Biodiversity and the Geography of Extinctions

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In pragmatic terms, conserving biological diversity distills down to a simple, but challenging goal: maintaining diversity

How do we keep as many of the 'parts' as possible?

"*To keep every cog in the wheel is the first precaution of intelligent tinkering*"

- Aldo Leopold (1953)

The impact of extinction…

Goals and learning objectives

1) Previous mass extinctions – what extinctions have occurred, what mechanisms were responsible, how do we measure it?

2) Examine the 6th extinction– how does our contemporary crisis compare to historical episodes? What are the challenges in assessing species loss?

3) Understand the process of extinction through patterns in range collapse. How does this help to guide recovery efforts?

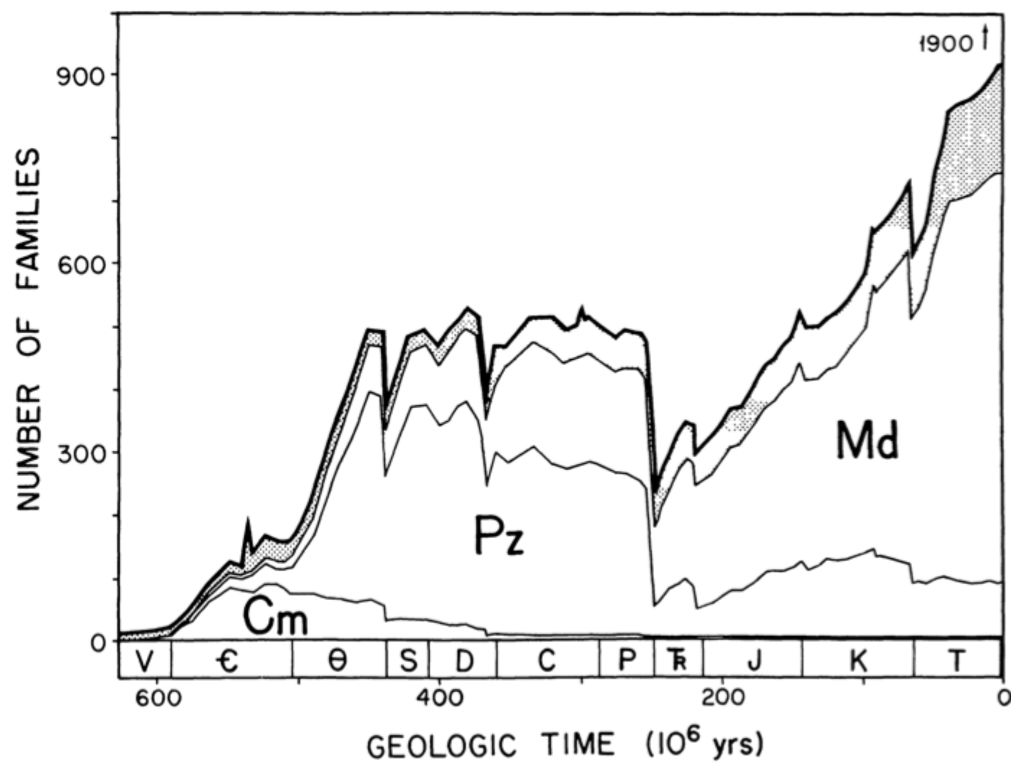
4) Examine ways to prioritize areas for conservation – a look at biodiversity hotspots.

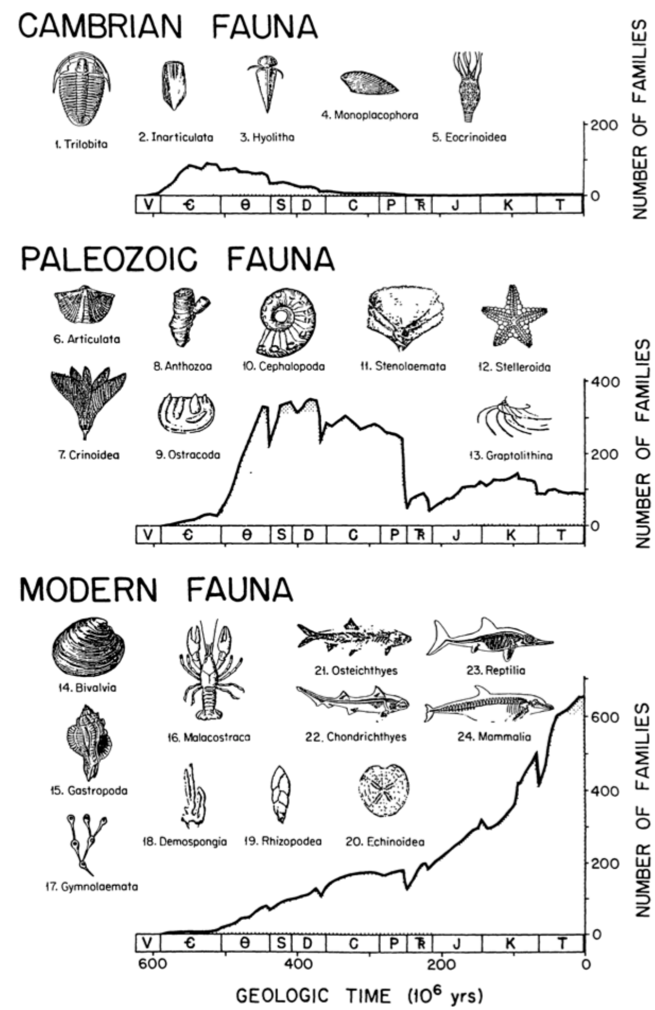
5) Evaluate how we can map extinction threat, using quantitative strategies for targeting species and populations

Previous Mass Extinctions

Extinctions of species have been a regular occurrence throughout Earth's history.

Paleontologists characterize mass extinctions as times when Earth loses >75% of species in a geologically short interval (<2 my), as has happened five times in the past ~ 540 million years.

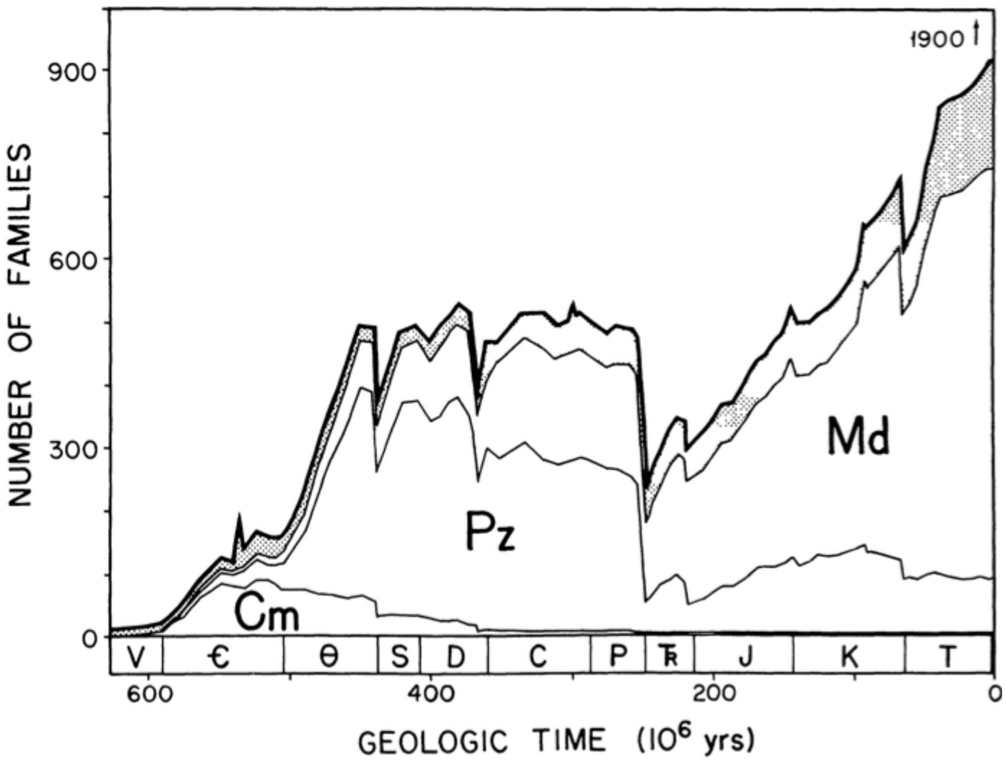


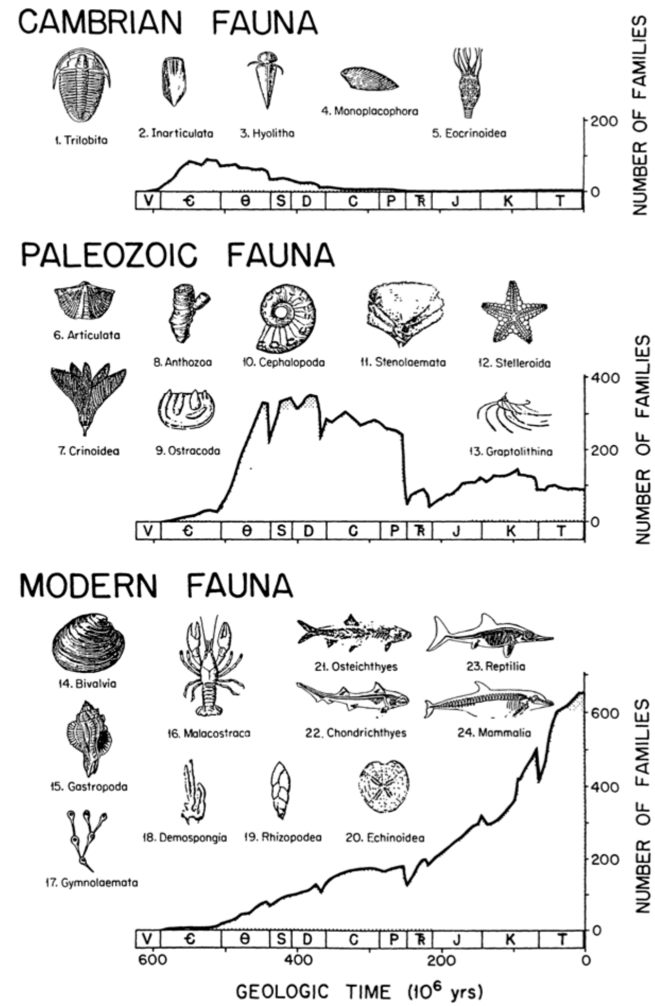


Previous Mass Extinctions

Extinctions of species have been a regular occurrence throughout Earth's history.

Historically, extinction has been balanced by subsequent speciation and opportunity for diversification…





Previous Mass Extinctions – the Big Five

Event	Proposed Causes
Ordovician event ended ~443 Myr ago; within 3.3 to 1.9 Myr 57% of genera were lost, 86% of species	Onset of alternating glacial and interglacial episodes; repeated marine transgressions and regressions. Uplift and weathering of Appalachians affecting atmospheric and ocean chemistry. Sequestration of CO_2.
Devonian event ended ~359 Myr ago; within 29-2 Myr 35% of genera were lost, 75% of species	Global cooling (followed by global warming), possibly tied to diversification of land plants, with associated weathering and drawdown of global CO_2. Evidence for widespread deep-water anoxia and spread of anoxic waters by transgressions.
Permian event ended ~251 Myr ago; within 2.8 Myr to 160 Kyr 56% of genera were lost, 96% of species	Siberian volcanism. Global warming. Spread of deep marine anoxic waters. Elevated H_2S and CO_2 concentrations in both marine and terrestrial realms. Ocean acidification.
Triassic event ended ~200 Myr ago; within 8.3 Myr to 600 Kyr 47% of genera were lost, 80% of species	Activity in the Central Atlantic Magmatic Province (CAMP) thought to have elevated atmospheric CO_2 levels, which increased global temperatures and led to a calcification crisis in the world oceans.
Cretaceous event ended ~65 Myr ago; within 2.5 Myr to less than a year 40% of genera were lost, an estimated 76% of species	A meteor impact in the Yucatan is thought to have led to a global cataclysm and caused rapid cooling. Preceding the impact, biota may have been declining owing to a variety of causes: Deccan volcanism contemporaneous with global warming; tectonic uplift altering biogeography and accelerating erosion, potentially contributing to ocean eutrophication and anoxic episodes. CO_2 spike just before extinction, drop during extinction.

Table recreated from Barnosky *et al.* 2011 *Nature*

Previous Mass Extinctions – the Big Five

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Table recreated from Barnosky *et al.* 2011 *Nature*

What constitutes a mass extinction?

Extinction involves both *rate* and *magnitude*

Rate considers the number of extinctions divided by the time over which they occurred (or the fraction of species that have gone extinct per unit time)

Magnitude is the percentage of species that have gone extinct

What constitutes a mass extinction?

Extinction involves both *rate* and *magnitude*

Mass extinction is when extinction rates accelerate relative to origination rates such that over 75% of species disappear within a geologically short interval (i.e., < 2 my)

To establish whether the current extinction episode lies on the mass extinction scale (defined by the Big Five) requires us to know:

1) whether current extinction rates are above background rates (and if so how far above)
2) how closely historic and projected biodiversity losses approach 75% of Earth's species

The sixth mass extinction?

Scientists are recognizing modern extinctions of species and populations attributed to humans through combined effects by:

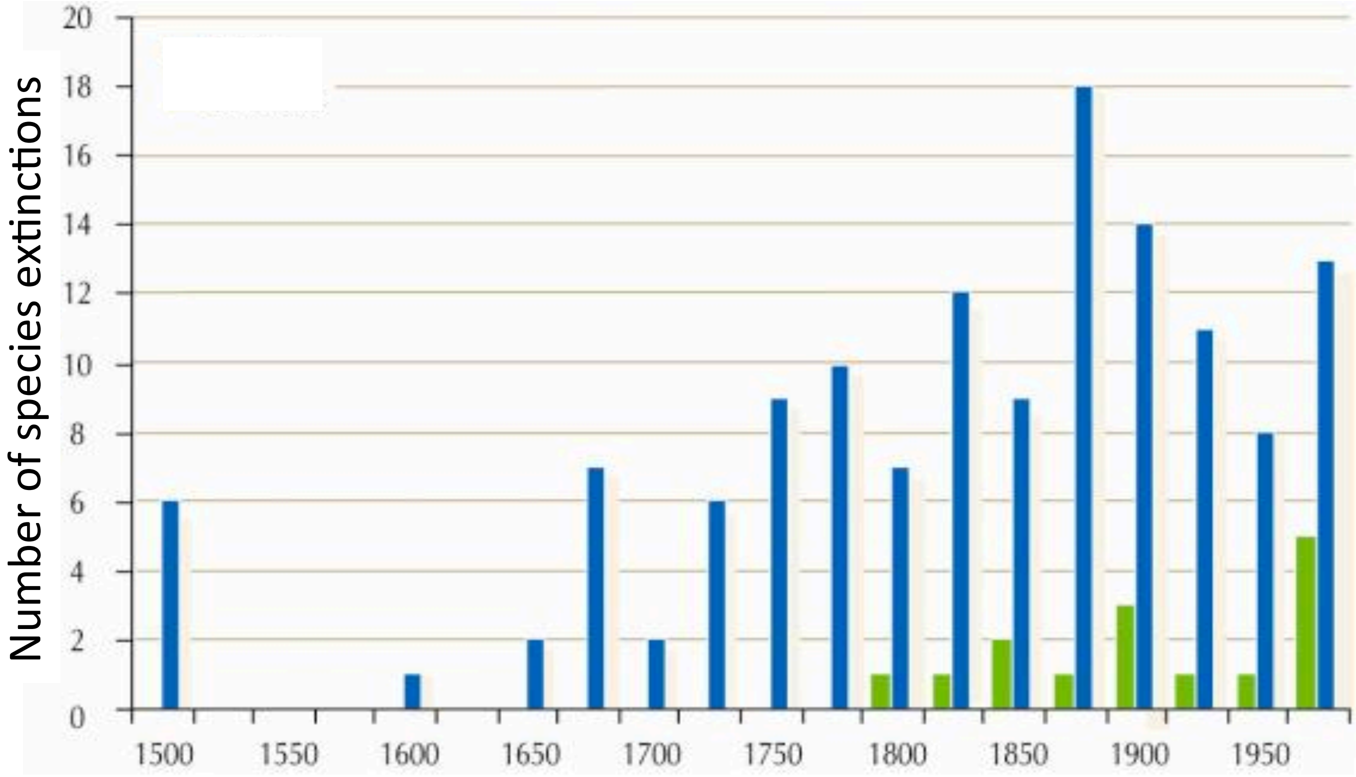
- Co-opting resources
- Fragmenting habitats
- Introducing non-native species
- Spreading pathogens
- Killing species directly
- Changing global climate

The sixth mass extinction? - birds

Extinctions are probably better documented for birds than for any group

~150 bird species have gone extinct in the last 500 years (19 species lost in the last 35 years, 3 species suspected to have gone extinct since 2000)

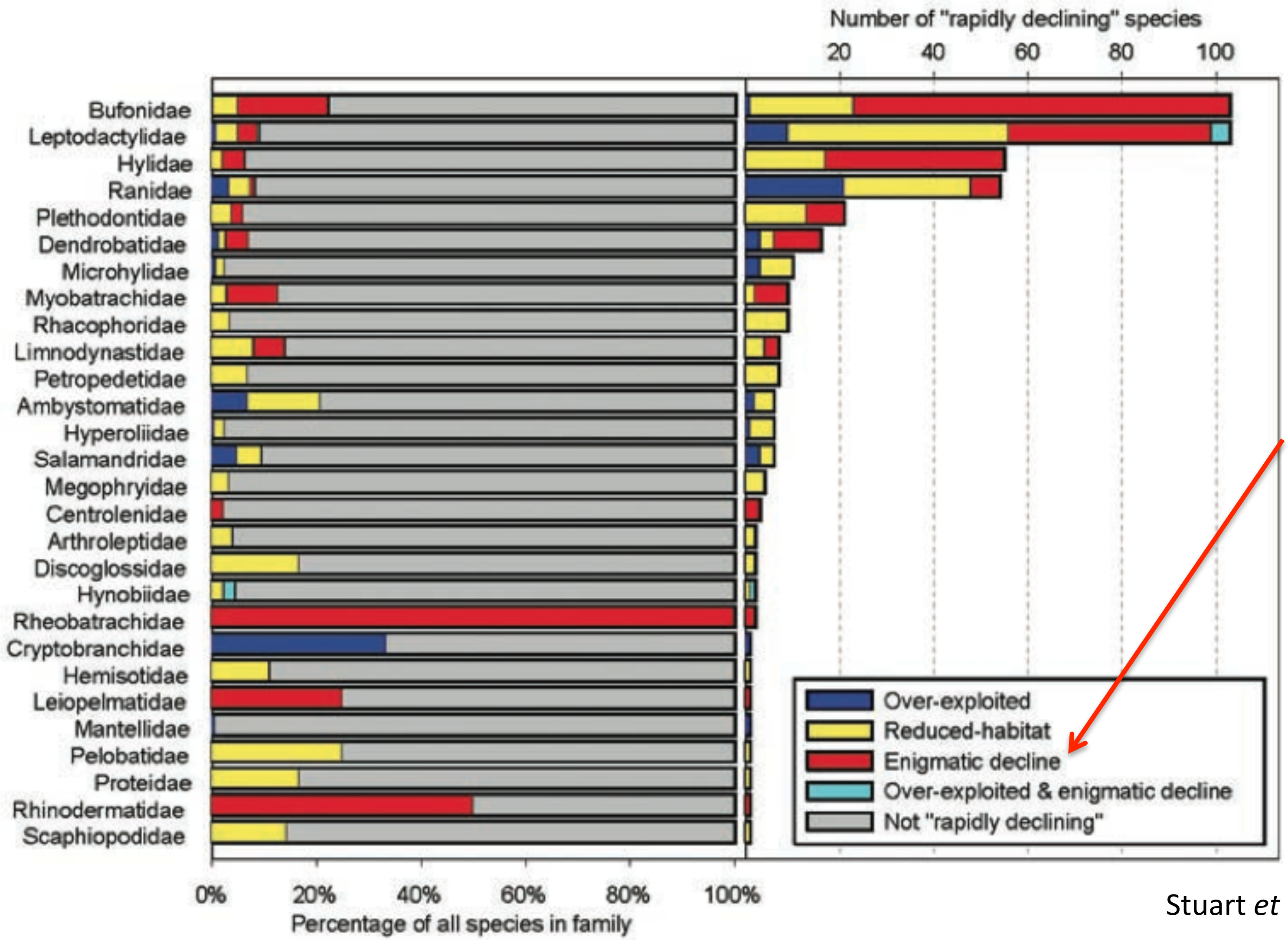
Estimated rate of extinction during the Quaternary Period (i.e., over the past 2.5 my) was one extinction every 83 years



Birdlife International 2011

The sixth mass extinction? - amphibians

Percentages and numbers of rapidly declining species in amphibian families (with at least one rapidly declining species) classified by cause of rapid decline

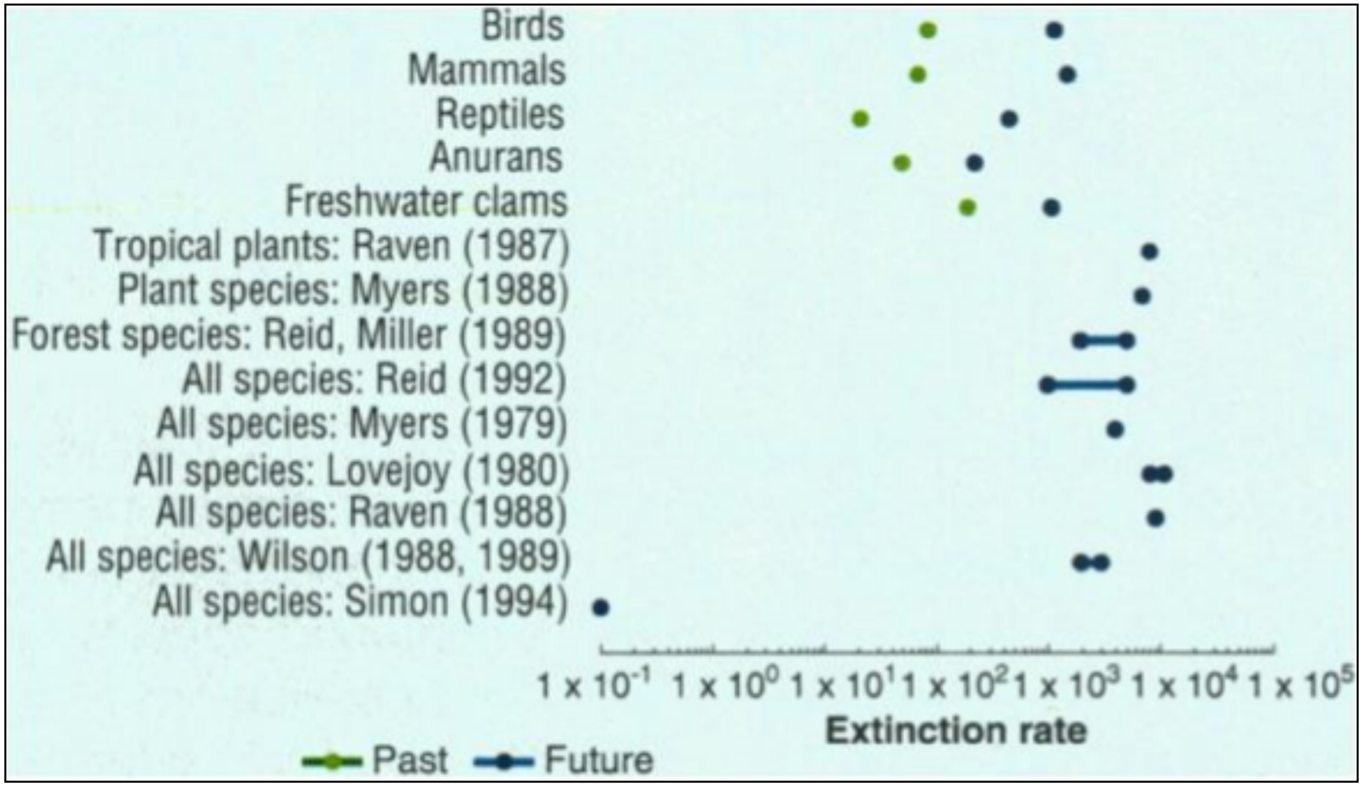


Species showing dramatic declines even where suitable habitat remains, for reasons not fully explained.

Stuart *et al.* 2004 *Science*

The sixth mass extinction?

Estimates of extinction rates (extinctions per million species years) over the past 100 years, and the next 100 years assuming all threatened species go extinct.



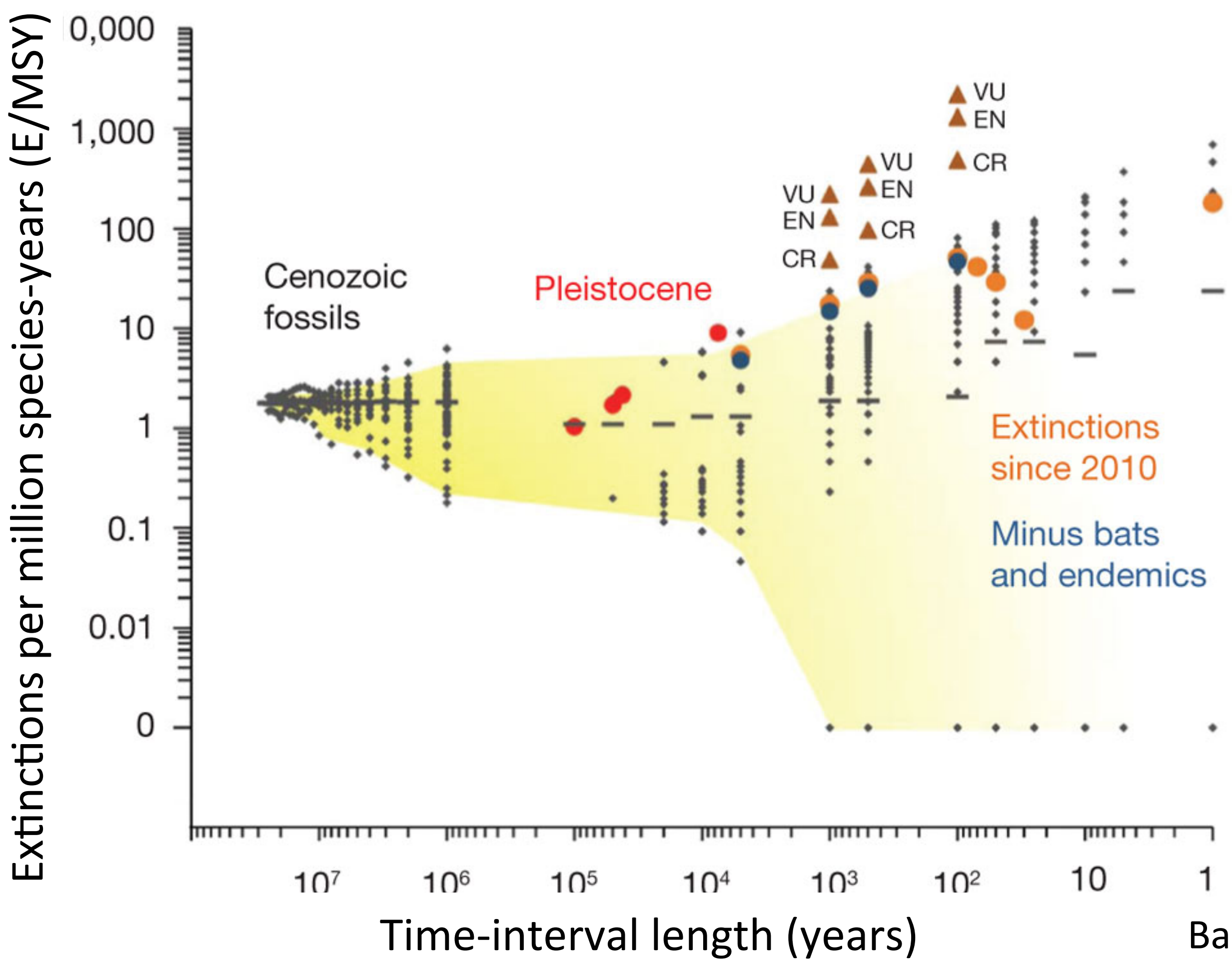
Recent extinction rates are 100 to 1000 times pre-human levels in well-known, but taxonomically diverse groups from widely different environments. If all species currently deemed "threatened" become extinct in the next century, then future extinction rates will be 10 times recent rates.

Pimm *et al*. 1995 *Science*

The sixth mass extinction?

A conservative assessment of ongoing extinction crisis through comparisons to diversity loss that characterized the "Big Five" – **Extinction Rate**

Relationship between extinction rates and time interval over which it is calculated, for mammals



Yellow shading indicates 95% CI (increasing uncertainty)

Horizontal lines indicate mean for each time bin

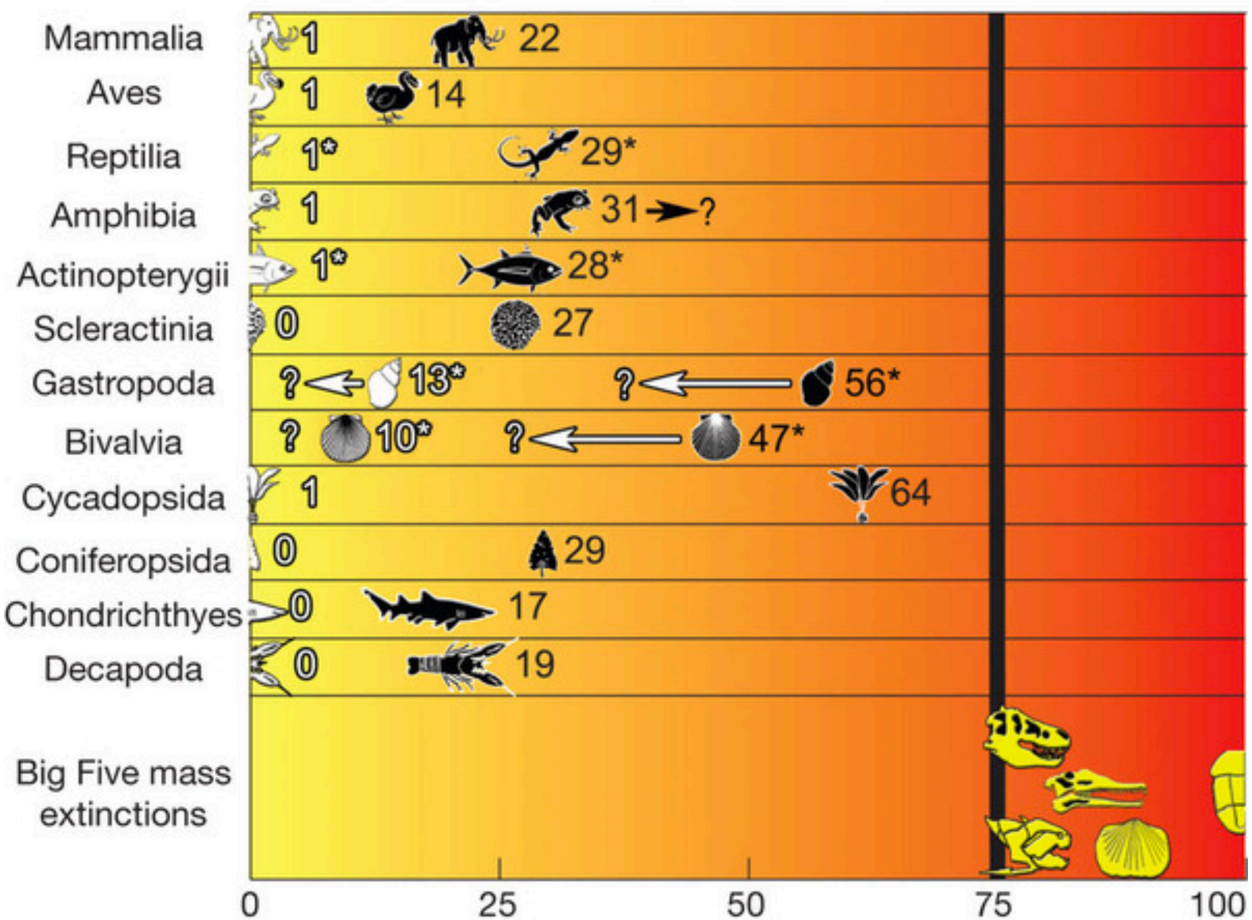
Large coloured blue/orange dots show rates since 2010

Triangles project rates if IUCN status mammals go extinct within ~ 100 years

Barnosky *et al.* 2011 *Nature*

The sixth mass extinction?

A conservative assessment of ongoing extinction crisis through comparisons to diversity loss that characterized the “Big Five” – **Extinction Magnitude**



Extinction magnitude (percentage of species)

Numbers next to each icon indicate percentage of species

White icons indicate species ‘extinct’ and ‘extinct in wild’

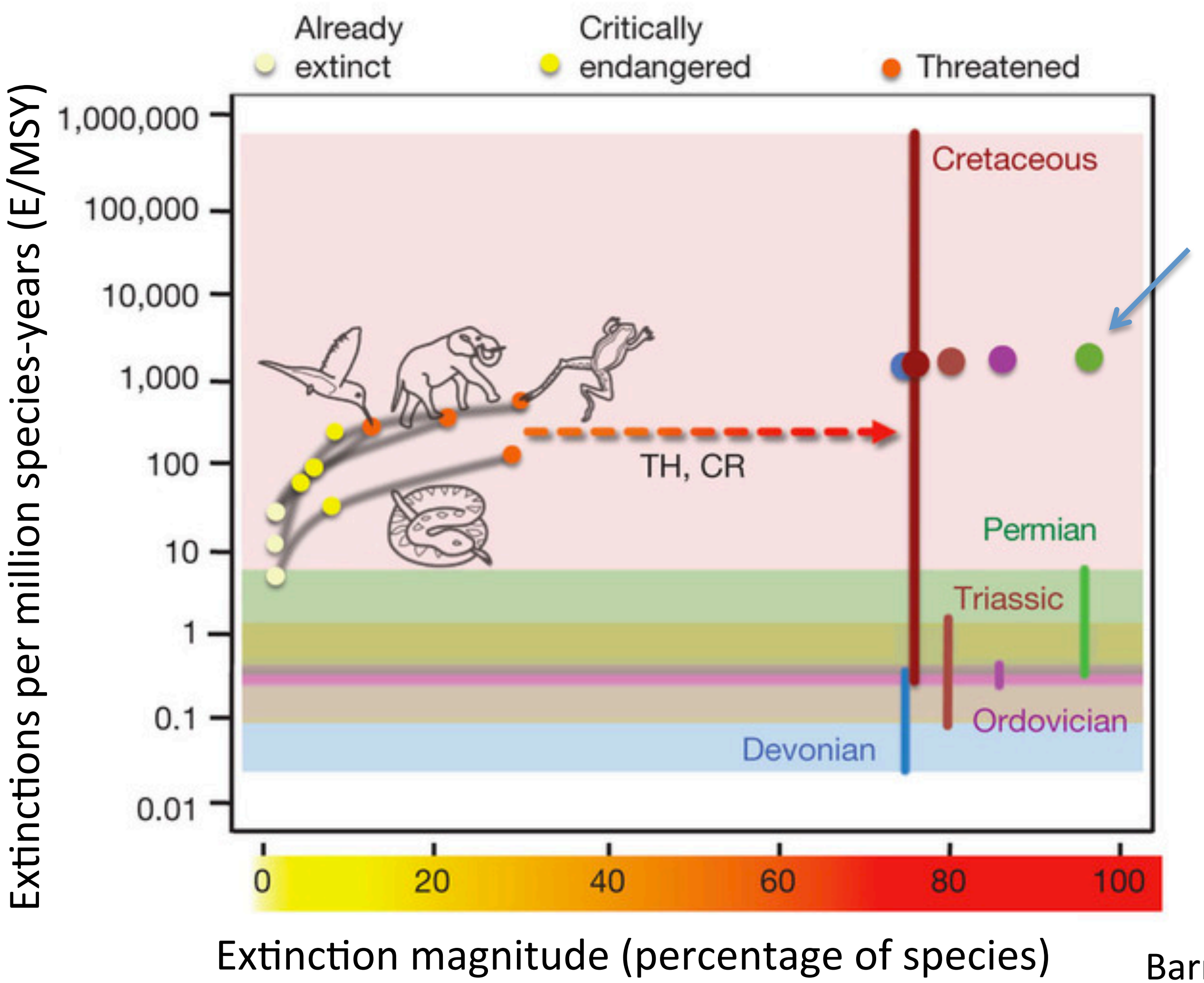
Black icons add currently ‘threatened’ species to those already extinct

Amphibian percentage may be as high as 43%

Barnosky *et al*. 2011 *Nature*

The sixth mass extinction?

A conservative assessment of ongoing extinction crisis through comparisons to diversity loss that characterized the "Big Five" – **Extinction Rate + Magnitude**



Coloured dots indicate what extinction rate would have been if extinctions happened over only 500 years (hypothetically).

If all threatened species go extinct, the time to 75% species loss would be ~240 – 540 years

Dots on left connected by lines indicate rate for past 500 years for vertebrates:

Light yellow = extinct species
Dark yellow = critically endangered
Orange = threatened

Barnosky *et al*. 2011 *Nature*

Challenges in measuring extinction

Measures of species extinctions may, in fact, underestimate the problem...

We could be losing species we don't even know we have:

- there could be as many as 50 million species on earth, yet fewer than 5 million have been discovered

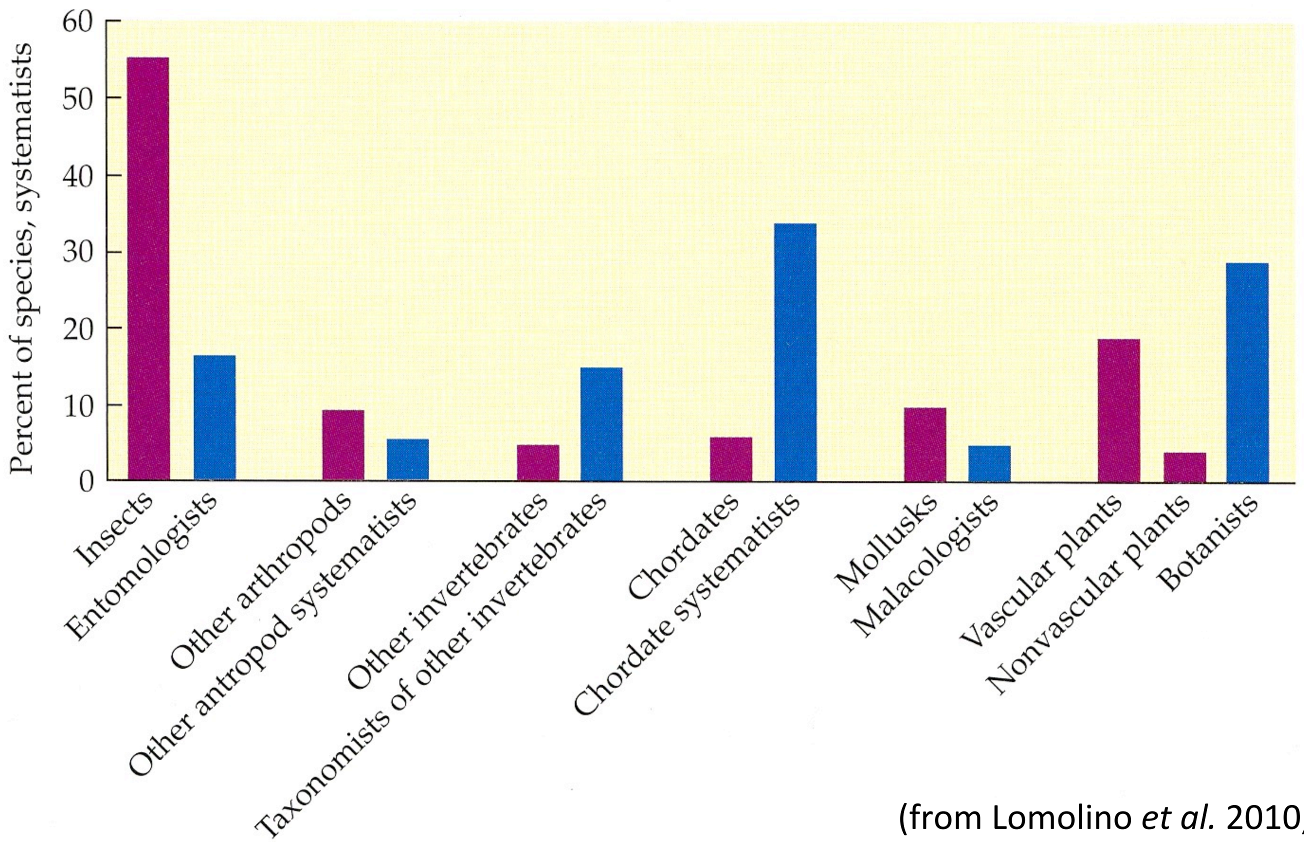
Linnaean Shortfall: the disparity between the number of known species and the number of species that actually exist

- 3 new families of flowering plants discovered in Mexico in last 20 years
- 349 species of mammals discovered between 1992 and 2008
- At least 12 species of birds discovered in the Andes since 2002
- Other diverse taxonomic groups (insects, fungi) may have millions of undescribed species
- Mora *et al*. 2011 estimated that 8.7 million species exist on Earth (86% of existing species on Earth, 91% of species in the ocean await description)

Challenges in measuring extinction

Measures of species extinctions may, in fact, underestimate the problem...

Part of the problem is the biased geographic distribution of taxonomists and systematists, and the shortfall in expertise for the most diverse taxa. The majority live, are trained, and work in temperate regions of the holarctic, which isn't where most of the species are.



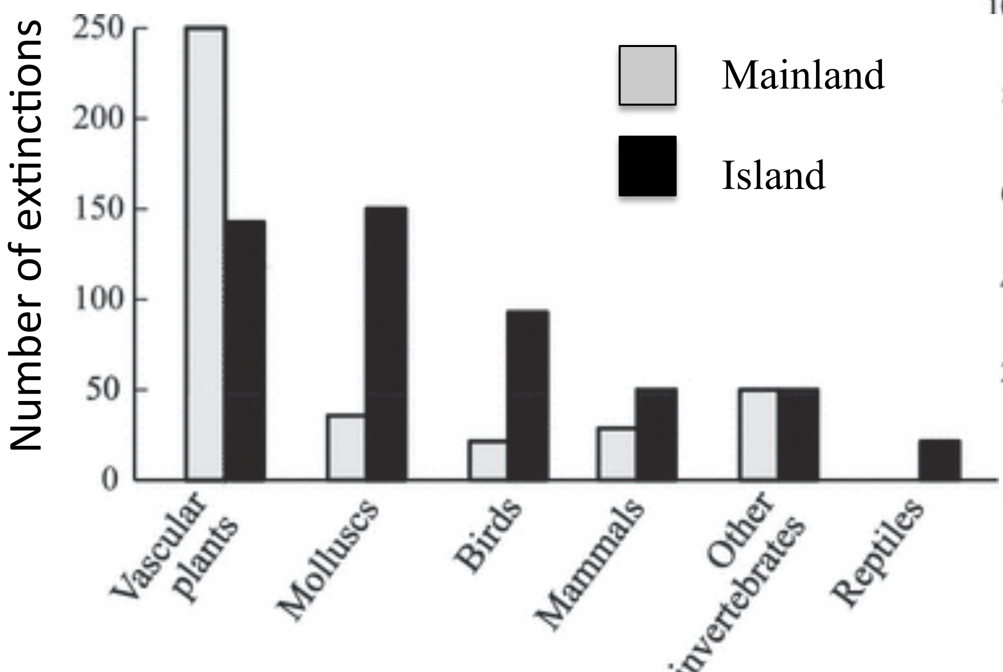
The majority of animals are insects, spiders, and other invertebrates, but only ~30% of systematists specialize in these groups

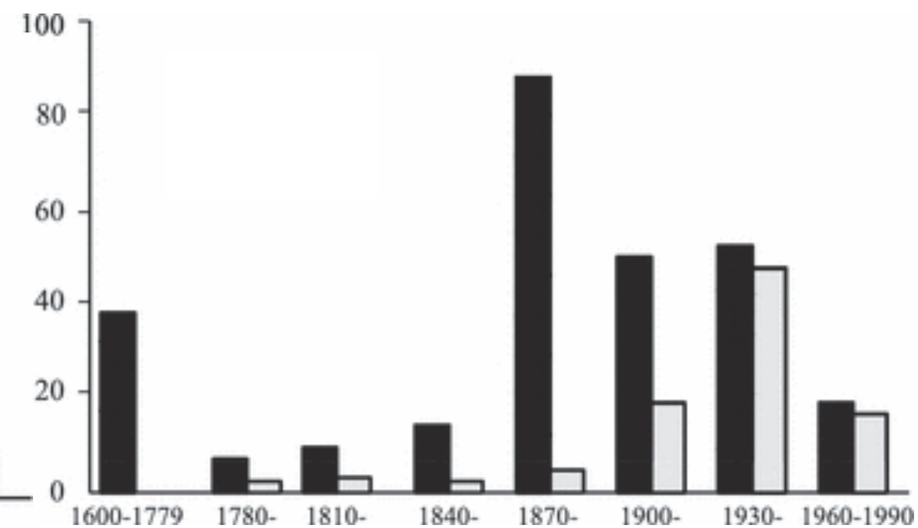
(from Lomolino *et al.* 2010, after Barrowclough 1992)

Patterns of Extinction

Overall, island life has been more susceptible to extinction – disproportionate number of extinctions of insular vs. continental animals over the past 500 years, mostly resulting from introduced species (including humans)

In recent decades extinction rates of continental animals have risen relative to oceanic islands – this may also be due to “insularity” caused by habitat conversion and fragmentation



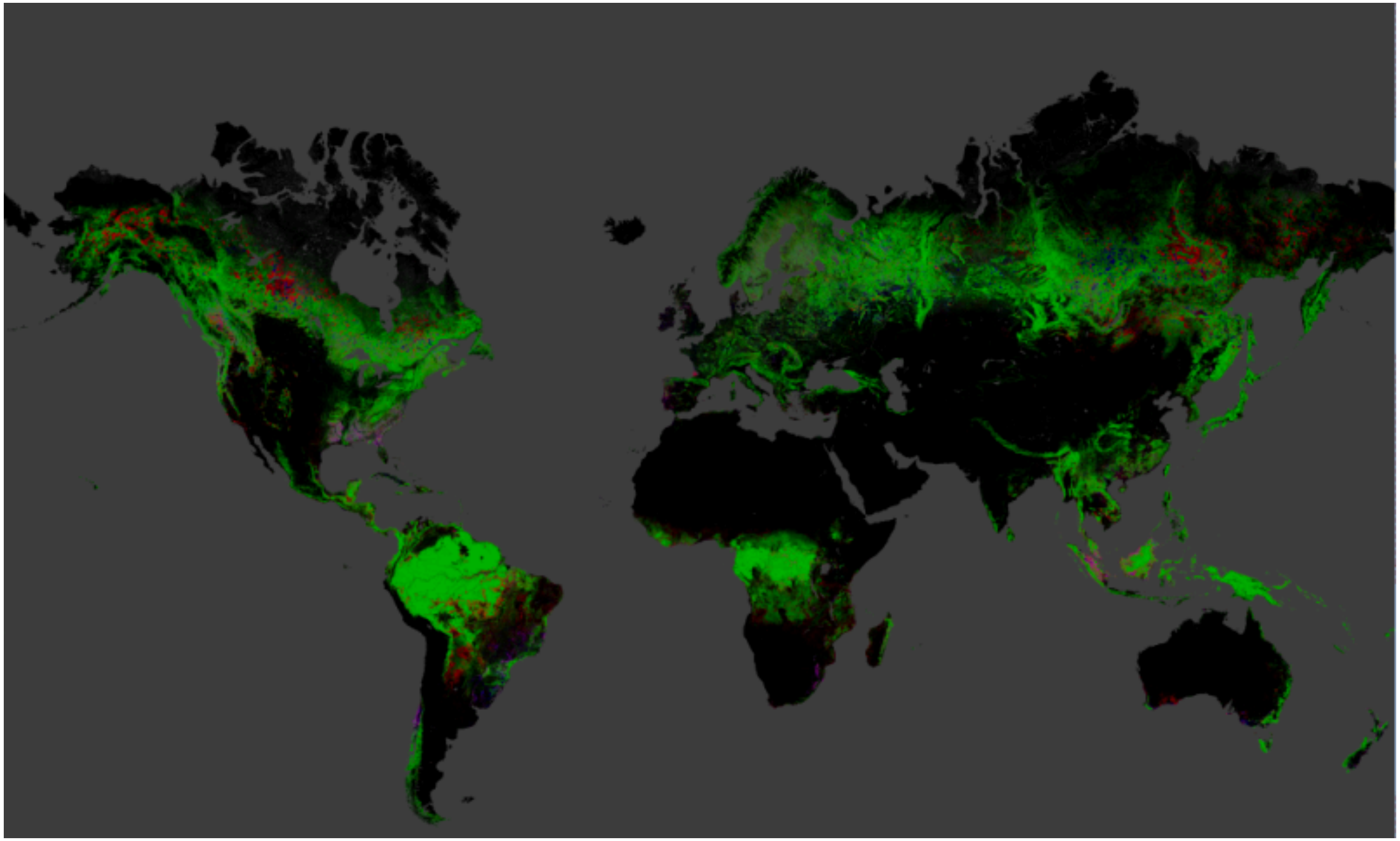


(Mammals, Molluscs and Birds)

Lomolino 2010, *Journal of Biogeography*

Patterns of Extinction

Change in global forest cover between 2000 - 2012. Green shows forest cover that has not changed. Black shows non-forest. Red shows forest loss. Blue shows forest gain. Magenta shows areas that are regrowing.



http://earthenginepartners.appspot.com/science-2013-global-forest, Hansen et al. 2013
CHECK OUT: http://www.globalforestwatch.org/map

Patterns of Range Collapse

Extinctions are preceded by declines in geographic ranges.

Which parts of the range are lost first?

- central or peripheral?
- poleward or equatorial?
- high or low elevation?

This question has important implications for:

- the reintroduction or translocation of endangered species
- the location of reserves
- the search for remnant populations

…Our restoration efforts could benefit from developing a "spatial search image" for the locations to protect that would yield the most favorable results.

Patterns of Range Collapse

Following some principles from biogeographic theory, we should prioritize efforts to protect core areas in the center of the range…

- Abundance – center hypothesis: population density tends to decrease moving from the range center to the periphery (e.g., Blackburn et al. 1999)
  - Range edges often represent population sinks
- "Melting range hypothesis" – dwindling populations should implode, with the final populations remaining near the center of a species historic range (Gaston 2003)

Patterns of Range Collapse

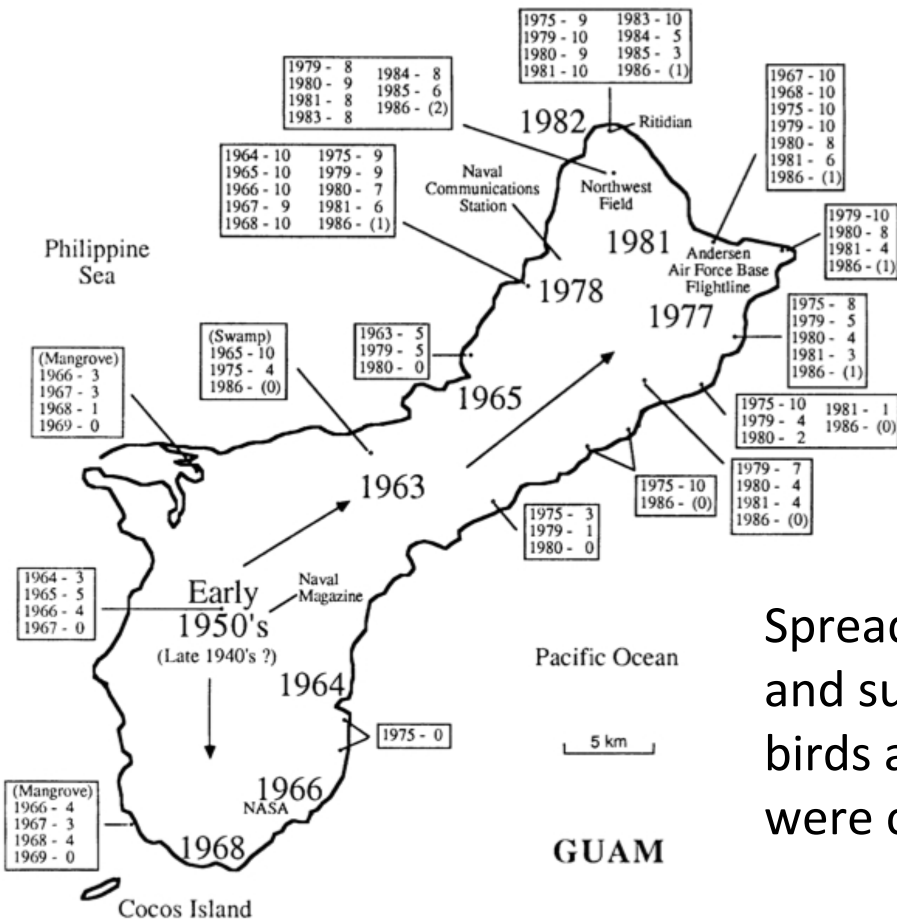
Following some principles from biogeographic theory, we should prioritize efforts to protect core areas in the center of the range…

…But patterns of collapse often show a different dynamic: general macroecological patterns of population density and variability are overwhelmed by anthropogenic disturbance

So we must consider the source and the nature of the threats that species and their populations face.

Patterns of Range Collapse

Patterns of collapse often show a different dynamic – general macroecological patterns of population density and variability are overwhelmed by anthropogenic disturbance



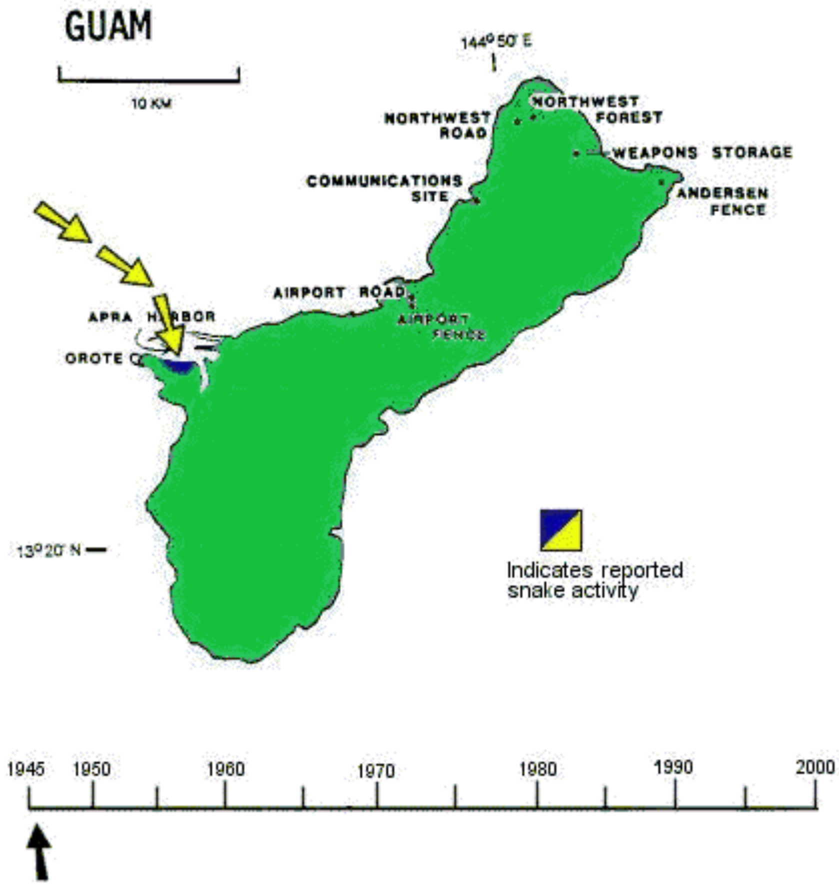
Brown tree snake (*Boiga irregularis*)

Spread of brown tree snake on Guam (arrows) and subsequent declines in numbers of native birds across years. Last remaining populations were concentrated in the north of the island.

Savidge 1987 *Ecology*

Patterns of Range Collapse

Patterns of collapse often show a different dynamic – general macroecological patterns of population density and variability are overwhelmed by anthropogenic disturbance



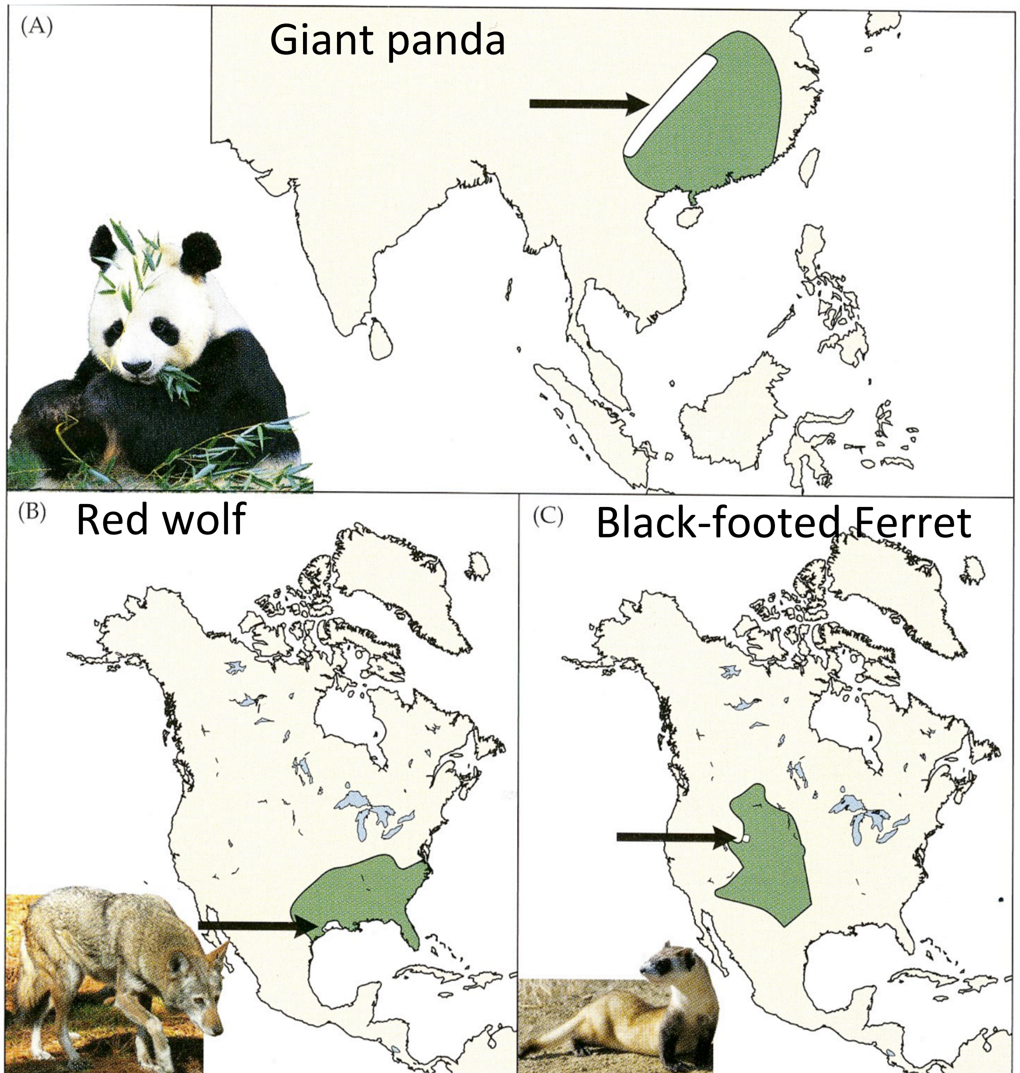
Brown tree snake (*Boiga irregularis*)

USGS Timeline of the Brown tree snake travel across Guam

http://www.fort.usgs.gov/resources/education/bts/invasion/colonize.asp#dispersal

Patterns of Range Collapse

Extinctions are preceded by declines in geographic ranges



Patterns of range collapse for three species of terrestrial mammals

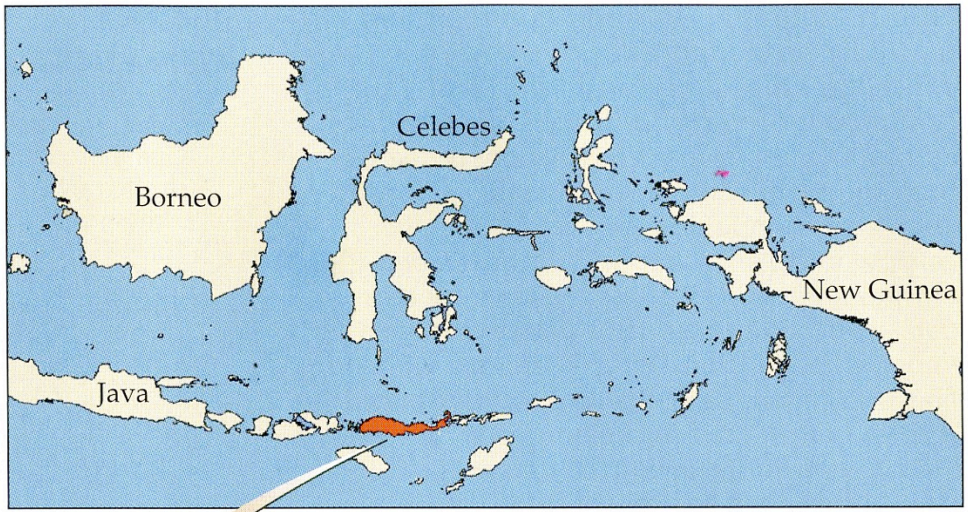
Each maintains a small remnant population (white) at the periphery of the historical range (green)

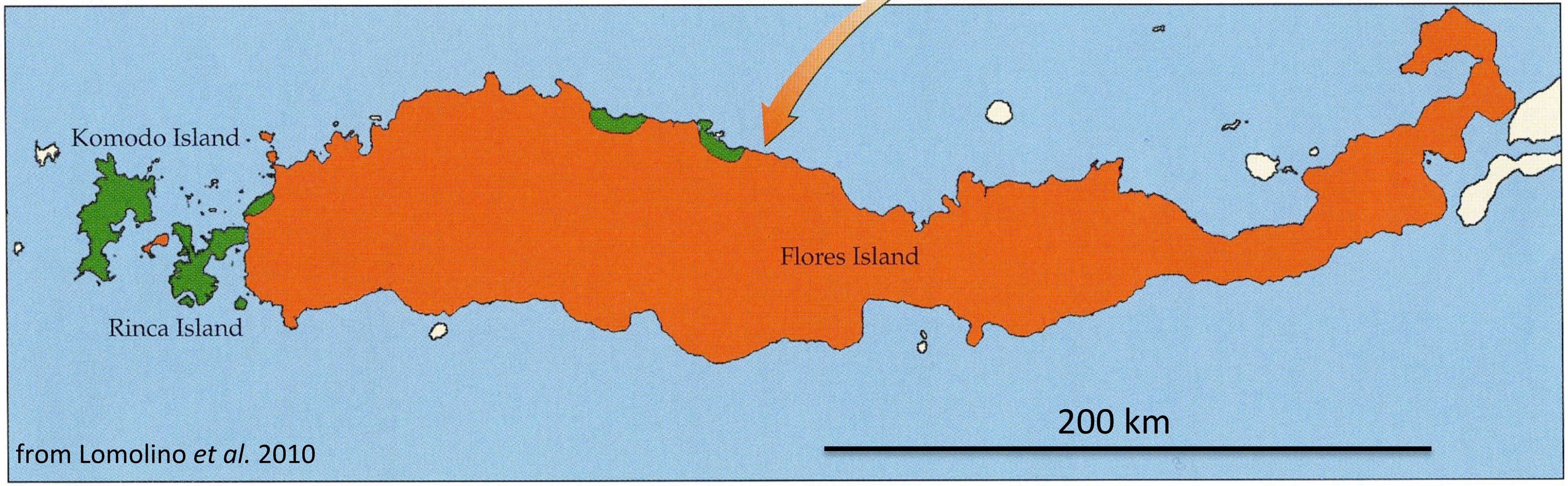
from Lomolino *et al.* 2010

Patterns of Range Collapse

Extinctions are preceded by declines in geographic ranges

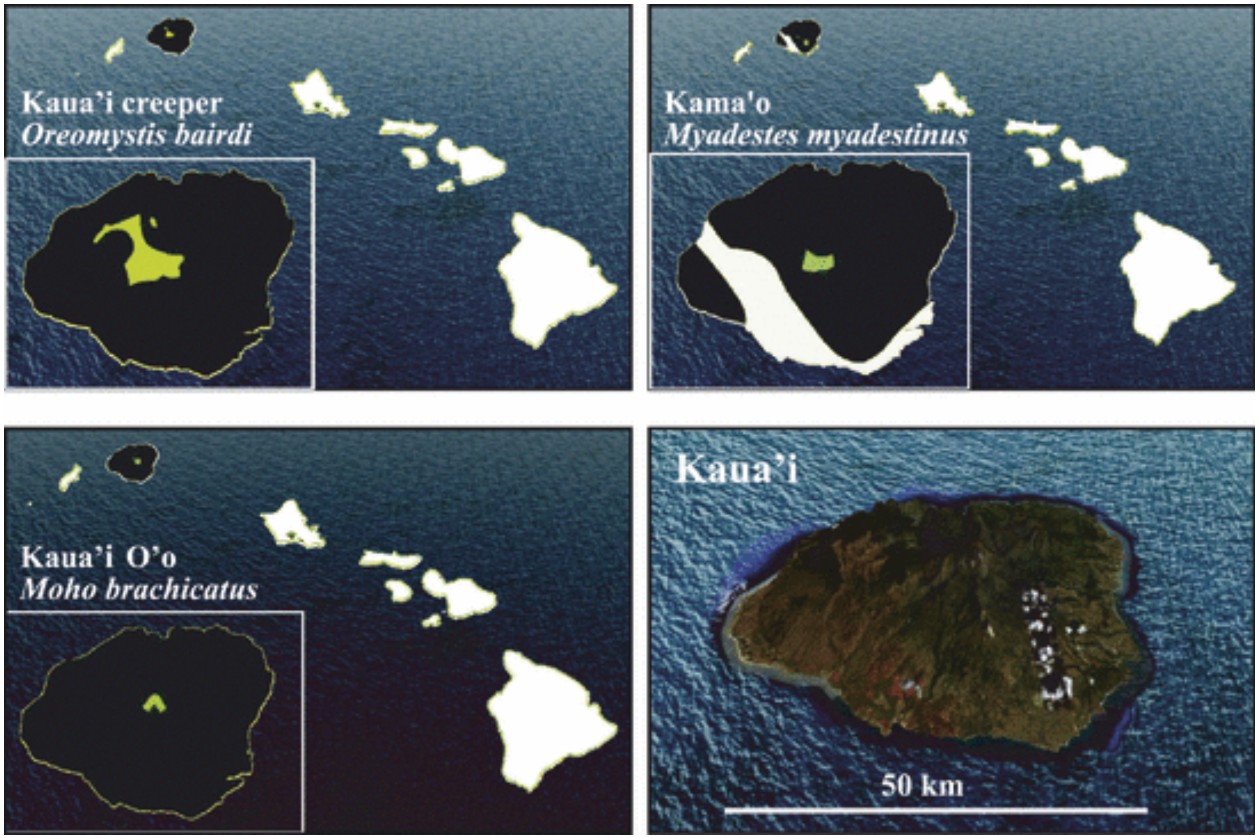
Komodo dragon persists on true islands and isolated regions in periphery of former range





Patterns of Range Collapse

Extinctions are preceded by declines in geographic ranges



Historical range

Extant/final range

Why are native bird species only found in the center of the island?

What habitats are found there, how could that be associated with the cause and pattern of population decline?

Lomolino 2010, *Journal of Biogeography*

Patterns of Range Collapse

Extinctions are preceded by declines in geographic ranges

Anthropogenic disturbances are nonrandom and predictably dynamic – they tend to spread like a contagion across the landscape.

Contagion Hypothesis: populations persist in isolated areas, as extinction proceeds along predictable routes

Populations along the periphery of a range represent more numerous potential "pockets", possibly with greater variation among populations (physiological, behavioural, ecological, genetic).

Peripheral diversity/preadaptation hypothesis: higher diversity of peripheral areas and adaptation to diverse marginal environments may allow persistence of peripheral populations

Biodiversity and the Geography of Extinctions

Overview:

Previous Mass Extinctions

Current Extinction Rates

Patterns of Range Collapse

Biodiversity Hotspots

Mapping global diversity and extinction threat (Ex. Mammals)

Identifying Evolutionary Significant Units (ESUs)

Evolutionary Distinct Globally Endangered (EDGE) Species

If we can't protect everything, what should we prioritize?

Biodiversity Hotspots

Biodiversity Hotspots: areas where geographic ranges of many species overlap

Hotspots can be defined by high species richness or high endemism, or both.

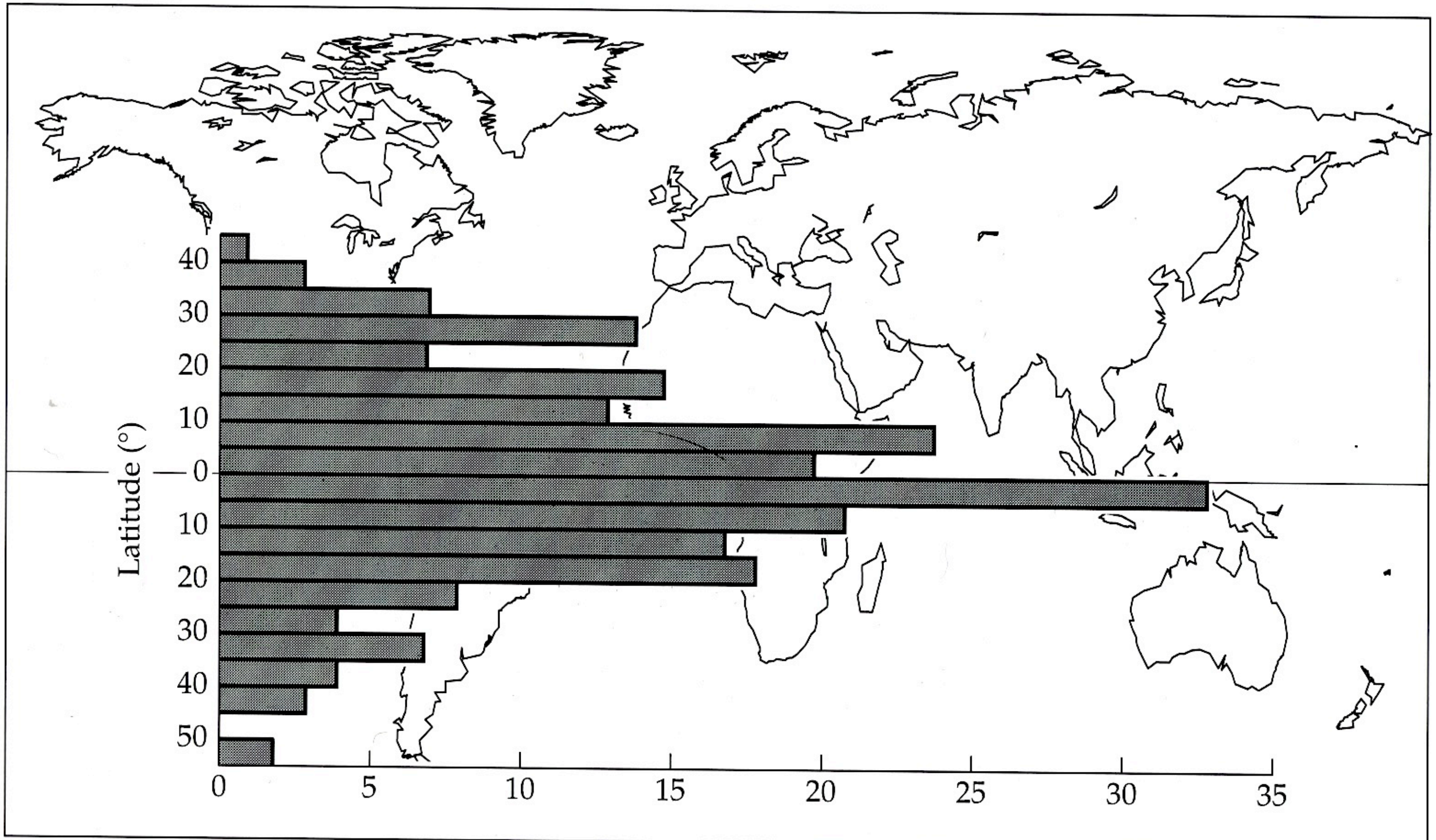
Hotspots with high endemism are particularly important:

- The probability of extinction increases with decreased range size.
- Hotspots of endemism are regions where habitat loss could result in the greatest loss of biodiversity per unit area.

Biogeographic surveys that identify such hotspots can help prioritize areas for conservation attention.

Biodiversity Hotspots

For birds, like many species, endemism is concentrated in tropical regions.



Latitudinal trend in the distribution of Endemic Bird Areas: areas containing breeding ranges of at least two restricted-range species (Brown & Lomolino 1998)

Biodiversity Hotspots

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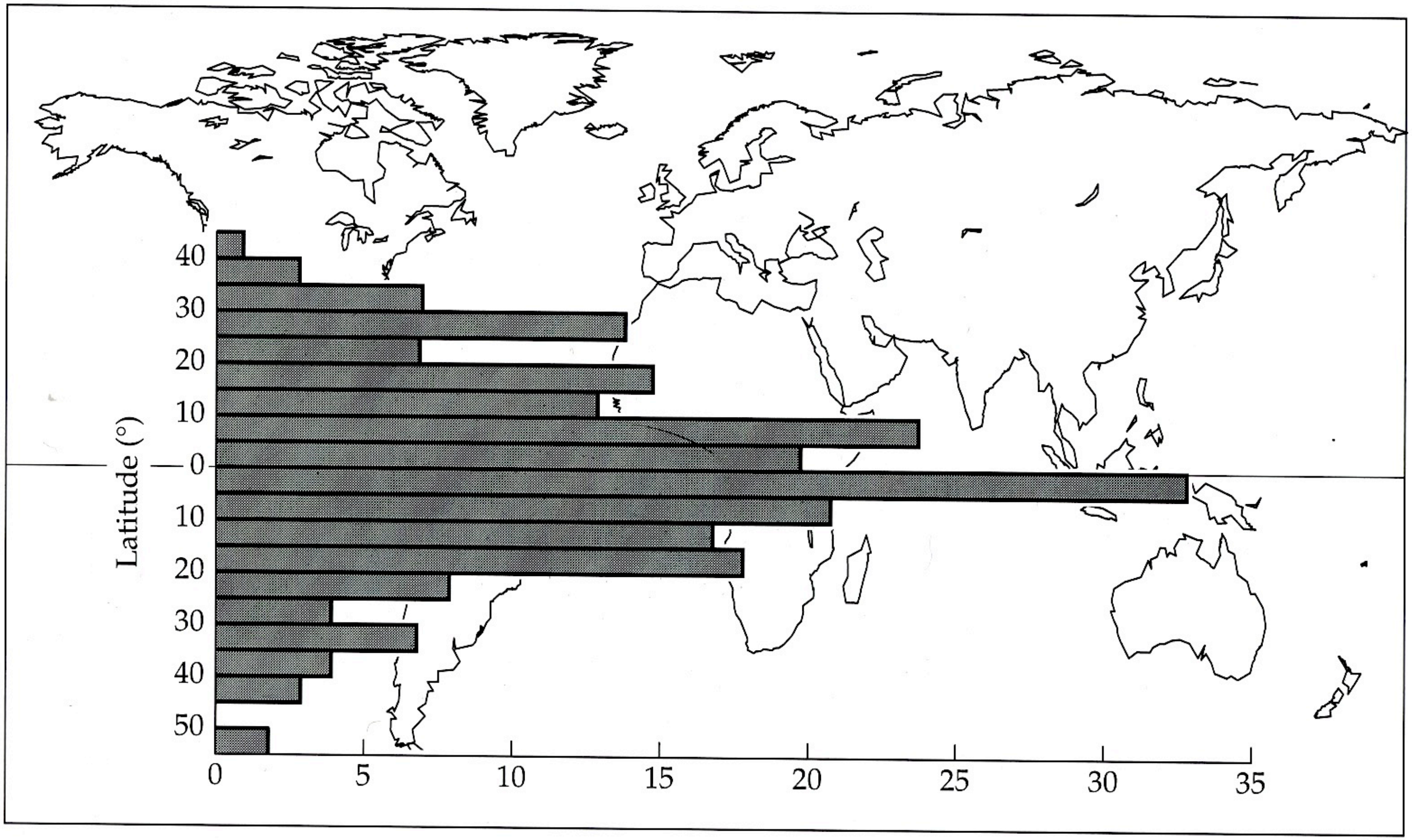


Recall Rapoport's Rule: species have larger range sizes at higher latitudes.
As a corollary, species in the tropics have smaller ranges ~ higher rates of endemism

Biodiversity Hotspots

Myers *et al.* 2000. Biodiversity hotspots for conservation priorities. *Nature* 403: 853-858

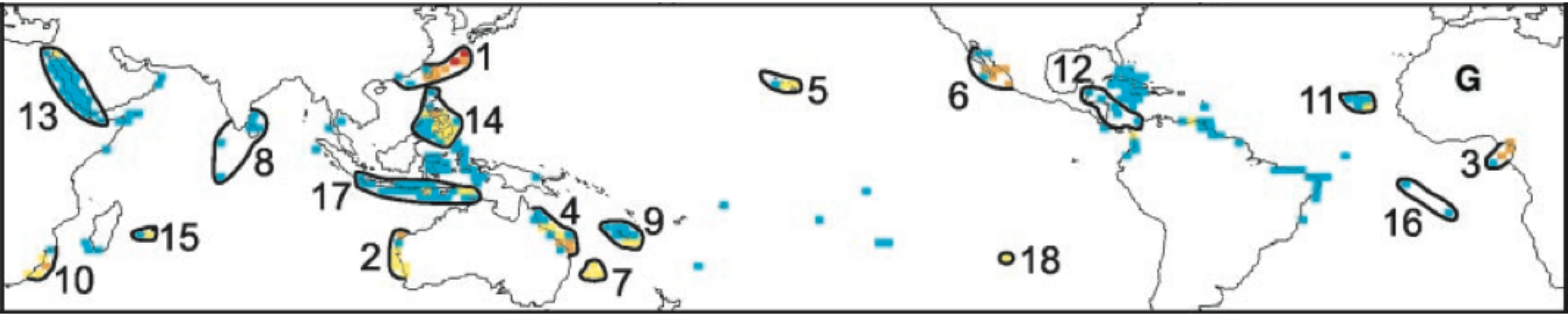
Cited 20,426 times – Google Scholar

Conservationists are far from able to assist all species under threat, if only for lack of funding. This places a premium on priorities: how can we support the most species at the least cost? One way is to identify 'biodiversity hotspots' where exceptional concentrations of endemic species are undergoing exceptional loss of habitat. As many as 44% of all species of vascular plants and 35% of all species in four vertebrate groups are confined to 25 hotspots comprising only 1.4% of the land surface of the Earth. This opens the way for a 'silver bullet' strategy on the part of conservation planners, focusing on these hotspots in proportion to their share of the world's species at risk.

Biodiversity Hotspots

Roberts *et al.* 2002. Marine biodiversity hotspots and conservation priorities for tropical reefs. *Science* 295: 1280-1284. Cited 1248 times – Google Scholar

Analyses of the geographic ranges of 3235 species of reef fish, corals, snails, and lobsters revealed that between 7.2% and 53.6% of each taxon have highly restricted ranges, rendering them vulnerable to extinction. Restricted-range species are clustered into centers of endemism, like those described for terrestrial taxa. The 10 richest centers of endemism cover 15.8% of the world's coral reefs (0.012% of the oceans) but include between 44.8 and 54.2% of the restricted-range species.



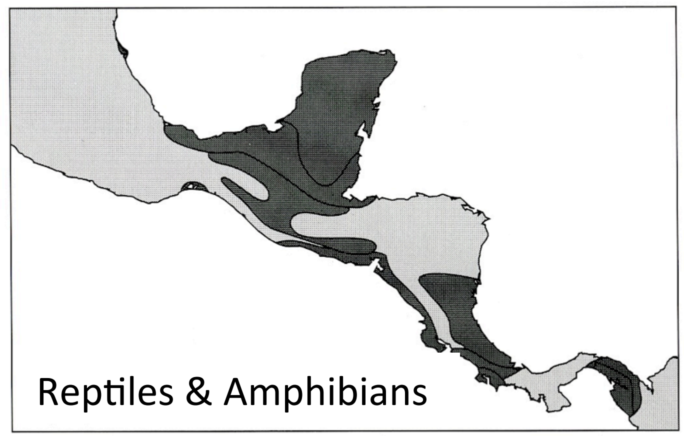
Marine biodiversity hotspots with adjacent terrestrial hotspots (after Myers *et al.* 2000) in parentheses:

1. South Japan	(Philippines)	10. Eastern South Africa	(Cape Floristic Province)
2. Western Australia	(Southwest Australia)	11. Cape Verde Islands	(none)
3. Gulf of Guinea	(West African Forests)	12. West Caribbean	(Mesoamerica)
4. Great Barrier Reef	(none)	13. Red Sea	(none)
5. Hawaiian Islands	(Polynesia / Micronesia)	14. Philippines	(Philippines)
6. Gulf of California	(Mesoamerica)	15. South Mascarene Islands	(Madagascar)
7. Lord Howe Island	(New Zealand)	16. St. Helena and Ascension Islands	(none)
8. North Indian Ocean	(Western Ghats and Sri Lanka)	17. Sunda Islands	(Sundaland / Wallacea)
9. New Caledonia	(New Caledonia)	18. Easter Island	(Polynesia / Micronesia)

Biodiversity Hotspots

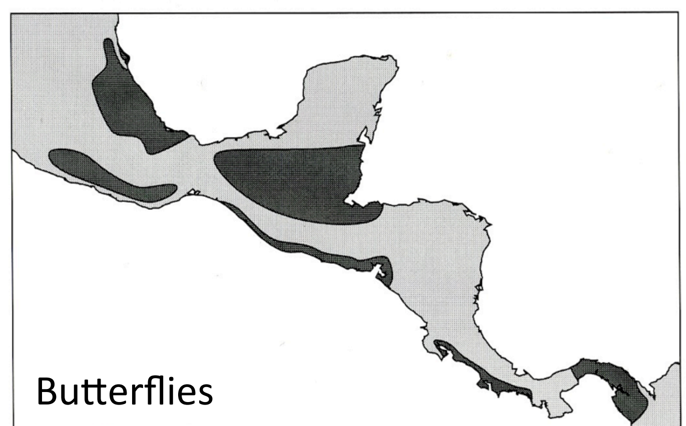
Hotspots are usually restricted to a subset of taxa

- The terrestrial hotspots proposed by Myers *et al.* (2000) don't consider invertebrates, which comprise 95% of all animal species.
- Frequently, areas of endemism for different taxa do not overlap.



This figure shows shows the overlap (or lack of) in areas of endemism in Central America for birds, herps and butterflies

(from Brown & Lomolino 1998)



Global diversity and extinction threat in mammals

Covers all 5487 mammal species recognized as extant since 1500

Data on taxonomy, distribution, habitats, population trends, including threats to, human use of, ecology of and conservation measures for species

Used hexagonal grid cells of 22,300 km^2

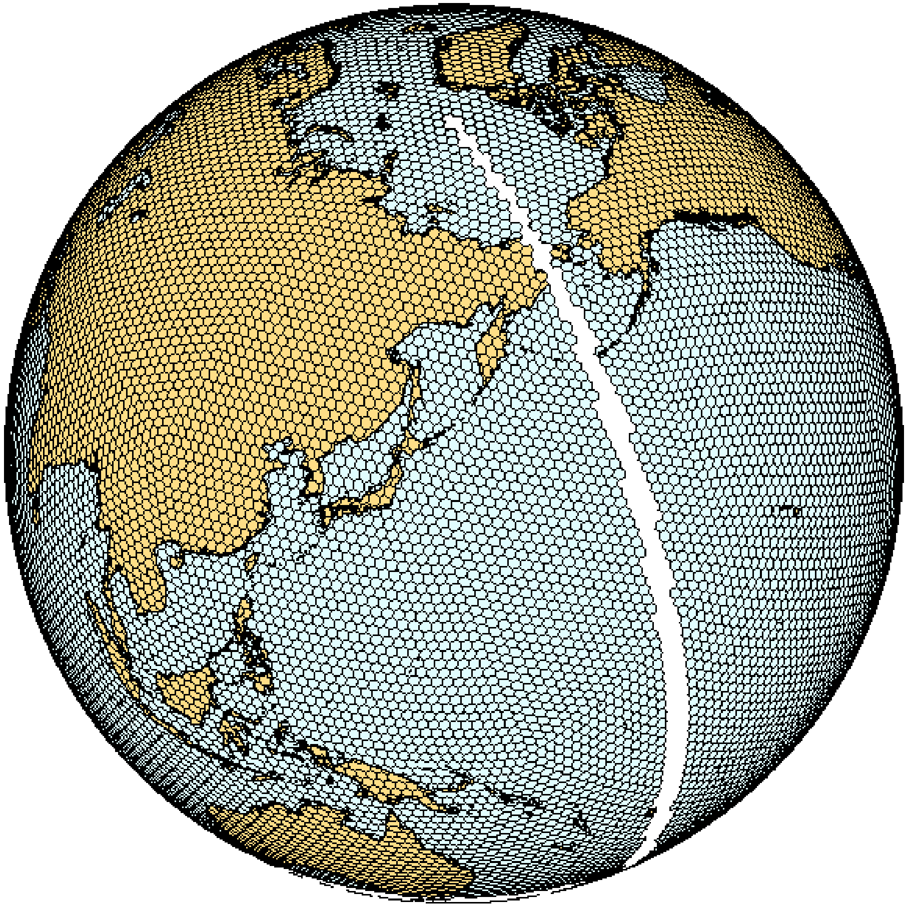


Figure S2. from Schipper et al. 2008, *Science*

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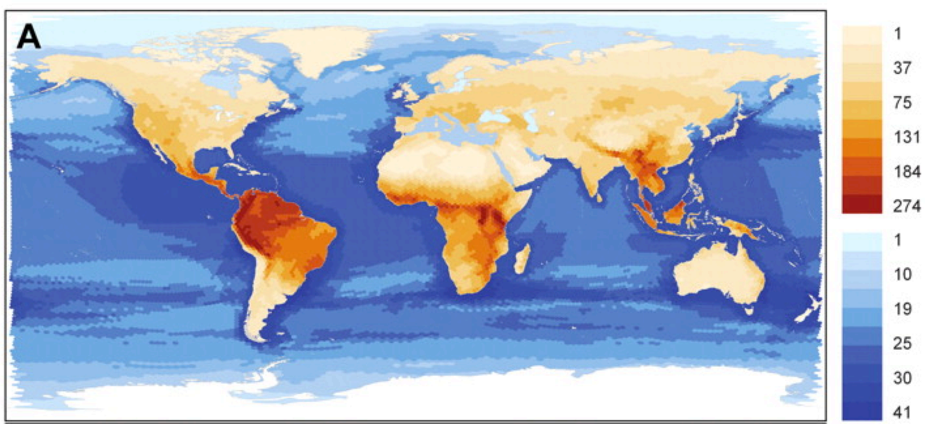
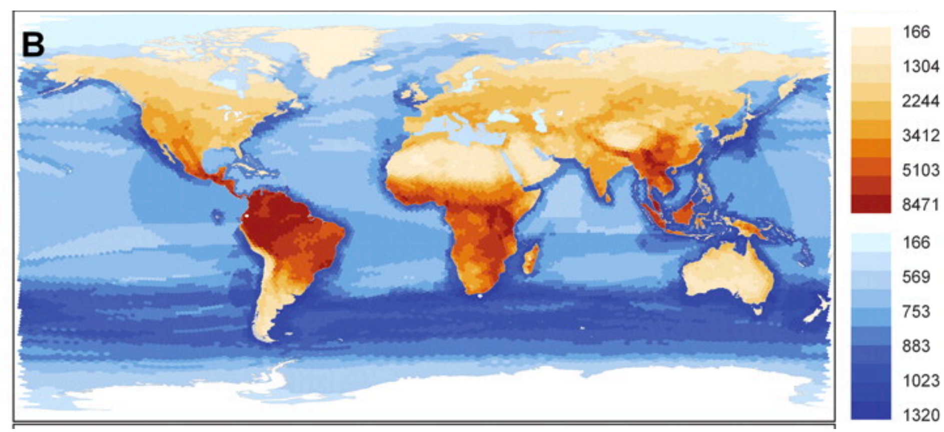
Species Richness



Phylogenetic diversity



Terrestrial/freshwater (brown); Marine (blue)

Phylogenetic diversity = total branch length of phylogenetic tree representing those species within each cell (in millions of years)

Schipper et al. 2008, *Science*

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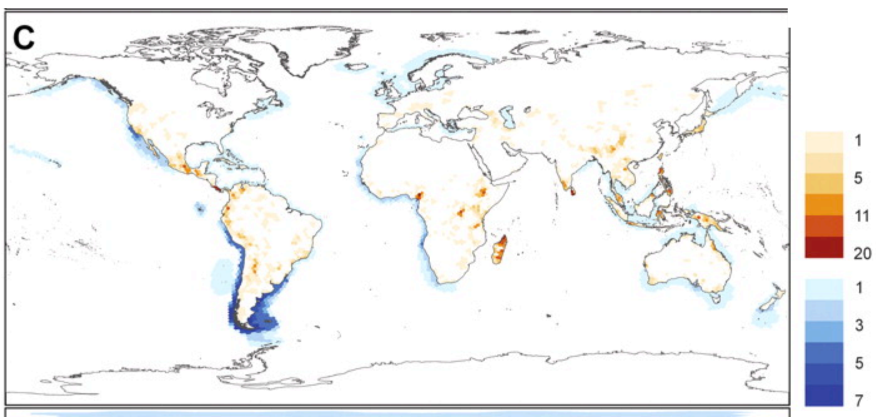
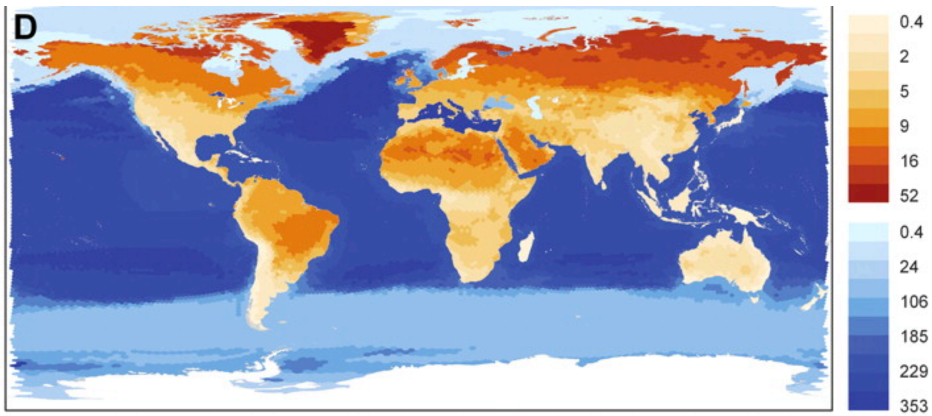
Number of restricted-range species



Median range size of species (in million km^2)



Terrestrial/freshwater (brown); Marine (blue)

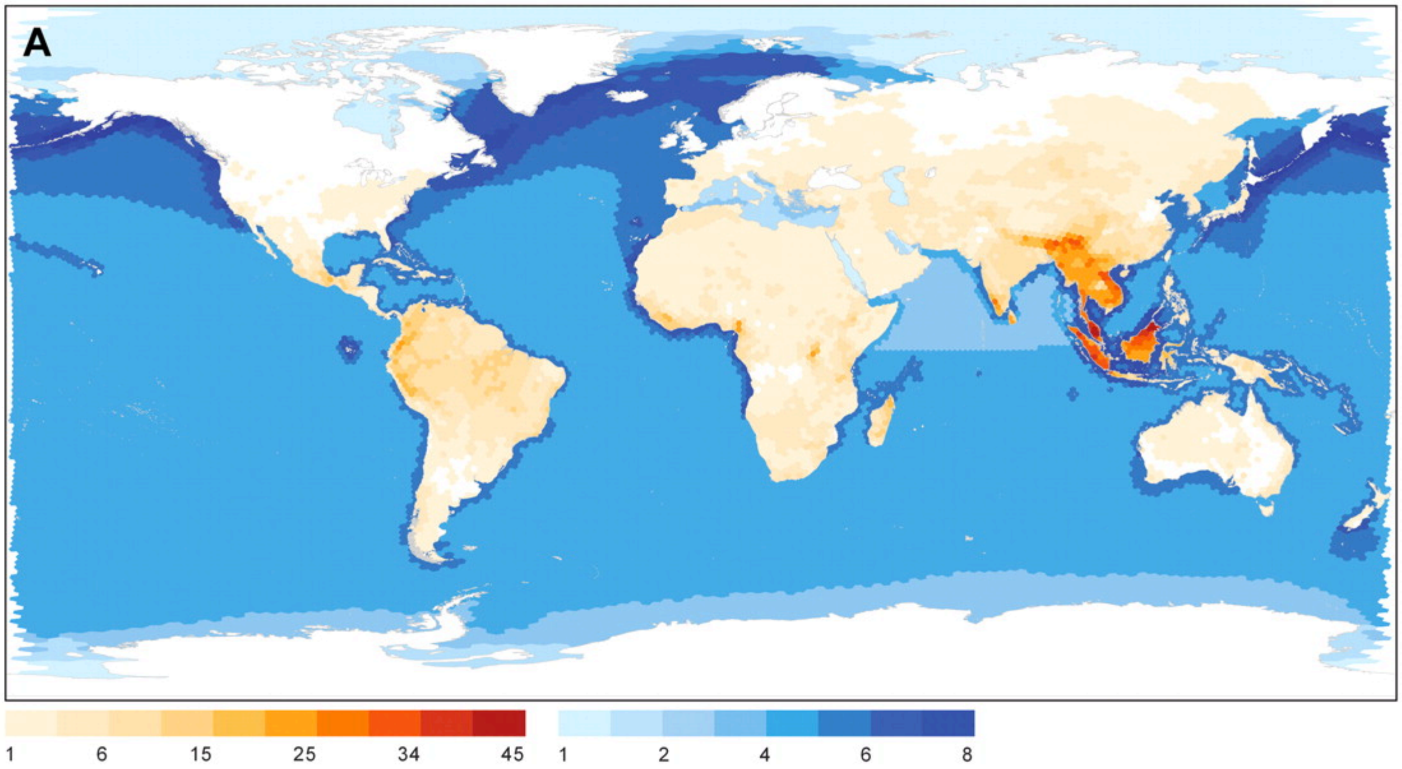
Restricted-range species = those 25% species with the smallest ranges

Schipper et al. 2008, *Science*

Global diversity and extinction threat in mammals

Global patterns of threat for Terrestrial (brown); Marine (blue)

Number of globally threatened species (Vulnerable, Endangered or Critically Endangered



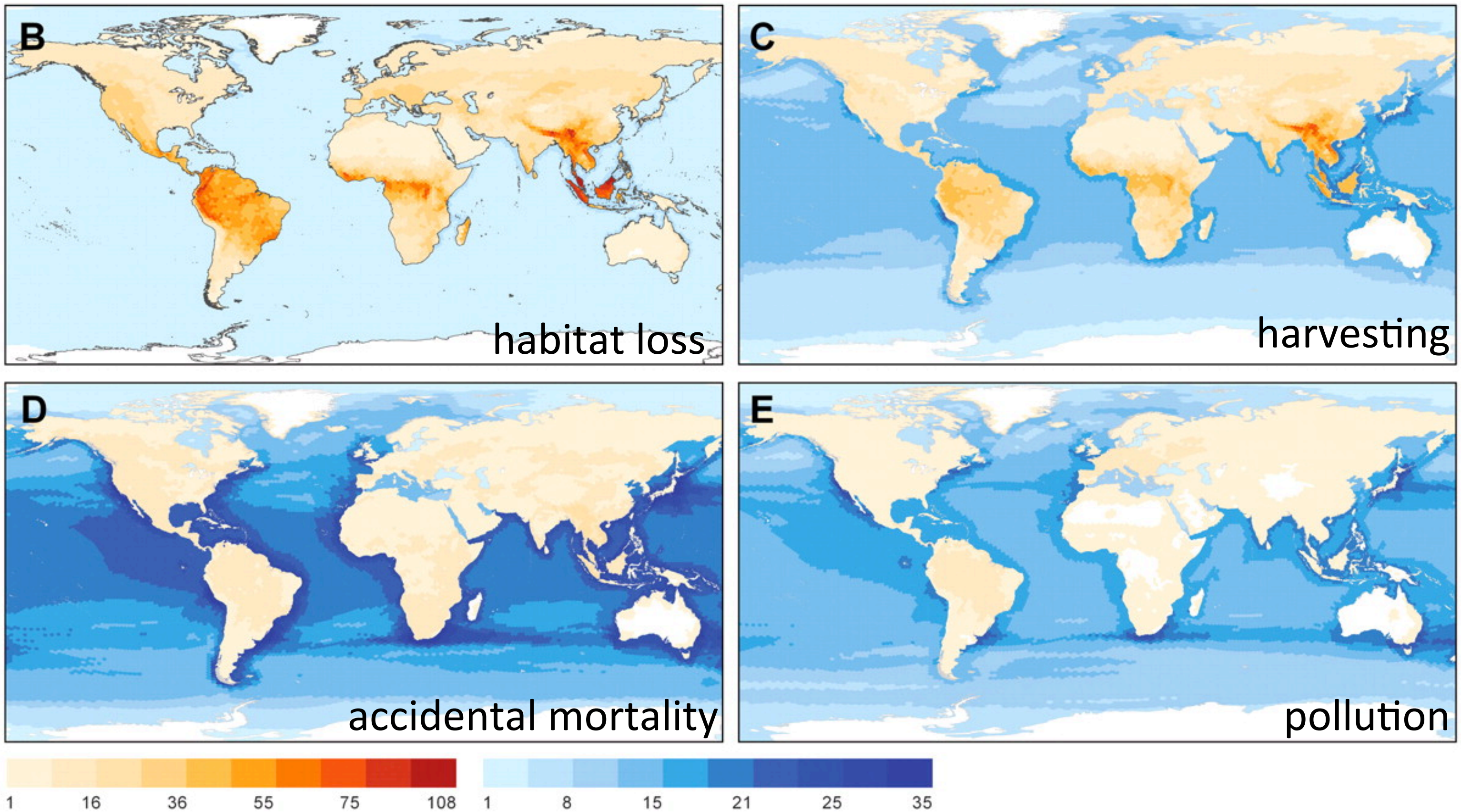
Threatened land animals are concentrated in South/Southeast Asia (e.g., 79% of primates)
Threatened marine species are concentrated in the N. Atlantic and Pacific and Southeast Asia

Schipper et al. 2008, *Science*

Global diversity and extinction threat in mammals

Global patterns of threat for Terrestrial (brown); Marine (blue)

Number of species affected by different threats (same color scale, directly comparable)

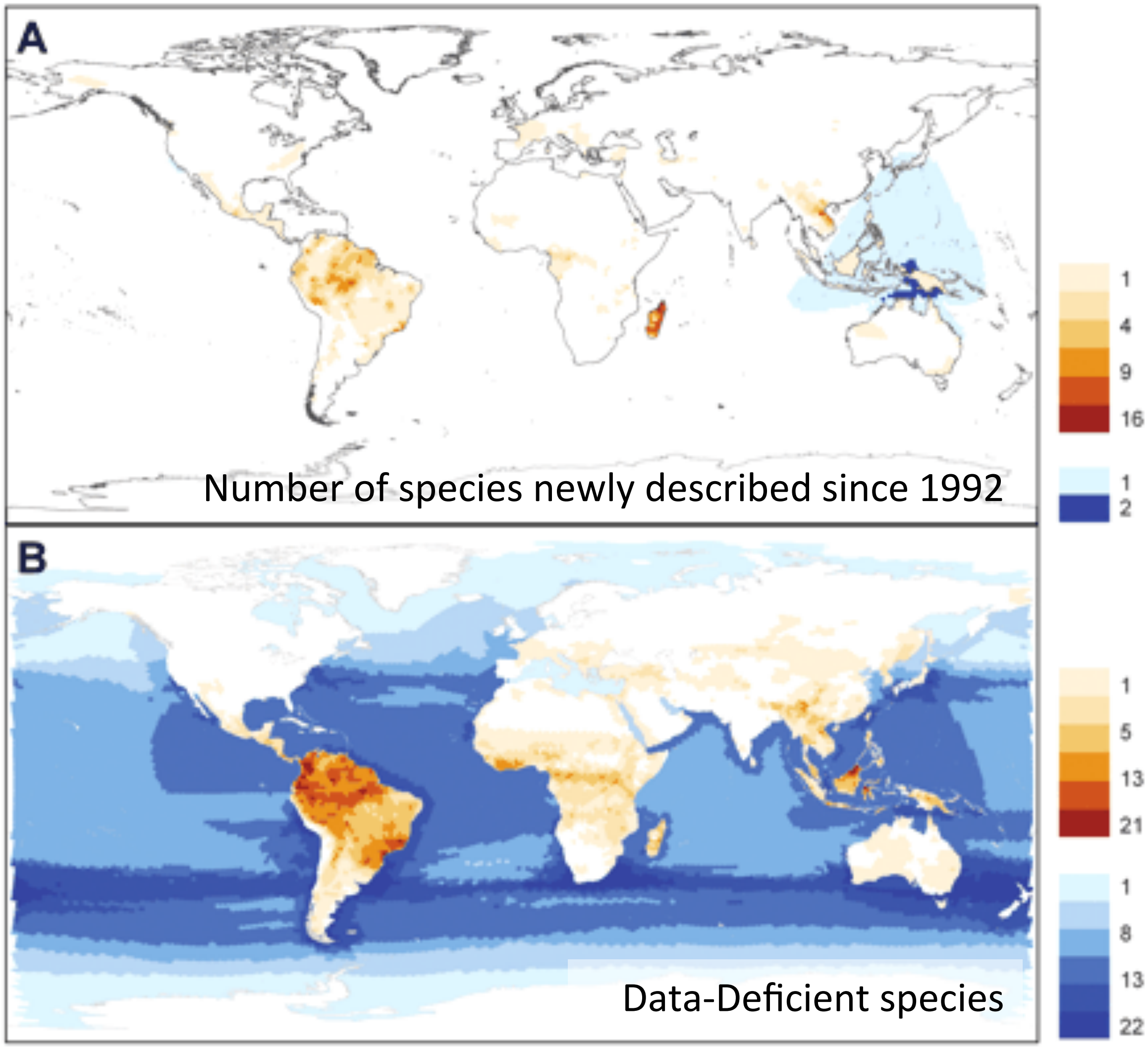


Terrestrial habitat loss is prevalent across tropics; harvesting is highest in Asia. Marine mammals highly affected by by-catch and vessel strikes, ocean pollution, climate change and harvesting.

Schipper et al. 2008, *Science*

Global diversity and extinction threat in mammals

Global patterns of knowledge for Terrestrial/freshwater (brown); Marine (blue)



Mammals are best known taxon but are still discovered at high rates

Number of recognized species increased by 10% since 1992

349 newly described species

512 taxa elevated to species level

Most data-deficient species on land are in tropical forests

Marine data-deficient species are concentrated along Antarctic Convergence (e.g., beaked whales)

Schipper et al. 2008, *Science*

Identification of Evolutionary Significant Units

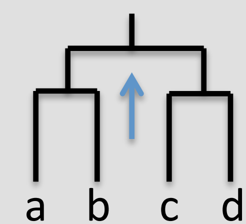
Biogeographical principles are used to identify Evolutionarily Significant Units

The term *evolutionarily significant unit* (ESU) was coined in the mid-1980s to develop an empirical definition of intraspecific groups that are the most important units for conservation below the species level (see Ryder 1986). These ESUs represent the heritage of a species as well as groups with distinct characteristics and tendencies.

Evolutionarily Significant Unit (ESU): a population, or group of populations, that is substantially reproductively isolated from other such groups and which represent an *important* part of the evolutionary legacy of a species (Waples 1995).

How much divergence is enough?

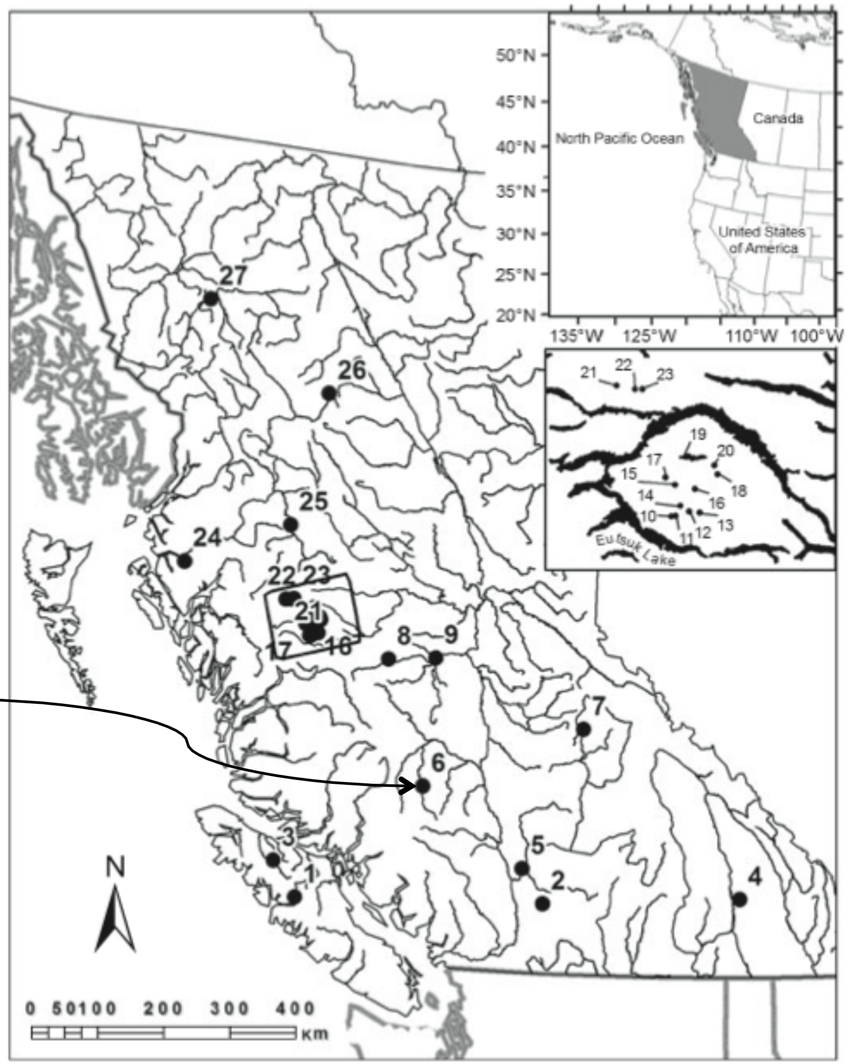
Groups of populations with reciprocally monophyletic mtDNA lineages and differ significantly in allele frequencies at nuclear loci (Moritz 1994).



Identification of ESUs

Biogeographical principles are used to identify Evolutionarily Significant Units

Fish Lake

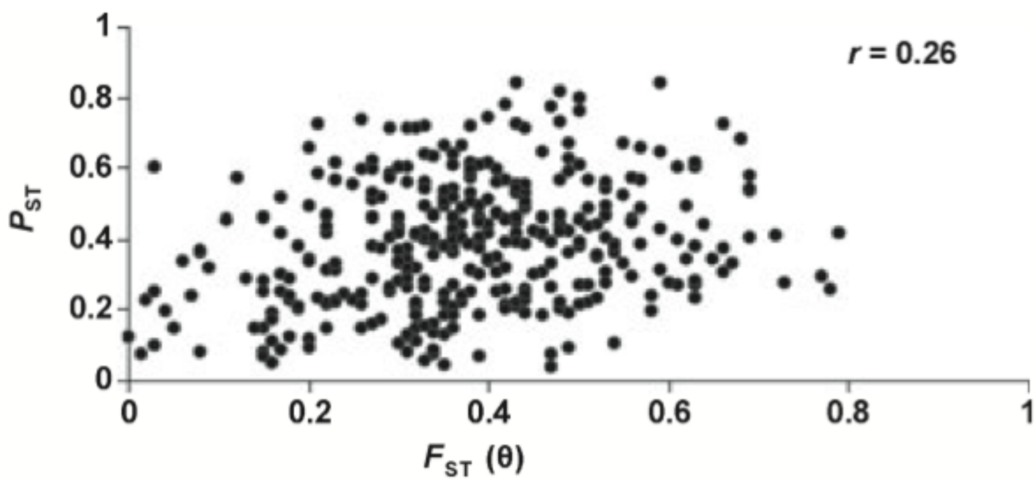


Taylor *et al.* (2011) measured the genetic and morphological distinctiveness of rainbow trout (*Oncorhynchus mykiss*) populations across BC.

Identification of ESUs

Biogeographical principles are used to identify Evolutionarily Significant Units

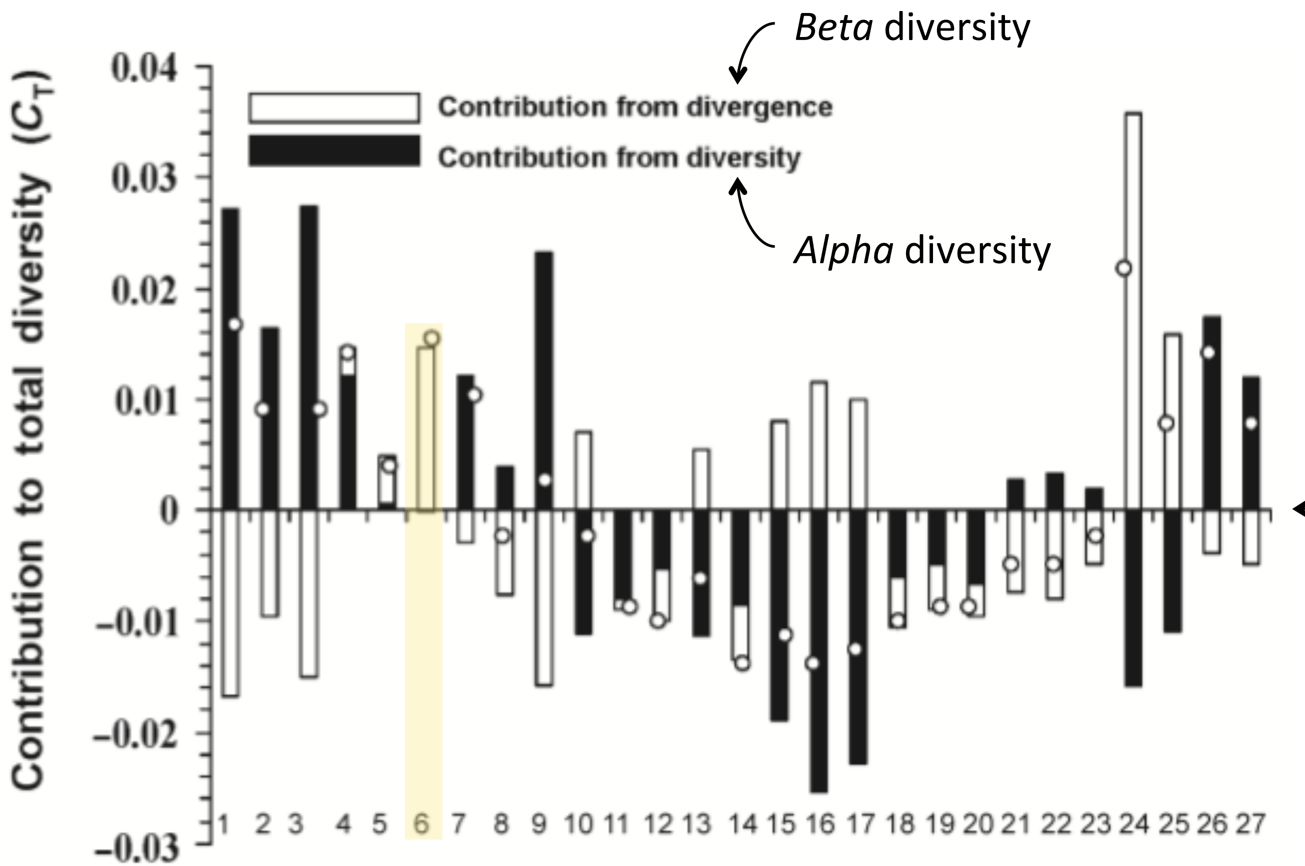
To be considered evolutionarily important, a population should usually occupy an unusual habitat or display an unusual phenotype. Phenotypic traits are suspected to have significant adaptive value. Genetic distinctiveness is often considered as a proxy for phenotypic distinctiveness.



Taylor *et al.* (2011) found a significant relationship between morphological divergence (P_{ST}) and genetic divergence (F_{ST}), suggesting that genetic divergence can be a proxy for the history or 'biological heritage' of a taxon as well as reflect contemporary biology (e.g., demographic bottlenecks in population size) and future evolutionary potential.

Identification of ESUs

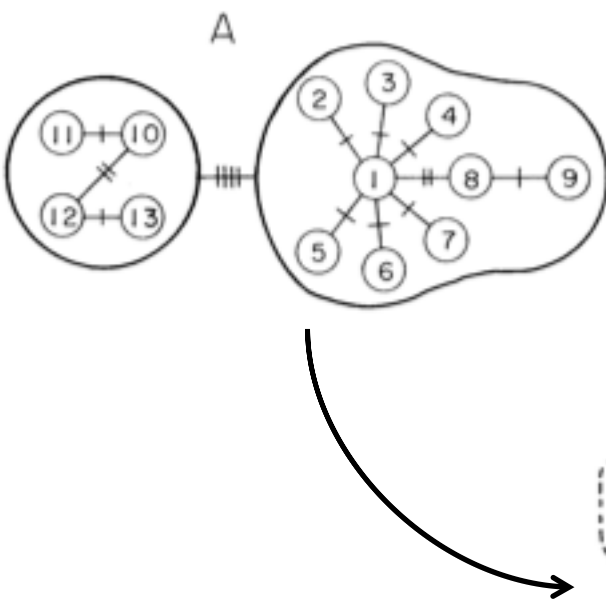
Biogeographical principles are used to identify Evolutionarily Significant Units

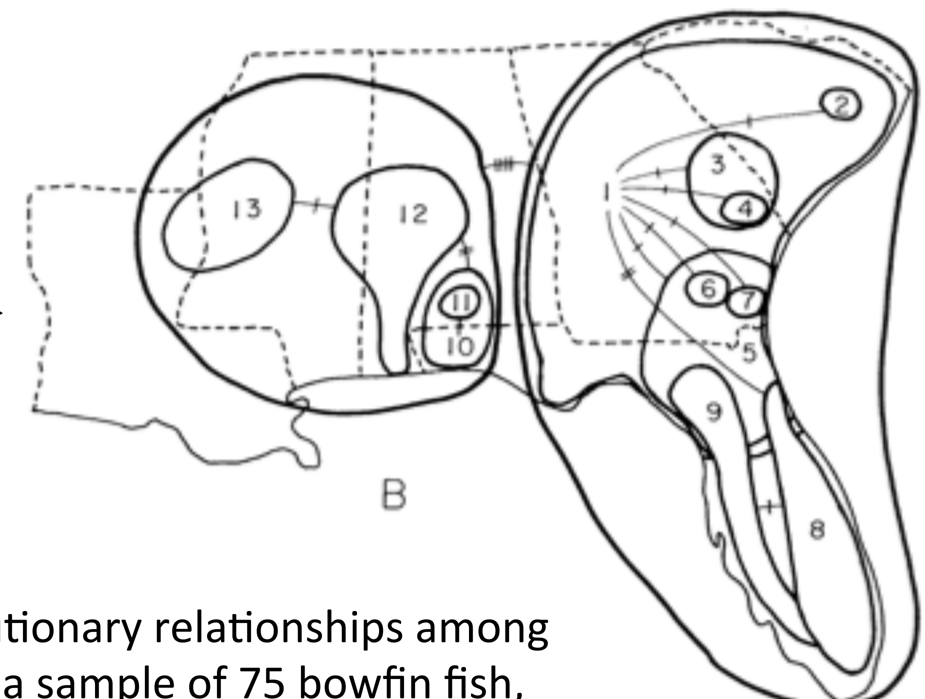


Contribution to total rainbow trout genetic diversity in BC by 27 populations. Open circles indicate total contribution to diversity, black bars show contribution from *alpha* diversity (allelic diversity within populations), white bars show contribution from *beta* diversity (allelic divergence from other populations). Note that Fish Lake (number 6) is among the most divergent populations (Taylor *et al.* 2011).

Identification of ESUs

Biogeographical principles are used to identify Evolutionarily Significant Units

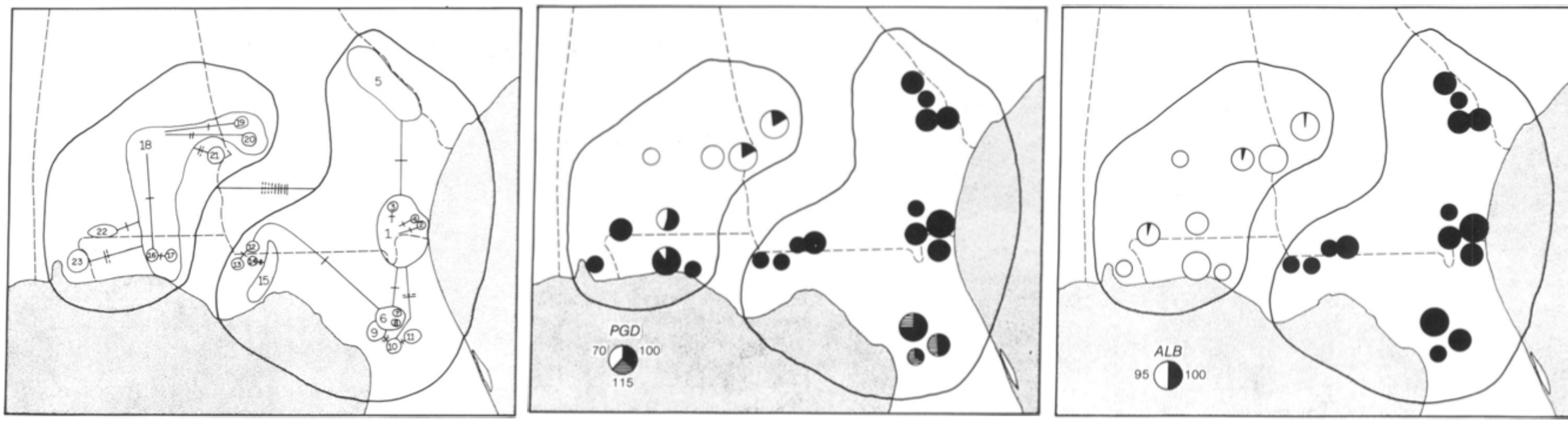




Haplotype network showing evolutionary relationships among 13 mtDNA genotypes observed in a sample of 75 bowfin fish, *Amia calva* (Avise 1987).

Identification of ESUs

Biogeographical principles are used to identify Evolutionarily Significant Units

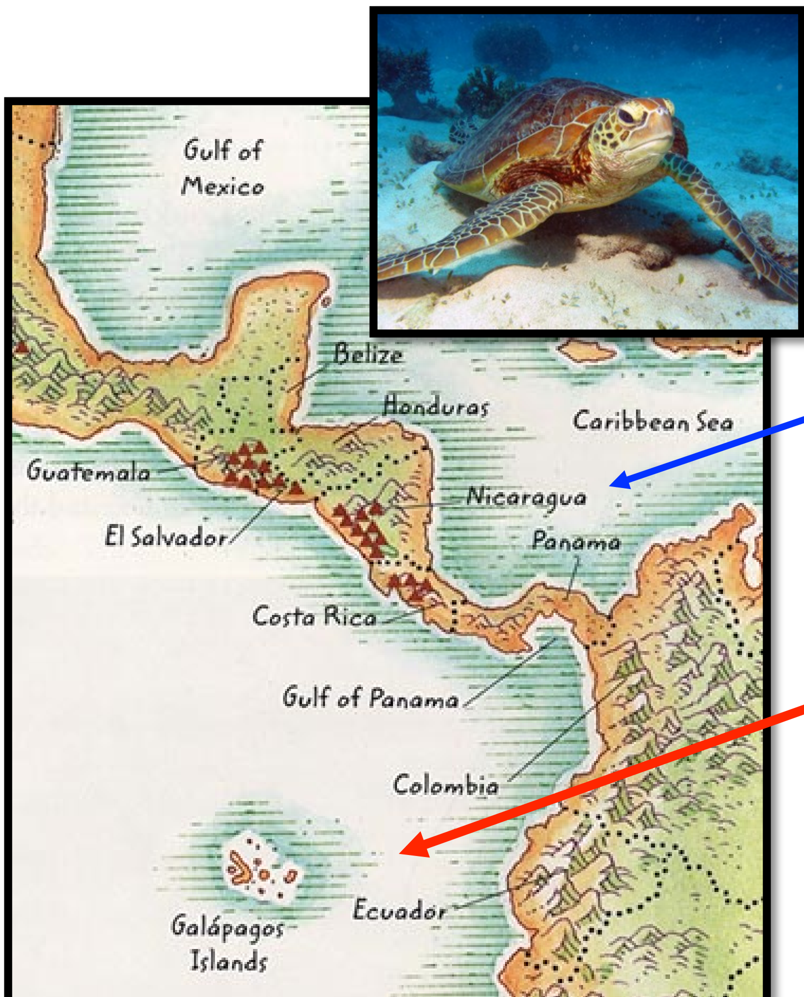


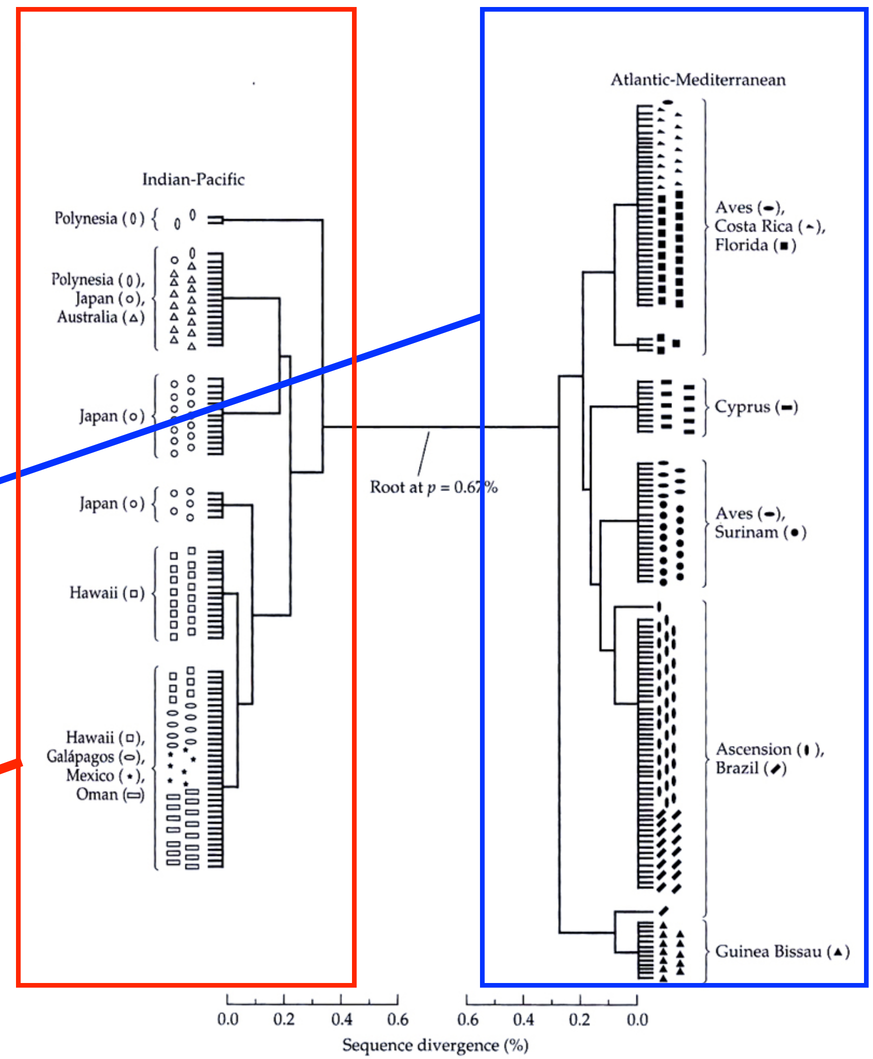
Geographic distribution of mtDNA haplotypes and nuclear-encoded protein electromorphs of southern pocket gophers, *Geomys pinetis* (Avise *et al.* 1979).

Identification of ESUs

Biogeographical principles are used to identify Evolutionarily Significant Units

Green Turtle (*Chelonia mydas*)



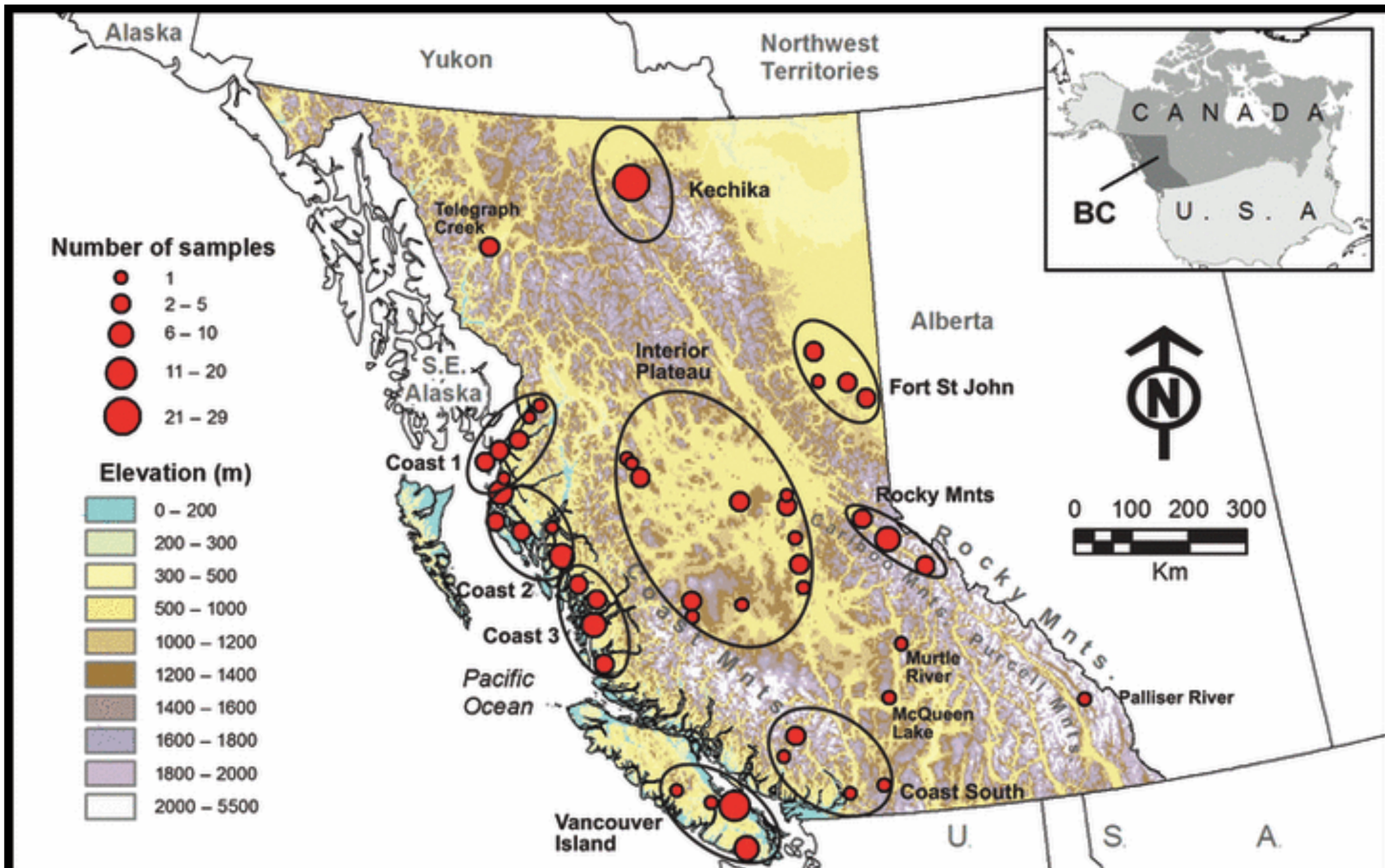


(Bowen et al. 1992)

Identification of ESUs

Biogeographical principles are used to identify Evolutionarily Significant Units

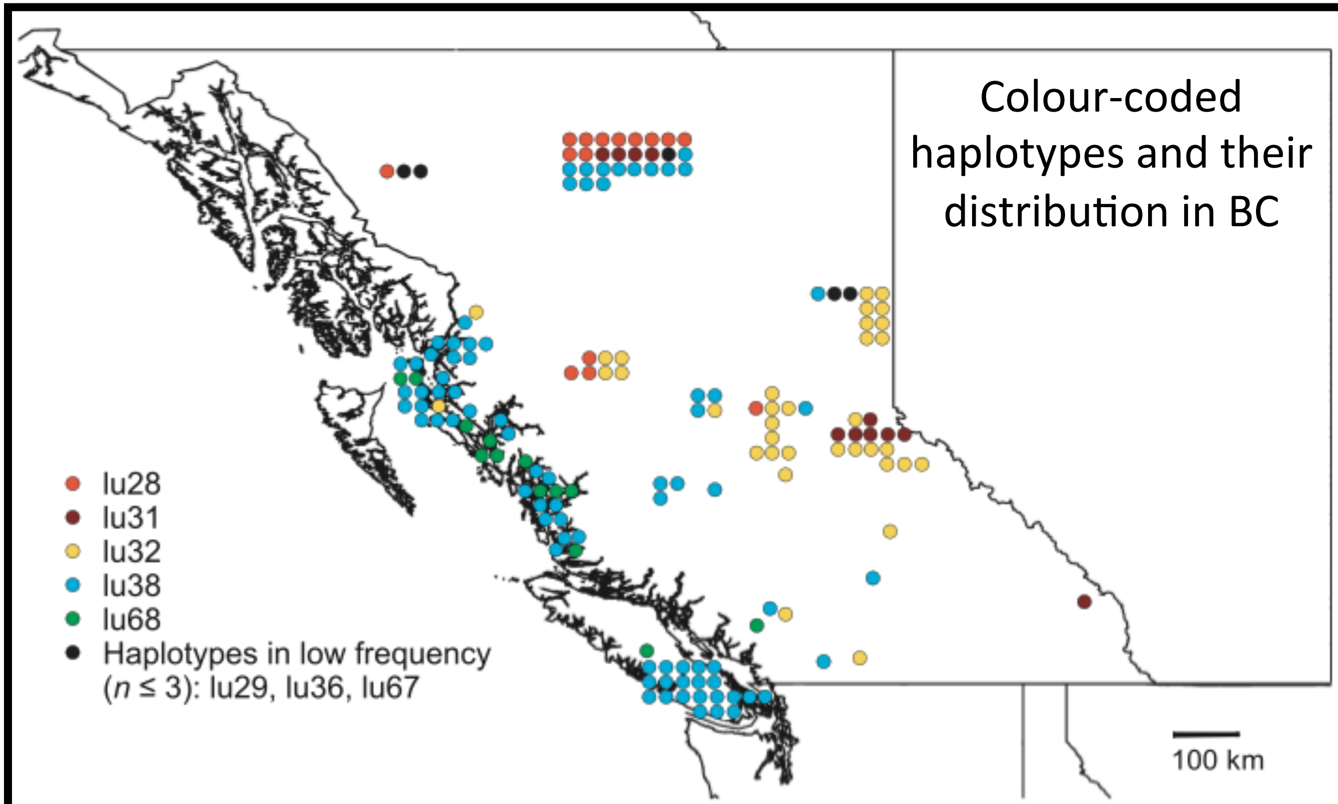
Groups of sampling areas for analysis east of the Coast Mountains and interior BC



(Muñoz-Fuentes *et al.* 2009)

Identification of ESUs

Biogeographical principles are used to identify Evolutionarily Significant Units



Strong genetic differentiation between adjacent populations of grey wolves (*Canis lupus*) from coastal and inland British Columbia hypothesized to reflect important behavioural (perhaps dietary) differences between coastal and inland populations (Muñoz-Fuentes *et al.* 2009).

Evolutionarily Distinct and Globally Endangered (EDGE) Species

The first rule of intelligent tinkering is to save all the parts…

But if we can't save all of the parts, which parts do we save? Triage!

"The aim of conservation biology should be the preservation of the information content contained in the DNA of all species on Earth" – E. O. Wilson

If phylogenetic trees represent shared and unique evolutionary content, it also represents Wilson's recipe for "information content."

Save as much of the tree as possible!

Also consider level of endangerment of species. Which species are most at risk?

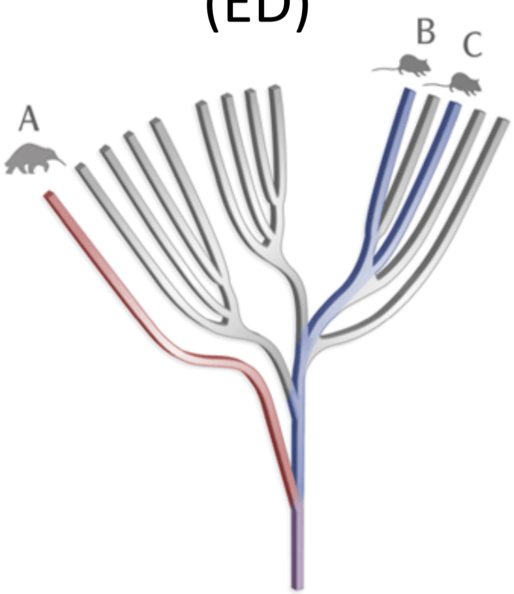
Evolutionarily Distinct and Globally Endangered (EDGE) Species

Uses a scientific framework to identify the world's most evolutionarily distinct and globally endangered species: http://www.edgeofexistence.org/index.php

EDGE species are scored based on:

1) Amount of unique evolutionary history represented (Evolutionary Distinctiveness, or ED)
2) Conservation status (Global Endangerment, or GE)

(ED)



\+

(GE)

IUCN RED LIST

THE IUCN RED LIST OF THREATENED SPECIES™

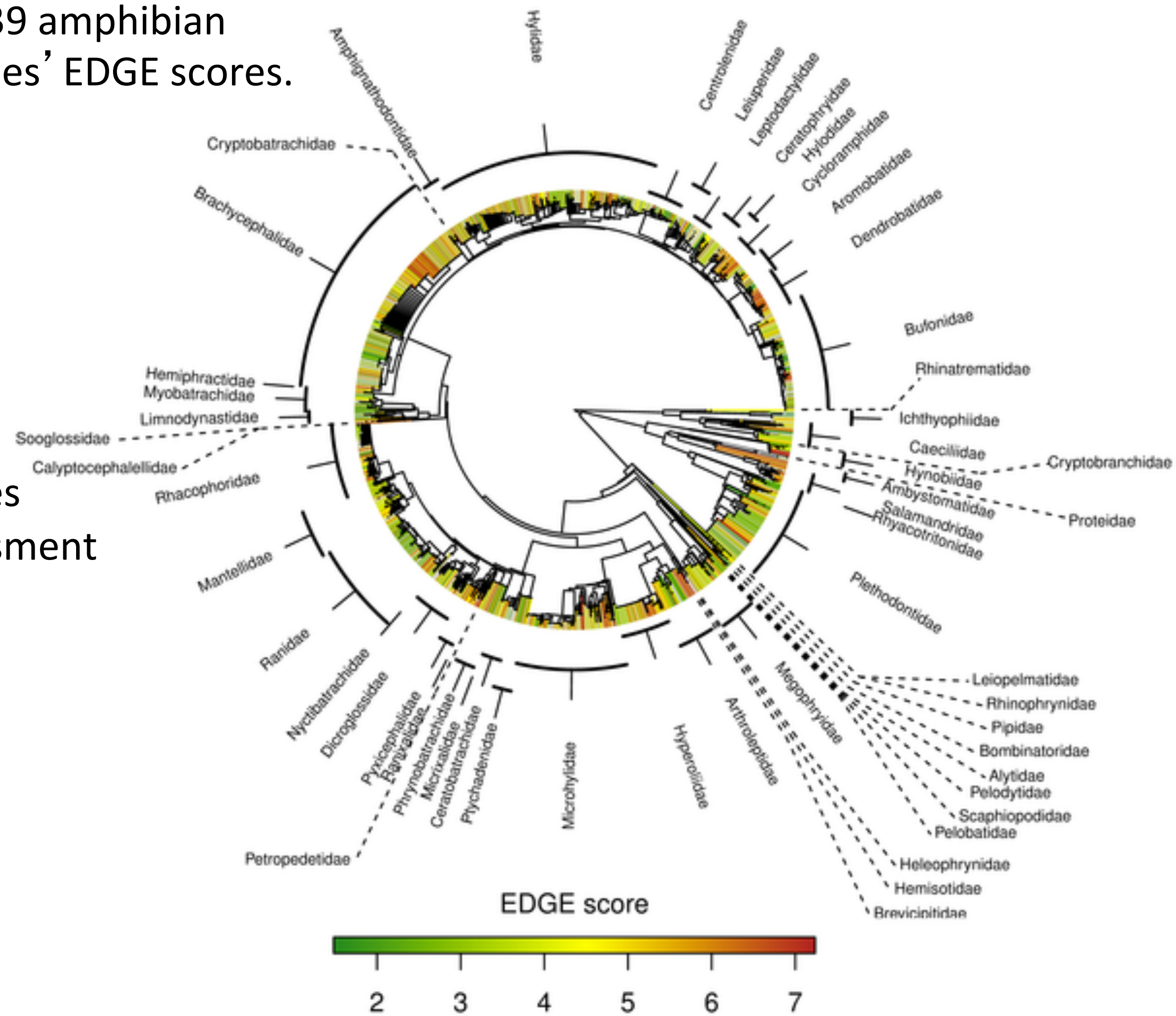
Evolutionarily Distinct and Globally Endangered (EDGE) Species

Species level phylogeny of 4339 amphibian species, colour-coded by species' EDGE scores.

Data Deficient and Extinct species are omitted.

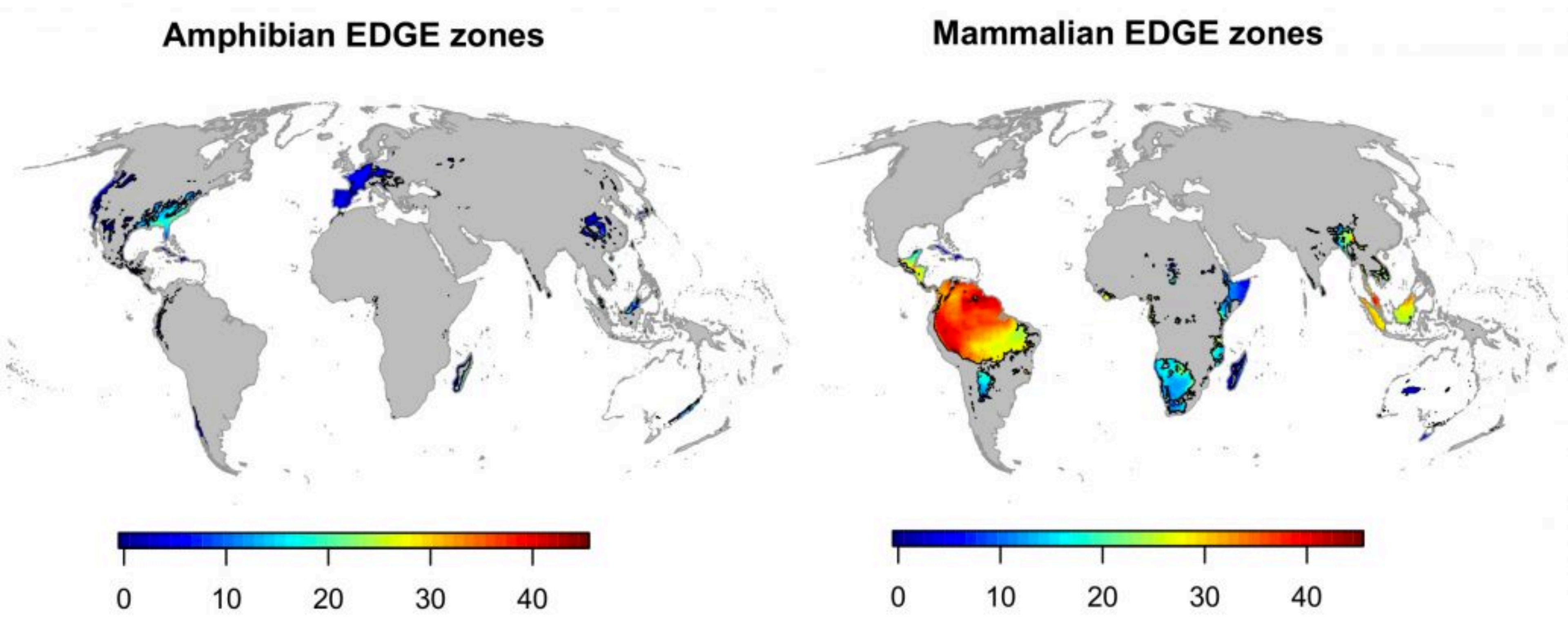
Calculated ED scores for each amphibian species

Used extinction risk (GE) scores from Global Amphibian Assessment



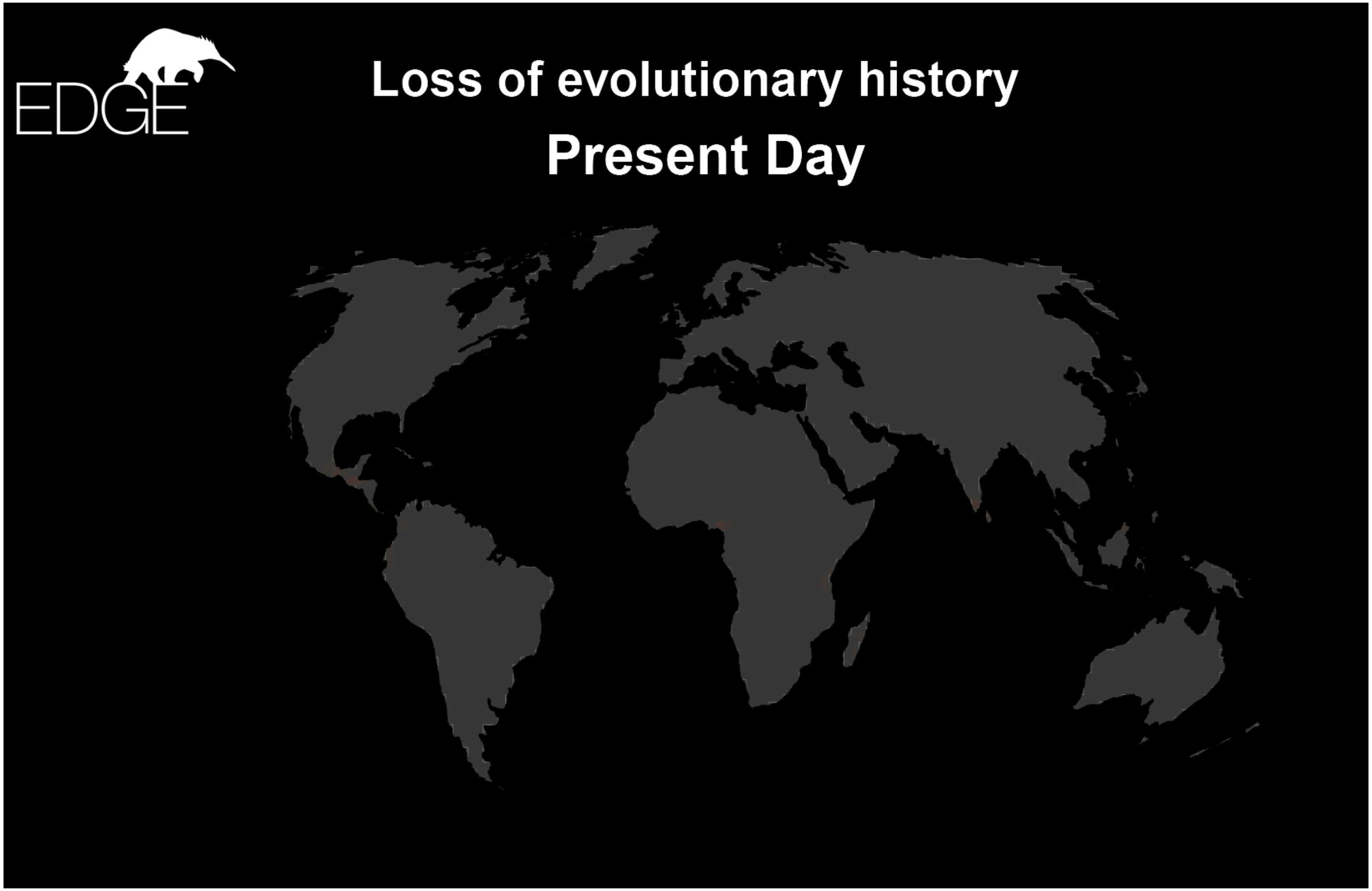
Isaac *et al*. 2012, *PLoS One*

Evolutionarily Distinct and Globally Endangered (EDGE) Zones – Amphibians & Mammals



EDGE Zones were developed in 2013, representing hotspots of biodiversity that contain disproportionate amounts of threatened evolutionary history - https://www.edgeofexistence.org/science/prioritisation/

Evolutionarily Distinct and Globally Endangered (EDGE) - Projected loss of evolutionary history



https://www.edgeofexistence.org/science/prioritisation/

Other challenges in assessing risk

Decisions for protection are often made within the national or provincial level, but species distributions and behaviors do not abide by geopolitical boundaries

Species at Risk Act in Canada

Decisions for protection are often made within the national or provincial level, but species distributions and behaviors do not abide by geopolitical boundaries

"SARA is a result of the implementation of the Canadian Biodiversity Strategy, which is in response to the United Nations Convention on Biological Diversity. The Act provides federal legislation to prevent wildlife species from becoming extinct and to provide for their recovery."

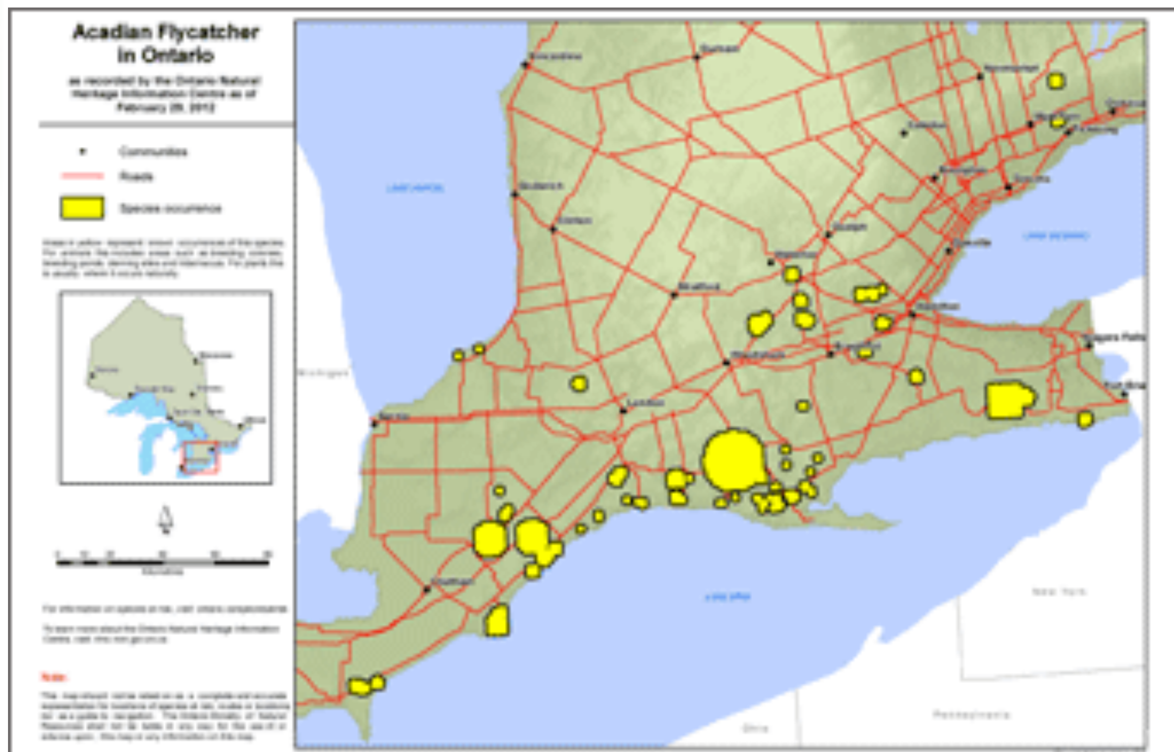
Is this Species at Risk (?)

Acadian flycatcher

range in Ontario

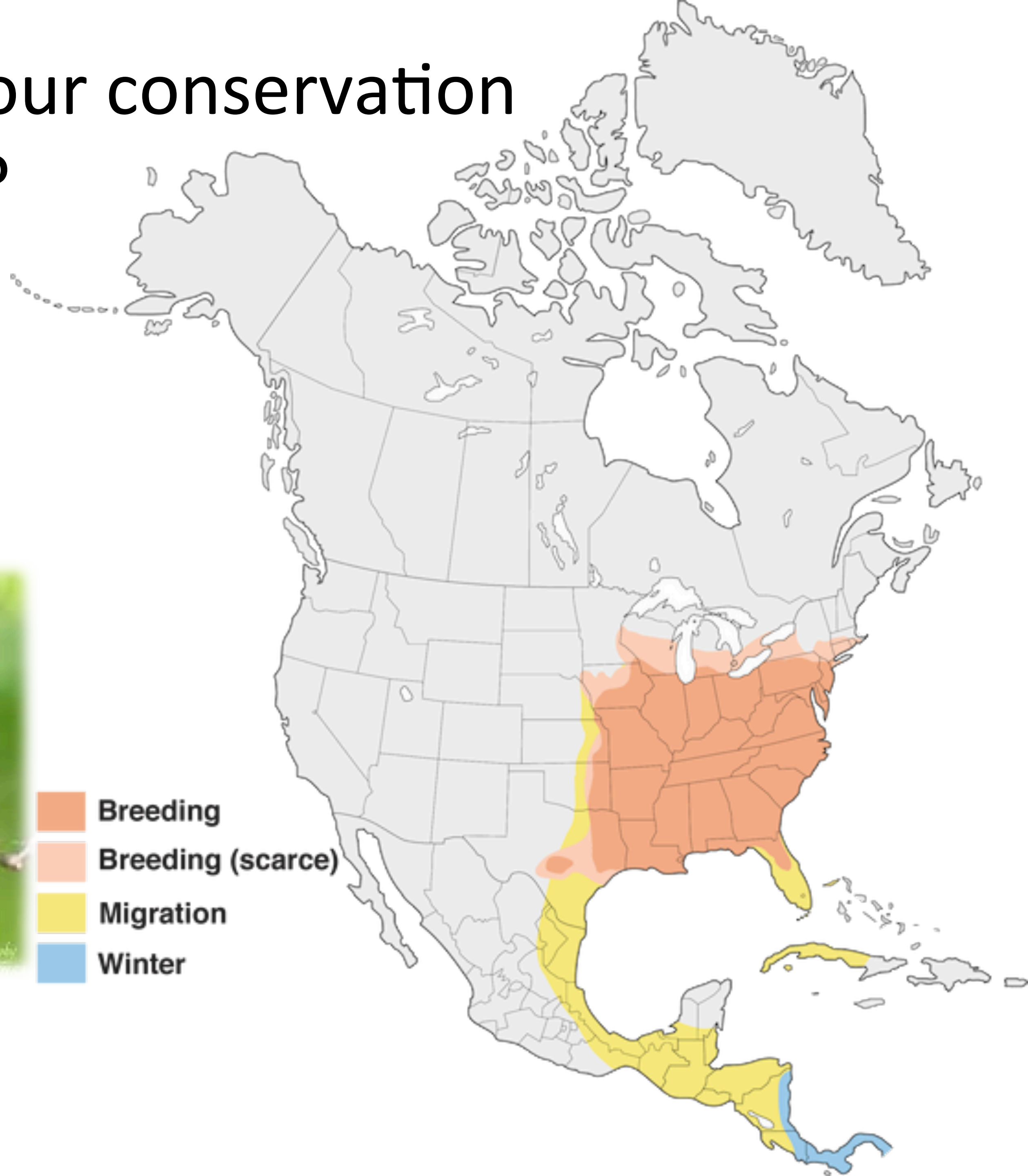
Status: Endangered

The species lives in the wild in Ontario but is facing imminent extinction or extirpation



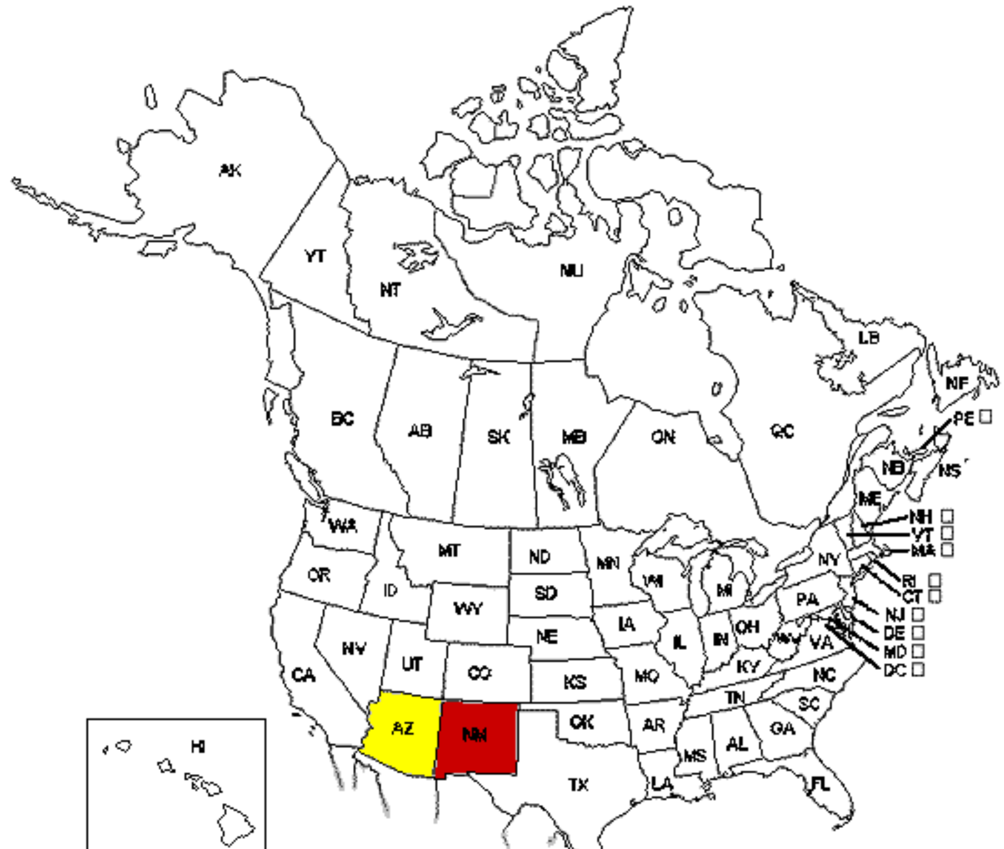
What should our conservation plan look like?

Acadian flycatcher range



What should our conservation strategy be?

Elegant Trogon range



What should our conservation strategy be?

Elegant Trogon range

Biodiversity and the geography of extinction

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