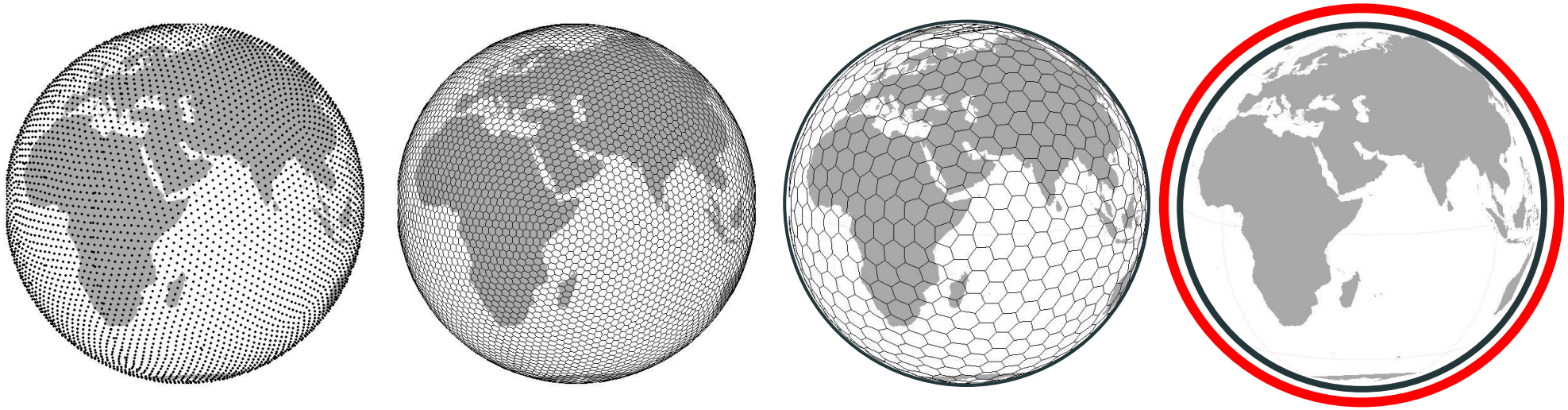
Evolution of global biodiversity

Melanie Tietje

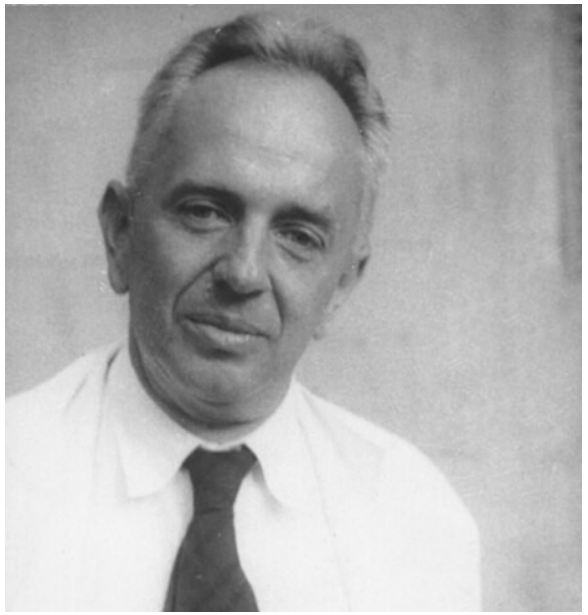


Some words about evolution

Nothing in Biology Makes Sense

Except in the Light of Evolution

THEODOSIUS DOBZHANSKY



Link to essay

„Seen in the light of evolution, biology is, perhaps intellectually the most satisfying and inspiring science. Without that light it becomes a pile of sundry facts – some of them interesting or curious but making no meaningful picture as a whole.“

- T. Dobzhansky (1973)

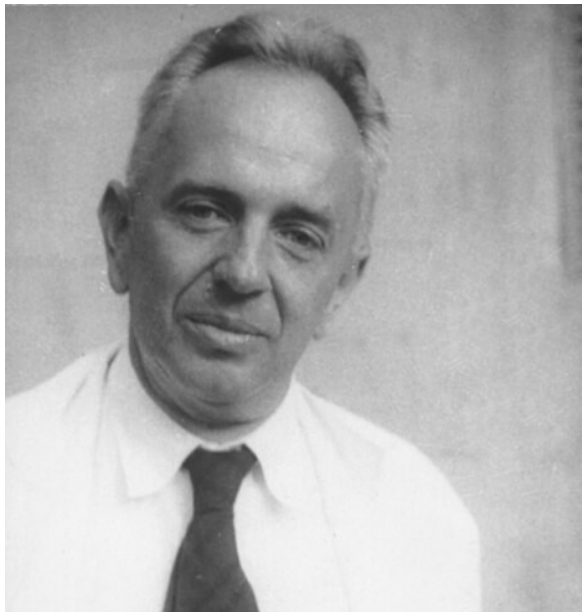
Some words about evolution

Nothing in Biology Makes Sense

Except in the Light of Evolution

THEODOSIUS DOBZHANSKY

Link to essay



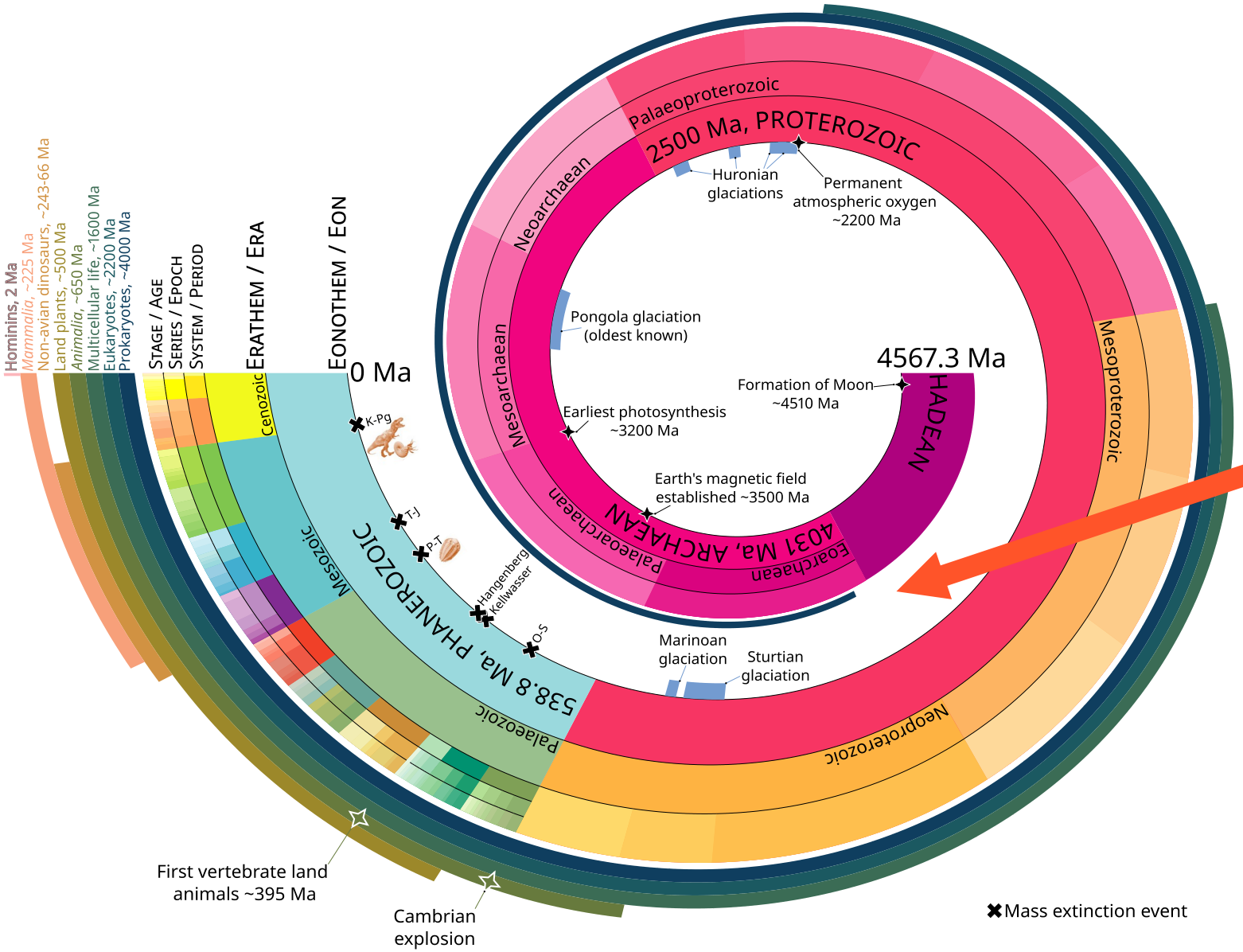
What is evolution?

"The process by which new species or populations of living things develop from preexisting forms through successive generations" (Websters dictionary)

Origins of biodiversity

Biodiversity through geological time

Biodiversity through geological time



When did it all begin?

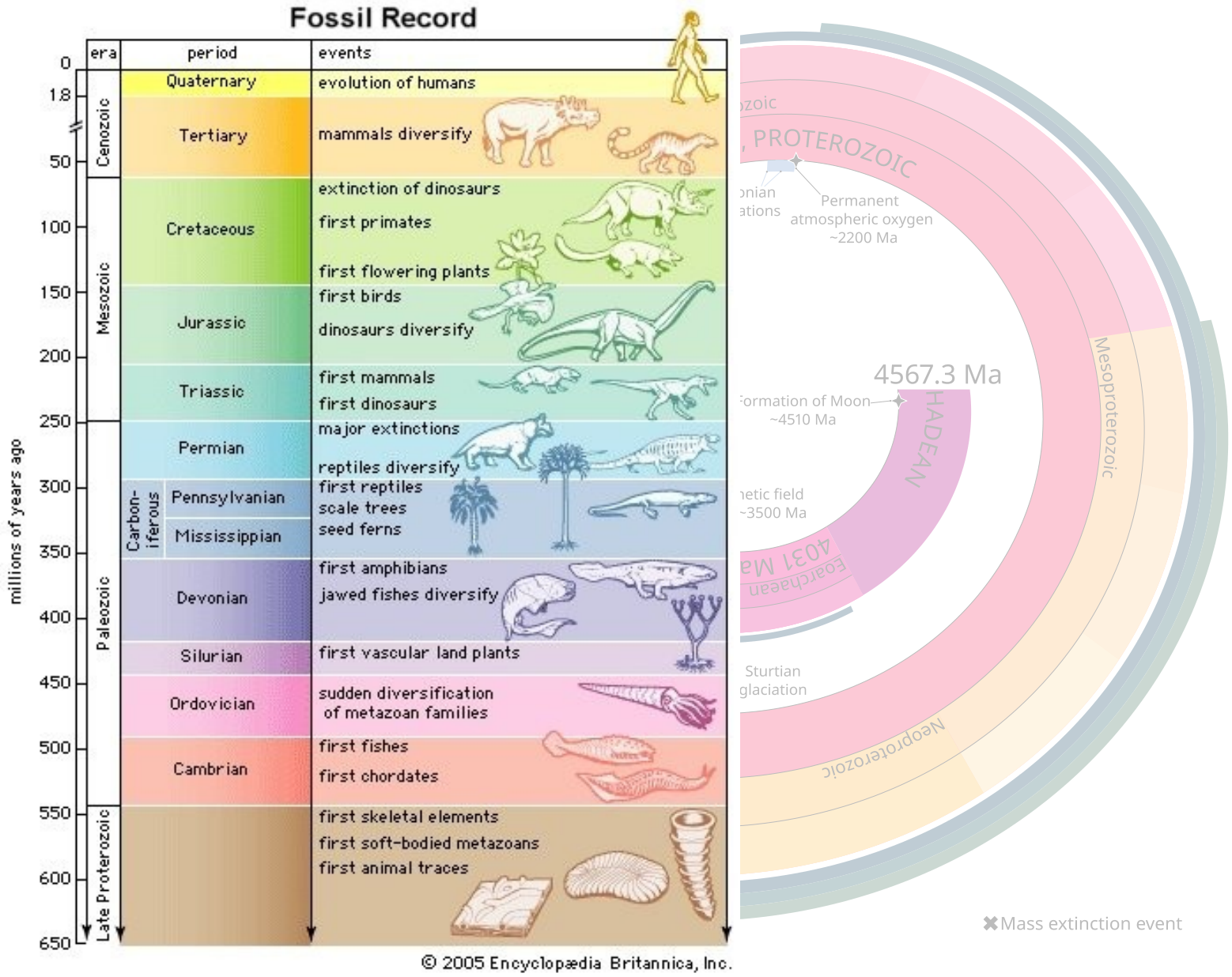
Here!

Fossilized stromatolite in Western Australia, about 3.4 billion years old

Modern stromatolites

Paul Harrison CC BY-SA 3.0

Biodiversity through geological time



When did it all begin?

How species disappear

Extinctions and mass extinctions

Extinction

What is extinction?

= the termination of a species;
i.e., the dying out of all individuals that belong to a species

How can we define and compare extinctions?

- **Spatial:**
  - Global extinctions vs. local- to regional-scale extirpations
- **Temporal:**
  - Extinctions from the fossil record vs. recent historical extinctions
  - Length of the time interval to calculate extinction rates (past vs. present)
- **Other types:**
  - species can become ecologically or functionally extinct before all individuals are dead
    - → “dead clade walking“ or extinction debt: Not extinct yet, but will not recover
    - Example: abundances too low to form a viable population

The passenger pigeon (*Ectopistes migratorius*) - the fast track to extinction

RESEARCH ARTICLE | BIOLOGICAL SCIENCES

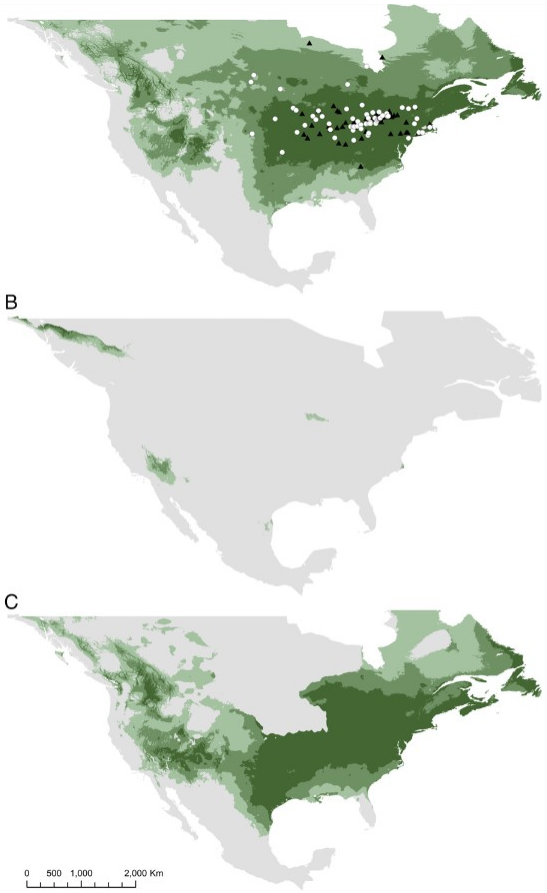
Drastic population fluctuations explain the rapid extinction of the passenger pigeon

Chih-Ming Hung, Pei-Jen L. Shaner, Robert M. Zink, +3, and Shou-Hsien Li Authors Info & Affiliations

Edited by Wen-Hsiung Li, University of Chicago, Chicago, IL, and approved May 27, 2014 (received for review January 24, 2014)

June 16, 2014 | 111 (29) 10636-10641 | https://doi.org/10.1073/pnas.1401526111

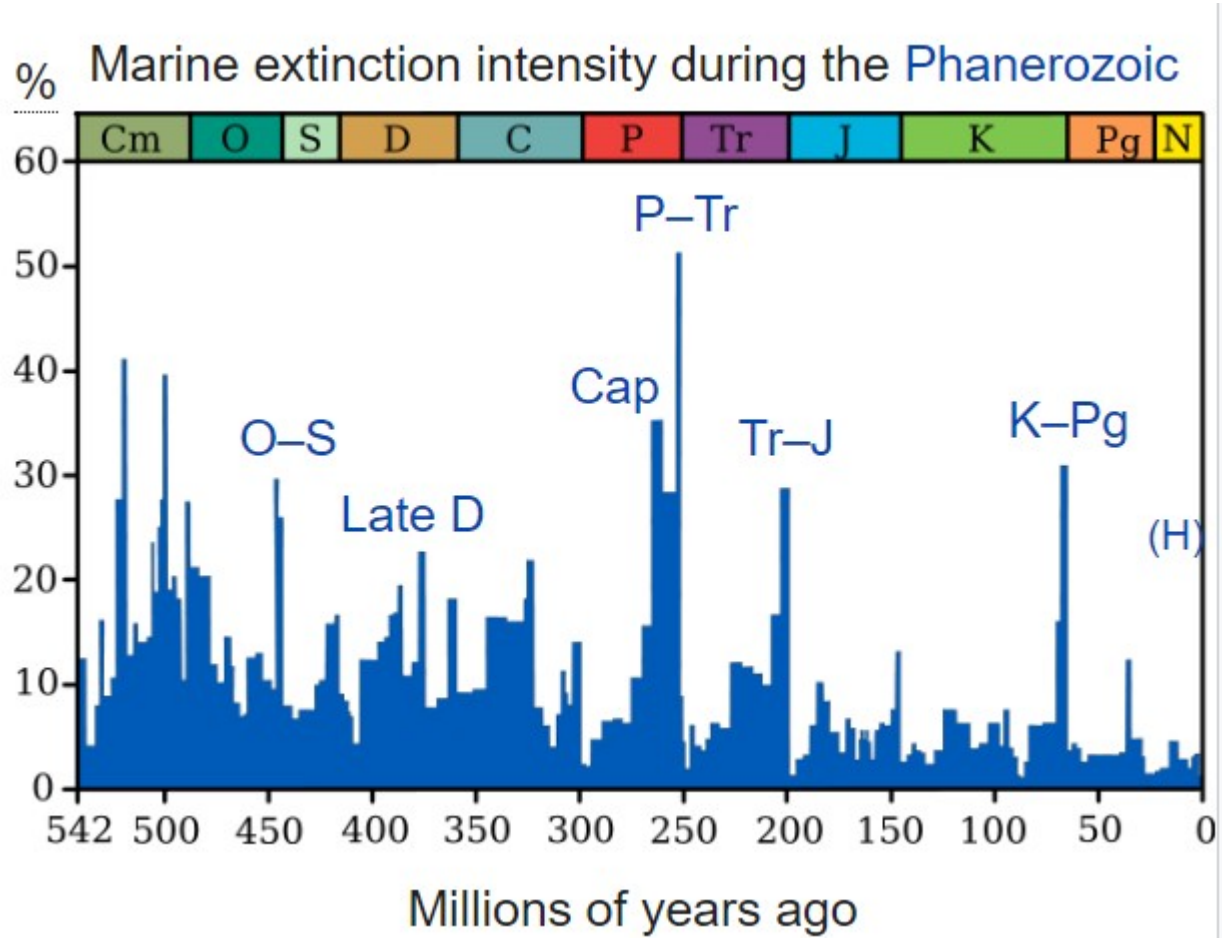
PDF/EPUB



- The most abundant bird in North America in the early 1800s (3-5 billion individuals)
- Millions of individuals were hunted every year by the settlers for meat
- The species was eradicated within a human life span (approx. 70 years)
- Birds bred in massive colonies of billions of individuals, making them vulnerable to density-dependent regulatory factors (e.g., infectious diseases, overexploitation)

MARTHA
Last of her species, died 1914, age 29, in the Cincinnati Zoological Garden

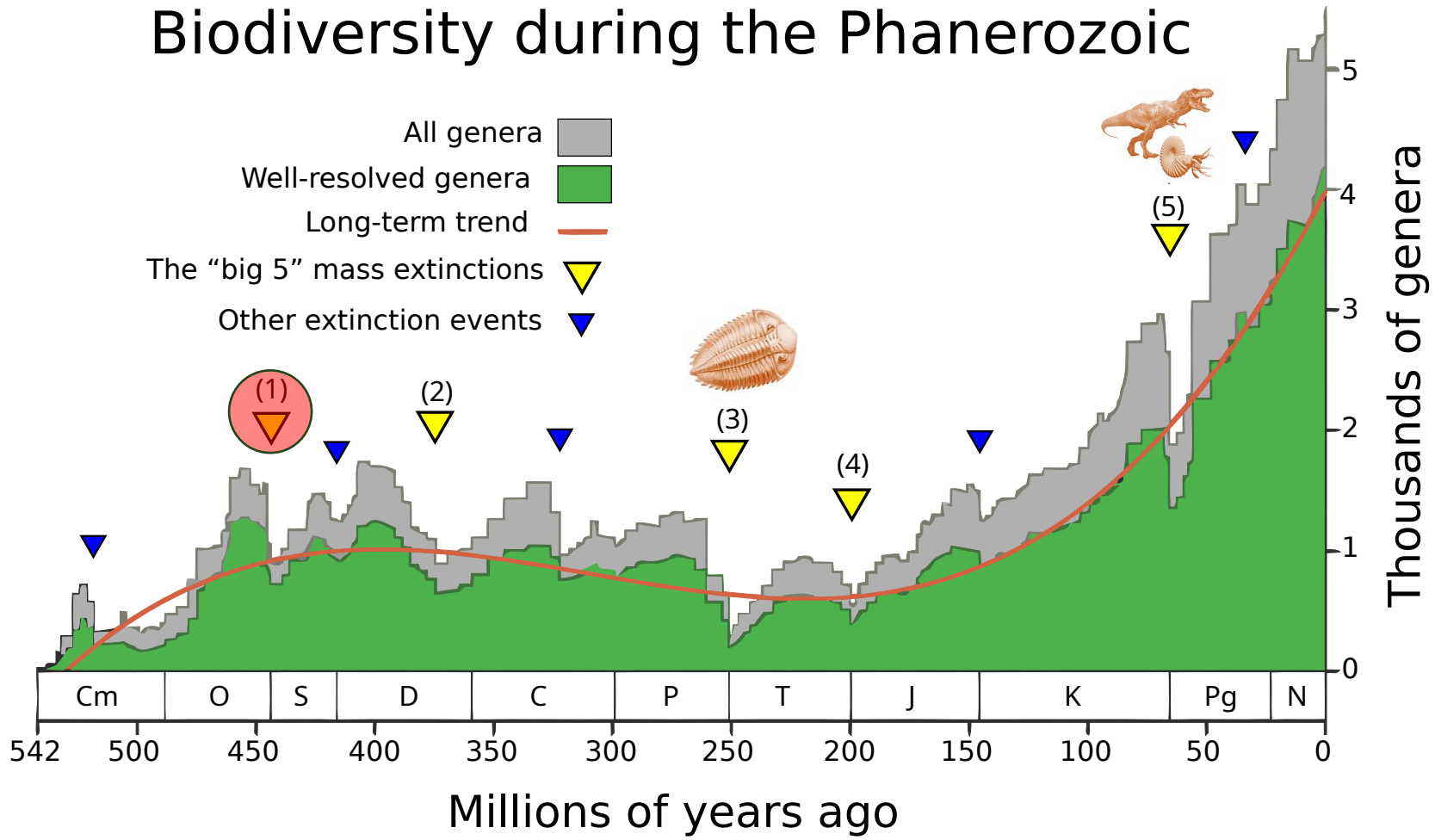
Mass Extinctions



- The usual background rate is ca **0.1-1 per million species-year** (for fossilizing organisms)
- mass extinctions are much more extinction than usual
- when both marine and terrestrial taxa considered, then it's roughly 30-80% of extinct genera per big event

→ Mass extinction events mark geologic period changes

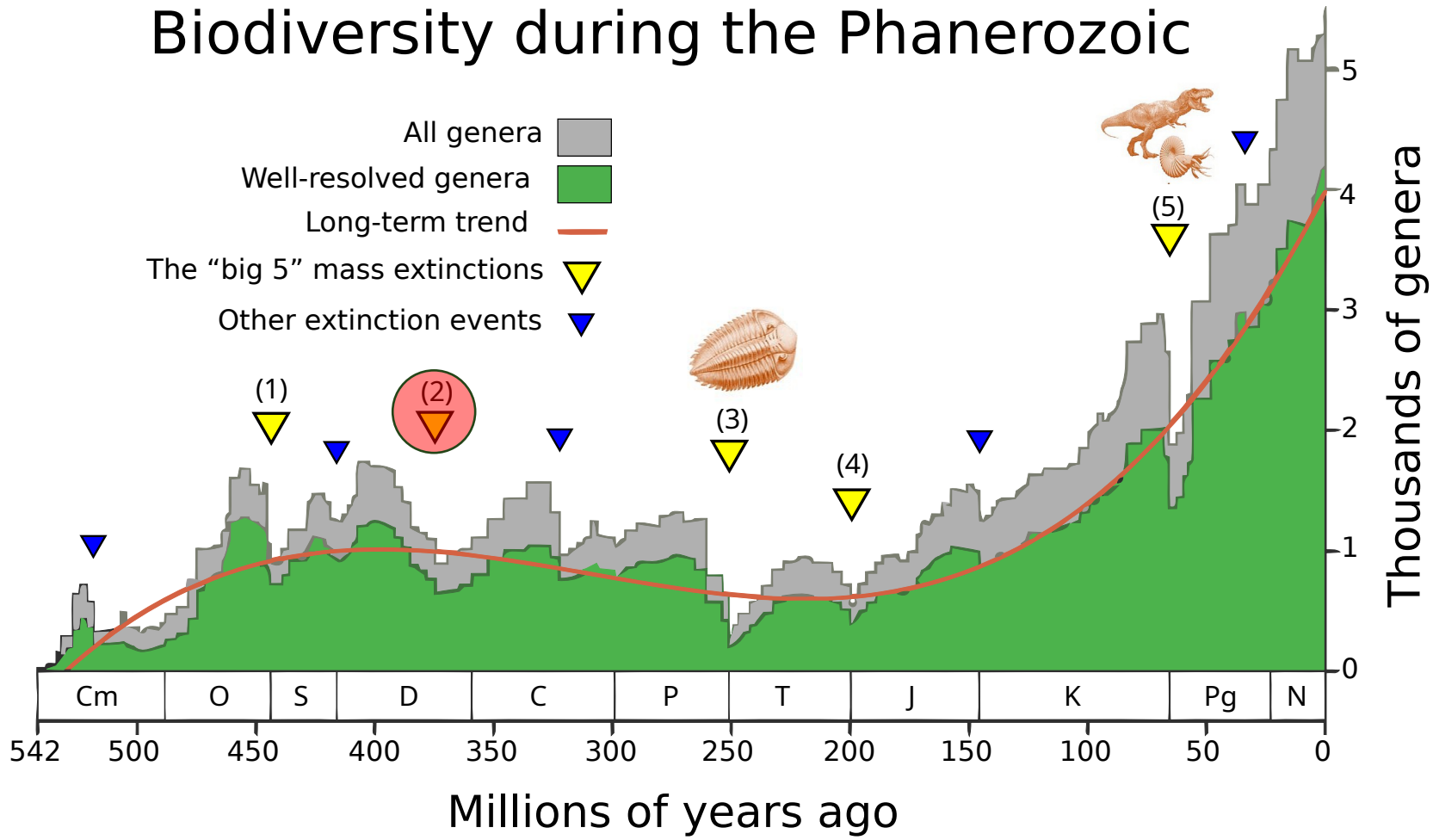
“The Big 5” Mass Extinctions: 1/5



Ordovician – Silurian extinction

Time: ~443 Mya
Impact: 85% of marine species extinct
Cause: Rapid cooling, extensive glaciation

“The Big 5” Mass Extinctions: 2/5



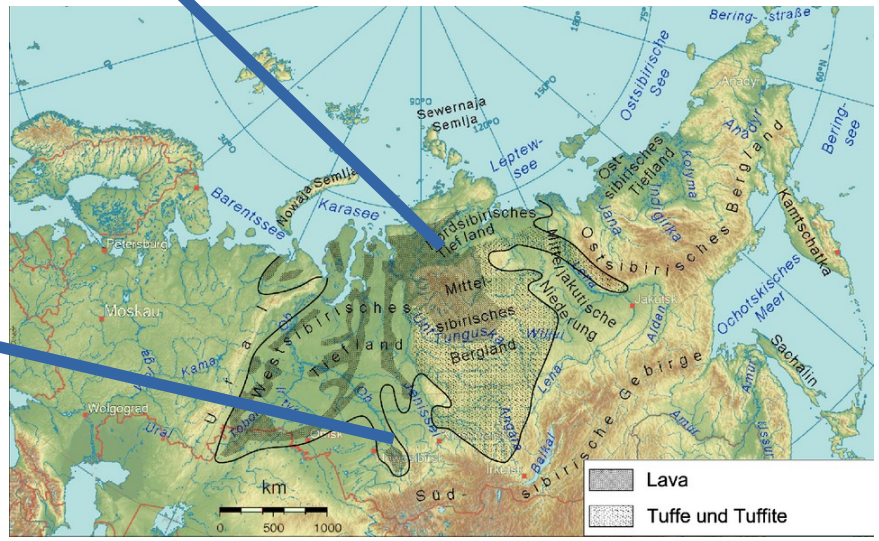
End-Devonian extinction

Time: 365 Mya
Impact: 40% of marine species extinct
Cause: Debated, maybe weathering (new land plants cause nutrient influx) and resulting anoxia

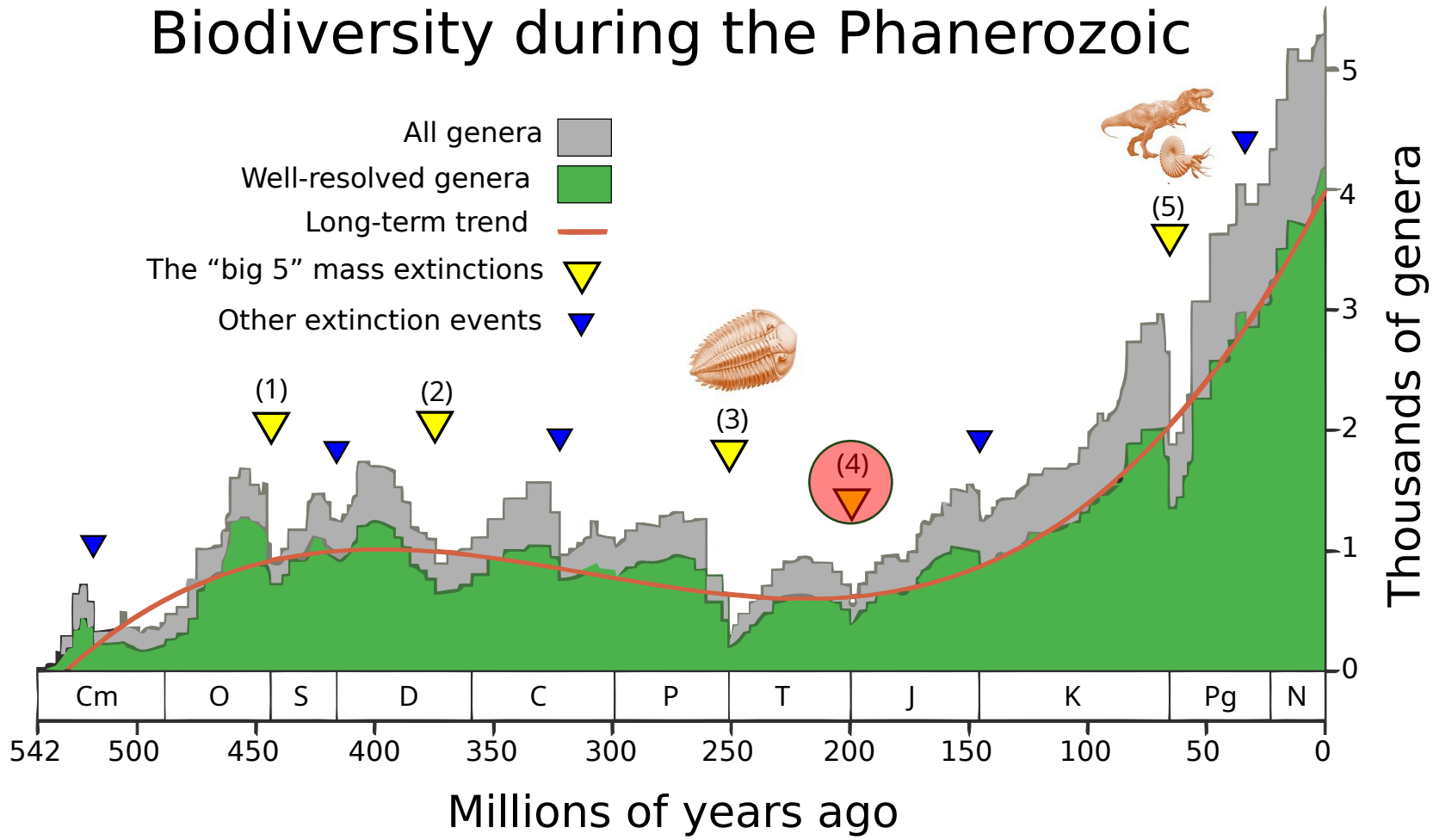
Biodiversity during the Phanerozoic

Permian-Triassic extinction

Time: 250 Mya
Impact: 81% of marine & 70% terrestrial species extinct
Cause: Massive volcanism (Siberian Traps), methane release, anoxic and acidic oceans



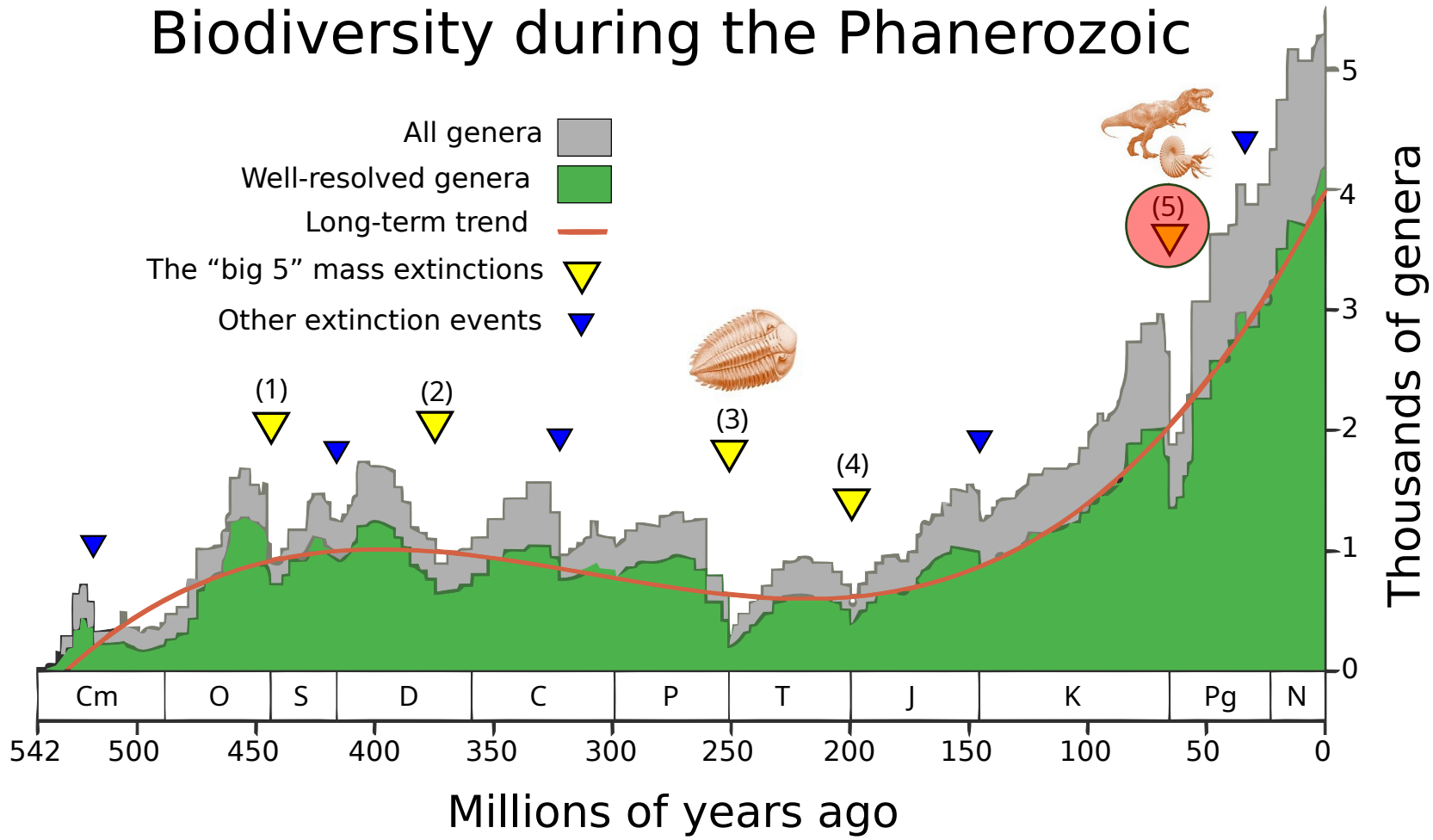
“The Big 5” Mass Extinctions: 4/5



End-Triassic extinction

Time: 200 Mya
Impact: 60%(?) of species extinct. Loss of large-bodied amphibianser, plants and marine species
Cause: vulcanism & CO2

“The Big 5” Mass Extinctions: 5/5

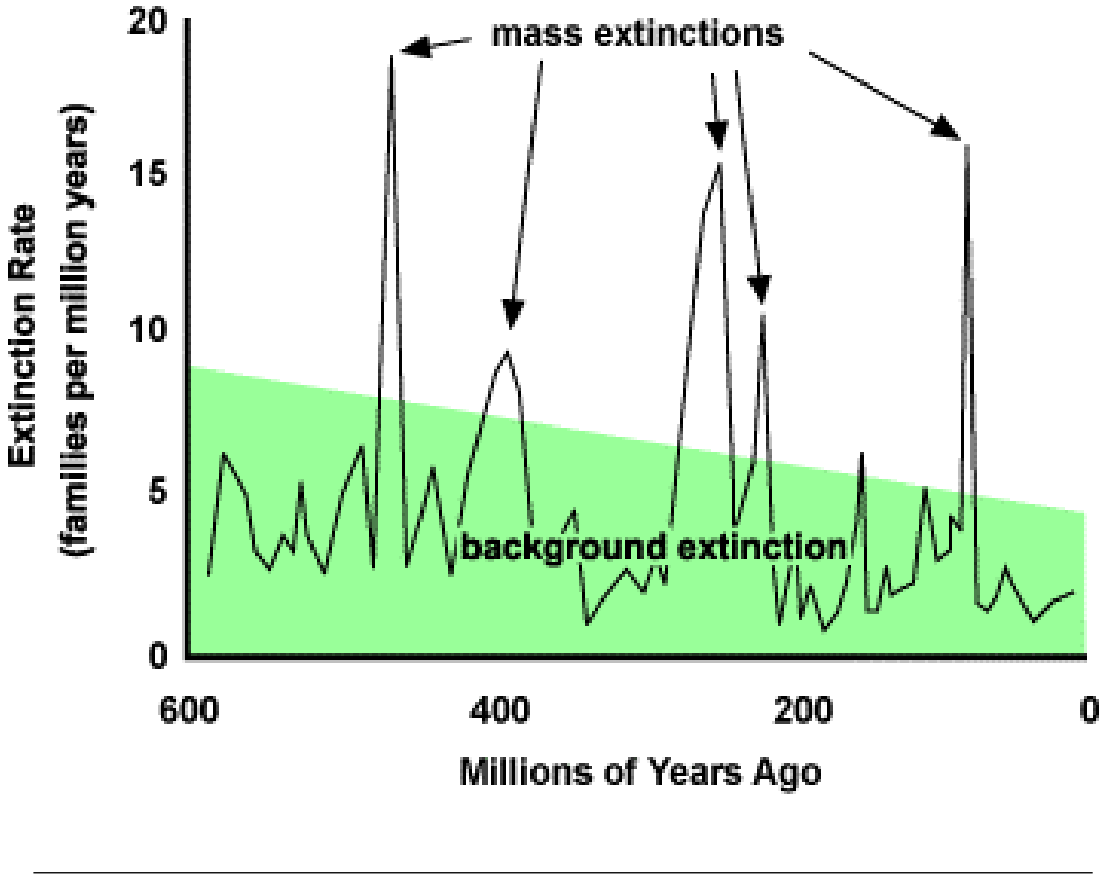


Cretaceous-Paleogene extinction (K-T event)

Time: 66 Mya
Impact: 75% of species extinction. Best known for extinction of non-avian dinosaurs
Cause: Asteroid impact (southern Mexico)

How does normal extinction look like: background extinction

- How do we know it's not just business-as-usual?

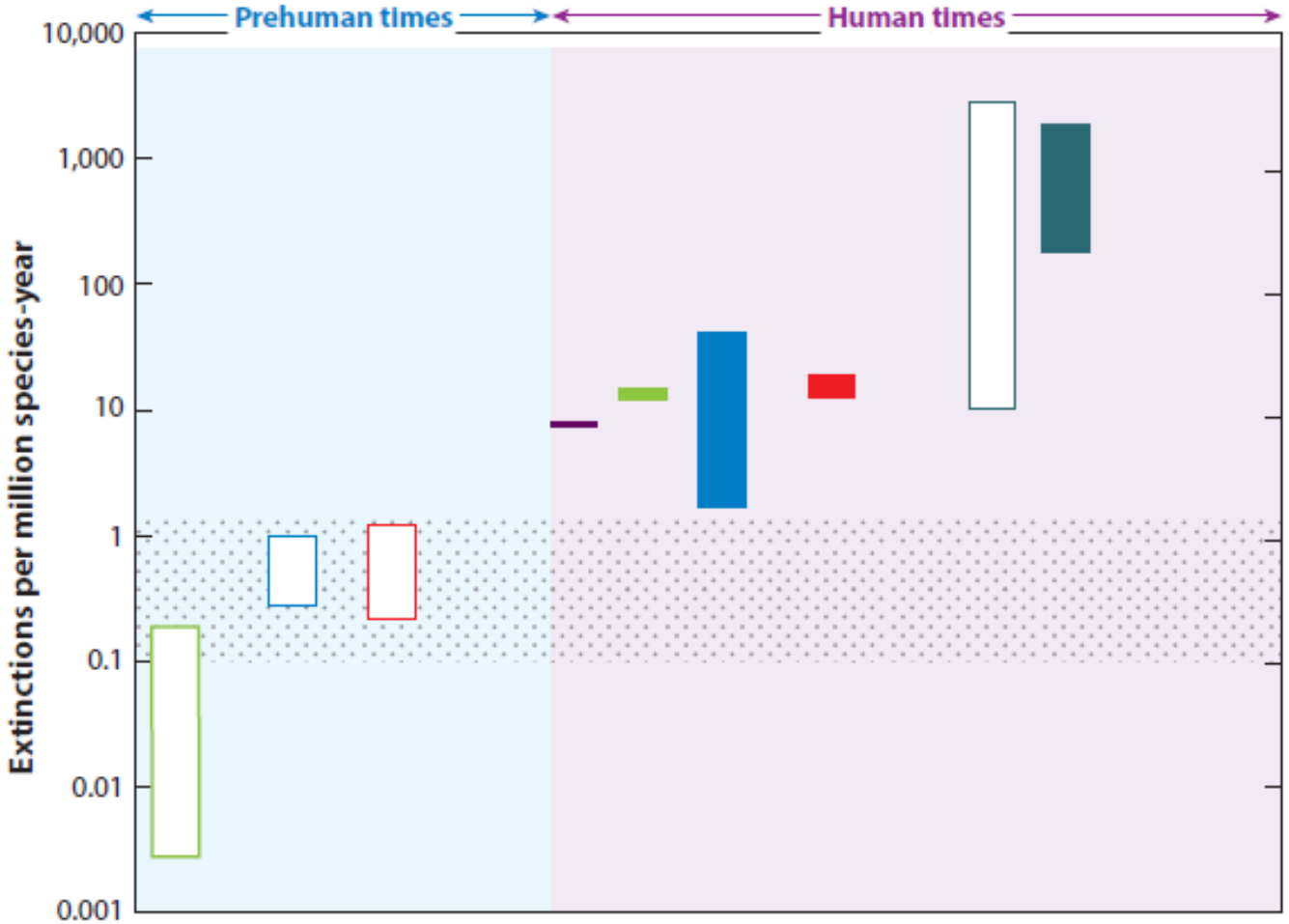


The background rate of extinction = the average extinction rate due to non-human causes over geological history (approx. 1 E/MSY on average)

e.g., Mammal background rate = 2 mammal extinctions per 10,000 species per 100 years (that is, 2 E/MSY) (Ceballos, Ehrlich et al. 2015, *SciAdv*)

‘Sixth Mass Extinction’ – How do we know?

- How do we know it’s not just business-as-usual?



Overall background extinction rate (Purvis et al. 2019)
Background for plants (De Vos et al. 2015)
Background for invertebrates (Rounsevell et al. 2020)
Background for mammals (Proença & Pereira 2013)
Maximum for Pleistocene megafaunal diversity crash (Barnosky et al. 2011)
Seed plants 1900–2018 (Humphreys et al. 2019)
Invertebrates last 50–300 years (Rounsevell et al. 2020)
Terrestrial vertebrates 1500–2019 (Rounsevell et al. 2020)
All current species (estimate) (Rounsevell et al. 2020)
All current described species (Rounsevell et al. 2020)

Trends in
Ecology & Evolution

Opinion

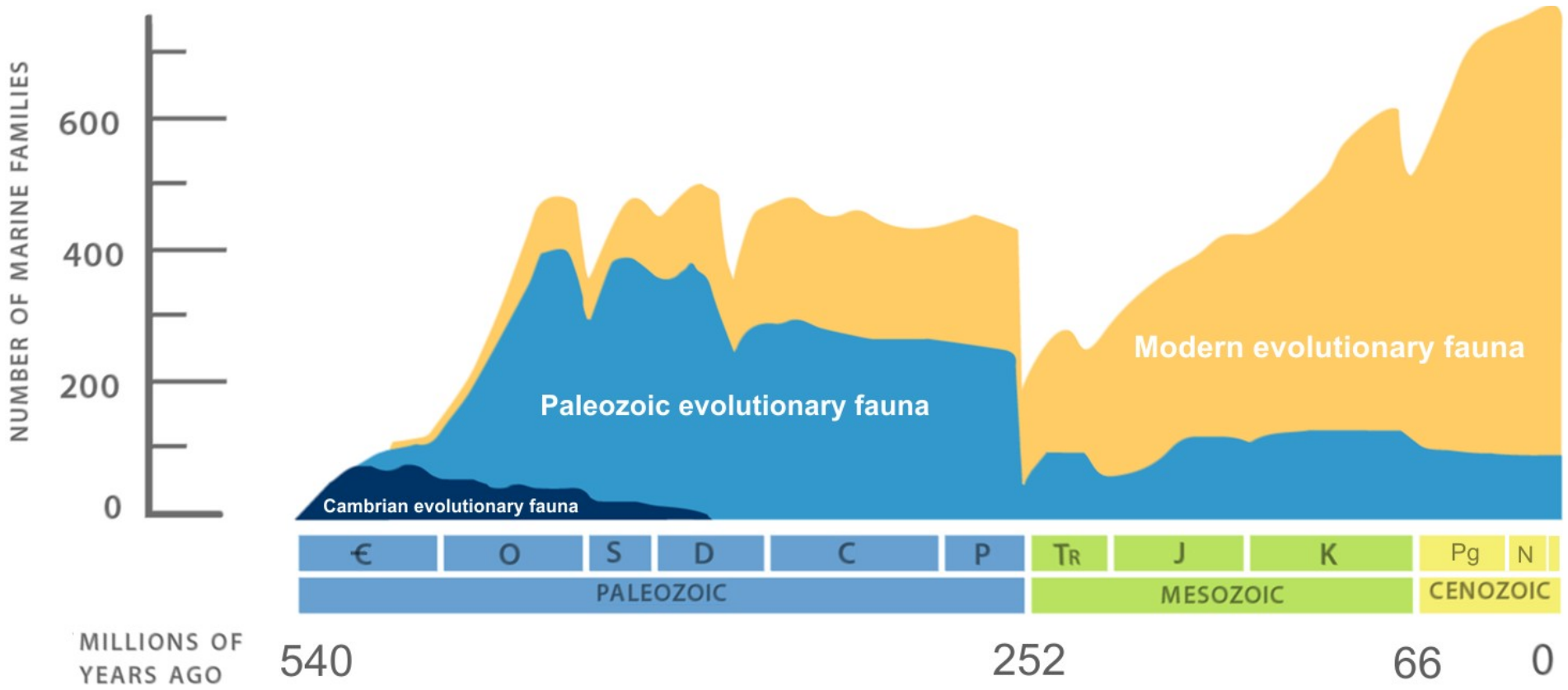
Questioning the sixth mass extinction

John J. Wiens [1,*] and Kristen E. Saban [1,2]

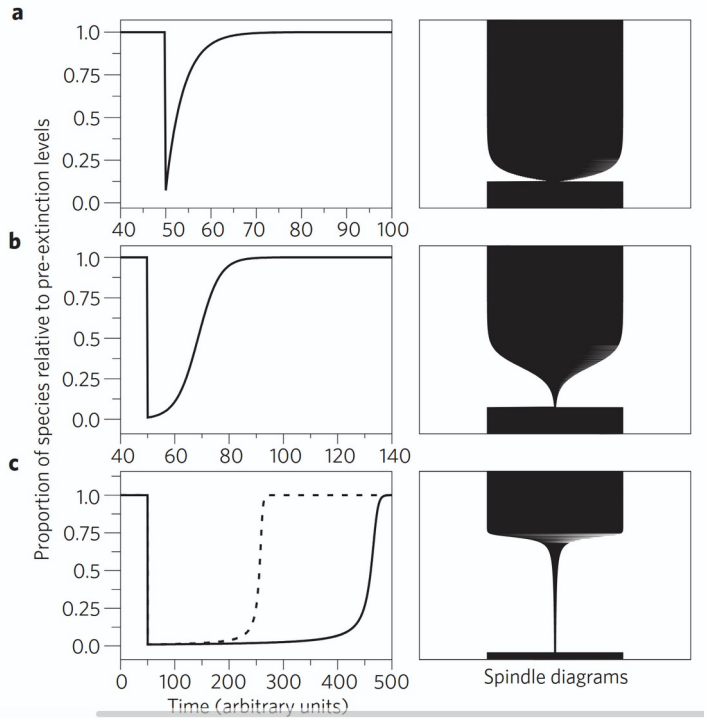
https://doi.org/10.1016/j.tree.2025.01.002

Díaz & Malhi (2022) *Annu. Rev. Environ. Res*

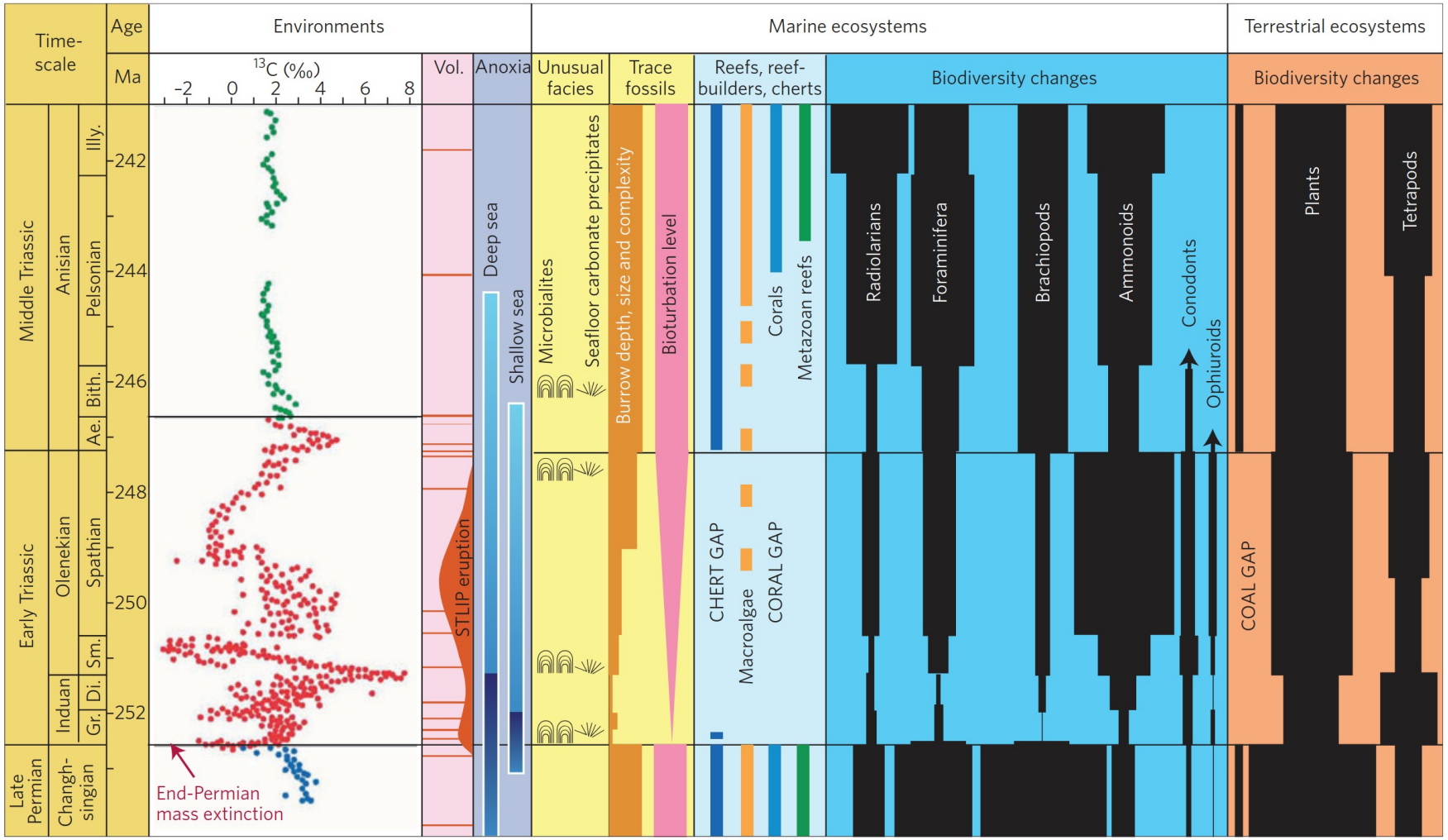
After a mass extinction event: biodiversity increases again



How does biodiversity recover from extinction? – Evolutionary perspective



Chen & Benton 2012, *Nature Geoscience*



Chen & Benton 2012, *Nature Geoscience*

Lineage through time (LTT) - plots

How new species emerge

Speciation

Speciation

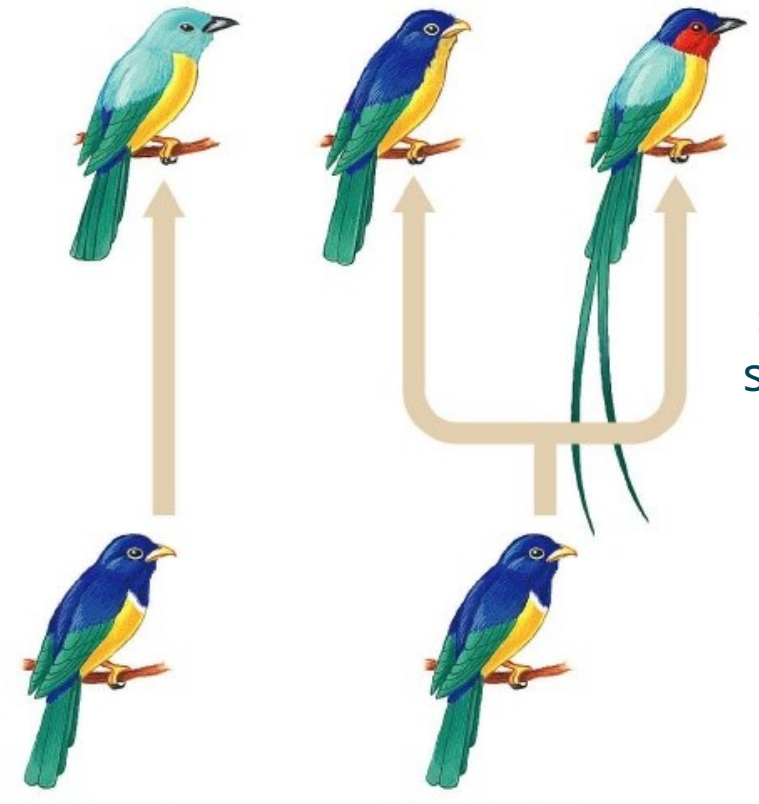
What is speciation?

= the process by which new biological species arise

= the splitting of lineages (cladogenesis)

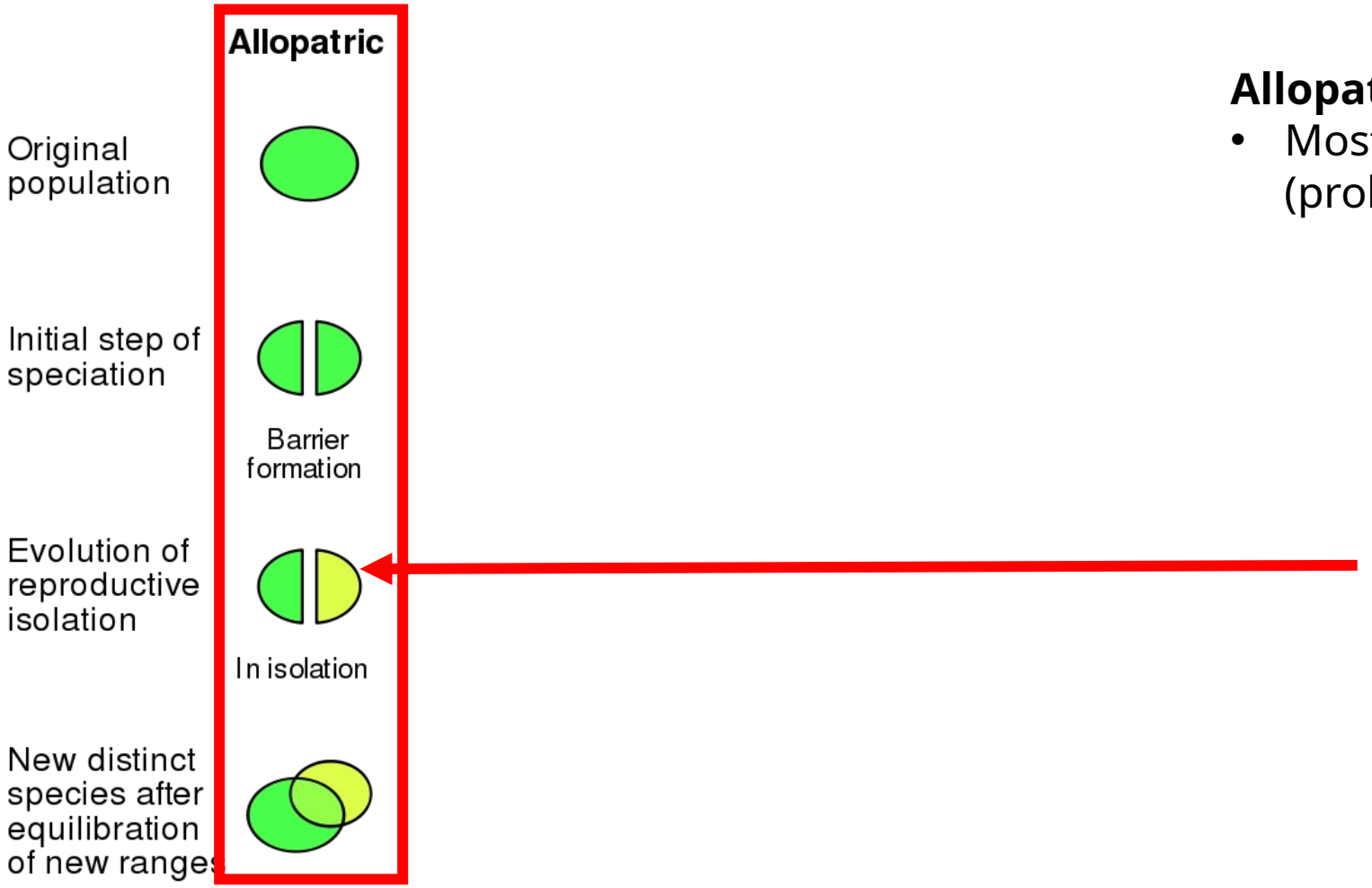
Anagenesis **Cladogenesis**

non-branching process that transforms one ancestral species into a single descendant



splitting of an ancestral species into two or more daughter species

Modes of speciation



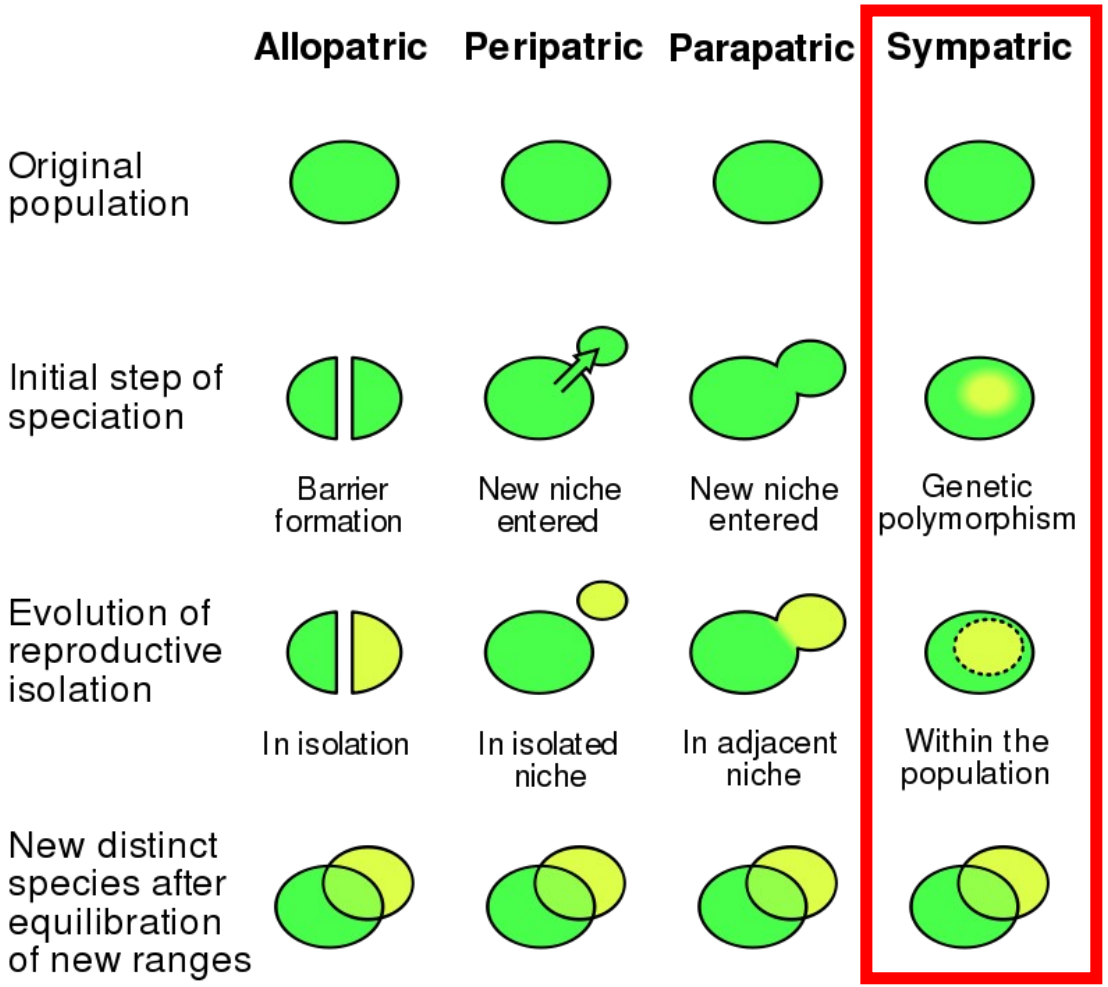
Allopatric speciation:

- Most common speciation mode (probably)

This can only work when **species change in time!**

This happens through **genetic drift** (mutations), or **adaptation to new environment**

Modes of speciation



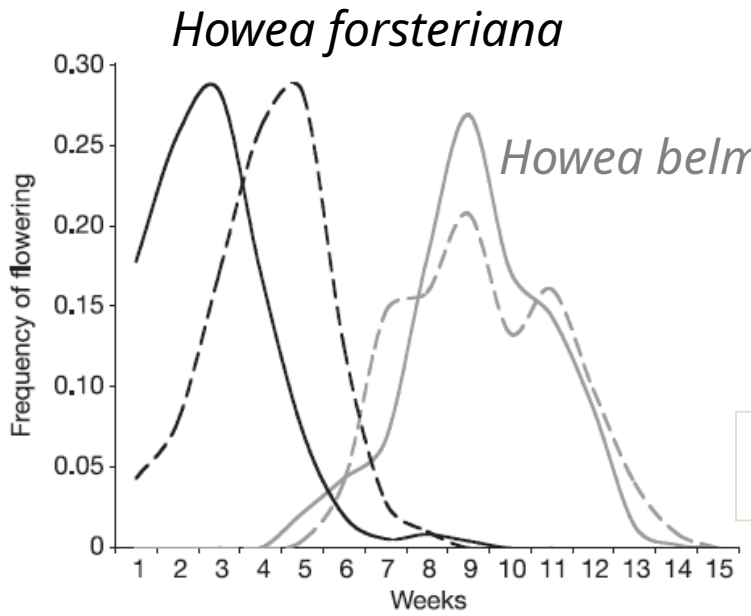
Sympatric speciation:

- Speciation within spatially overlapping populations
- Either due to *disruptive selection* (adaptation to two different environmental regimes) or *chromosomal changes* (e.g. polyploidy)
- Pretty common in plants

Example: Sympatric speciation of *Howea* palms

Sympatry: two palm species on Lord Howe Island
Sister relationship: phylogeny shows sister relationships and divergence after island formation
Reproductive isolation: different flowering time

Cause: Possibly disruptive selection (= adaptation to different soil types)



males (solid line) and female (dotted line)

Savolainen et al. 2006 *Nature*

Speciation rates - How do we know?

- Can be derived using the **number of species that are alive** and **time** (i.e., a dated phylogeny!)
- Species diversity = Speciation rate – Extinction rate
- Background: genetics and the accumulation of mutations through time (molecular clock)
- Assumption: Speciation occurs when two populations have evolved a certain amount of genetic distance between them via being isolated for some time
    - simplest assumption: speciation is exponential: one lineages splits into two new lineages
- Extinction = unknown, but we can derive it mathematically by assessing the deviation from the exponential assumption for speciation
- **Keep in mind:**
    - strongly dependent on completeness of the phylogeny (if species are missing, rates will not be estimated correctly – but we can account for it if we know how many species are missing)
    - There may be other processes of speciation (e.g., anagenesis) that do not rely on the

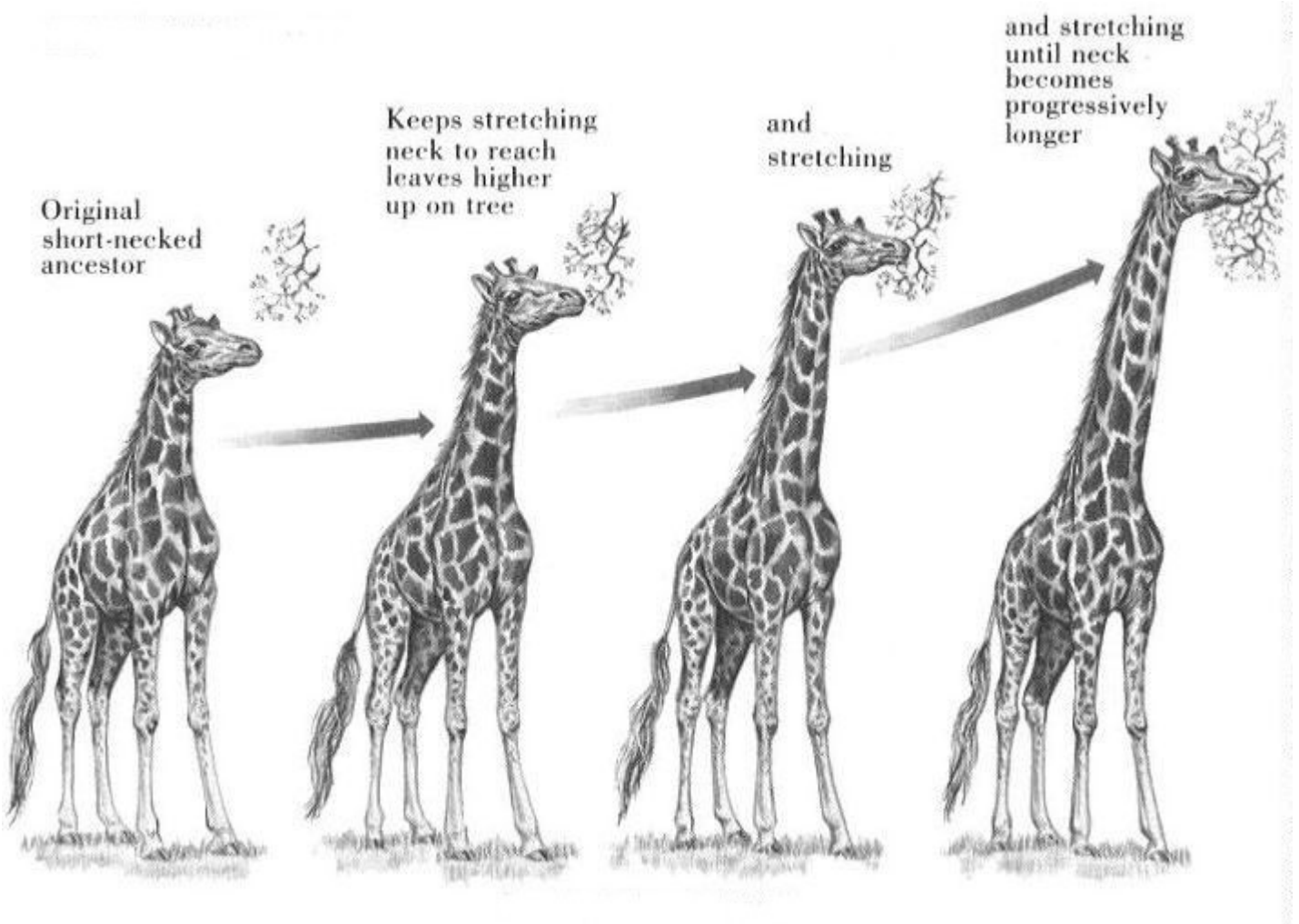
How species change

Natural selection, adaptation and diversification

How species change: according to Lamarck

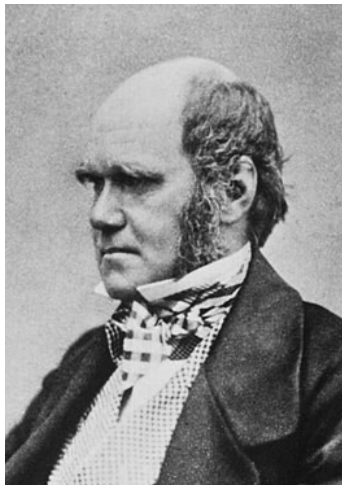
Jean-Baptiste Pierre Antoine de Monet, Chevalier de la Lamarck (1744 – 1829)

The theory of species transformations



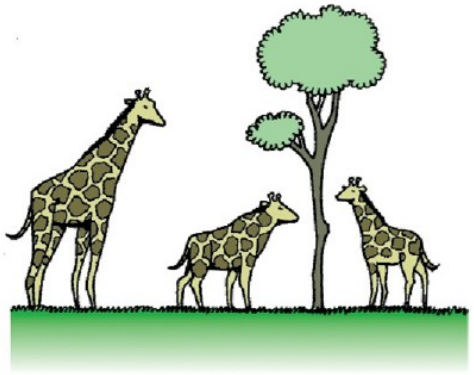
Not quite right, but acknowledging changes in species was a step in the right direction

How species change: according to Darwin (natural selection)

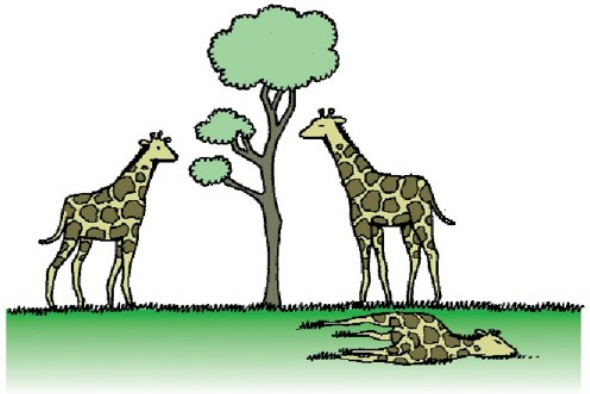


Darwin (1859) *On the Origin of Species*

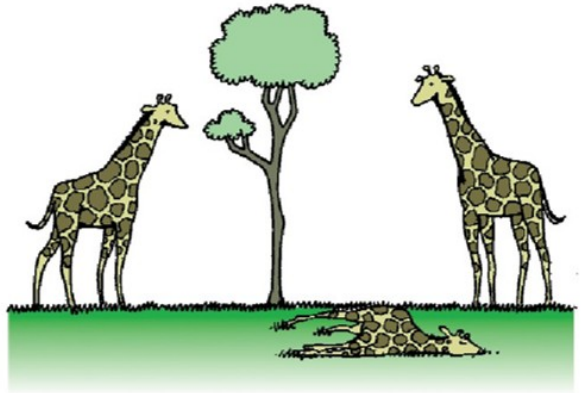
The theory of natural selection



Not all giraffes have equally long necks. Giraffes inherit their neck length from their parents. It is largely fixed by genes.



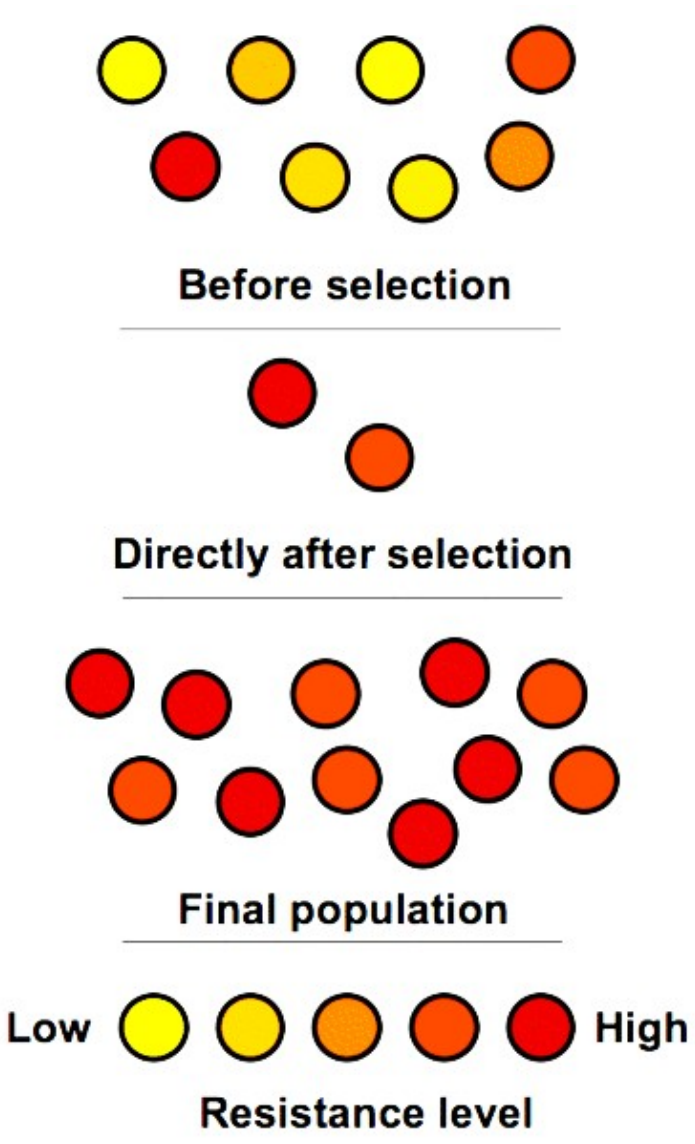
Food that are easily accessed will be eaten by many animal species, and is therefore easily gone. If this happens, giraffes with longer neck are more likely to survive. They can reach food that few other can reach.



Over time, more and more of the giraffes came to have long necks (the short ones never made it to reproduction). This is what we call natural selection and evoluationary adapation.

Natural selection is **passive** (the environment selects) and acts over generations

Adaptation

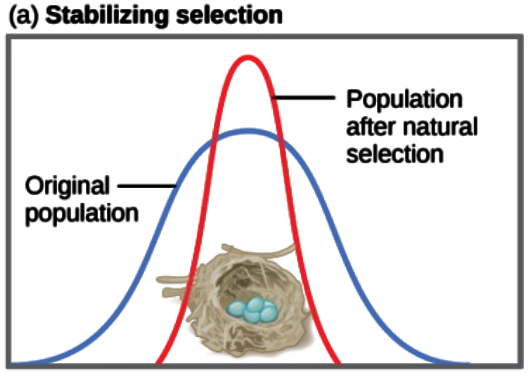


Adaptation

- a feature (trait) produced by natural selection for its current function to enhance the fitness
- **Example**: co-adaptation of pollinators and plants

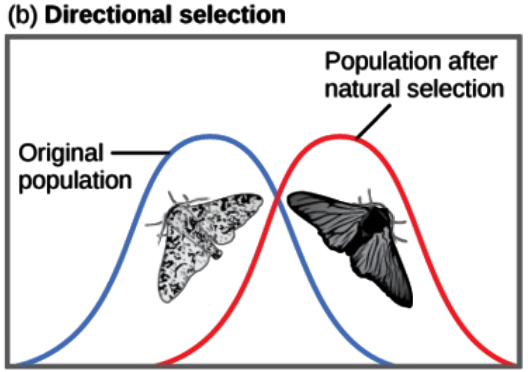
Organisms do not adapt during their lifetime, they merely reproduce and die

Types of natural selection: **Examples**



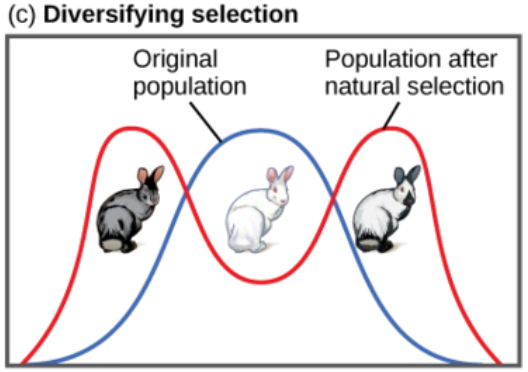
Stabilizing selection:

- Robins typically lay four eggs
- Larger clutches may result in malnourished chicks
- Smaller clutches may result in no viable offspring



Directional selection:

- Light-colored peppered moths are better camouflaged against a pristine environment
- Dark-colored peppered moths are better camouflaged against sooty environment
- As the industrial revolution progressed in 19th century England, the color of the moth population shifted from light to dark



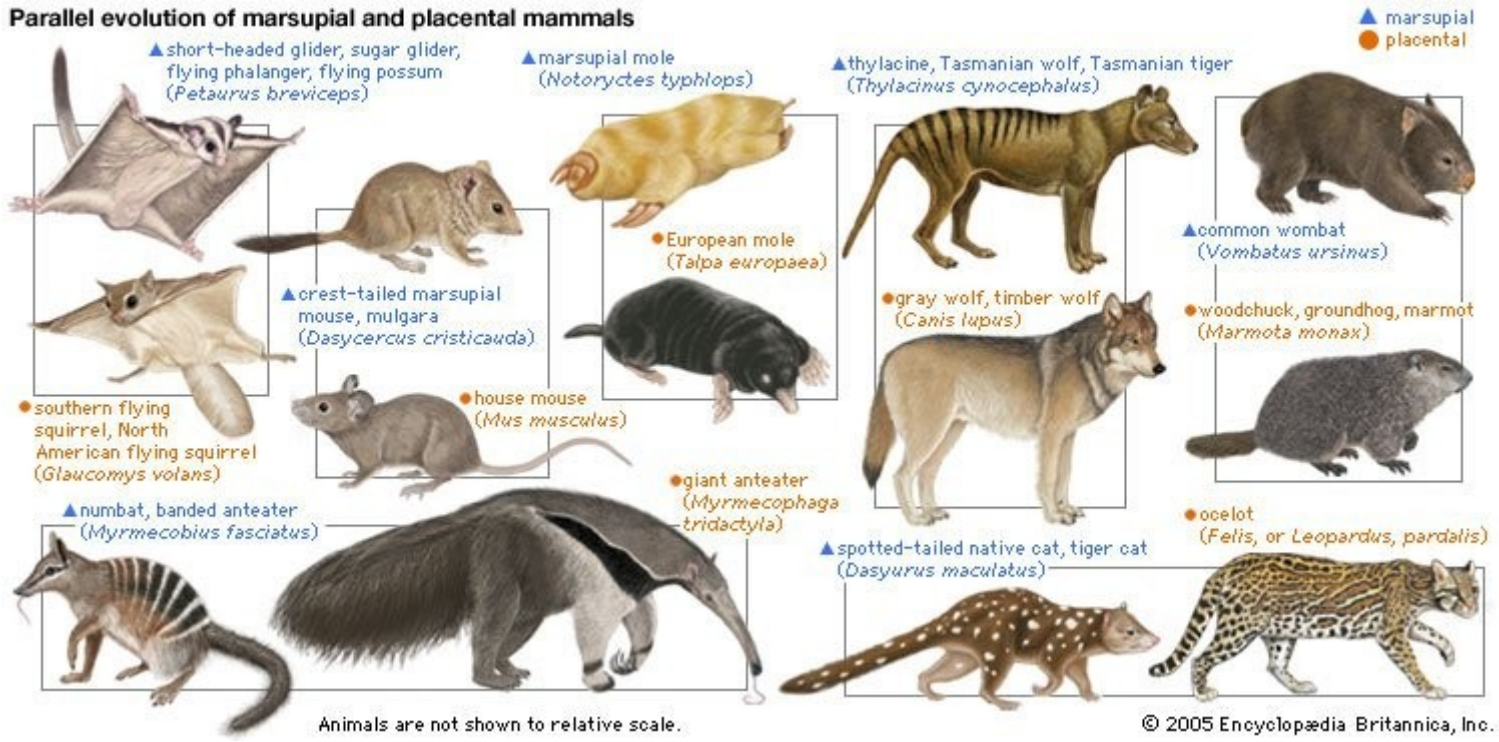
Diversifying / Disruptive selection:

- In a rocky environment, gray, and gray and white rabbits are better camouflaged than white rabbits in their natural habitat
- Leads to diversification

What supports the idea of evolution?

Evolution is a scientific theory, not a fact.
→ Facts are the data, theories interpret the data.

- Hierarchical structure of similarity in nature.
- The existence of homologies and parallel evolution.
- Fossils.
- Imprints in embryonal development.
- Imperfect nature of some traits.
- Non-random distribution of organisms and traits.
- It can also be re-created by humans, either experimentally (on *drosophila*, bacteria, …), or by breeding

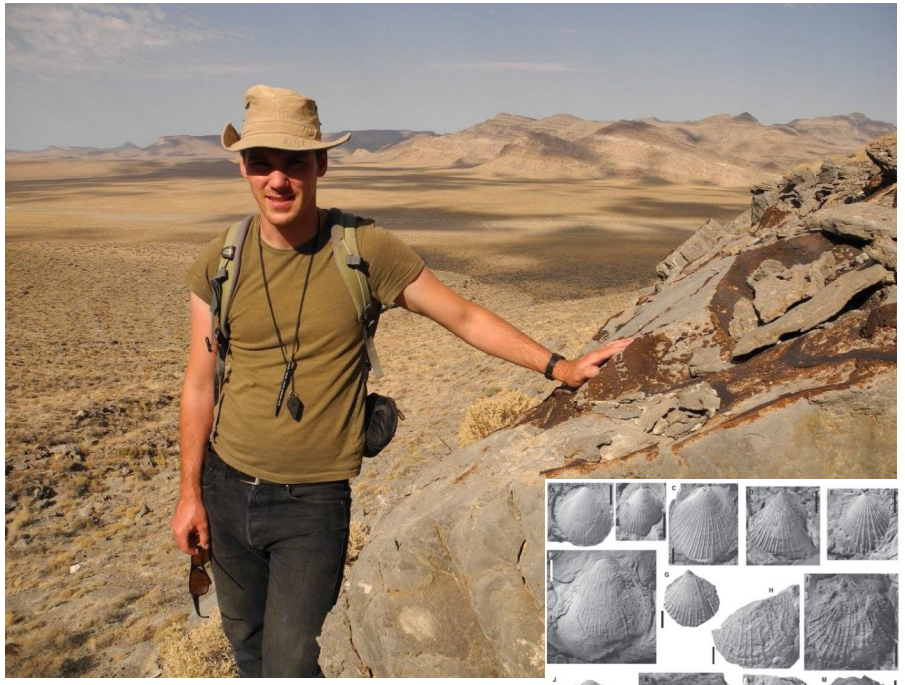


How to explore past life

The fossil record vs phylogenetic trees

How did biodiversity look in the past, and how do we know?

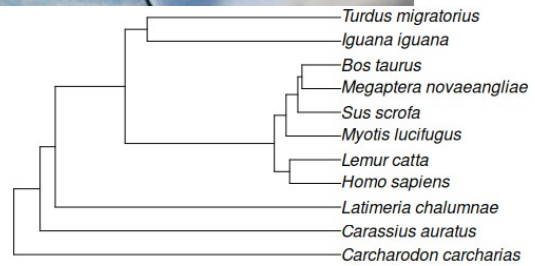
The fossil record <--> Phylogenies



Richard Hofmann

Hofmann et al. *Palaeontology*, 2014

Public Health Image Library, Centers for Disease Control and Prevention.



How did biodiversity look in the past, and how do we know?

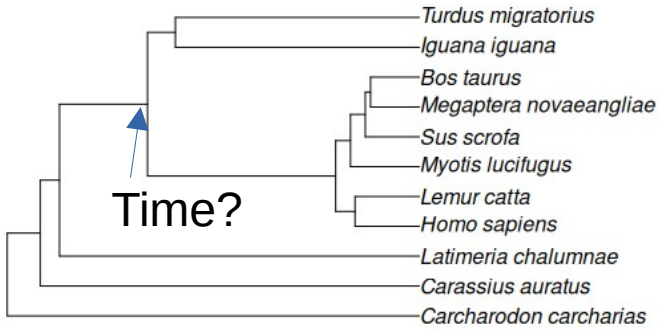
The fossil record	Phylogenies
• Direct evidence: based on fossils • Morphology • Temporal ranges • Geographic distribution (but plate tectonics!) • Extinctions • Behavioral clues: fossilized tracks, gut content	• Indirect evidence: phylogenies are hypotheses about relatedness based on molecular or morphological data • Measures of relatedness • Divergence times • Ancestral state reconstruction (e.g. morphology) • Biogeographic patterns

How did biodiversity look in the past, and how do we know?

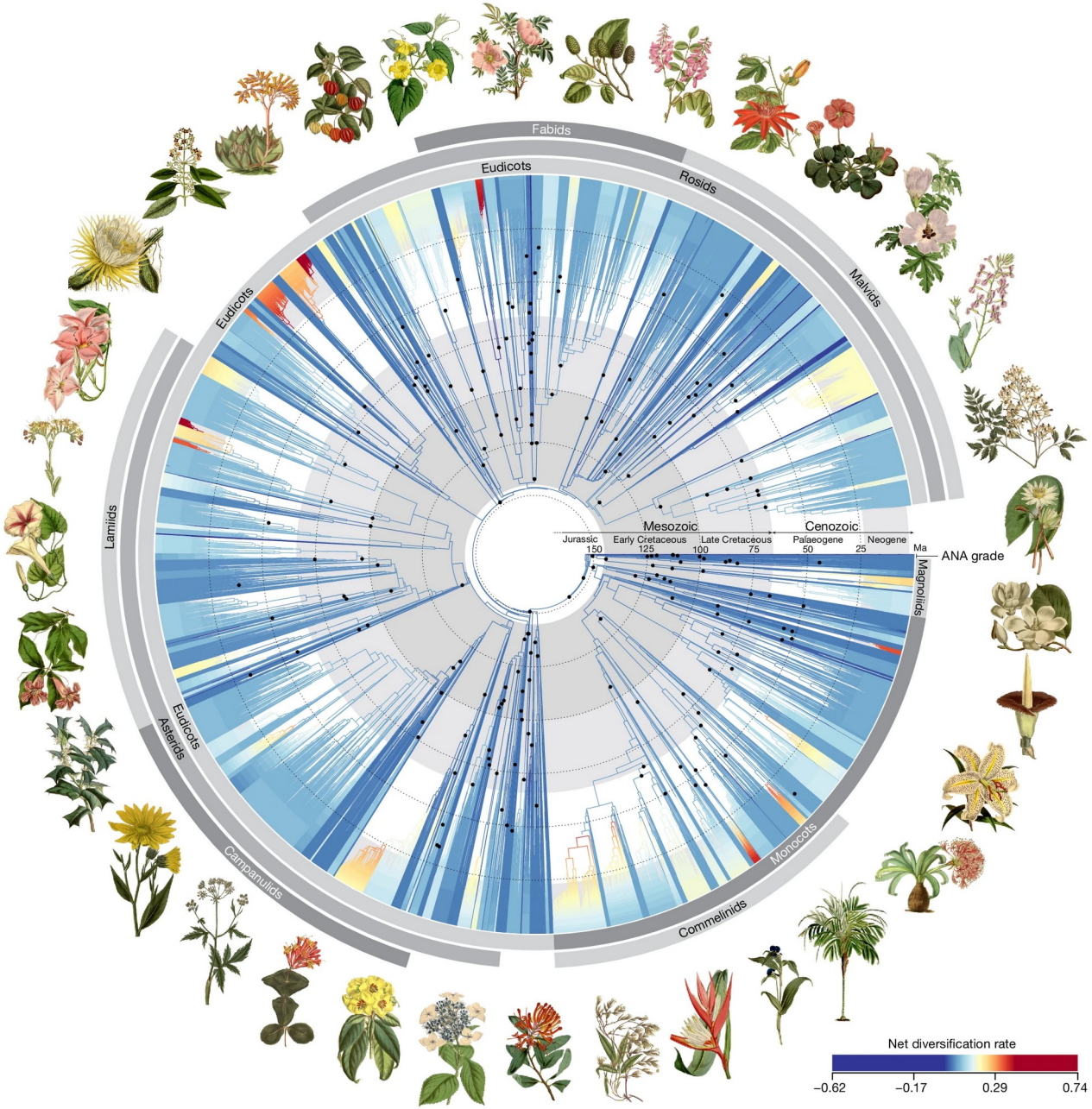
The fossil record	Phylogenies
Direct evidence: based on fossils	Indirect evidence: phylogenies are hypotheses about relatedness based on molecular or morphological data
• Morphology • Temporal ranges • Geographic distribution (but plate tectonics!) • Extinctions • Behavioral clues: fossilized tracks, gut content, reproduction	• Measures of relatedness • Divergence times • Ancestral state reconstruction (e.g. morphology) • Biogeographic patterns in relatedness

Dating?

They are complementary
→ phylogenies are dated with fossil calibration points:



How did biodiversity look in the past, and how do we know?



Dating?

Time-calibrated phylogenetic tree for angiosperms

→ Black dots at nodes are fossil calibrations

Zutini et al. 2024 Nature

How to date the fossil record?

Relative dating

Stratigraphy Fossils found in lower rock layers are older than those in higher layers: Law of Superposition

Biostratigraphy Uses index fossils (high abundance, big range, but short-lived species) to correlate and date rock layers globally

Absolute dating

Radiometric Dating Measures the decay of radioactive isotopes

Carbon-14 (^{14}C) Used for organic remains (e.g. bone, wood) up to ~50,000 years

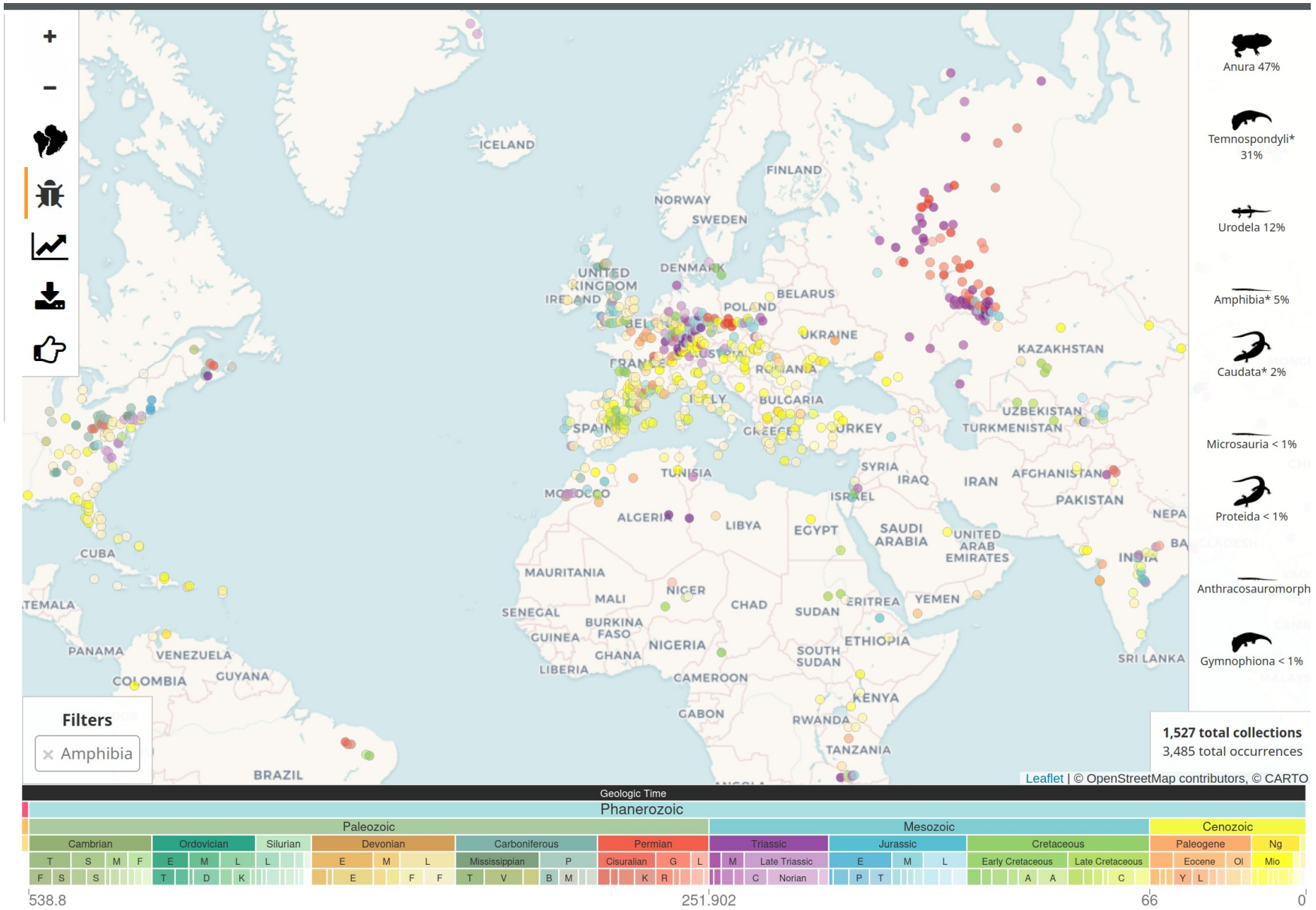
Cedar Mesa, Utah

na Barrandově skále v Praze, Devonian limestone

What to do with the fossil record?

The Paleobiology Database

https://paleobiodb.org/#/

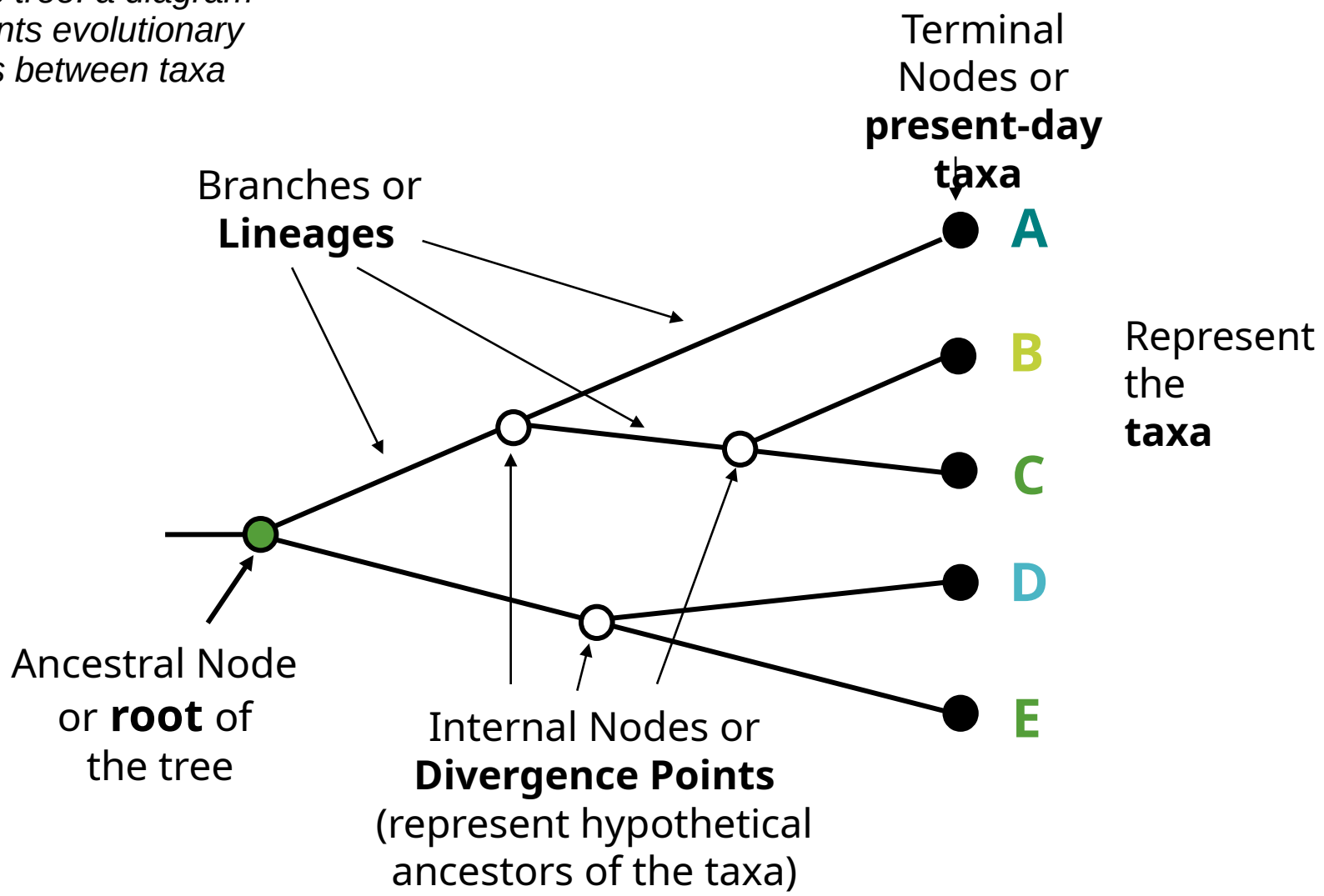


Phylogeny

Evolutionary trees and how to read them

How to read a phylogeny

phylogenetic tree: a diagram that represents evolutionary relationships between taxa



Types of phylogenetic trees

- **Cladogram**

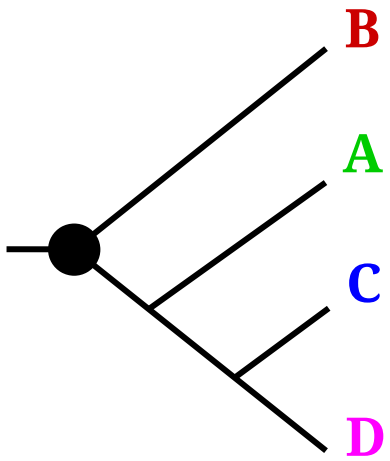
  = only represents the branching-pattern, but is unscaled (branch lengths are not representative of anything)

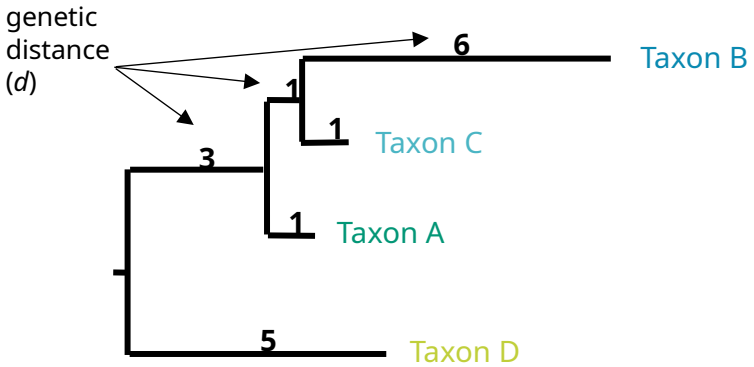
- **Phylogram**

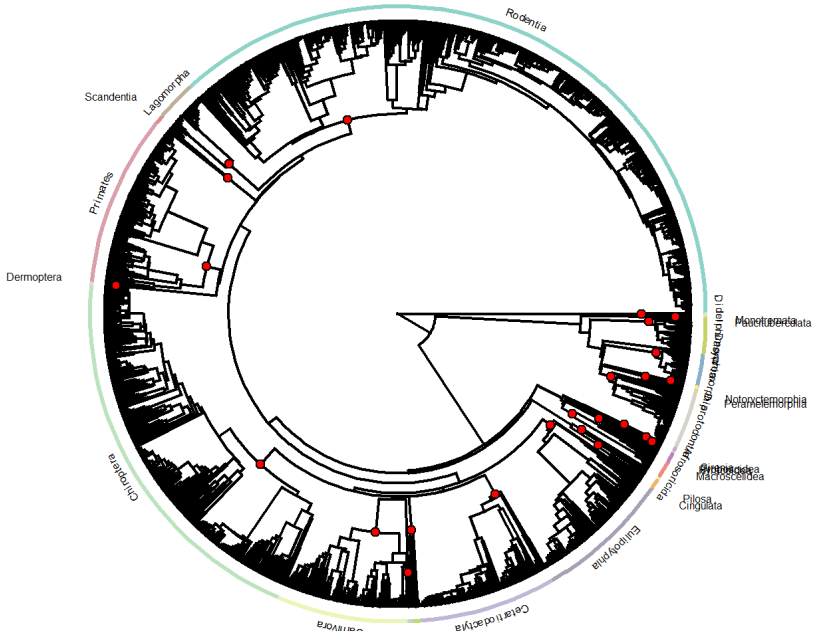
  = Branch lengths are proportional to the amount of character change (e.g., genetic distance)

- **Chronogram**

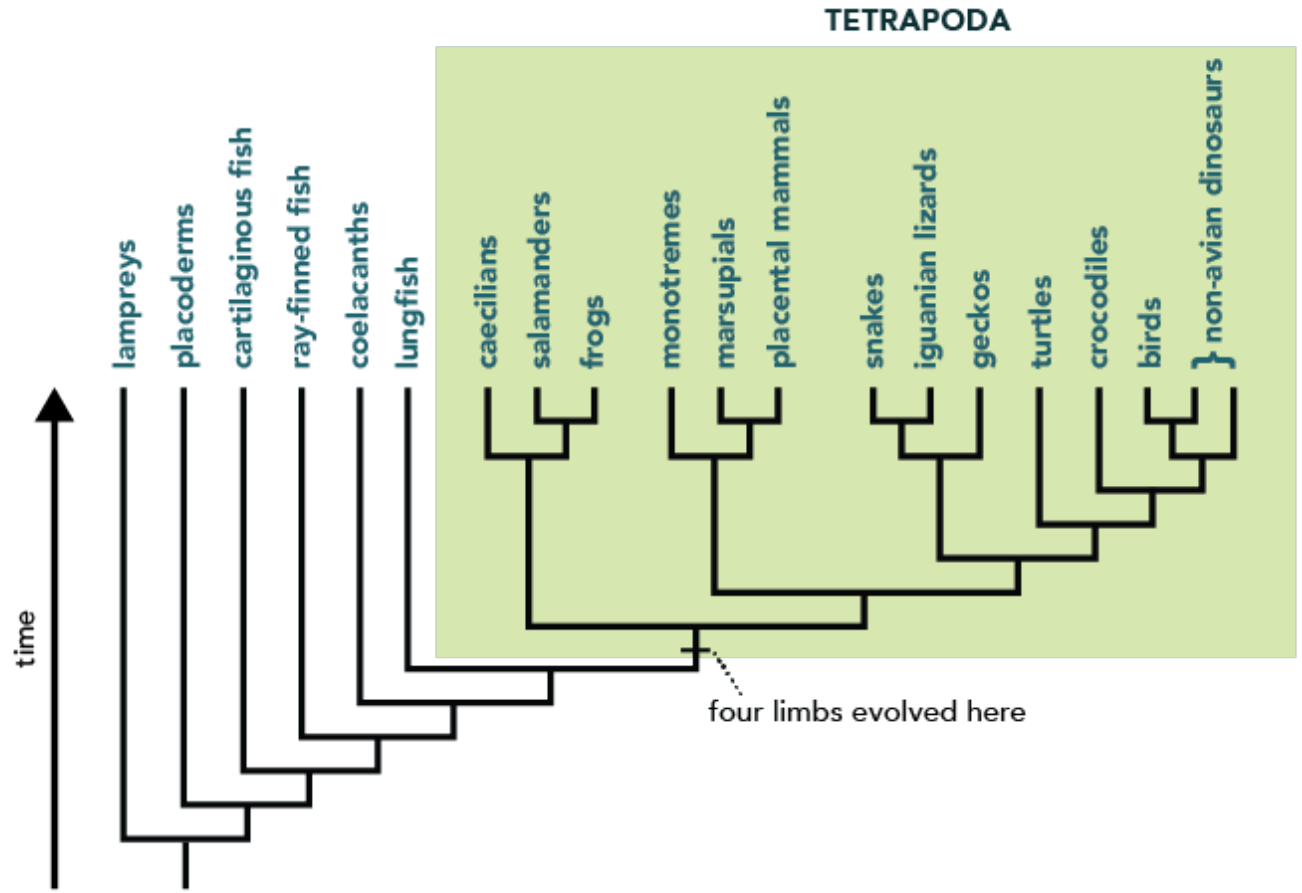
  = Branch lengths represent time







How do we get a phylogeny?

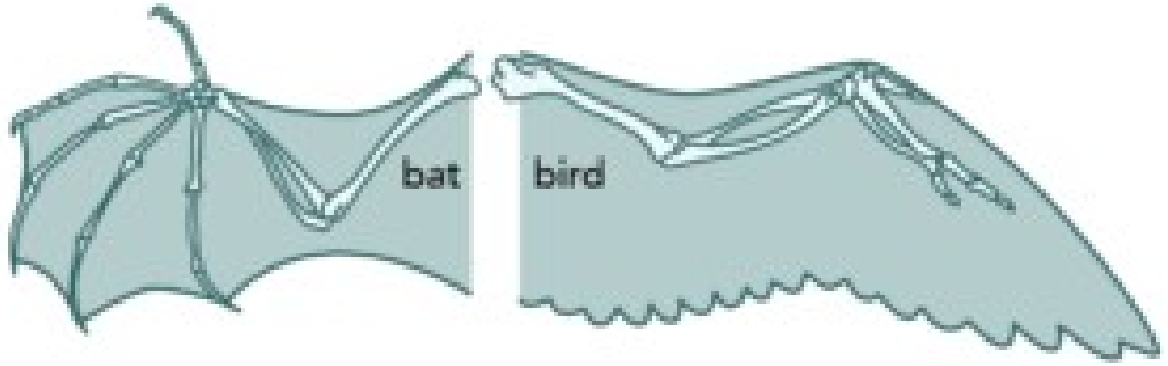


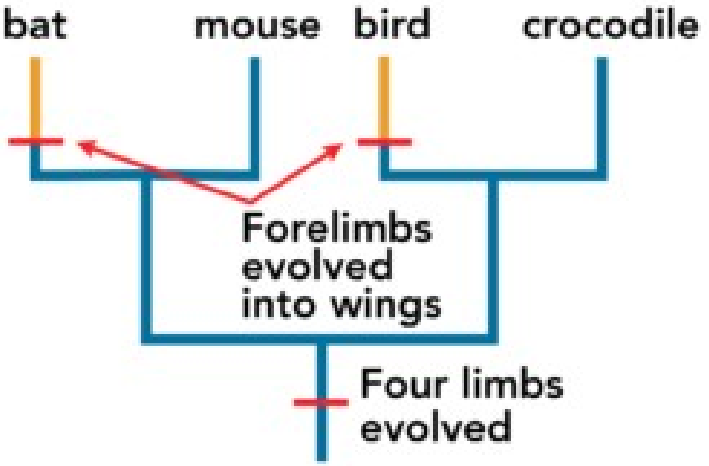
evolution.berkeley.edu

We use **homologous characters** — characters in different organisms that are similar because they were inherited from a common ancestor that also had that character. An example of homologous characters is the four limbs of tetrapods. Birds, bats, mice, and crocodiles all have four limbs. Sharks and bony fish do not. The ancestor of tetrapods evolved four limbs, and its descendents have inherited that feature — so the presence of four limbs is a homology.

These can be **morphological**, or **molecular**.

Do not confuse homology with **analogy**





Bat wings consist of flaps of skin stretched between the bones of the fingers and arm. Bird wings consist of feathers extending all along the arm. These structural dissimilarities suggest that bird wings and bat wings were not inherited from a common ancestor with wings.

→ separate evolutionary origins, but same function
→ developed independently

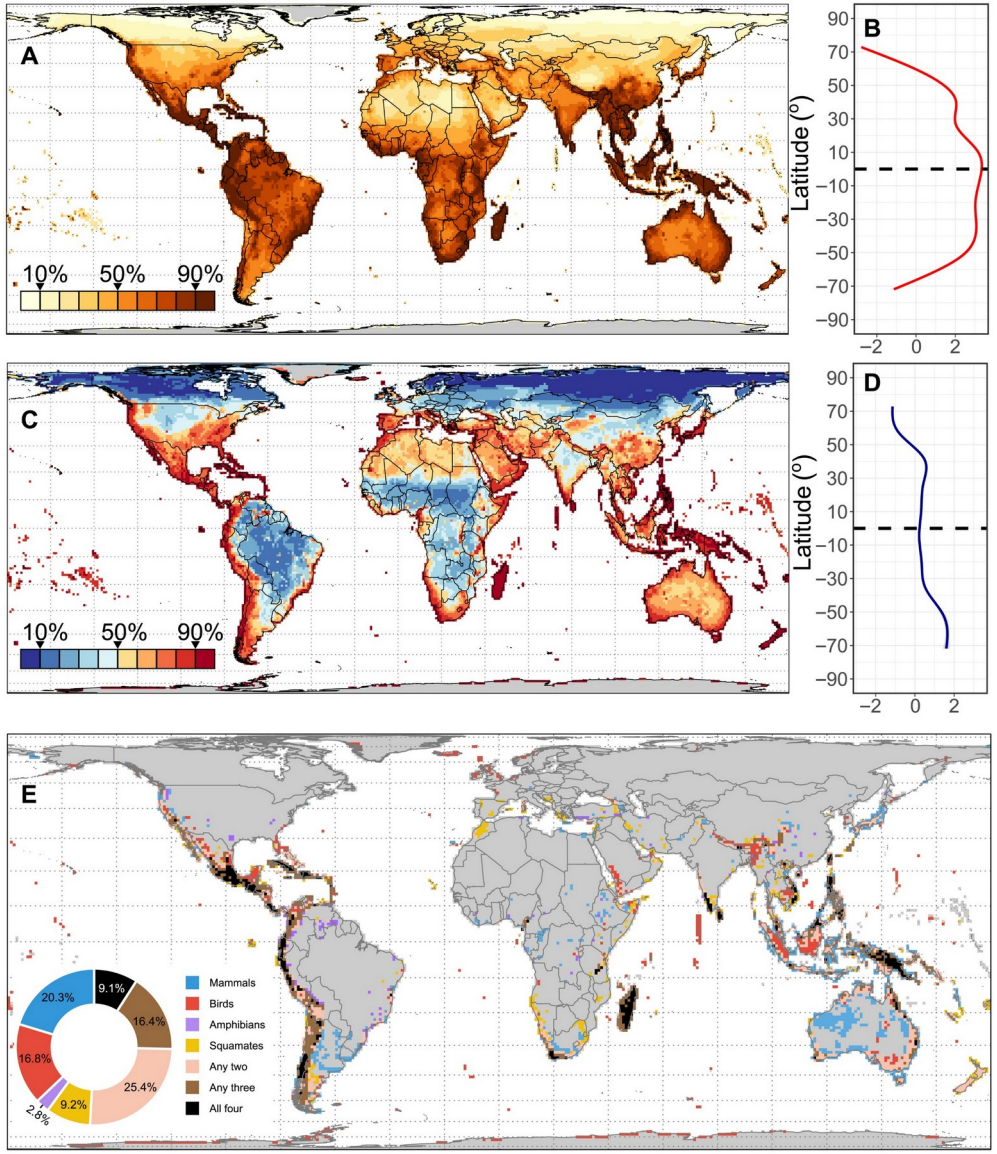
---

evolution.berkeley.edu

What are phylogenies good for in ecology and conservation?

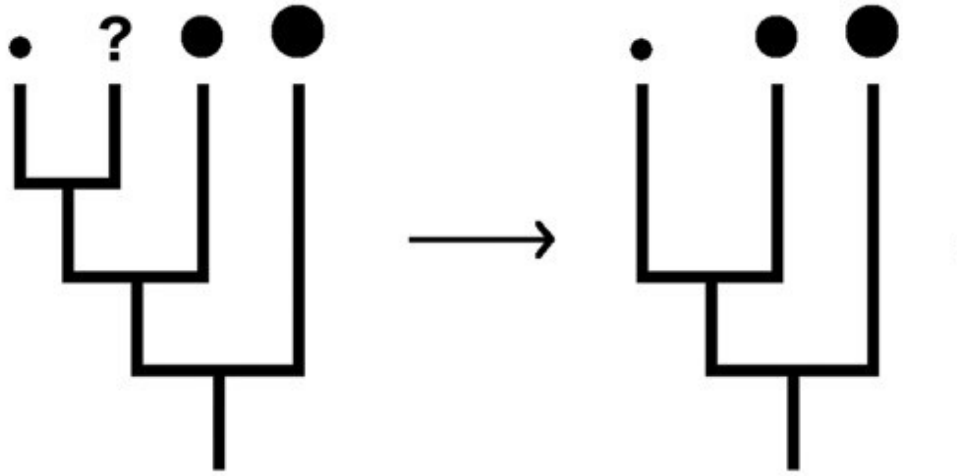
Phylogenetic endemism and evolutionary distinctness

Global patterns of phylogenetic endemism and congruence of phylogenetic endemism hotspots for tetrapods.
(**A**) Spatial and (**B**) latitudinal patterns of phylogenetic endemism (uncorrected for richness; red). (**C**) Spatial and (**D**) latitudinal patterns of phylogenetic endemism (corrected for richness; blue). Note that the values of phylogenetic endemism uncorrected for richness are log-transformed in graph (B), and the fitted line is from loess regression. (**E**) Congruence map of phylogenetic endemism hotspots.



Murali et al. (2021) *Science Advances*

Phylogenetic imputation



We can guess values of traits in species for which we have no information.

Examples:

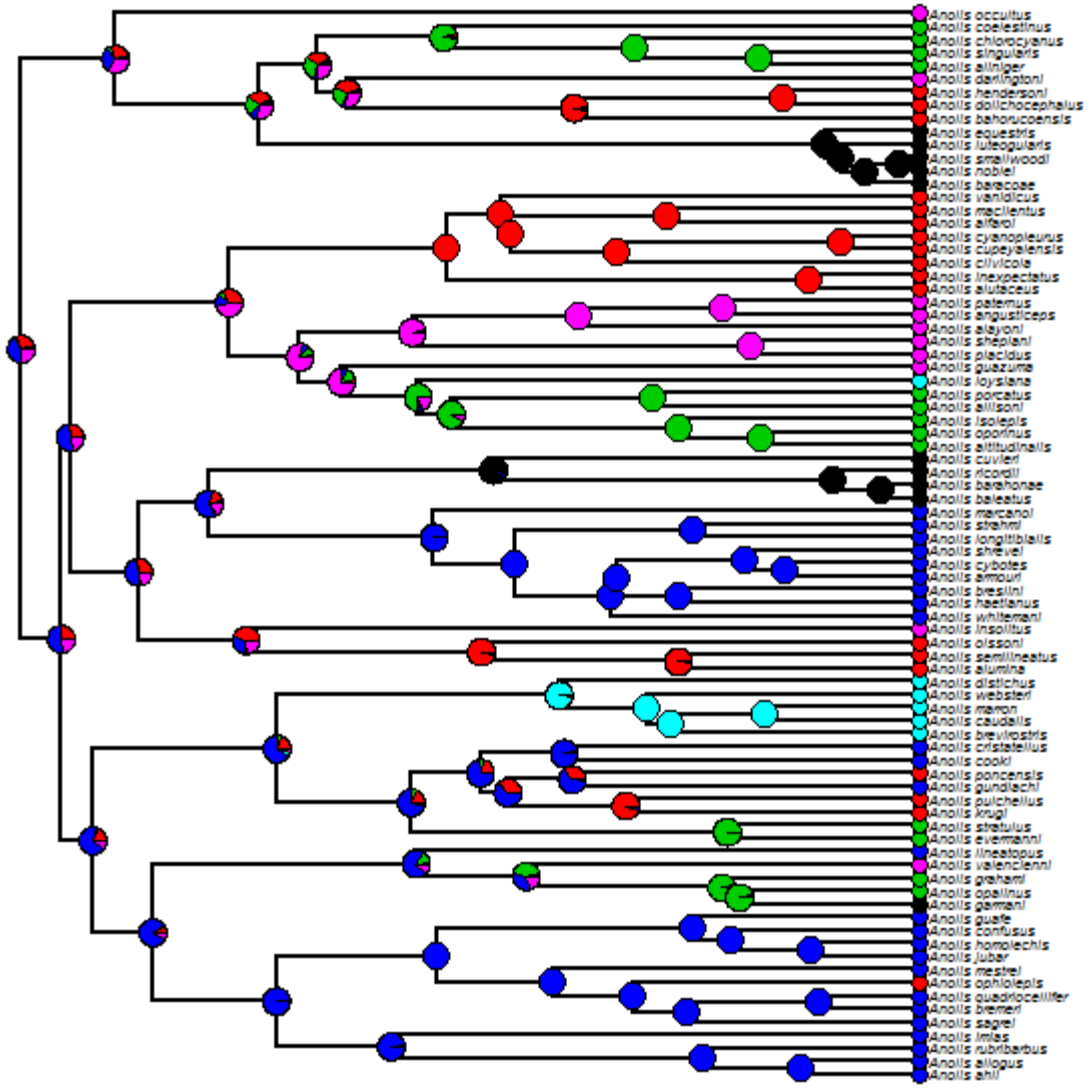
- body size

- thermal requirements

- conservation threat status

Jetz & Freckleton (2015) *Philos Trans R Soc B*

Ancestral state reconstruction



Phytools (Liam Revell)

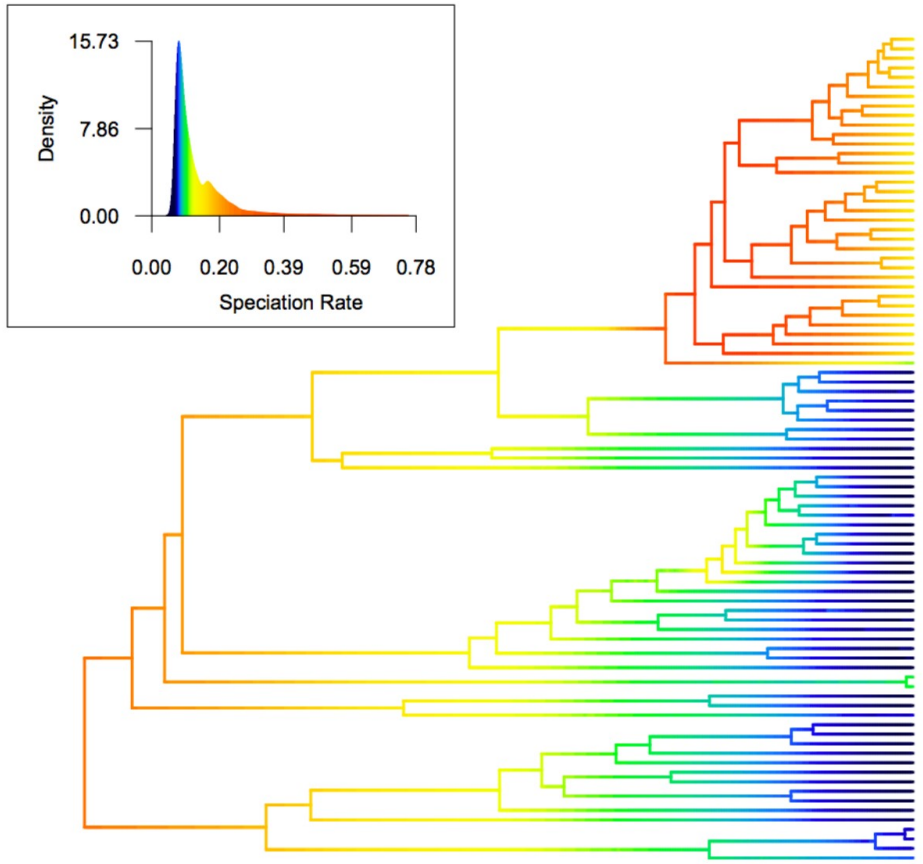
Reconstruct the most likely *ancestral* state:

- morphology

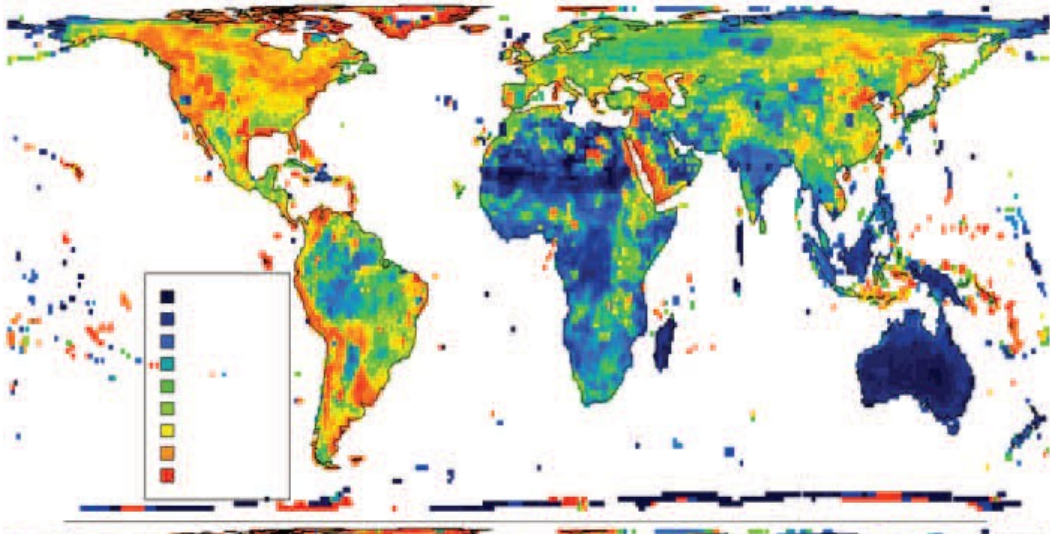
- biogeographic origin

→ e.g. origins in tropics or temperate areas?

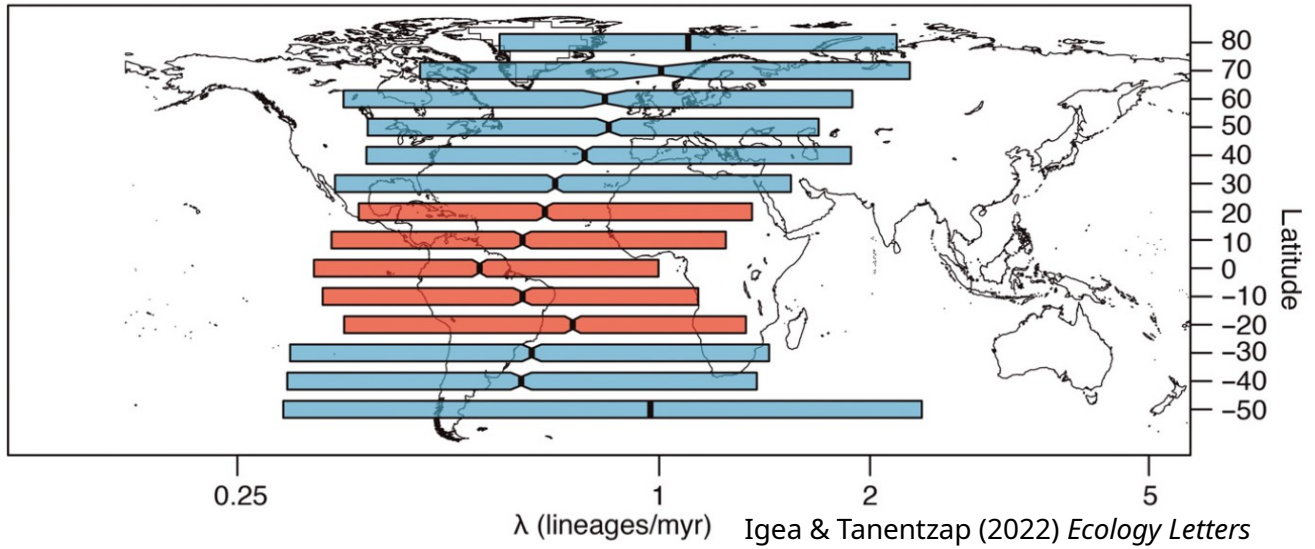
Get diversification rates & map them



BAMM (Bayesian analysis of macroevolutionary mixtures) example for whales



Jetz et al. (2012) *Nature*



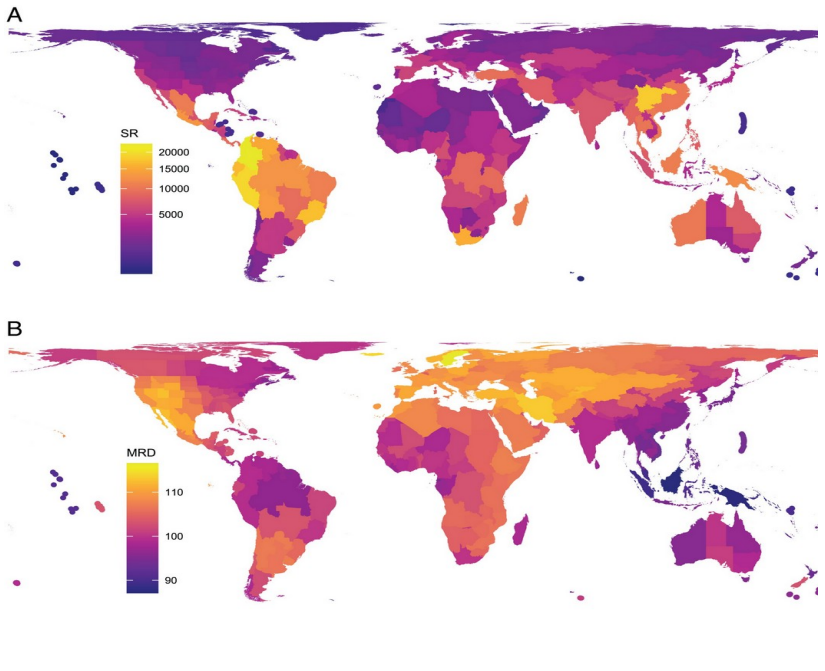
Igea & Tanentzap (2022) *Ecology Letters*

Zooming out: comparing with other biodiversity measures

Species Richness

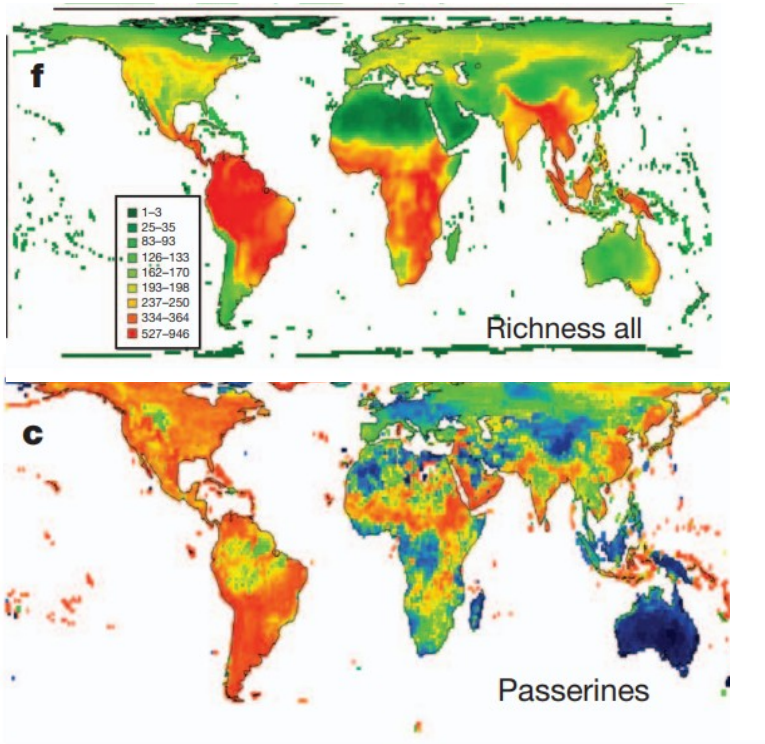
Diversification rates

Plants



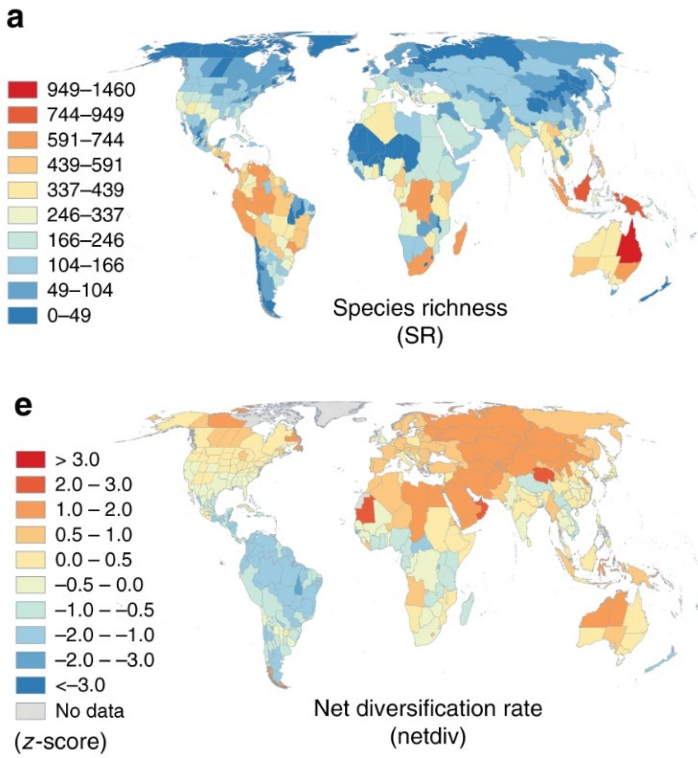
Tietje et al., 2022, *PNAS: Global variation in diversification rate and species richness are unlinked in plants*

Birds



Jetz et al., 2012, *Nature*: *The global diversity of birds in space and time*

Ants



Economo et al., 2018, *Nature Comms: Macroecology and macroevolution of the latitudinal diversity gradient in ants*

Phylogenetic comparative methods

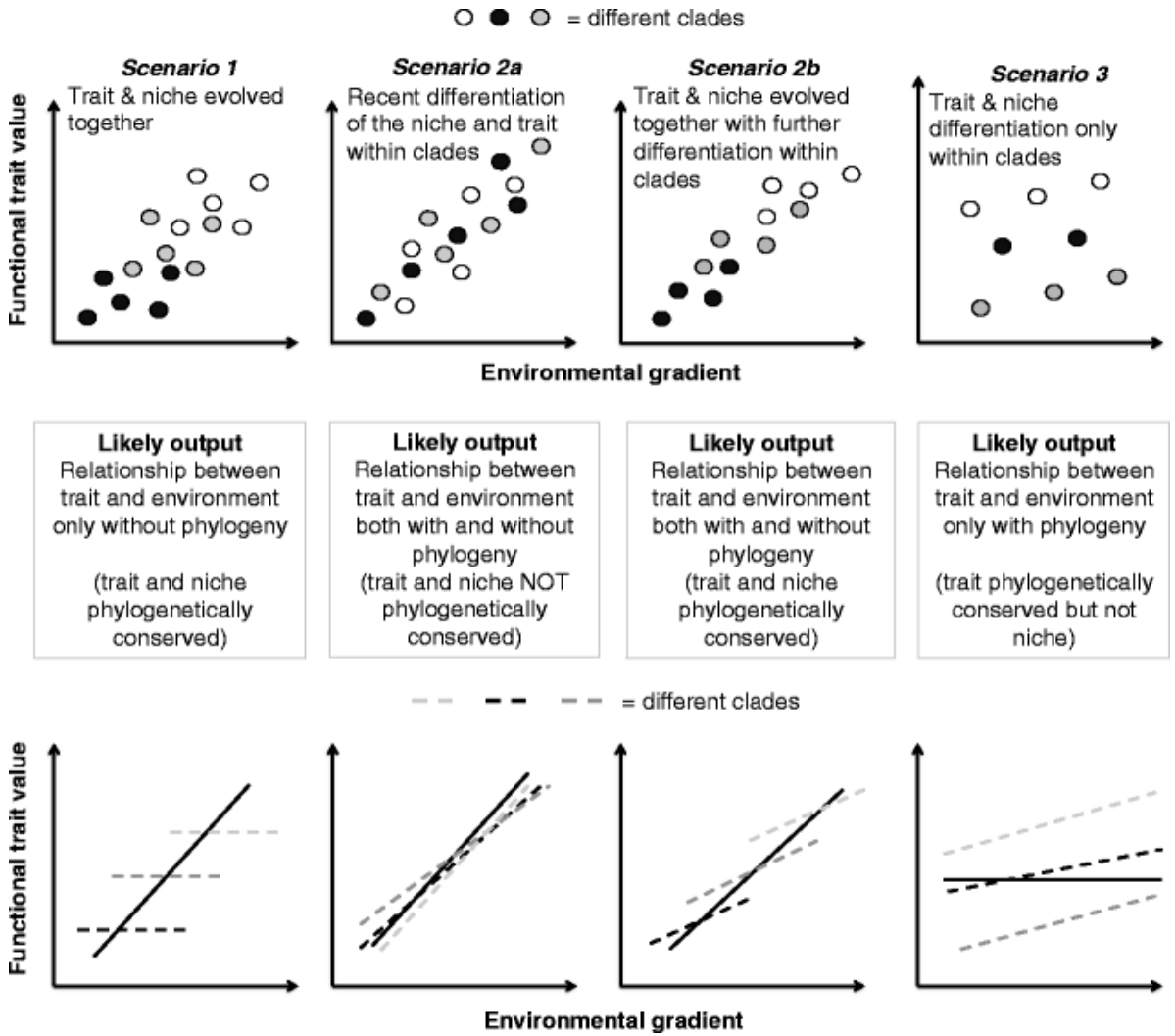
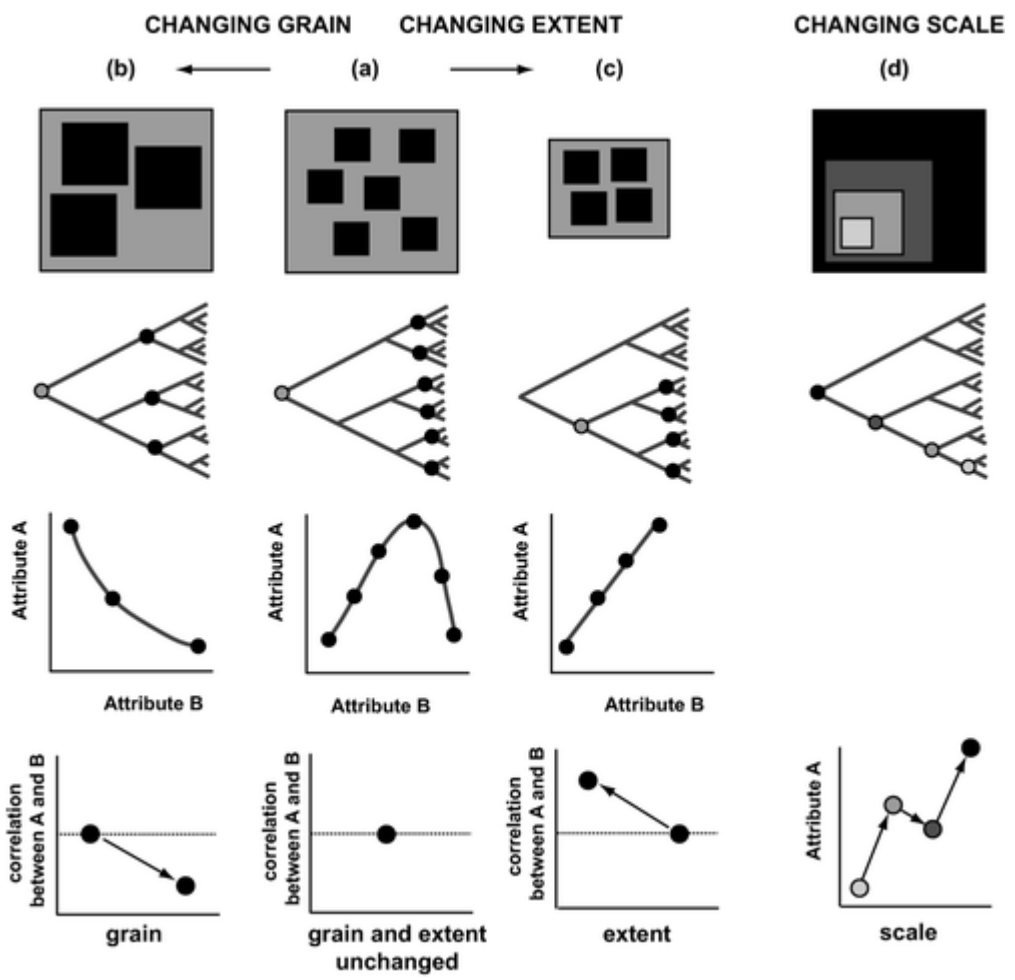
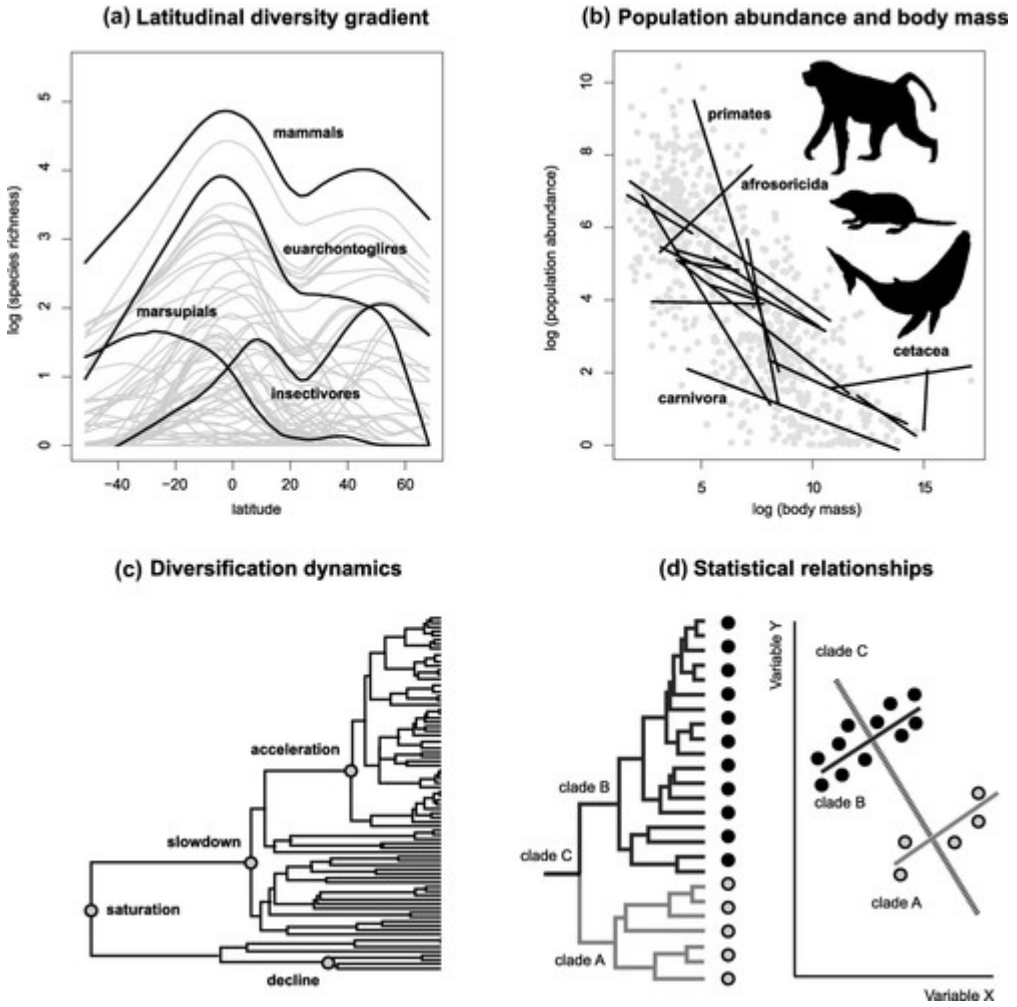


Fig.1 Possible results when assessing the relationship between species traits and species environmental preferences. In the figure, each species is represented by one circle, with different colours indicating different clades. Solid lines show relationship between trait and environment without taking phylogeny into account. Dashed lines show relationships between trait and environment taking phylogeny into account (i.e. within clades). Ecological niche refers to species preferred environmental conditions.

De Bello et al. 2015 Folia Geobotanica

Phylogenetic scale





Graham et al. 2018 *Global Ecology and Biogeography*

The end

What you should remember

- The number of taxa steadily increased through geological time
- There have been 5 major extinction events (the “big five”) and we might be in the midst of another one
- Apart from extinction, the other process generating biodiversity is speciation
- You should know the principle of Darwinian natural selection, and how it’s connected to speciation
- Evolutionary relationships among organisms are represented by a phylogeny a.k.a. phylogenetic tree