Biodiversity Science

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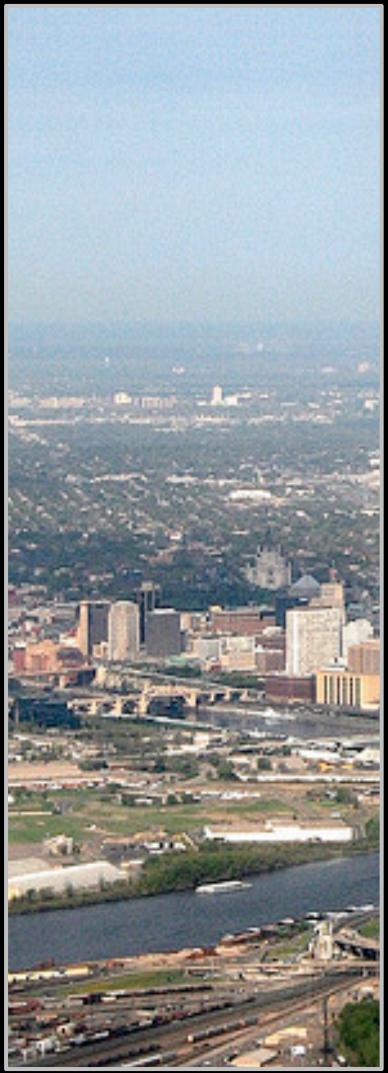
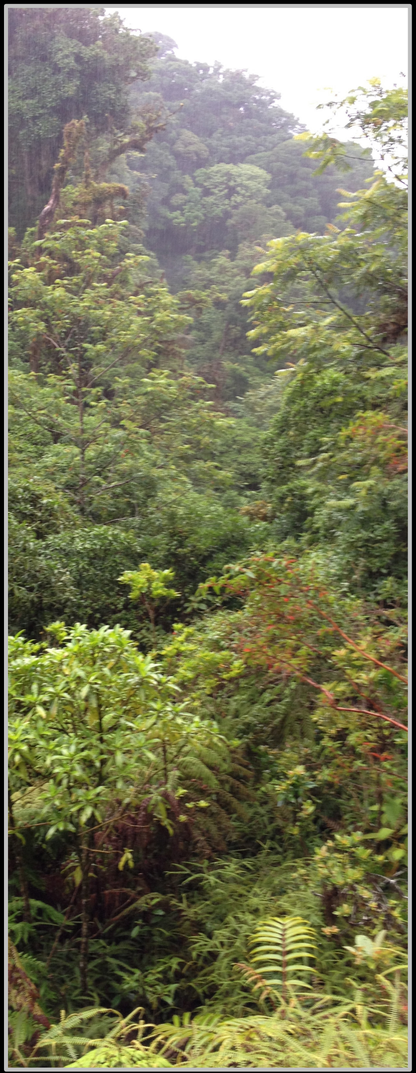
University of Minnesota

- Why monitor biodiversity?
- Origins of biodiversity
- Explaining spatial patterns of biodiversity
- Metrics of biodiversity
- Biodiversity and ecosystem function
- Towards global biodiversity monitoring

Monitoring biodiversity and how it is changing is critical to sustaining Planet Earth for humanity

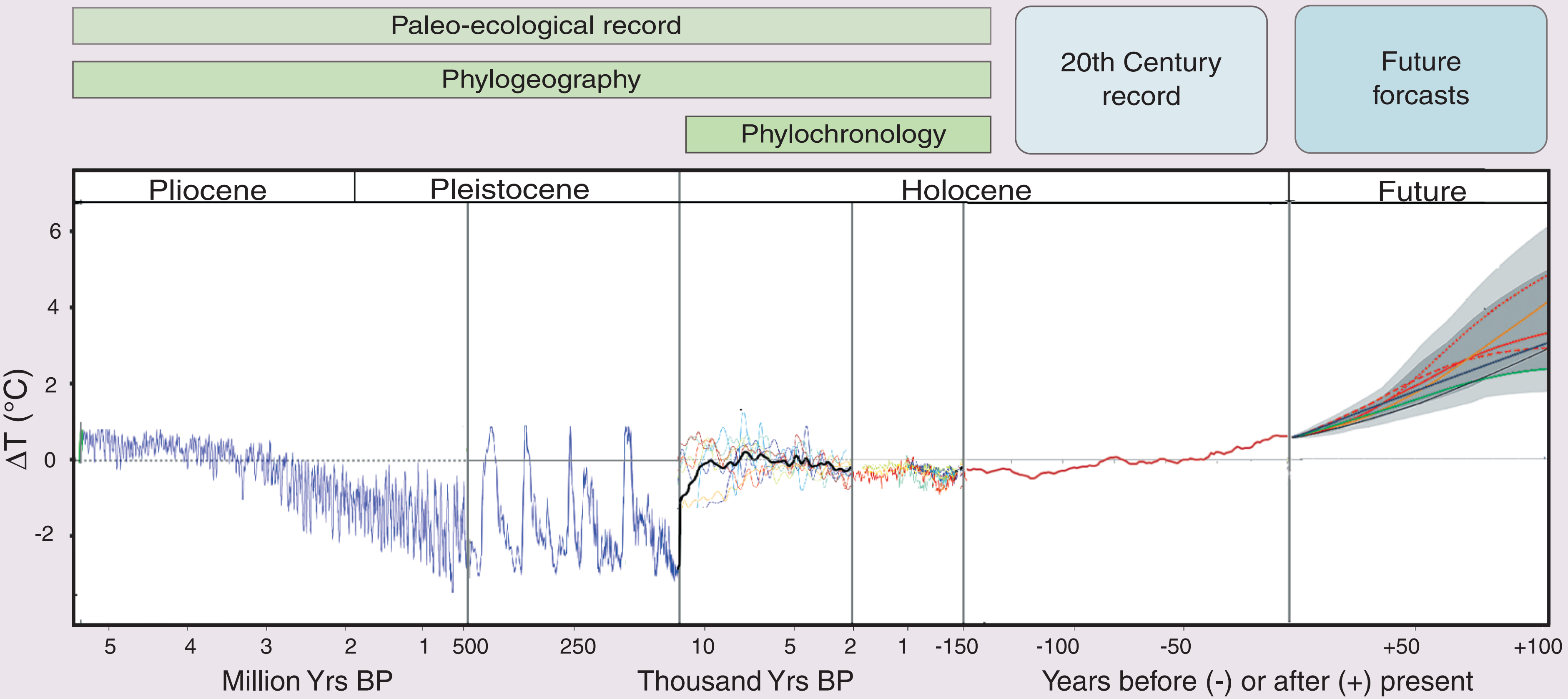




Biodiversity crisis

dreersouthafrica.wordpress.com/2014/11/

Future climate will depart from previous climates of the last 5 MYR



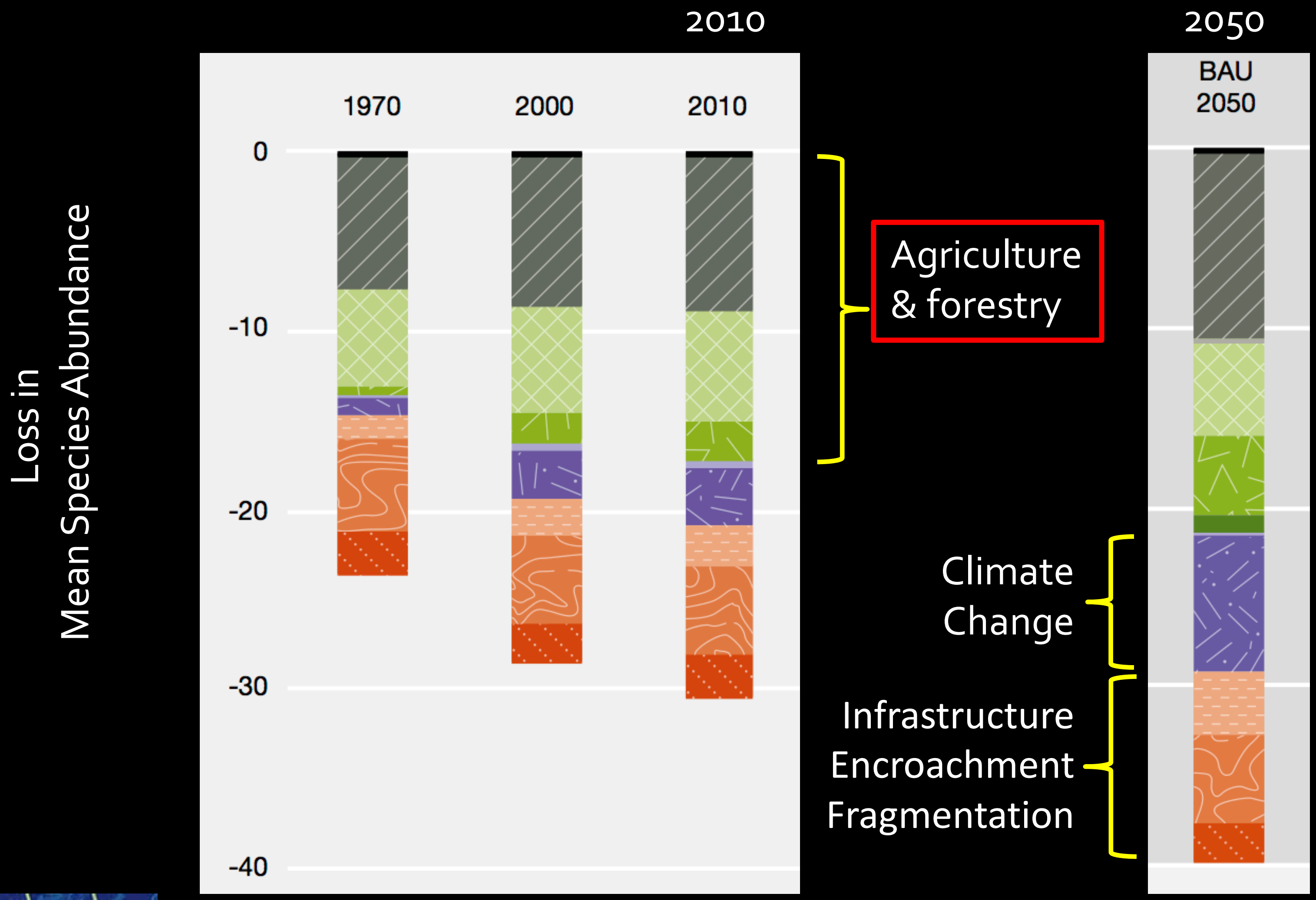
Moritz and Agudo, *Science* 2013

Fire and climate change threats

Disease threats

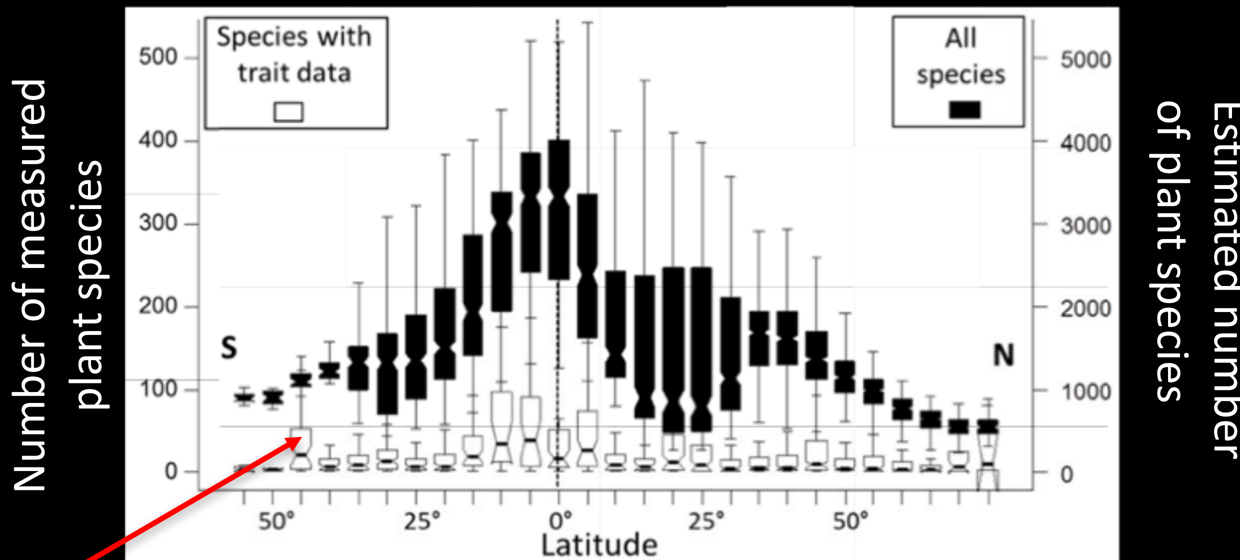
Oak Wilt, Emerald Ash Borer, Woolly Adelgid, Dutch Elm

Pressures driving biodiversity loss in the Americas

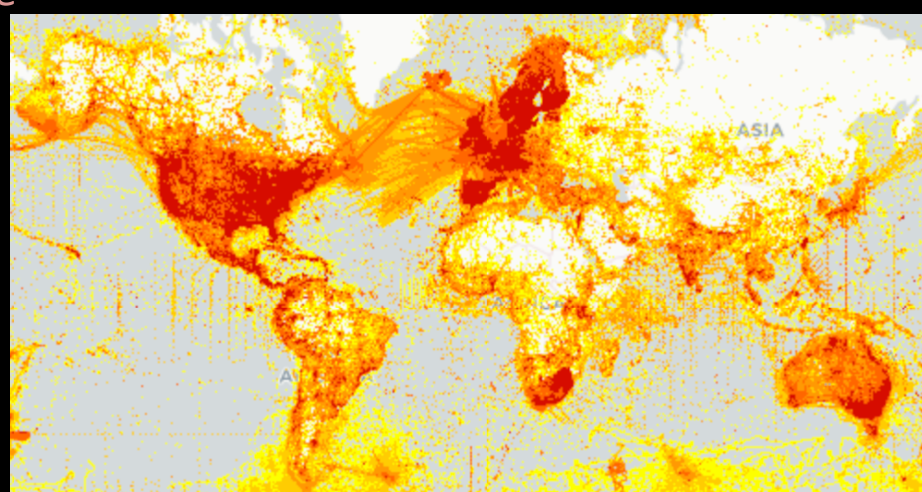


Data gap: most species are left unmeasured and unmonitored

NCEAS "Observing Biodiversity from Space," Jetz et al 2016

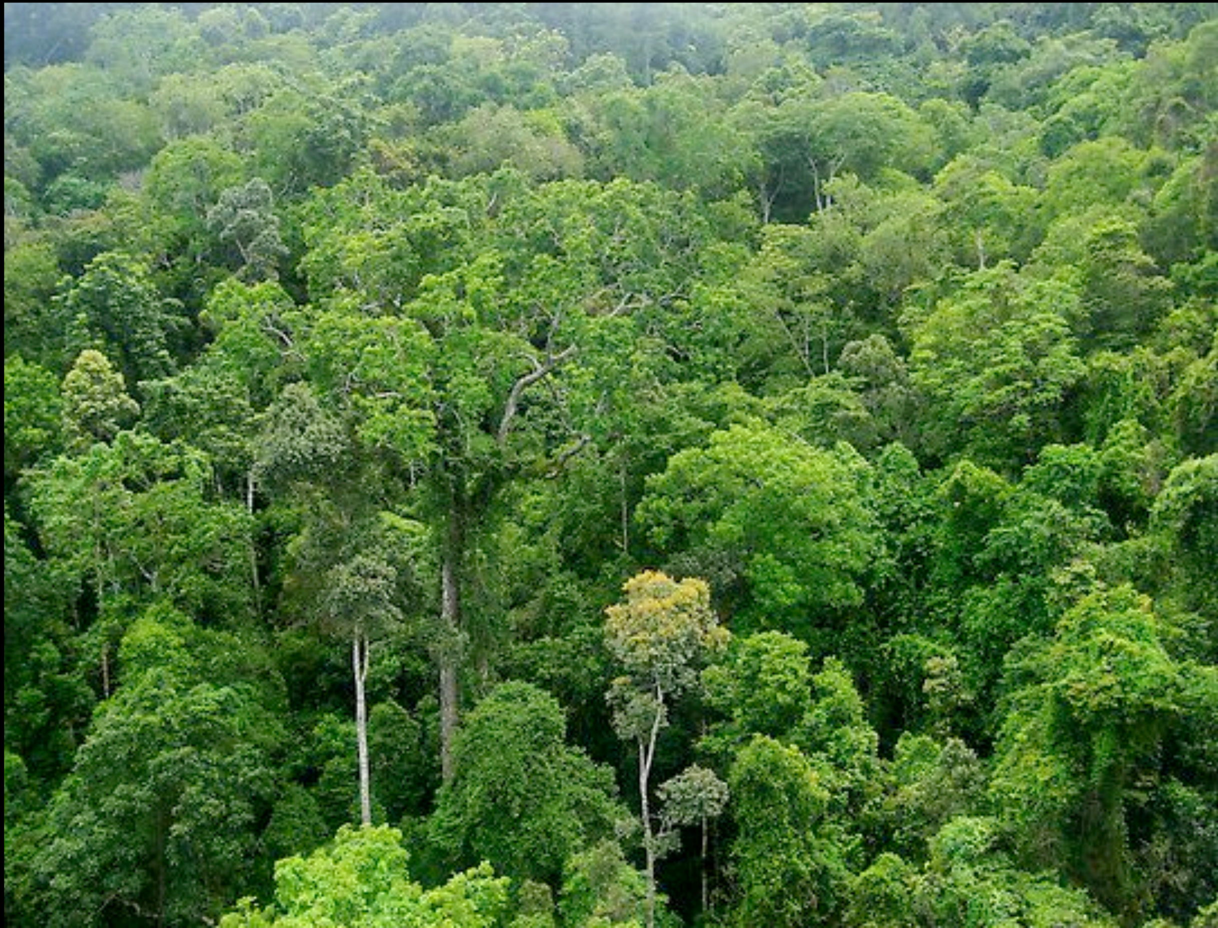


TRY trait database

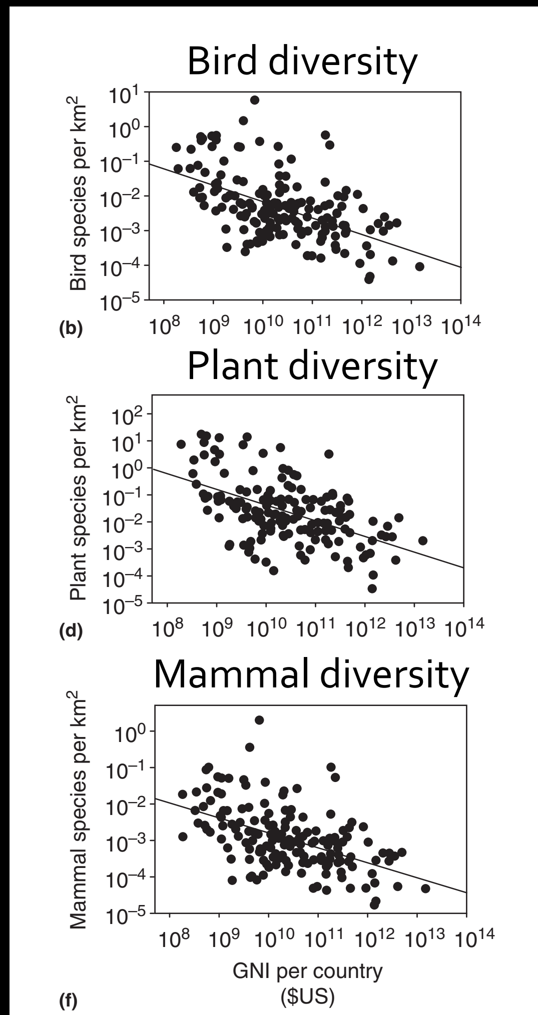


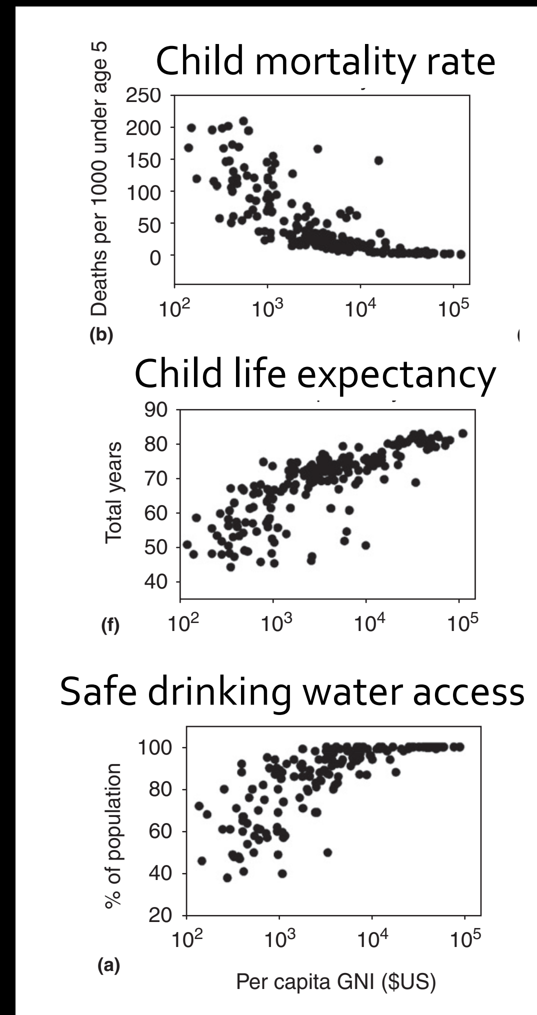
GBIF.org

We know a lot about a small number of species and very little about most



Human needs are often not met in regions where biodiversity is highest, creating conflicting goals

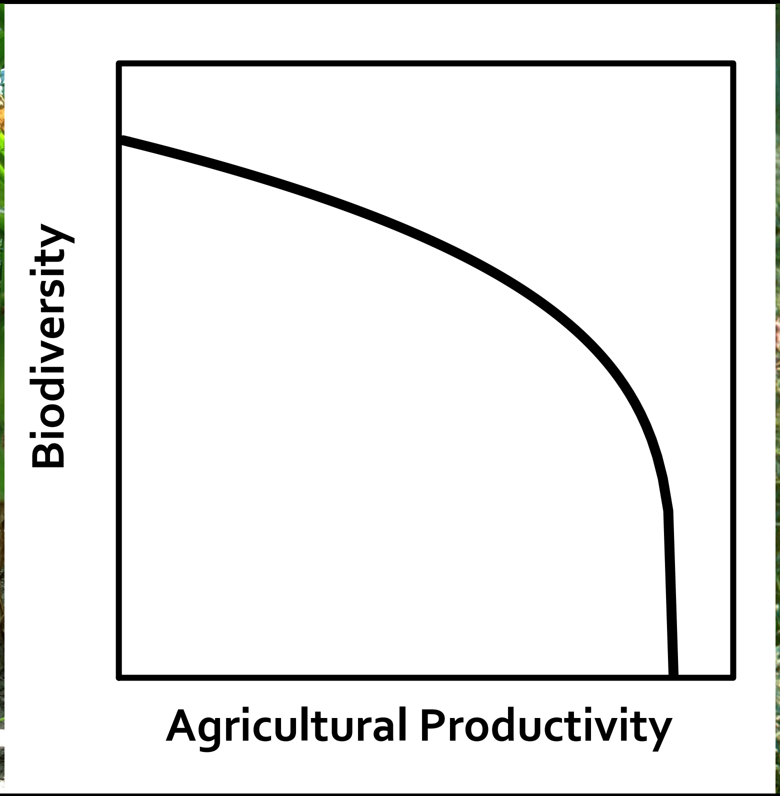




Cavender-Bares et al 2013

For examples, there are direct trade-offs between biodiversity and food production

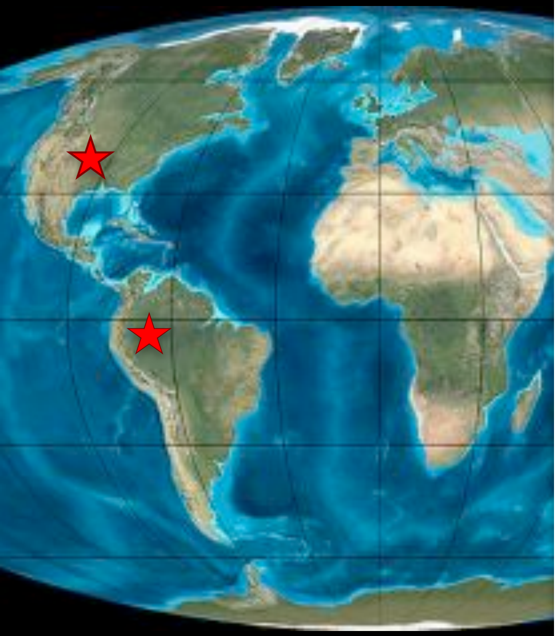
Knowledge about biophysical constraints (e.g., how much biodiversity is possible in a region) is critical to managing the trade-offs

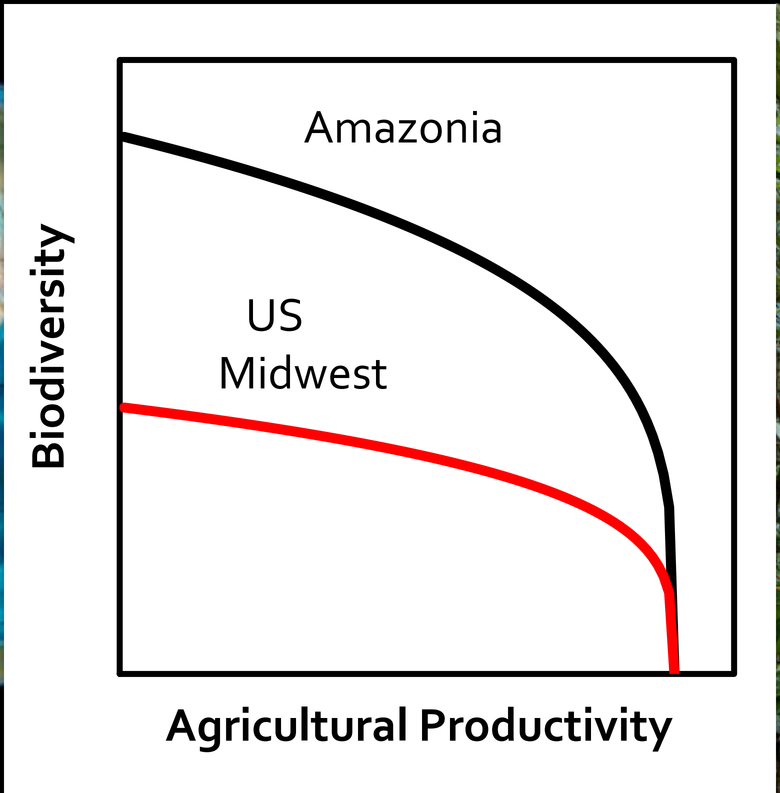


Cornfield US Midwest

Cedar Creek LTER

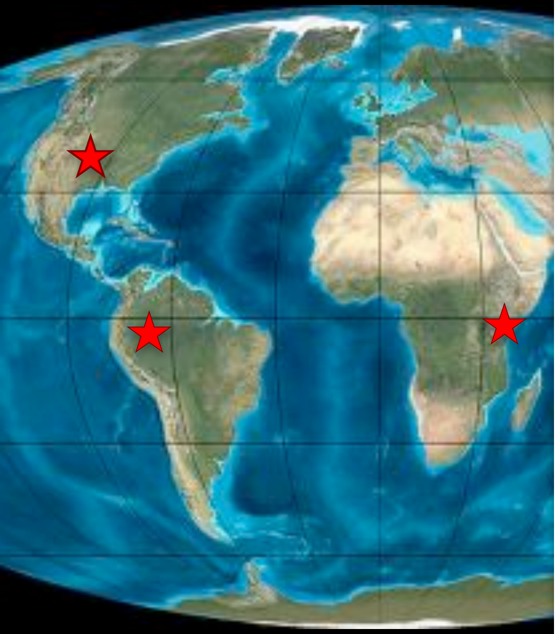
Regions differ in maximum biodiversity

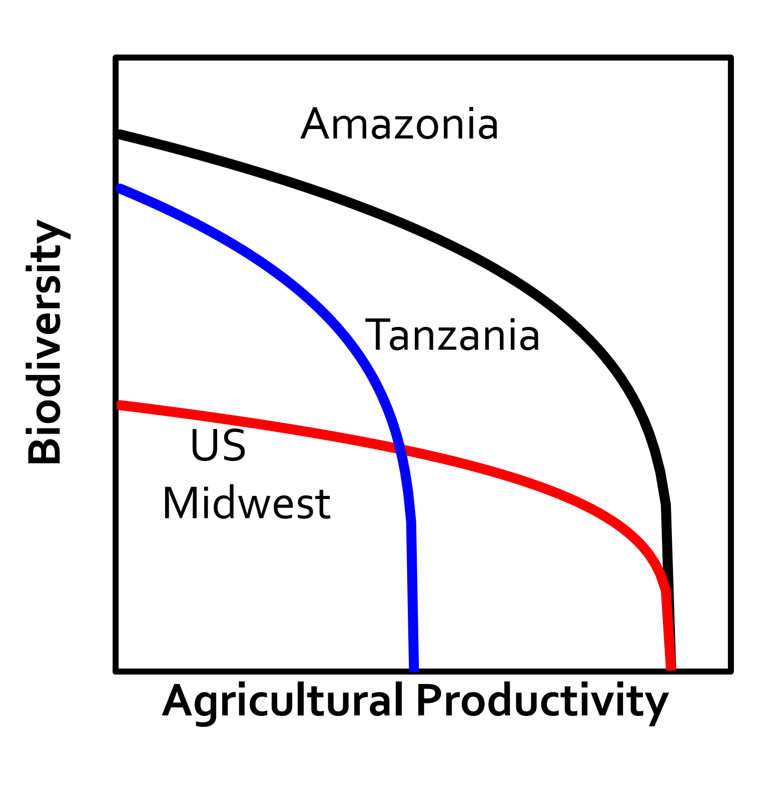




Amazonia has a higher capacity to sustain biodiversity than US Midwest

Regions differ in the biophysical constraints that underlie trade-offs in biodiversity and food production capacity



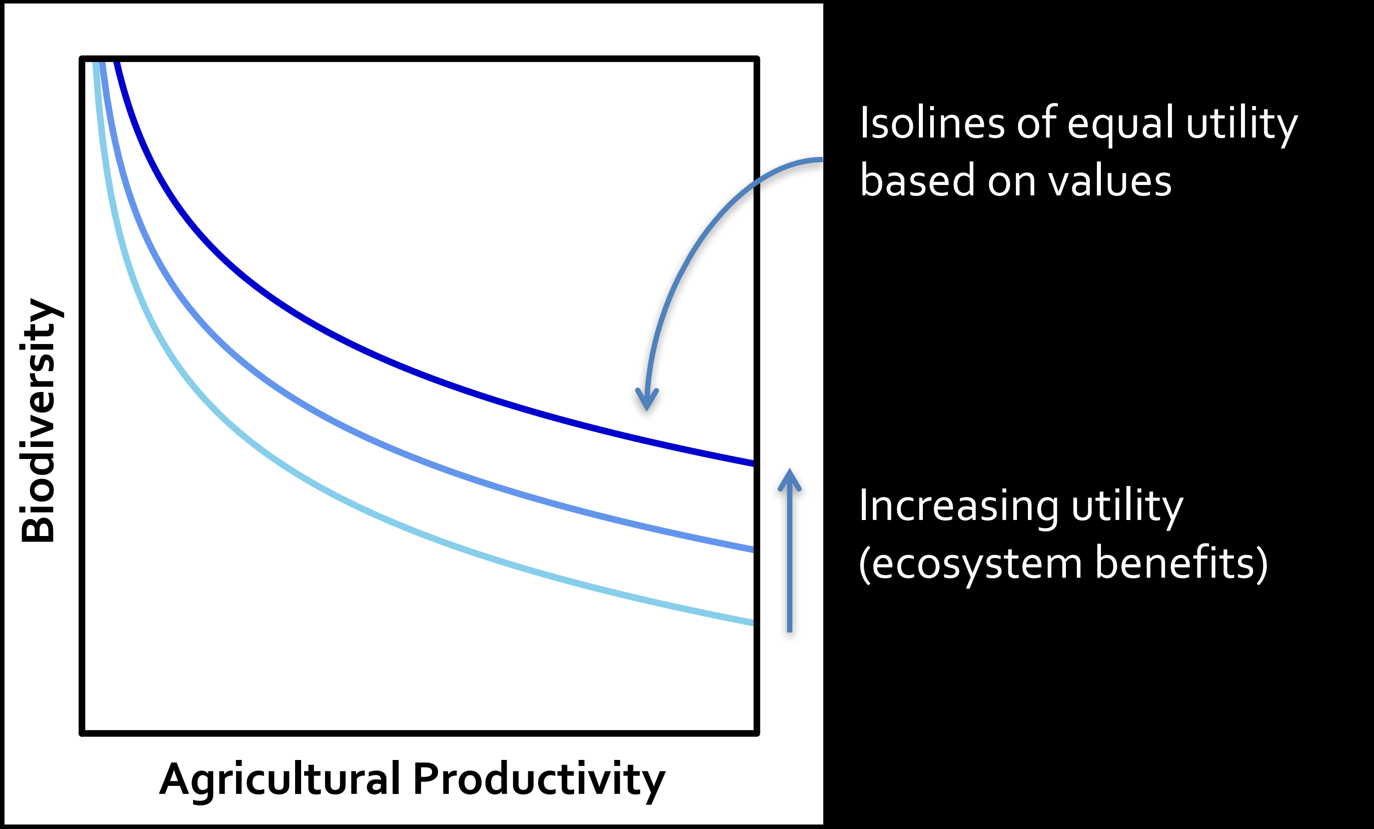


Agricultural capacity is higher in the US Midwest or regions of Amazonia than western Africa

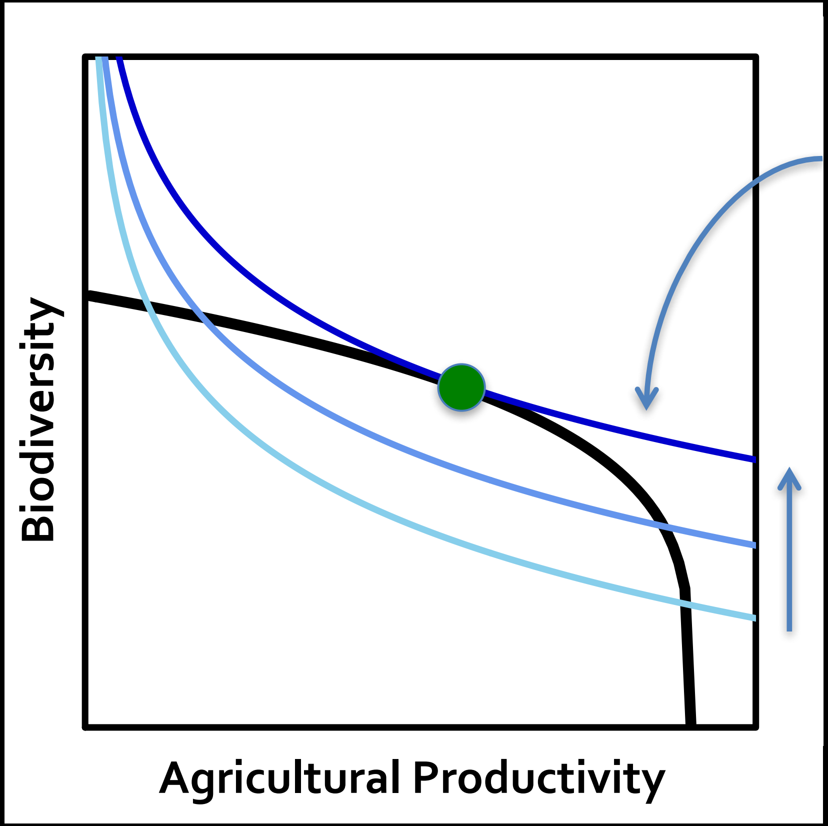
Tanzania
Photo: Tuyeni Mwampamba


Photo: Tuyeni Mwampamba
Biophysical constraints limit the combination of biodiversity and food production that is possible to sustain

Human values underlie the biodiversity and ecosystem benefits we prefer



Human values underlie the ecosystem benefits we prefer



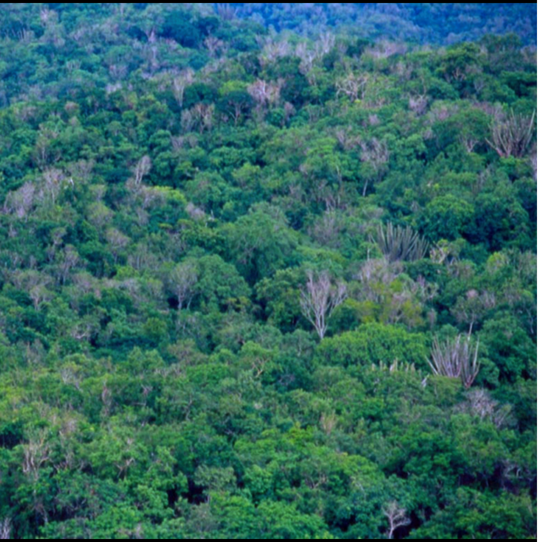
Isolines of equal utility based on values

Increasing utility (ecosystem benefits)

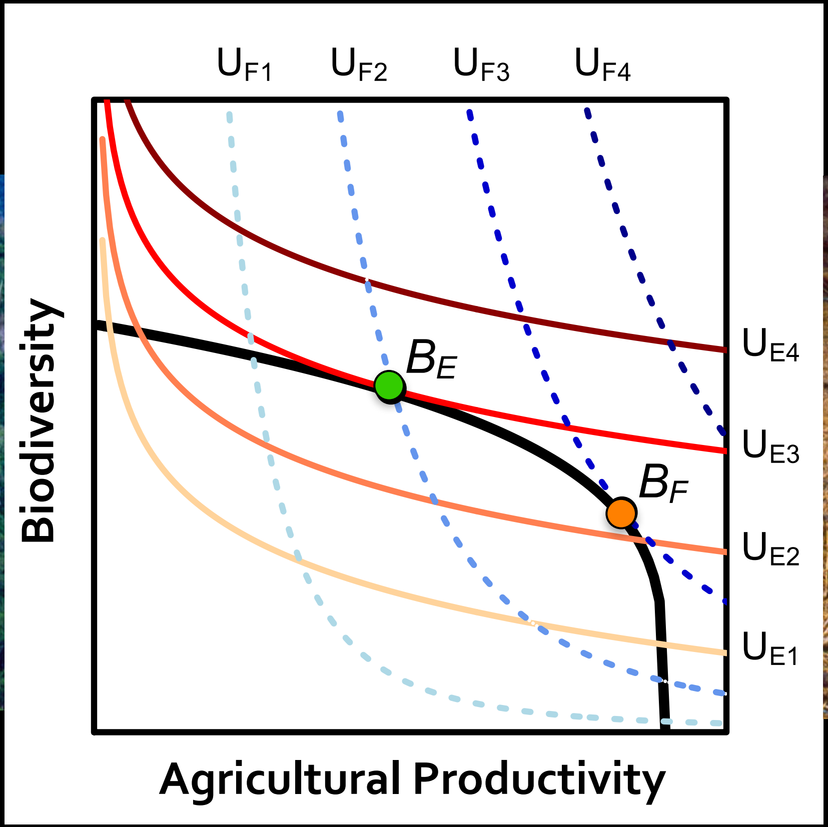
The combination of diversity and food production that we aim for depends on our values.

Preferences differ among stake holders
Outcomes depend on various factors – including knowledge

● Environmentalists



Chamela, Mexico
Photo: P. Balvanera



● Farmers

Photo: P. Balvanera

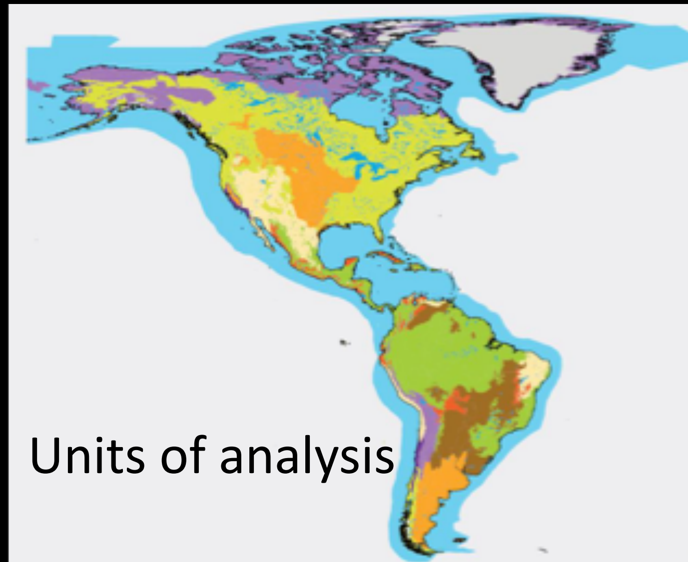
Remote sensing offers potential to determine
the biophysical constraints for decision makers

Cavender-Bares et al 2015

IPBES: **Assessing trends in diversity and ecosystem function**

(expert opinion…)

We can do better!

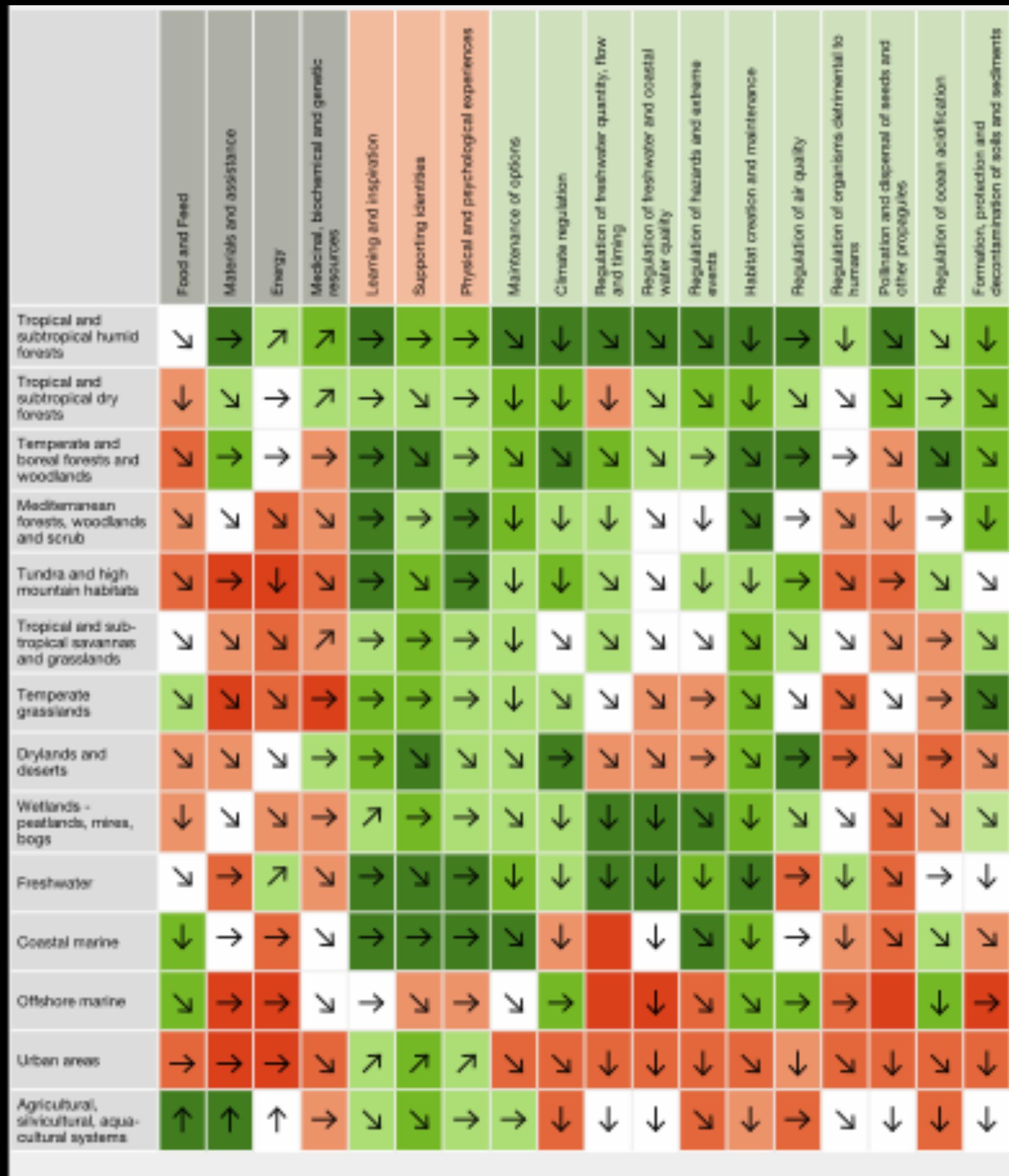


	Units of analysis	Recent trends (40 yrs)				
		Habitat amount	Habitat degradation	Native species diversity	Threatened species	Alien & Invasive species
North America	Temperate and boreal forests and woodlands	↗....	↗....	↘...	↔....	↗...
	Mediterranean forests, woodlands and scrub	↘....	↗....	↘....	↗....	↗....
	Tundra and high mountain habitats	↔..	↗....	↔....	↔....	↗..
	Temperate grasslands	↘....	↗....	↘....	↗....	↗....
	Drylands and deserts	↘....	↗....	↘....	↗....	↗....
	Wetlands - peatlands, mires, bogs	↘....	↗....	↘.	↗.	↗....
	Freshwater	↘.	↗....	↘...	↗...	↗....
	Coastal marine	↘....	↗....	↘...	↗..	↗....
	Sea Ice	↘..	↗.	↔..	↔..	↗..

ipbes

Contributions of biomes to ecosystem services and recent trends

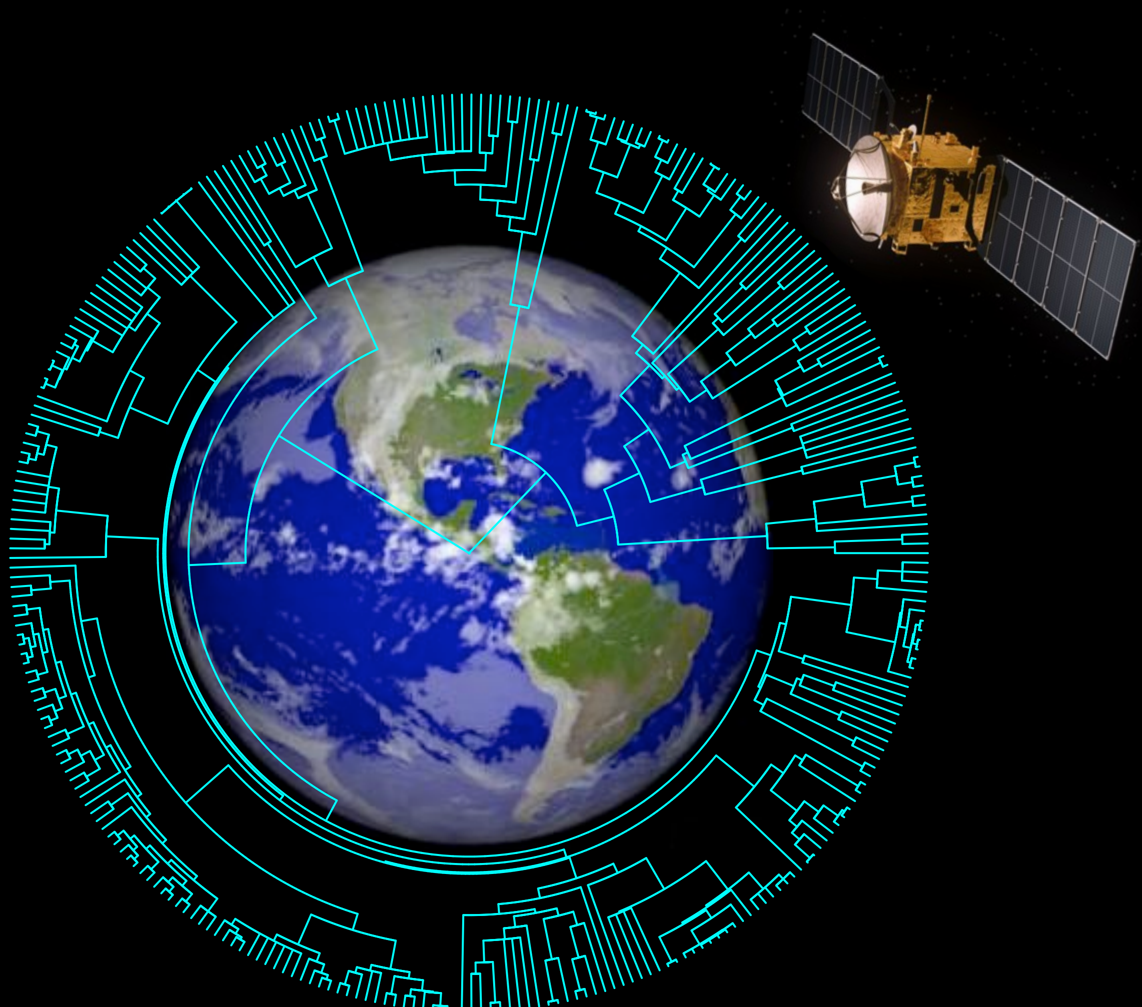
Nature's Contributions to People (Ecosystem services)



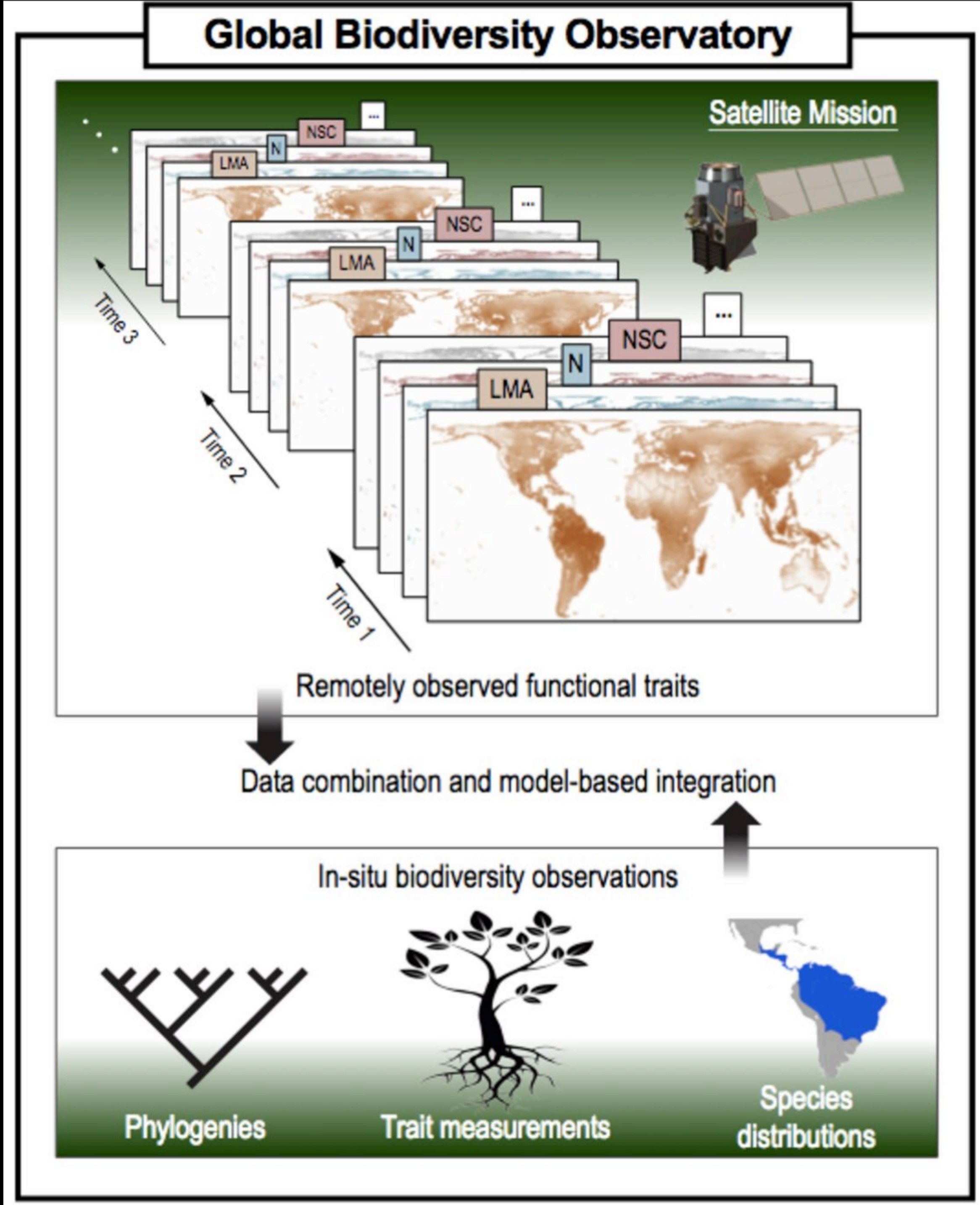
Units of Analysis (Biomes)

SPM Americas
IPBES 2018

Needed: A satellite mission for continuous global detection of changes in the functions and functional diversity of plants and their ecosystem consequences



Jetz et al 2016



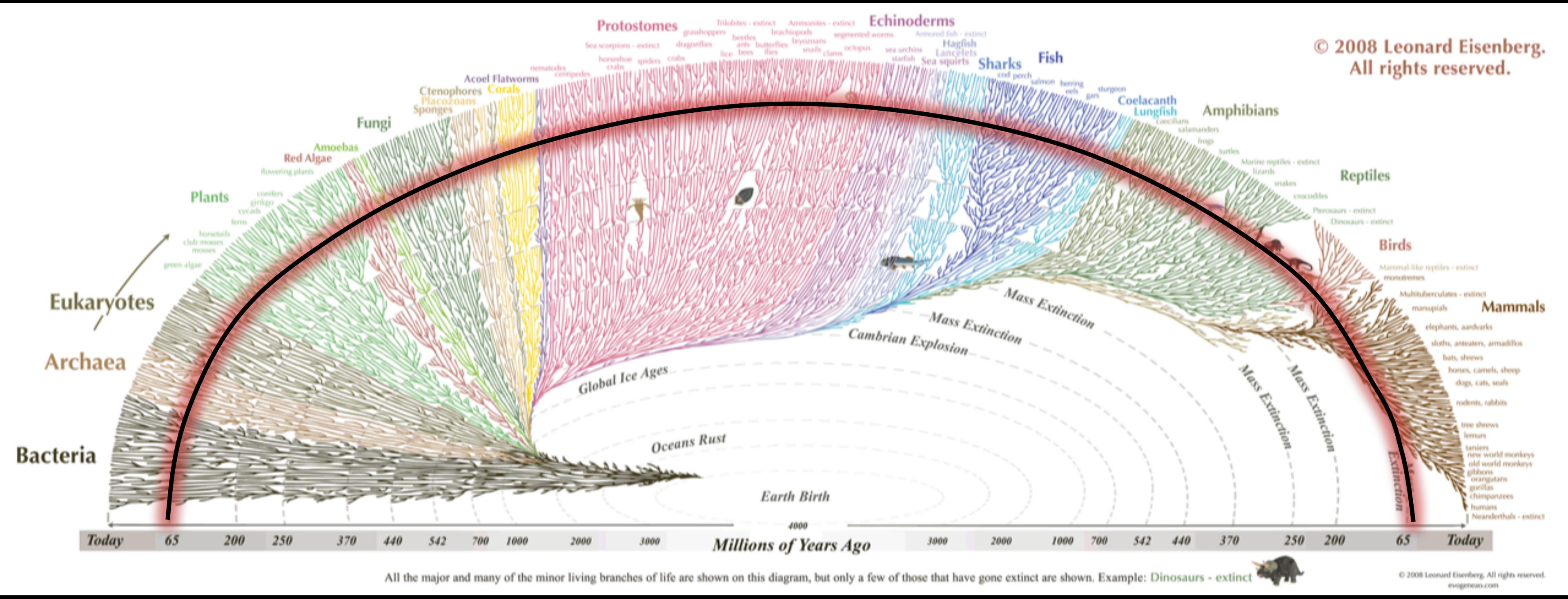
Jetz et al 2016

Definition of biodiversity

Biodiversity is the variability among living organisms from all sources….including diversity within species, between species, and of ecosystems.

"Biodiversity is the living fabric of our planet - the source of our present and our future."

Origins of biodiversity on Planet Earth

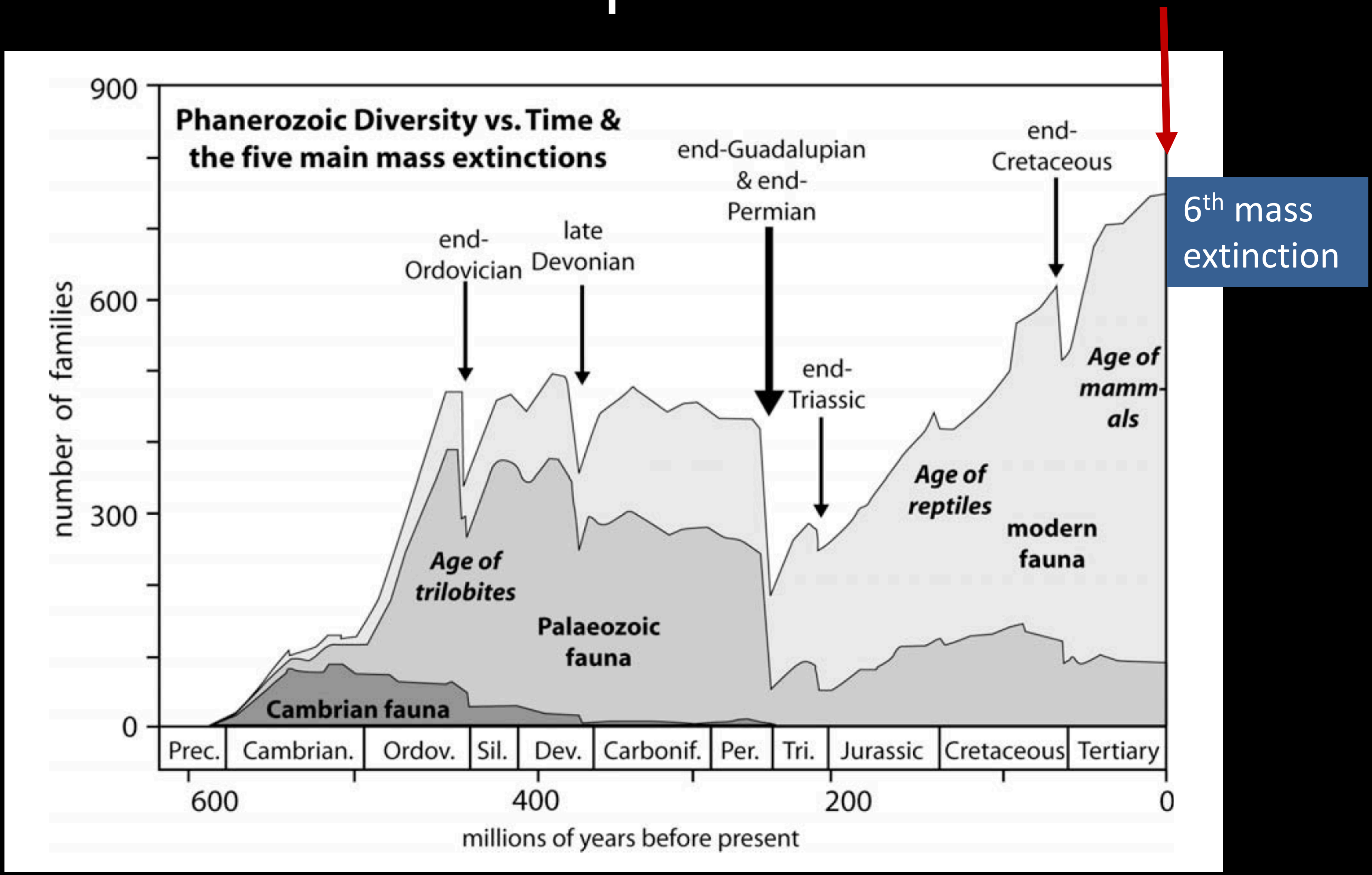


65 mya

65 mya

Speciation, extinction, diversification of the major lineages in the tree of life

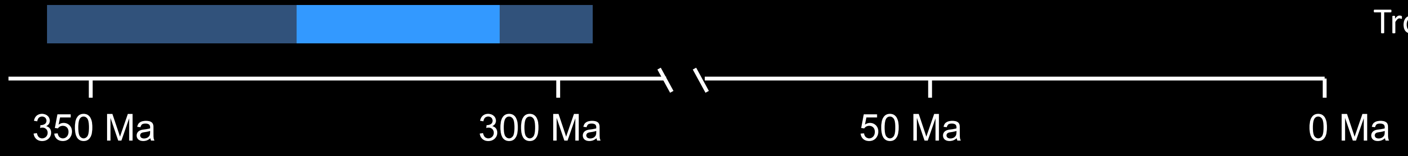
Five mass extinctions before the Anthropocene



Metcalfe and Isozaki 2009 after Sepkoski, 1984

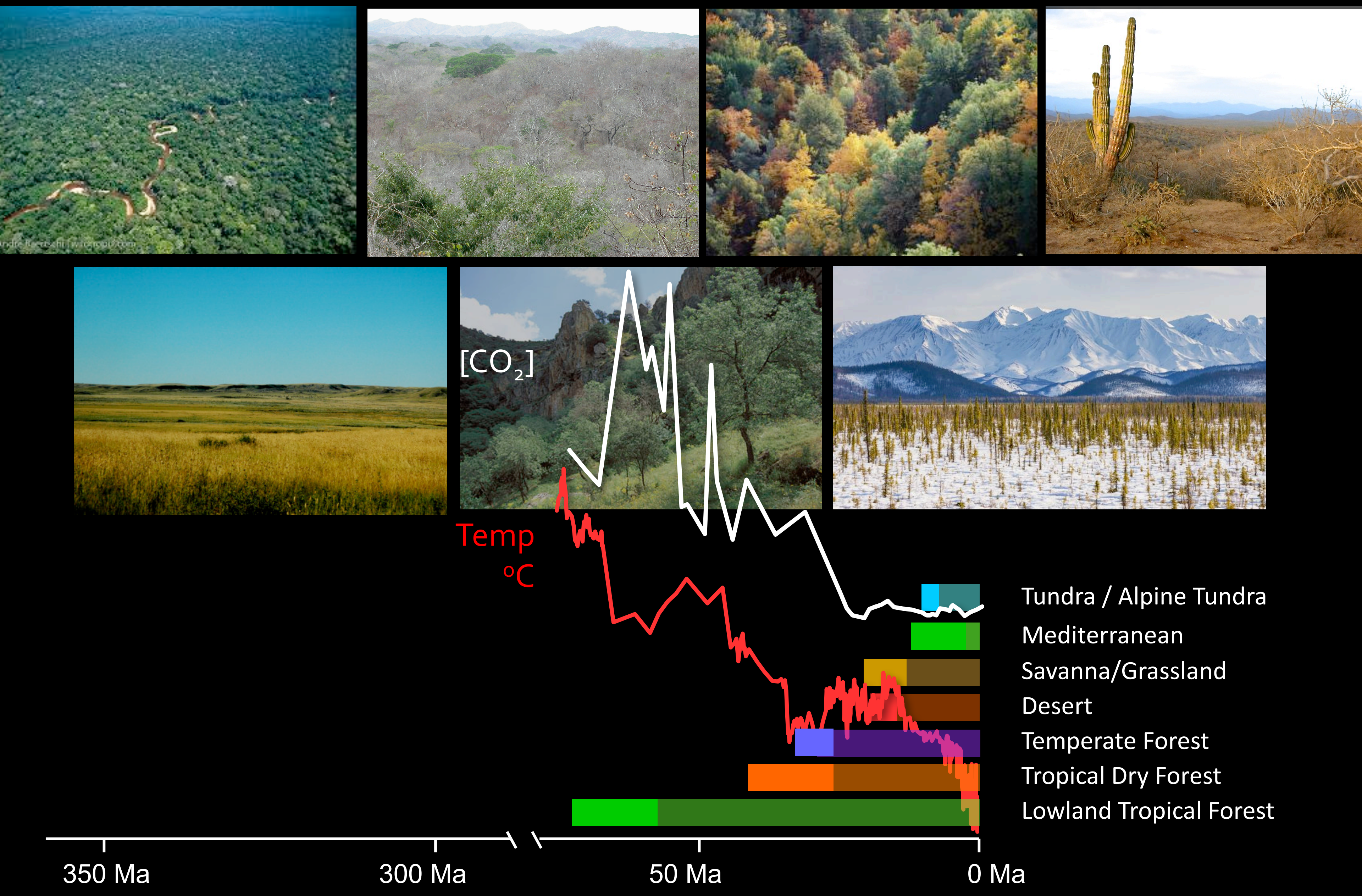
Earth’s biota looked very different in the deep past

Jan Vriesen (artist) and Kirk Johnson, Denver Museum of Nature and Science
Image from Jonathan Wilson

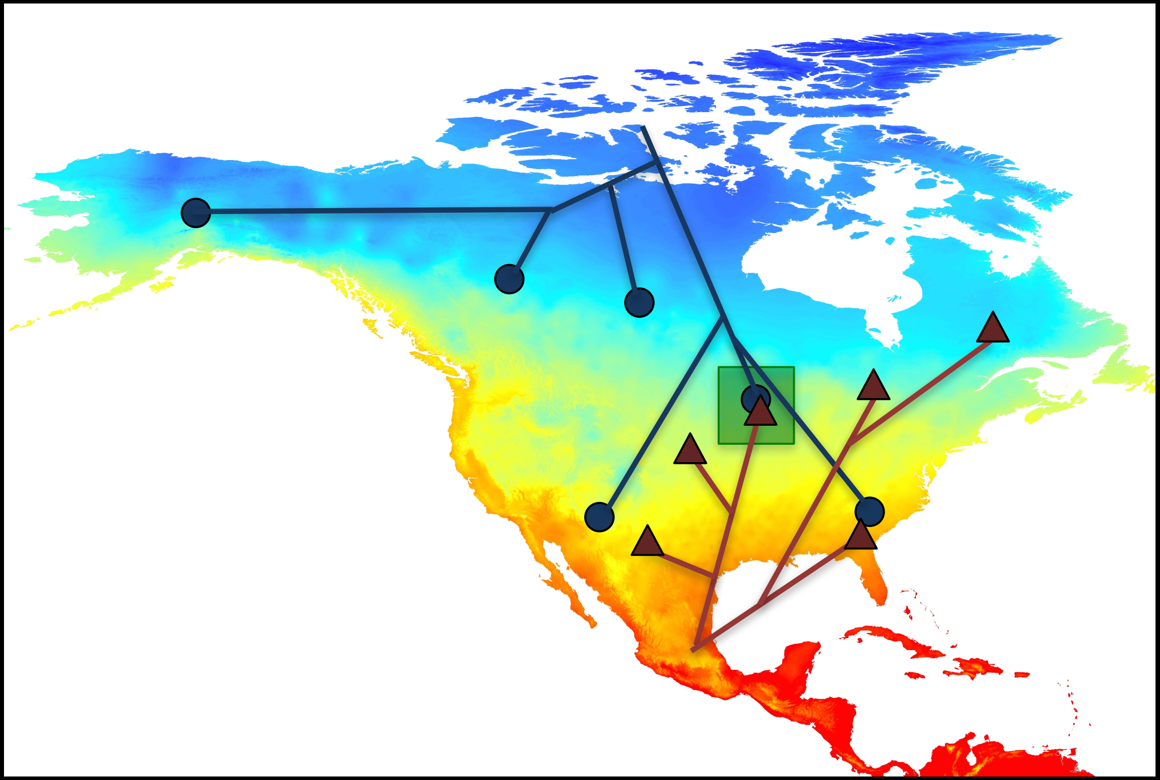


Tropical Swamp Forest

Biomes expanded and contracted with paleoclimate change

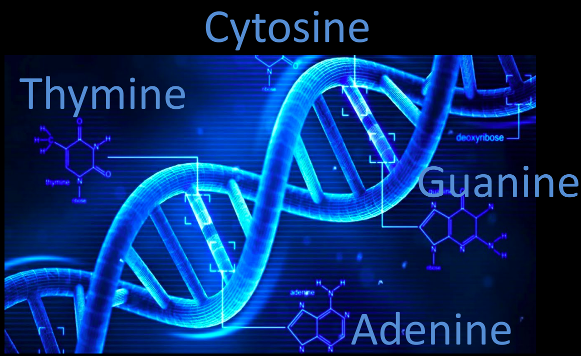


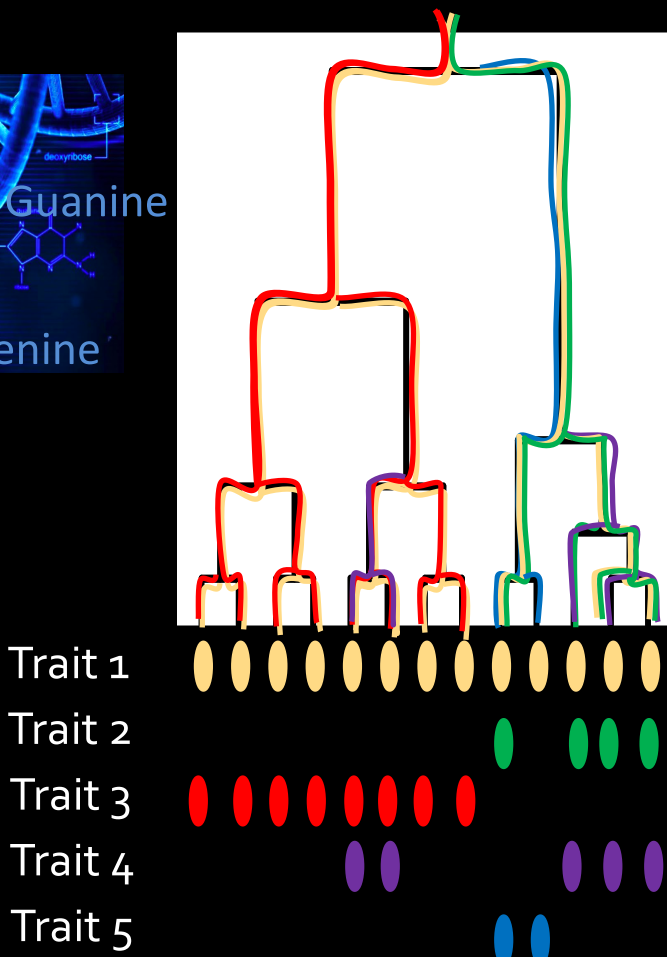
Biogeographic origins leave legacies on the functions of species

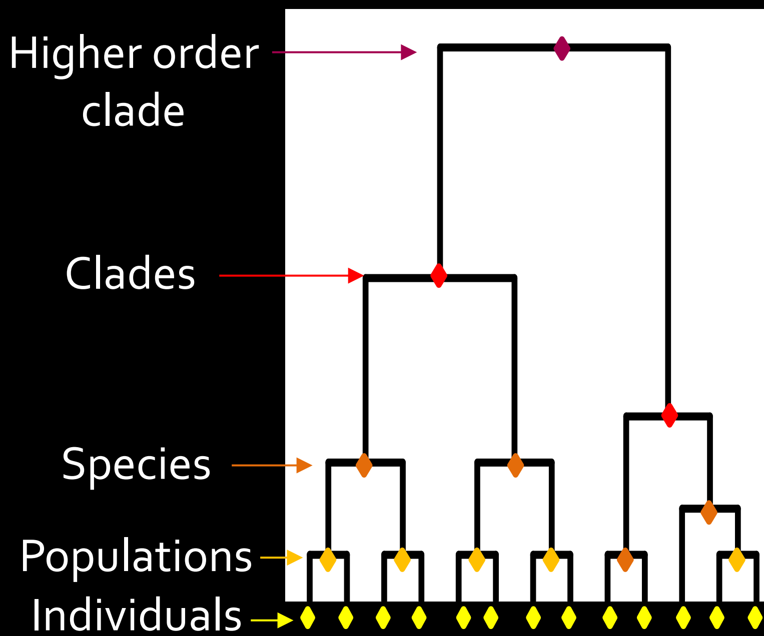


Cavender-Bares, Ackerly, Hobbie and Townsend 2016 *AREES*

Biodiversity is hierarchically organized as a consequence of shared ancestry encoded in DNA



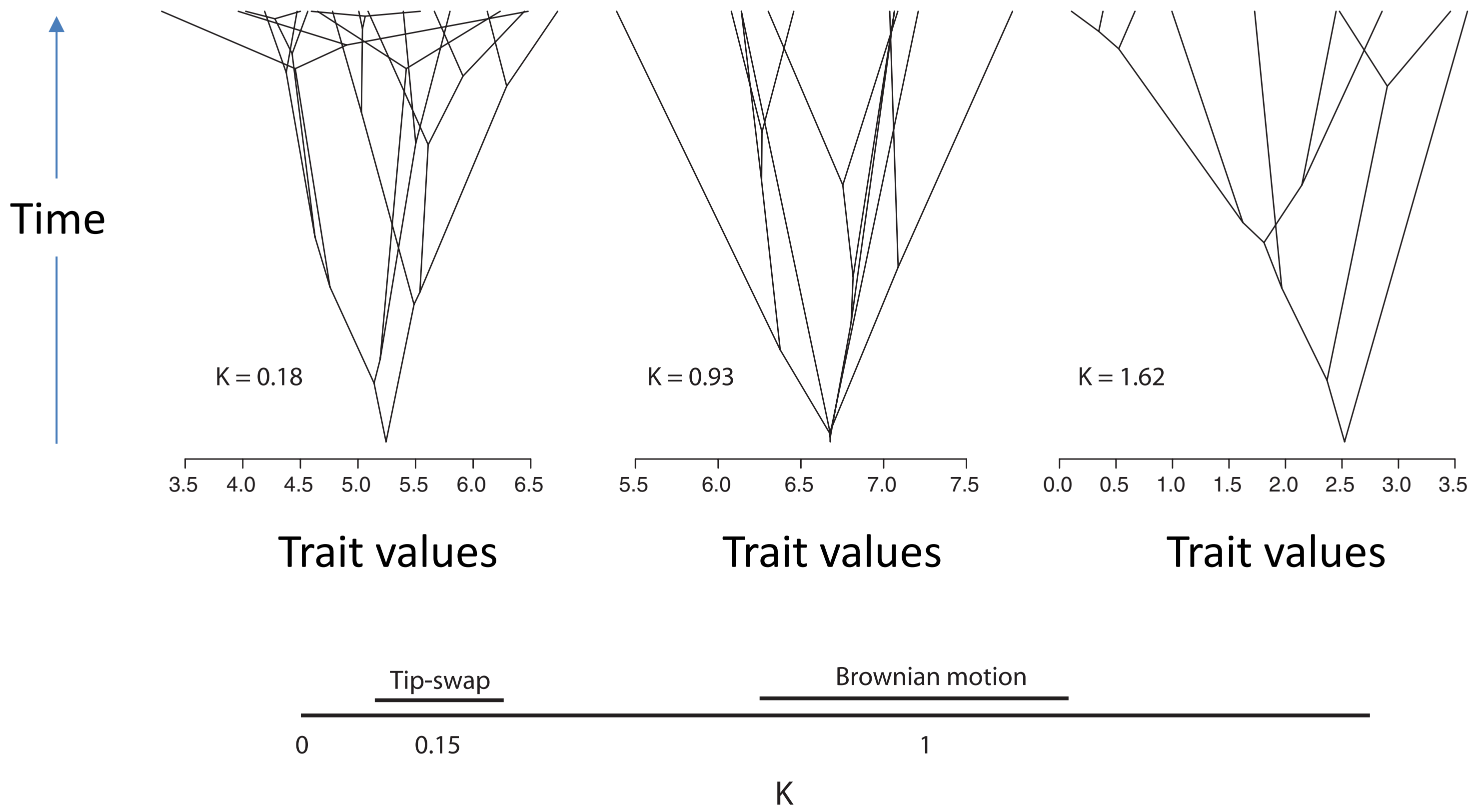




Trait attributes and phylogenetic relationships

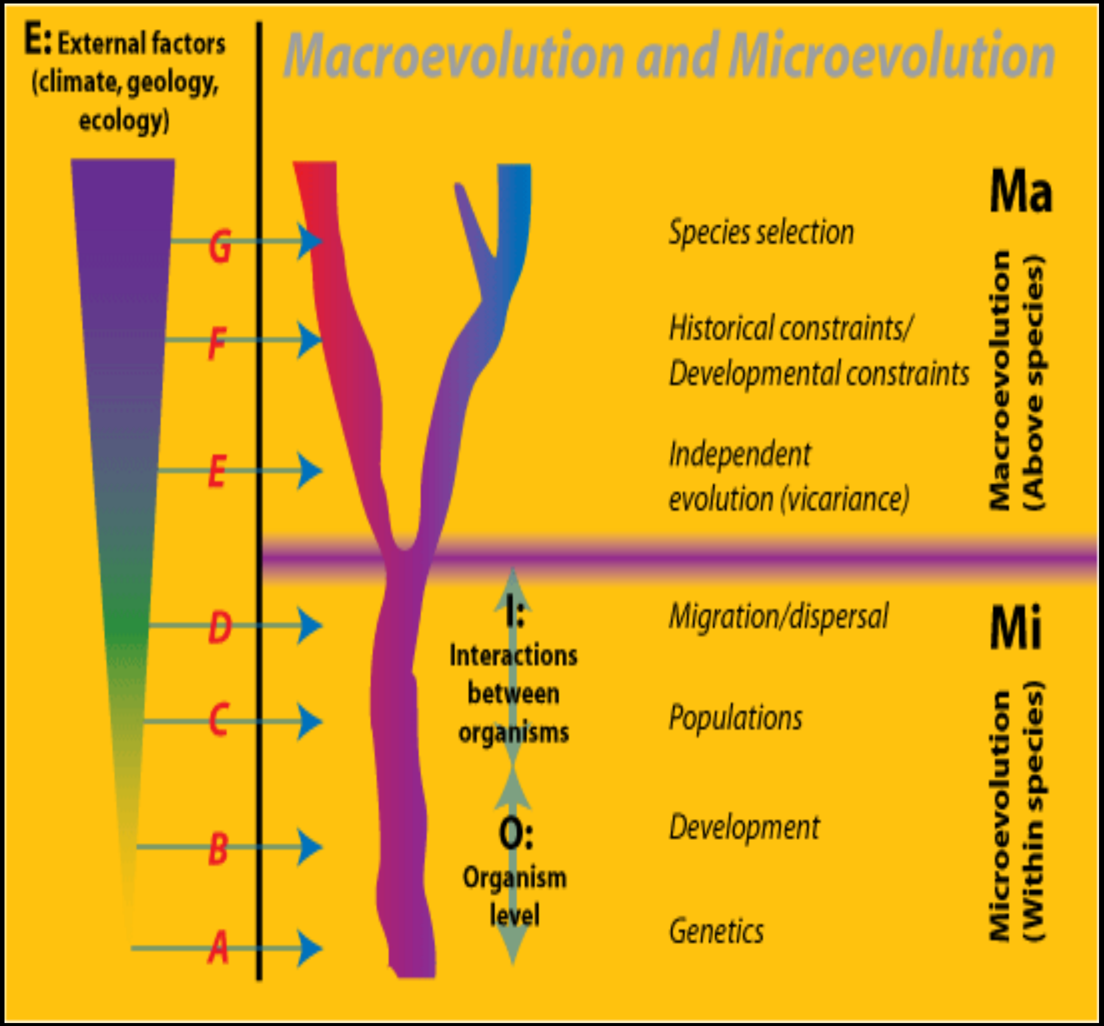
Distant relatives have similar function (**convergence**)

Distant relatives have dissimilar function (**conservatism**)



Ackerly 2009

Macroevolution and Microevolution



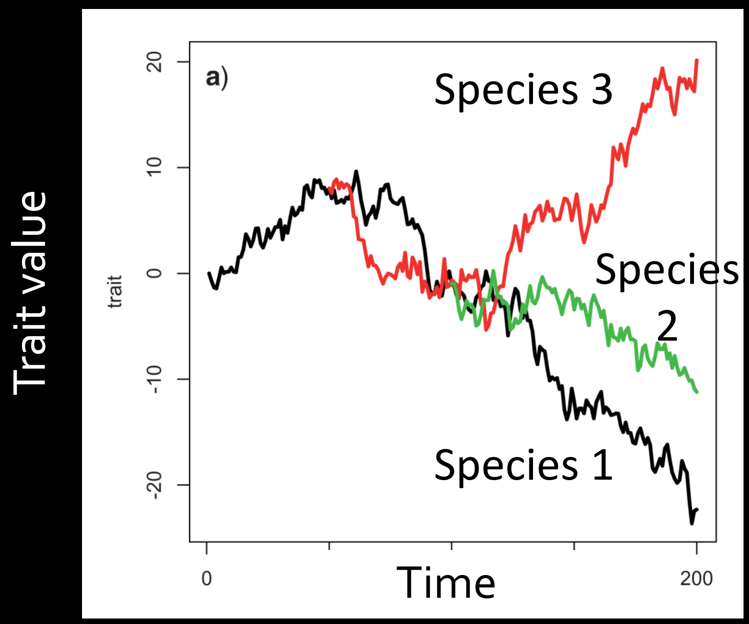
Forces of evolution:

mutation, gene flow, genetic drift, and natural selection

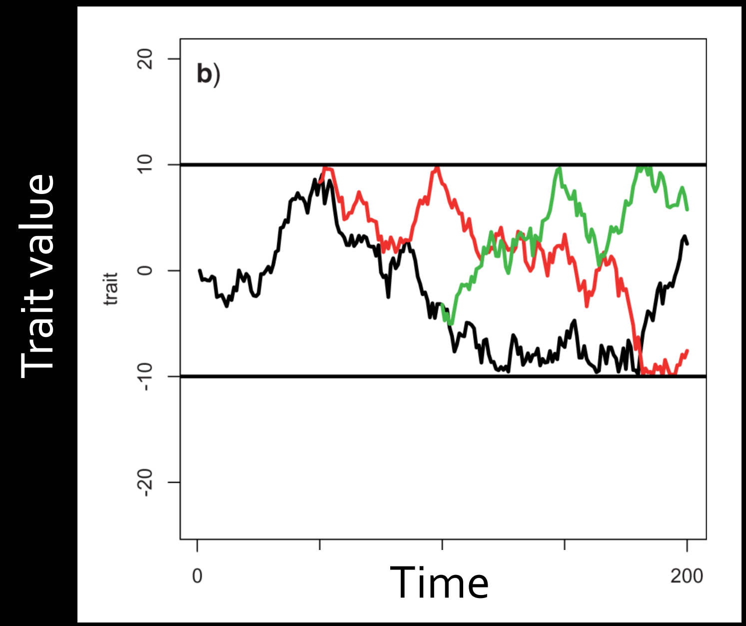
http://www.talkorigins.org/faqs/macroevolution.html

How do functional traits evolve over time?

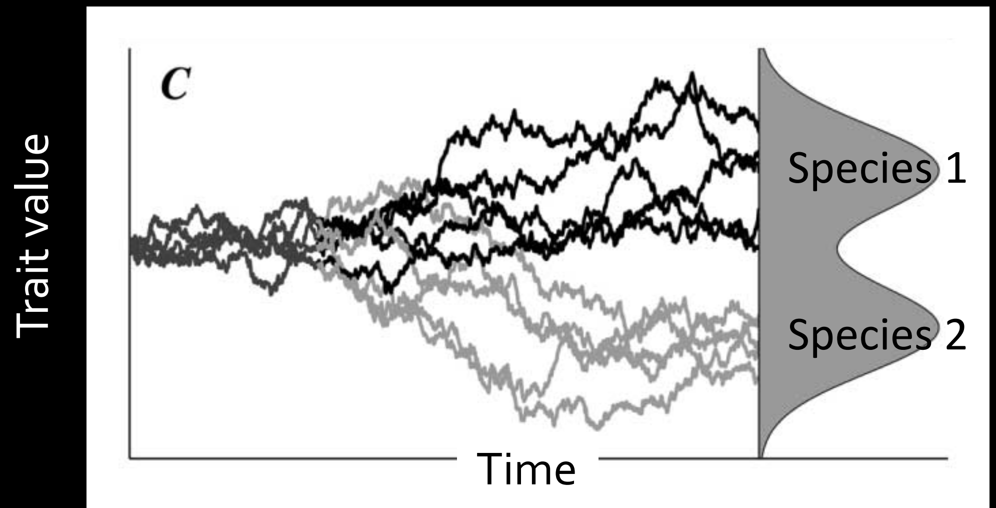
Brownian Motion model
(without bounds)



Brownian Motion model
with bounds



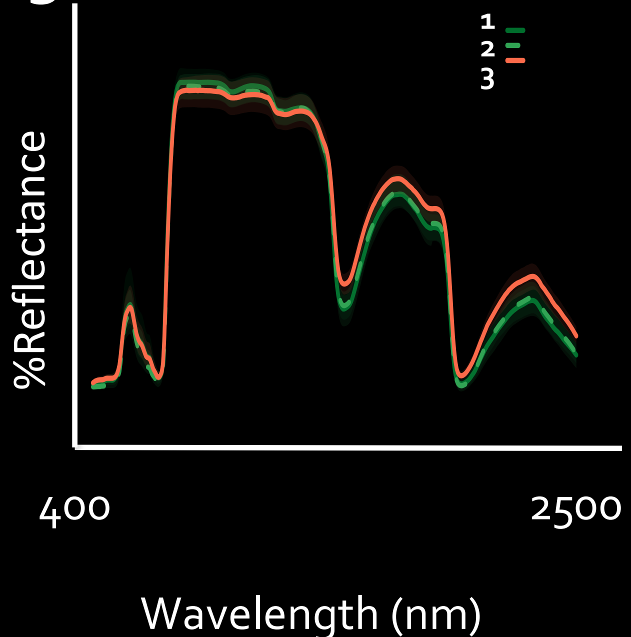
Boucher & Démery 2016



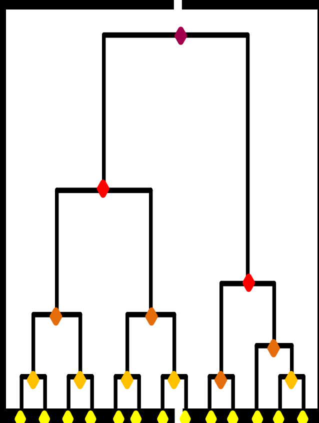
OU model

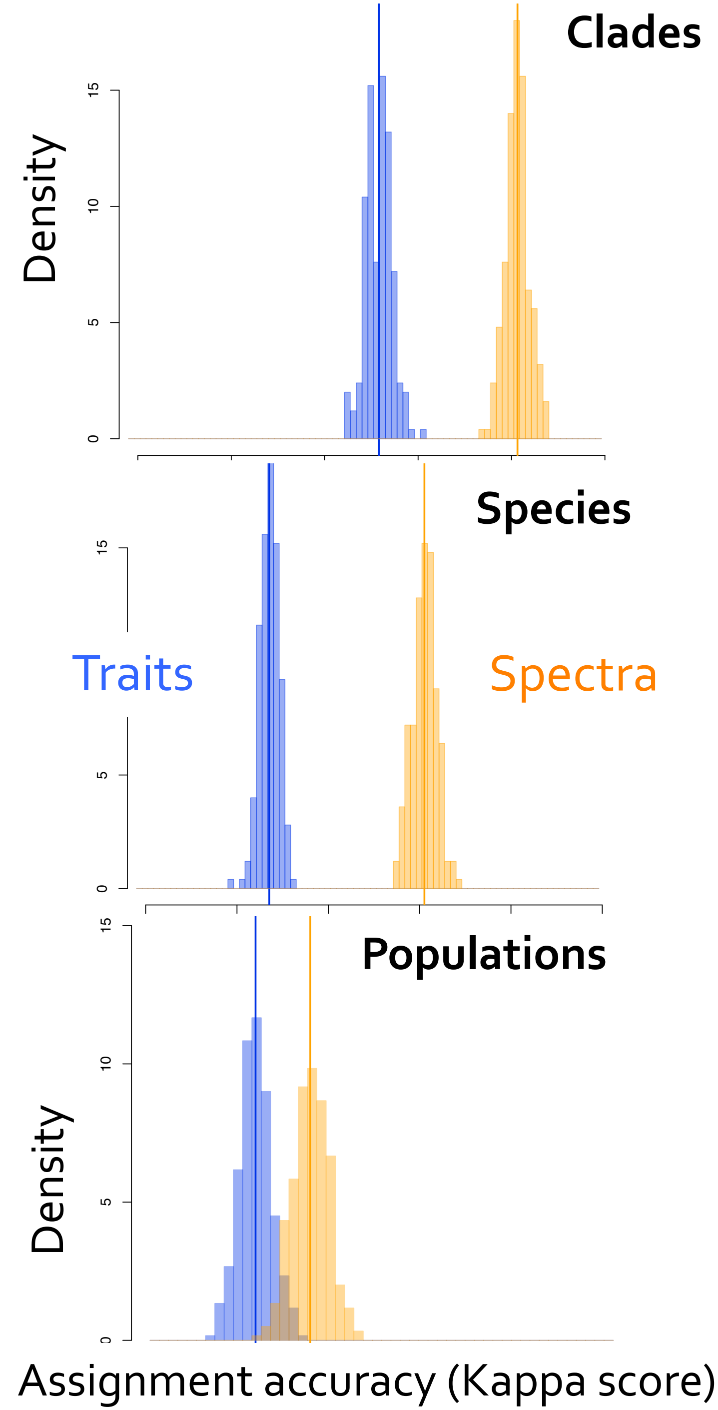
Butler & King 2004

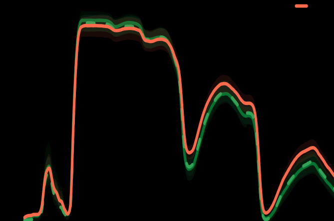
The hierarchical organization of plant diversity that results from evolutionary history provides a framework for predicting functional and spectral similarity of organisms



Greater accuracy with increasing phylogenetic levels







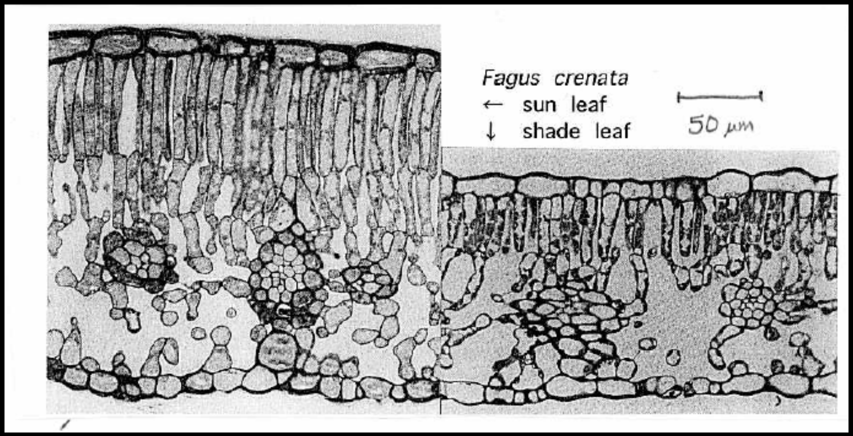
Spectra always discriminate taxa with higher accuracy than traits

Cavender-Bares, Meireles et al 2016

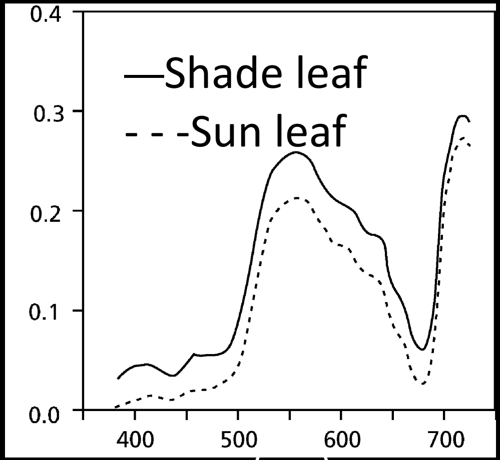
Genotype and phenotype

- The genetic program—or "genotype"—of an organism interacts with its environment to express the "phenotype" we can observe
- "Plasticity" is the phenotypic variation we see under different environmental conditions

Lambers et al 1998



Sun Shade



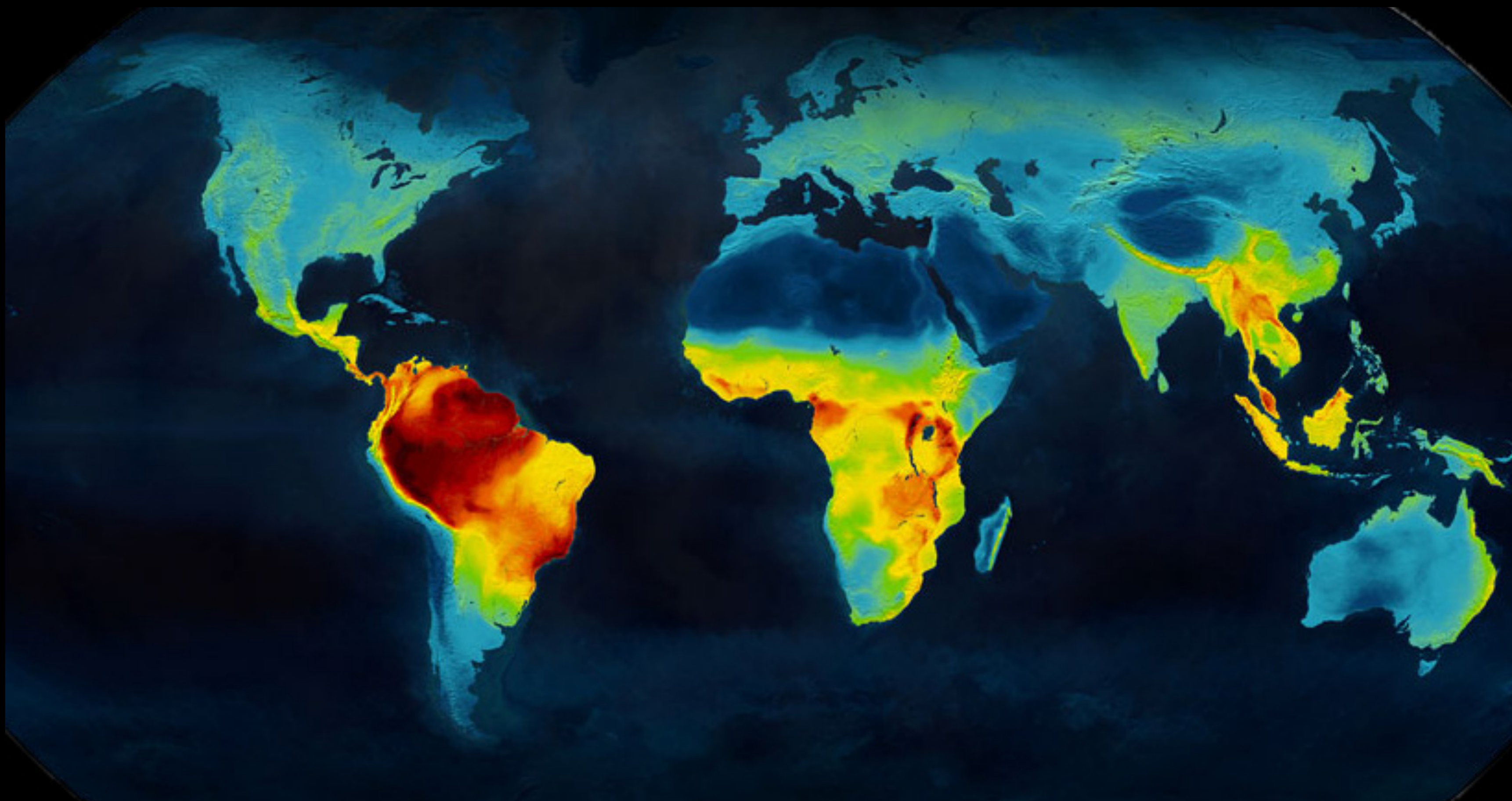
(nm)

(oil immersed – control)

DeLucia 1996

Spatial patterns of biodiversity

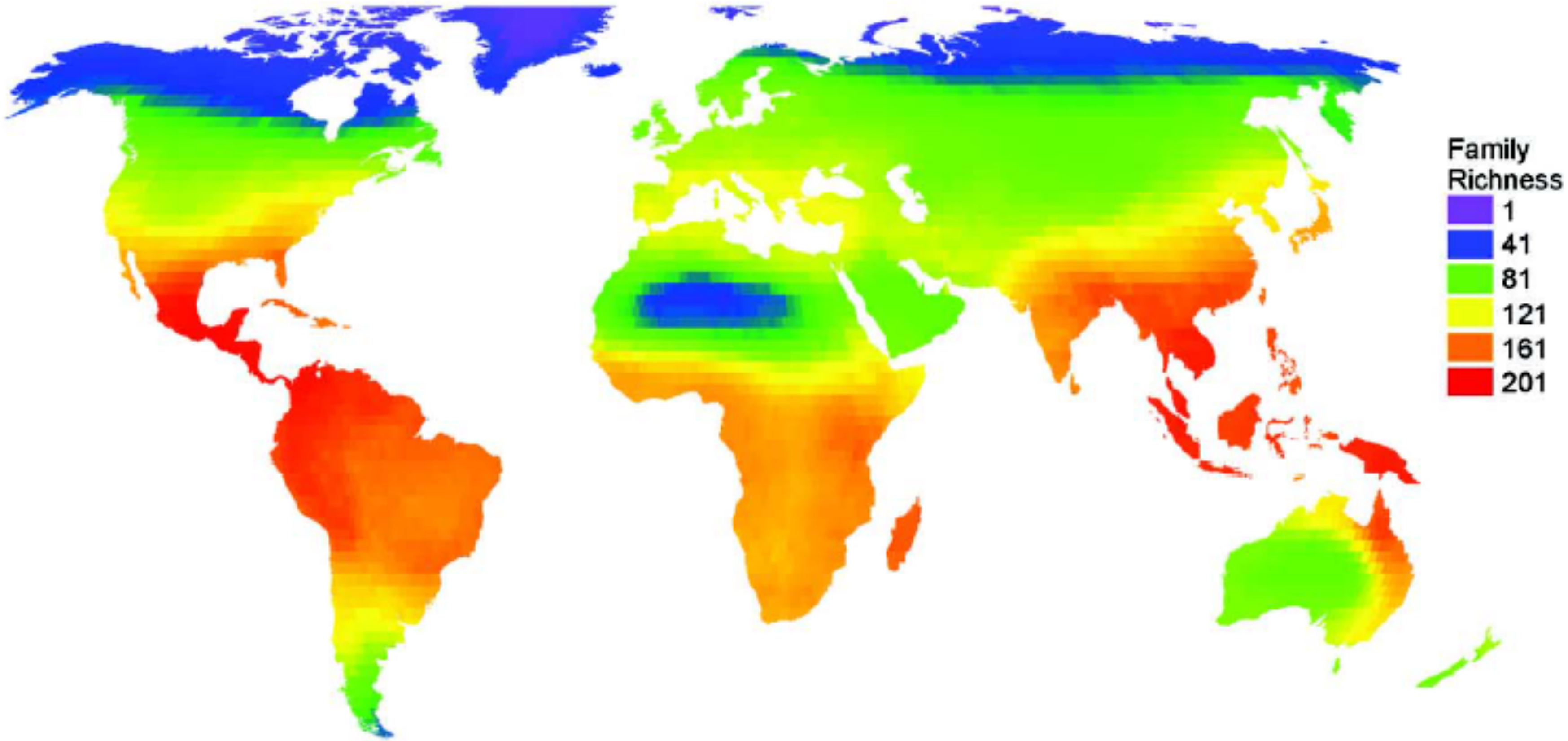
Global terrestrial vertebrate biodiversity map



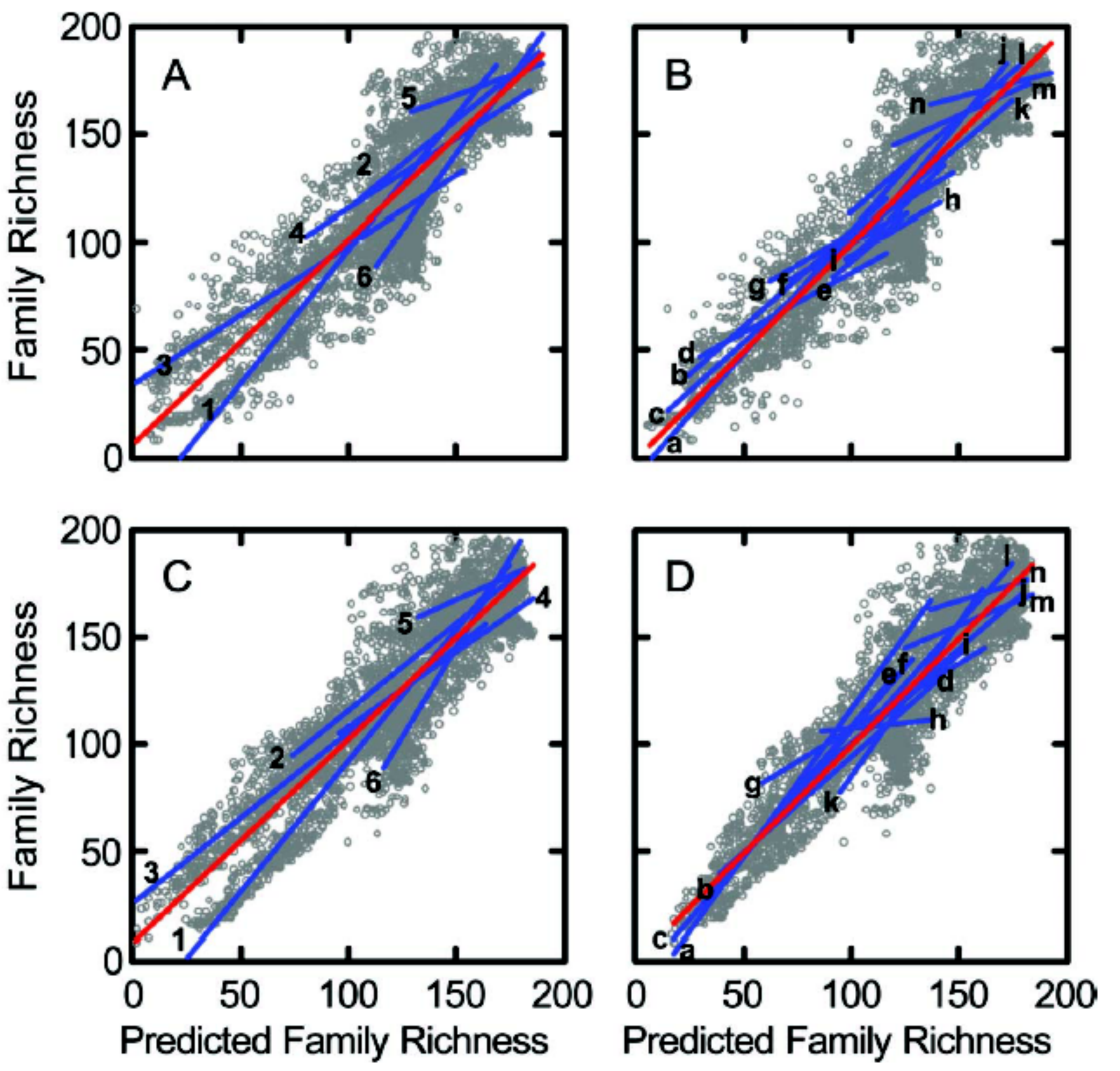
Are there more species in the tropics because the tropics is an earlier biome and has been around longer?

Mannion et al. 2014

Angiosperm plant family richness



Francis and Currie 2003



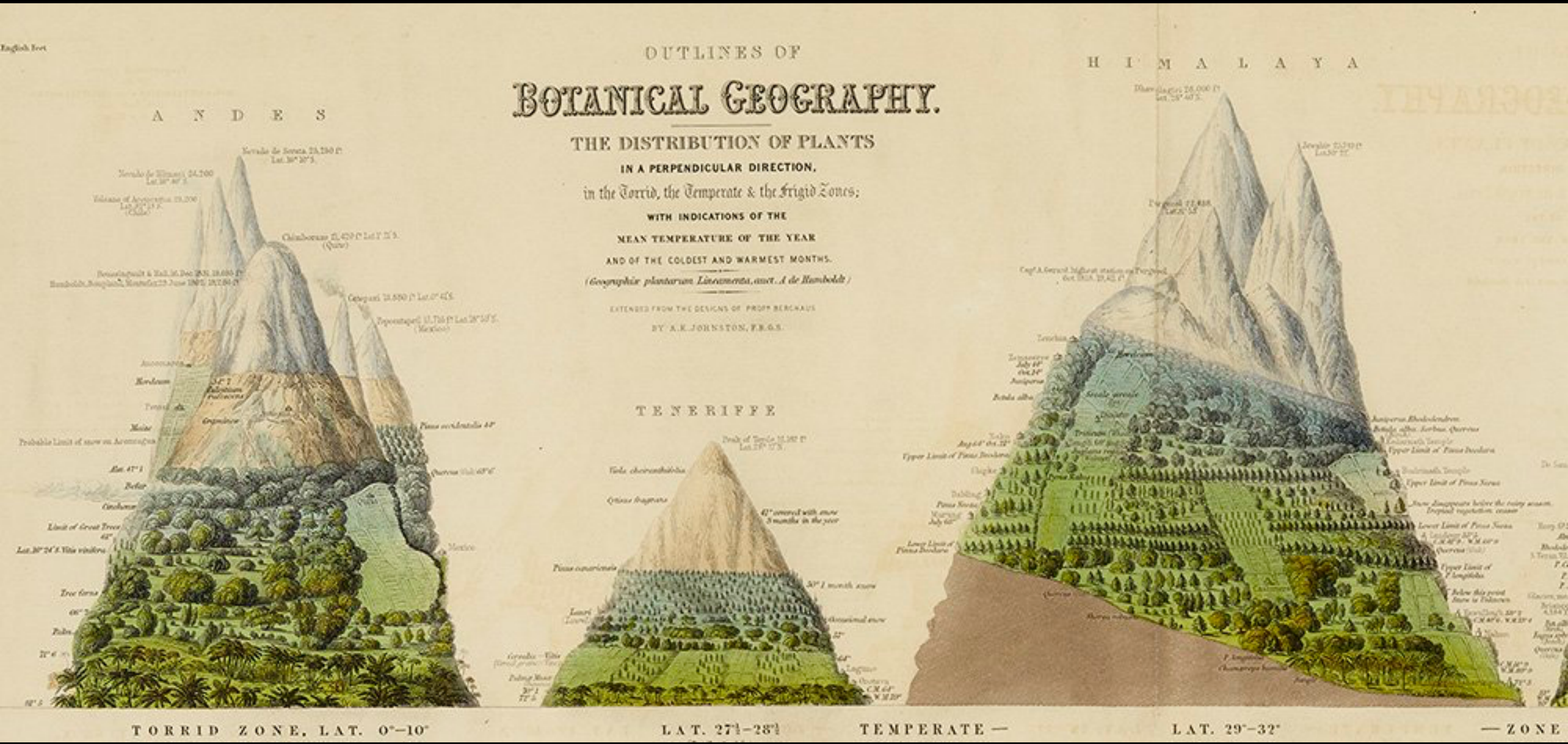
Temperature–water deficit model

PET–water deficit model

Models based on integrated climate—temperature, precipitation and potential evapotranspiration—predict angiosperm family richness well

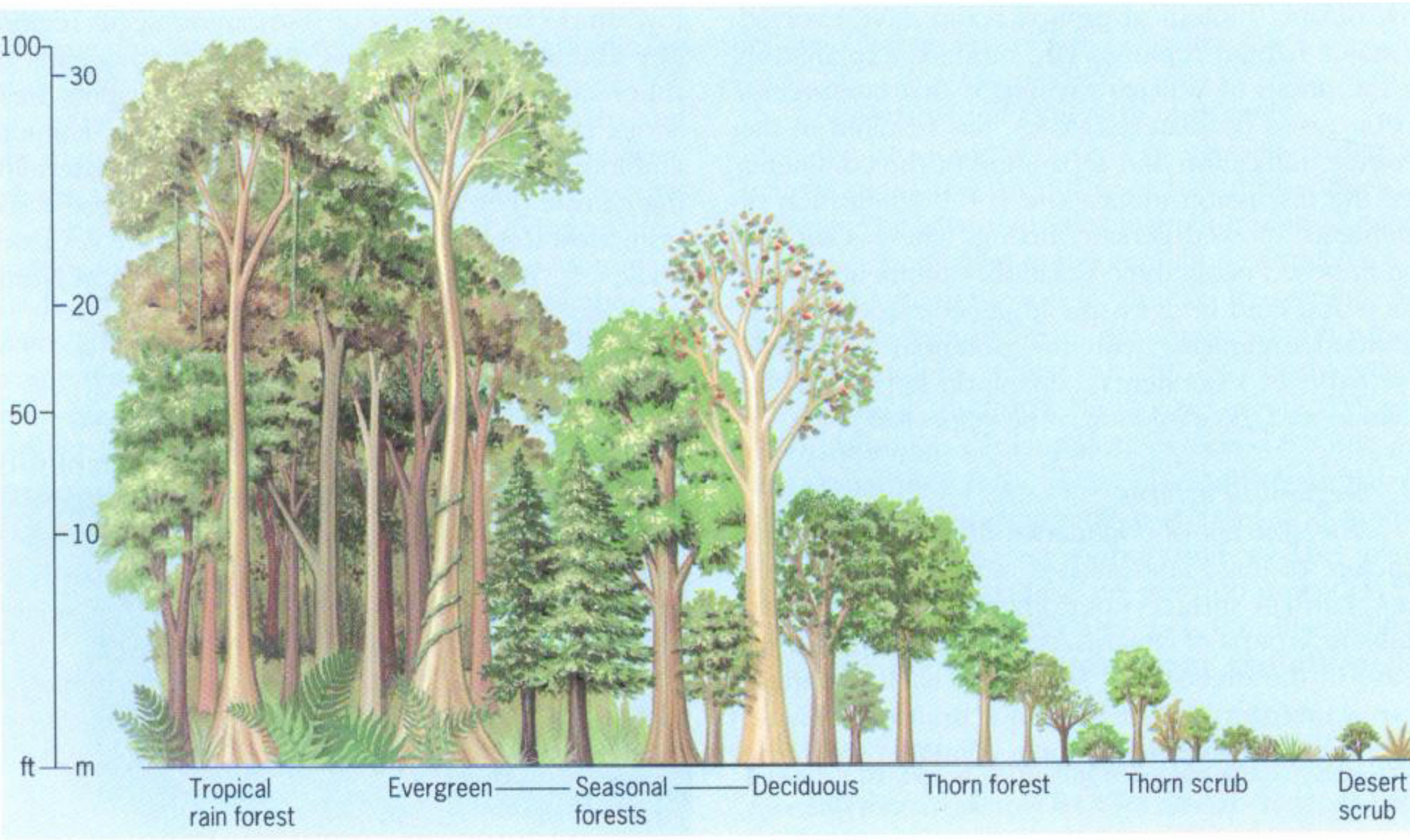
Francis and Currie 2003

Humboldt hypothesized the shifting role of abiotic and biotic factors in structuring biodiversity at high and low latitudes and altitudes



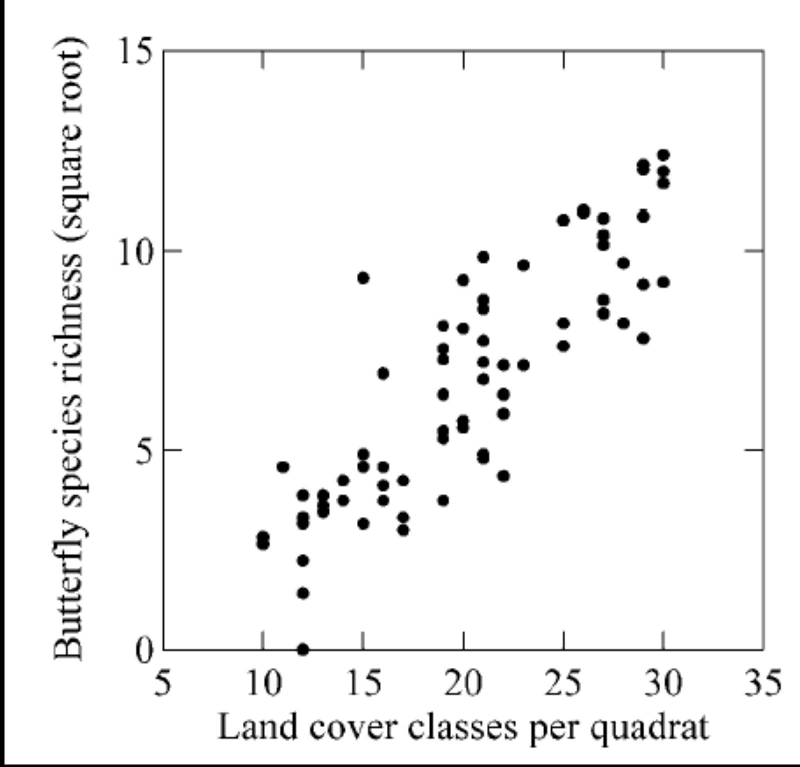
von Humboldt 1817

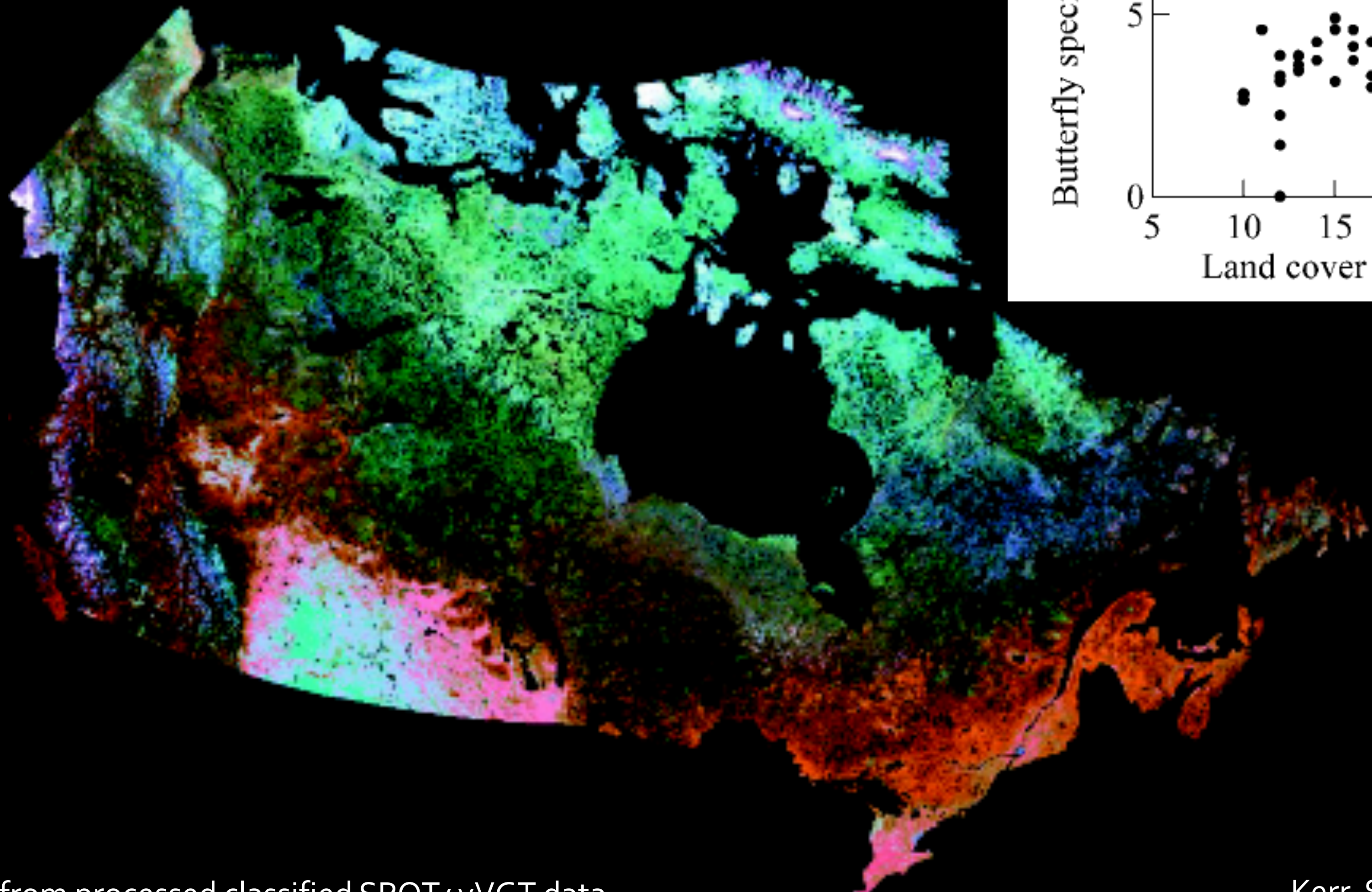
Stress gradients - rainfall



Adapted from Whittaker 1975, *Communities and Ecosystems*

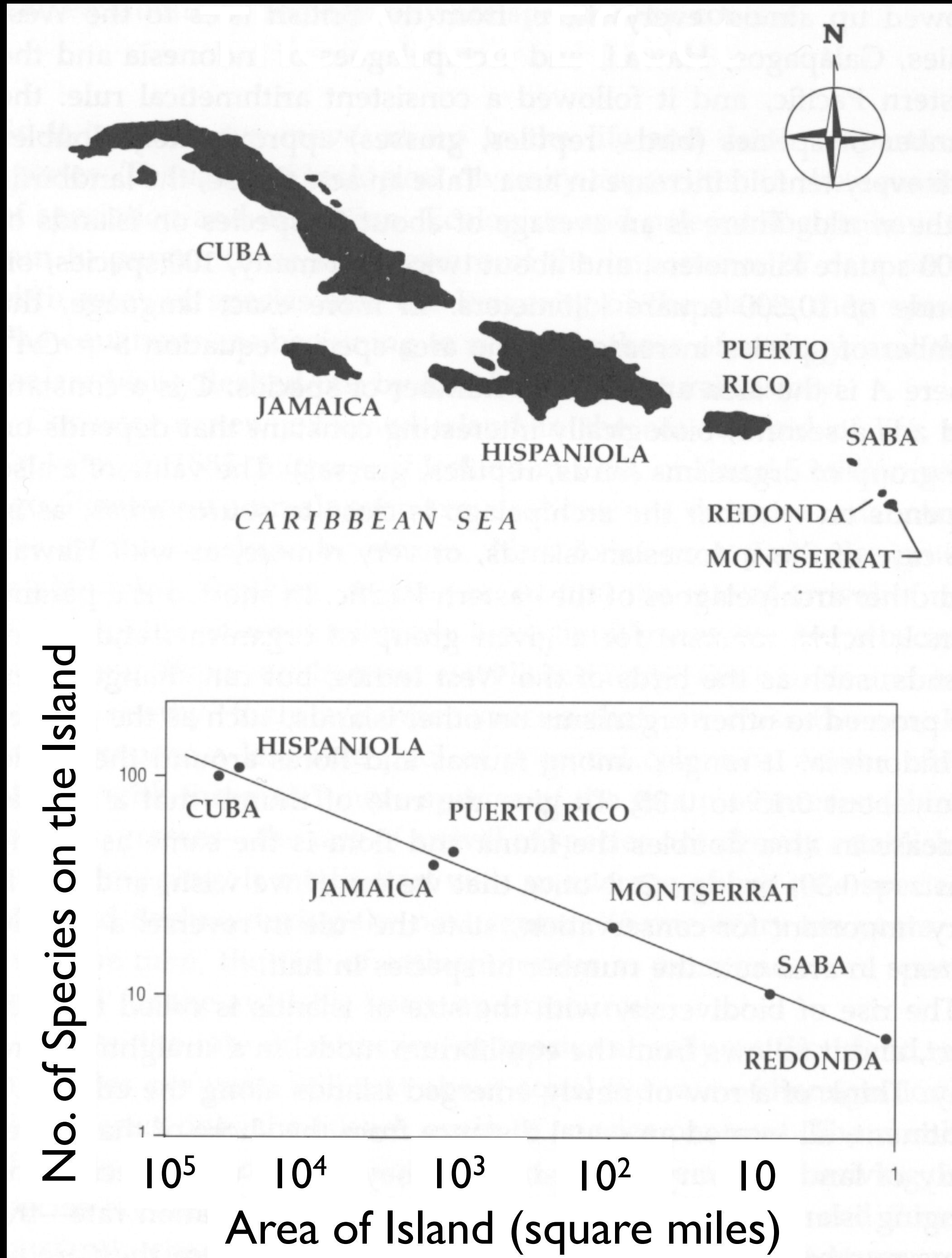
Butterfly diversity is correlated with habitat heterogeneity in Canada





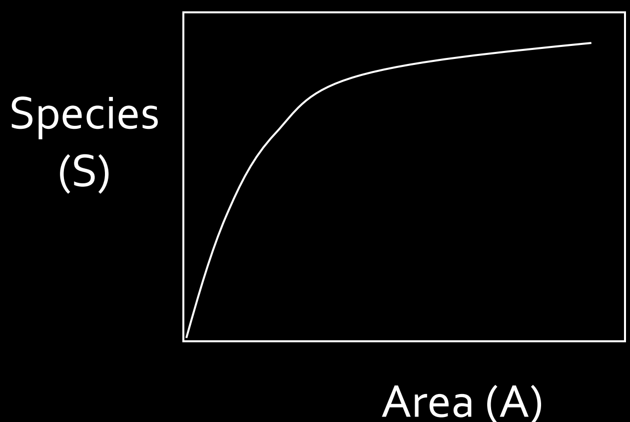
from processed classified SPOT4yVGT data

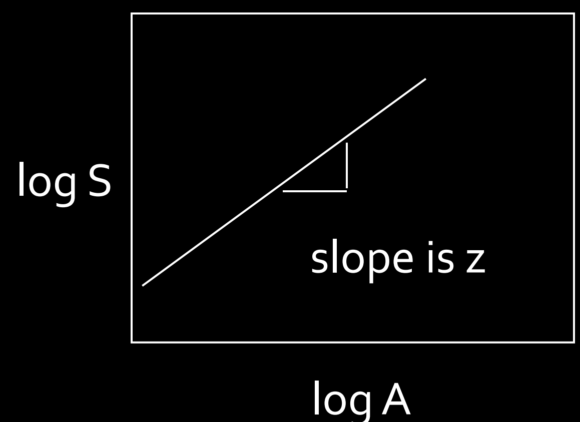
Kerr, Southwood, Cihlar. 2001



Darlington 1957
(in Wilson 1992)

Species - Area Curves





$$S = cA^z$$

$$\log(S) = \log(c) + z\log(A)$$

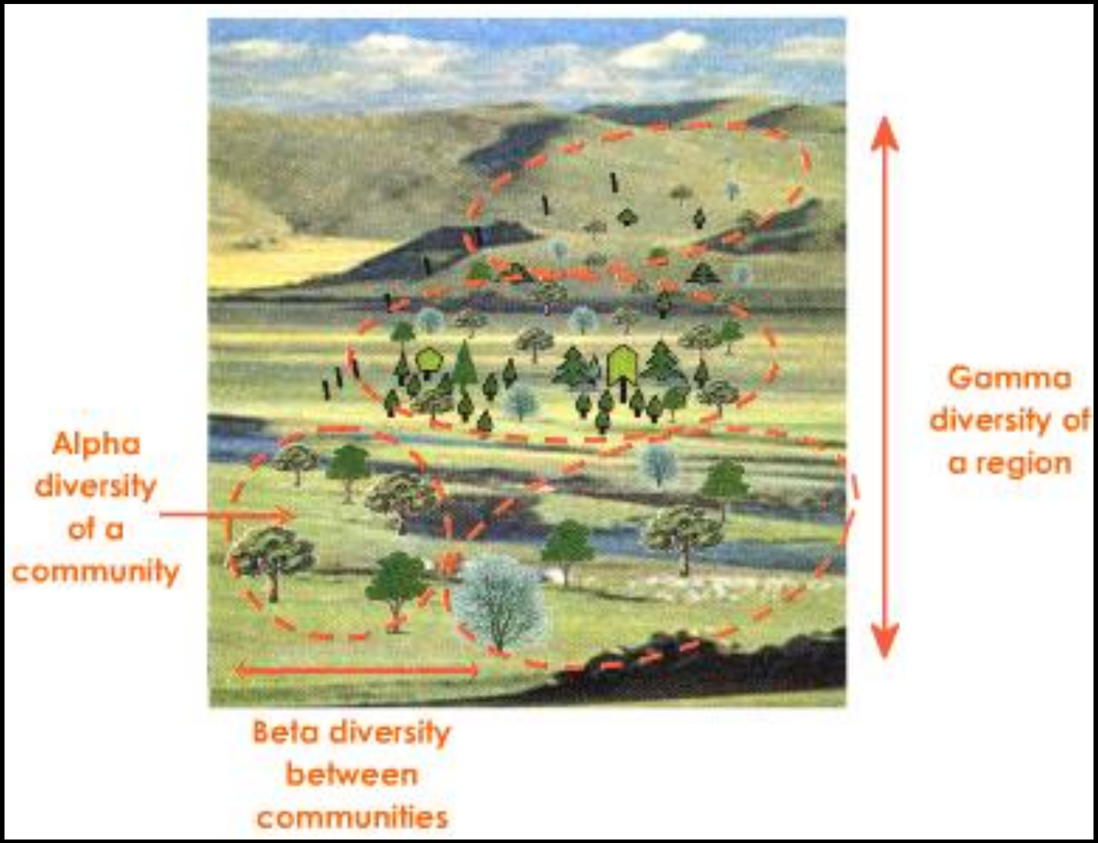
Alpha (α), beta (β) and gamma (γ) diversity

Total species in a region:
Gamma (γ) diversity

Mean species per location:
Alpha (α) diversity

Beta diversity tells us how many more species the landscape (γ) contains compared to an average subunit within it (α)

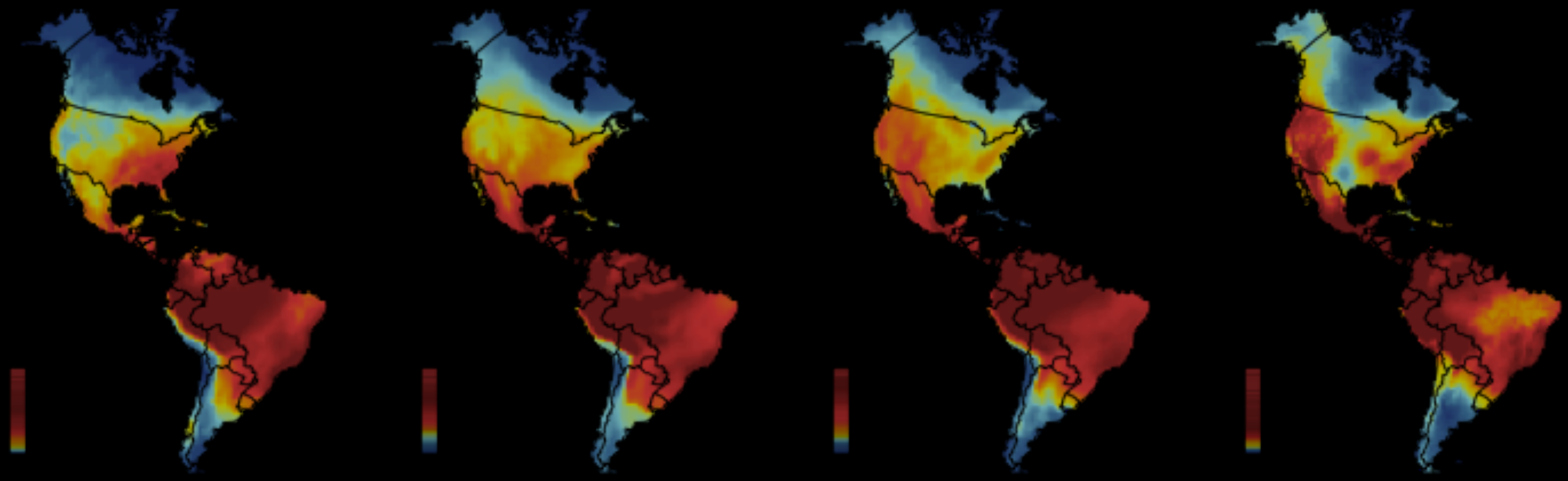
$$\beta = \gamma/\alpha$$



R. H. Whittaker 1972

Species richness increases towards the tropics

Amphibians | Birds | Mammals | Plants



IPBES Americas Chap 3

Latitudinal gradients in diversity

One of the most studied patterns in macroecology!

Hypotheses:

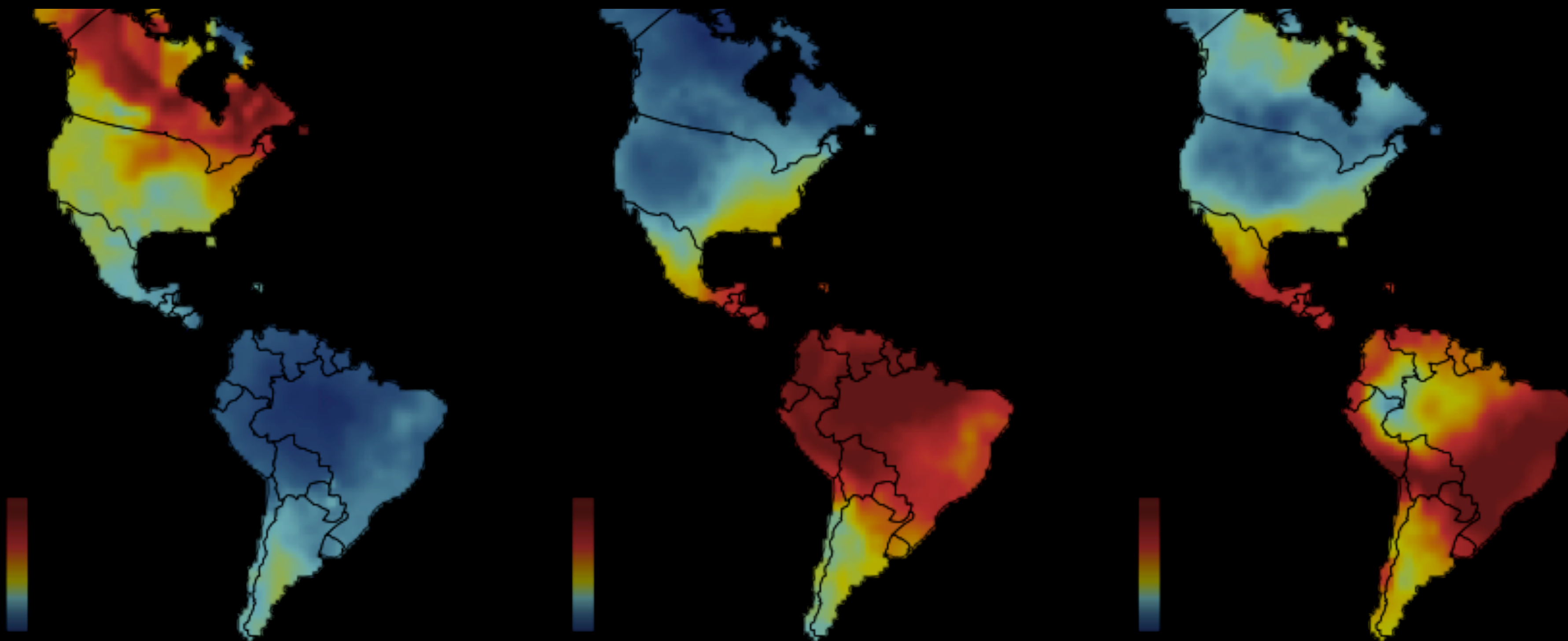
- Tropical environments have been around longer in Earth's history and covered greater area over time, so more species evolved in the tropics – fewer lineages have adapted to other biomes
- Tropical environments support more species – more solar energy, which permits more metabolic energy
- Greater stability (less (glacial) disturbance, less seasonal stress)
- Pathogen and pest pressure prevents competitive displacement
- More spatial heterogeneity, greater niche differentiation (??)

Lambir, Borneo 1,200 species in 52-ha plot

Photo: Cristian Zeigler

Plant Functional Diversity

Specific Leaf Area Seed Mass Max Plant Height



IPBES Americas Chap 3

Functional traits and the leaf economic spectrum

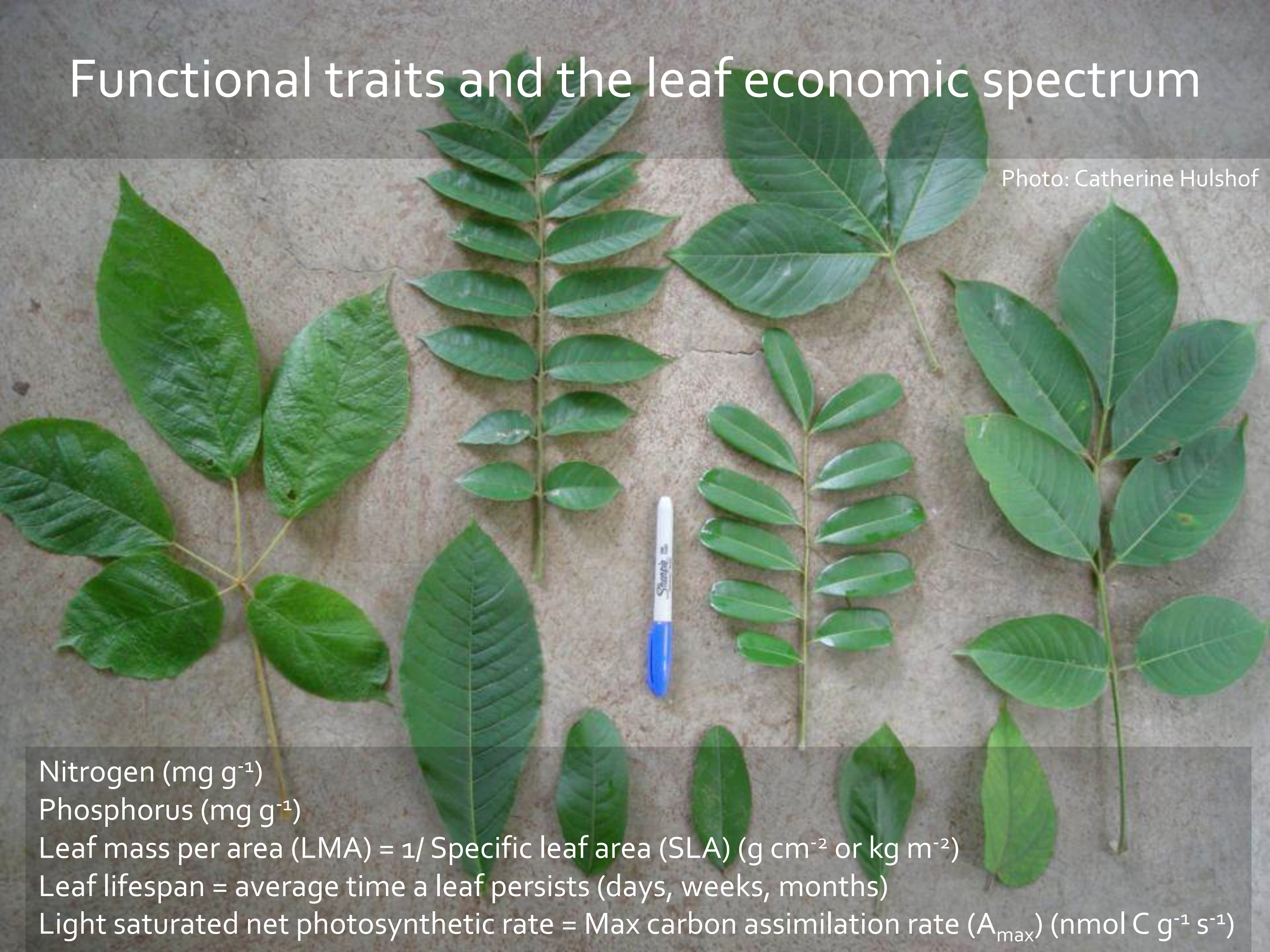
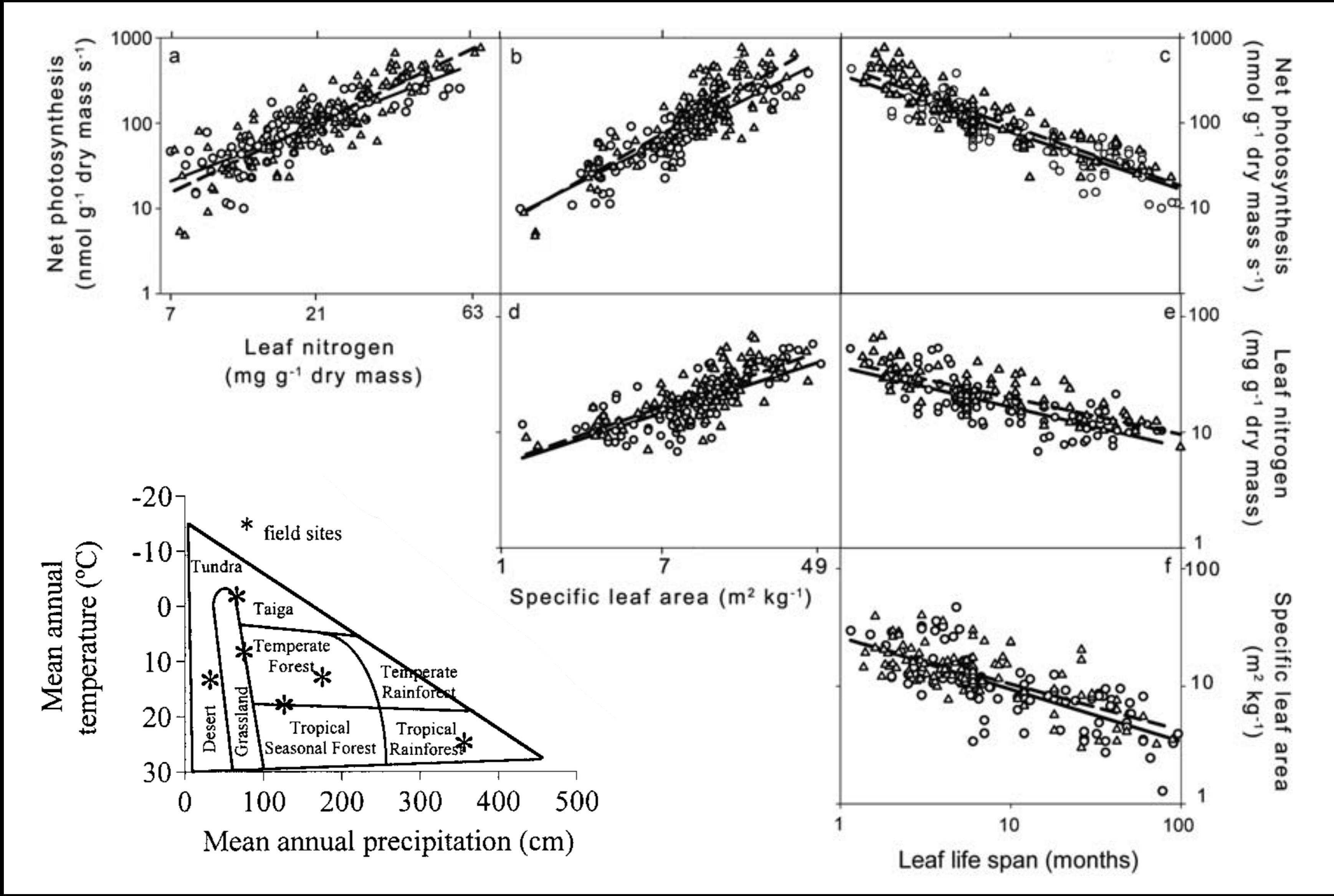


Photo: Catherine Hulshof

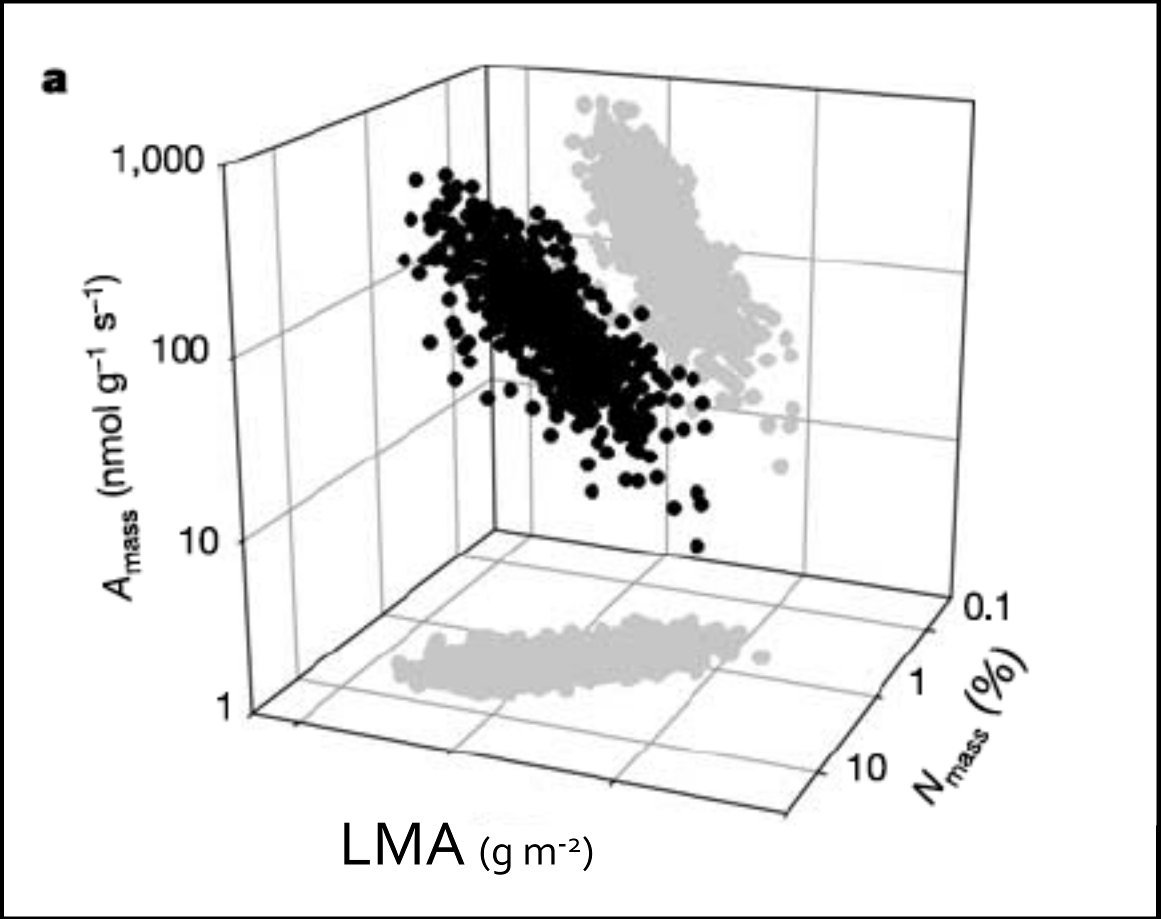
Nitrogen (mg g^{-1})
Phosphorus (mg g^{-1})
Leaf mass per area (LMA) = 1/ Specific leaf area (SLA) (g cm^{-2} or kg m^{-2})
Leaf lifespan = average time a leaf persists (days, weeks, months)
Light saturated net photosynthetic rate = Max carbon assimilation rate (A_{max}) (nmol C g^{-1} s^{-1})

Leaf functional traits are correlated: a consequence of biophysical constraints and natural selection?



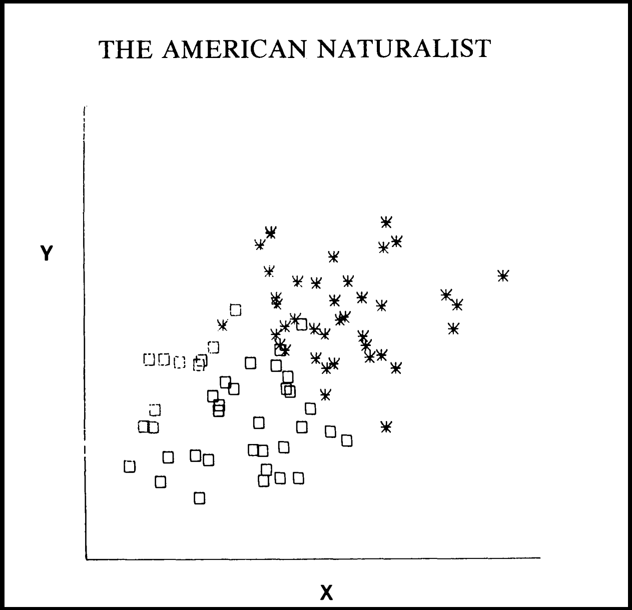
Reich et al 1997

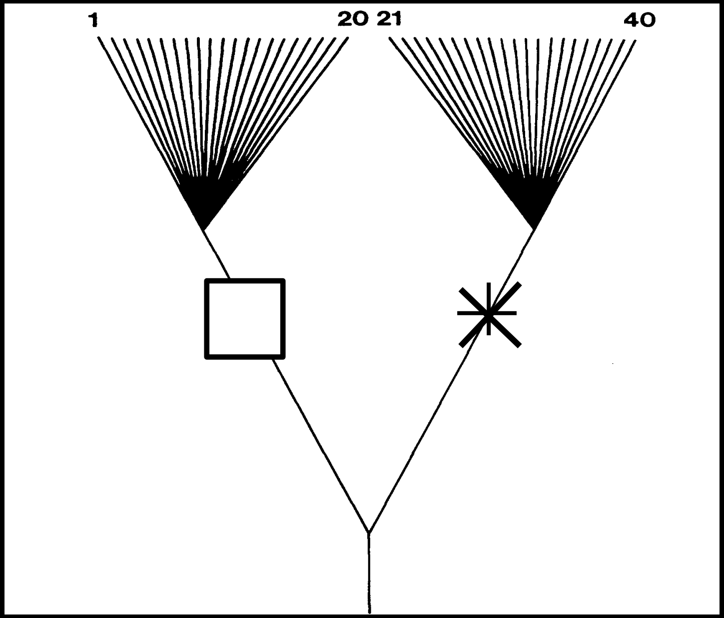
Leaf economic spectrum:
the slow-fast continuum – a major axis of life history variation



Wright et al 2004

Due to shared ancestry, species are non-independent units of observation and standard correlations are problematic





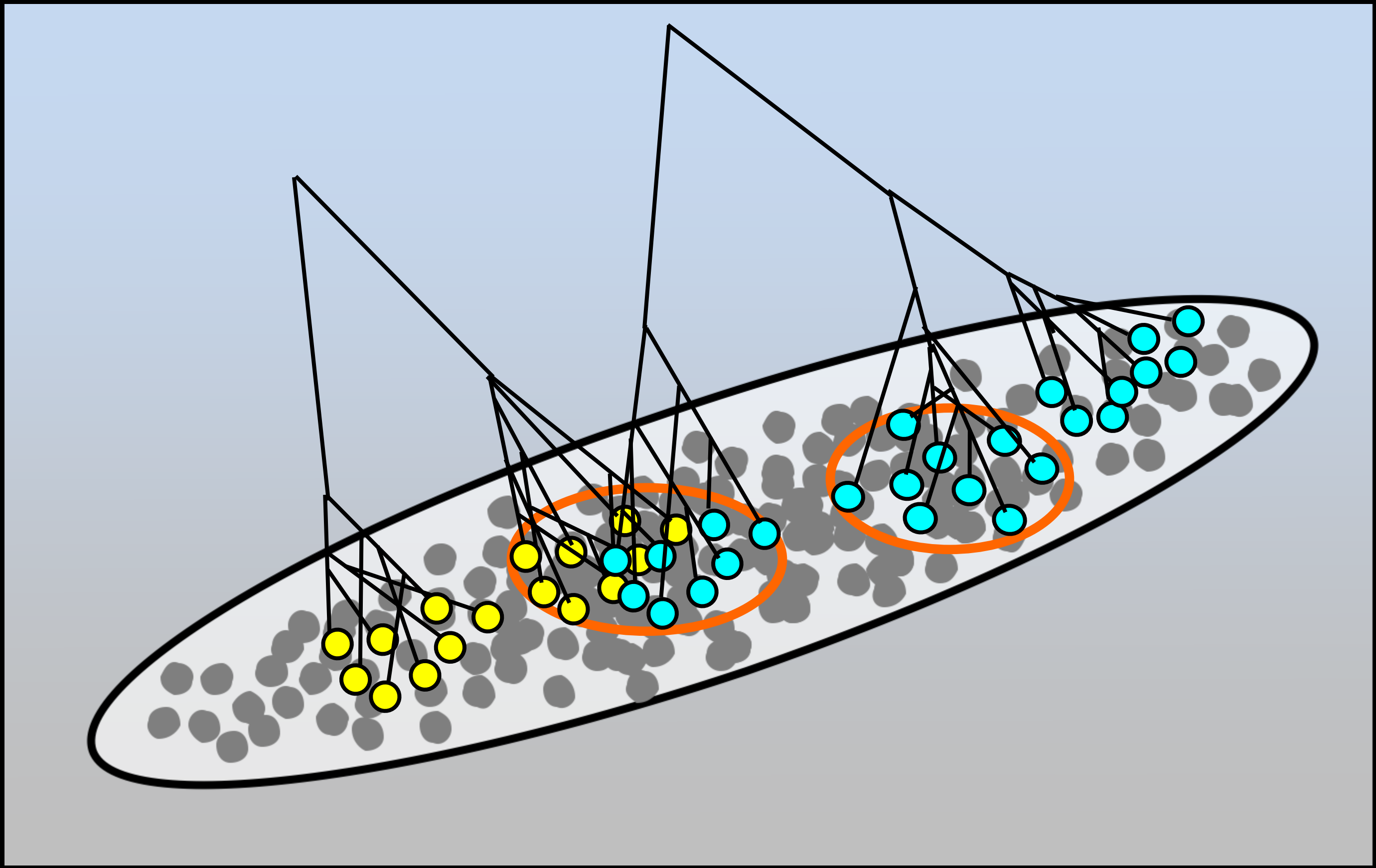
-> Method of independent contrast correlations

Ackerly & Reich 1999 showed that after taking phylogeny into account most relationships still held, but leaf area correlations disappeared

Felsenstein 1985

Traits can be uncorrelated within lineages but still correlated across them – they also may be convergent

Trait A



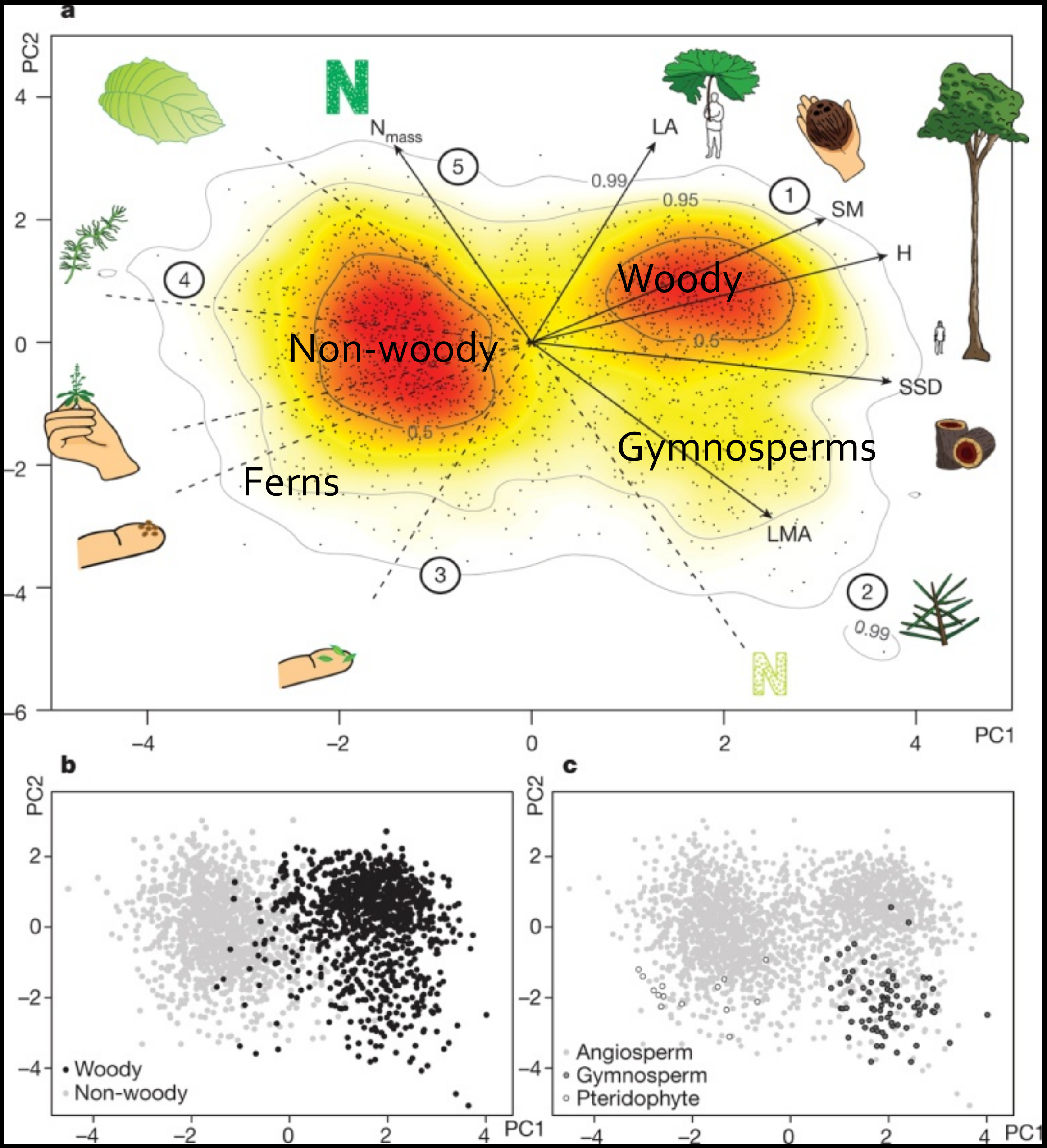
Trait B

Cavender-Bares et al 2009

The global spectrum of plant form and function.

Occupancy of six-dimensional trait space is strongly concentrated, indicating coordination and trade-offs.

Three-quarters of trait variation is captured in a two-dimensional global spectrum of plant form and function.



Díaz *et al.* 2015

Metrics of biodiversity

- Taxonomic diveristy: Species or family richness
- Phylogenetic diversity
- Genetic diversity
- Functional diversity
- Spectral diversity
- Geodiversity, etc.

Components of (alpha) diversity metrics

- Number of species (or entities)
- Abundance

- Evolved distance between species

- Functional distance between species (or pixels)
- Dispersion in trait space

Simpson's Diversity Index, D

(incorporates richness and evenness)

$$D = \frac{1}{\sum_{i=1}^{S} P_i^2}$$

***P**$_i$* is the proportion of species *i* relative to the total number of species, S.

	Community I	Community II
Species A	99	50
Species B	1	50

Community I

$$D = \frac{1}{(.99)^2 + (.01)^2} = \frac{1}{.98} = 1.02$$

Community II

$$D = \frac{1}{(.5)^2 + (.5)^2} = \frac{1}{.5} = 2$$

Phylogenetic Diversity

Faith's PD: the sum of the lengths of all phylogenetic branches (from the root to the tip) spanned by a set of species

Faith 1992

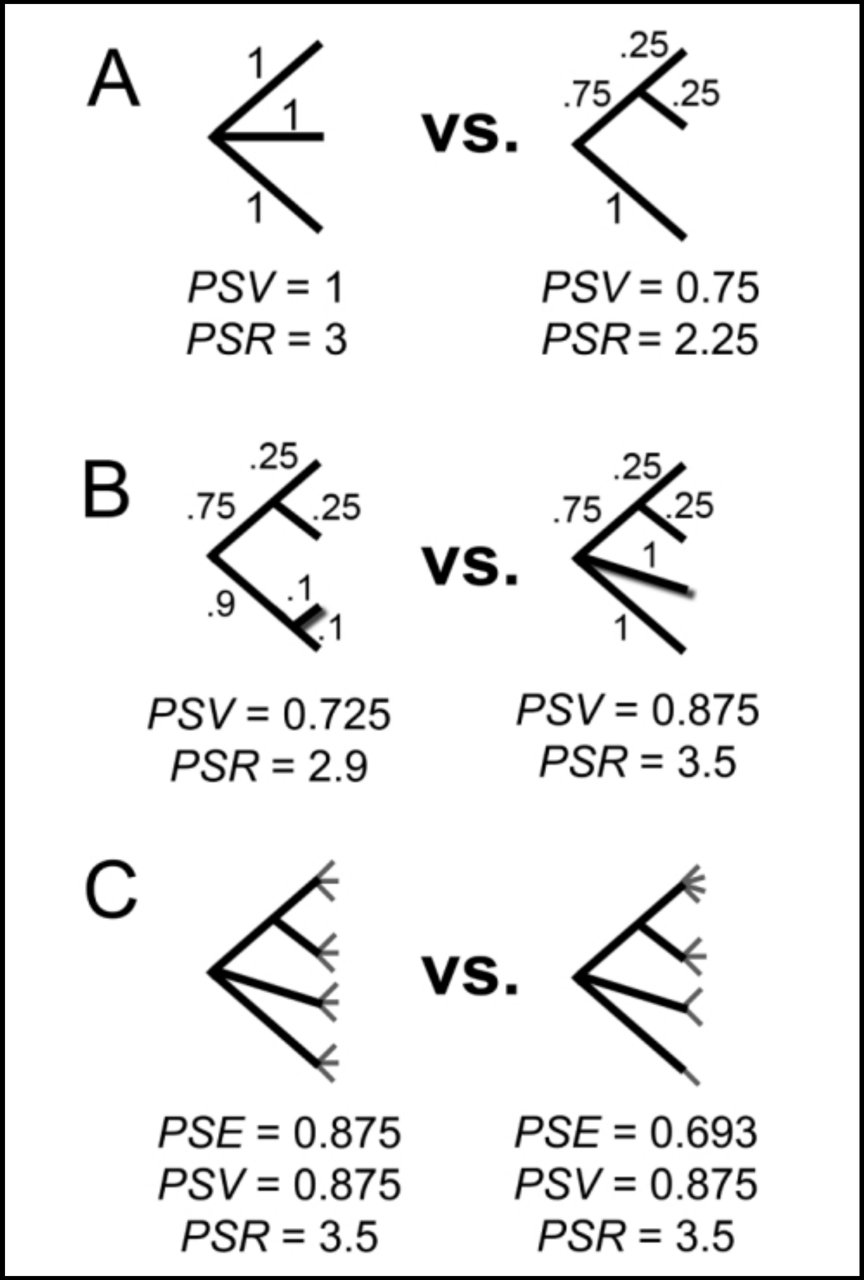
Phylogenetic species variability (**PSV**)
Independent of number of species
Phylogenetic species richness (**PSR**)
Increases with number of species
Phylogenetic species evenness (**PSE**)
Includes abundance

Helmus 2007

Phylogenetic Hill number
$^{q}D(T)$
Effective number of equally abundant and equally distinct lineages

Phylogenetic branch diversity
$^{q}PD(T)$
Effective total lineage-length (total evolutionary history of an assemblage since time T (root node)

Chao 2010



Helmus et al 2007

Functional Diversity

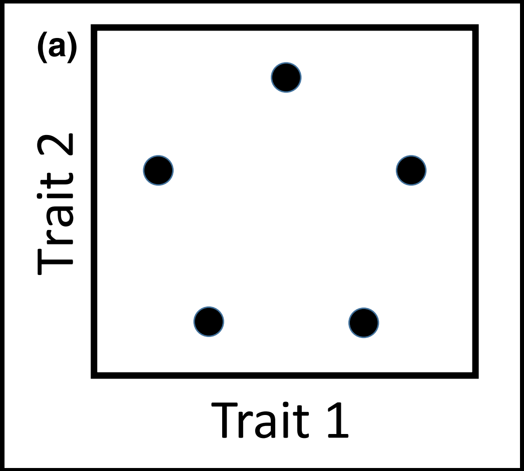
Table S1. Metrics of functional diversity

Metric	Symbol	Description	Formula	Quantities	Source
Functional diversity	FD	Sum of branch lengths	$i' \times h2$	Distance	(Petchey & Gaston 2002)
Functional attribute diversity	FAD	Sum of pairwise distances	$\sum_{i=1}^{S}\sum_{j=1}^{S} d_{ij}$	Distance	(Walker, Kinzig & Langridge 1999)
Functional richness	FRic	Convex hull volume	Quickhull algorithm	Distance	(Cornwell, Schwilk & Ackerly 2006)
Functional evenness	FEve	Sum of branch lengths weighted by abundance	$\frac{\sum_{i=1}^{S-1} \min(PEW_i, \frac{1}{S-1}) - \frac{1}{S-1}}{1 - \frac{1}{S-1}}$	Distance, abundance	(Villéger, Mason & Mouillot 2008)
Rao's quadratic entropy	Q	Sum of pairwise distances weighted by relative abundance	$\sum_{i=1}^{S}\sum_{j=1}^{S} d_{ij}p_ip_j$	Distance, abundance	(Rao 1982)
Total functional diversity	^{q}FD(Q)	Functional trait-weighted abundance diversity	$\left(\sum_{i=1}^{S}\sum_{j=1}^{S} d_{ij}\left(\frac{p_ip_j}{Q}\right)^q\right)^{1/(1-q)}$	Distance, abundance, effective number of distinct species	(Chiu & Chao 2014)
Functional distance	FDis	Mean distance from the centroid weighted by relative abundance	$\frac{\sum_{i=1}^{S} d_ip_i}{\sum_{i=1}^{S} p_i}$	Distance, abundance	(Laliberté & Legendre 2010)
Functional divergence	FDiv	Deviance from the centroid of the convex hull weighted by abundance	$\frac{\Delta d + \overline{dG}}{\Delta\lvert d\rvert + \overline{dG}}$	Distance	(Villéger, Mason & Mouillot 2008)

Scheiner et al al 2016

Scheiner's functional trait dispersion ${}^qD(TM)$

Based on the uniqueness concept -- maximum diversity is when each species occurs at the boundary of trait space and they are as equally far apart from each other as possible



When all species are equally distant, D(T) is maximized

$$M = \sum_i^S \sum_j^S d_{ij} / S^2$$

Magnitude of dispersion

$$^{q}H(T) = \left(\sum_i^S \sum_j^S f_{ij}^q\right)^{\frac{1}{(1-q)}},$$

Variability among pairwise distances

$$^{q}D(T) = \frac{1 + \sqrt{1 + 4\,{}^{q}H(T)}}{2}.$$

Effective number of equally distant species

$${}^qD(TM) = 1 + {}^qD(T) \times M$$

Equivalent to:

$${}^qD(TM) = 1 + (S-1) \times {}^qE(T) \times M'$$

Number of species (or pixels) ● evenness of dispersion ● magnitude of distances

Scheiner et al 2016

Taxonomic, Phylogenetic and Functional Beta Diversity can also be calculated in multiple ways

Table 1 Two major classes of phylogenetic similarity measures based on the transformations of phylogenetic beta diversity when species importance measures are incidences (for $q=0$), relative abundances or absolute abundance (for $q=1$ and 2). The corresponding differentiation measures are the one-complements of the similarity measures. When all lineages are completely distinct (this includes $T \to 0$, ignoring phylogeny), these phylogenetic measures reduce to the corresponding non-phylogenetic versions. All measures can also be applied to non-ultrametric trees if $\bar{T}$ is substituted for T

Order	Species importance measure	Phylo-local-overlap	Phylo-regional-overlap
		$\bar{C}_{qN}(T) = \dfrac{\left[1/{}^q\bar{D}_\beta(T)\right]^{q-1} - (1/N)^{q-1}}{1-(1/N)^{q-1}}$	$\bar{U}_{qN}(T) = \dfrac{\left[1/{}^q\bar{D}_\beta(T)\right]^{1-q} - (1/N)^{1-q}}{1-(1/N)^{1-q}}$
$q=0$	Incidences	Phylo-Sørensen (= *PhyloSør* for $N=2$) $\dfrac{N - L_\gamma(T)/L_\alpha(T)}{N-1}$	Phylo-Jaccard (=1–*UniFrac* for $N=2$) $\dfrac{L_\alpha(T)/L_\gamma(T) - 1/N}{1-1/N}$
$q=1$	Relative abundances	Phylo-Horn $1-\dfrac{H_{P,\gamma}-H_{P,\alpha}}{T\log N}$	Phylo-Horn $1-\dfrac{H_{P,\gamma}-H_{P,\alpha}}{T\log N}$
	Absolute abundances	$\dfrac{H_{P,\alpha}-H_{P,\gamma}-T\sum_{k=1}^{N}\frac{z_{+k}}{z_{++}}\log\left(\frac{z_{+k}}{z_{++}}\right)}{T\log N}$	$\dfrac{H_{P,\alpha}-H_{P,\gamma}-T\sum_{k=1}^{N}\frac{z_{+k}}{z_{++}}\log\left(\frac{z_{+k}}{z_{++}}\right)}{T\log N}$

A. Chao et al.

T= age of root node of tree

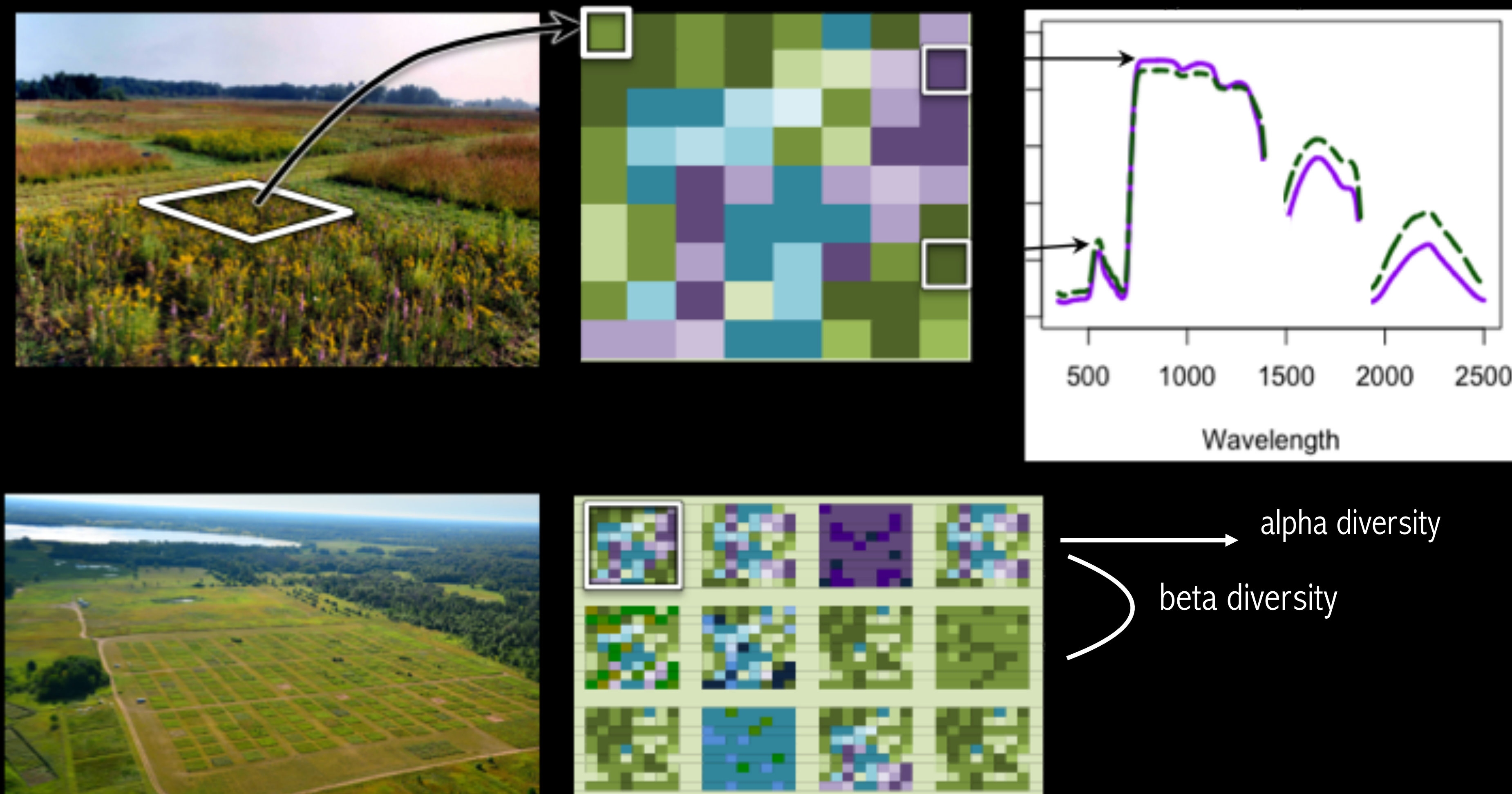
L = branch length

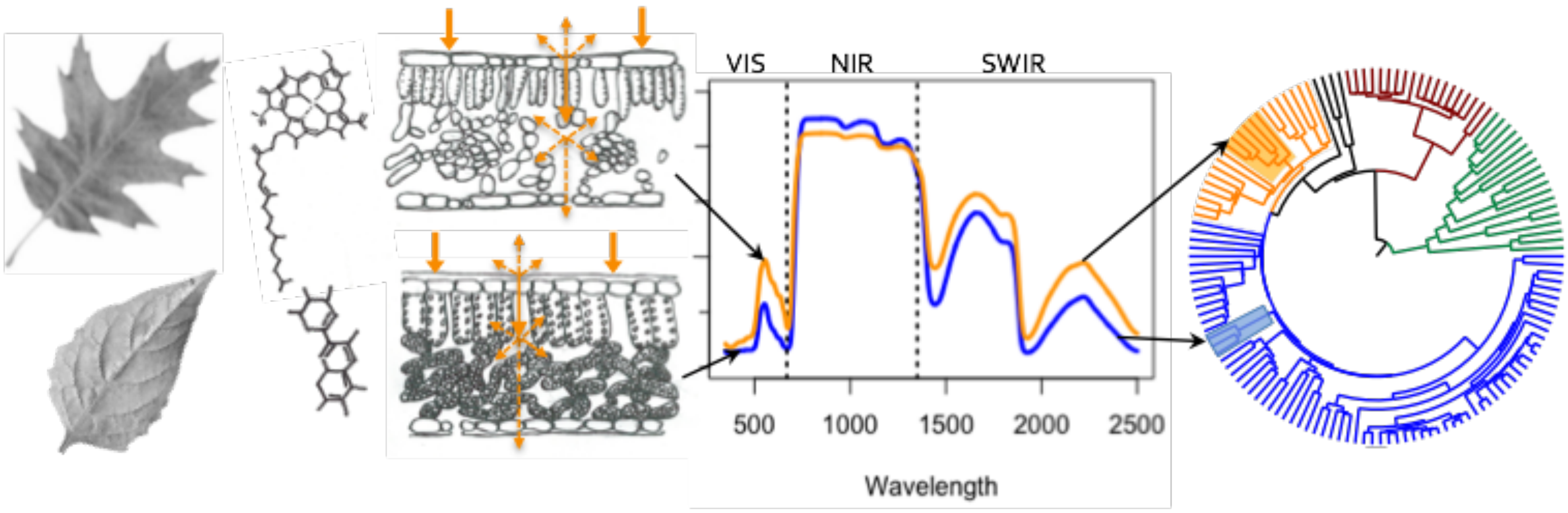
a = relative abundance from branch I

N= number of distince (not shared) lineages

Chao et al 2016

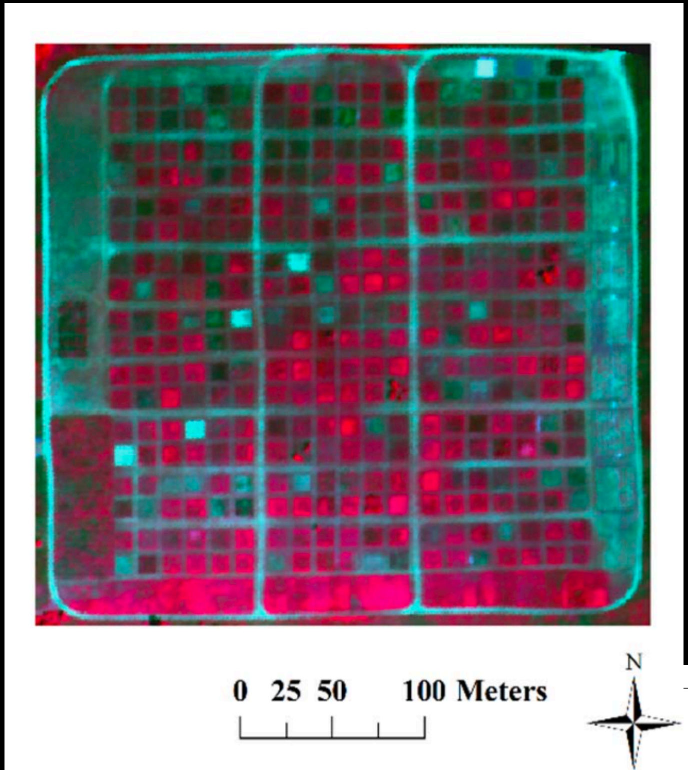
Detecting plant diversity in manipulated experiments



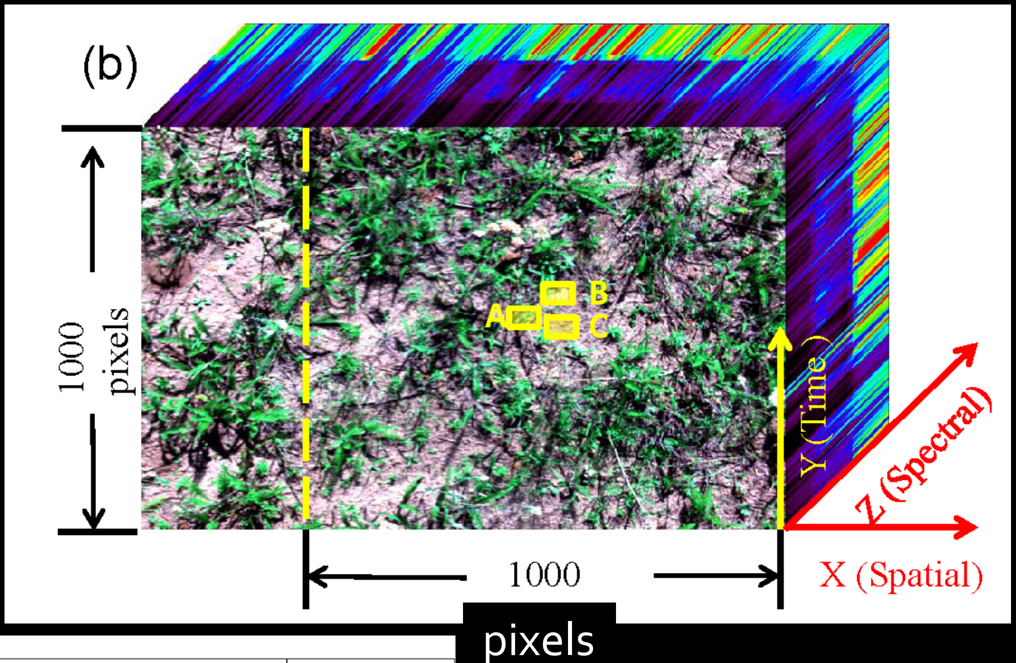


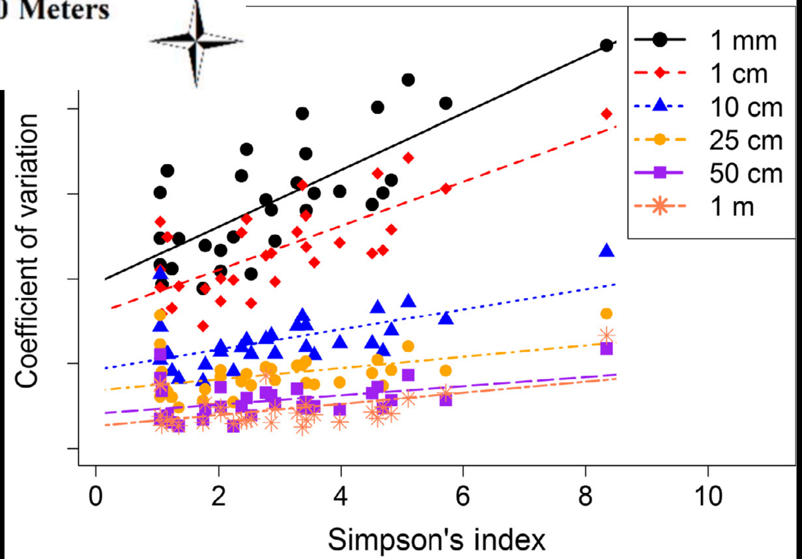
Cavender-Bares et al 2017

Spectral diversity (CV across pixels) correlates with plant diversity depending on spatial resolution



Cedar Creek

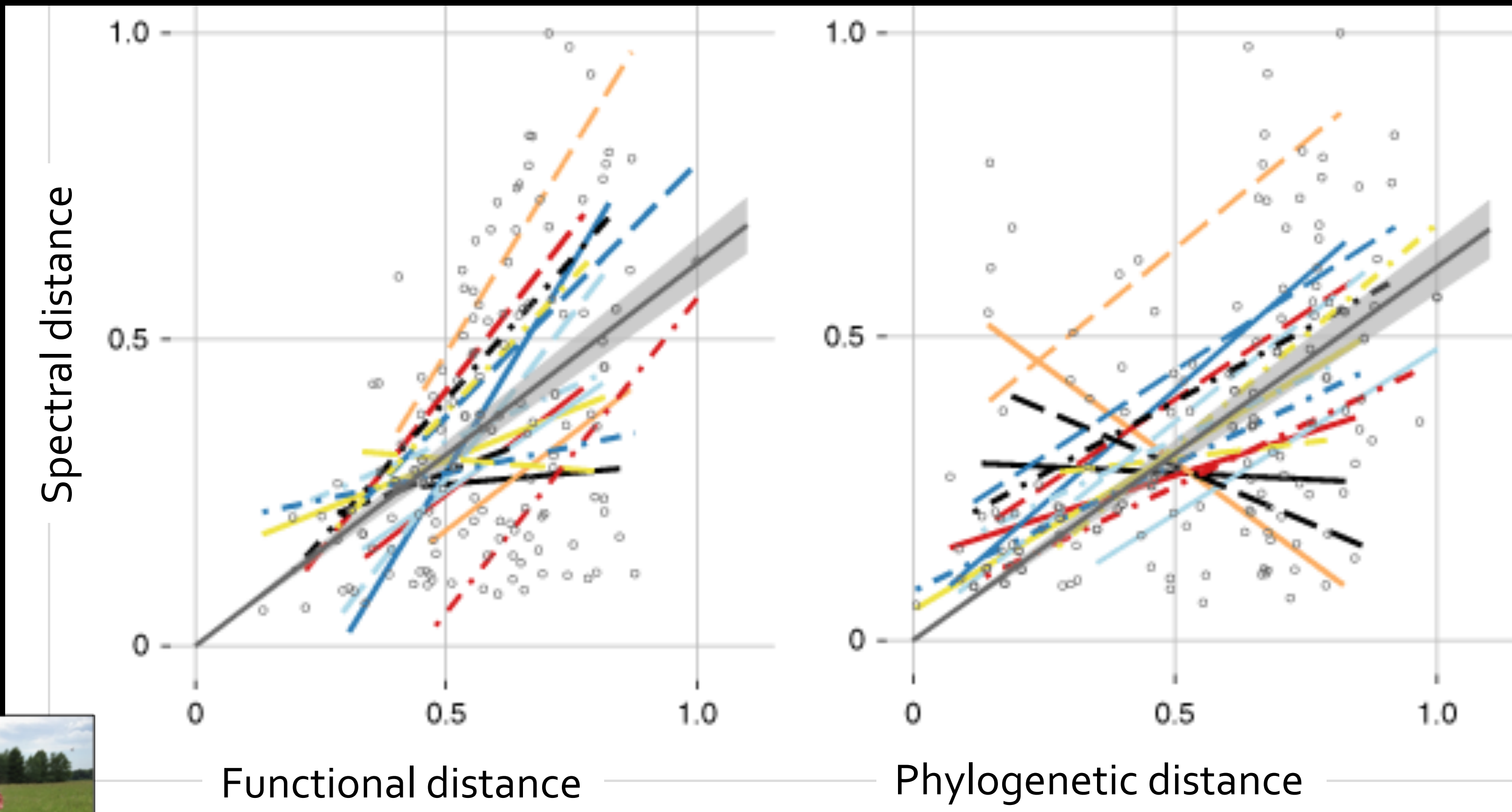




Ran Wang

Wang, Gamon et al EcoApp, 2018

Spectral distance is associated with functional and phylogenetic distance between species

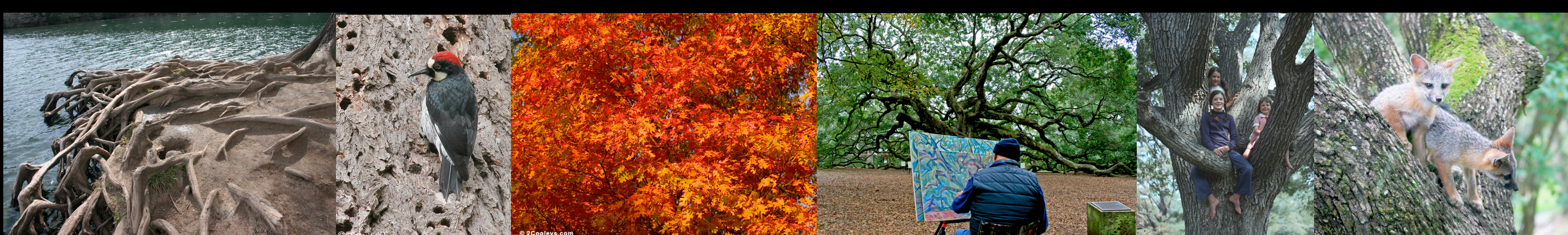


Anna Schweiger

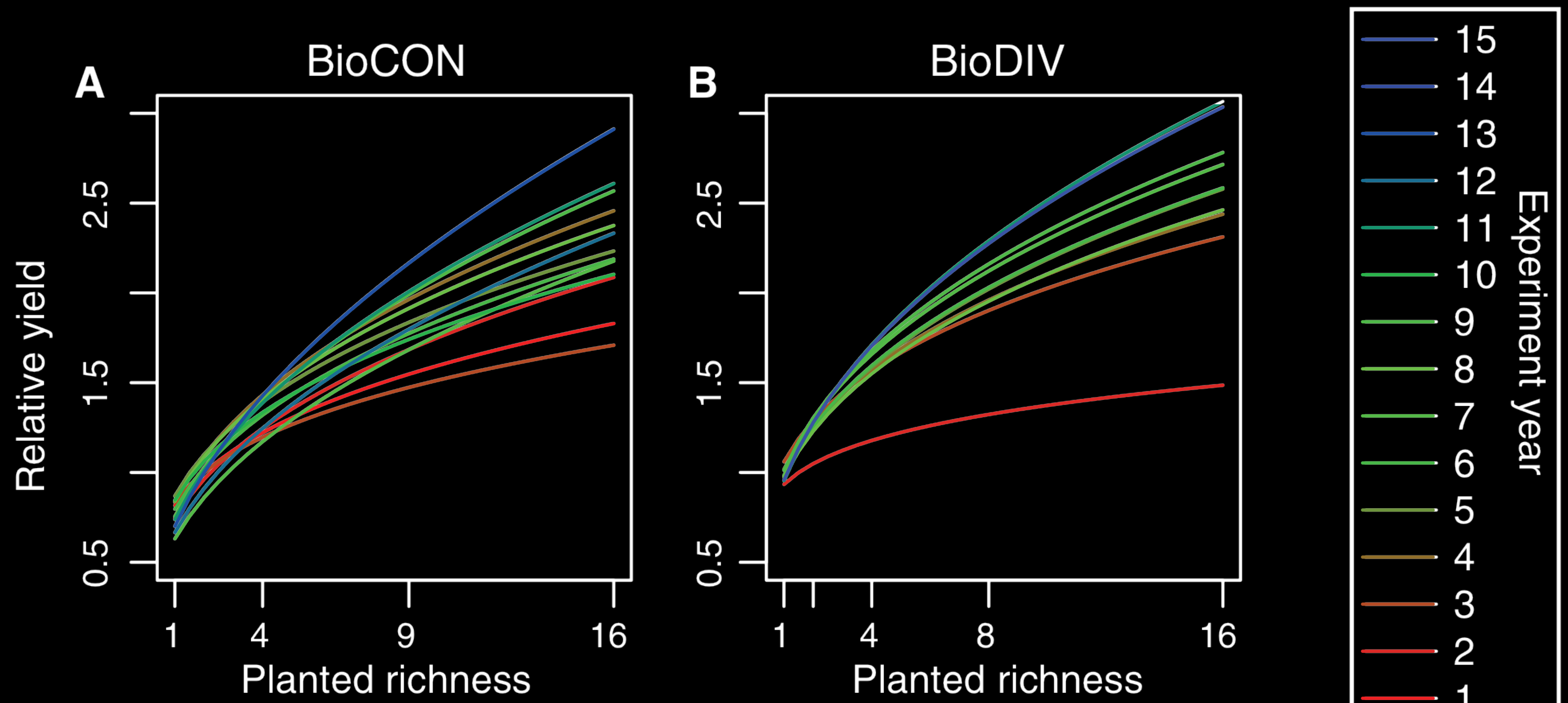
Schweiger, Cavender-Bares et al, Nature EE 2018

Consequences of biodiversity

- Ecosystem function
- Stability and resistance to disturbance
- Other trophic levels
- Links to ecosystem services

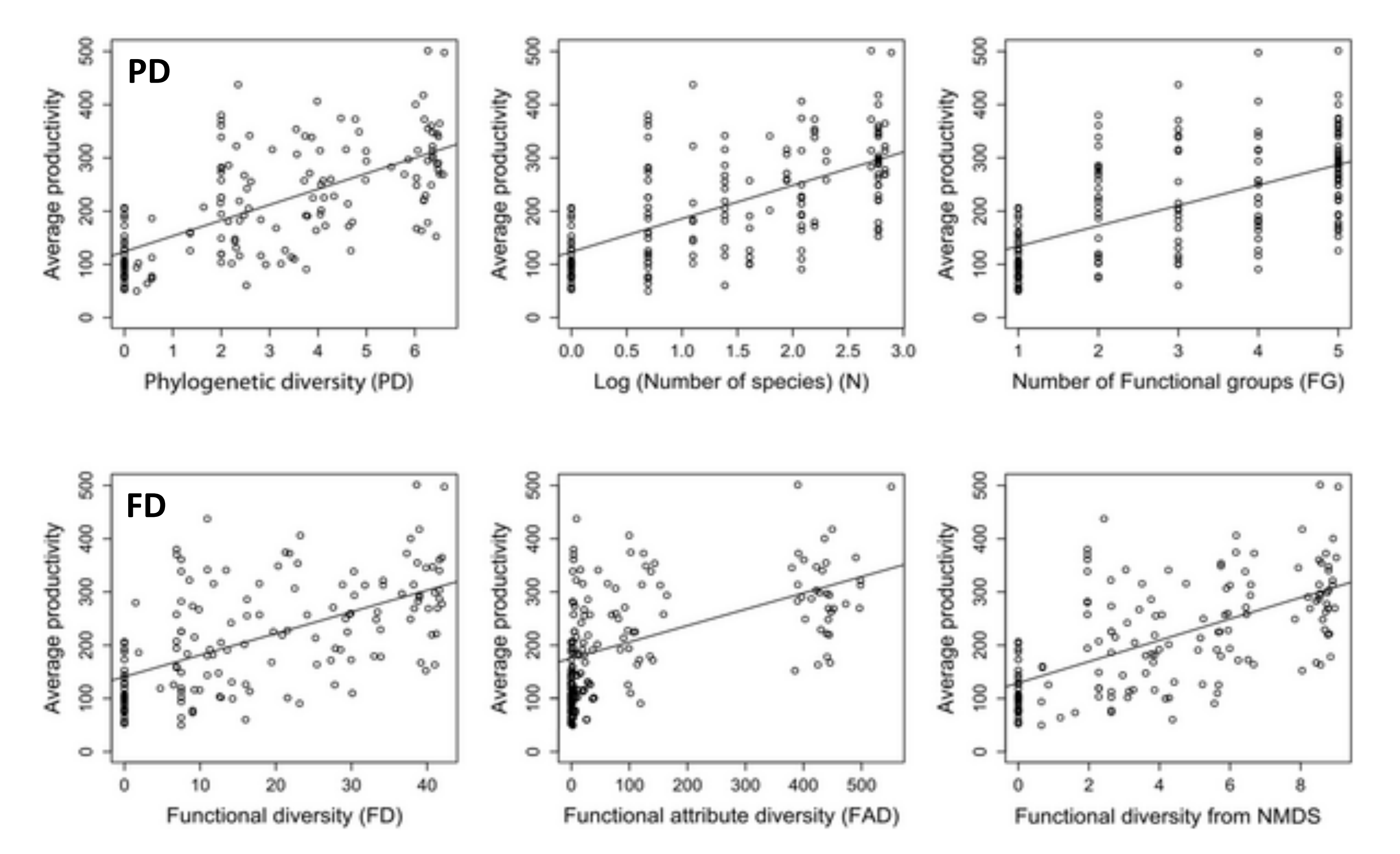


Biodiversity predicts ecosystem productivity in manipulated experiments - the relationship has increased through time



Reich, Tilman, Isbell, Mueller, Hobbie, Flynn, Eisenhauer 2012 *Science*

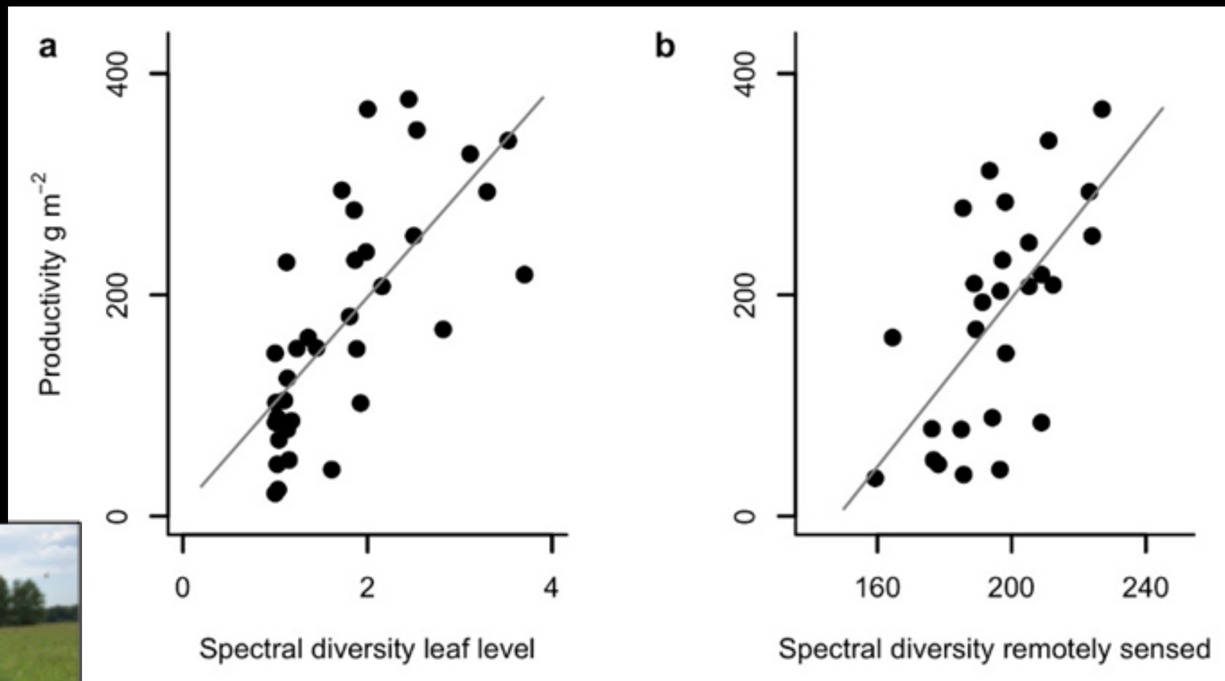
Relationship between average annual plot productivity and six diversity metrics

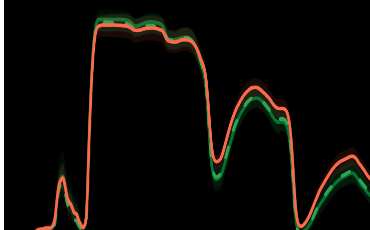


Cadotte, Cavender-Bares, Tilman, Oakley 2009

Spectral diversity also predicts productivity

Plant Productivity (g m^{-2})



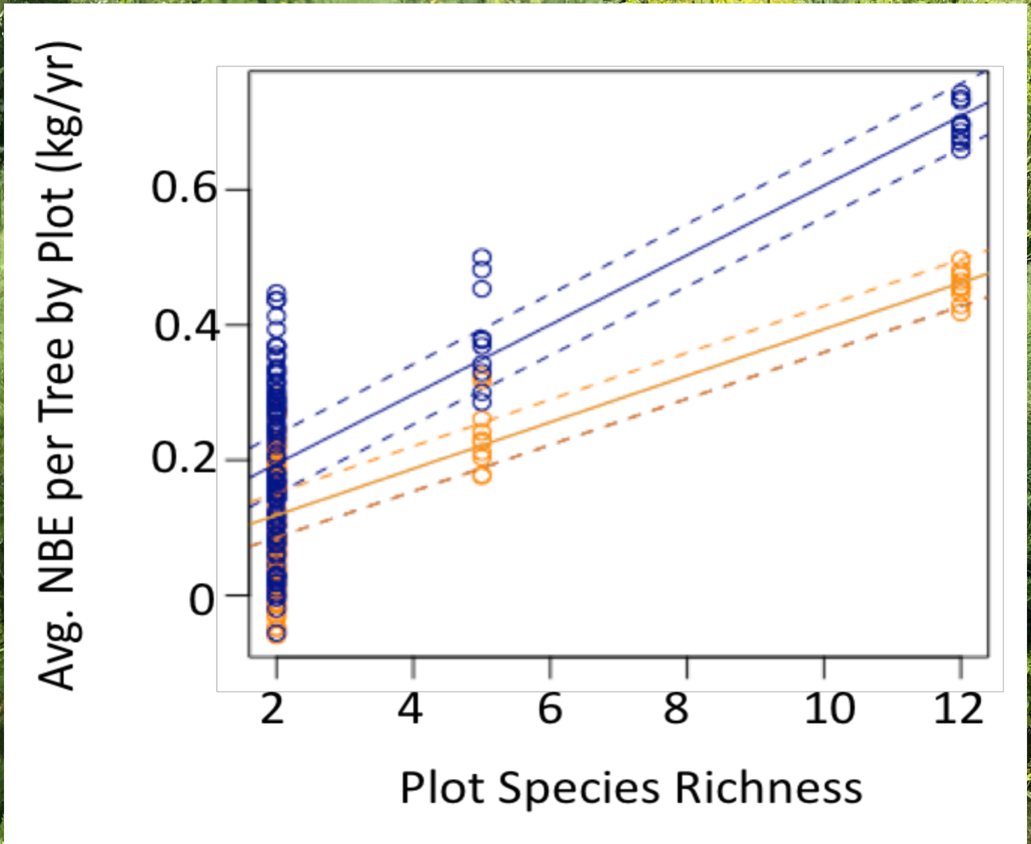


Anna Schweiger

Spectral diversity

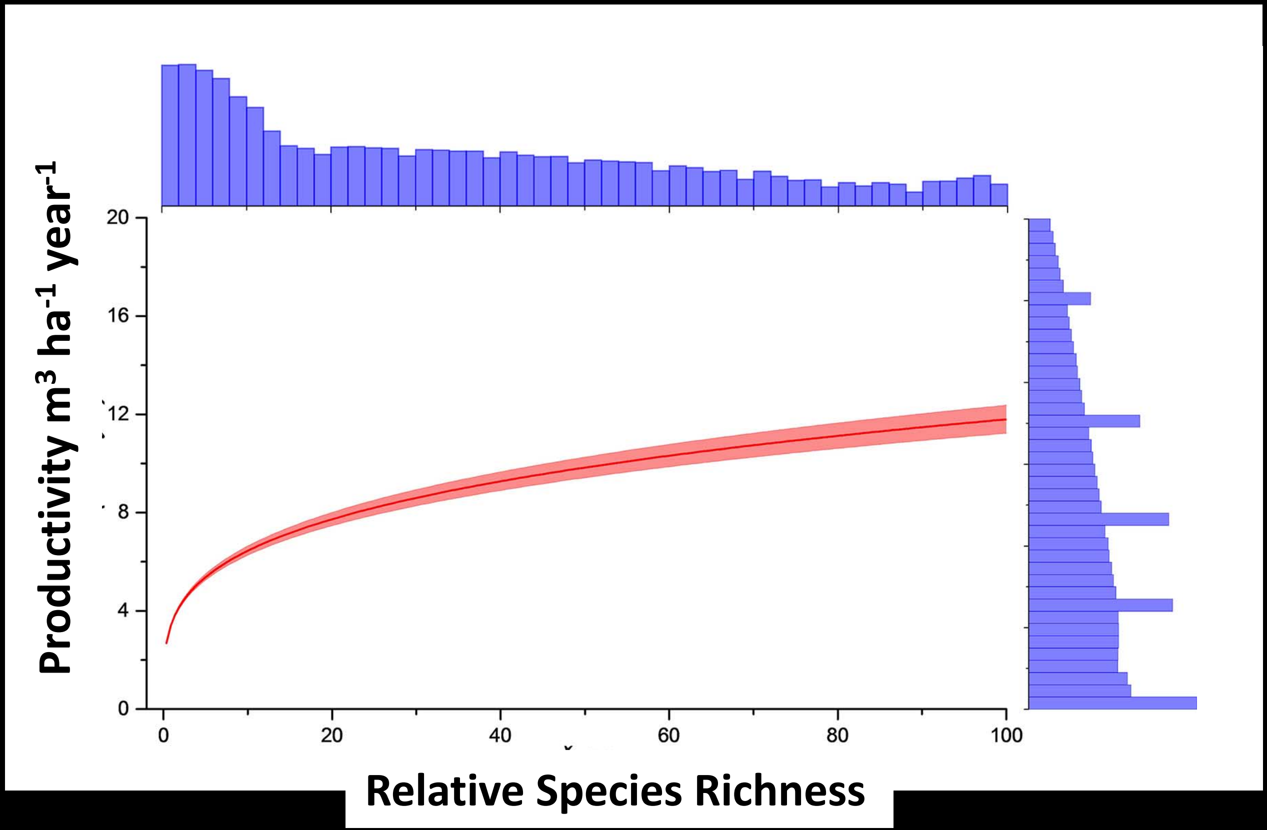
Schweiger et al, Nature EE 2018

Forest and Biodiversity Experiment at Cedar Creek

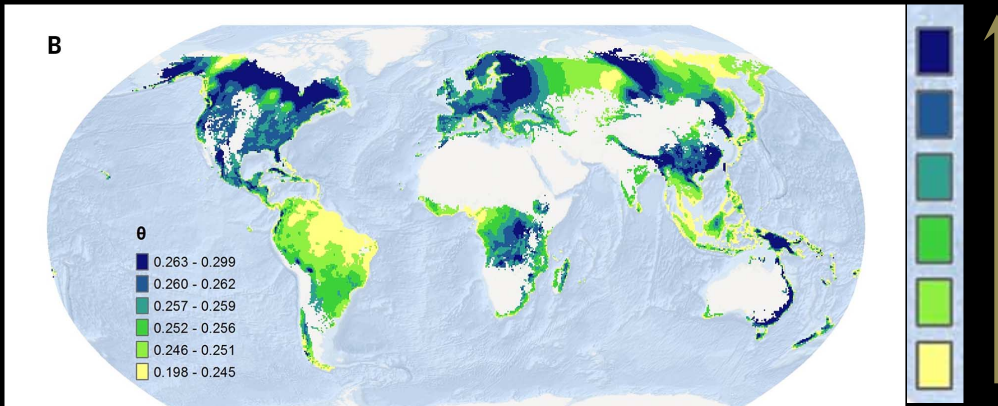


Tree species richness was a significant predictor of per-tree Net Biodiversity Effects (NBE) on tree biomass after 1 (orange) and 2 (blue) years of treatment.

Global forest inventory records indicate biodiversity loss would result in declines in forest productivity



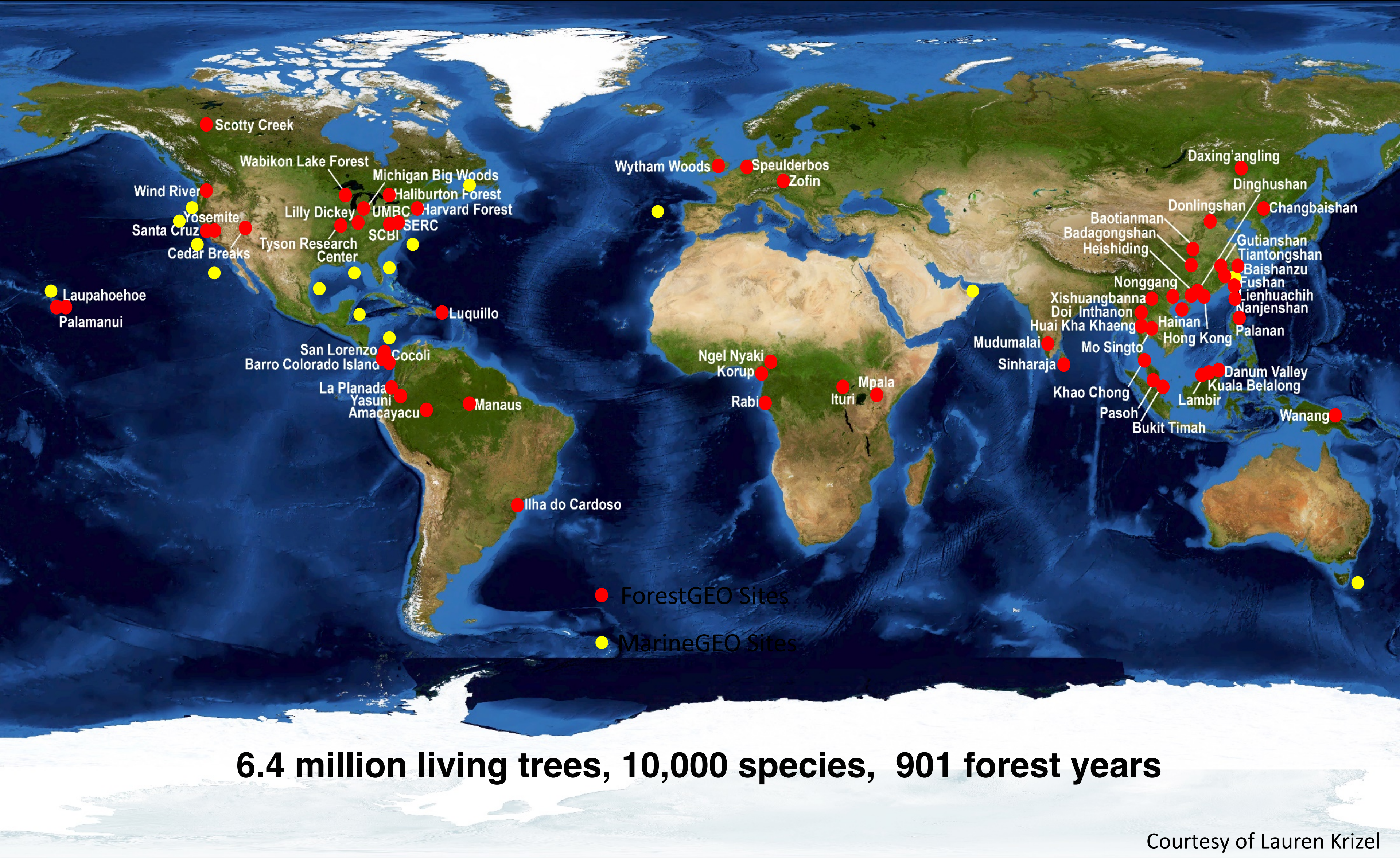
In natural forests around the globe, higher tree species richness is linked to higher productivity



Influence of biodiversity on productivity

Liang et al 2016 *Science*

67 sites, 26 countries, >100 partner institutions

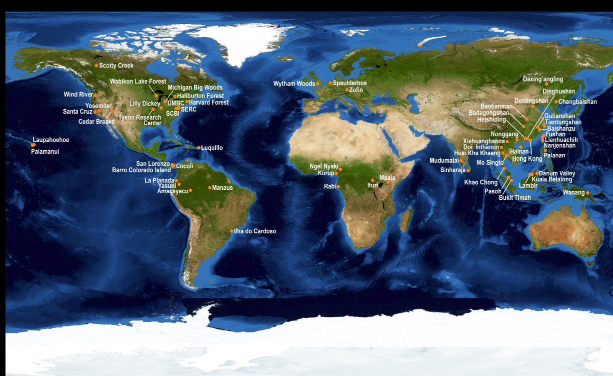


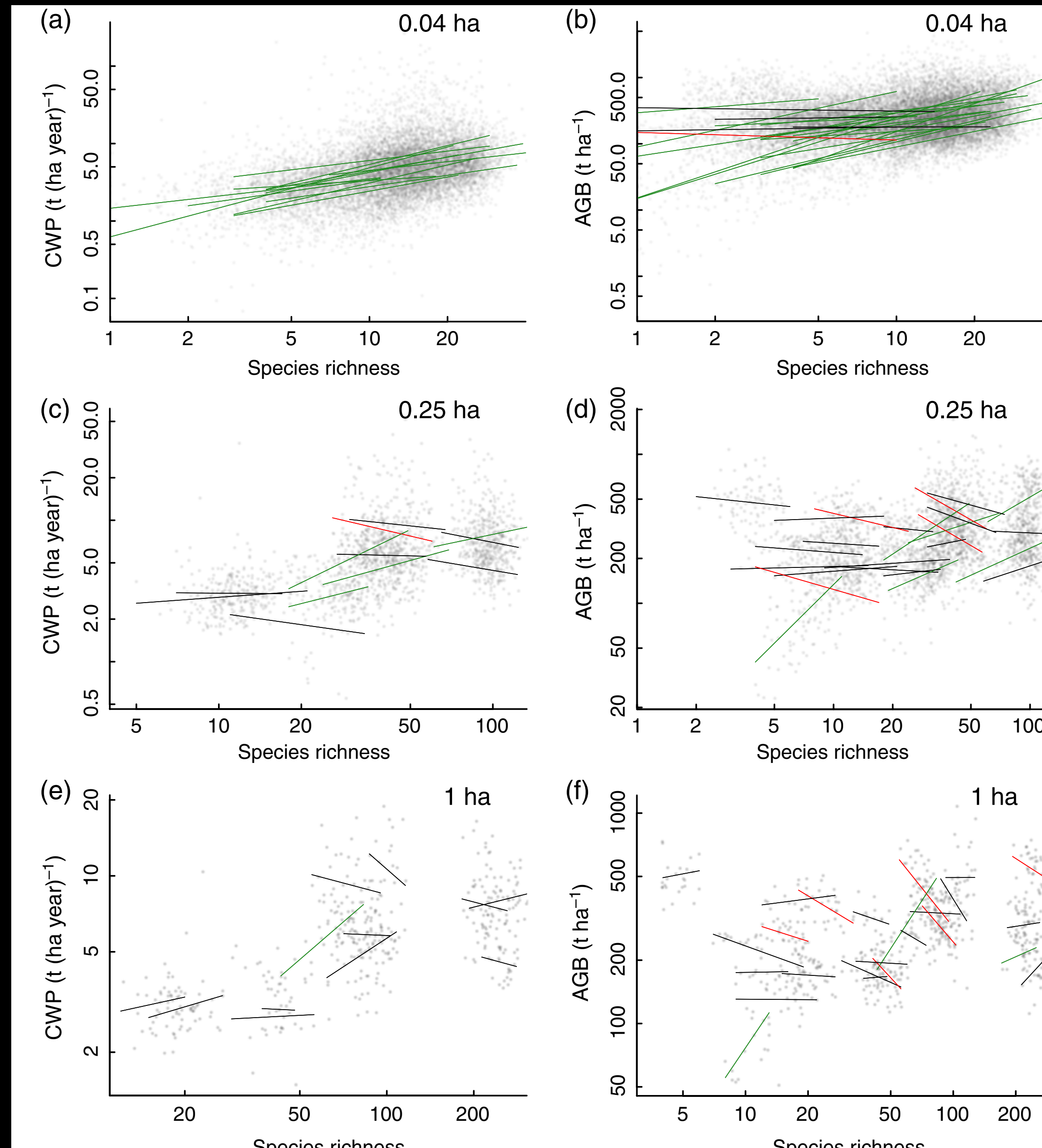
6.4 million living trees, 10,000 species, 901 forest years

Courtesy of Lauren Krizel

At small spatial grains (0.04 ha) species richness was correlated with productivity

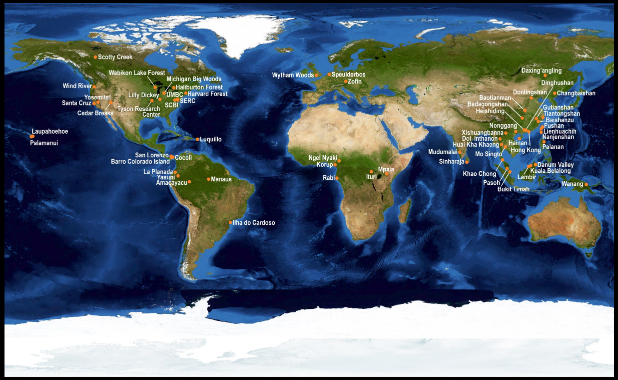
At larger spatial grains (0.25 ha, 1 ha), results were mixed, with negative relationships becoming more common.

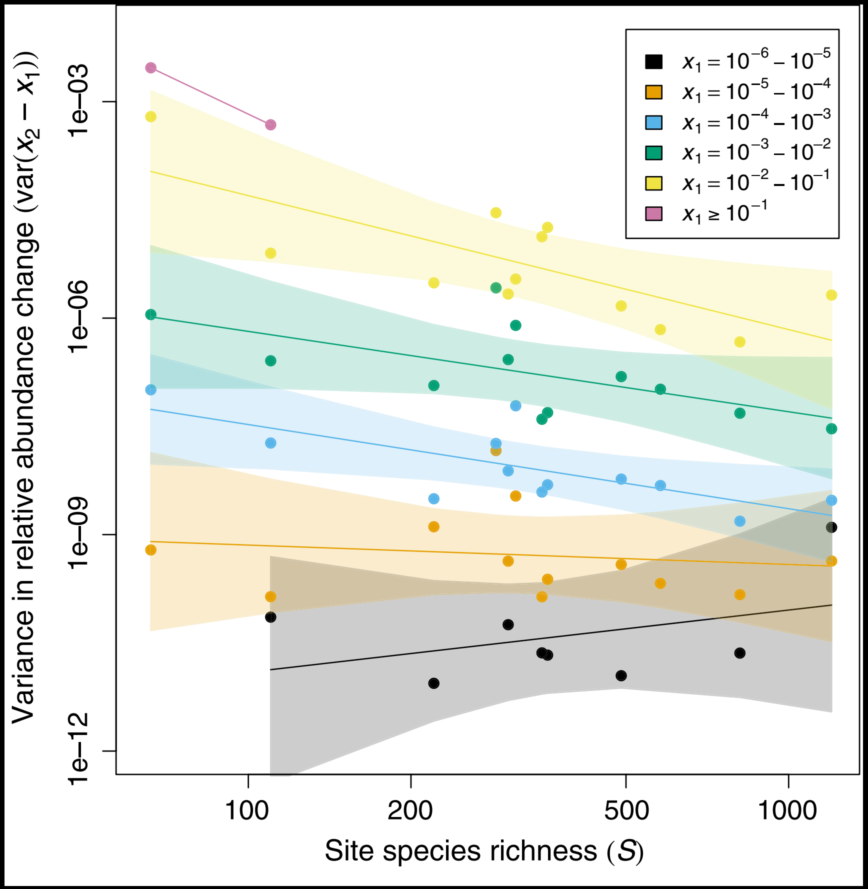




Chisholm et al 2013

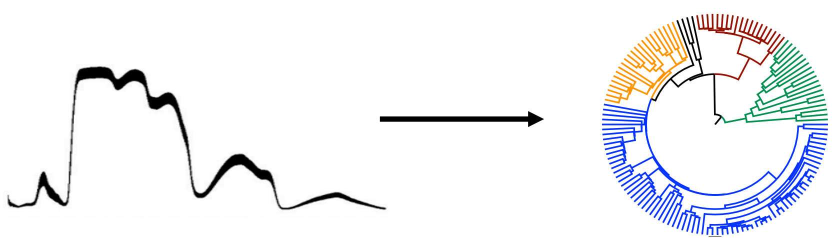
Abundance fluctuations were smaller at species-rich sites, consistent with the idea that stable environmental conditions promote higher diversity





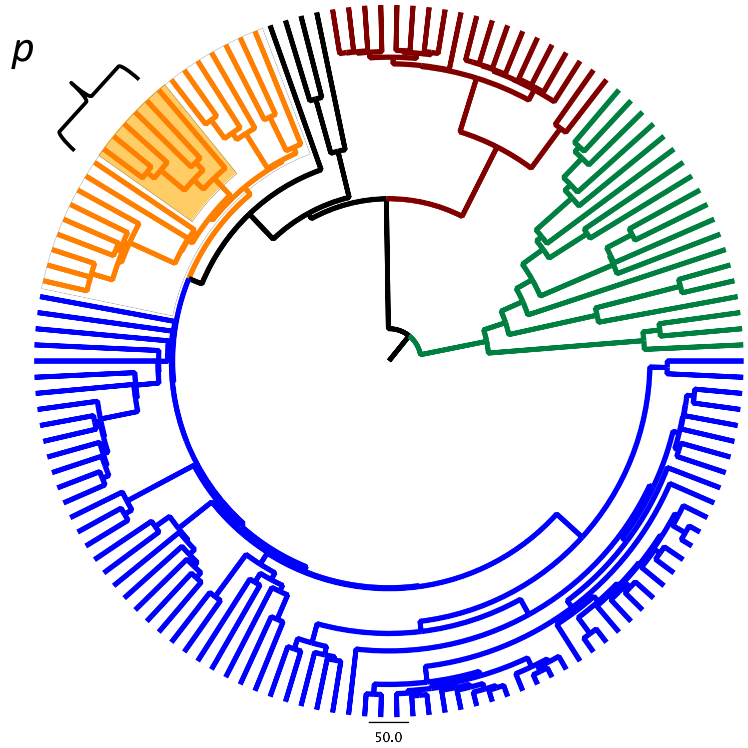
NIMBioS Working Group:

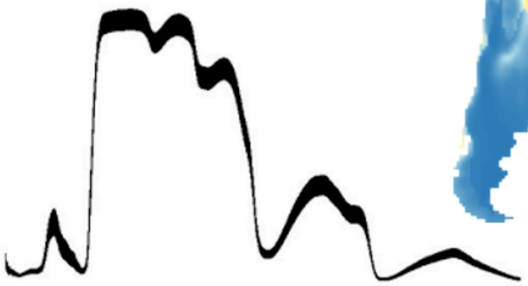
Remotely Sensing Biodiversity

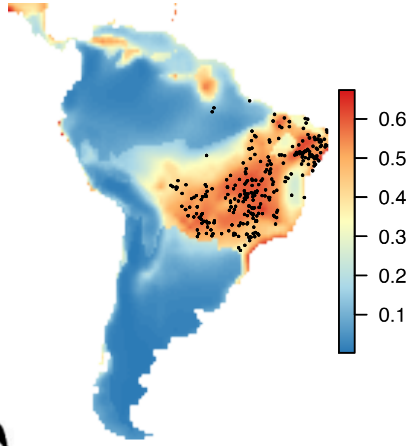


Prospects for global biodiversity detection

Constrain RS data using species distribution models



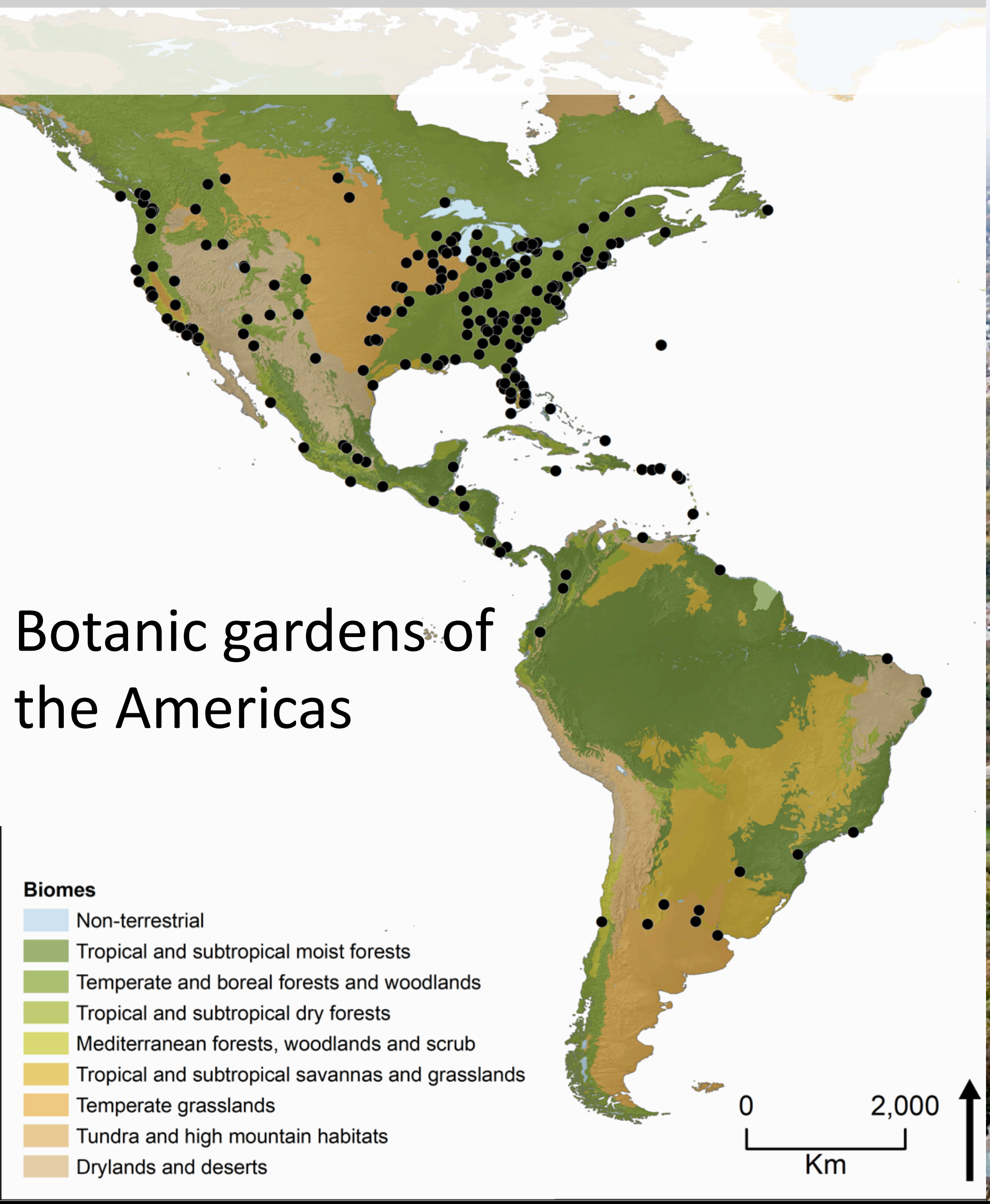




Place an unknown leaf spectrum within the plant tree of life and derive the probability that it falls within a given clade

NIMBioS workig group on *Remote Sensing of Biodiversity*

Generate canopy spectral profiles for the plant tree of life…



IPBES Americas Regional Assessment

Global Botanical Gardens

- Maintain 16,976 of the 60,065 known tree species (4370 genera)

  --> **28%**

- And include 240 of the 267 total plant families with trees

  --> **90%**

GLOBAL TREE SEARCH

THREAT SEARCH

PLANT SEARCH

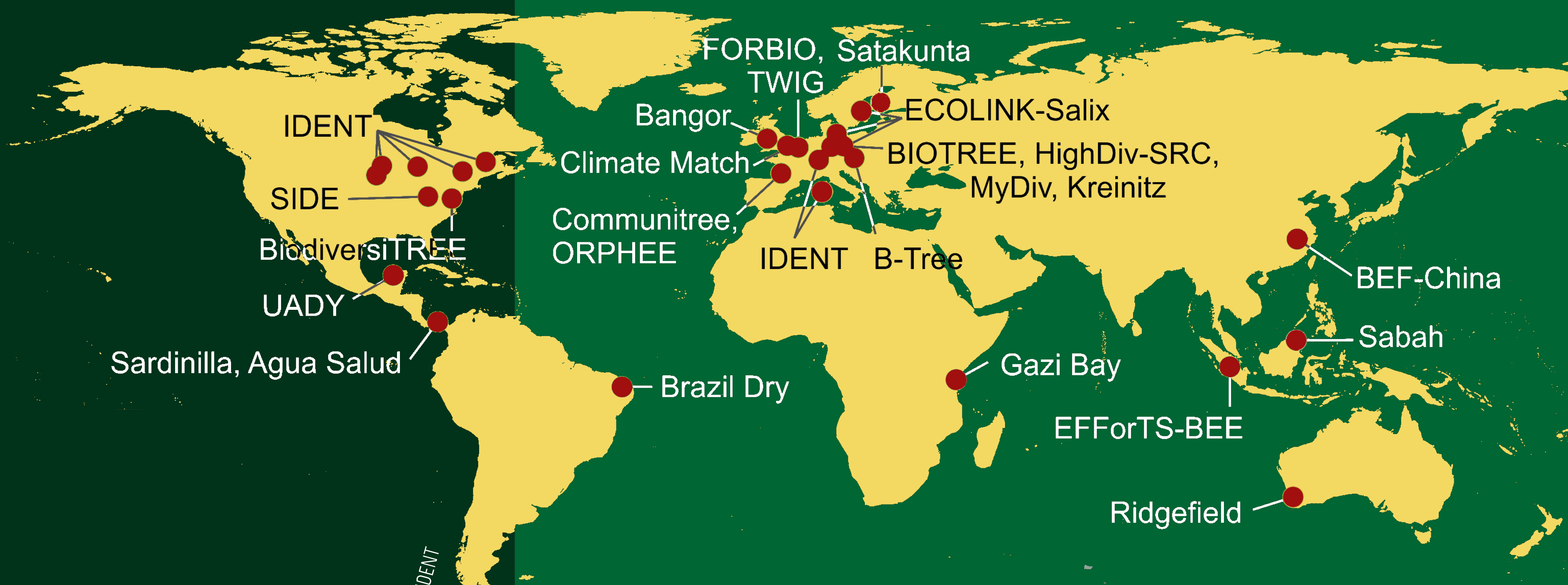
BGCI

Forest biodiversity and ecosystem functioning

TreeDivNet

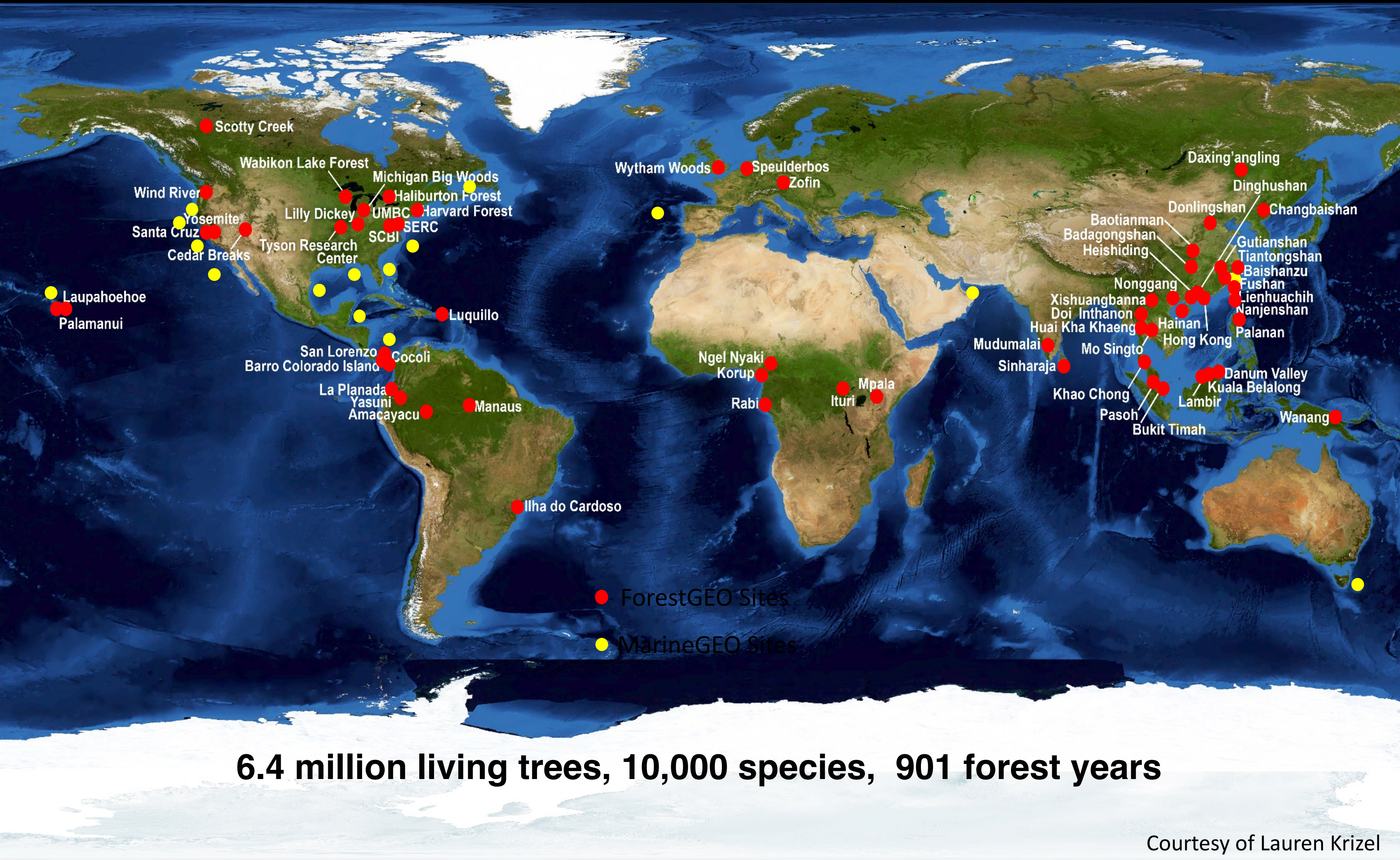
Tree Diversity Network • www.treedivnet.ugent.be

25 experiments • 45 sites • 6 continents



> 4,000 plots ~ 800 ha > 1,050,000 planted trees

67 sites, 26 countries, >100 partner institutions

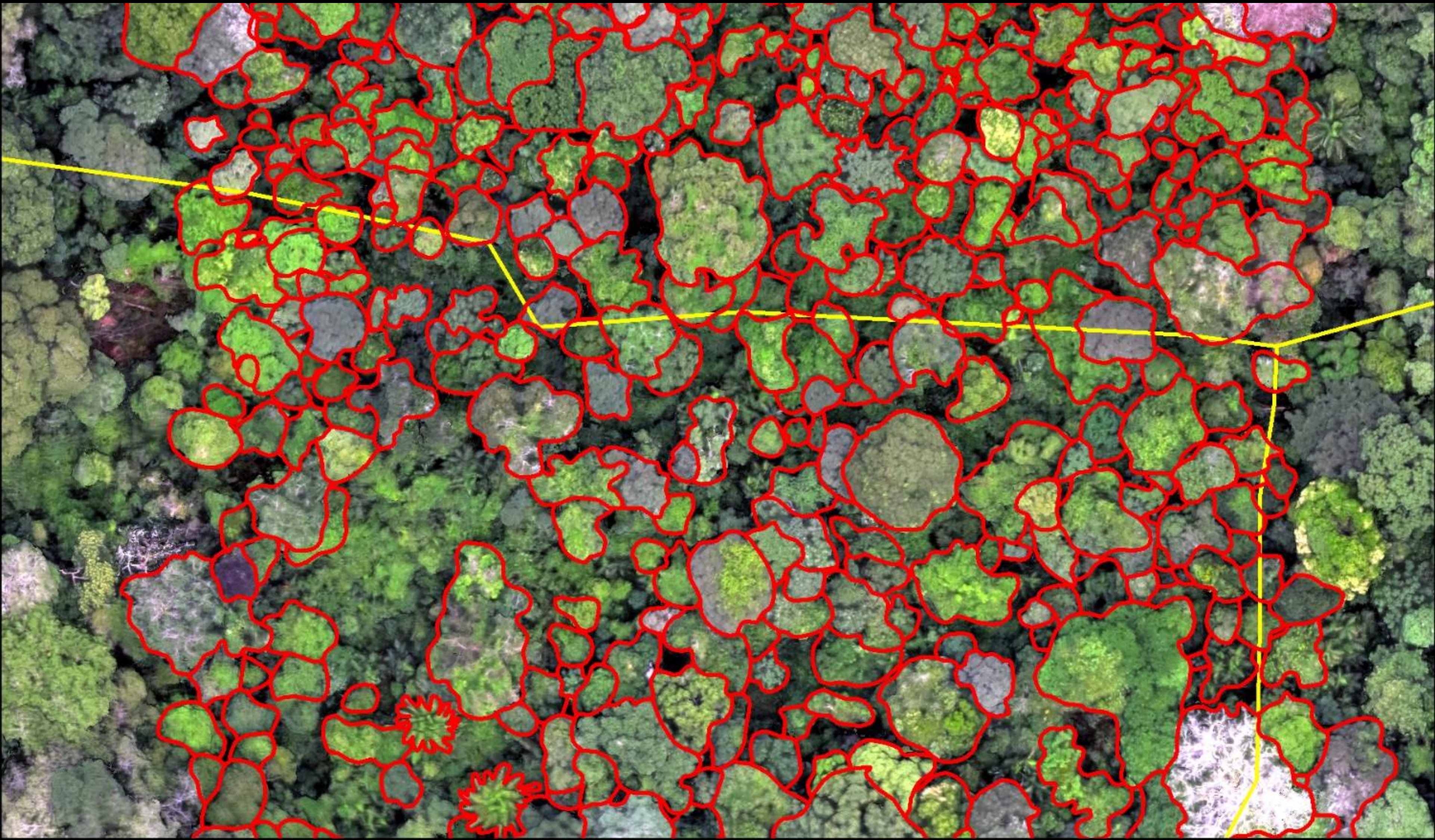


6.4 million living trees, 10,000 species, 901 forest years

Courtesy of Lauren Krizel

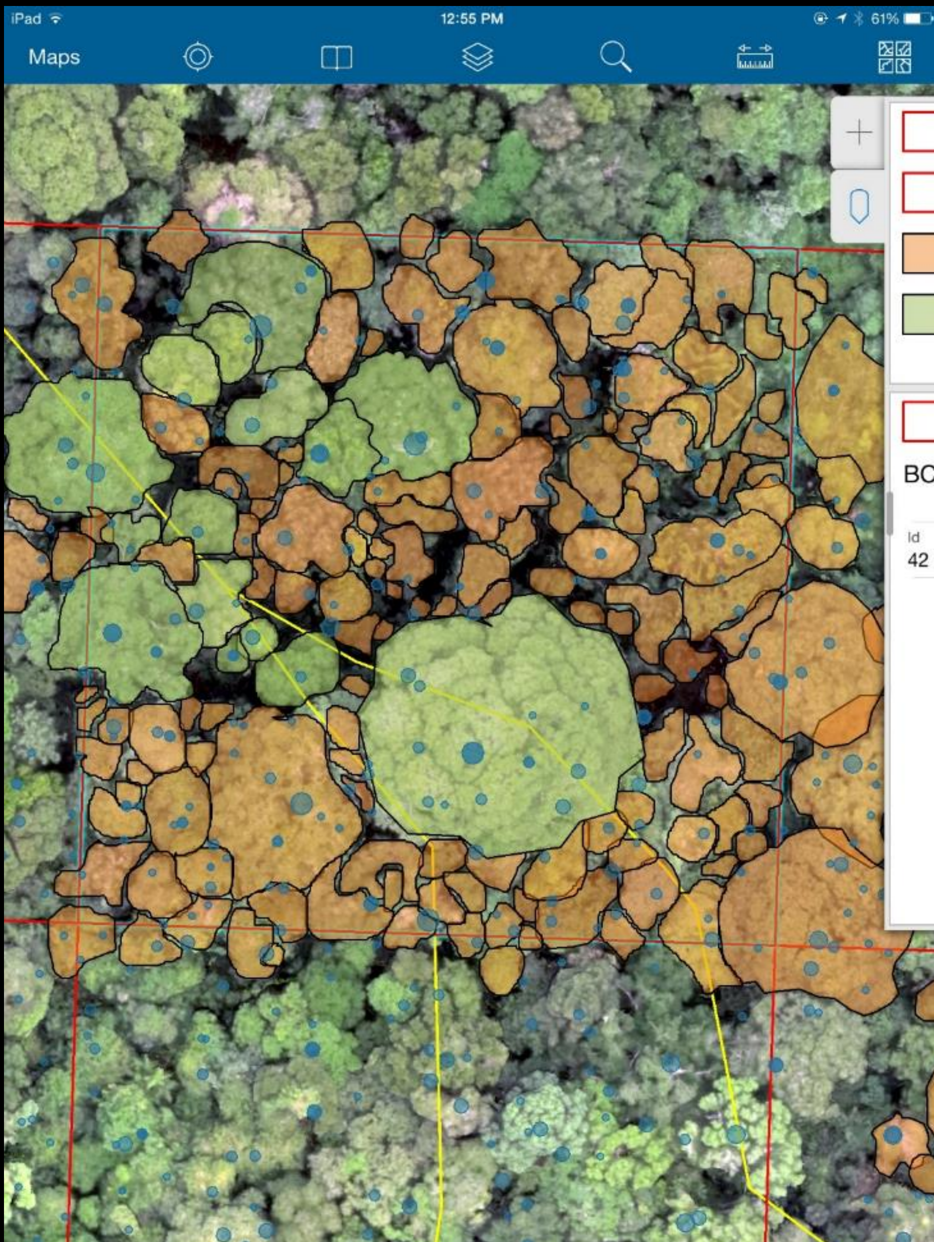
Barro Colorado Island 50 ha plot ortho-image mosaic generated from UAV-collected photos (every point seen from above)

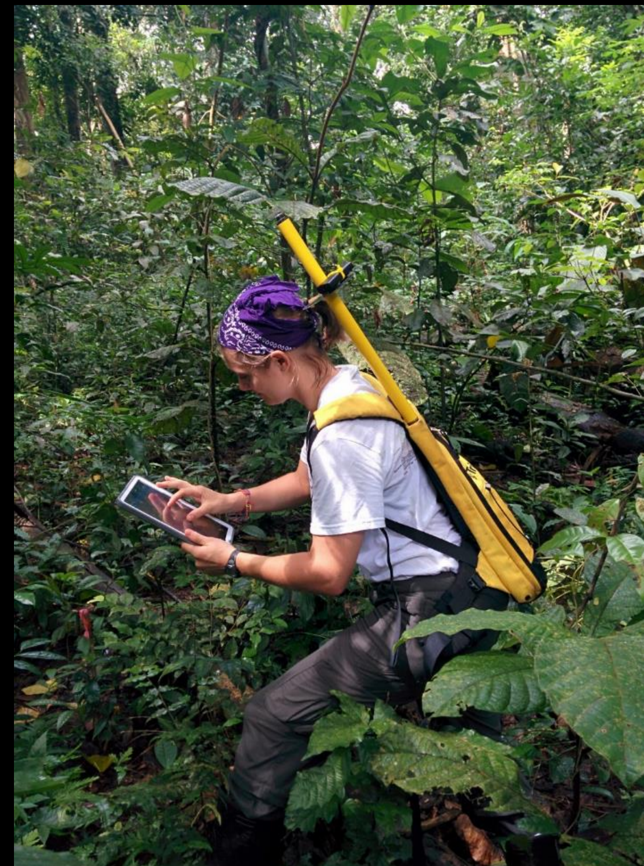
Digitization (manual) of all overstory crowns (>50 m^2) in the BCI 50 ha plot



Barro Colorado Island, Panama

Linking individual crowns to tagged tree stems in the field





Field work by Carrie Tribble, Pablo Ramos, Paulino Villareal, and Areli Benito

Thank you