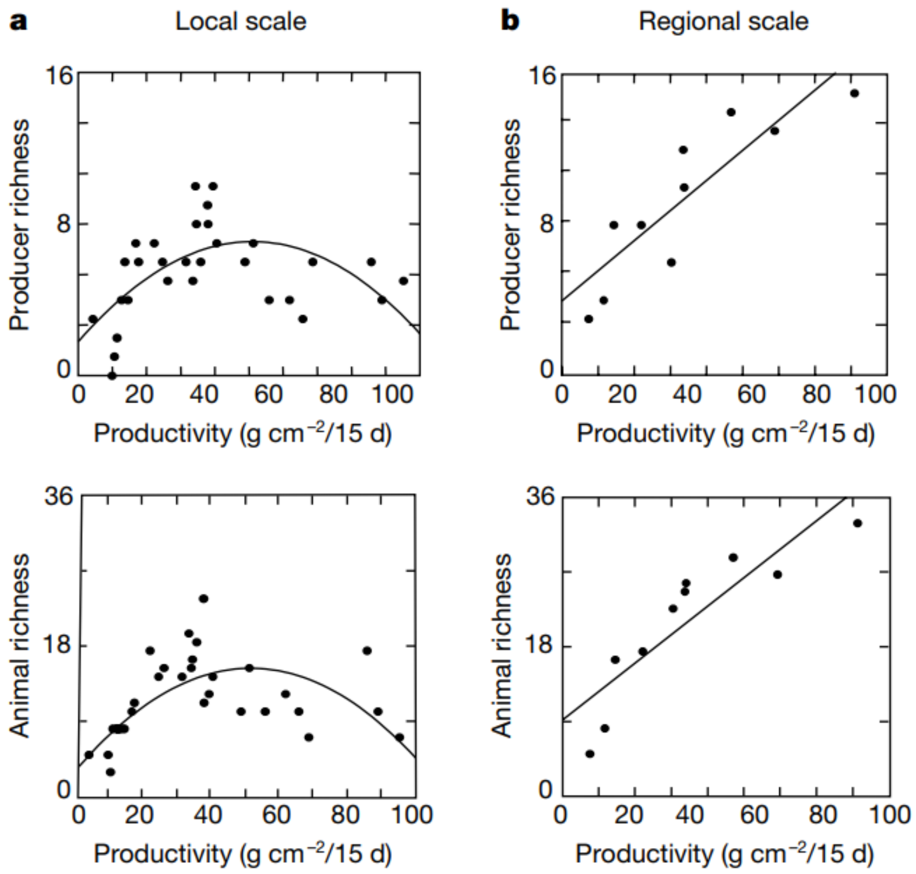


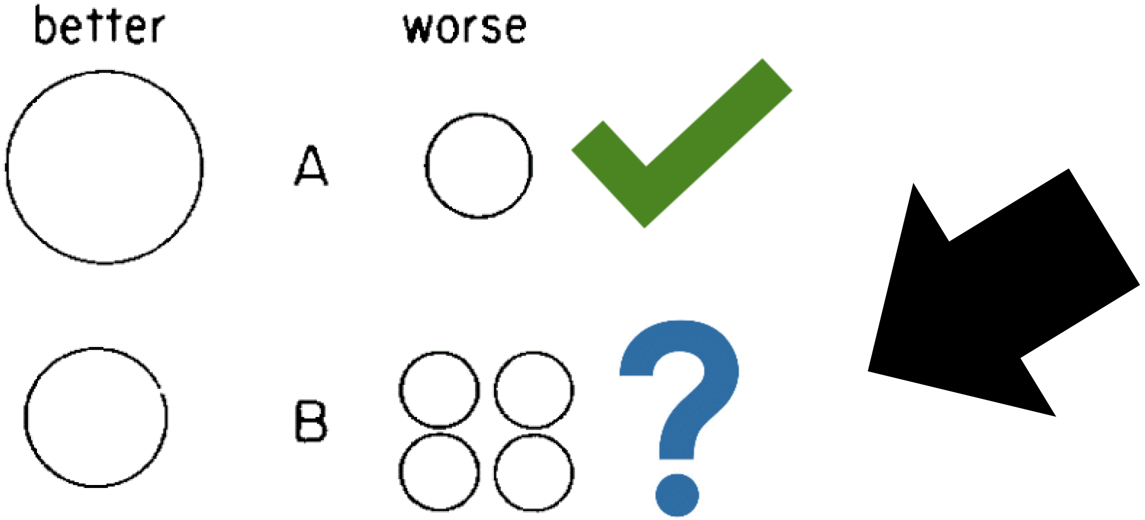
Figure 1 Results from the survey of pond species diversity relative to *in situ* primary productivity at local and regional scales. Top panels, producers (vascular plants and macroalgae); bottom panels, benthic animals (insects, crustaceans, amphibians, and so on). **a**, Local, within-pond, species diversity ($N = 30$). Both relationships are significantly unimodel ($P < 0.05$) (see text for explanation of statistical methodology). The line represents the estimated quadratic function. **b**, Regional, within-watershed, species diversity. For both producers (regression: $N = 10$, $R^2 = 0.74$, $P < 0.001$) and benthic animals (regression: $N = 10$, $R^2 = 0.75$, $P < 0.001$) regional species diversity was linearly related to primary productivity.

Chase and Liebold (2004) https://www.nature.com/articles/416427a.pdf

Scales often explain why we get different results when answering the same questions

Applications in conservation

Example 1: Single Large Or Several Small (SLOSS)?

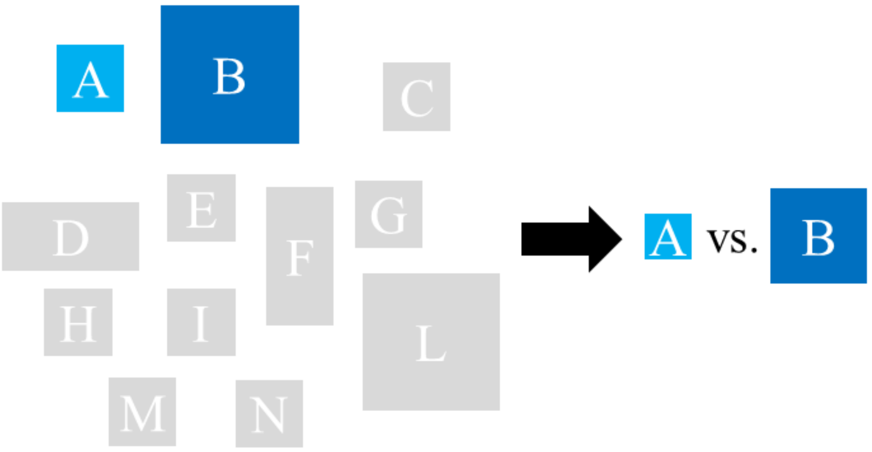


"Like previous reviews, I found that SS > SL dominates empirical findings"
Fahrig 2020

Fahrig 2020 https://onlinelibrary.wiley.com/doi/full/10.1111/geb.13059
Diamond 1975 https://www.sciencedirect.com/science/article/abs/pii/000632077590052X

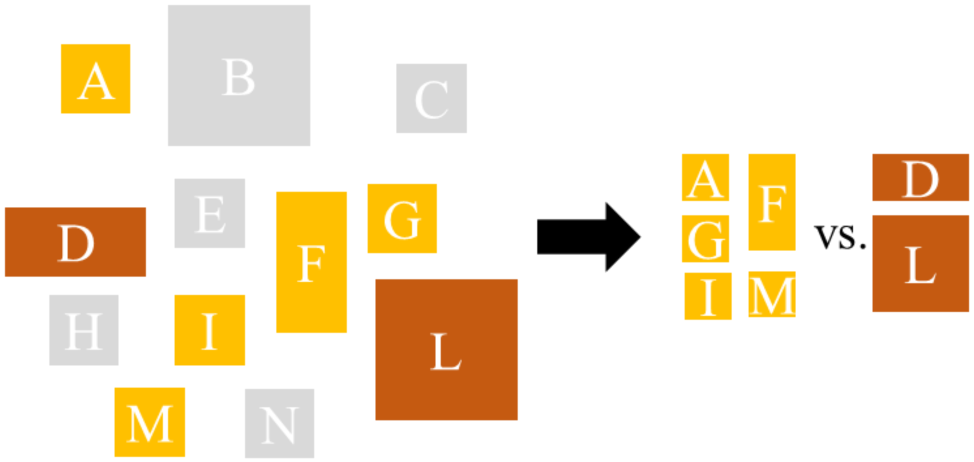
Extinction risk, patch size, and the landscape scale

Patch scale



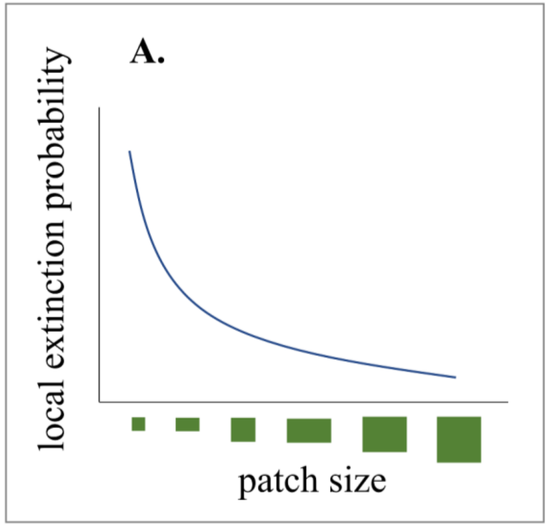
Comparing two patches
- Same number of patches
- Different area

Landscape scale



Comparing two sets of patches
- Same area
- Different number of patches

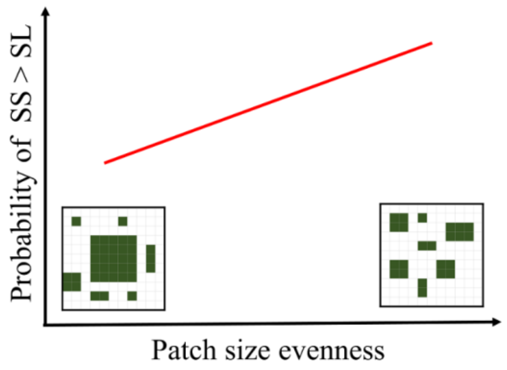
Patch scale



Landscape scale

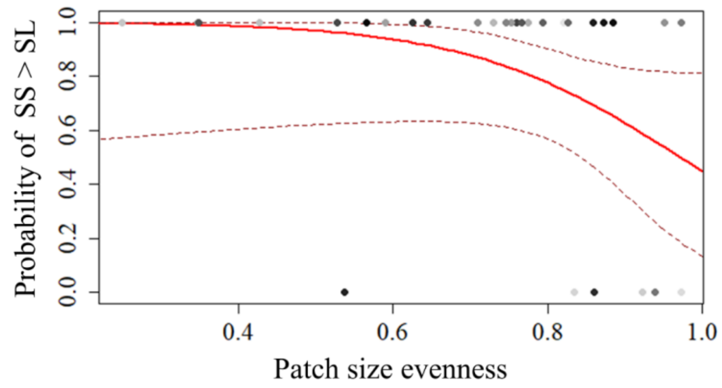
Prediction

If higher extinction in small than large patches plays a role in the outcome of SLOSS, then SL > SS should be less likely, and SS > SL should be more likely, for sets of patches that are more similar in size.



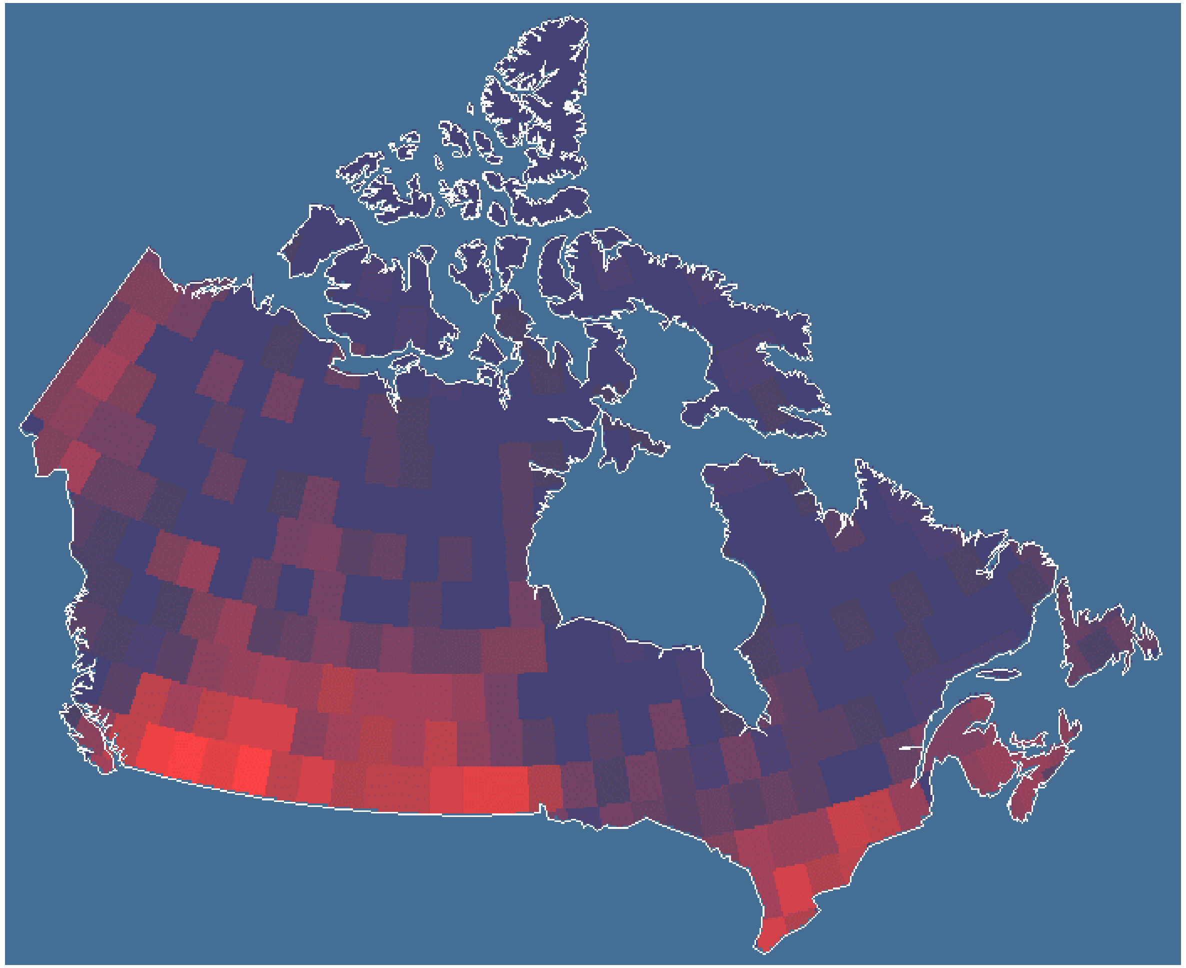
Result

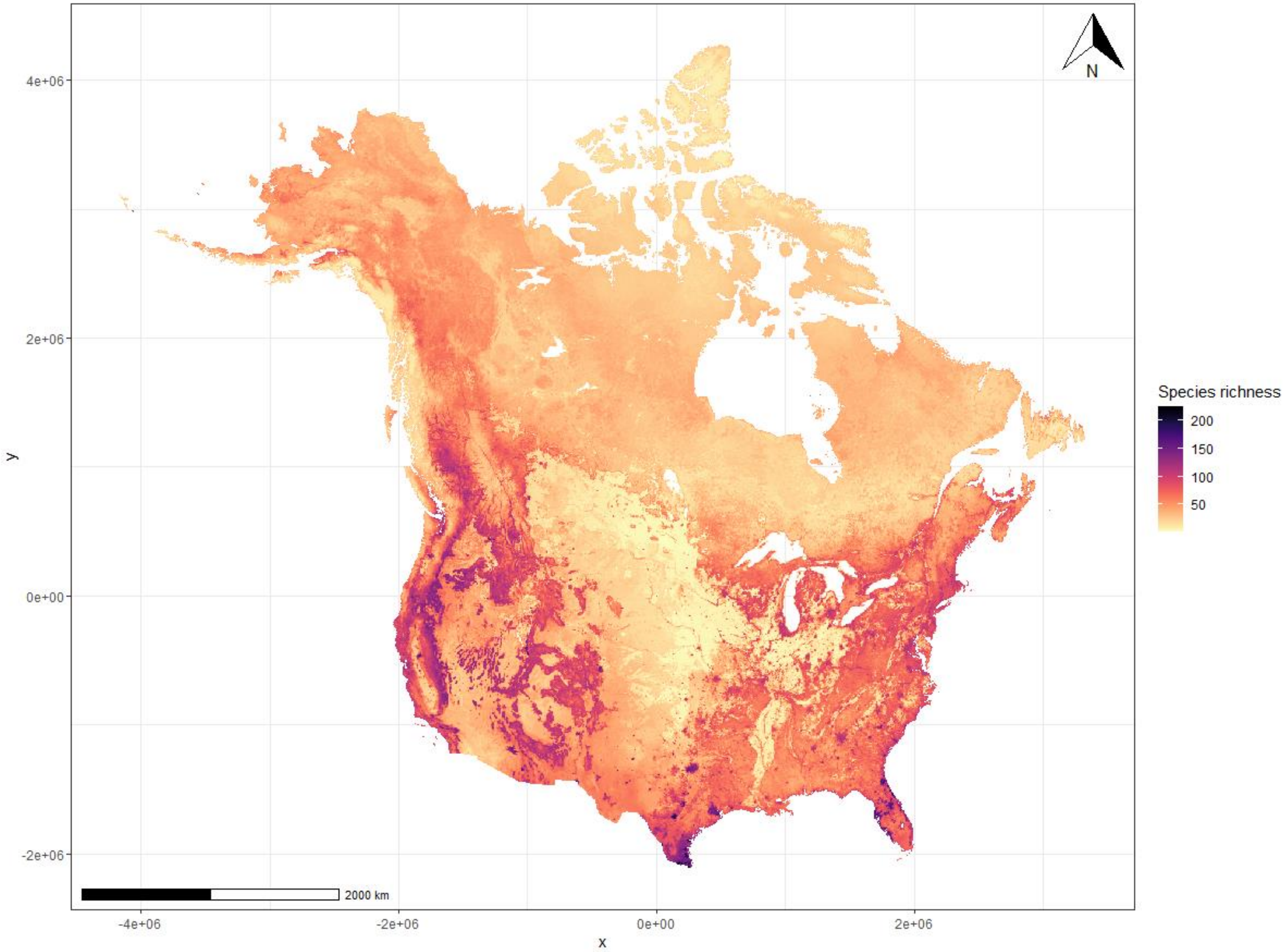
Analysis of 32 datasets shows the opposite pattern to the prediction, suggesting that higher extinction in small than large patches does not play a role in the outcome of SLOSS.



Riva and Fahrig in review

Example 2: Big data and remote sensing

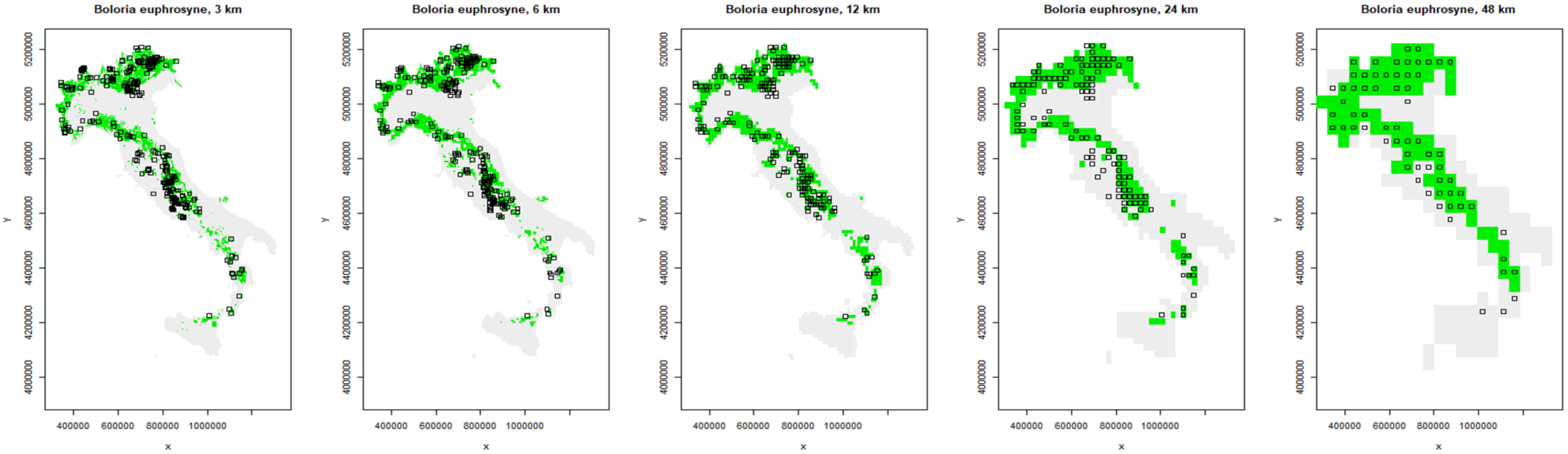




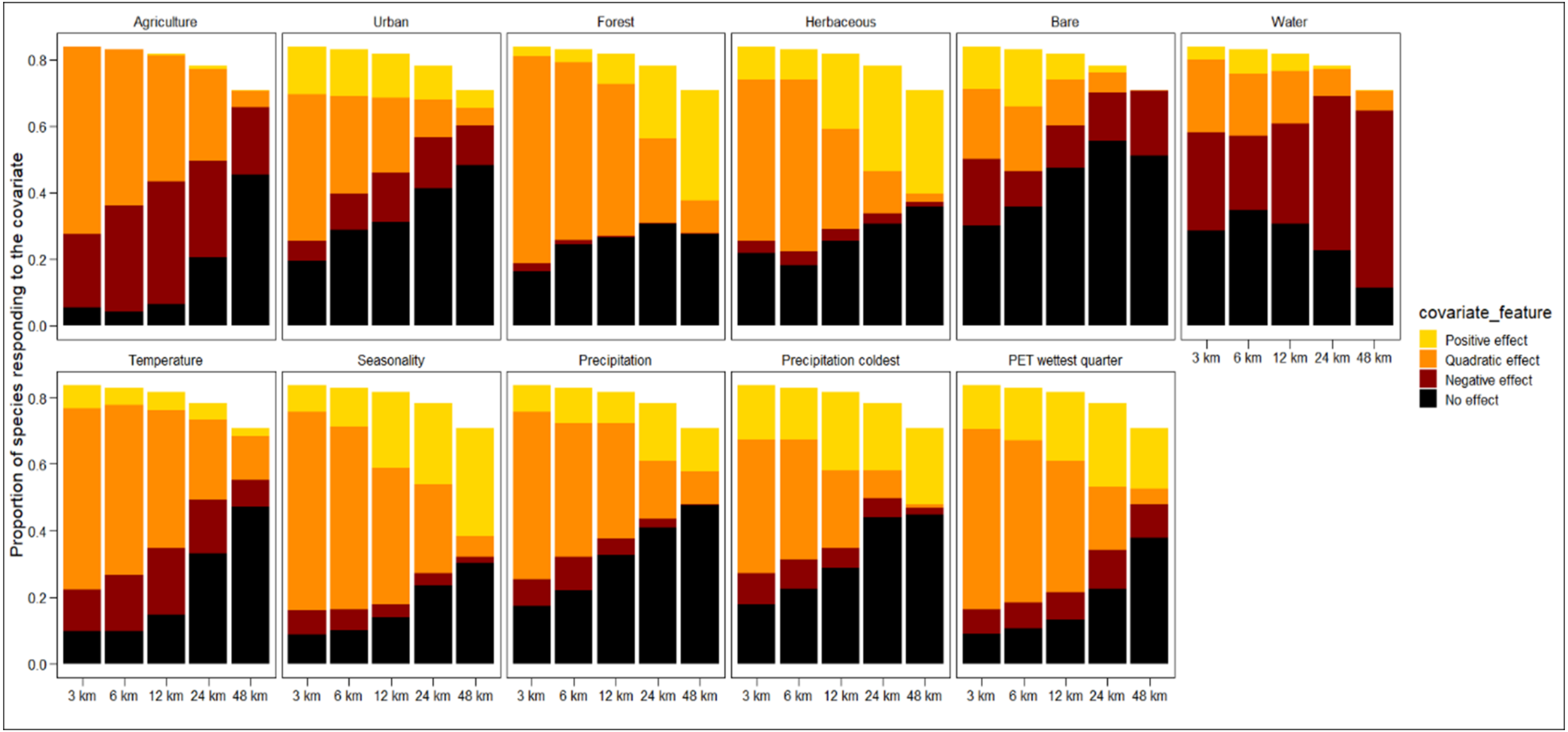
Kerr 2001: https://www.ecologyandsociety.org/vol5/iss1/art10/
371 cells, 2 degrees (~ 200 km) grain

Riva et al. (in prep)
2.3 million cells, 5-km grain

Grain affects the relationship between species distribution and the environment



Riva et al. in preparation

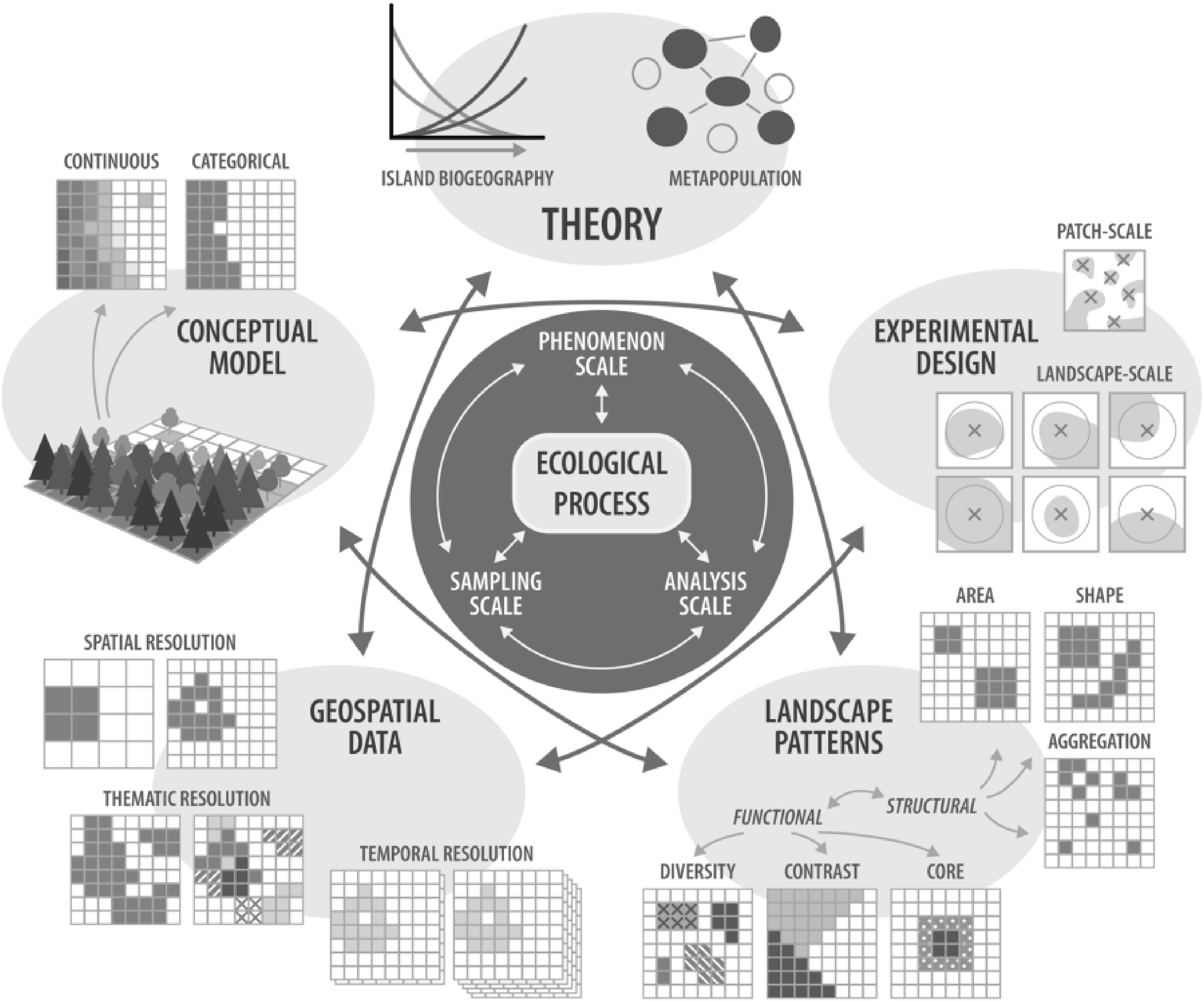


Riva et al. in preparation

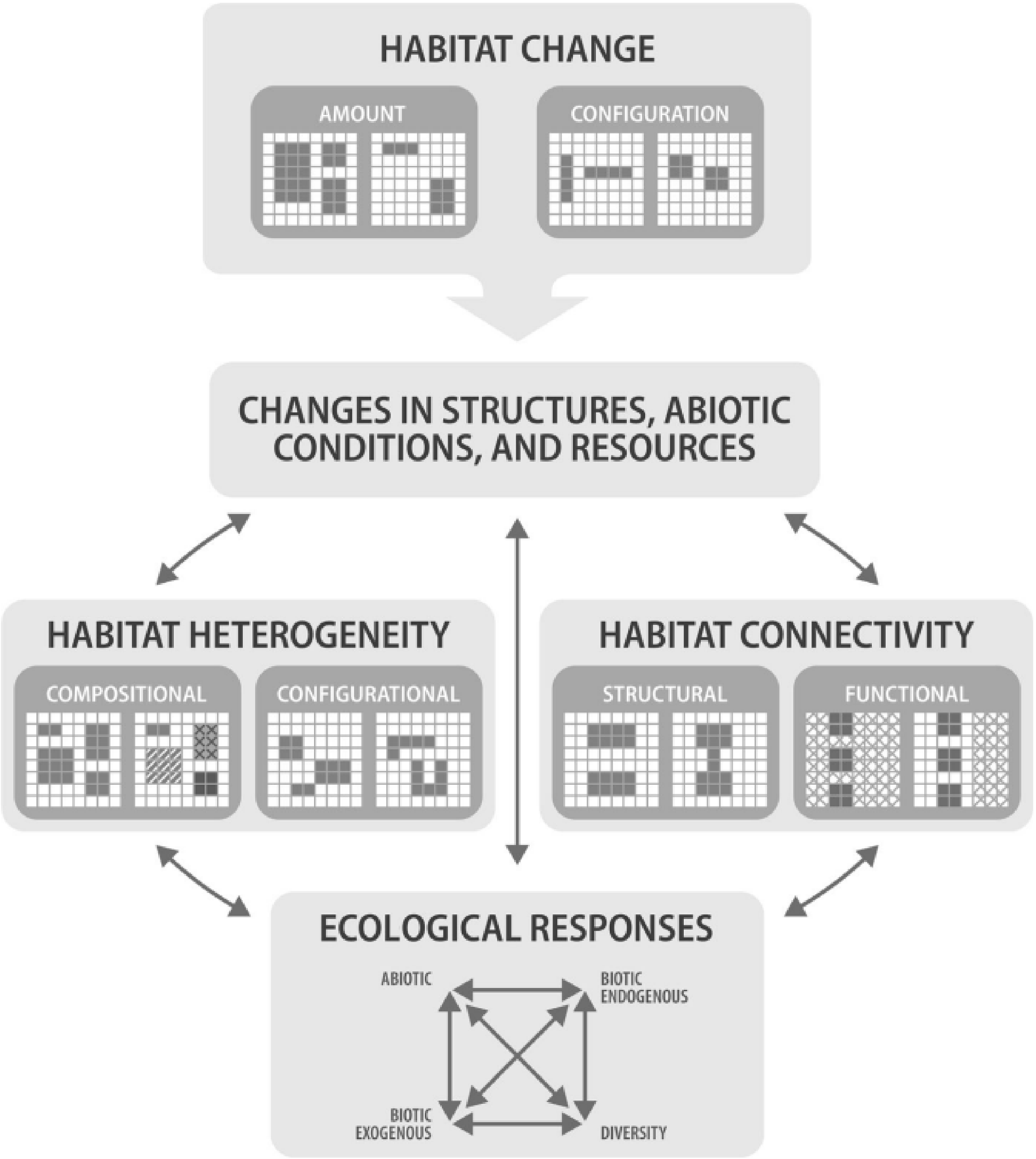
Conclusions

Scaling does matter – what can we do?

- Always think about the ecological process of interest
  - E.g., for conservation, are you interested in large scale, regional patterns, or in *in situ* protection and management of species?
  - Why are you designing an analysis at a given spatial and temporal scale?
  - Taxonomic scales, other scales?
- How can scales affect your conclusion, and why?

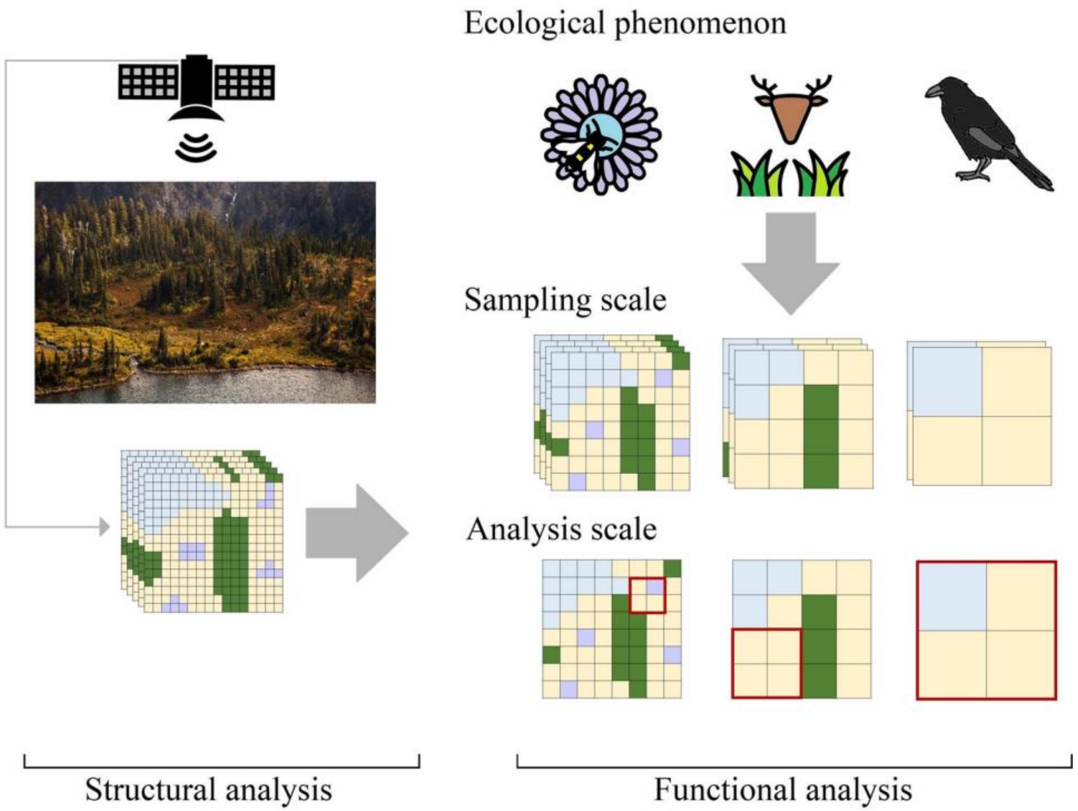


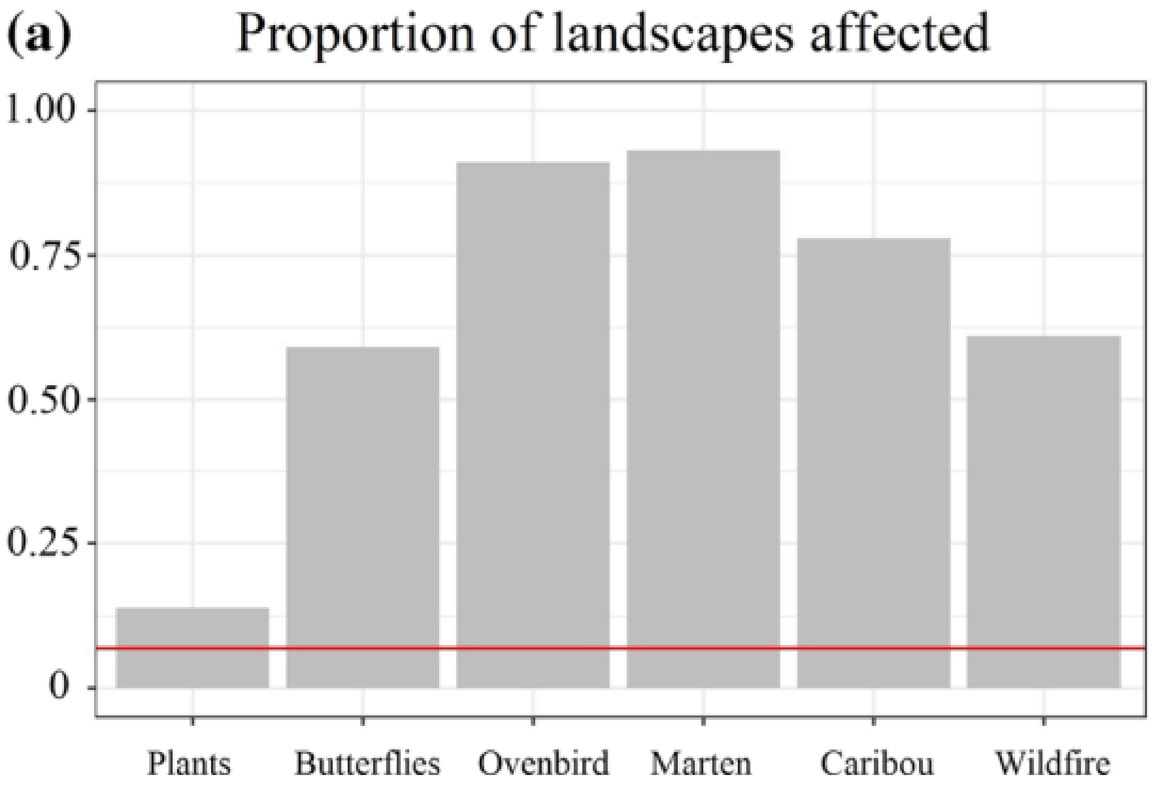
Riva and Nielsen (2020) https://ace-lab.ca/assets_b/Riva-Nielsen2020_Article_SixKeyStepsForFunctionalLandsc.pdf



Riva and Nielsen (2020) https://ace-lab.ca/assets_b/Riva-Nielsen2020_Article_SixKeyStepsForFunctionalLandsc.pdf

Measuring functional habitat loss





Riva and Nielsen (2021) https://ace-lab.ca/assets_b/Riva-Nielsen2021_Article_AFunctionalPerspectiveOnTheAna.pdf

McGill University, BIOL 310 - Scaling in ecology

Riva, Federico

03/02/2022

Introduction

This is a tutorial complementing the lecture on scales, available at https://github.com/FedericoRiva. We will focus on three main parts: 1) spatial data preparation; 2) scale dependency in species rarity; and 3) scale dependency in biodiversity trends

Spatial data preparation

```r
# set up
# packages needed in the tutorial
packages = c("data.table", "raster", "sp", "maptools", "dplyr","vegan")

# load the packages; if missing, install & load
package.check <- lapply(
  packages,
  FUN = function(x) {
    if (!require(x, character.only = TRUE)) {
```