Section 3:
Species range shifts

Learning outcomes

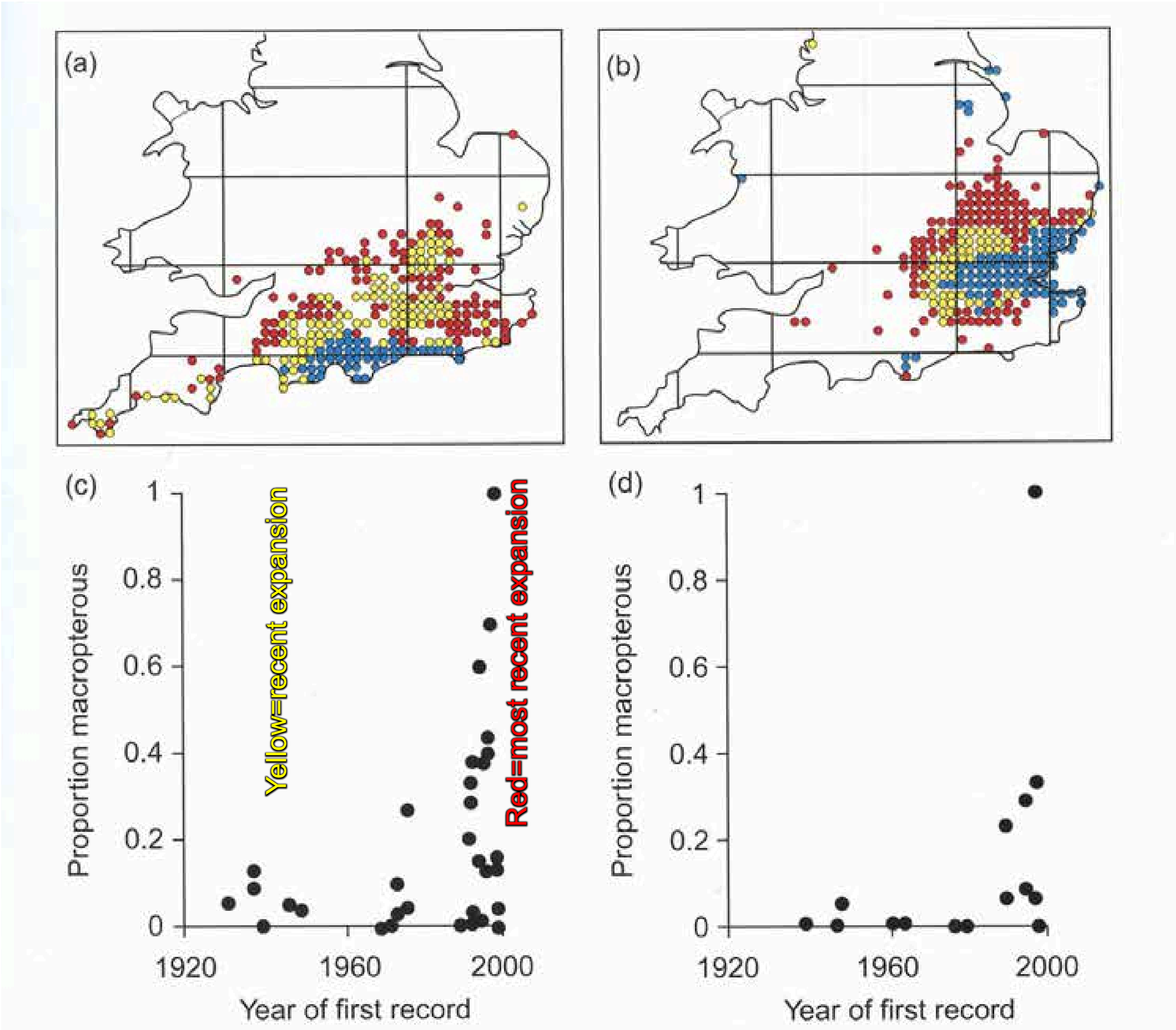
- understand concepts and mechanisms of range shifts
- give examples of the direct effect of climate change on range shifts as well as the indirect effects
- describe how range shifts have been used as evidence for climate change

Adaptation: Evolution

Blue=historical range
Yellow=recent expansion
Red=most recent expansion

conehead bush cricket Roesel's bush cricket

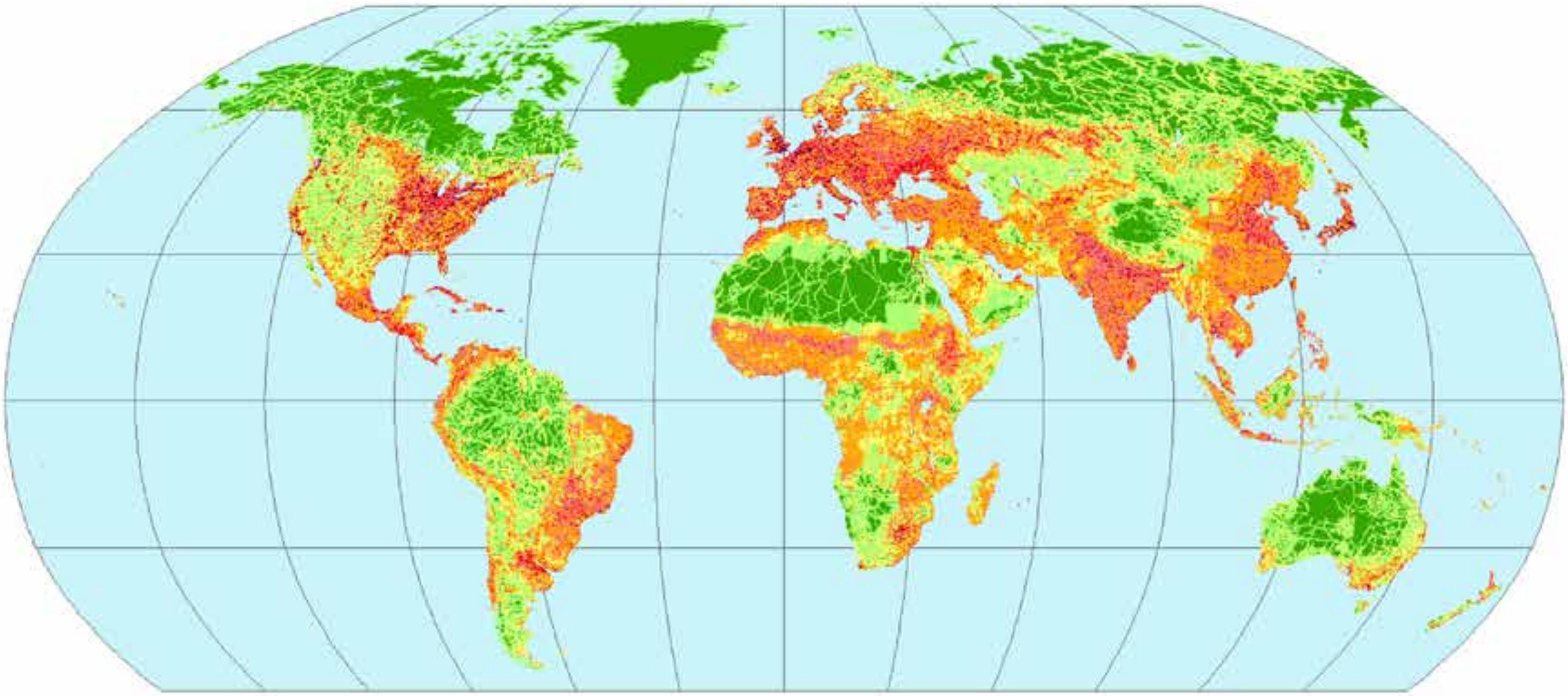
proportion longwinged



Hannah 2011

The Human Footprint ver. 2

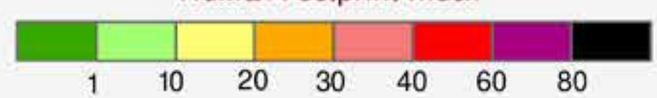
Global



Robinson Projection

The Human Footprint Index

The Human Footprint Index (HF) expressses as a percentage the relative human influence in each terrestrial biome. HF values range from 0 to 100. A value of zero represents the least influenced - the "most wild" part of the biome with value of 100 representing the most influenced (least wild) part of the biome.



Copyright 2008. The Trustees of Columbia University in the City of New York. Source: Center for International Earth Science Information Network (CIESIN), Columbia University, and Wildlife Conservation Society, the Bronx Zoo, New York. The Last of the Wild Data set. Available at http://www.sedac.ciesin.columbia.edu/wildareas

Publish Date: 03/07/08

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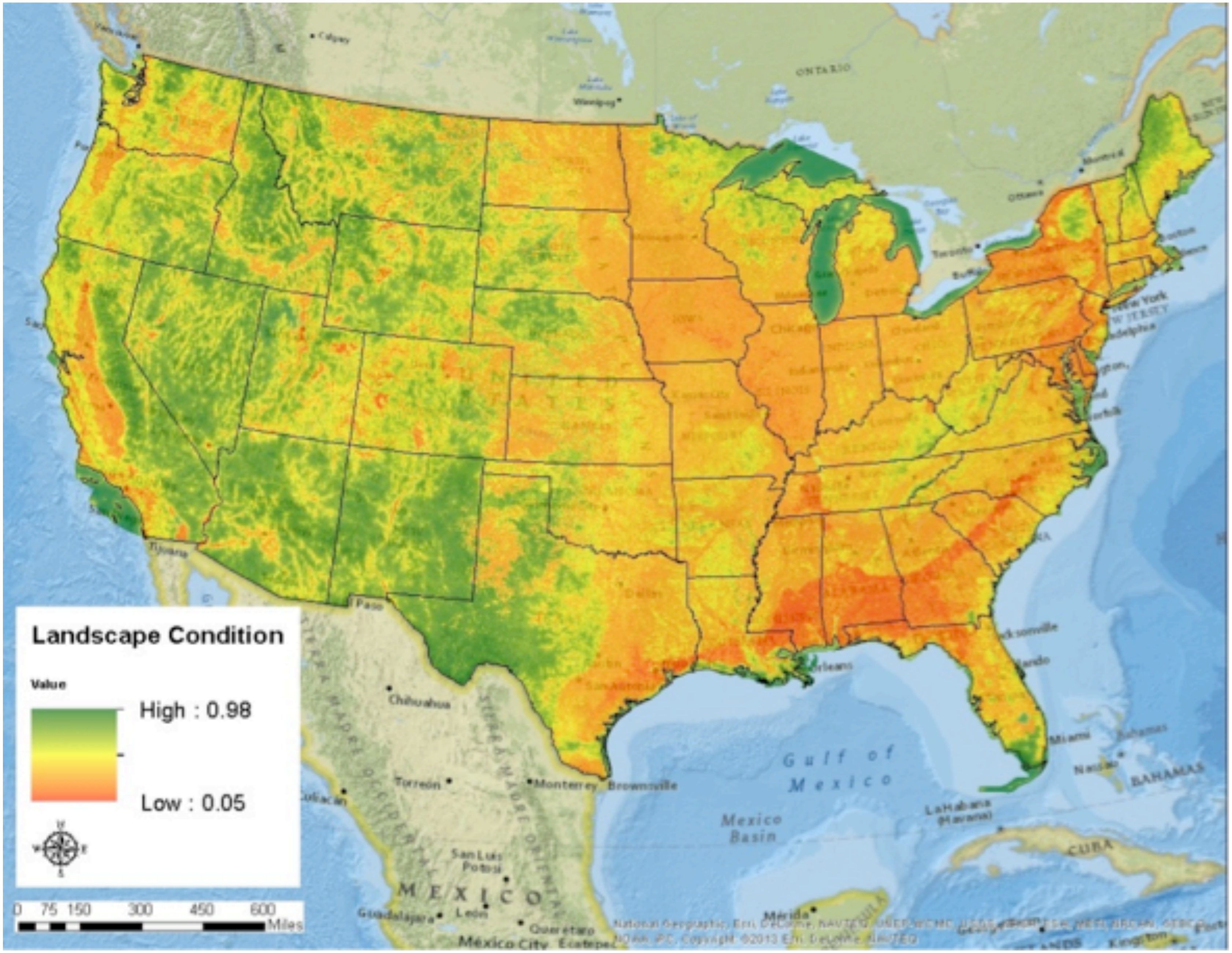
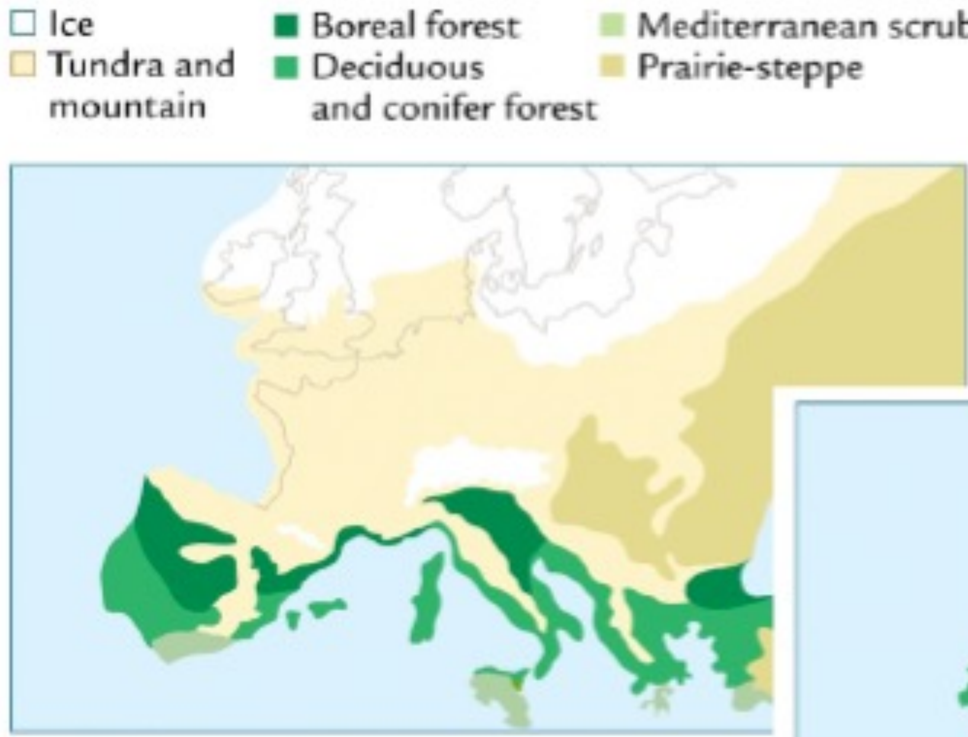


NatureServe

Vegetation cover changes from LGM to present in Europe



B Glacial vegetation

A Modern vegetation

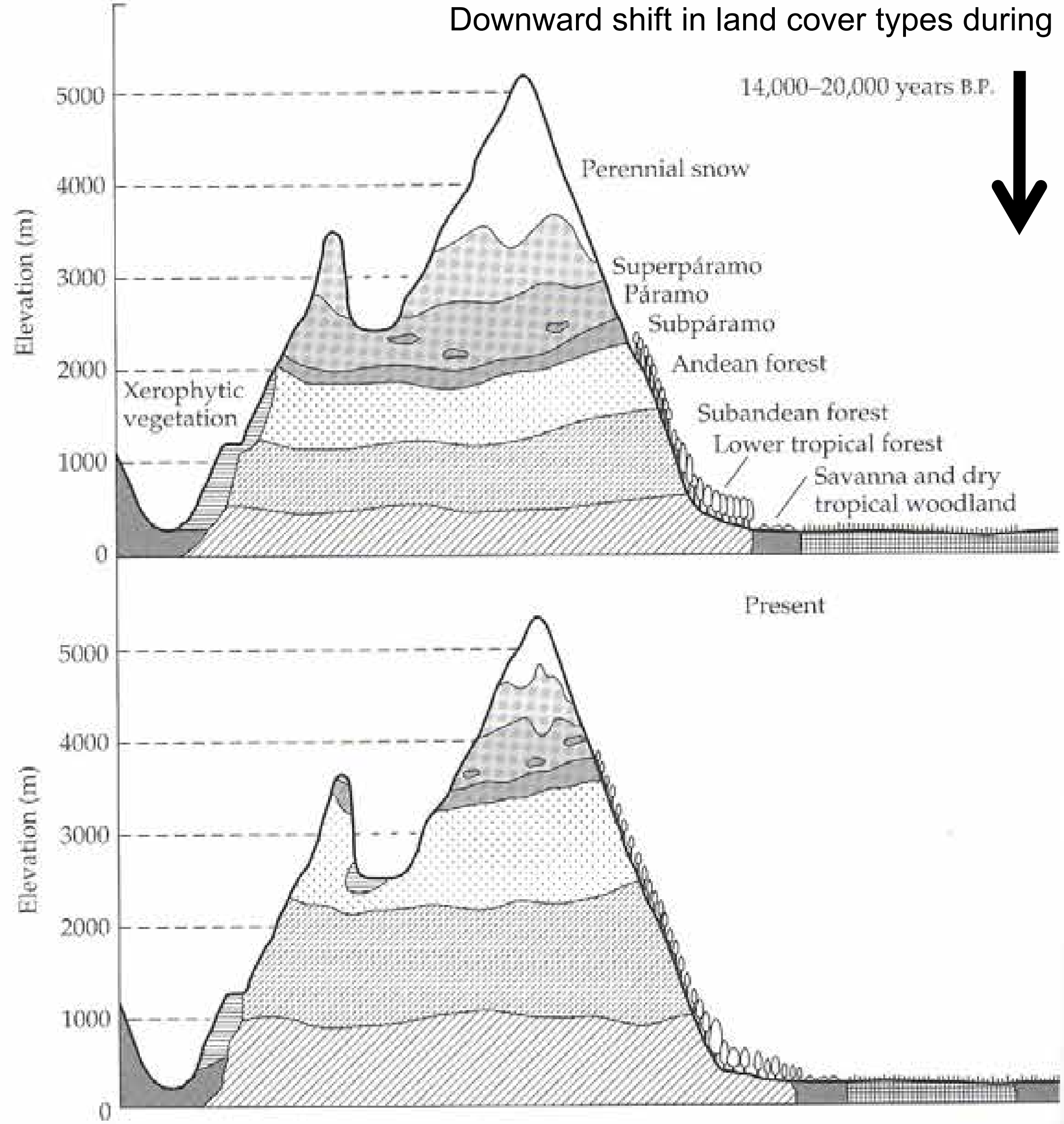
Image Credit: *Earth's Climate* by W. Ruddiman

Slide courtesy C. Still

Equatorial Mountain Changes

FIGURE 9.15 Elevational shifts in vegetation zones in the eastern Cordillera of the Andes in Colombia in response to climatic change following the most recent glacial maximum. Note that while all zones tended to shift in concert, the upper zones became narrower as they shifted upward in response to global warming. (After Flenley 1979a.)

Downward shift in land cover types during LGM



Lomolino et al., 2006

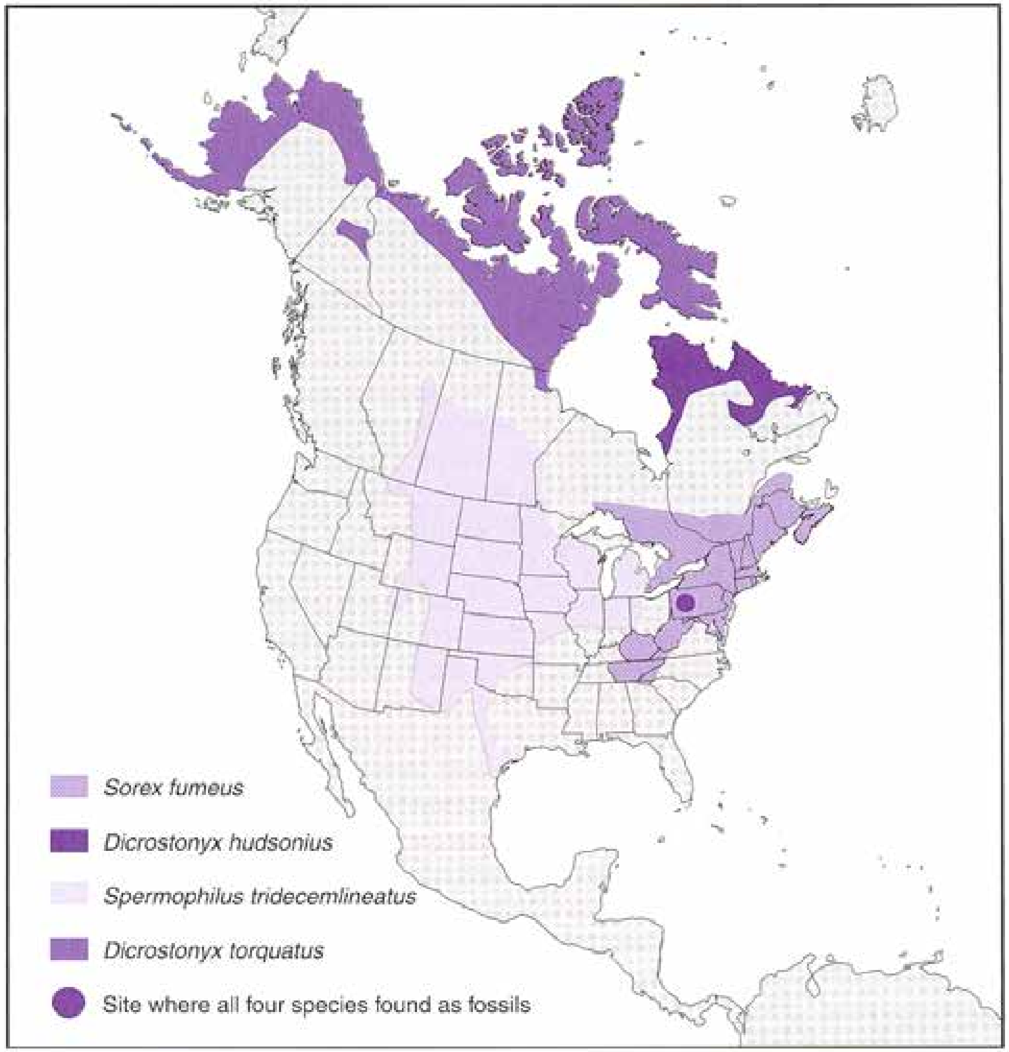


FIGURE 7.8 The modern distributions of eastern shrew *(Sorex fumens)*, eastern collared lemming *(Dicrostonyx hudsonius)*, prairie ground squirrel *(Spermophilus tridecemlineatus)*, and western collared lemming *(Dicrostonyx torquatus)*, and a site in Pennsylvania where fossil evidence indicates that all four species coexisted during the last glacial maximum, although they clearly do not live together today (after Graham, 1986; Graham et al., 1996; Brown and Lomolino, 1998).

Differential species responses:
rates, direction

different climate sensitivities? habitat requirements? predators/parasites?

MacDonald 2009

Examples of recent range shifts

Edith's checkerspot butterfly: northward and upward in elevation shift

FIGURE 3.5 Edith's Checkerspot Butterfly *(Euphydryas editha).*
From http://www.nps.gov/pinn/naturescience/butterfly.htm.

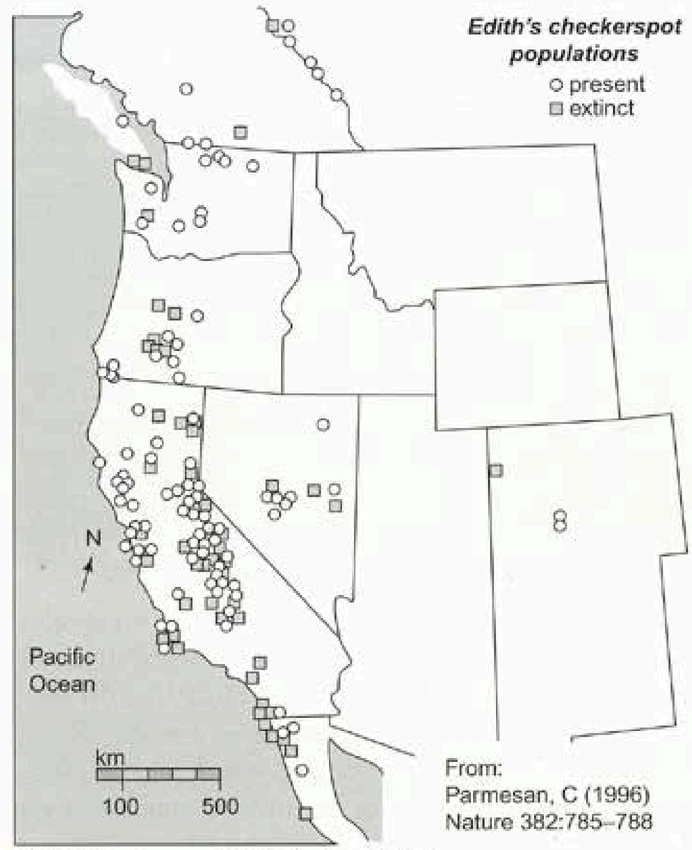


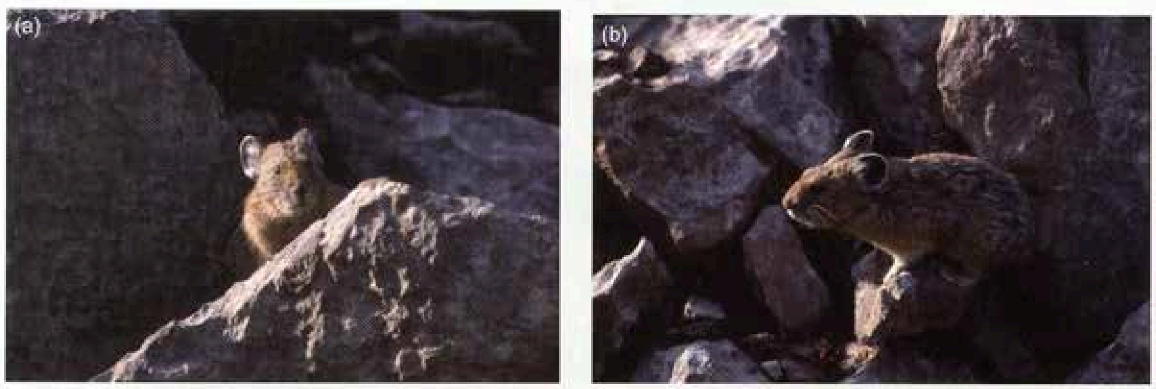
FIGURE 3.4 Edith's Checkerspot Butterfly Range Shift.
Southern populations of Edith's checkerspot butterfly are becoming extinct (shaded squares) more frequently than northern and montane populations, resulting in a northward and upslope range shift.
Reprinted by permission from Macmillan Publishers Ltd.

Hannah 2011

Examples of recent range shifts

pika: a cautionary tale

THE DISAPPEARING PIKA: CLIMATE AND PHYSIOLOGY



Pika (*Ochotona princeps*). From National Park Service, U.S.A.

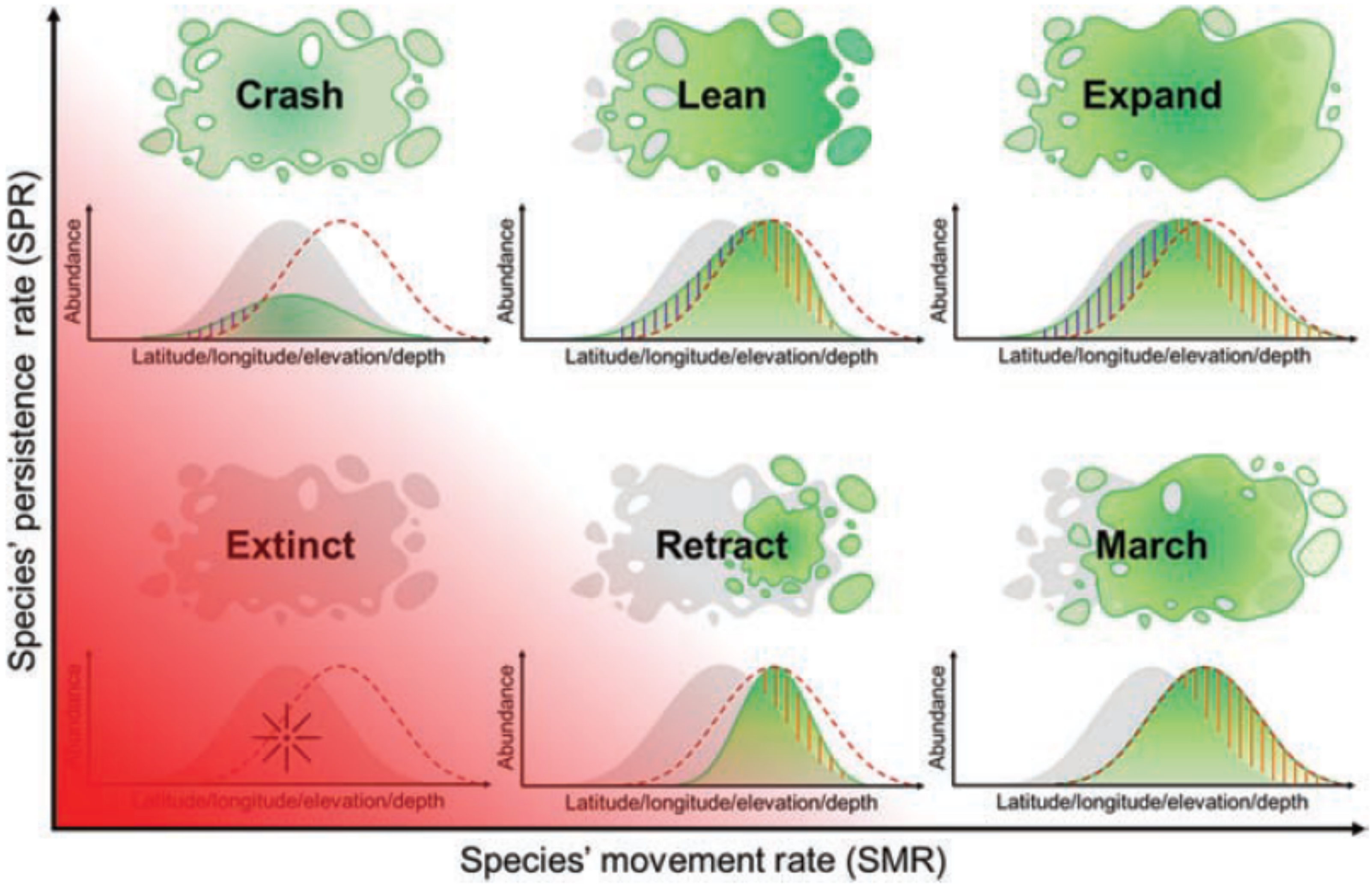
Pika, small high mountain residents, are disappearing due to climate change. The physiology of the Pika renders it susceptible to direct death from warming when its alpine habitats reach high temperatures, and elevated temperature inhibits foraging as a result. By 2004, Pika had disappeared from 7 of 25 sites in the western United States, most at lower, warmer elevations.

- sensitive to summer temperature
- recently, lower elevation populations have disappeared
- but pikas exist in hot places

Tricky to understand the role of climate change!

Hannah 2011

Theoretical framework for characterizing different range shift responses to climate change

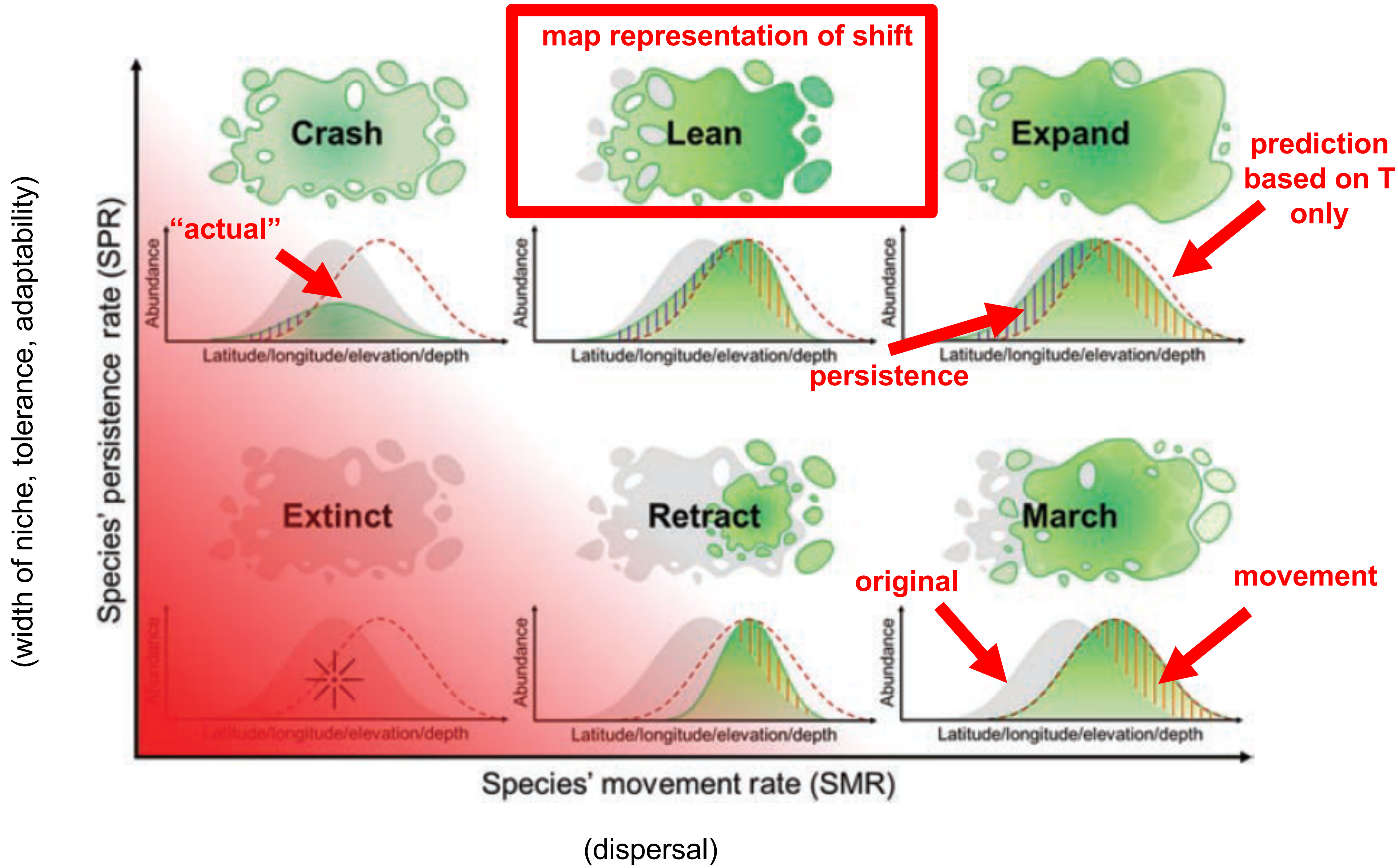


(width of niche, tolerance, adaptability)

(dispersal)

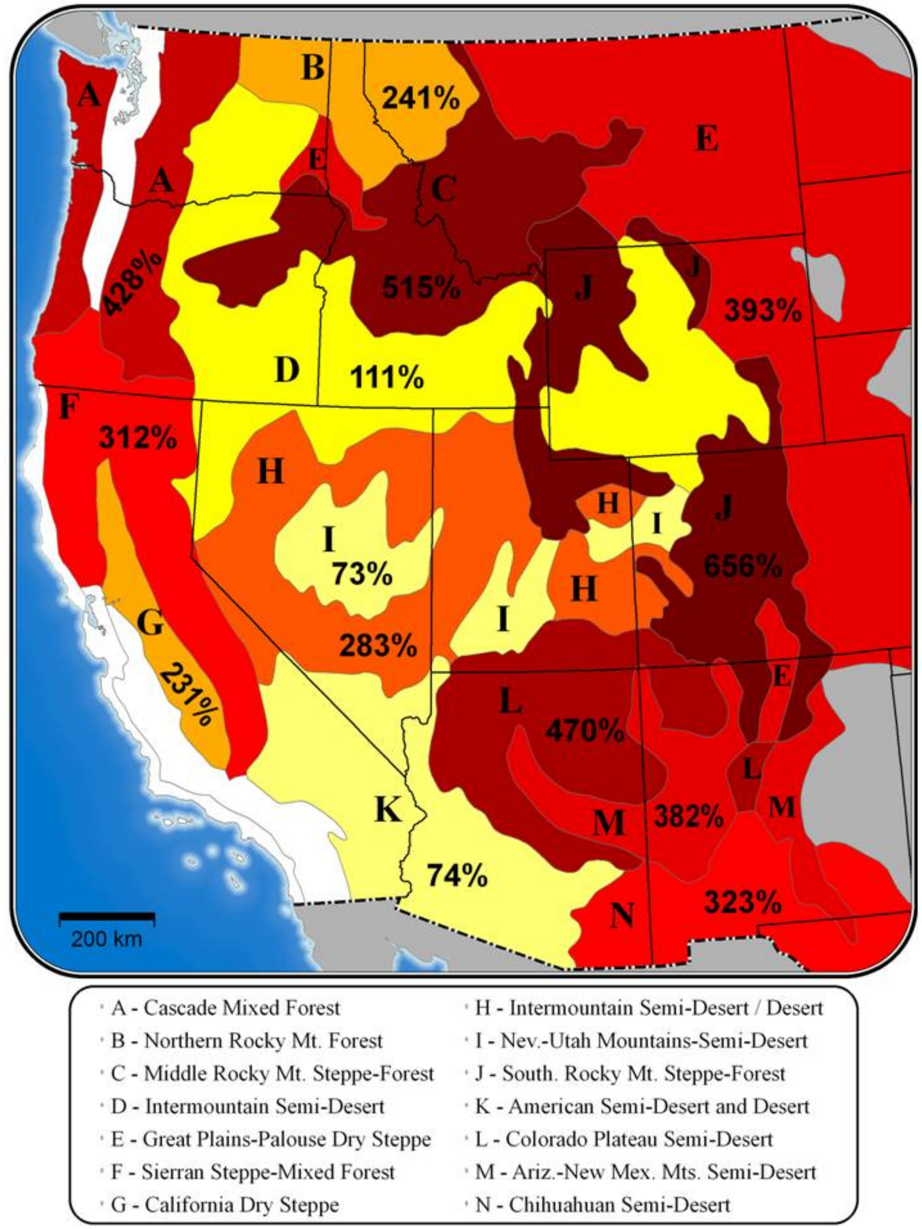
Lenoir and Svenning, Ecography, 2015

Theoretical framework for characterizing different range shift responses to climate change



Lenoir and Svenning, Ecography, 2015

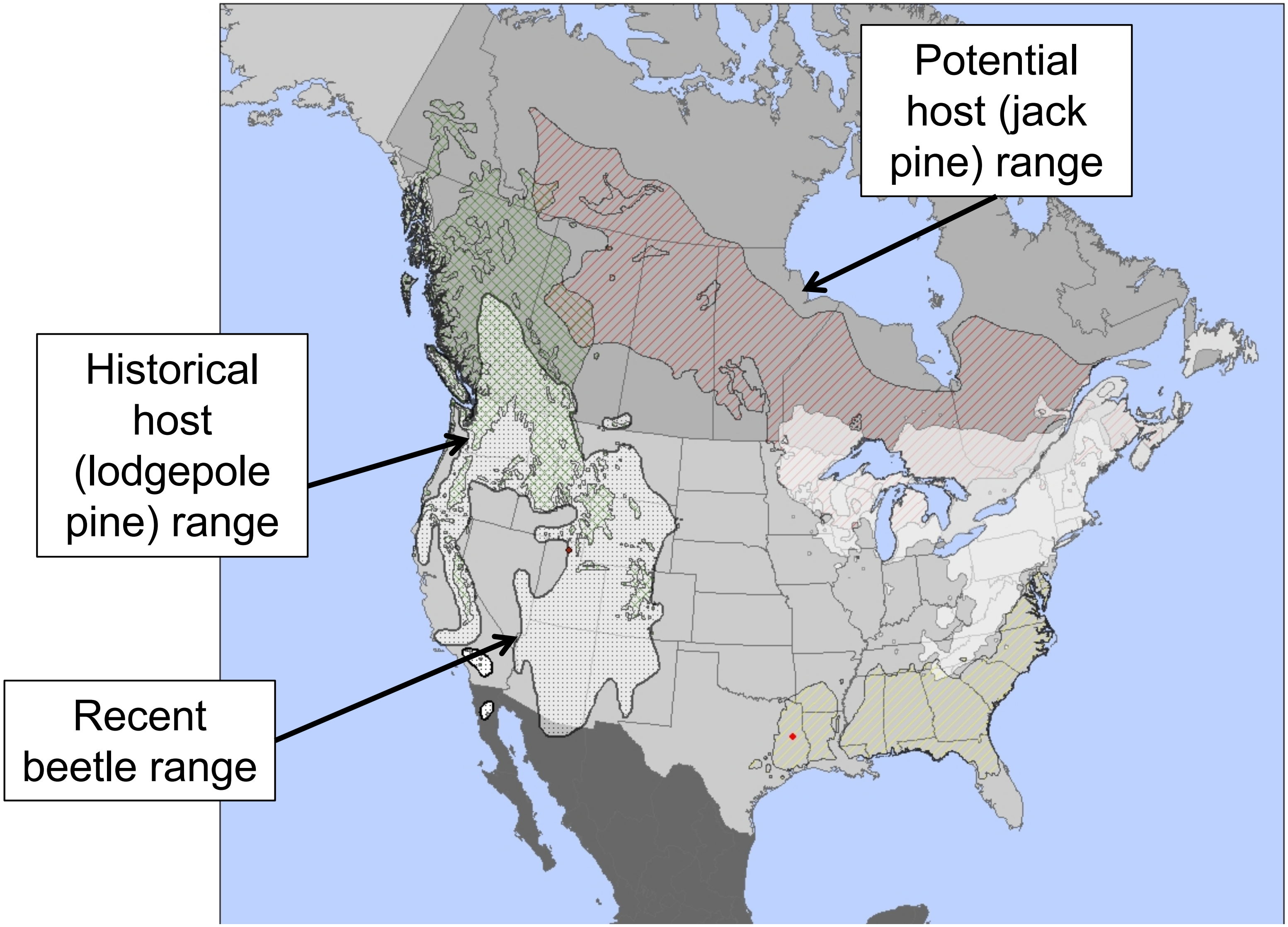
Indirect effects of climate change that lead to range shifts



increase in burned area for 1º C increase in temperature

Littell et al., *Ecological Applications*, 2009; National Academies, *Climate Stabilization Targets*, 2010

Expansion of mountain pine beetle into novel host



Logan and Powell 2001

Indirect effects of climate change that lead to range shifts

Competition with other species

Arctic fox (a) and red fox (b). *From (a) Wikimedia Commons and (b) U.S. Fish and Wildlife Service.*

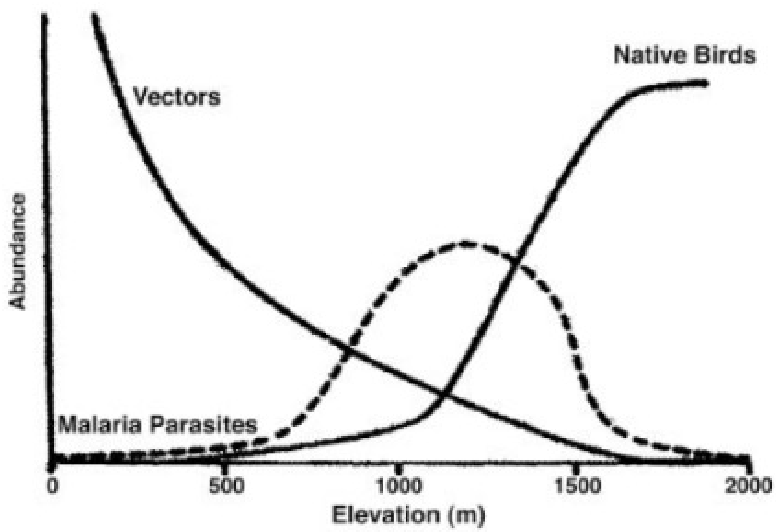
southern range limit retreating northward

northward expansion

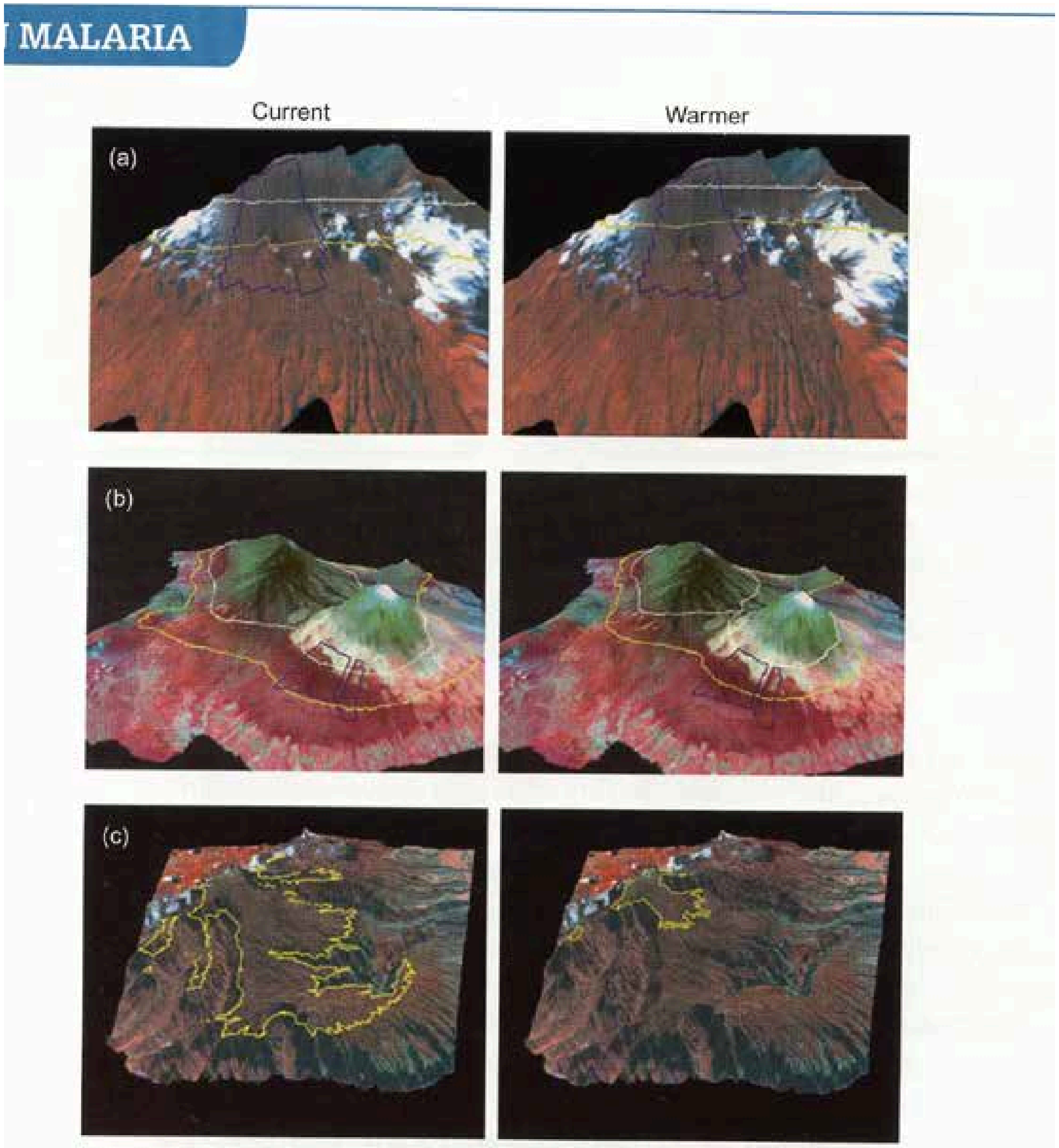
Hannah 2011

Interactions between climate change and biological invasions

- 30 species of Hawaiian honeycreepers (*Drepanididae*)
  - endemic to Hawaiian islands



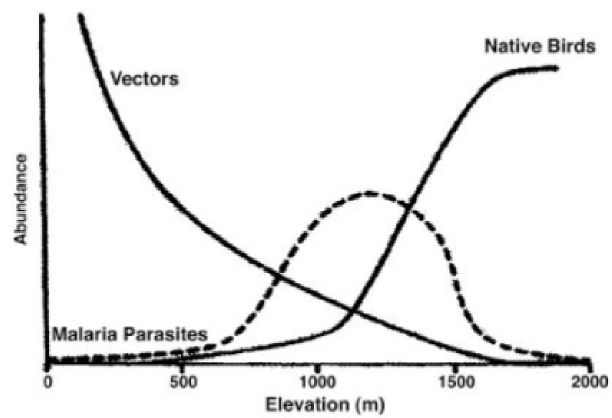
Benning et al., *Proc. Natl. Acad. Sci.* Volume 99 Number 22, 29 October 2002



Projected changes in 17° (yellow) and 13°C (white) isotherms that limit the distribution of avian malaria under current and 2°C warming conditions. Changes are shown for Hanawi Reserve (blue boundary) on the island of Maui (a), Hakalau Refuge (blue boundary) on Hawaii (b), and the Alakai swamp region on the island of Kauai (c). *From Benning, T. L., et al. © 2002, National Academy of Sciences U.S.A.*

Warming => upward expansion of avian malaria parasite

Implications for native birds???



Hannah 2011

Climate change will facilitate invasions of exotic species

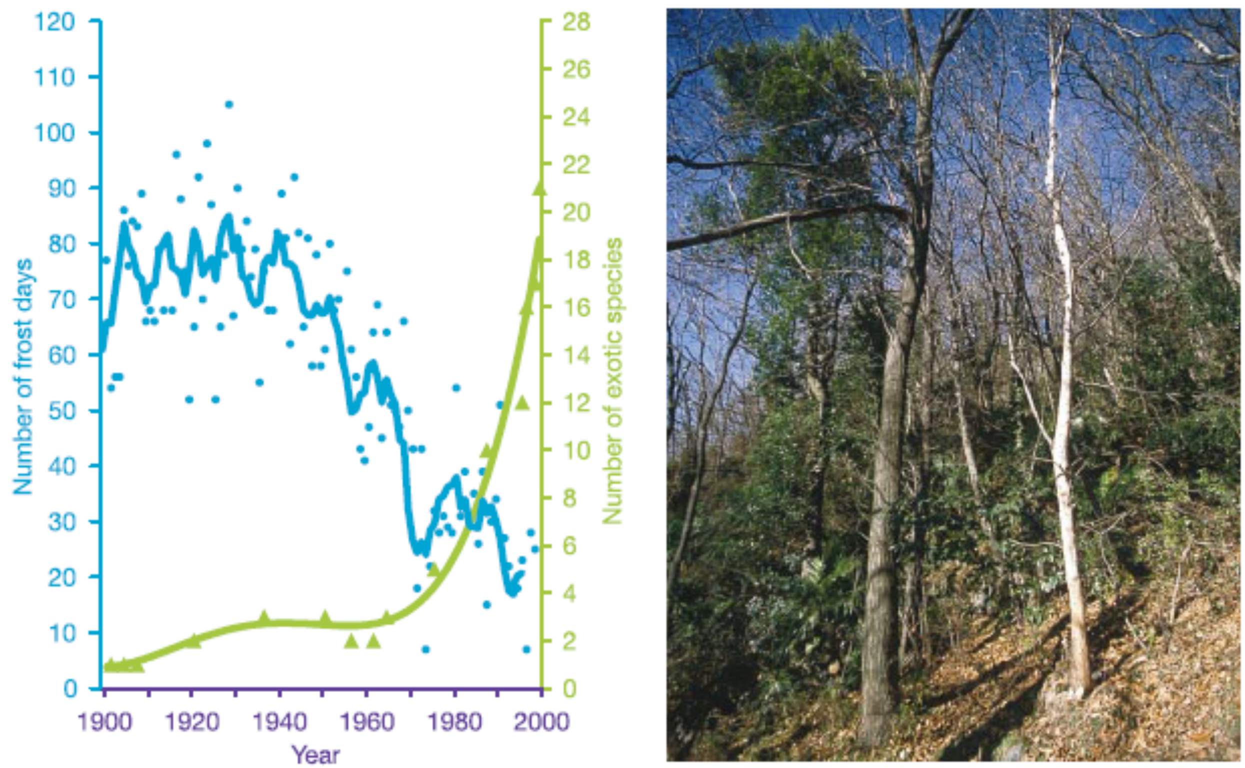


Figure 3 Vegetation shift from indigenous deciduous to exotic evergreen broad-leaved vegetation in southern Switzerland. The shrub layer is dominated by the growing number of spreading exotic evergreen broad-leaved species (see illustration) that appear to profit from milder winter conditions, indicated here by the decreasing number of days with frost per year (the smoothed curve gives five year averages for the number of frost days per year)[29].

Walther et al., 2002

Climate change and extinctions

IPCC AR5 WG 2 (Intergovernmental Panel on Climate Change, Fifth Assessment Report (2013), Working Group 2 (Impacts, Adaptation, and Vulnerability”)):

“Climate change may have already contributed to the extinction of a small number of species, such as frogs and toads in Central America, but the role of climate change in these recent extinctions is the subject of considerable debate.”

Rapid Range Shifts of Species Associated with High Levels of Climate Warming

I-Ching Chen,[1,2] Jane K. Hill,[1] Ralf Ohlemüller,[3] David B. Roy,[4] Chris D. Thomas[1*]

The distributions of many terrestrial organisms are currently shifting in latitude or elevation in response to changing climate. Using a meta-analysis, we estimated that the distributions of species have recently shifted to higher elevations at a median rate of 11.0 meters per decade, and to higher latitudes at a median rate of 16.9 kilometers per decade. These rates are approximately two and three times faster than previously reported. The distances moved by species are greatest in studies showing the highest levels of warming, with average latitudinal shifts being generally sufficient to track temperature changes. However, individual species vary greatly in their rates of change, suggesting that the range shift of each species depends on multiple internal species traits and external drivers of change. Rapid average shifts derive from a wide diversity of responses by individual species.

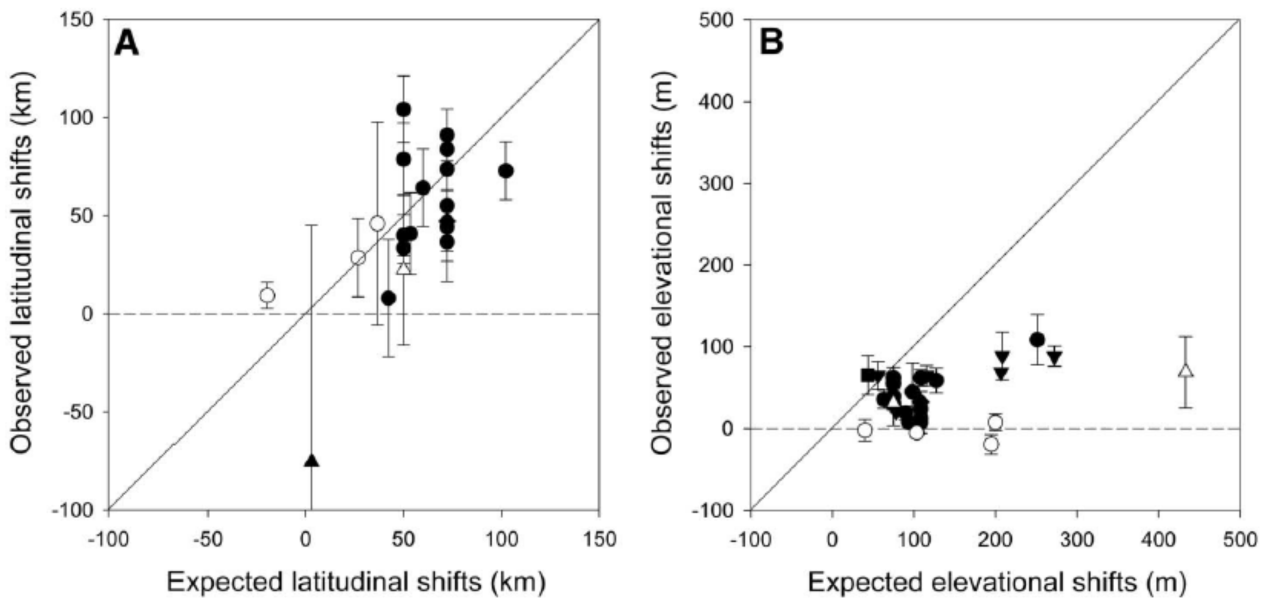
median rate of 16.9 km decade^{-1} (mean = 17.6 km decade^{-1}, SE = 2.9, $N = 22$ species group × region combinations, one-sample t test versus zero shift, $t = 6.10$, $P < 0.0001$). Weighting each study by the √(number of species) in the group × region combination gave a mean rate of 16.6 km decade^{-1}. For elevation, there was a median shift to higher elevations of 11.0 m uphill decade^{-1} (mean = 12.2 m decade^{-1}, SE = 1.8, $N = 30$ species groups × regions, one-sample t test versus zero shift, $t = 7.04$, $P < 0.0001$). Weighting elevation studies by √(number of species) gave a mean rate of uphill movement of 11.1 m decade^{-1}.

A previous meta-analysis (*14*) of distribution changes analyzed individual species, rather than the averages of taxonomic groups × regions that we used, and also included data on latitudinal and elevational shifts in the same analysis (*18*). It concluded that ranges had shifted toward higher latitudes at 6.1 km decade^{-1} and to high-

- 23 taxonomic groups, 764 species
- found that most studies indicated expected shifts in response to warming

Meta-analyses of impacts

- latitude
  - 17 km/decade
  - range shifts of many species can keep up with warming
- elevation
  - 11 m/decade
  - range shifts of many species cannot



expected based on climate change

Fig. 1. Relationship between observed and expected range shifts in response to climate change, for (**A**) latitude and (**B**) elevation. Points represent the mean responses (±SE) of species in a particular taxonomic group, in a given region. Positive values indicate shifts toward the pole and to higher elevations. Diagonals represent 1:1 lines, where expected and observed responses are equal. Open circles, birds; open triangles, mammals; solid circles, arthropods; solid inverted triangles, plants; solid square, herptiles; solid diamond, fish; solid triangle, mollusks.

Chen et al., Science, 2011

Meta-analyses of impacts

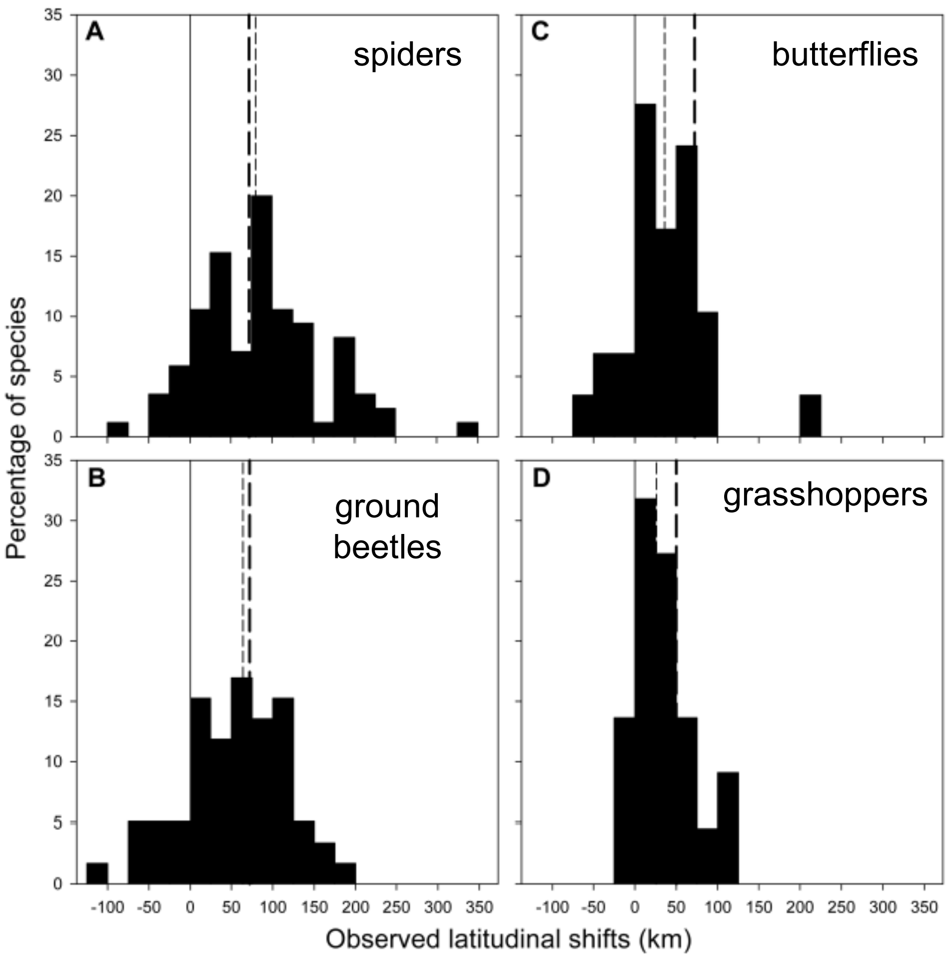
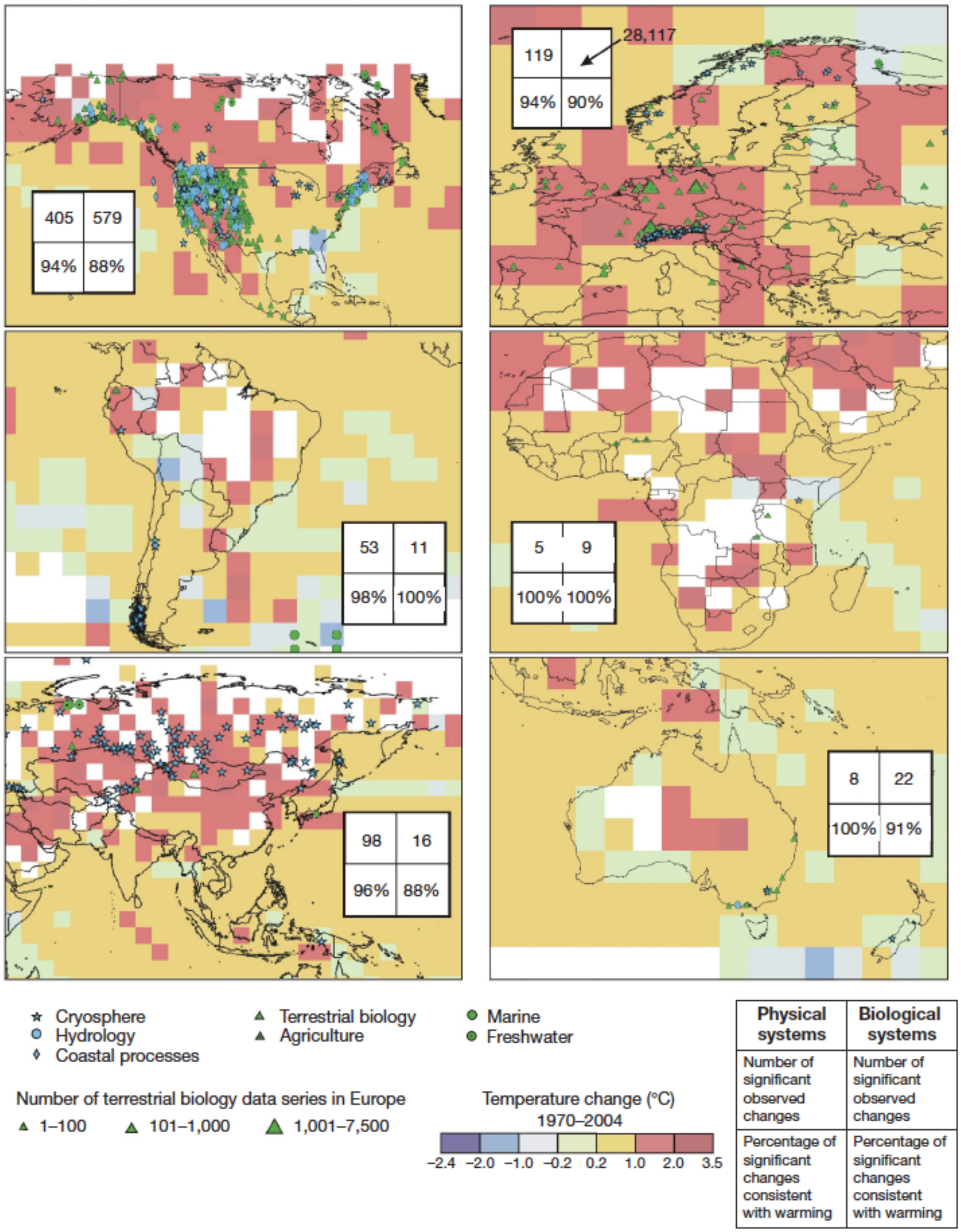


Fig. 2. Observed latitudinal shifts of the northern range boundaries of species within four exemplar taxonomic groups, studied over 25 years in Britain. (**A**) Spiders (85 species), (**B**) ground beetles (59 species), (**C**) butterflies (29 species), and (**D**) grasshoppers and allies (22 species). Positive latitudinal shifts indicate movement toward the north (pole); negative values indicate shifts toward the south (Equator). The solid line shows zero shift, the short-dashed line indicates the median observed shift, and the long-dashed line indicates the predicted range shift.

- substantial variability in species
- related to
  - time delays in responses
  - different physiological constraints
  - other drivers of change

Chen et al., Science, 2011

Meta-analyses of impacts



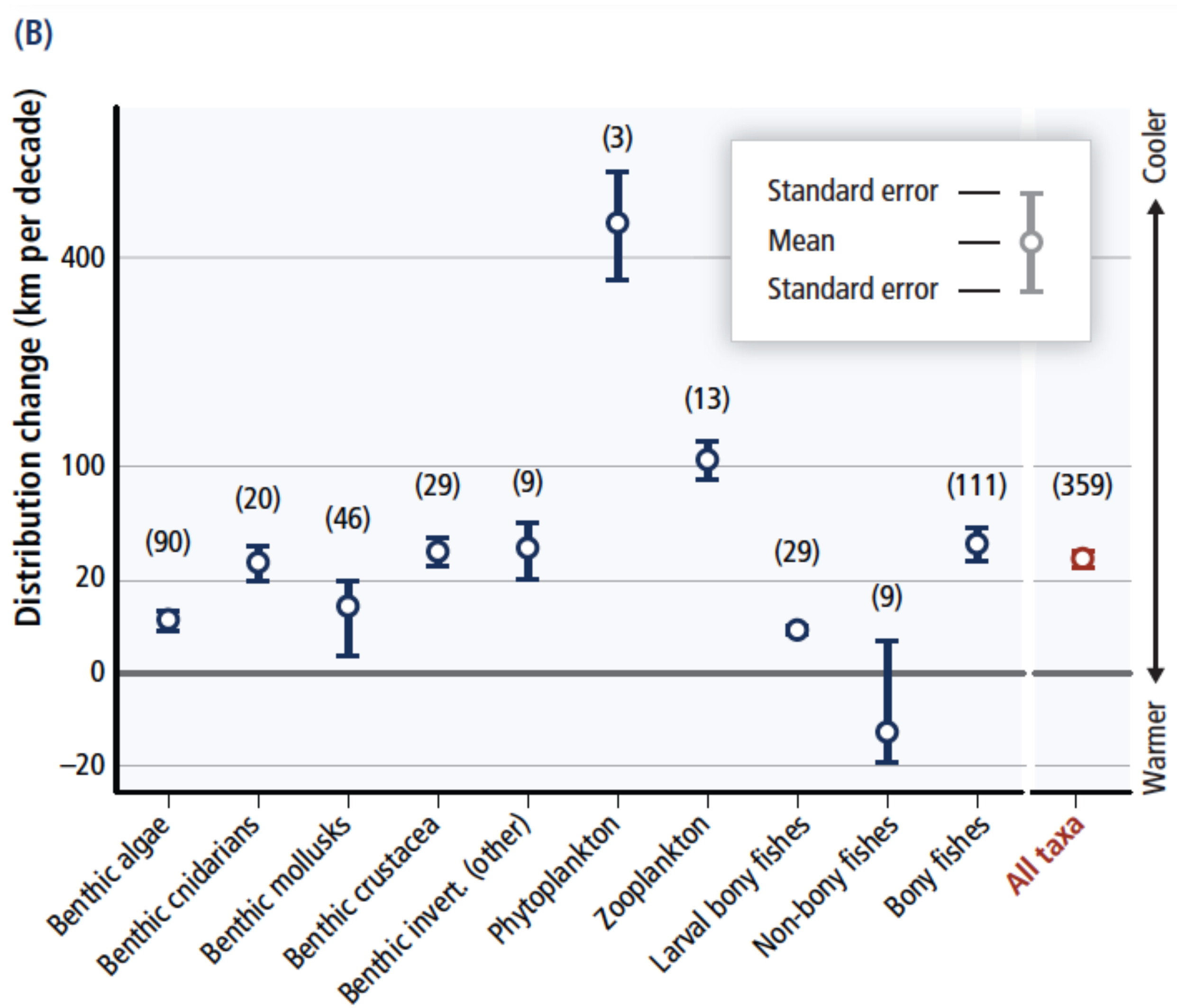
- physical and biological responses with observed changes
- 90% were consistent with warming
- consistent across continents
- very unlikely to be caused by natural climate variability

Rosenzweig et al., Nature, 2008

Prof. J. Hicke

Meta-analyses of impacts

Rate of range shifts for marine taxa, 1900-2010



IPCC AR5 WG2, 2013

Section 3:
Species range shifts

Patterns within the Patterns

…

"In the species-by-species study, the overwhelming majority of species showed the poleward and upslope shifts expected with warming. In 1700 species studied, poleward range shifts averaged 6 km per decade. A total of 279 of the species showed responses that tracked climate change—poleward shift during warming periods and shift away from the poles in cooling periods—but a net poleward shift. This gives strong indication of climate causality."

(Hannah p 72-73)
Hannah, Lee. *Climate Change Biology, 2nd Edition*. Academic Press, 11/2014. VitalBook file.

articles

A globally coherent fingerprint of climate change impacts across natural systems

Camille Parmesan* & Gary Yohe†

* *Integrative Biology, Patterson Laboratories 141, University of Texas, Austin, Texas 78712, USA*
† *John E. Andrus Professor of Economics, Wesleyan University, 238 Public Affairs Center, Middletown, Connecticut 06459, USA*

Causal attribution of recent biological trends to climate change is complicated because non-climatic influences dominate local, short-term biological changes. Any underlying signal from climate change is likely to be revealed by analyses that seek systematic trends across diverse species and geographic regions; however, debates within the Intergovernmental Panel on Climate Change (IPCC) reveal several definitions of a 'systematic trend'. Here, we explore these differences, apply diverse analyses to more than 1,700 species, and show that recent biological trends match climate change predictions. Global meta-analyses documented significant range shifts averaging 6.1 km per decade towards the poles (or metres per decade upward), and significant mean advancement of spring events by 2.3 days per decade. We define a diagnostic fingerprint of temporal and spatial 'sign-switching' responses uniquely predicted by twentieth century climate trends. Among appropriate long-term/large-scale/multi-species data sets, this diagnostic fingerprint was found for 279 species. This suite of analyses generates 'very high confidence' (as laid down by the IPCC) that climate change is already affecting living systems.

Nature, 2003

Table 1 **Summary of data studying phenological and distributional changes of wild species**

Taxon	Ref. number	Total no. of species (or species groups)	Spatial scale L	Spatial scale R	Spatial scale C	Time scale (range years)	Change in direction predicted (*n*)	Change opposite to prediction (*n*)	Stable (*n*)	No prediction (*n*)
Phenological changes										
Woody plants	20,23,24*,25*	*n* = 38 sp		2	1	35–132	30	1	7	–
Herbaceous plants	20,21*	*n* = 38 sp	1	1		63–132	12	–	26	–
Mixed plants	22*	*n* = 385 sp	1			46	279	46	60	–
Birds	20,21*,30,31,32,33	*n* = 168 sp	2	3	1	21–132	78	14	76	–
Insects	26	*n* = 35 sp		1		23	13	–	22	–
Amphibians	27,28	*n* = 12 sp	2			16–99	9	–	3	–
Fish	20	*n* = 2 sp		1		132	2	–	–	–
Distribution/abundance changes										
Tree lines	54,55,56*	*n* = 4 sp + 5 grps	2	1		70–1,000	3 sp + 5 grps	–	1	–
Herbs and shrubs	18,19,41*,42*	*n* > 66 sp, 15 detailed		3		28–80	13	2	–	–
Lichens	36	4 biogeographic grps (*n* = 329 sp)	1			22	43	9	113	164
Birds	8*	*n* = 3 sp		1		50	3	–	–	–
	16,57*	N sp (*n* = 46 sp)		2		20–36	13	15	18	
		S sp (*n* = 73 sp)		2		20–36	36	16	21	6
	43*	Low elevation (>91 sp)	1			20	71	11	9	–
		High elevation (>96 sp)	1			20	37	27	32	–
Mammals	37	*n* = 2 sp		1		52	2	–	–	–
Insects	17,49*	*n* = 36 sp		1	1	98–137	23	2	10	1
	17	N boundaries (*n* = 52 sp)		1		98	34	1	17	–
		S boundaries (*n* = 40 sp)		1		98	10	2	28	–
Reptiles and amphibians	43*	*n* = 7 sp	1			17	6	–	1	–
Fish	39	4 biogeographic grps (*n* = 83 sp)	1			–	2 grps	–	1 grp	1 grp
	40*	N sp (*n* > 1 sp)		1		70	>1	–	–	–
		S sp (*n* > 1 sp)		1		70	>1	–	–	–
Marine invertebrates	34*,40*	N sp (*n* > 21)	1	1		66–70	>19	2	–	>1 sp not classified
		S sp (*n* > 21)	1	1		66–70	>20	1	–	
		Cosmopolitan sp (*n* = 28 sp)	1			66	–	–	–	28
Marine zooplankton	40*	Cold water (*n* > 10 sp)		1		70	>10	–	–	>8 sp not classified
		Warm water (*n* > 14 sp)		1		70	>14	–	–	
	35	6 biogeographic grps (*n* ≥ 36 sp)			1	39	6 grps	–	–	–

N, species with generally northerly distributions (boreal/arctic); S, species with generally southerly distributions (temperate); L, local; R, regional (a substantial part of a species distribution; usually along a single range edge); C, continental (most or the whole of a species distribution). No prediction indicates that a change may have been detected, but the change was orthogonal to global warming predictions, was confounded by non-climatic factors, or there is insufficient theoretical basis for predicting how species or system would change with climate change.

*Study partially controlled for non-climatic human influences (for example, land-use change). Studies that were highly confounded with non-climatic factors were excluded. (See Supplementary Information for details of species classification.)

consistent with hypothesis

inconsistent with hypothesis

Table 2 **Summary statistics and synthetic analyses derived from Table 1**

Type of change	Changed as predicted	Changed opposite to prediction	*P*-value
Phenological ($N = 484/(678)$)	87% ($n = 423$)	13% ($n = 61$)	$<0.1 \times 10^{-12}$
Distributional changes			
At poleward/upper range boundaries	81%	19%	–
At equatorial/lower range boundaries	75%	25%	–
Community (abundance) changes			
Cold-adapted species	74%	26%	–
Warm-adapted species	91%	9%	–
$N = 460/(920)$	81% ($n = 372$)	19% ($n = 88$)	$<0.1 \times 10^{-12}$
Meta-analyses			
Range-boundaries ($N = 99$)	6.1 km m^{-1} per decade northward/upward shift*		0.013
Phenologies ($N = 172$)	2.3 days per decade advancement*		<0.05

Data points represent species, functional groups or biogeographic groups. *N*, number of statistically or biologically significant changes/(total number species with data reported for boundary, timing, or abundance processes). The no prediction category is not included here.

*Bootstrap 95% confidence limits for mean range boundary change are 1.26, 10.87; for mean phenological shift the limits are −1.74, −3.23.

out of 1700 species, 920 had data about distribution or abundance changes

out of the 920, 460 species had a statistically or biologically significant change

out of the 460, 81% changed as predicted based on climate change

Table 3 **Biological fingerprint of climate change impacts**

Sign-switching pattern	Percentage of species showing diagnostic pattern
Community	
Abundance changes have gone in opposite directions for cold-adapted compared with warm-adapted species. Usually local, but many species in each category. Diverse taxa, $n = 282$*.	80%
Temporal	
Advancement of timing of northward expansion in warm decades (1930s/40s and 1980s/90s); delay of timing or southward contraction in cool decades (1950s/60s), 30–132 years per species. Diverse taxa, $n = 44$*.	100%
Spatial	
Species exhibit different responses at extremes of range boundary during a particular climate phase. Data are from substantial parts of both northern and southern range boundaries for each species. All species are northern hemisphere butterflies, $n = 8$*.	100%

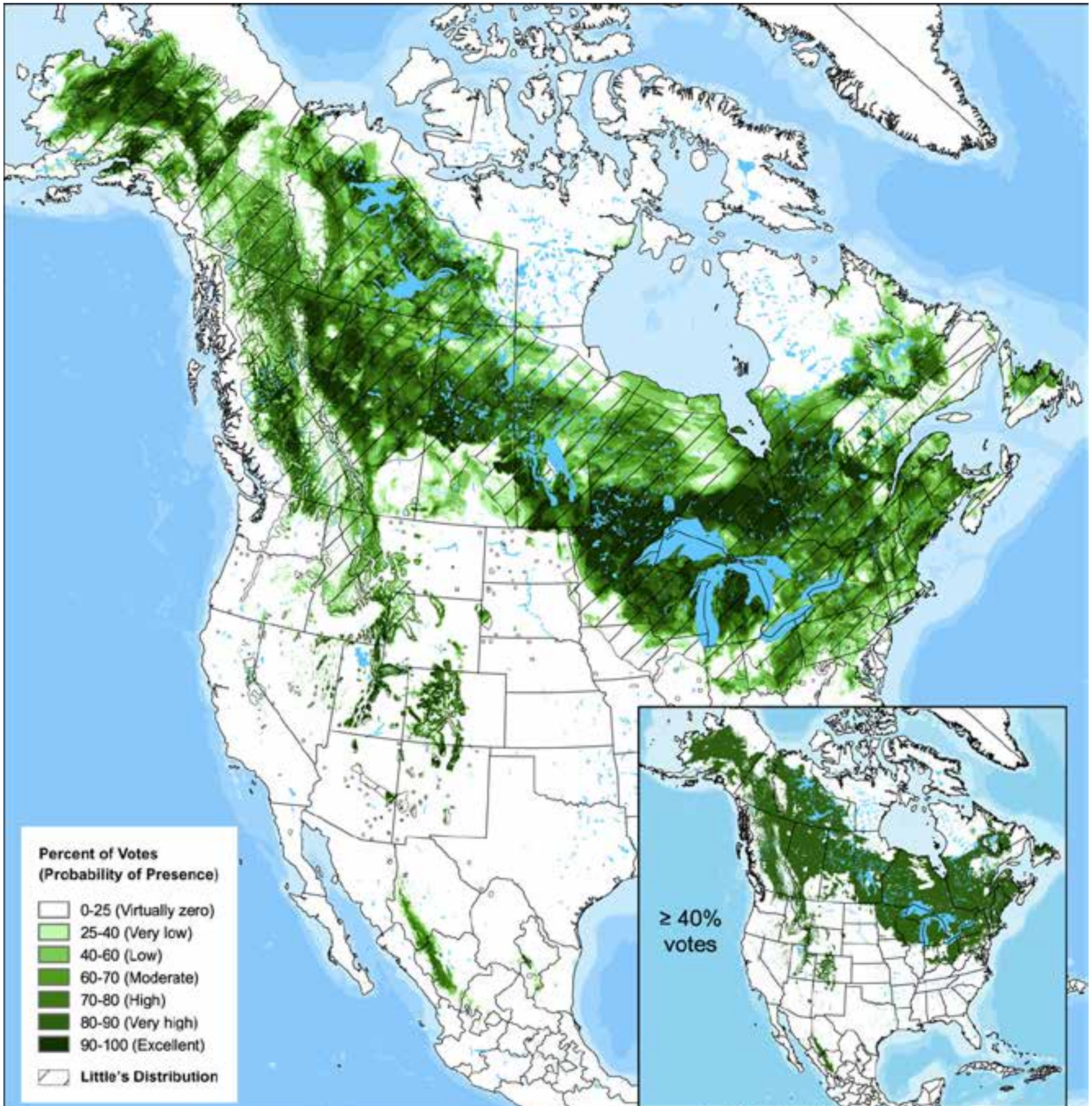
Differential sign-switching patterns diagnostic of climate change as the underlying driver.
*Numbers of species represent minimum estimates, as not all species were described in sufficient detail in each study to classify. A few species showed two types of sign switching, and so are included in more than one cell. Data are from references in text and from raw data provided by L. Kaila, J. Kullberg, J. J. Lennon, N. Ryrholm, C. D. Thomas, J. A. Thomas and M. Warren.

[in locations of overlapping ranges, polar (cold-adapted) species have responded negatively to warming whereas temperate (warm-adapted) species have responded positively]

out of 334 species, 279 showed one of these biological fingerprints

Parmesan and Yohe, Nature, 2003

Sudden aspen decline



distribution of fundamental niche of aspen based on species distribution model

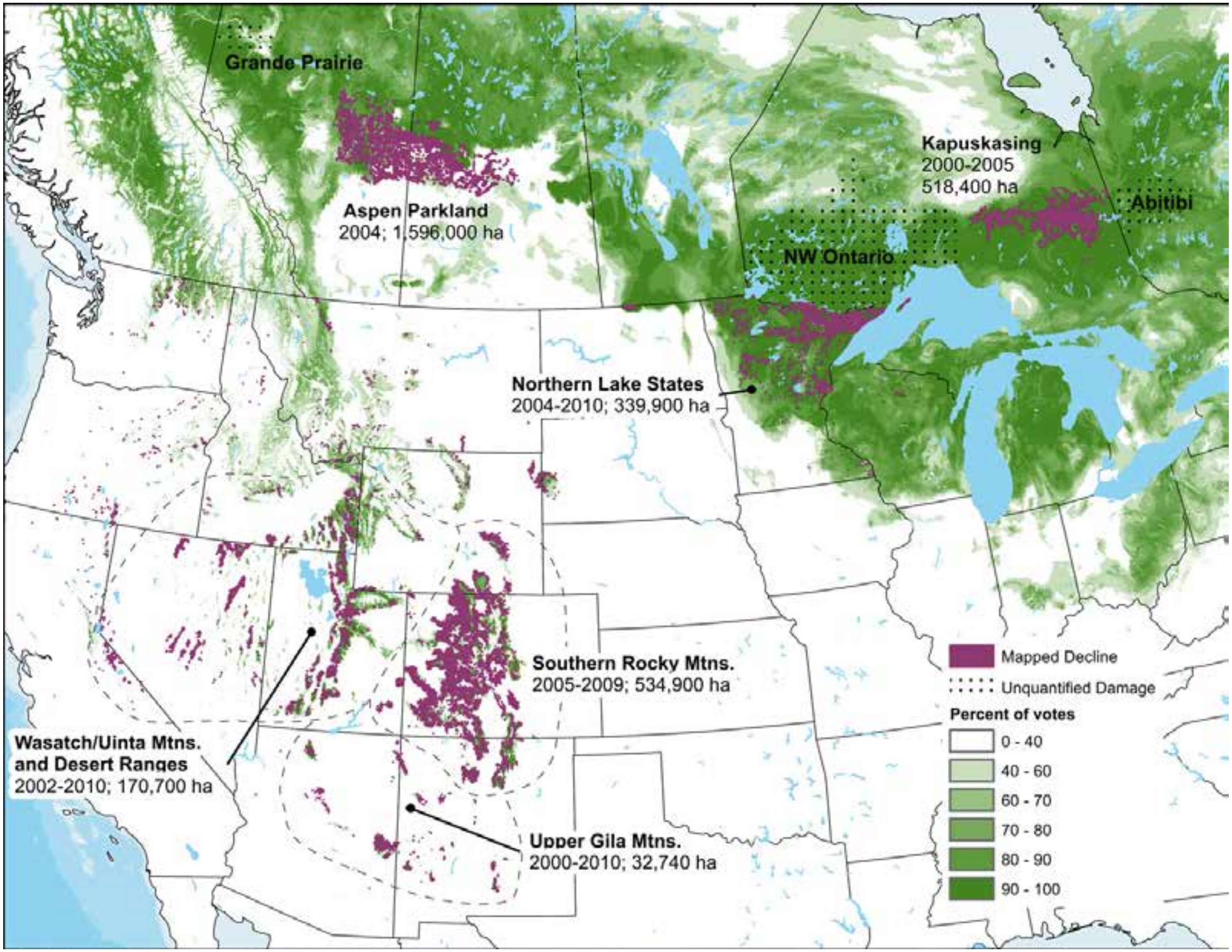
Worrall et al., Forest Ecology and Management, 2013

Sudden aspen decline

Photo courtesy of W. Anderegg

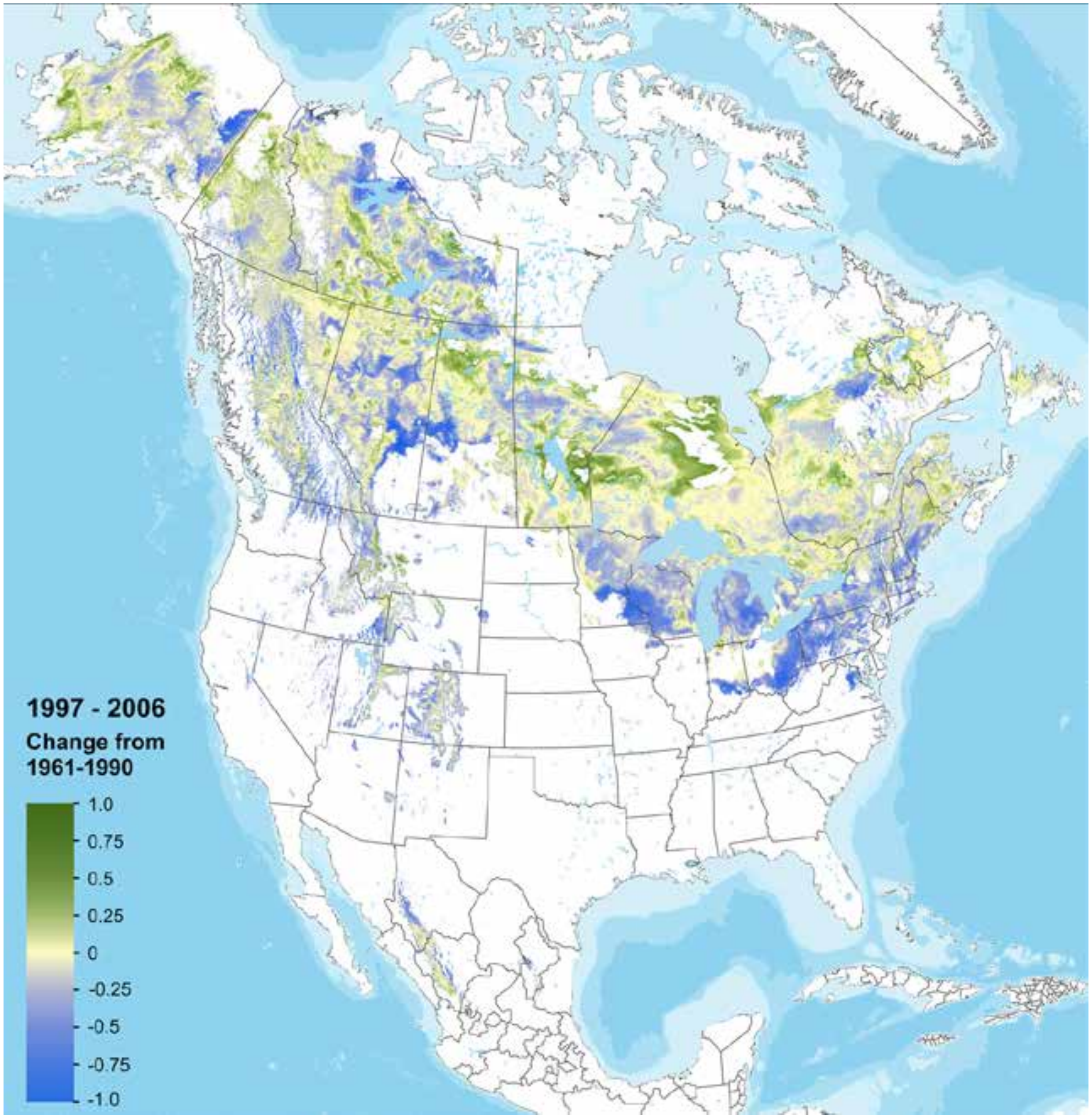
Sudden aspen decline

locations of SAD



Worrall et al., Forest Ecology and Management, 2013

Sudden aspen decline

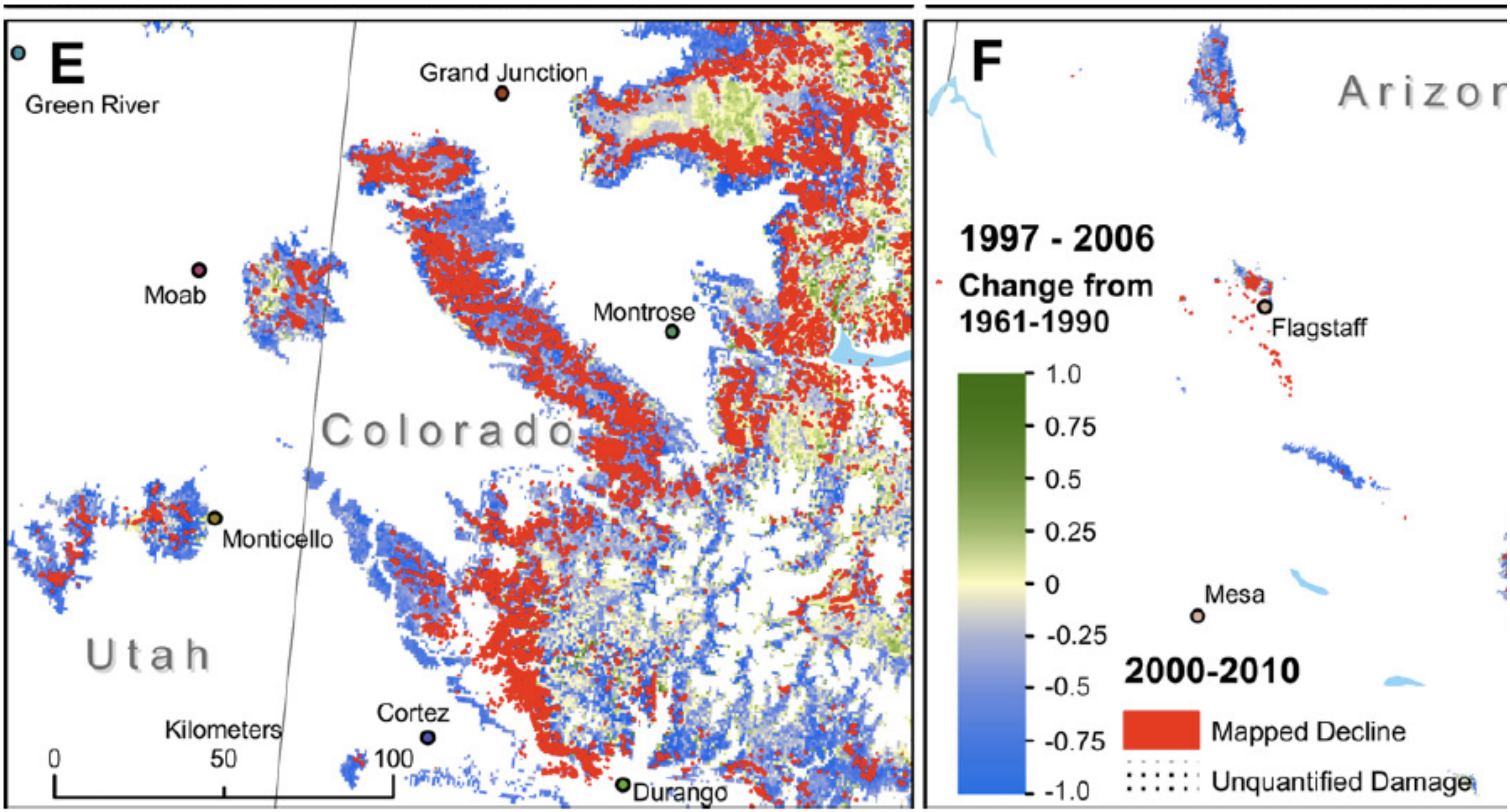


stress induced by recent changes in climate

Worrall et al., Forest Ecology and Management, 2013

Sudden aspen decline

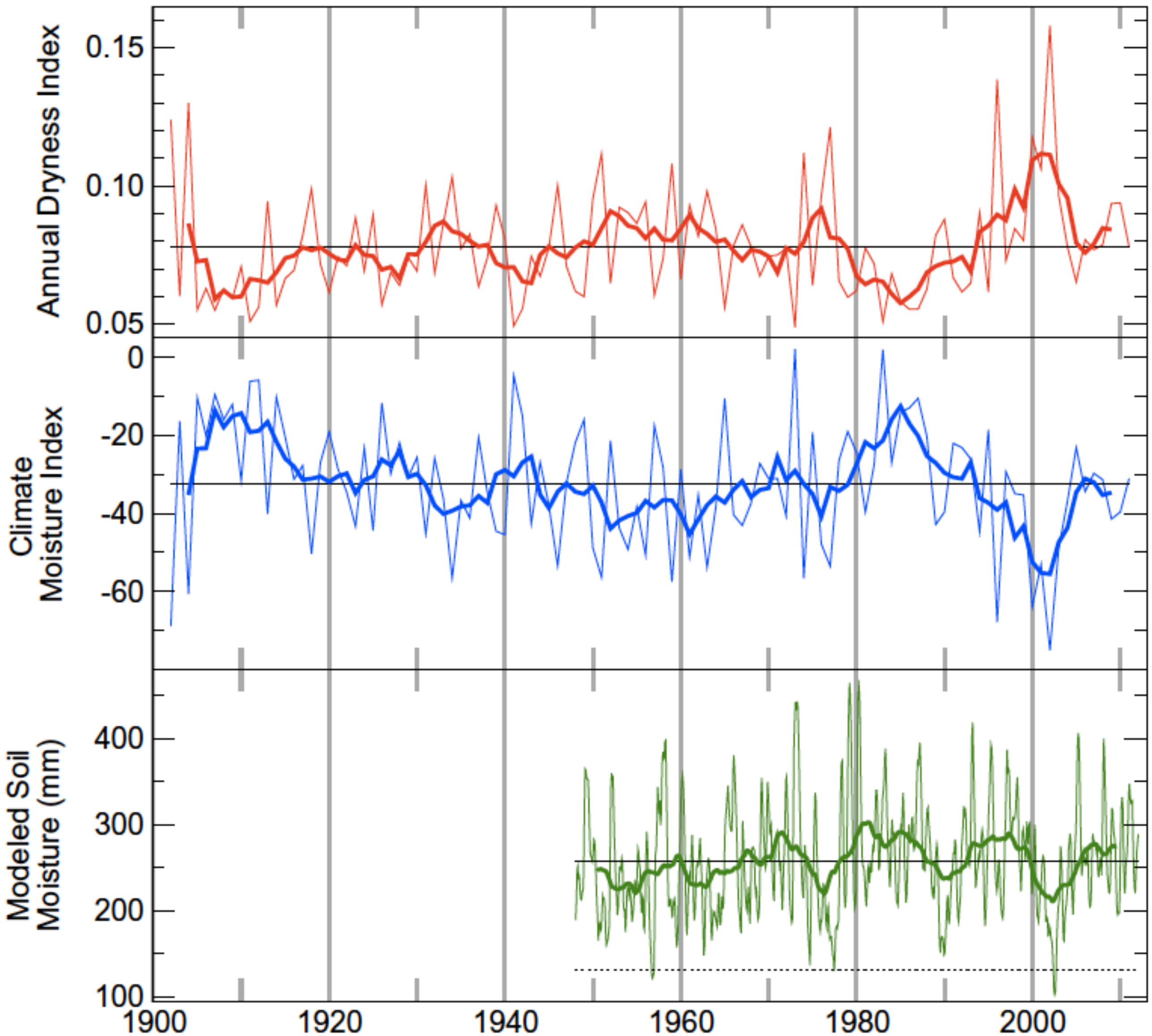
modeled stress (blue) and observed decline (red)



Worrall et al., Forest Ecology and Management, 2013

Sudden aspen decline

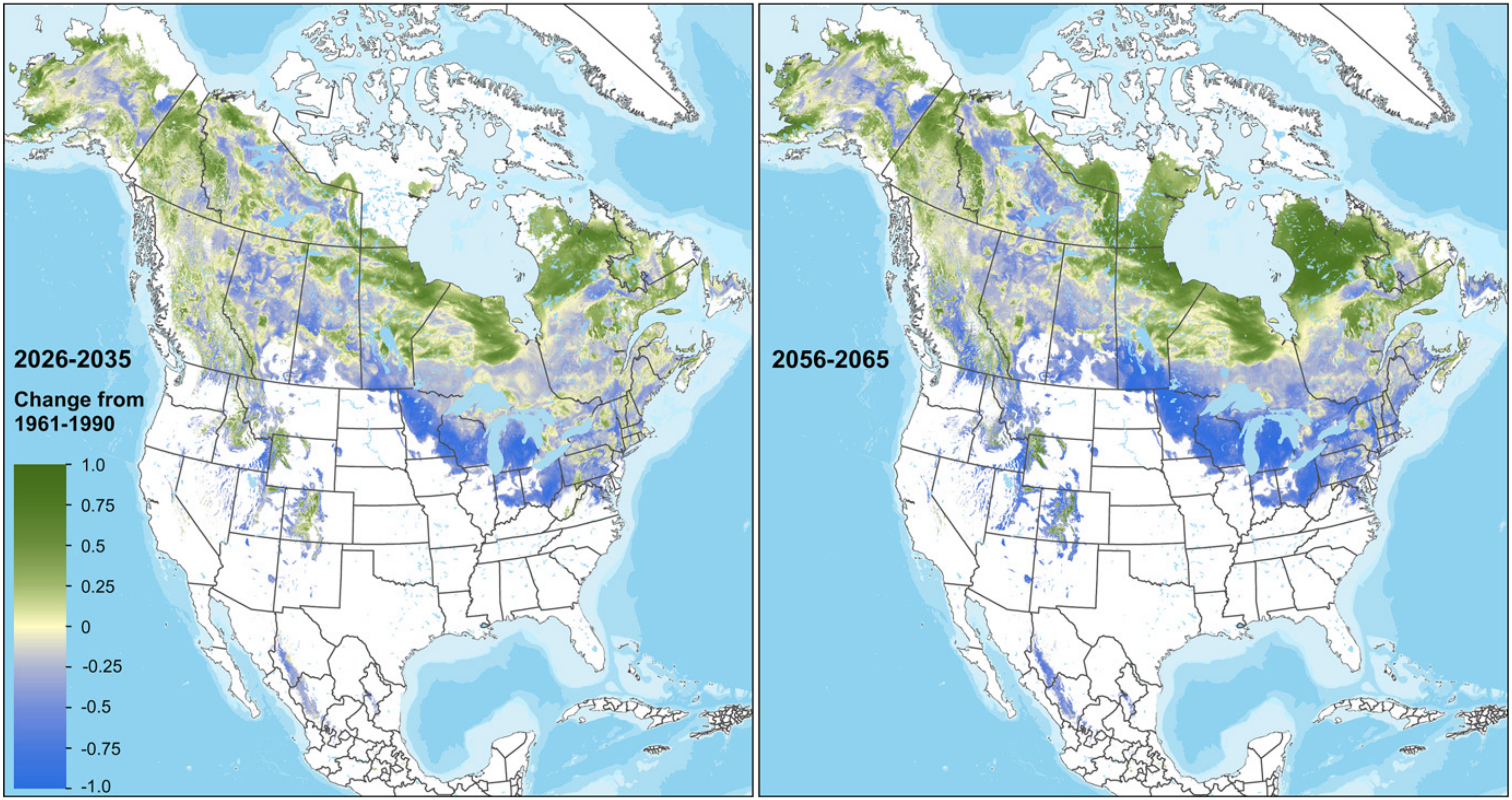
Climate in last 100 years in Colorado



Worrall et al., Forest Ecology and Management, 2013

Sudden aspen decline

projections of future climate stress



Worrall et al., Forest Ecology and Management, 2013