Section 5: Habitats, Communities, Ecosystems

Reading: Ch 3 (coral bleaching, ocean acidification, polar bear habitat); Ch 5

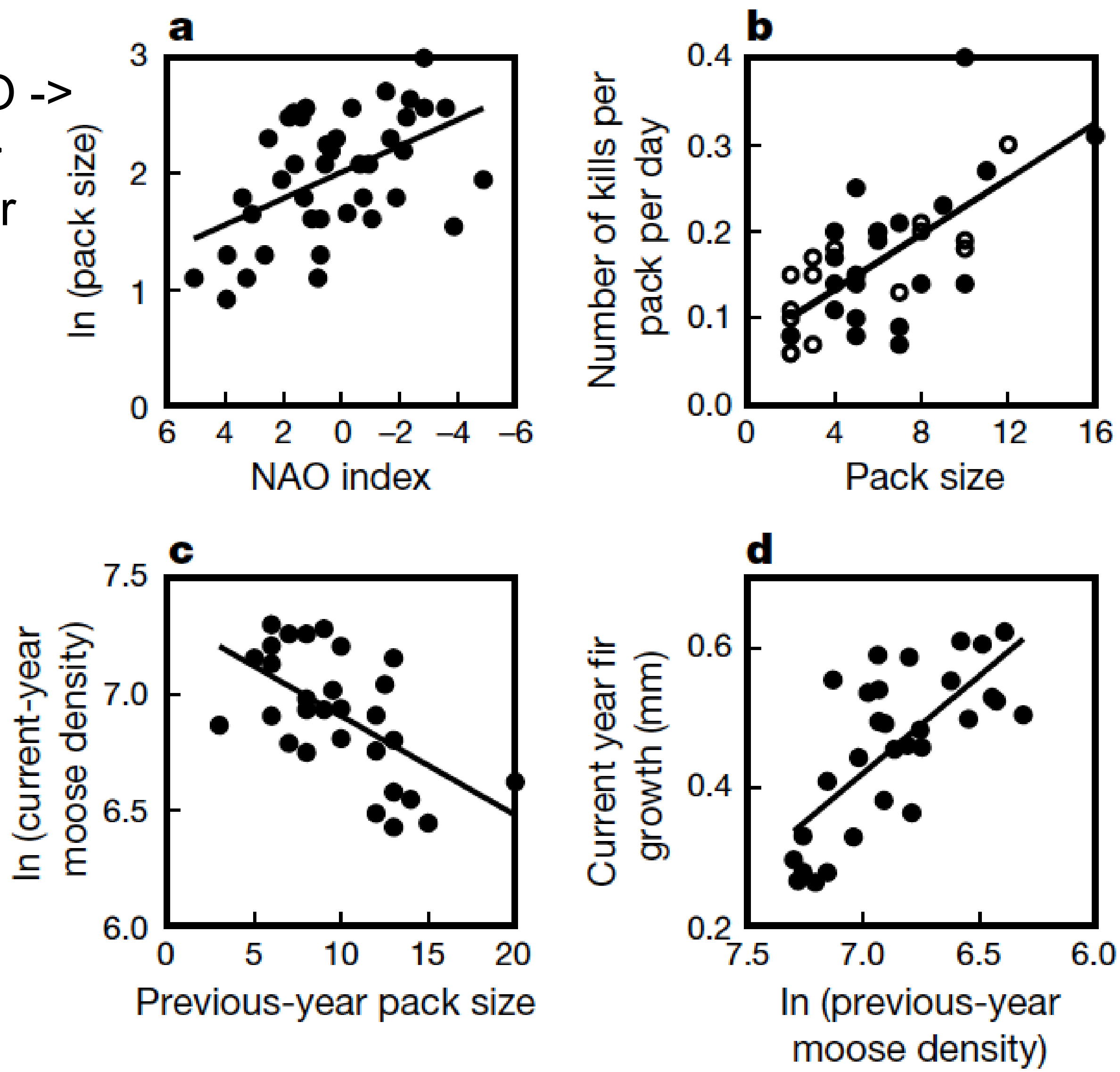
Learning outcomes

- understand definitions related to ecosystems
- explain how climate change affects biomes, and what the impacts are to ecosystem processes
- discuss examples of how climate change affects tropical, temperate, polar, freshwater, and marine ecosystems, and what the consequences of these changes are

“Ecosystem consequences of wolf behavioural response to climate”

(a) Higher NAO -> deeper snow -> hunting in larger pack

(b) larger pack size -> inc. kill efficiency per pack and per wolf

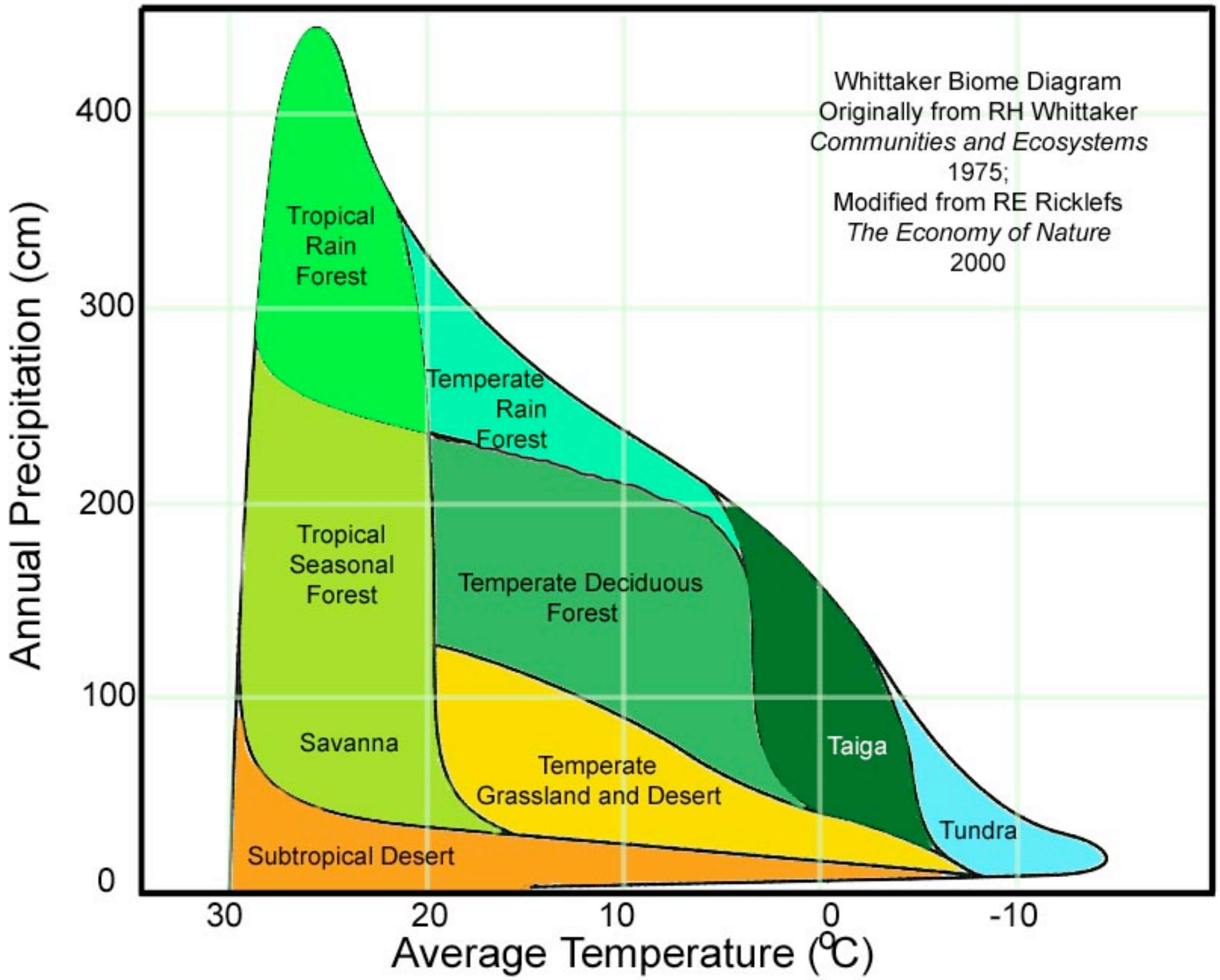


(c) larger packs, inc. kill efficiency -> fewer moose

(d) fewer moose -> higher fir growth

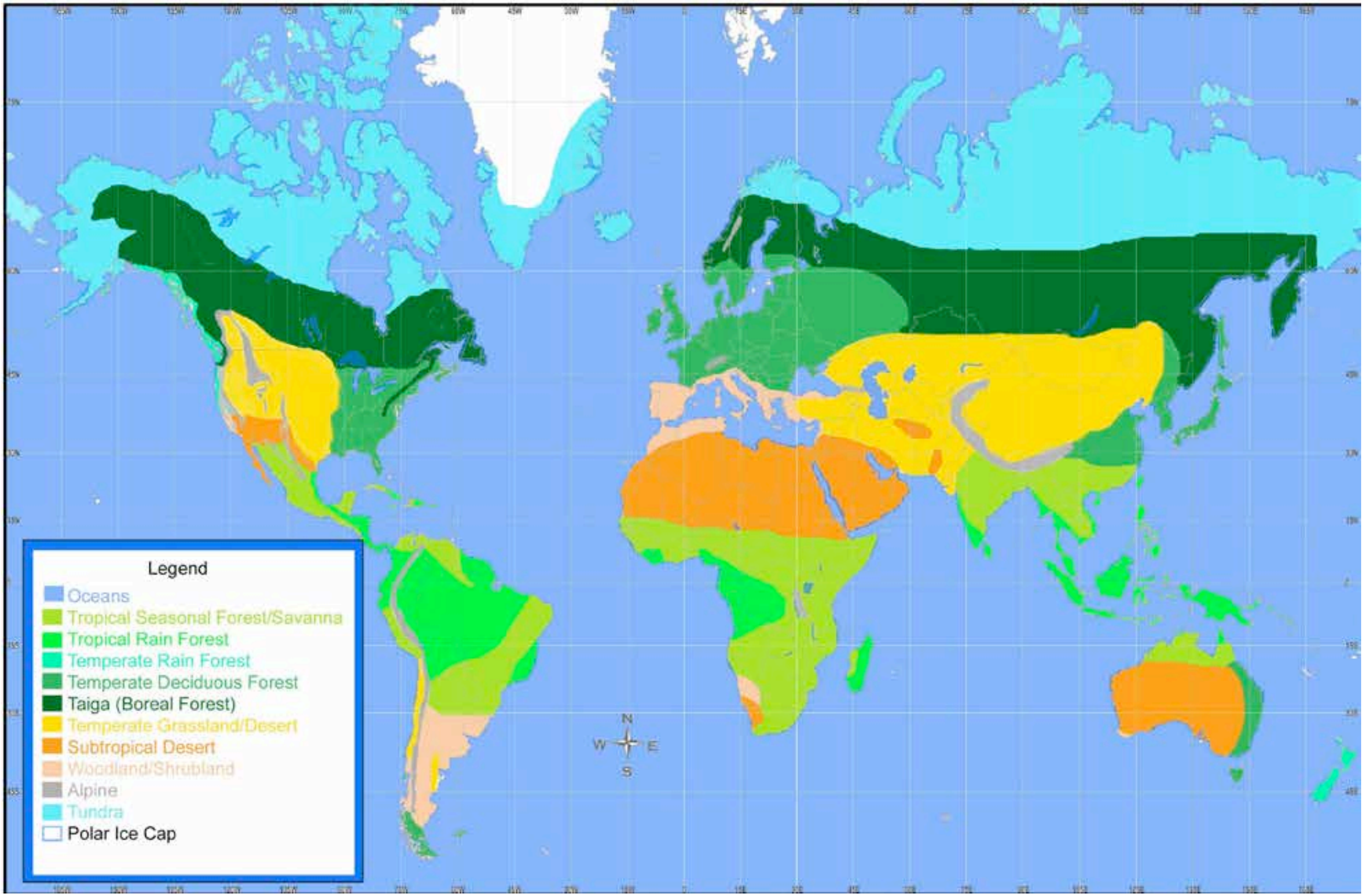
Post et al., 1999

Climate defines biomes



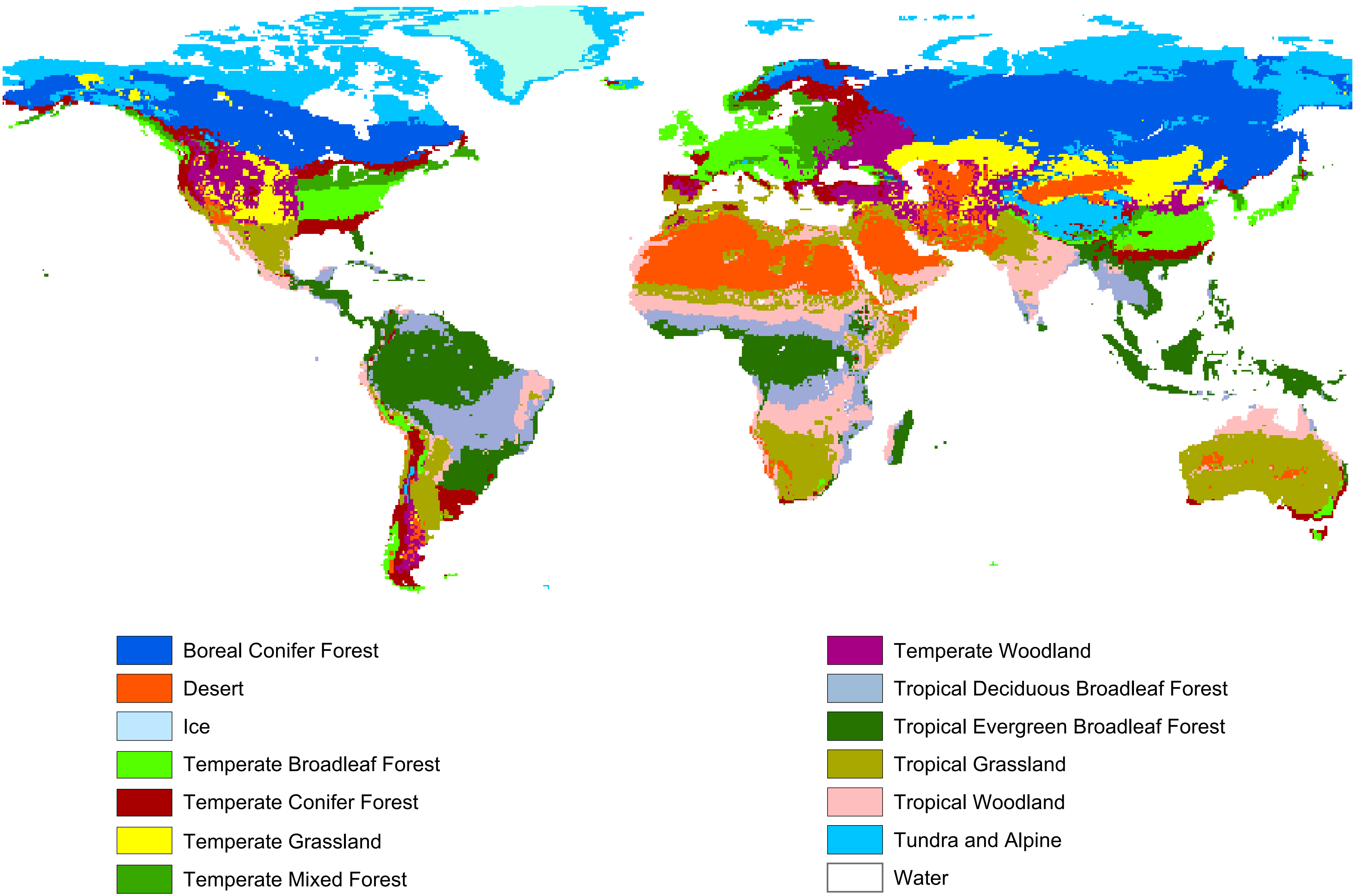
www.marietta.edu/~biol/biomes/biome_main.htm

Climate defines biomes



www.marietta.edu/~biol/biomes/biome_main.htm

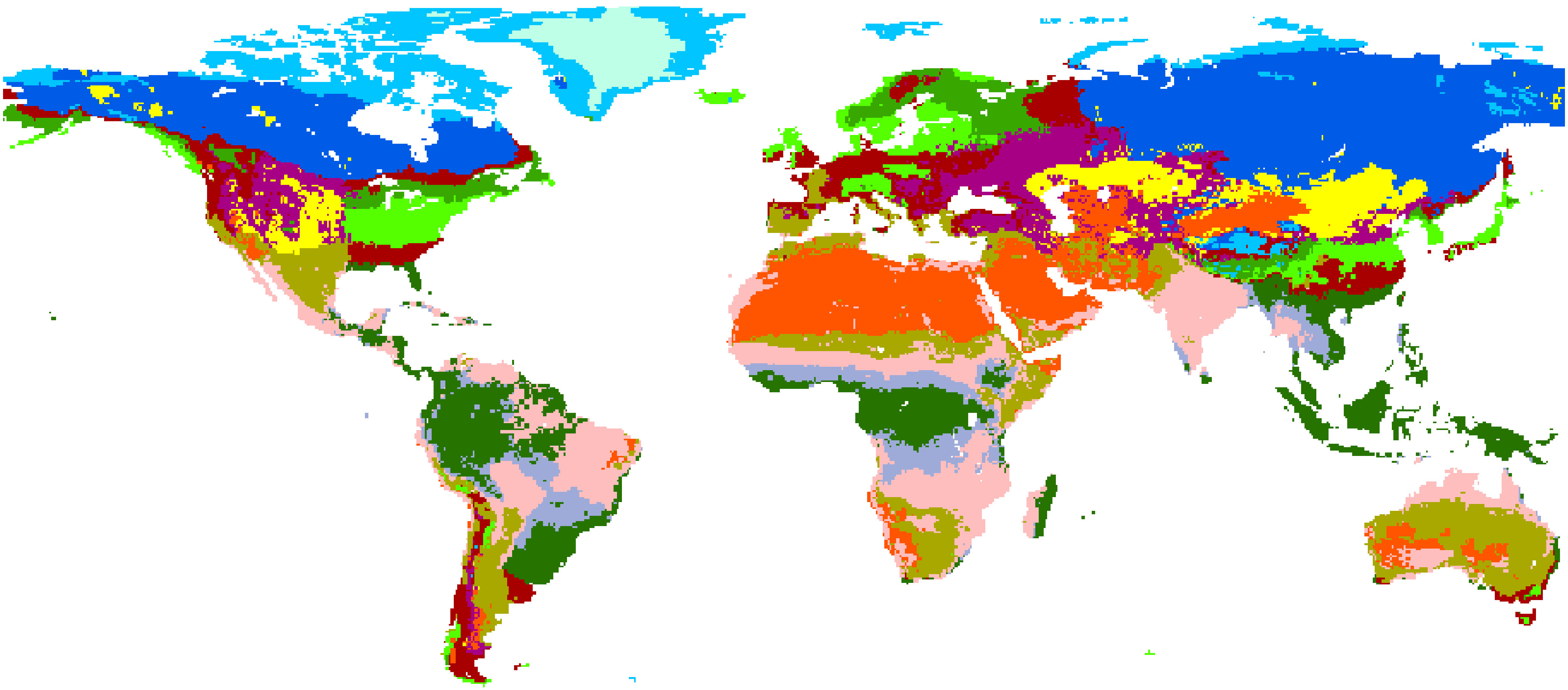
Biomes 1961-1990



Slide courtesy M. Jennings, TNC

Source: The Nature Conservancy Climate Change Initiative

Biomes 2071 - 2100, A1B Emission Scenario



Boreal Conifer Forest
Desert
Ice
Temperate Broadleaf Forest
Temperate Conifer Forest
Temperate Grassland
Temperate Mixed Forest
Temperate Woodland
Tropical Deciduous Broadleaf Forest
Tropical Evergreen Broadleaf Forest
Tropical Grassland
Tropical Woodland
Tundra and Alpine
Water

Slide courtesy M. Jennings, TNC

Source: The Nature Conservancy Climate Change Initiative

Uncertainty in projected future shifts of biomes: LPJ model, two climate change scenarios

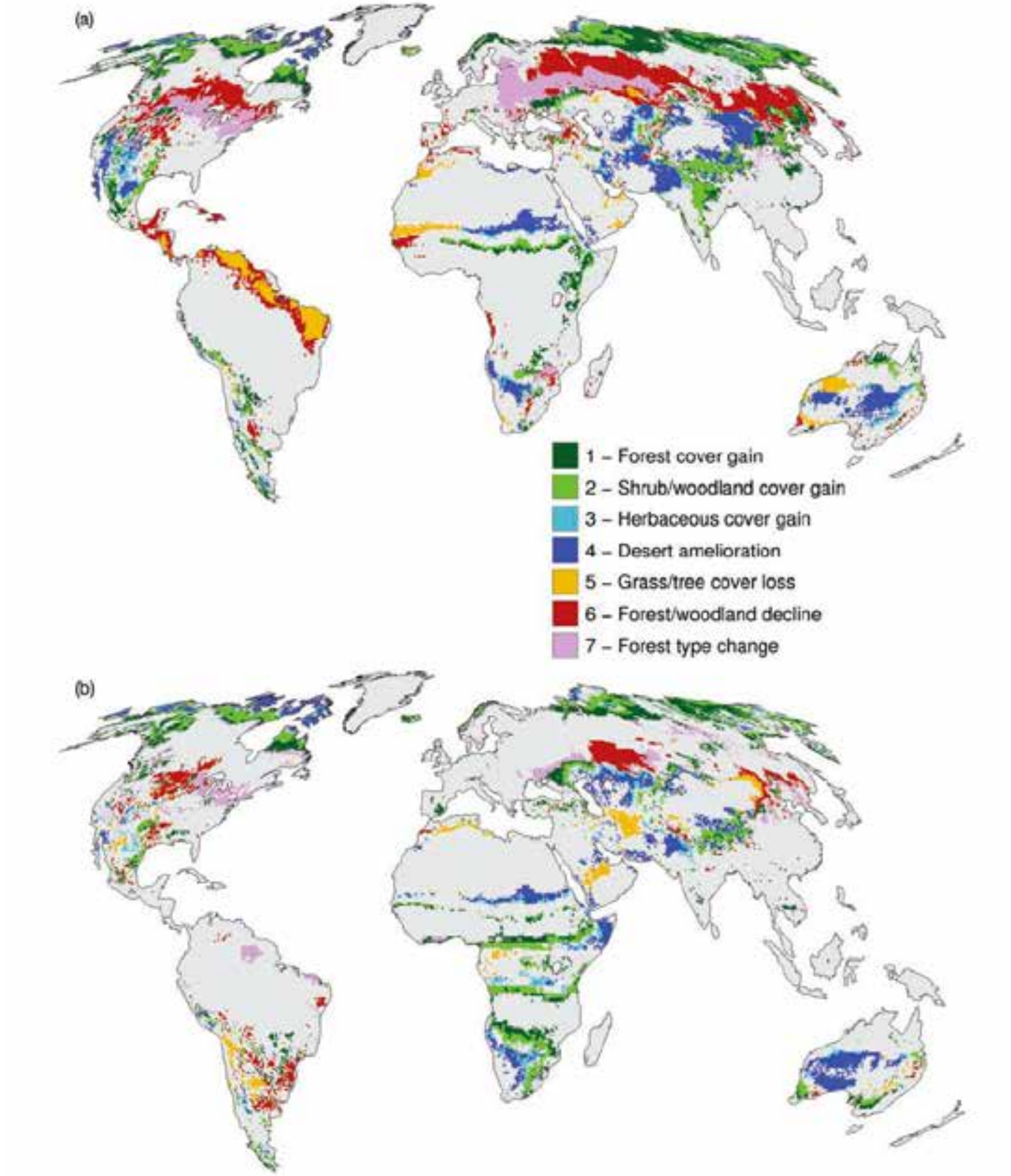


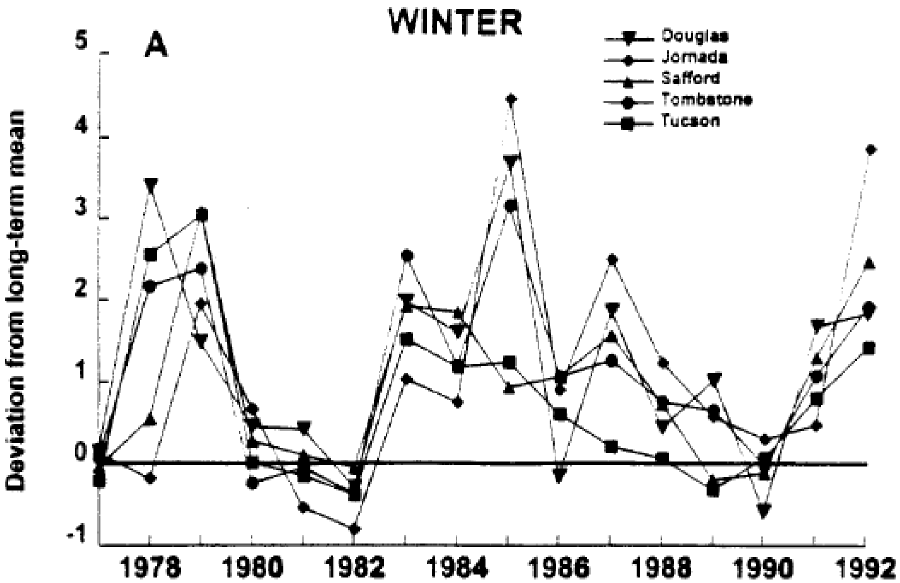
Figure 4.3. *Projected appreciable changes in terrestrial ecosystems by 2100 relative to 2000 as simulated by DGVM LPJ (Sitch et al., 2003; Gerten et al., 2004) for two SRES emissions scenarios (Nakićenović et al., 2000) forcing two climate models: (a) HadCM3 A2, (b) ECHAM5 B1 (Lucht et al., 2006; Schaphoff et al., 2006). Changes are considered appreciable and are only shown if they exceed 20% of the area of a simulated grid cell (see Figure 4.2 for further explanations).*

HADCM3 A2

ECHAM5 B1

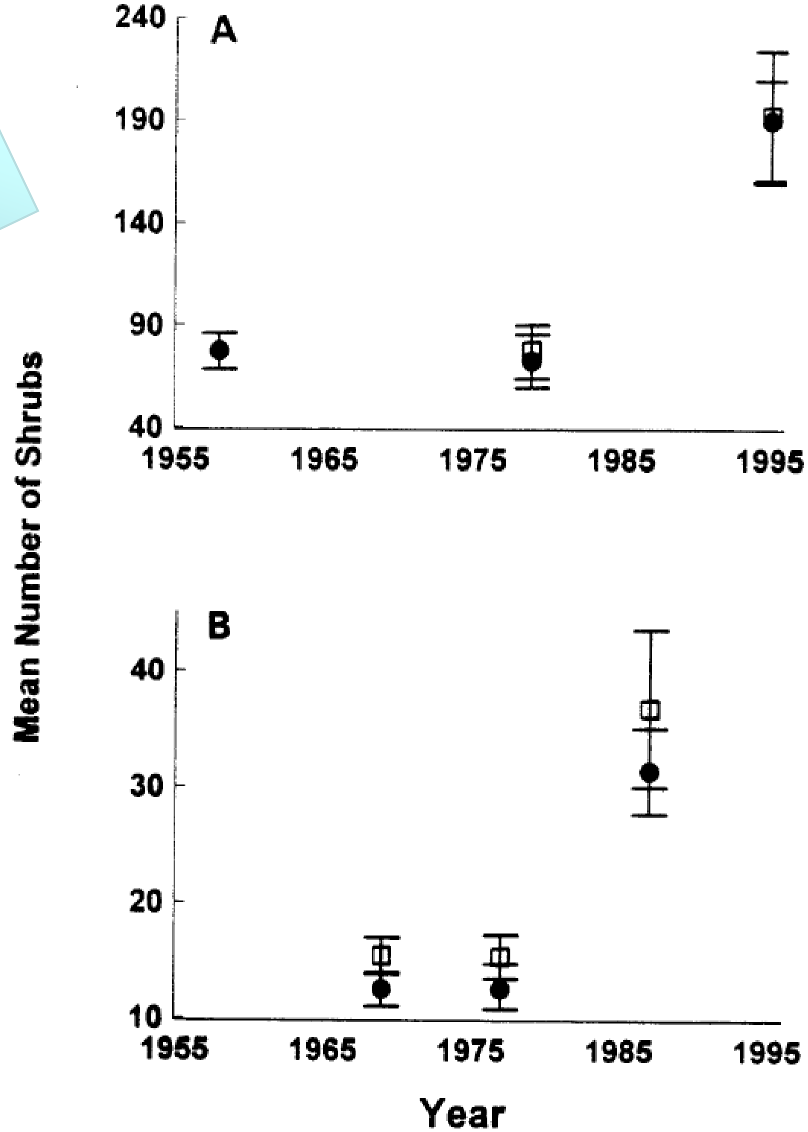
IPCC, WG II, AR4

Cascading impacts of changes: Arid ecosystems



Higher than average winter precip during 1977-1992

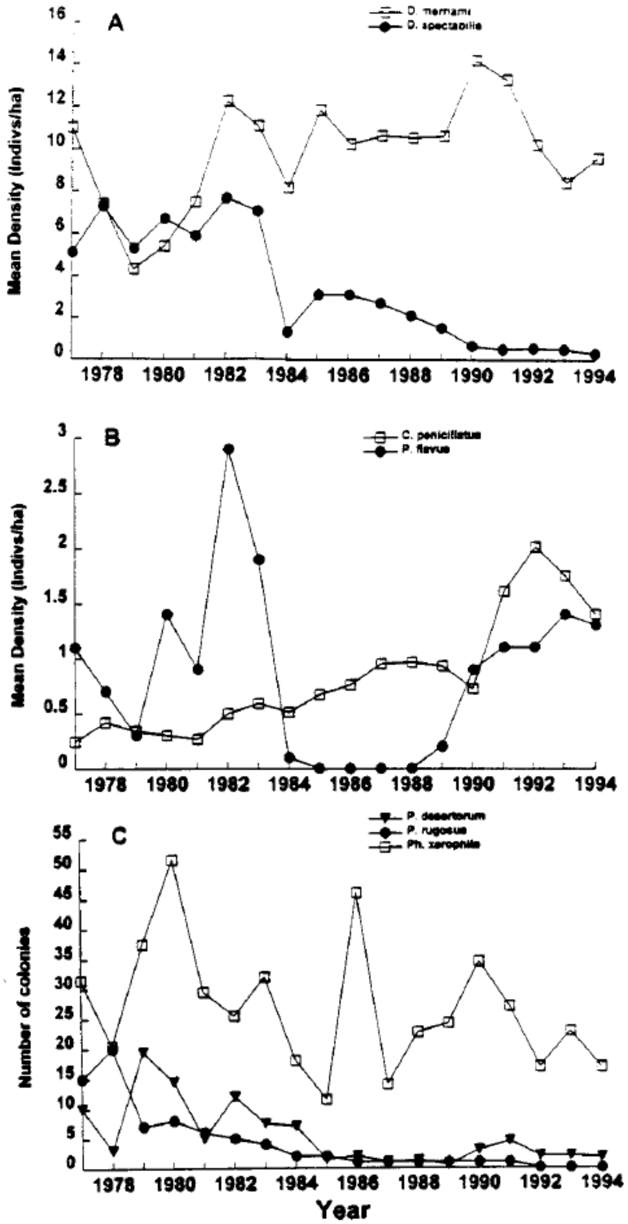
Increase in shrubs



Brown et al., 1997

Cascading impacts of changes: Arid ecosystems

Increases, decreases, and no change in animal populations

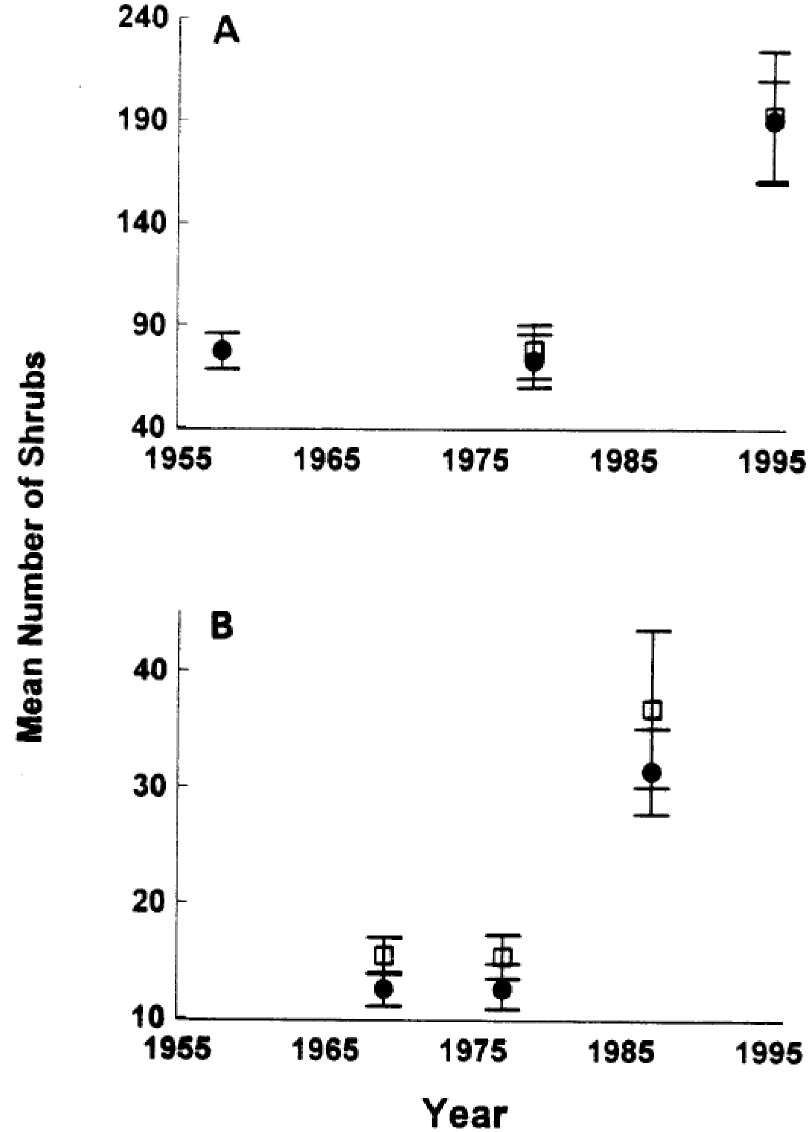


rodents

rodents

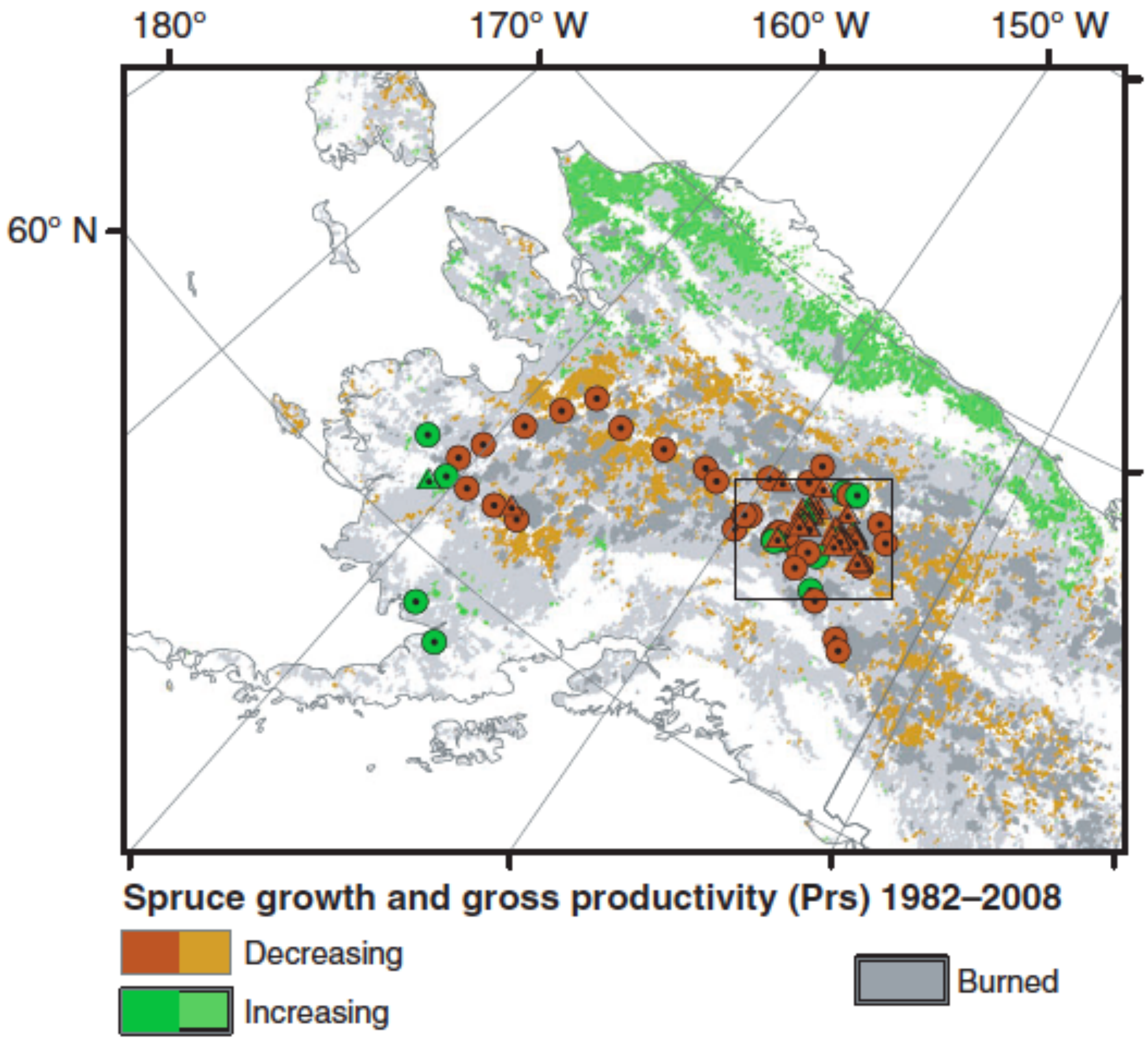
ants

Increase in shrubs



Brown et al., 1997

Evidence for biome shift:
Tree expansion at northern treeline



Beck et al., 2011

Evidence for biome shift: Tree expansion at northern treeline

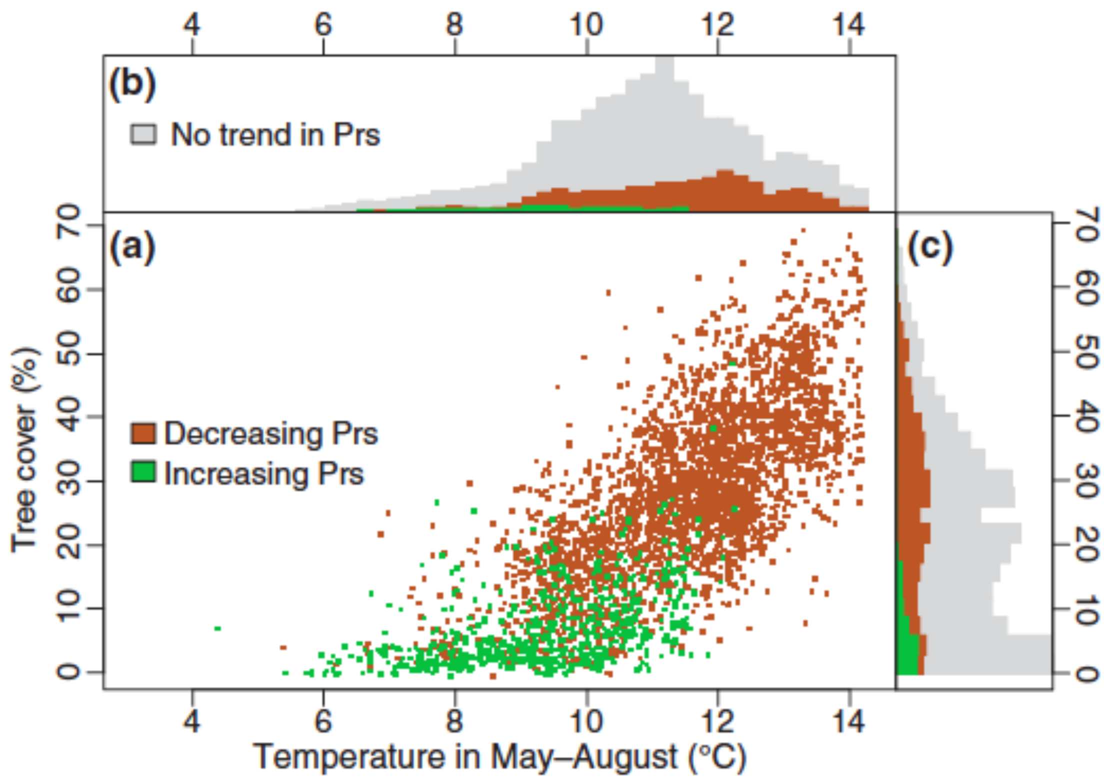


Figure 4 (a) Tree cover (Hansen *et al.* 2003) compared to mean air temperature in May–August in 1982–2007 for non-anthropogenic vegetated areas of interior Alaska, i.e. the mainland north of the Alaska Range and south of the Brooks Range. Only areas where gross productivity (Prs) shows a deterministic trend from 1982 to 2008 and where there were no wildfires between 1982 and 2007 are shown. Histograms represent the distribution of (b) temperature and (c) tree cover and include areas where no trend was detected.

Why does this figure provide evidence supporting tree expansion at northern treeline?

Beck et al., 2011

Recent shrub expansion in the Arctic

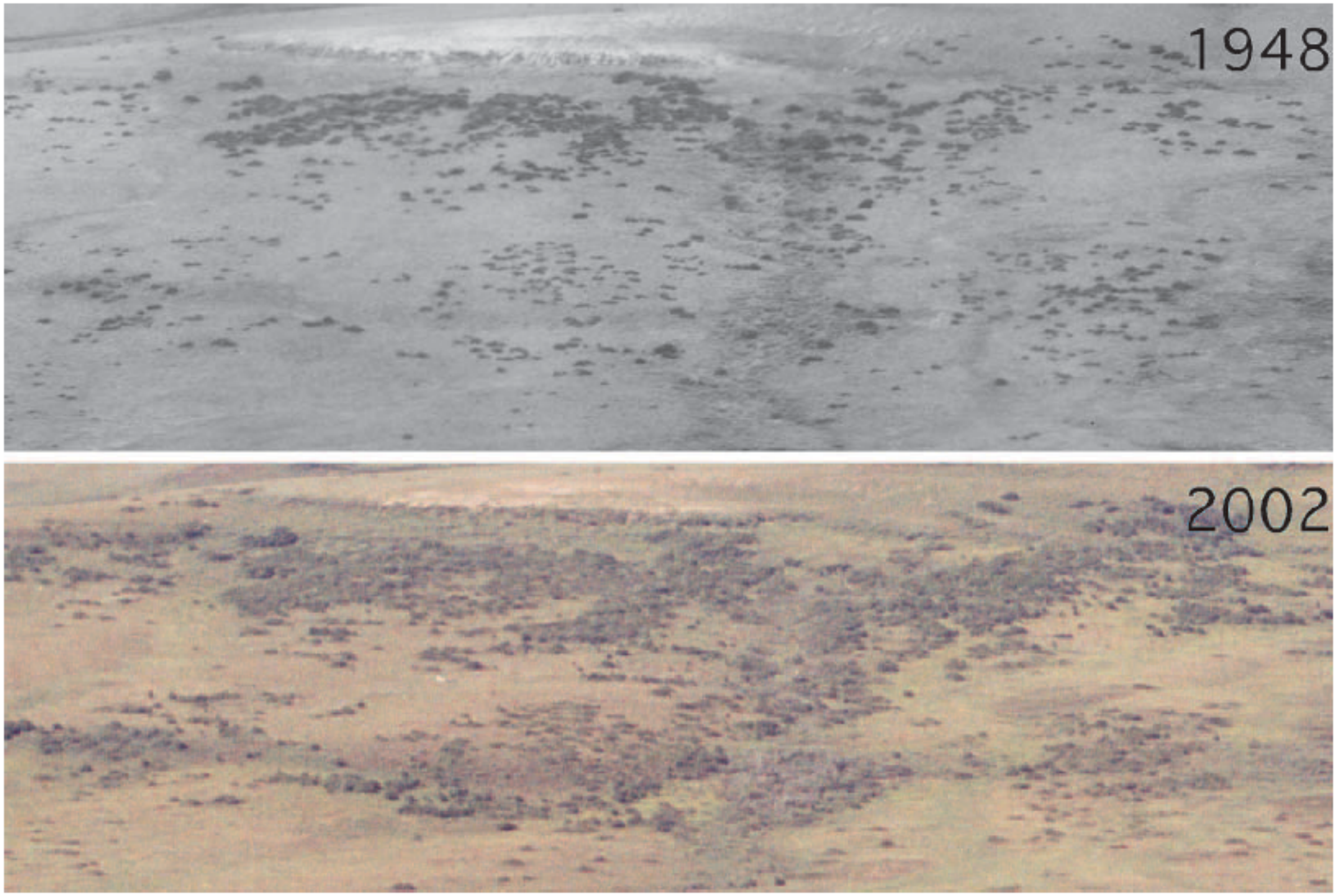


Figure 1. Increasing abundance of shrubs in arctic Alaska. The photographs were taken in 1948 and 2002 at identical locations on the Colville River (68° 57.9' north, 155° 47.4' west). Dark objects are individual shrubs 1 to 2 meters high and several meters in diameter. Similar changes have been detected at more than 200 other locations across arctic Alaska where comparative photographs are available. Photographs: (1948) US Navy, (2002) Ken Tape.

Sturm et al., 2005

Impact of biome shift on ecosystem functioning: Arctic shrub expansion

Table 2. Key differences in properties between shrubby and nonshrubby tundra.

Properties	Nonshrub tundra	Shrub tundra
Snow depth/duration	Shallower/shorter	Deeper/longer; more snow runoff
Albedo	Higher	Lower
Summer active-layer depth	Deeper	Shallower (because of shading)
Summer active-layer temperature	Warmer	Cooler
Soil temperature	Higher in summer, lower in winter	Lower in summer, higher in winter
Nutrient (nitrogen) cycling	Faster	Slower
Carbon cycling	Faster	Slower
Caribou forage access and quality	Higher	Lower
Winter CO_2 flux	Lower	Higher
Summer CO_2 exchange	Lower	Higher

CO_2, carbon dioxide.

Sturm et al., 2005

Impact of biome shift on ecosystem functioning: Arctic shrub expansion

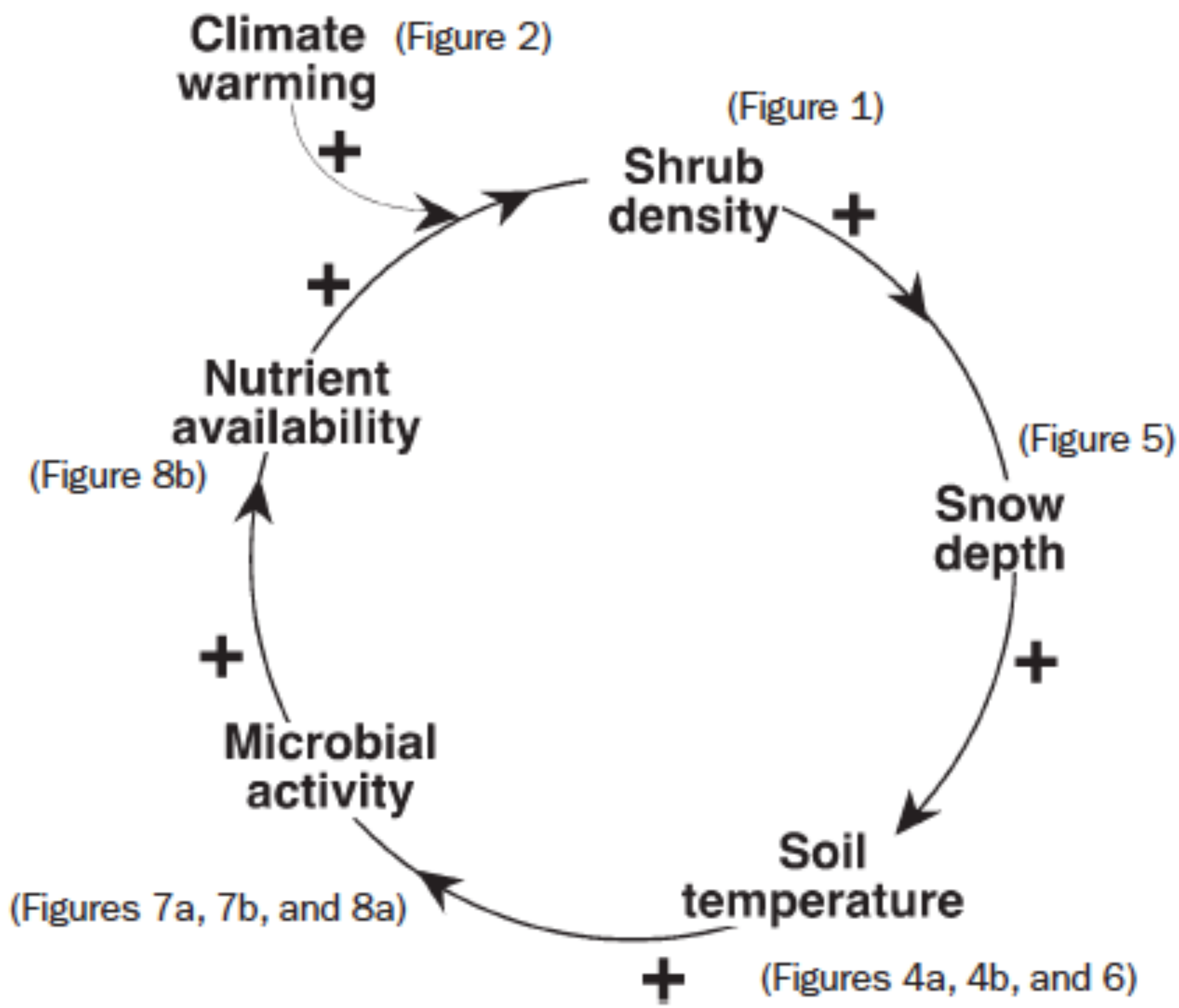


Figure 9. The snow–shrub–soil–microbe feedback loop (based on Sturm et al. 2001b).

Sturm et al., 2005

Impact of biome shift on ecosystem functioning: Arctic shrub expansion

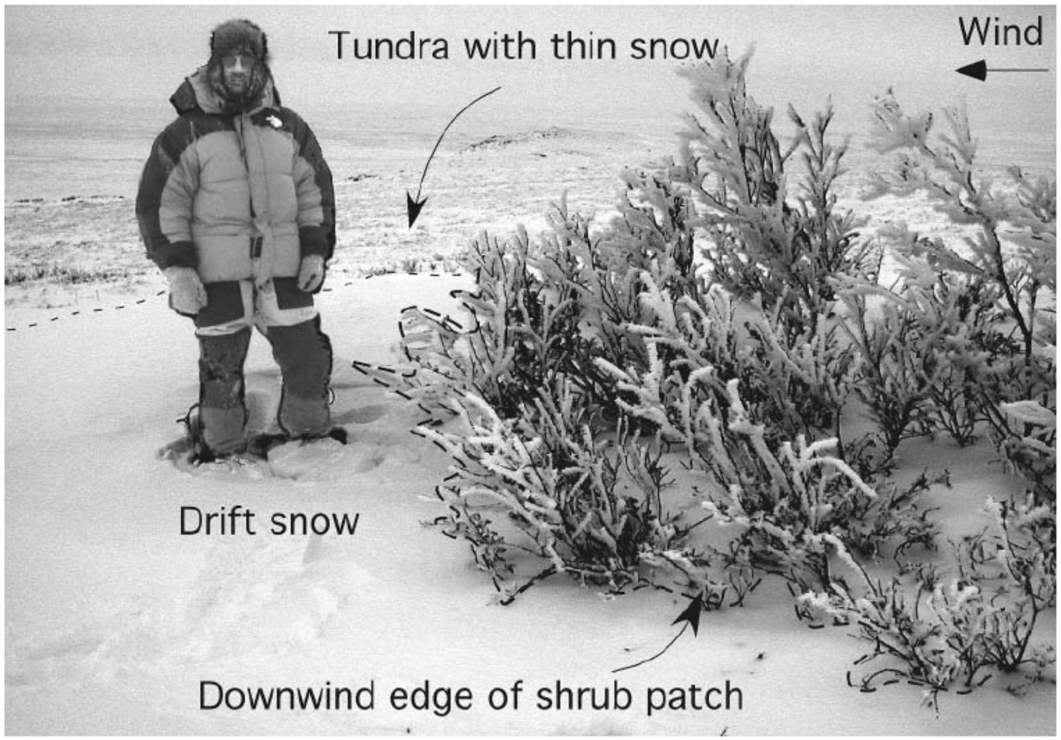


Figure 5. A shrub patch that has created a snowdrift in and downwind of the patch. The snow on the tundra behind the patch was about one-fifth as deep as the drift. Photograph: Matthew Sturm.

more soil biological activity projected in future

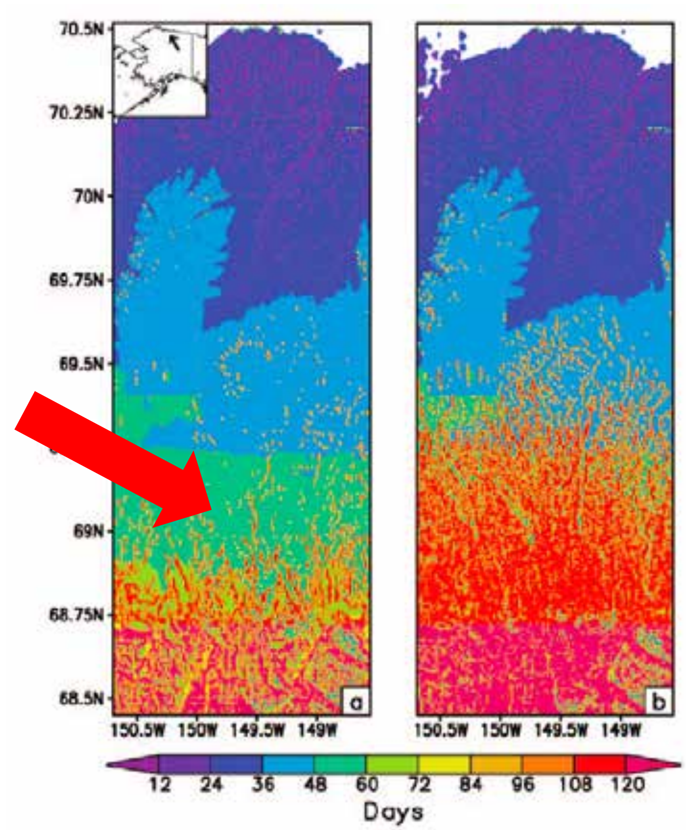
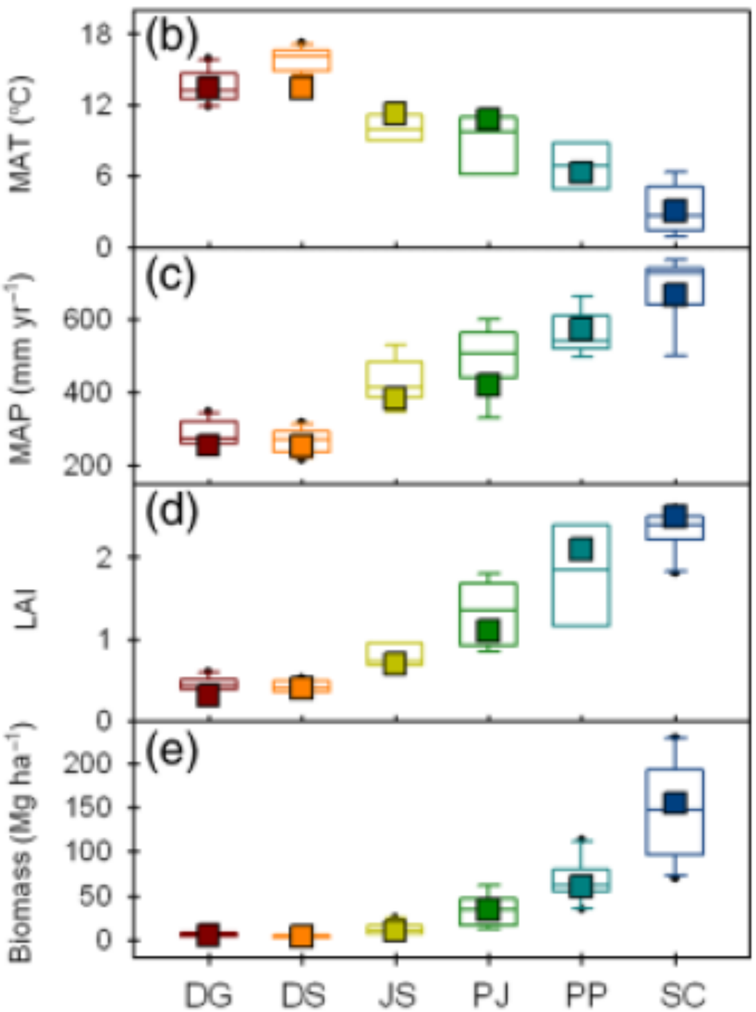


Figure 7. The Kuparuk Basin, showing a proxy index (number of days of microbial activity) for subsurface winter biological activity (a) under present conditions and (b) with projected increases in shrub growth. The index was computed by summing the number of days of the winter that the soil surface temperature is at or above –6 degrees Celsius (Taras et al. 2002). Note the strong latitudinal gradient in this index value. Snow depth increases as a function of vegetation growth, leading to significant increases in the index value, particularly in the middle and southern part of the basin.

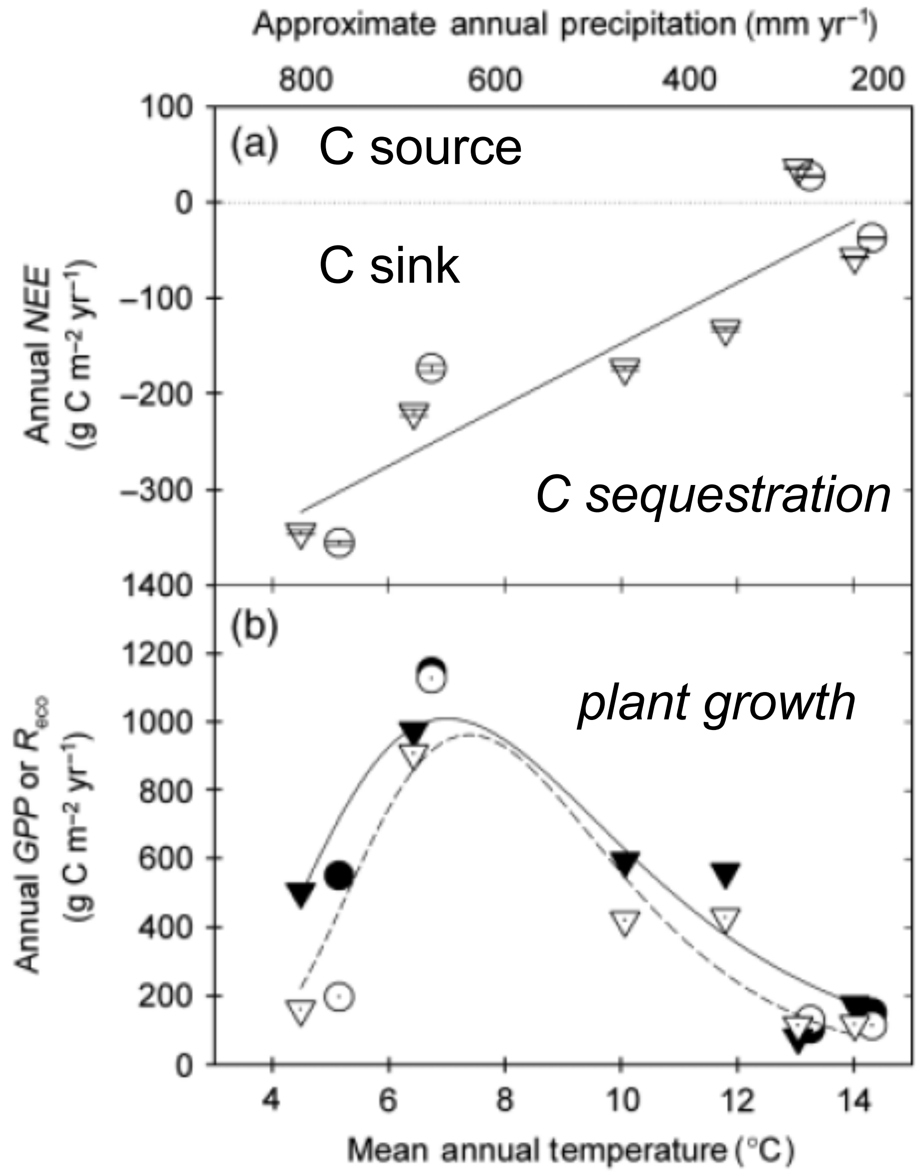
Sturm et al., 2005

Impact of biome shift on ecosystem functioning

New Mexico Environmental Gradient



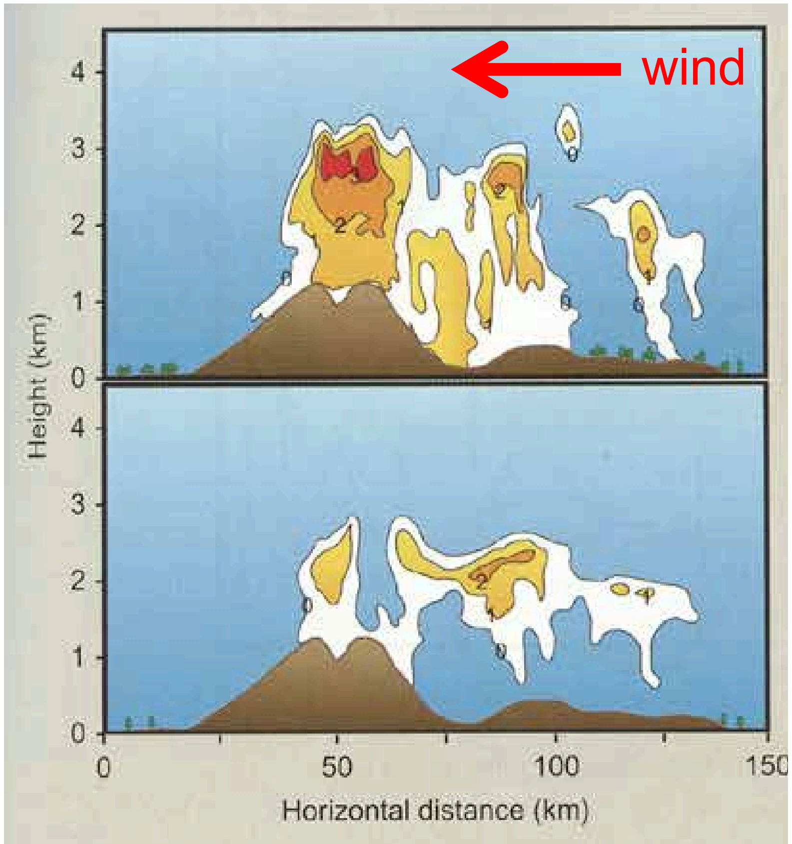
Desert Grass; Desert Shrub; Juniper Savanna; Pinyon-Juniper; Ponderosa Pine; Subalpine Conifer



Anderson-Teixeira et al., 2011

Tropical ecosystems: cloud forests

Projected changes in clouds



Tropical cloud forests form where clouds intersect mountain slopes (top). Under climate change or lowland land clearing, lowered relative humidity at altitude means clouds will form higher (bottom), reducing the area of intersection with mountains and decreasing the extent of cloud forest, possibly causing loss of some of the many endemic species found there. In this schematic, increasing relative humidity and cloud condensation are indicated by shades of orange. *Source: Lawton et al., 2001.*

Effects of dry periods on animals in cloud forest

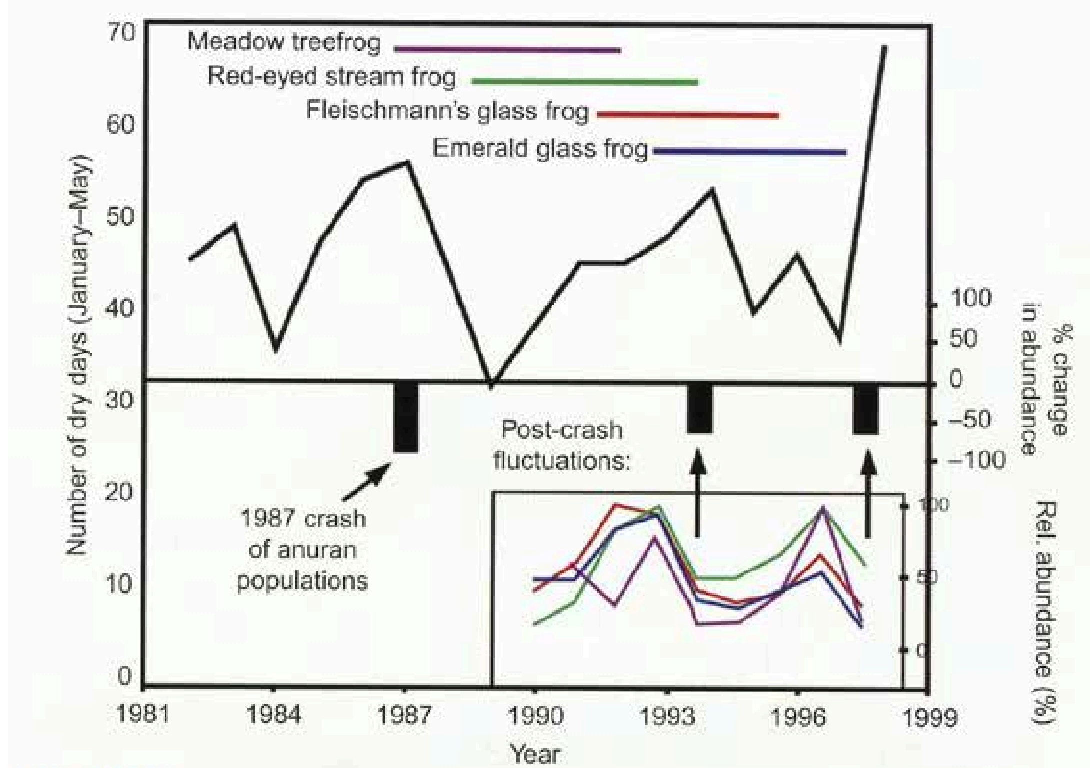


FIGURE 5.4 Monteverde Population Fluctuations Synched to Dry Days. Twenty species of frogs and toads disappeared from the Monteverde cloud forest in Costa Rica (first black bar) after an unusually long run of dry days (solid line). The golden toad (*Bufo periglenes*) was locally endemic, so its disappearance represented a global extinction, perhaps the first extinction linked to climate change. Subsequent long dry spells have caused other frog population crashes since 1987 (inset). Increasing frequency of dry spells in cloud forest is linked to climate change through the lifting cloud base effect. Dry periods appear to favor pathogenic growth of the fungus that is the ultimate cause of death in affected frogs. *Reproduced with permission from* Nature.

Hannah, 2011

Temperate forest ecosystems

Shifts in range of ponderosa pine

loss of PIPO

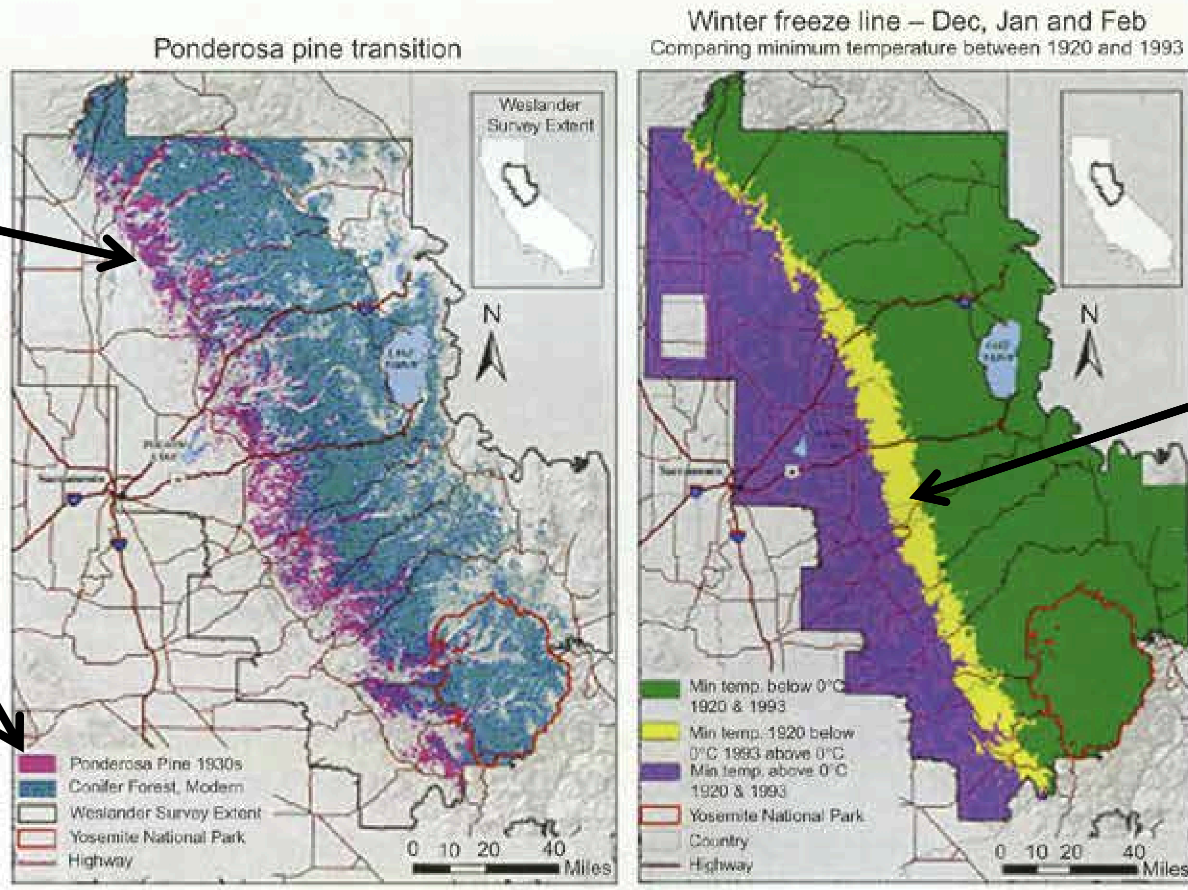
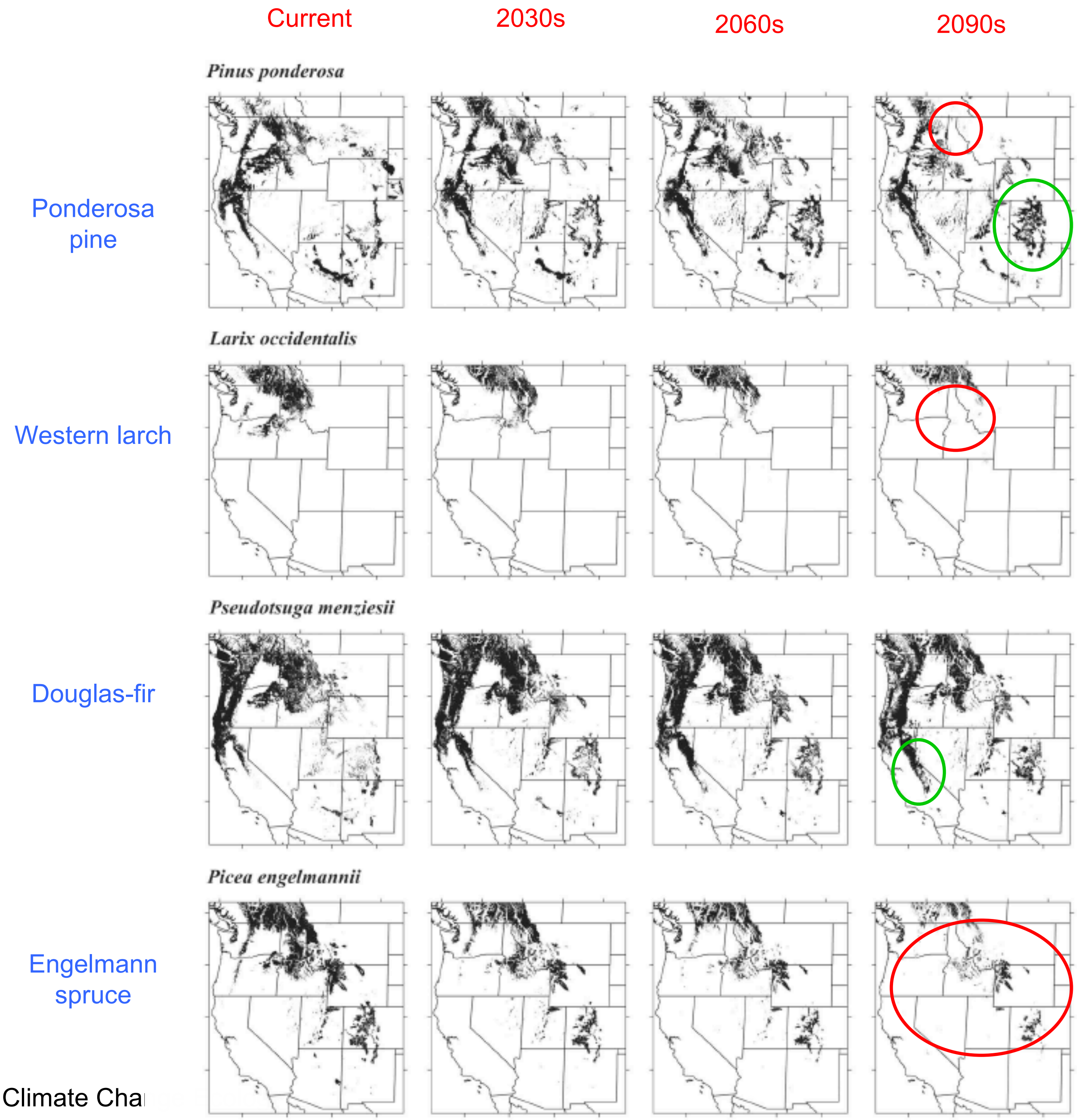


FIGURE 5.13 Map of Ponderosa Retreat in Sierras.
Ponderosa pine range has been reduced in the Sierra Nevada mountains of California since 1930. Upslope movement of montane hardwoods (dominated by *Quercus* sp.) has been replacing the lower range margin of ponderosa pine (left) while temperature has been increasing in the region (right). Upslope loss in ponderosa pine is detected by comparing vegetation surveys from the 1930s (Wieslander VTM survey) to modern vegetation maps. The area of retreat in freezeline (yellow, right) closely corresponds to the area of pine loss (red-purple, left). *Figure courtesy of Jim Thorne.*

new areas with T>0 deg C

Hannah, 2011

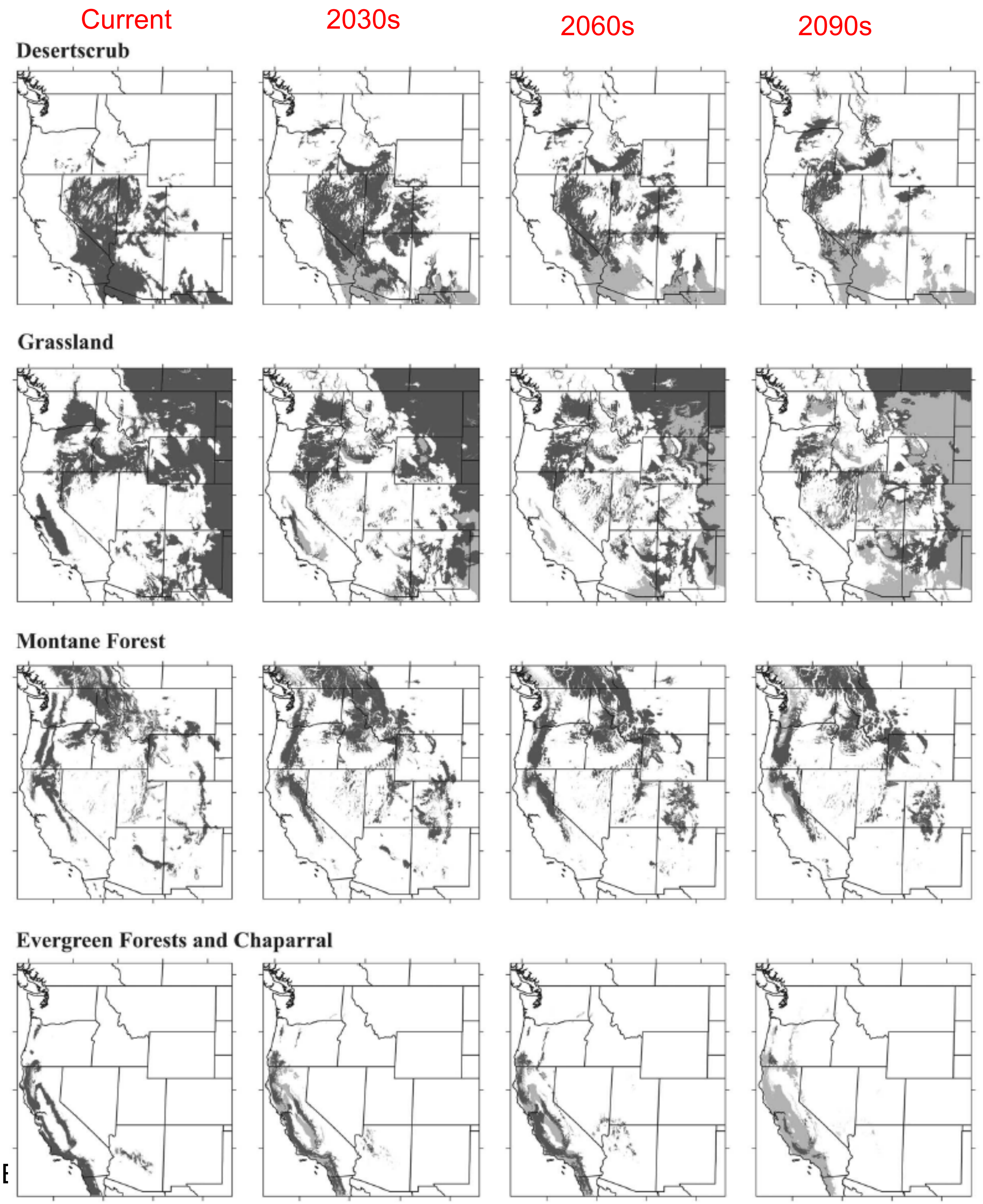
Predictions of major tree species in the West in response to climate change



expansions and contractions

Rehfeldt et al., 2006

Predictions of plant communities in the West in response to climate change



Rehfeldt et al., 2006

Climate influences regional fire years

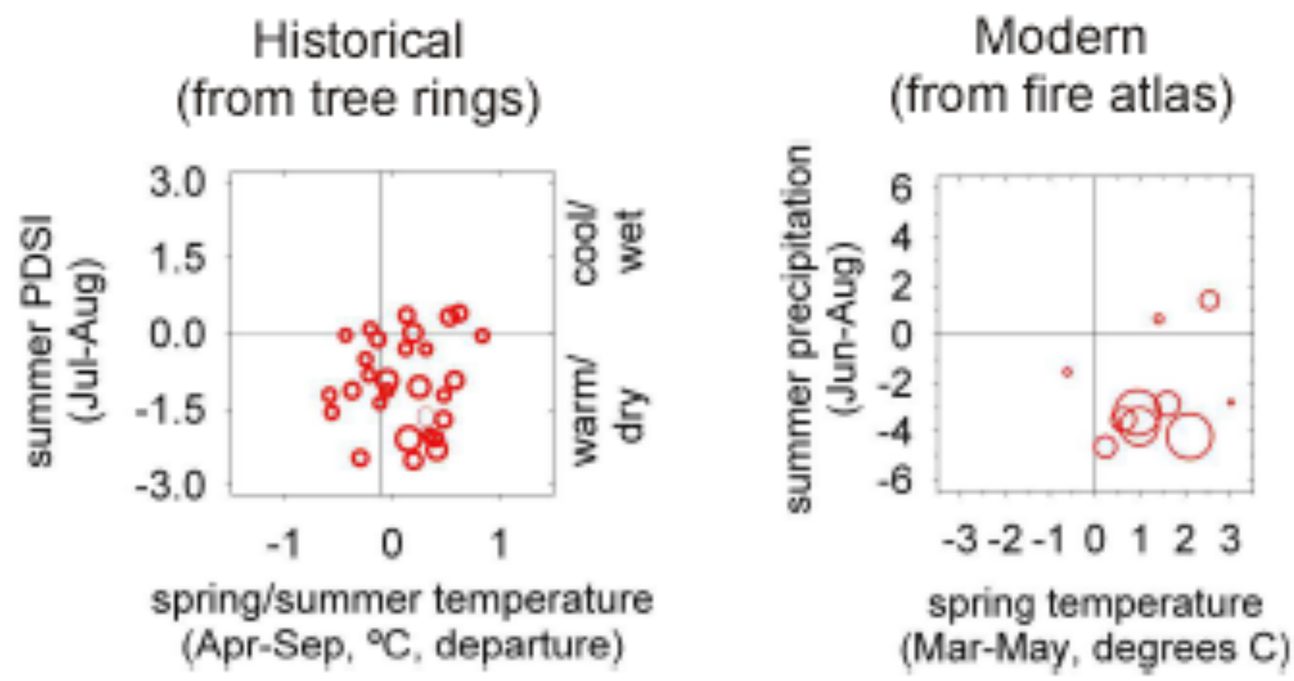
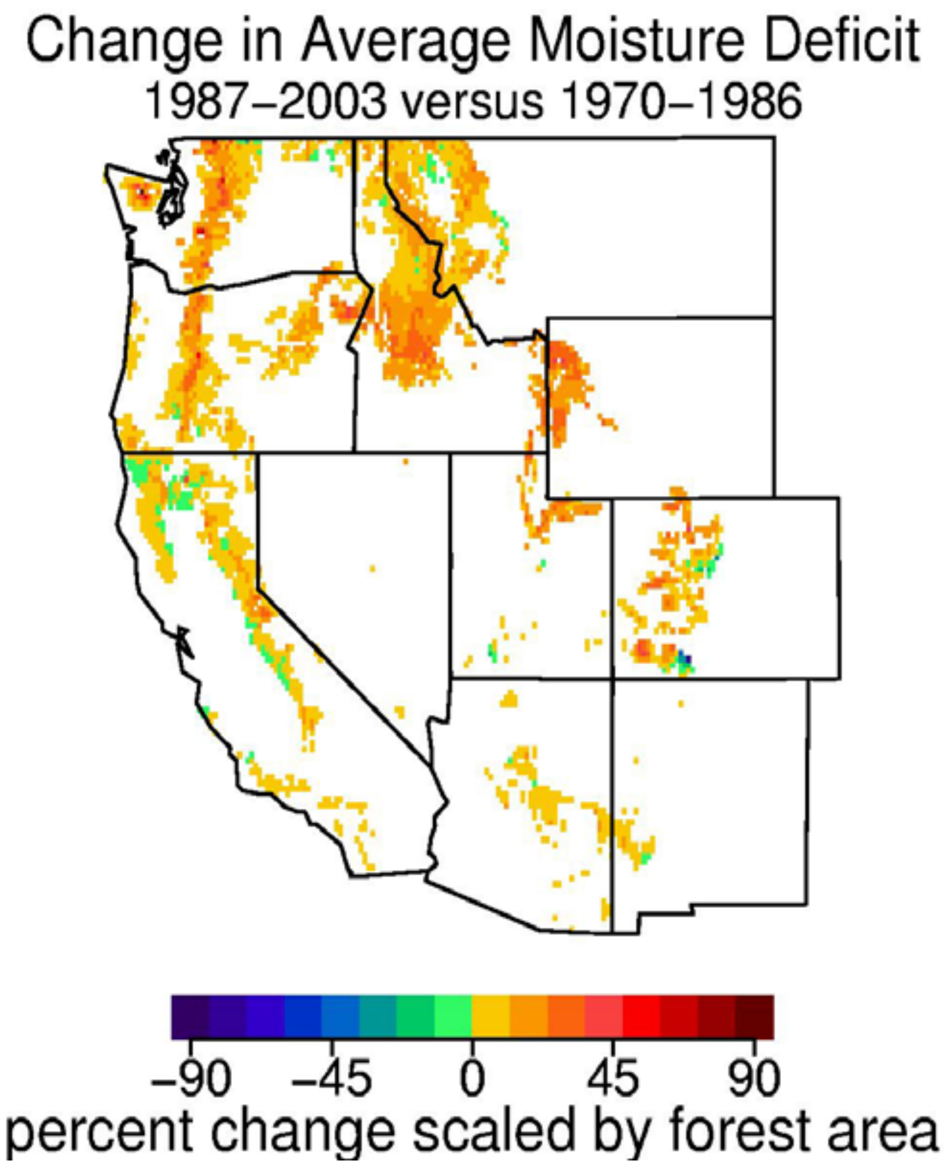


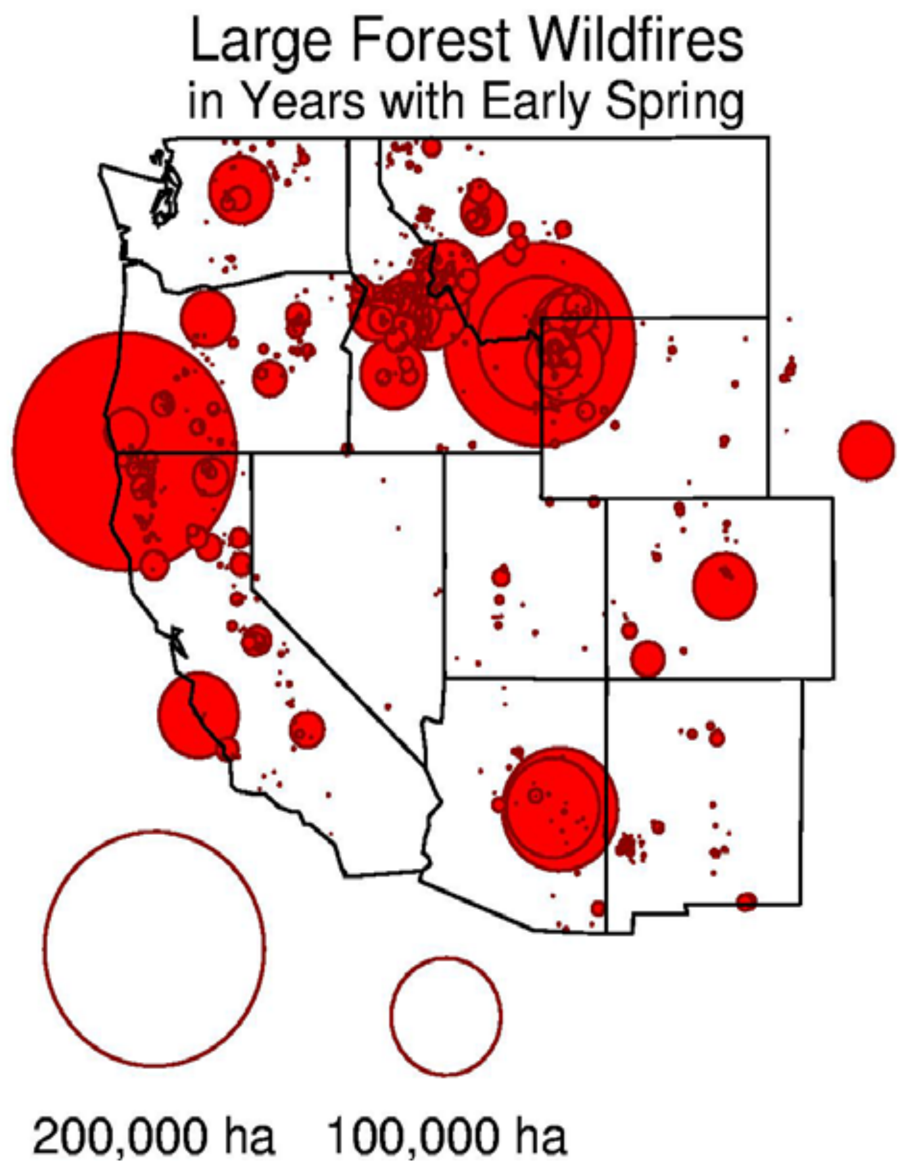
Figure 5. Interaction between spring and summer climate for historical (left) and modern (right) regional fire years. Circles are proportional to the degree of synchrony (25 to 57% of sites for historical fires and 81 ha to 1,167,458 ha for the fire atlas)

For roughly the past four centuries, regional fire years were ones of warm springs that were followed by dry summers (Figure 5).

Morgan et al., 2008

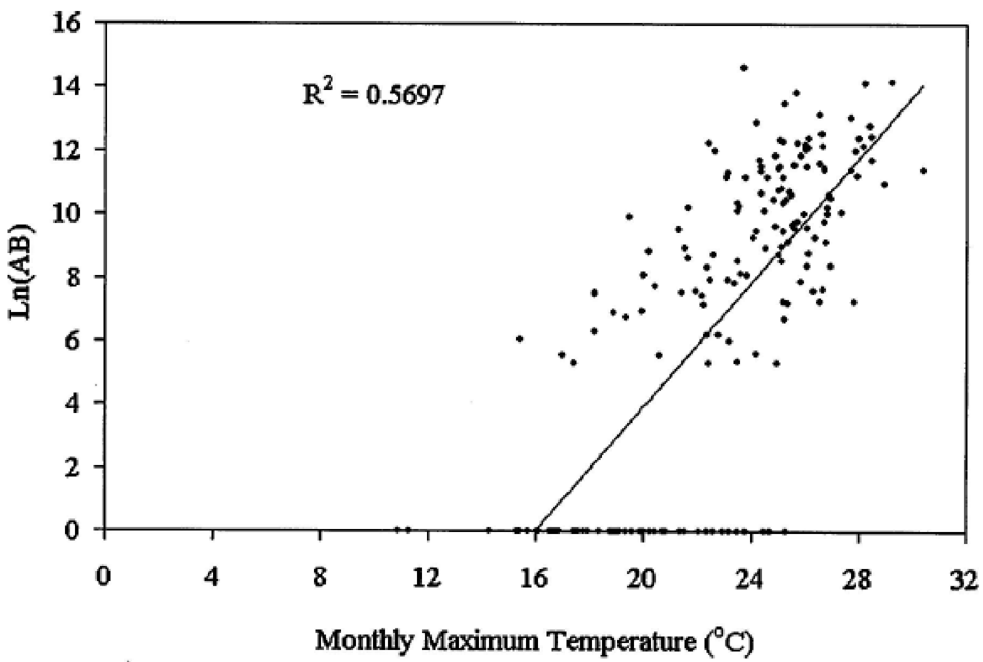
Early snowmelt and longer, drier summers => more large fires





 Westerling et al Science 2006, Running, Science 2006

Climate is a major driver of Canadian wildfires



Flannigan et al., 2005

Canadian GCM

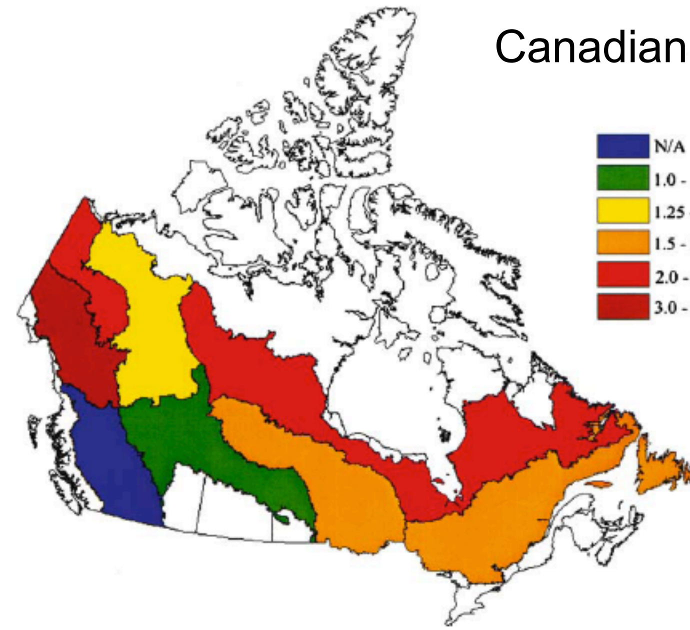
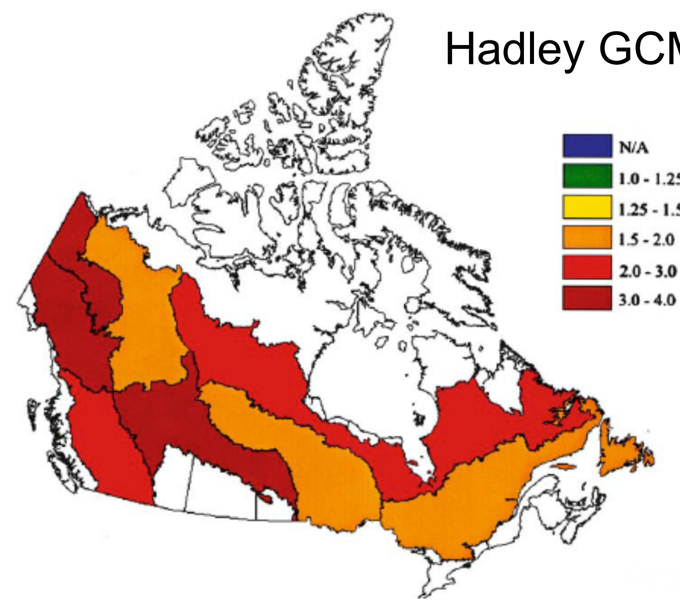
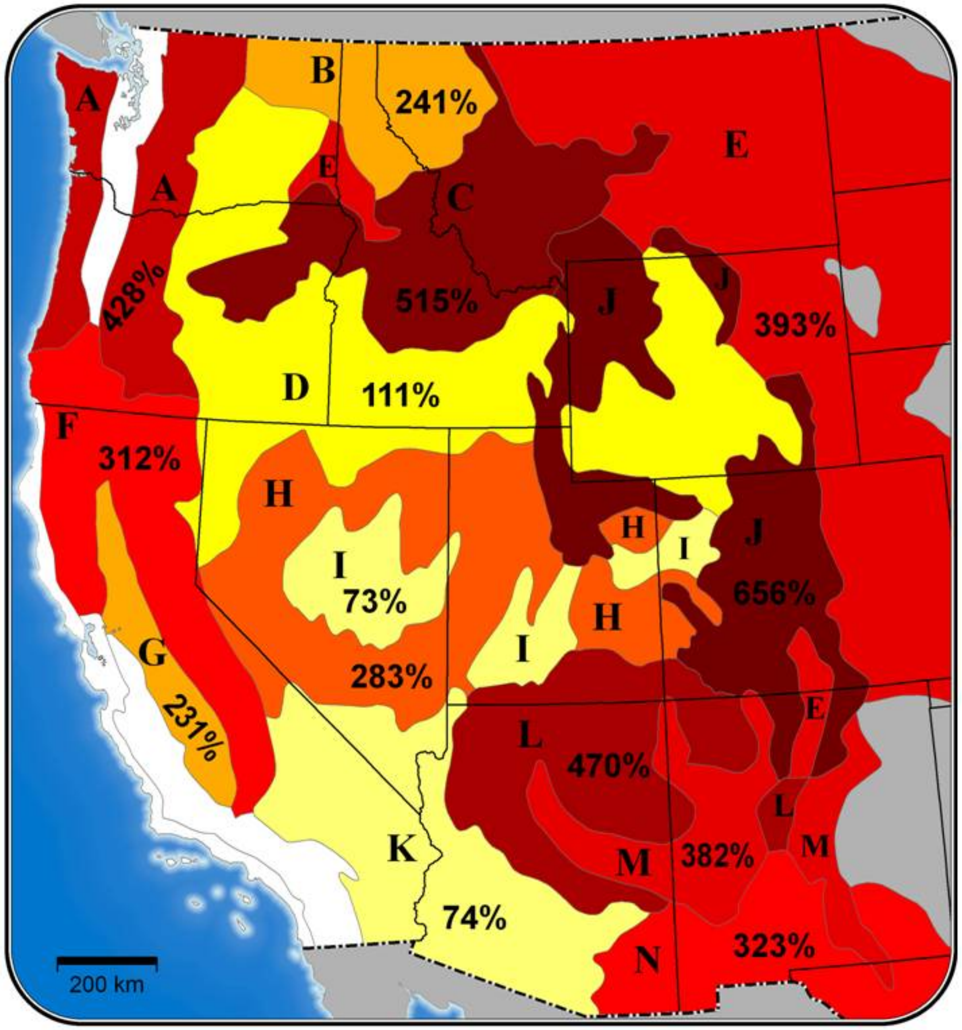


Figure 5. Ratio of $3 \times CO_2/1 \times CO_2$ area burned by Ecozone using the Canadian and Hadley GCMs, respectively. N/A, not applicable. The area burned model did not work for ecozone 14 with the Canadian GCM. (*Continued on next page.*)

Hadley GCM



Wildfire: Projections based on future climate change

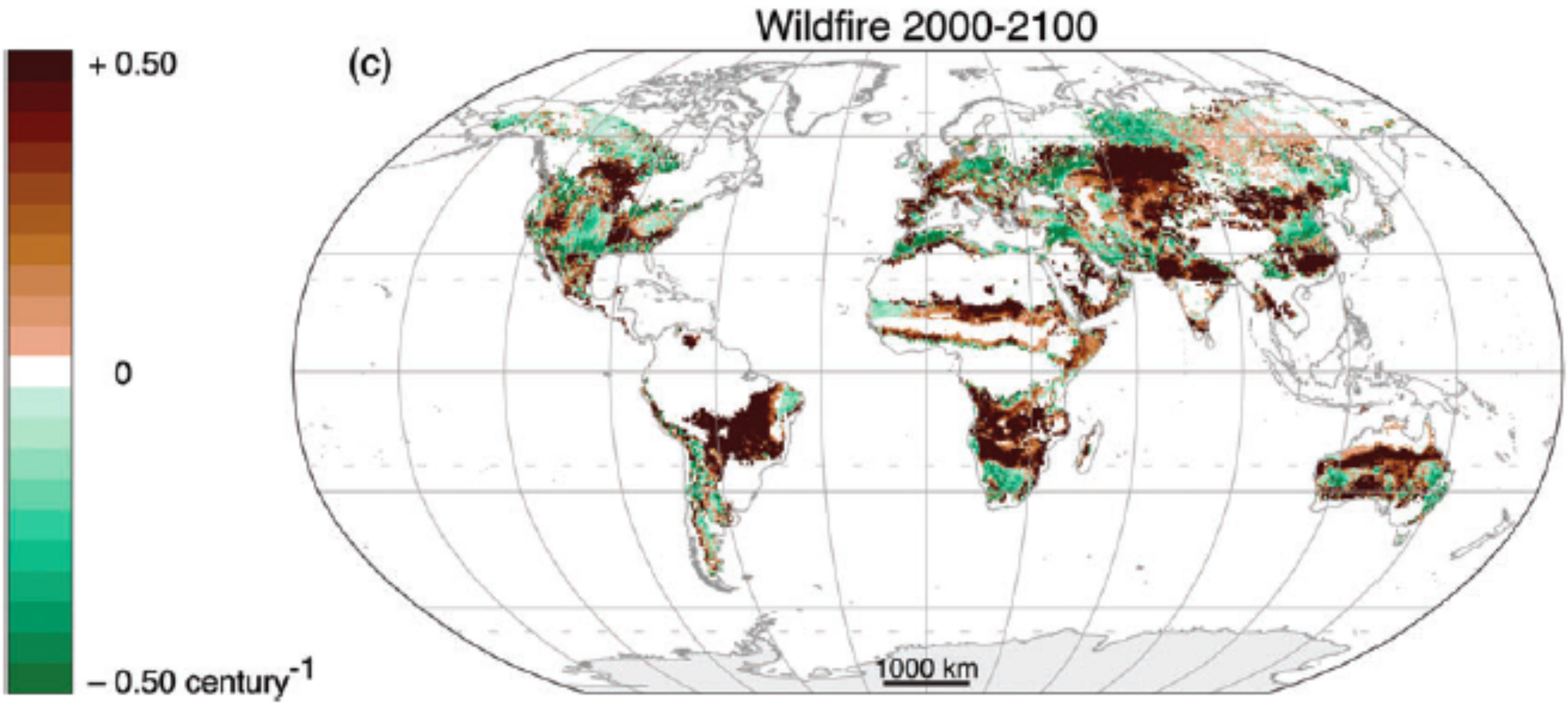


- A - Cascade Mixed Forest
- B - Northern Rocky Mt. Forest
- C - Middle Rocky Mt. Steppe-Forest
- D - Intermountain Semi-Desert
- E - Great Plains-Palouse Dry Steppe
- F - Sierran Steppe-Mixed Forest
- G - California Dry Steppe
- H - Intermountain Semi-Desert / Desert
- I - Nev.-Utah Mountains-Semi-Desert
- J - South. Rocky Mt. Steppe-Forest
- K - American Semi-Desert and Desert
- L - Colorado Plateau Semi-Desert
- M - Ariz.-New Mex. Mts. Semi-Desert
- N - Chihuahuan Semi-Desert

increase in burned area for 1º C increase in temperature

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

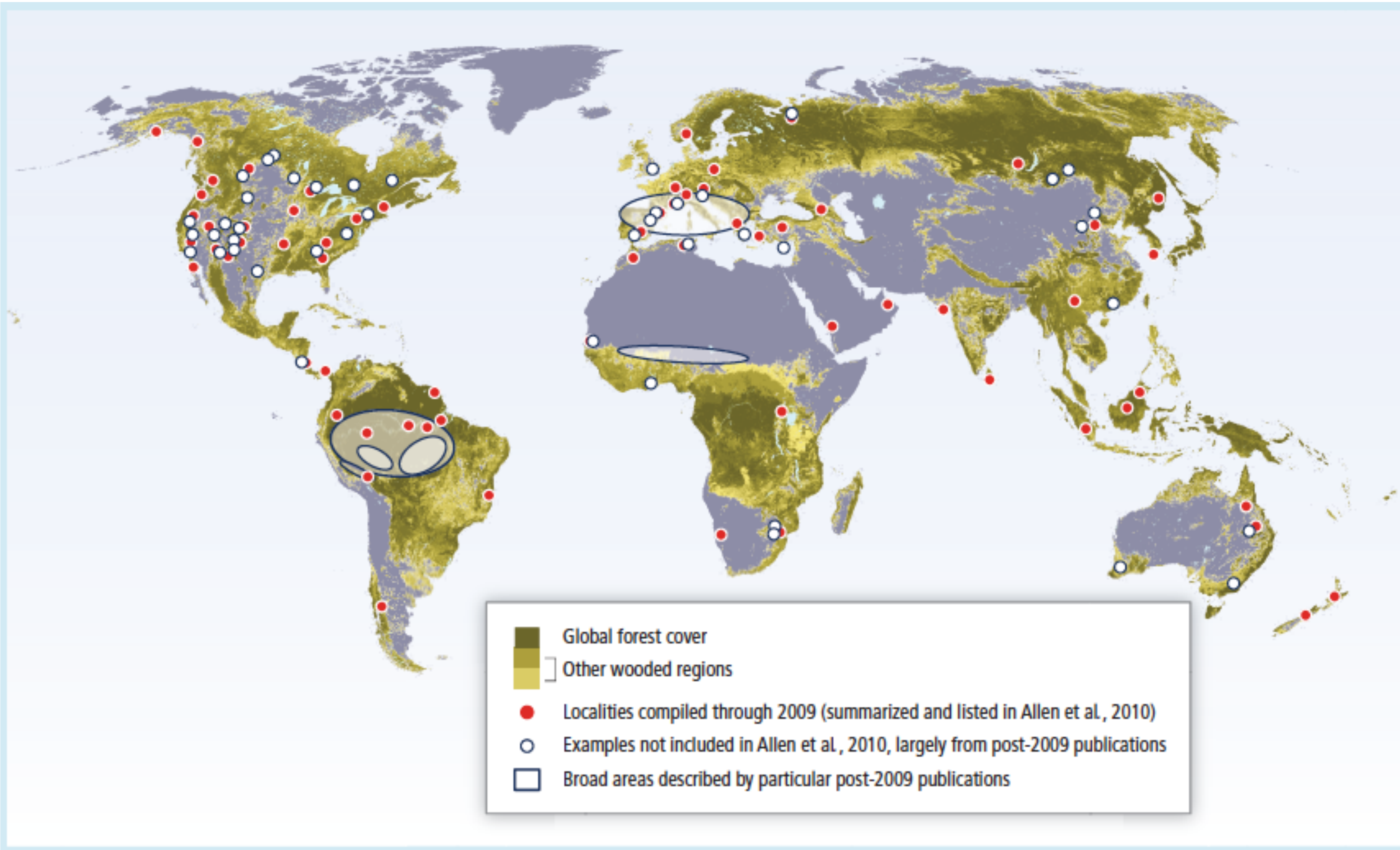
Projected future wildfire frequency



Average of three GCMs

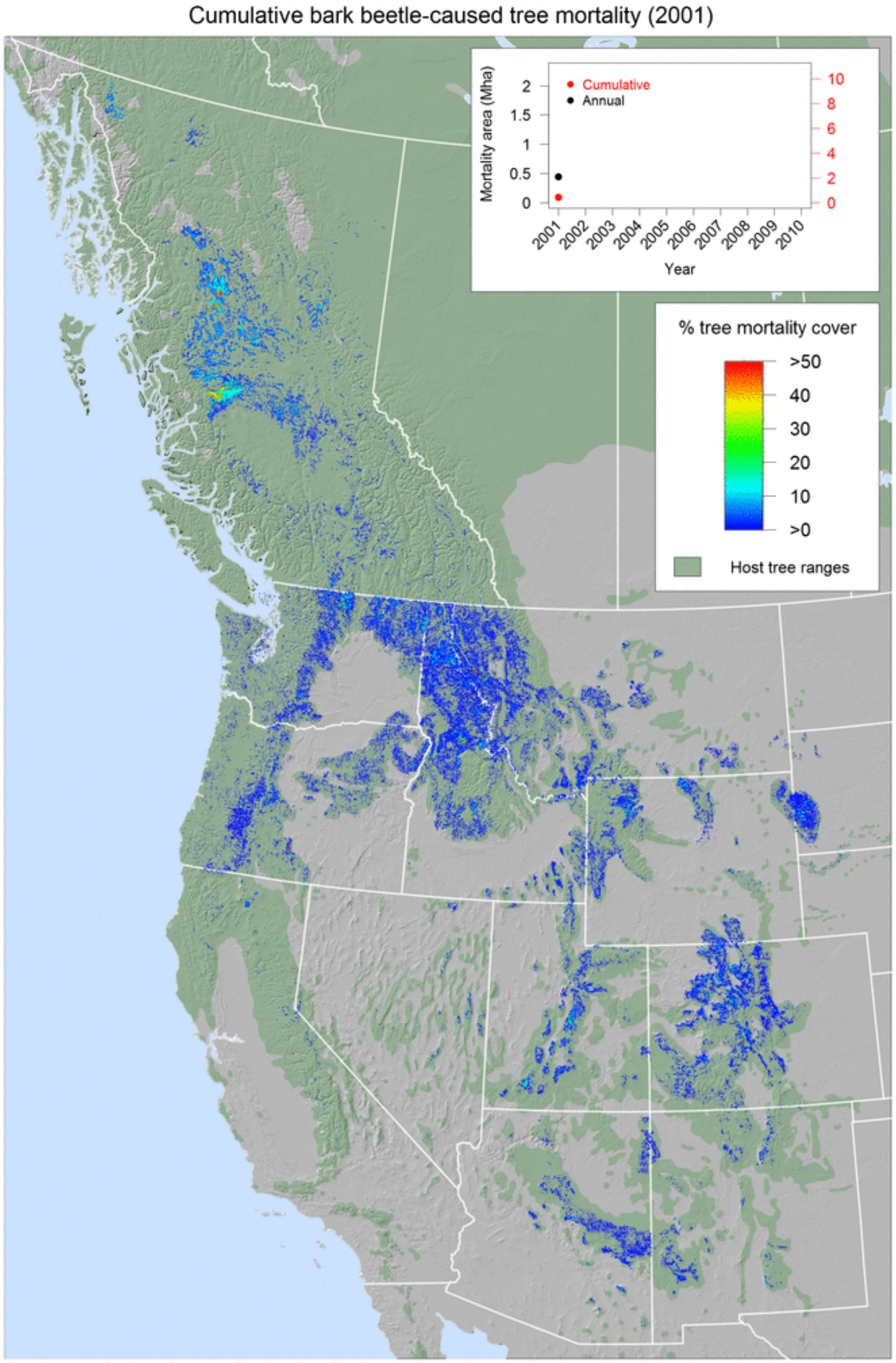
Gonzalez et al., 2010

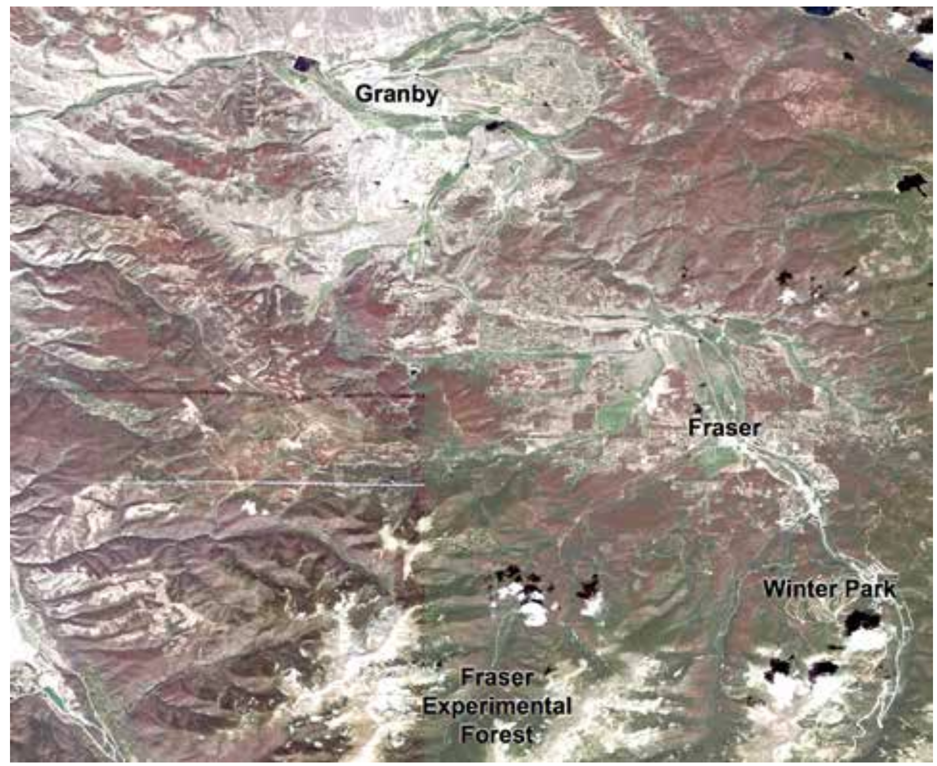
Observed tree dieoff from climate change



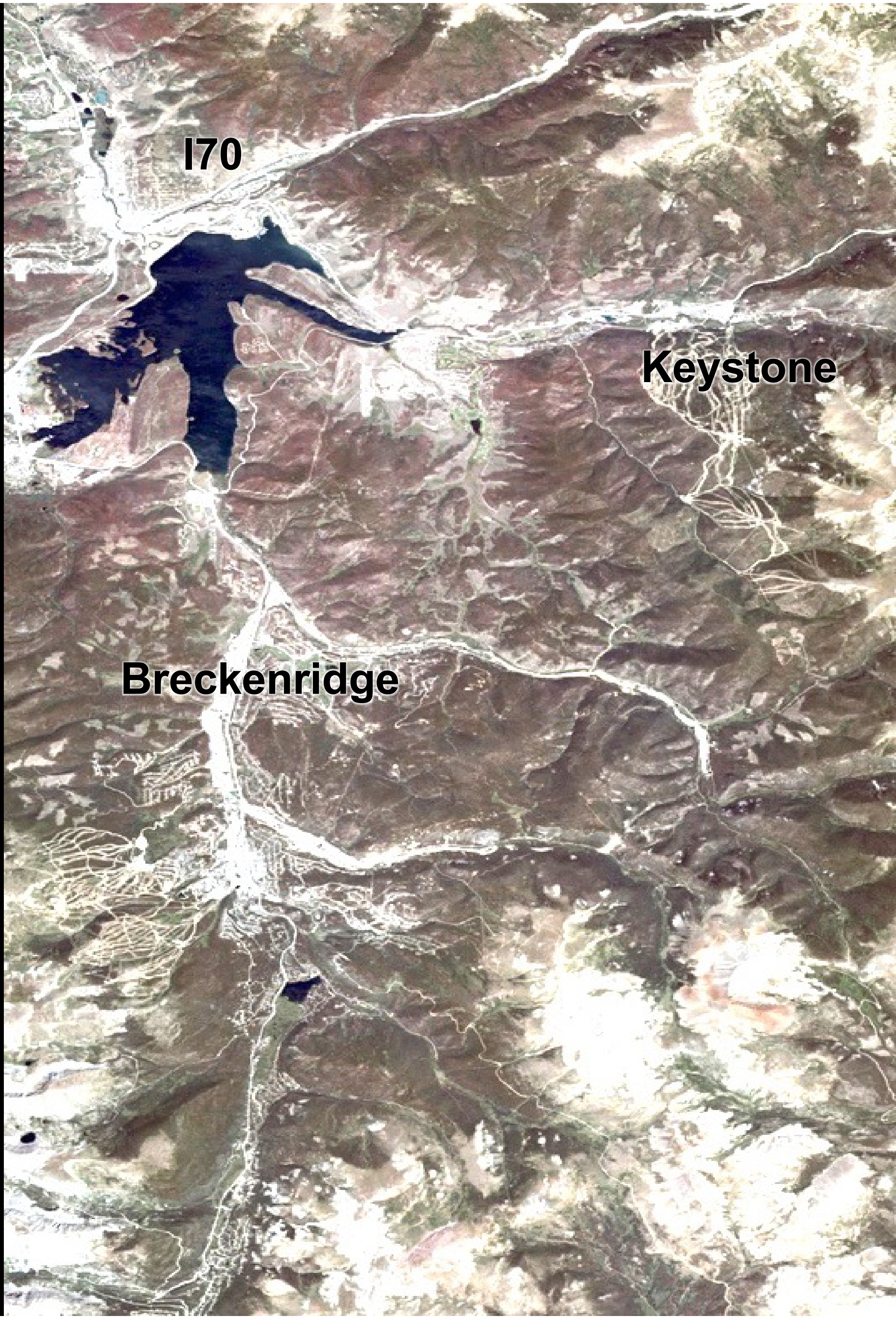
IPCC AR5, WG 2, 2013

Bark beetle outbreaks are widespread and extensive in western North America





Meddens et al., 2012; Hicke et al., 2016



Mountain pine beetle outbreak

Central Colorado

August 2007

QuickBird satellite imagery

100 km/62 miles north-south

Factors influencing mountain pine beetle epidemics

<u>Factors related to trees</u>:

- presence of host tree species
- stem density
- stand age
- drought stress on trees

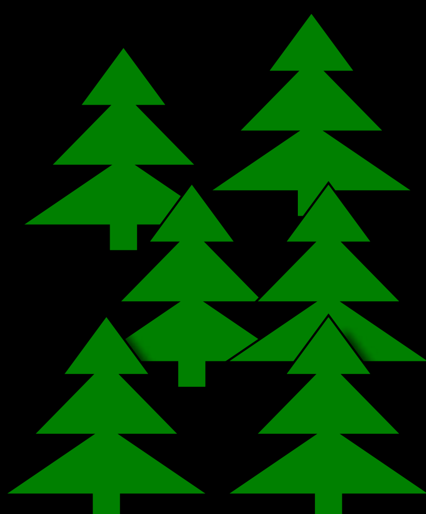


Photo courtesy USDA Forest Service, www.forestryimages.org

Safranyik et al. 1975; Shore and Safranyik 1992; Carroll et al. 2004; Logan and Powell 2001

Whitebark pine: Ecologically important

A keystone and foundation species

fineartamerica.com/featured/red-squirrel-with-pine-cone-gary-beeler.html

Photo P. Buotte

Photo Richard Perry

Photo P. Buotte

Photo James Mattil

Whitebark pine: recommended as threatened/endangered

climate

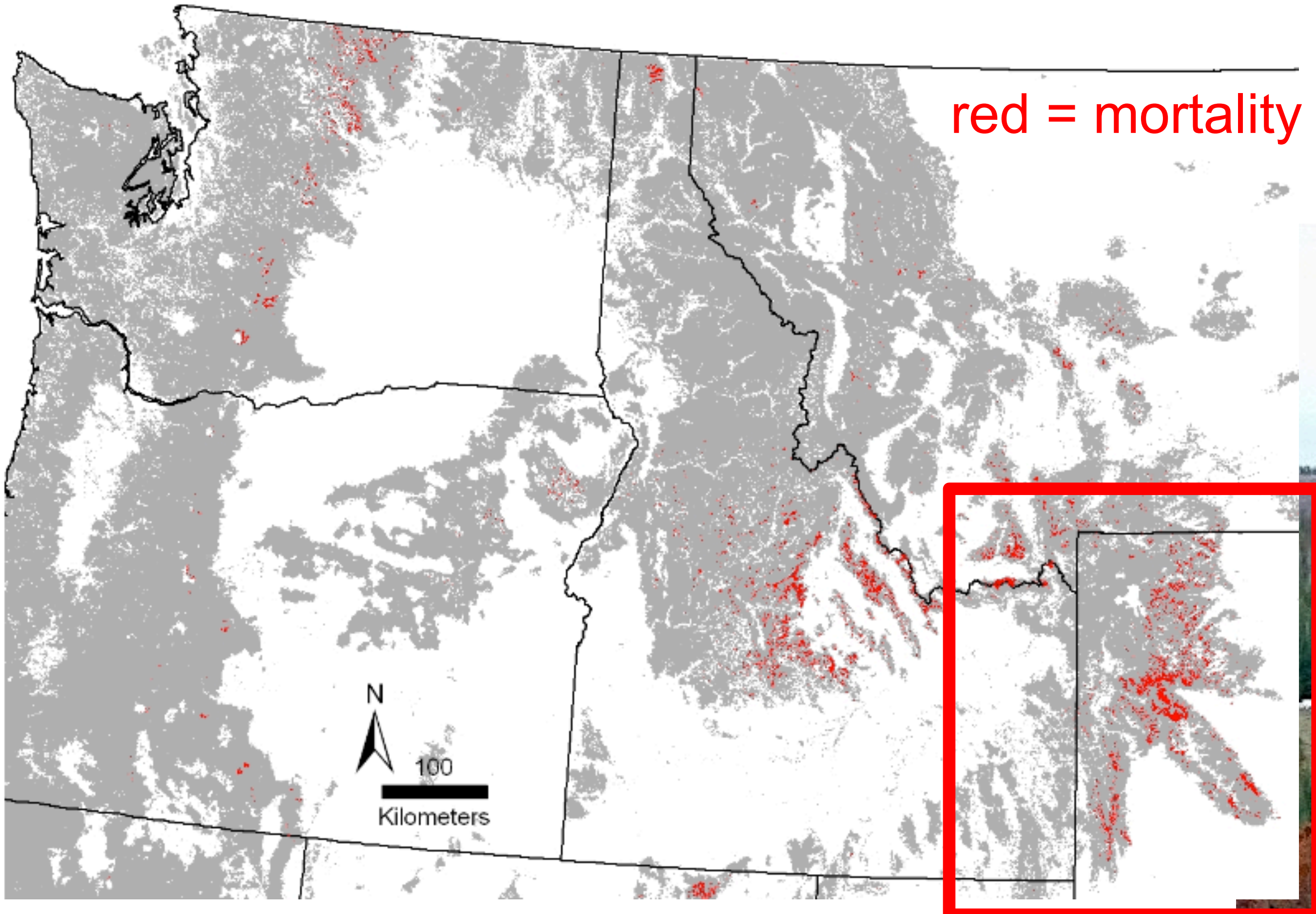
white pine blister rust

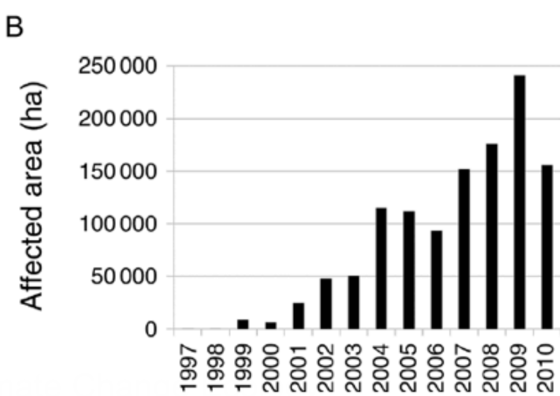
fire suppression

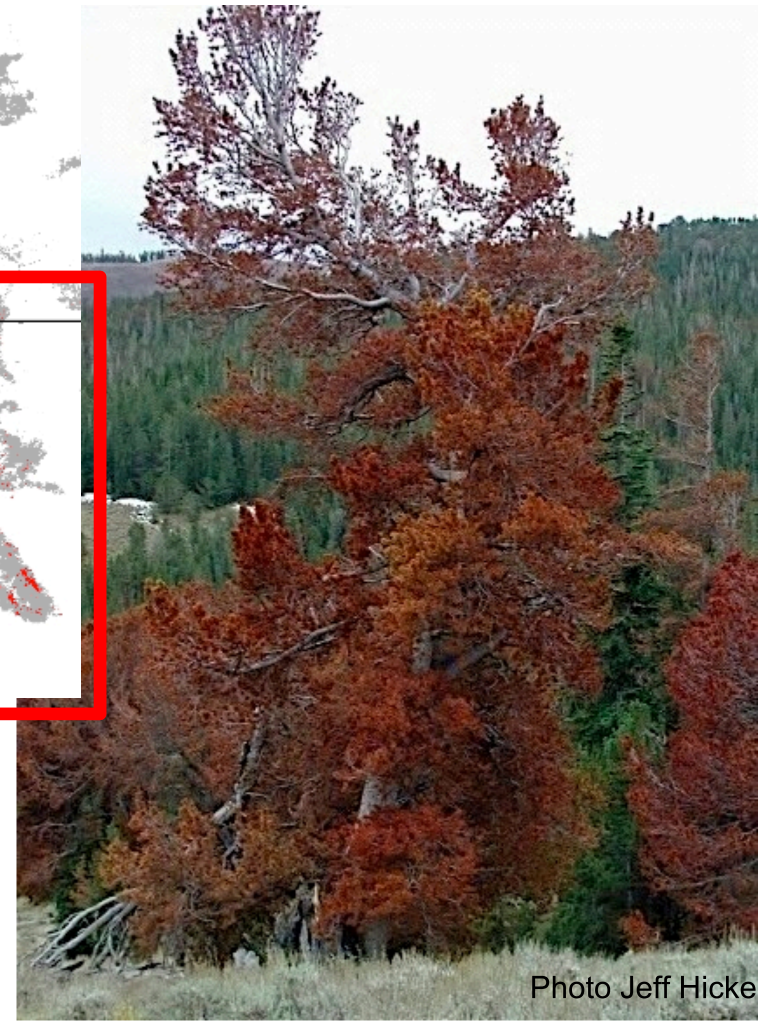
Photo P.
Buotte

mountain pine beetles

Whitebark pine mortality from beetles 1997-2010





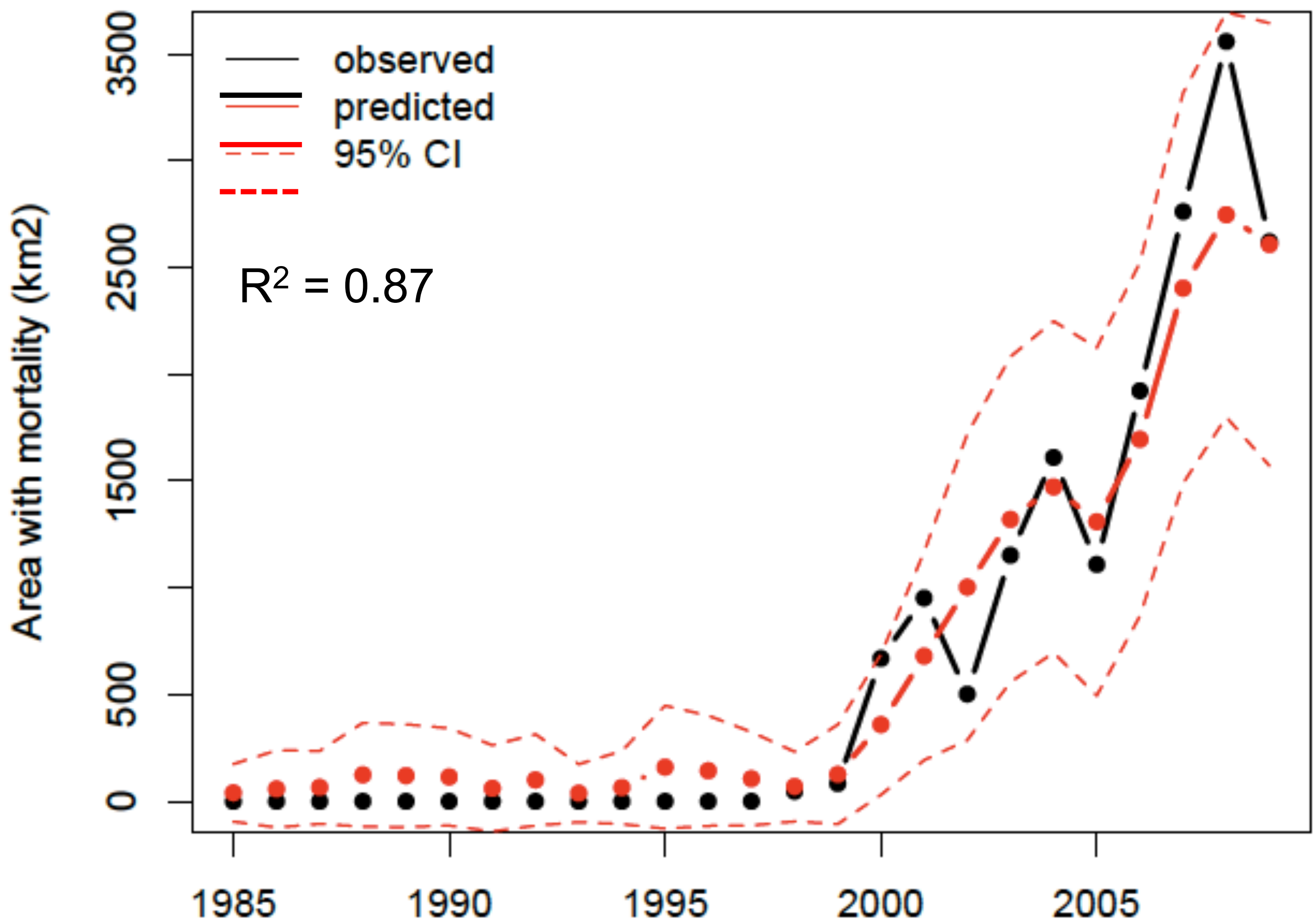


Weed et al., Ecological Monographs,2013

Prof. J. Hicke

Confidence in model predictions similar to observations

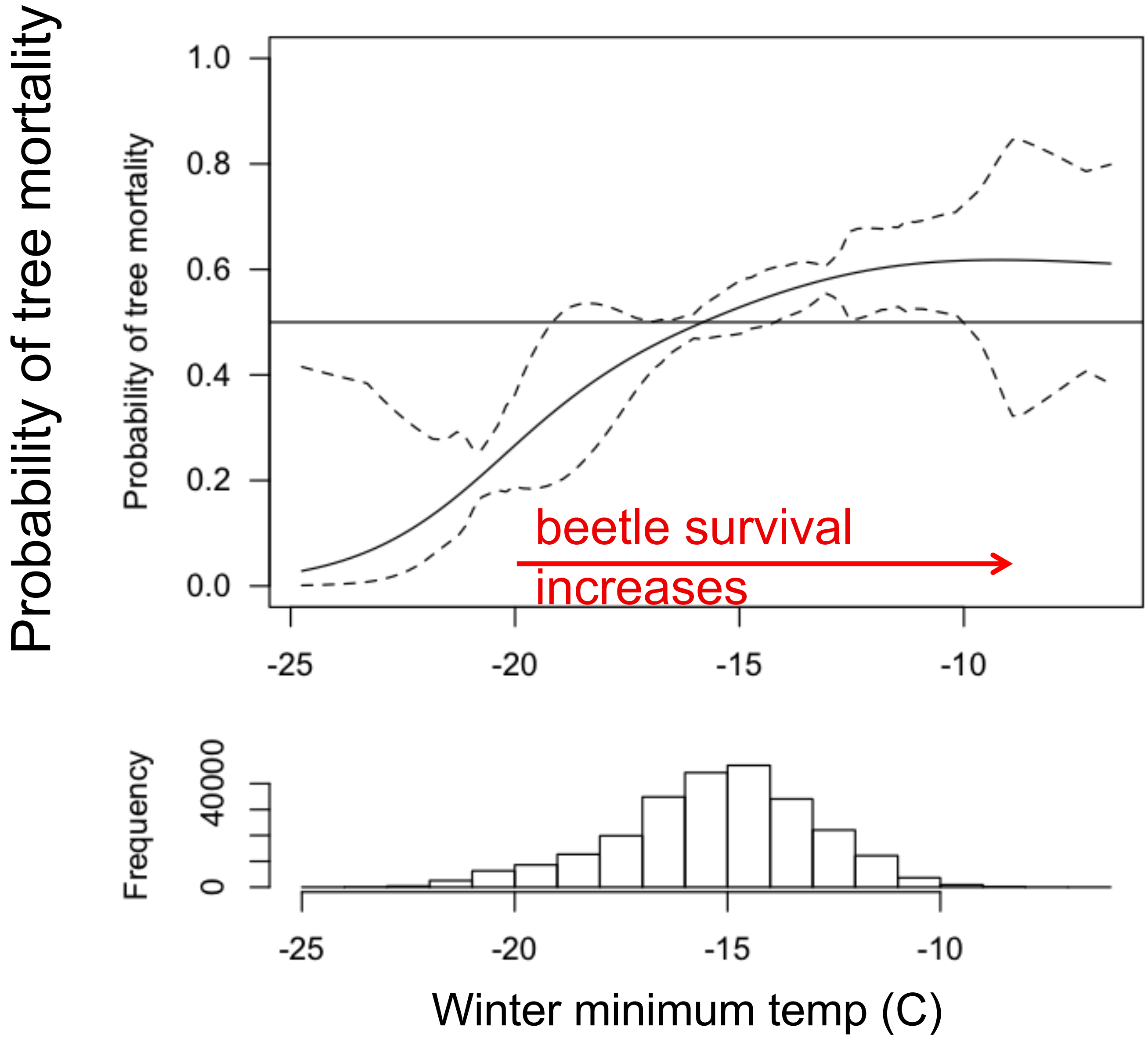
RMSE = 221 km
$R^2 = 0.97$



Buotte et al., Ecol. App., 2016

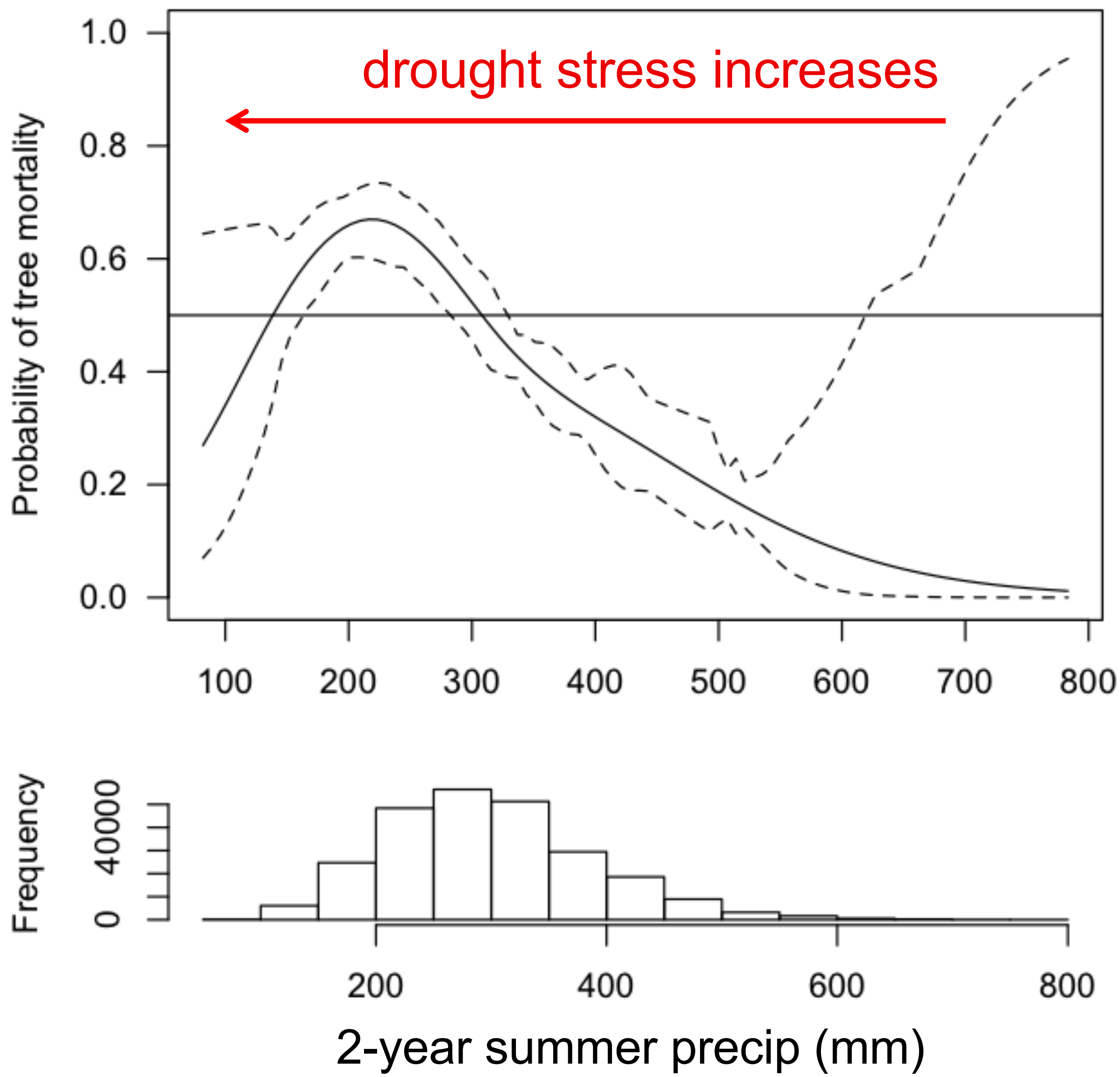
1. Climate-beetle relationships

winter mortality



Buotte et al., Ecol. App., 2016

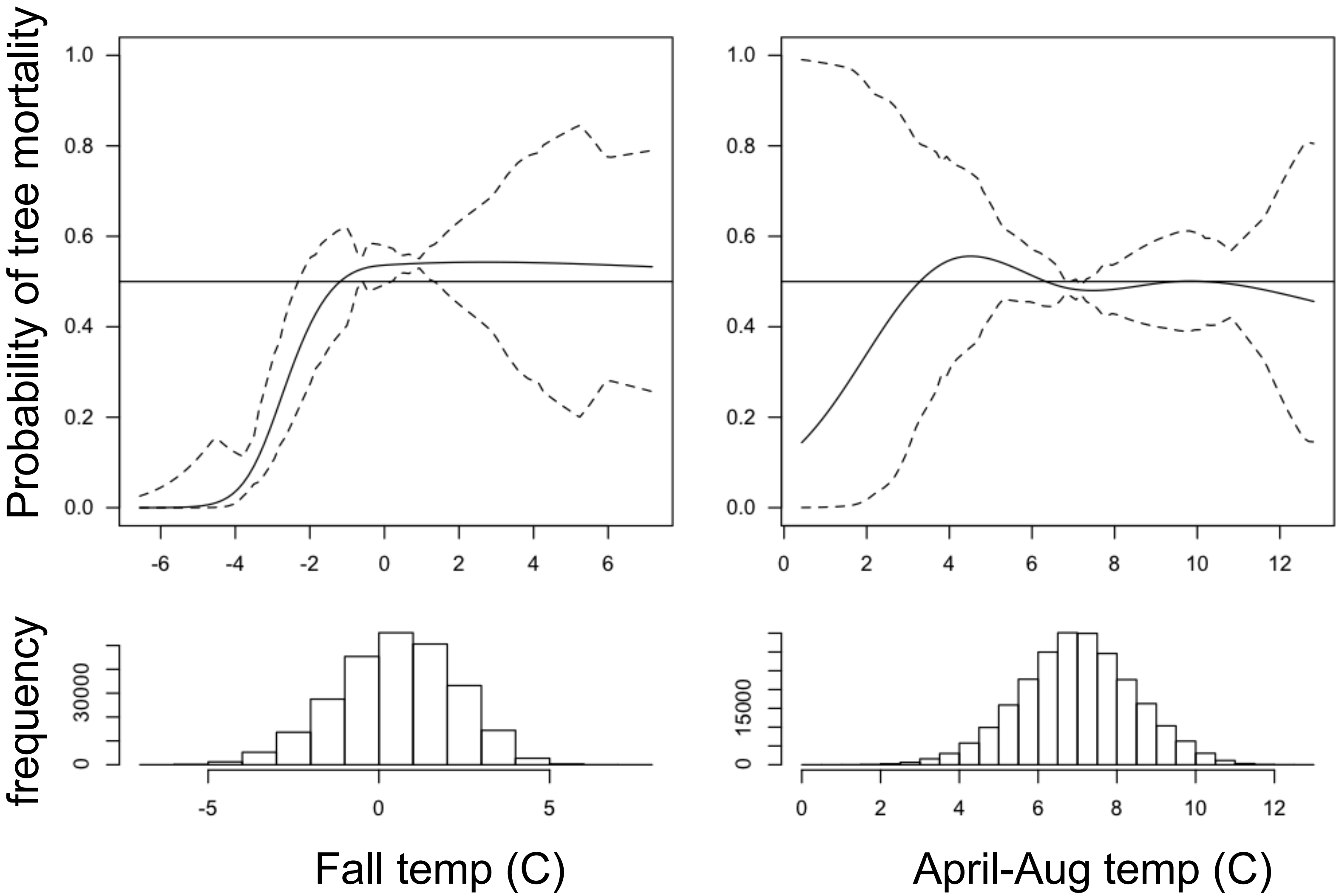
1. Climate-beetle relationships



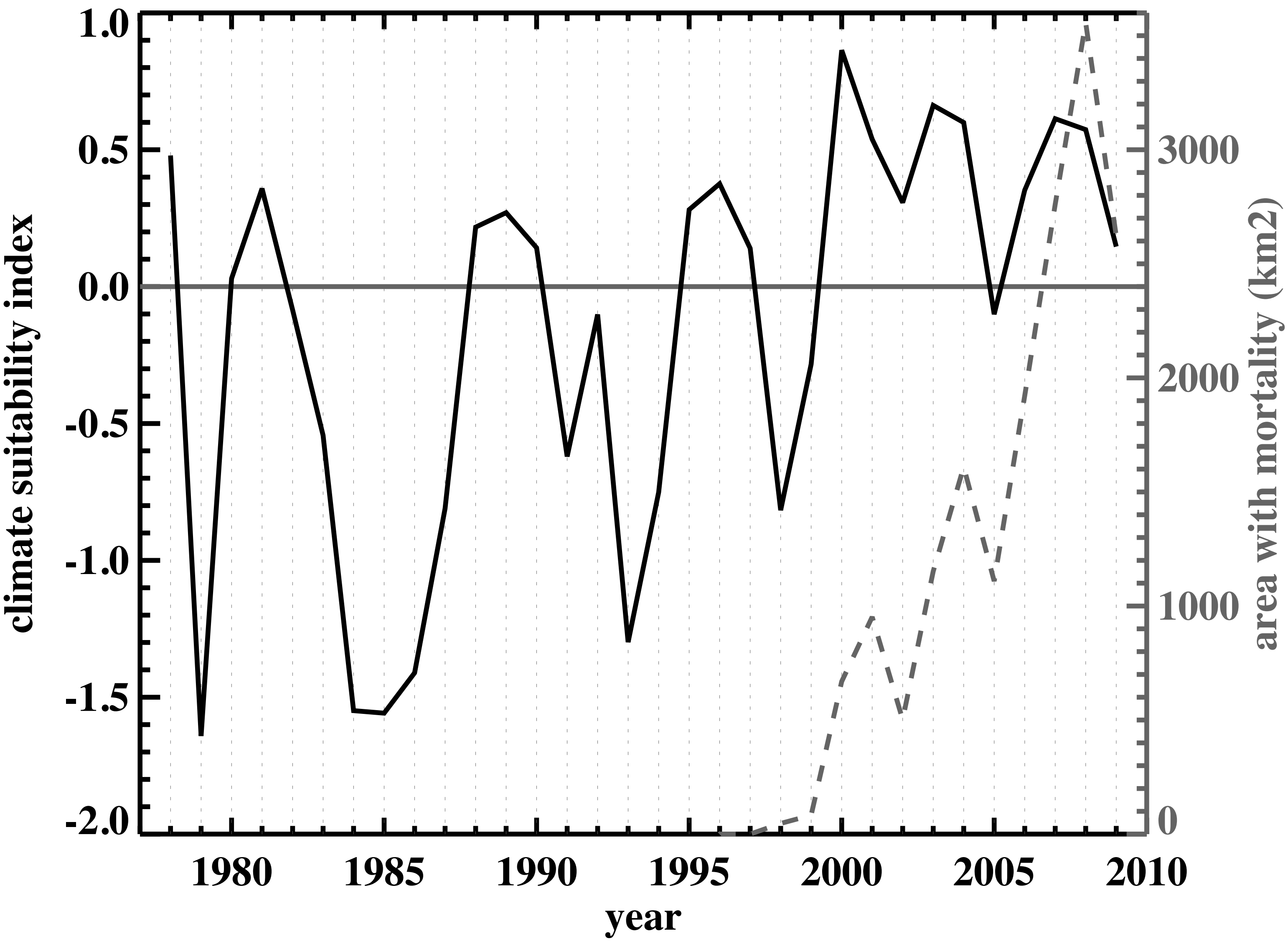
Buotte et al., Ecol. App., 2016

1. Climate-beetle relationships

year-round temperatures



2. Climate influences on recent outbreak



Buotte et al., Ecol. App., 2016

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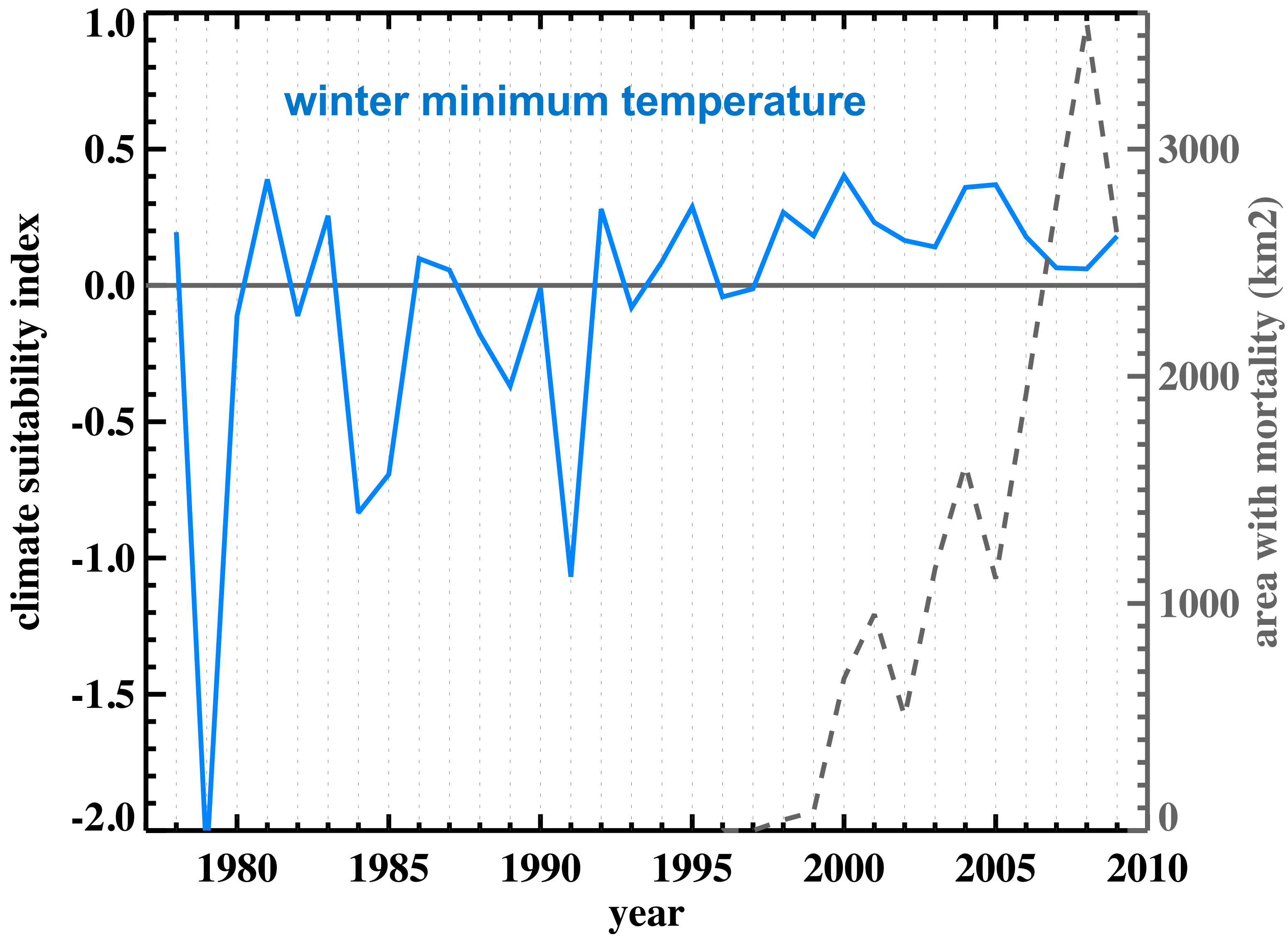

Buotte et al., Ecol. App., 2016

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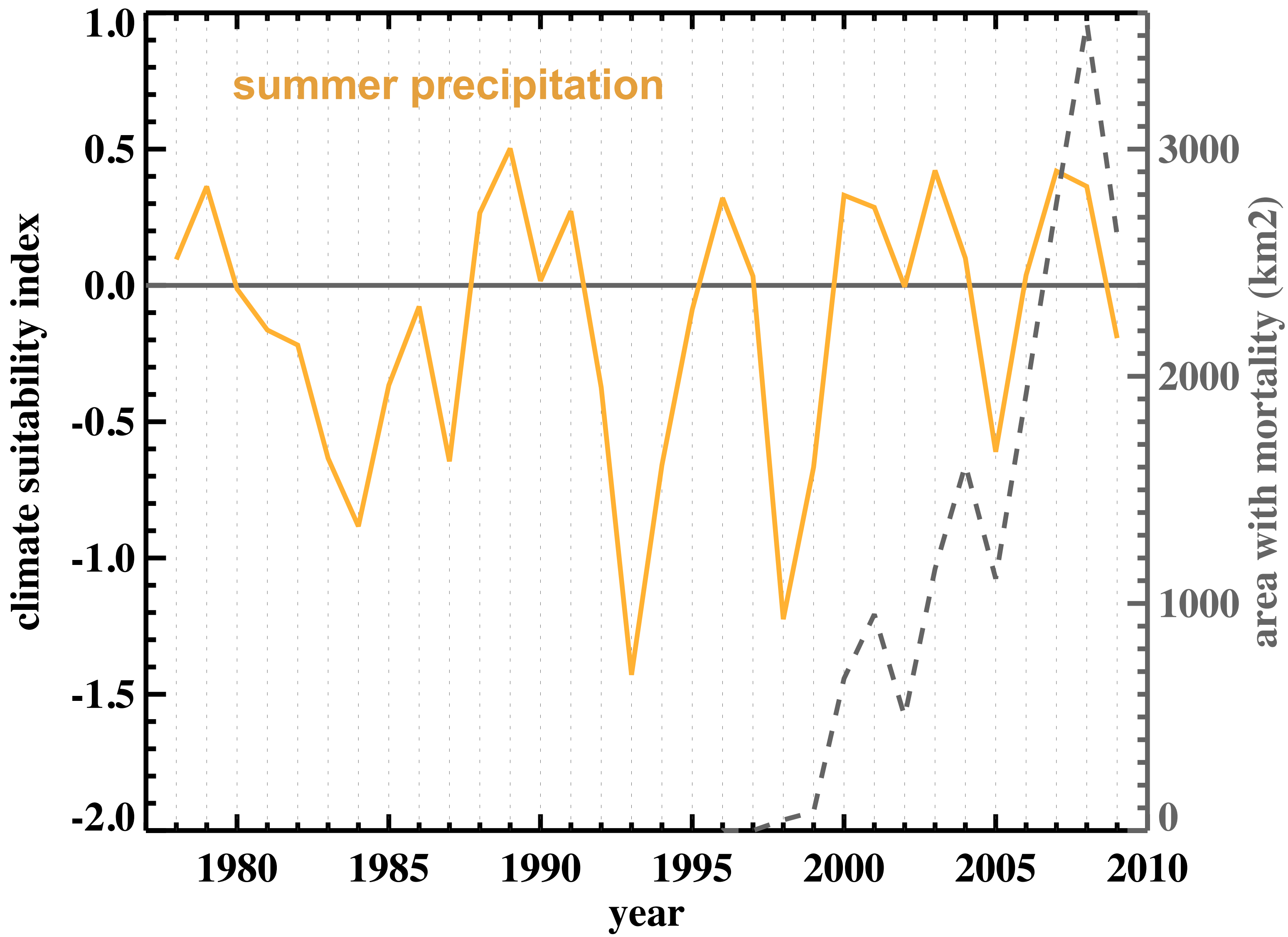

Buotte et al., Ecol. App., 2016

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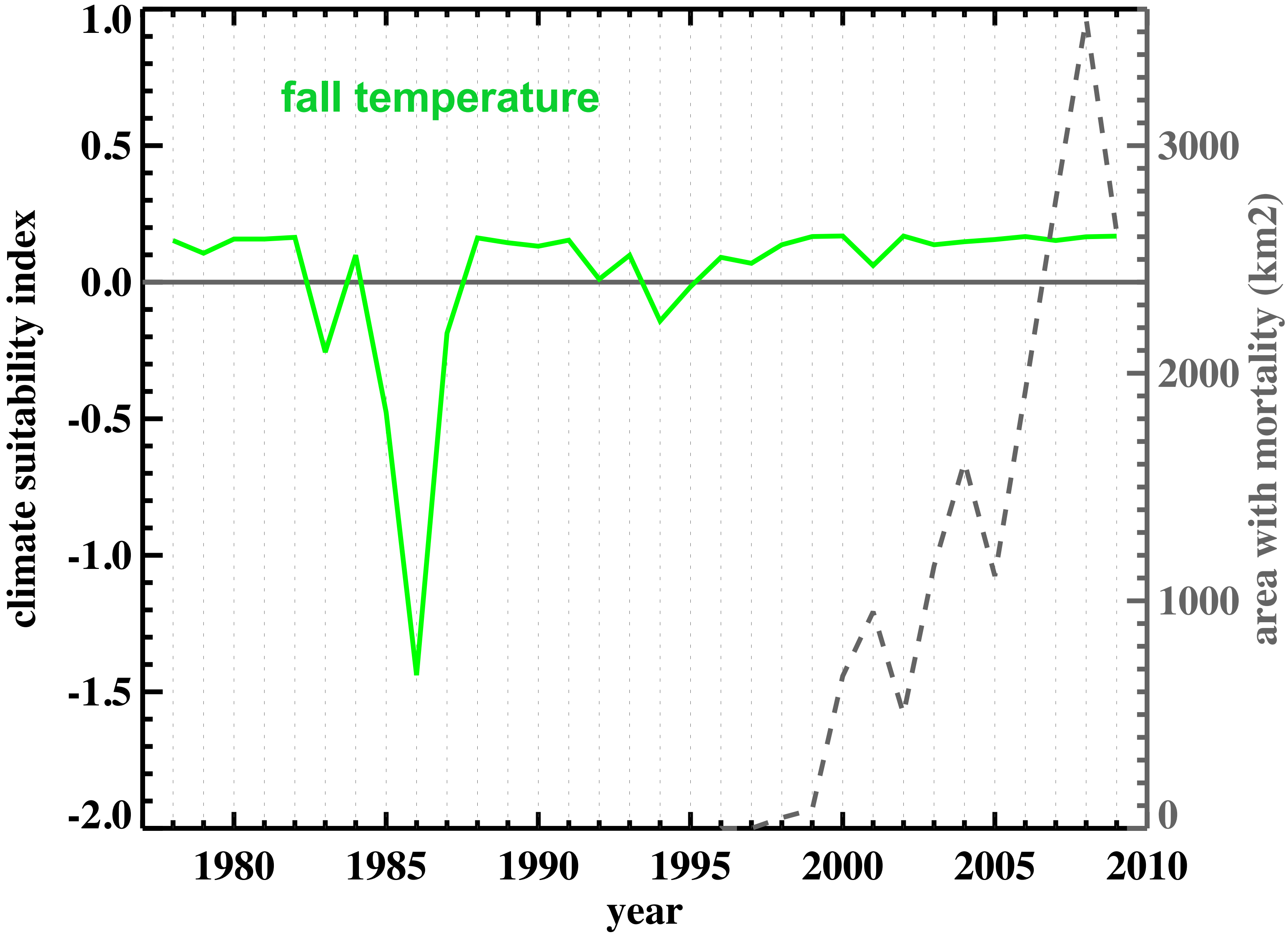
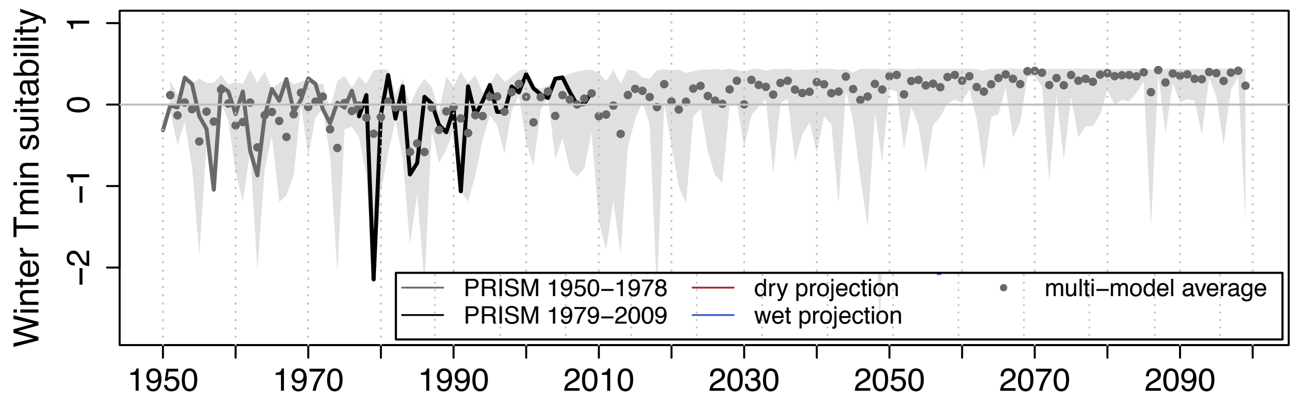


Buotte et al., Ecol. App., 2016

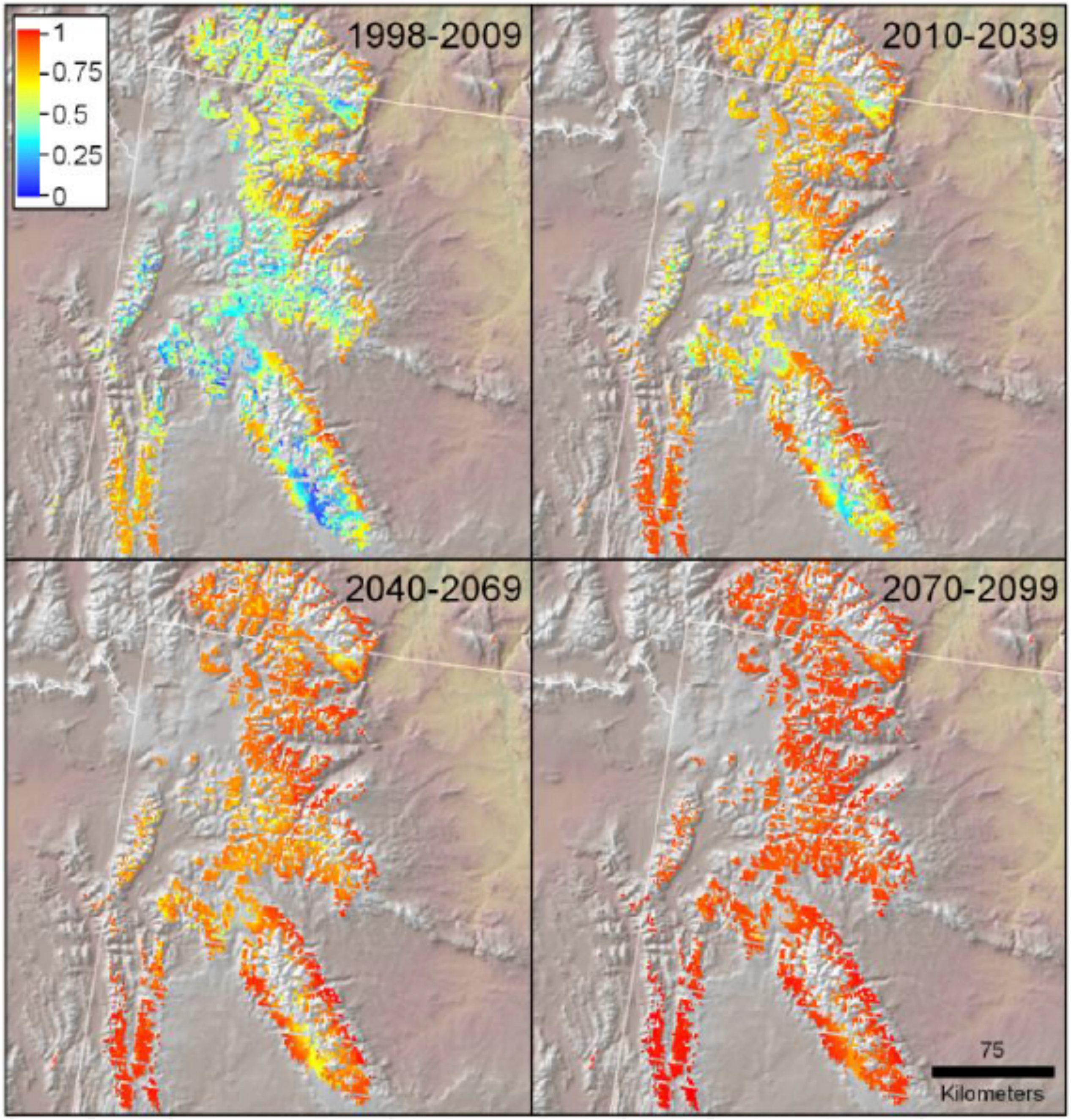
3. Estimates of future climate suitability

Winter temperature: increased suitability for outbreaks



Buotte et al., Ecol. App., 2016

3. Estimates of future climate suitability

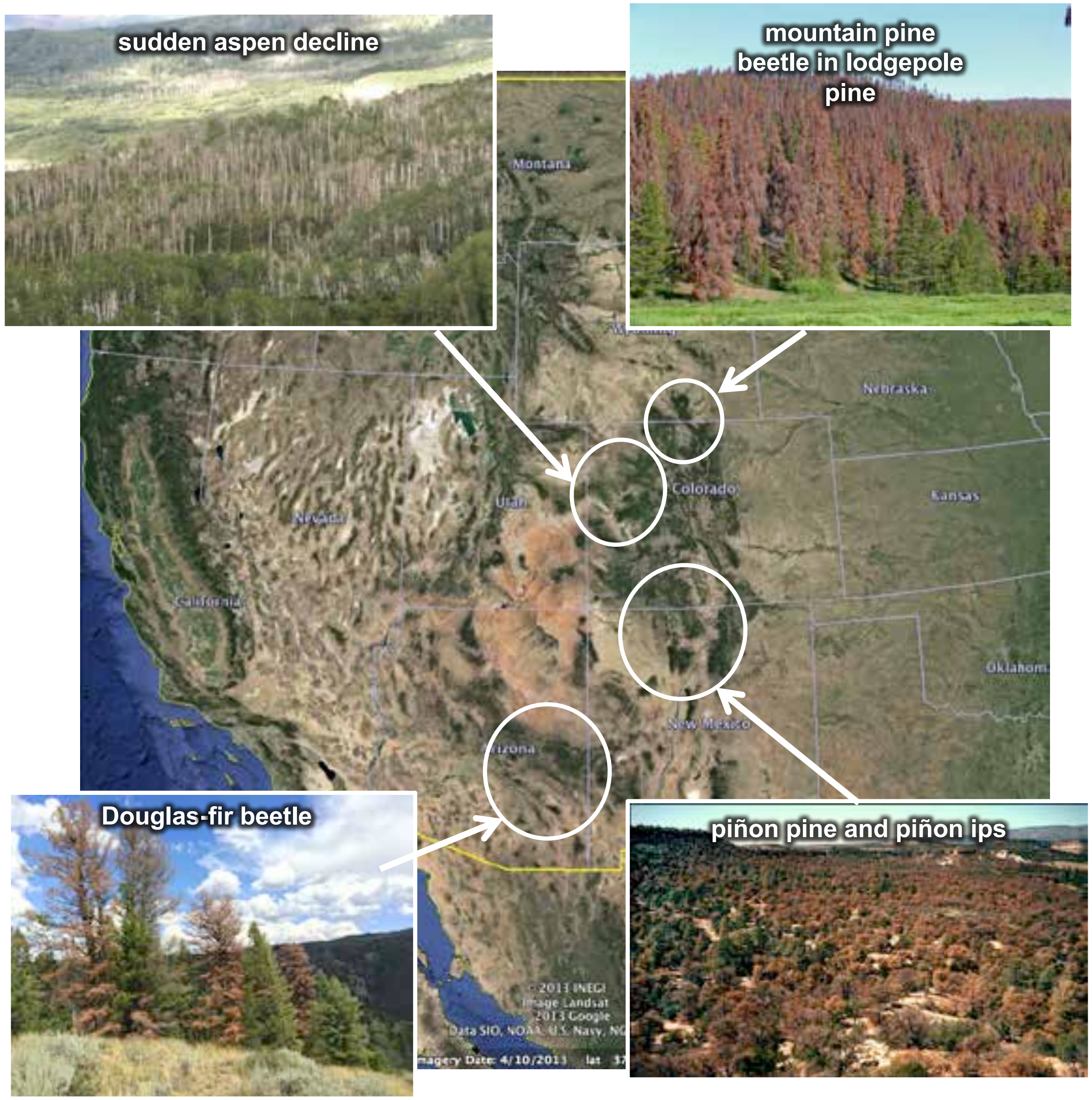


fraction of years with winter temperature suitable for beetle outbreaks

Buotte et al., Ecol. App., 2016

For some dieoff types, drought more important

Type 1: drought, no biotic agents



Type 3: drought triggers outbreaks

Type 4: outbreaks caused by multiple factors

Type 2: drought, with beetles present

Photos: J. A. Hicke; W. R. L. Anderegg; C. D. Allen
Background image: Landsat, Google Earth

Drought: Texas drought in 2011

Dr. Ron Billings, Texas Forest Service

Drought: Tree mortality in Texas

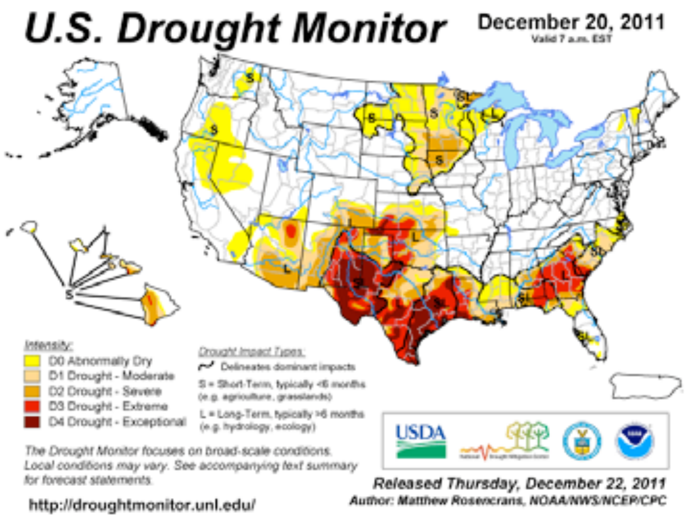
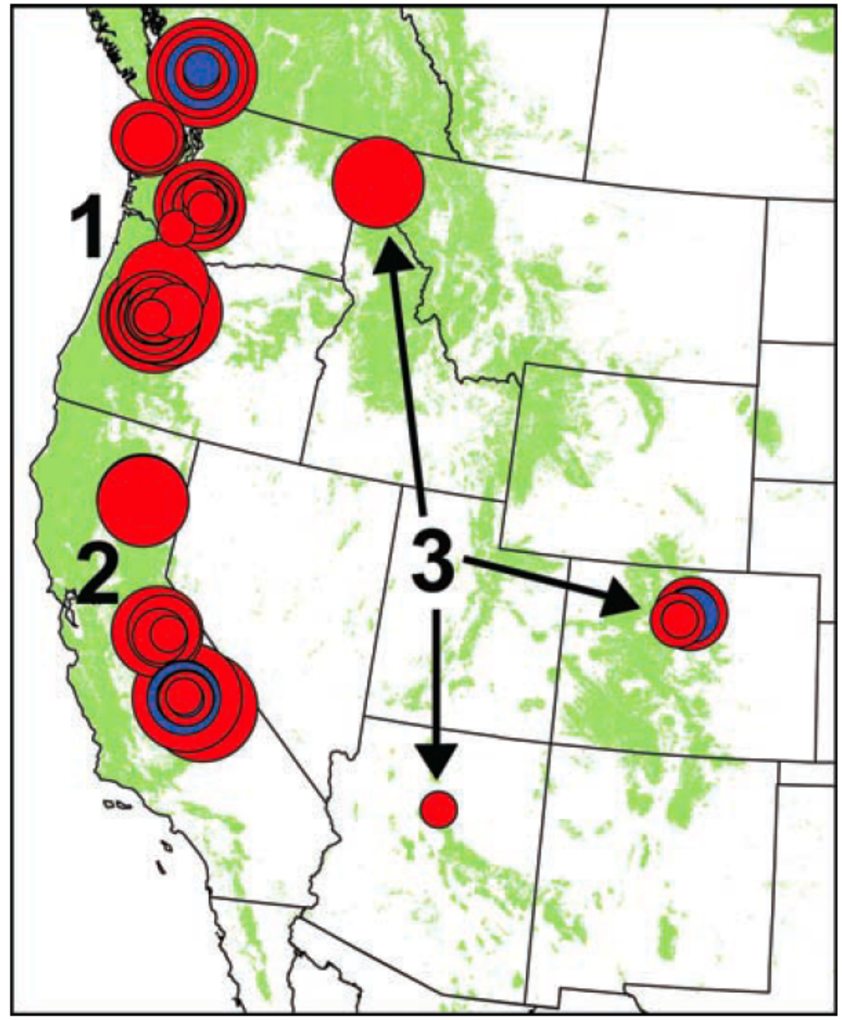


Photo credits: Dr. Ron Billings, Texas Forest Service

Increase in tree mortality rates in old-growth forests

Fig. 1. Locations of the 76 forest plots in the western United States and southwestern British Columbia. Red and blue symbols indicate, respectively, plots with increasing or decreasing mortality rates. Symbol size corresponds to annual fractional change in mortality rate (smallest symbol, <0.025 year^{-1}; largest symbol, >0.100 year^{-1}; the three inter-



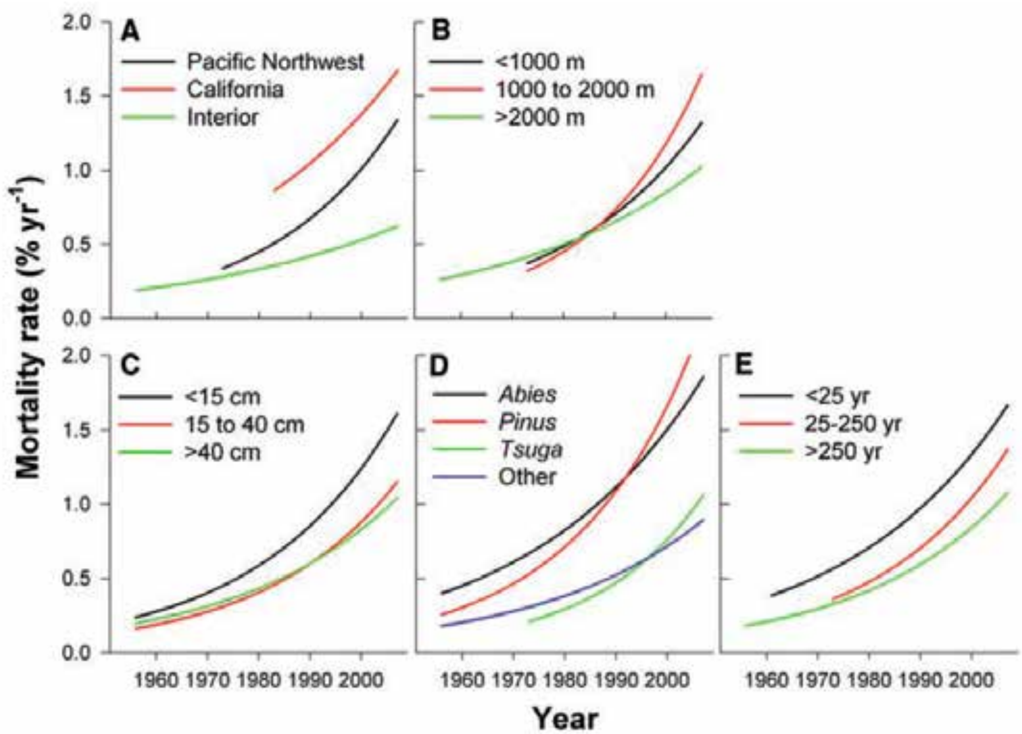


Fig. 2. Modeled trends in tree mortality rates for (**A**) regions, (**B**) elevational class, (**C**) stem diameter class, (**D**) genus, and (**E**) historical fire return interval class.

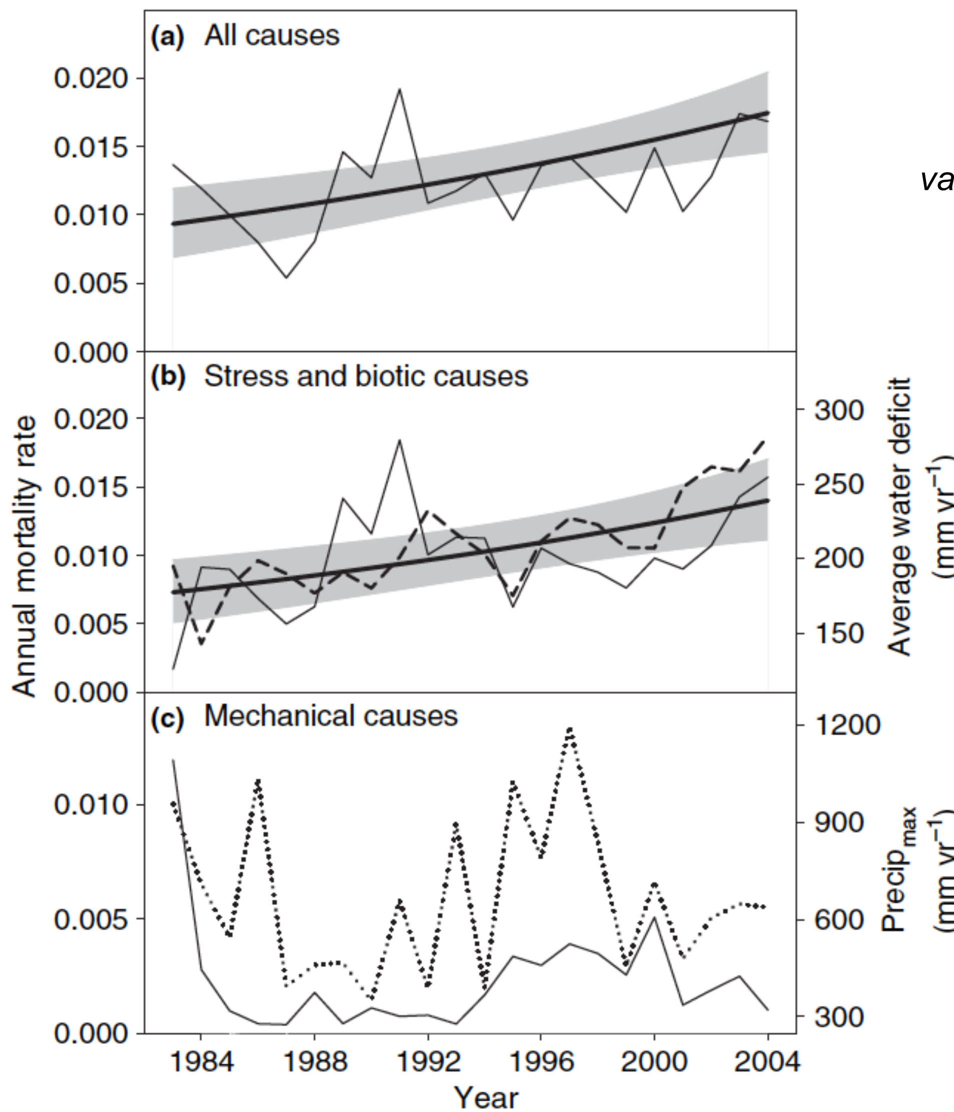
van Mantgem et al., Science, 2009

Increase in tree mortality rates in old-growth forests due to warming (stress, biotic causes)

observed mortality

likely cause

unlikely cause



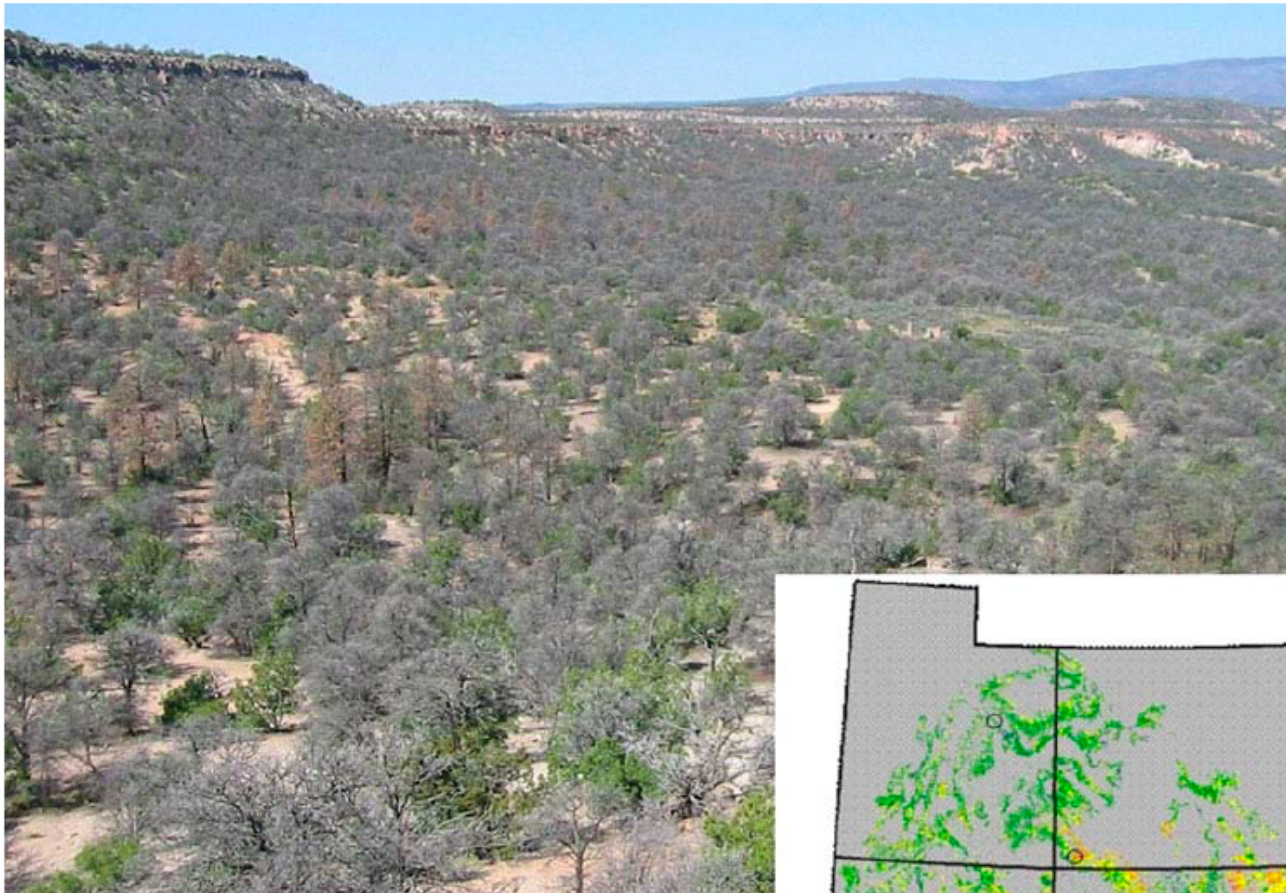
van Mantgem and Stephenson, Ecology Letters, 2007

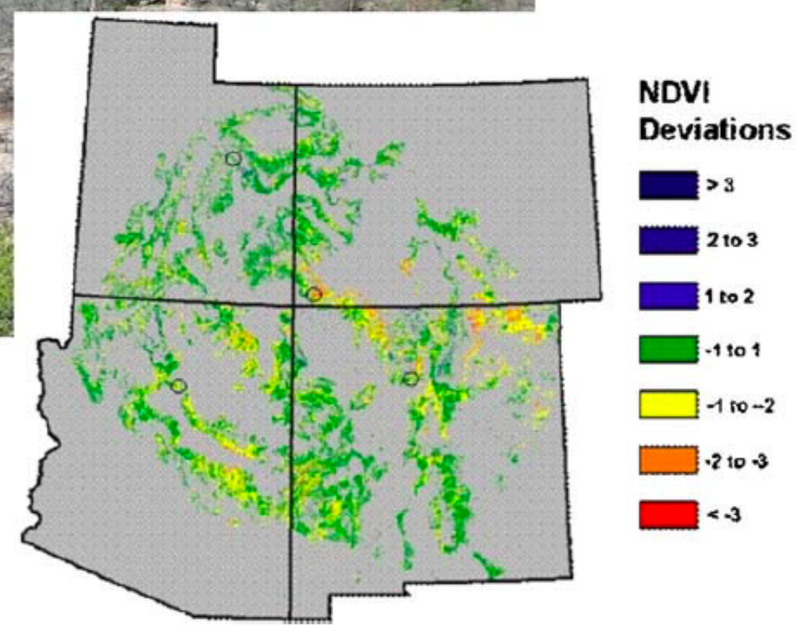
Figure 1 Annual tree mortality rates from 1983 to 2004 for 21 permanent forest plots in the Sierra Nevada, California. The thin solid line represents the annual mortality rate averaged among plots, with the thick solid line showing the expected mortality rate (± 2 SE, shaded area) from significant ($P < 0.05$) models of the annual trend (Table 1). (a) Mean annual mortality rate for all causes of death increased at 3% per year (Table 1). (b) Mean annual mortality rate for stress and biotic causes increased at 3% per year (Table 1). Average water deficit (dashed line), an index of drought (see text for definition), predicted changes in the stress and biotic mortality rate (Table 2). (c) Mean annual mortality rate for mechanical causes did not show a significant trend (Table 1), although Precip$_{max}$ (dotted line), an index of storm intensity (see text for definition), predicted annual variability in the mechanical mortality rate (Table 2).

Drought: Pinyon pine dieoff in Southwest in 2000s

Jemez Mts. near Los Alamos, October 2002 **Photo: Craig D. Allen, USGS**

Drought: Pinyon pine dieoff in Southwest in 2000s

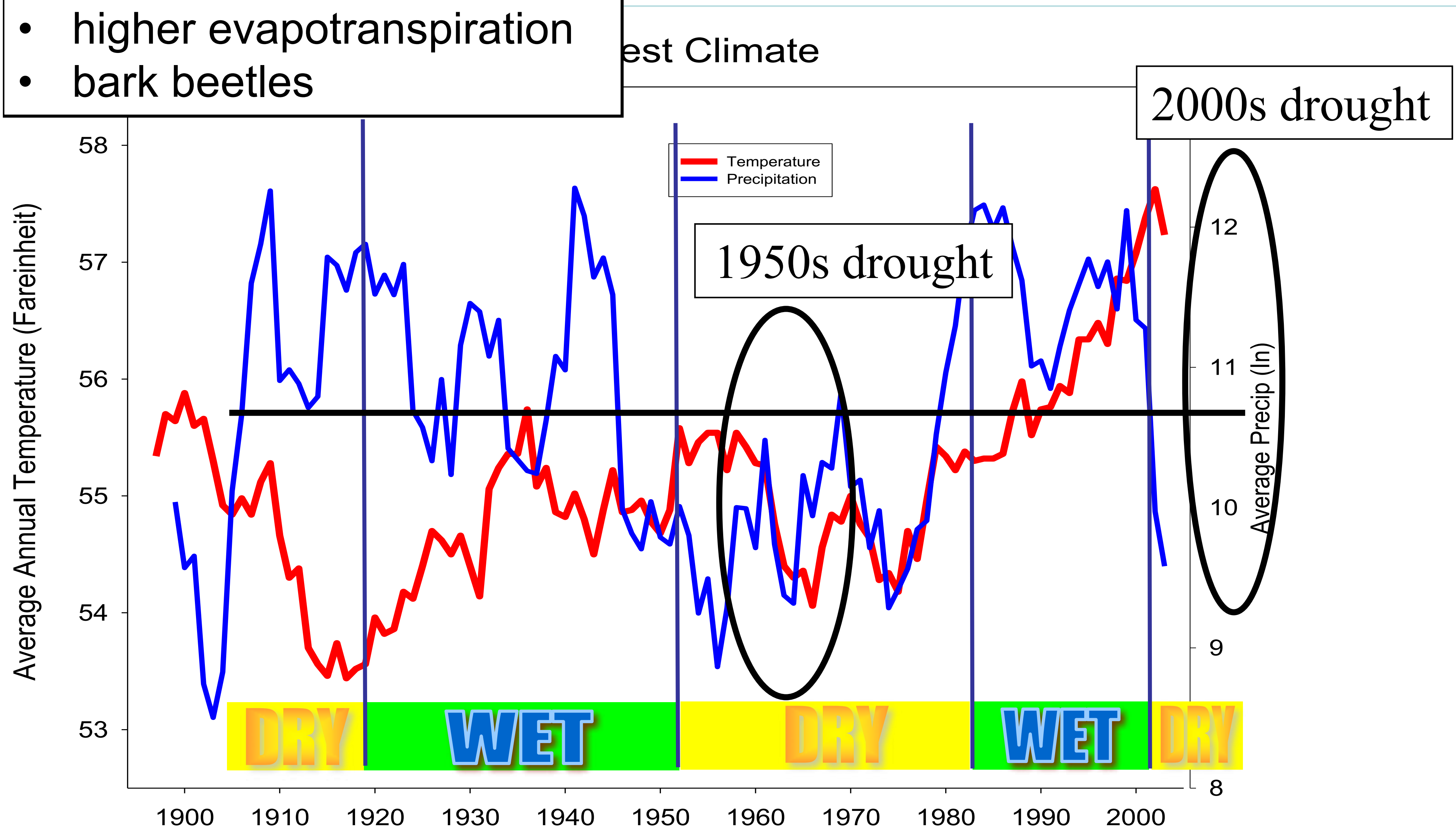




Breshears et al., 2011

Drought: Tree dieoff in Southwest

Warming:
- higher evapotranspiration
- bark beetles



Breshears et al. PNAS, October 18, 2005, vol. 102, no. 42, 15144-15148, and graphic from Neil Cobb

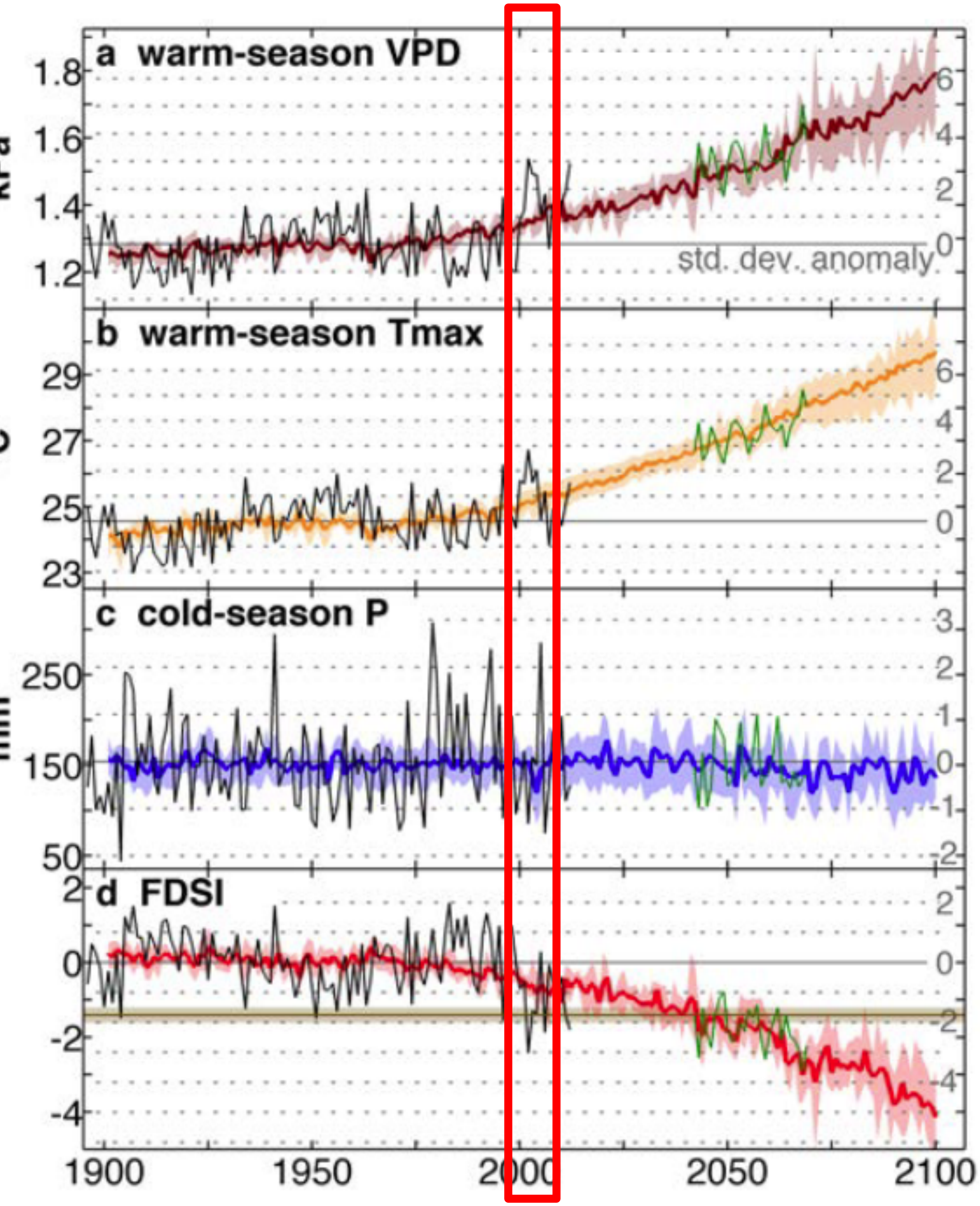
Drought: Tree dieoff in Southwest

evaporative demand by atmosphere

temperature

precipitation

Forest Drought Stress Index



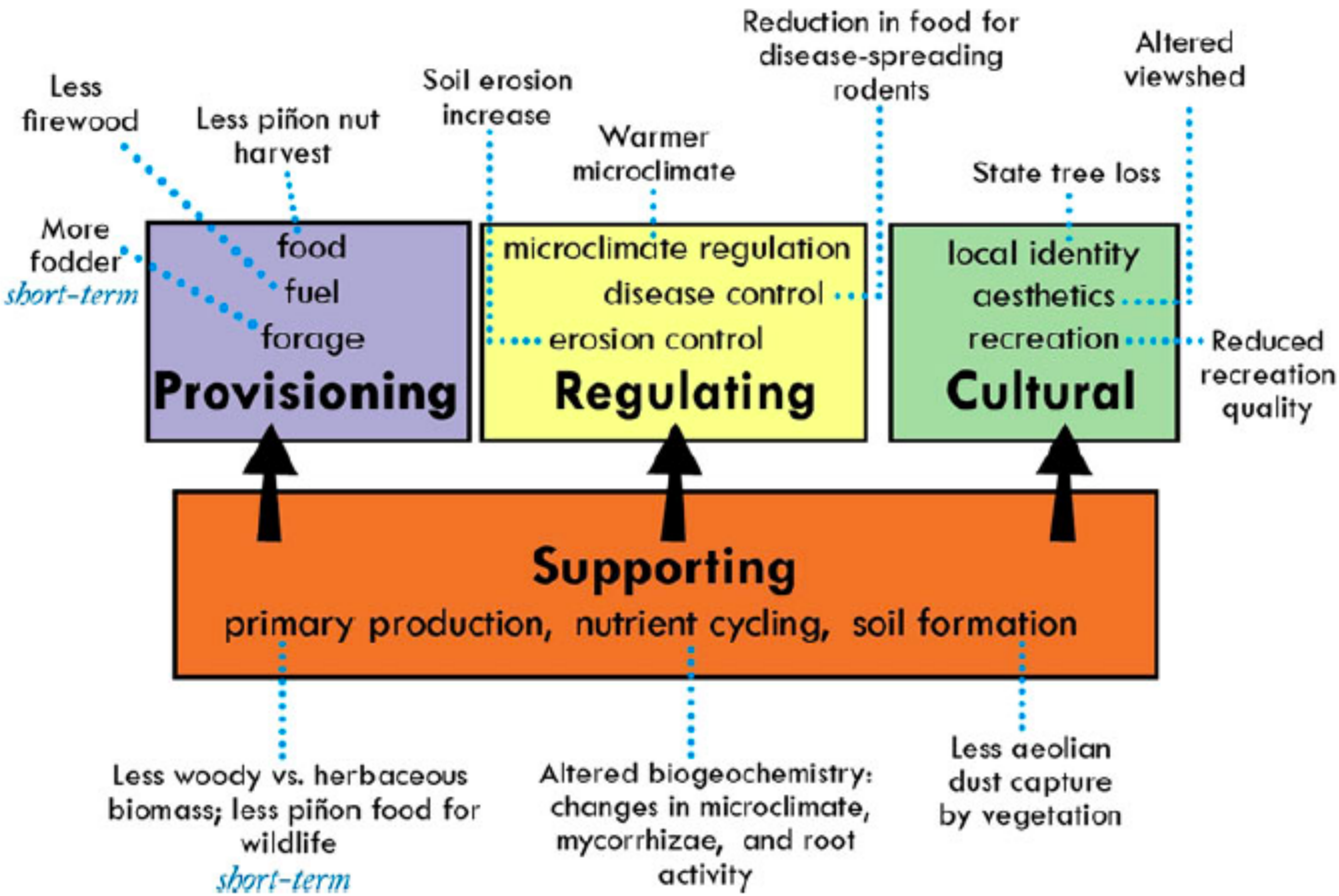
Drought: Projections of forest stress given climate change in the Southwest

1572-1587 megadrought

Williams et al., Nature Climate Change, 2012

Drought: Tree dieoff in Southwest

Tree die-off effects on ecosystem processes and services

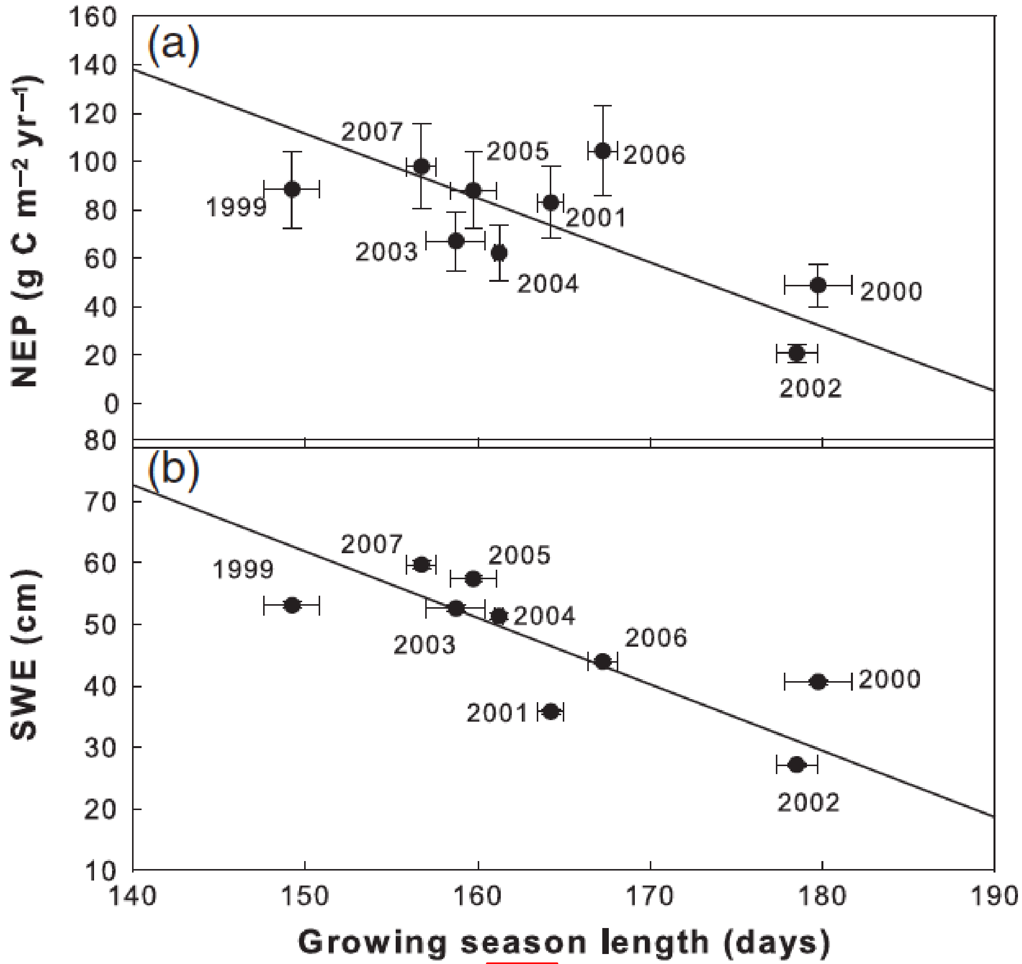


Breshears et al., 2011

Warming leads to longer growing season but reduced plant growth

3

1



2

Hu et al., Global Change Biology, 2010

Shallower snowpack => 1

longer growing season length but less water availability => 2

less plant growth (dependence on snow melt water) =>

less carbon storage (lower Net Ecosystem Productivity) 3

Fig. 2 (a) Relationship between annual GSL and NEP for 9 years. A significant, negative relationship between GSL and NEP ($P = 0.04$, $R^2 = 0.47$, $\text{NEP} = -2.66 \times \text{GSL} + 510.51$) demonstrate that longer growing seasons are correlated with lower annual rates of carbon sequestration by the forest. Vertical error bars correspond to 18% randomly generated NEP errors and horizontal error bars correspond to error in calculating the start and end of the growing season. (b) A significant, negative relationship between GSL and SWE ($P = 0.01$, $R^2 = 0.61$, $\text{SWE} = -1.08 \times \text{GSL} + 223.87$) demonstrates that years with a longer growing season are correlated with less available snow melt water. Horizontal error bars correspond to 1% instrument error. NEP, net ecosystem productivity; GSL, growing season length; SWE, snow water equivalent.

Reliance of trees on snow melt water, not summer precip in this area

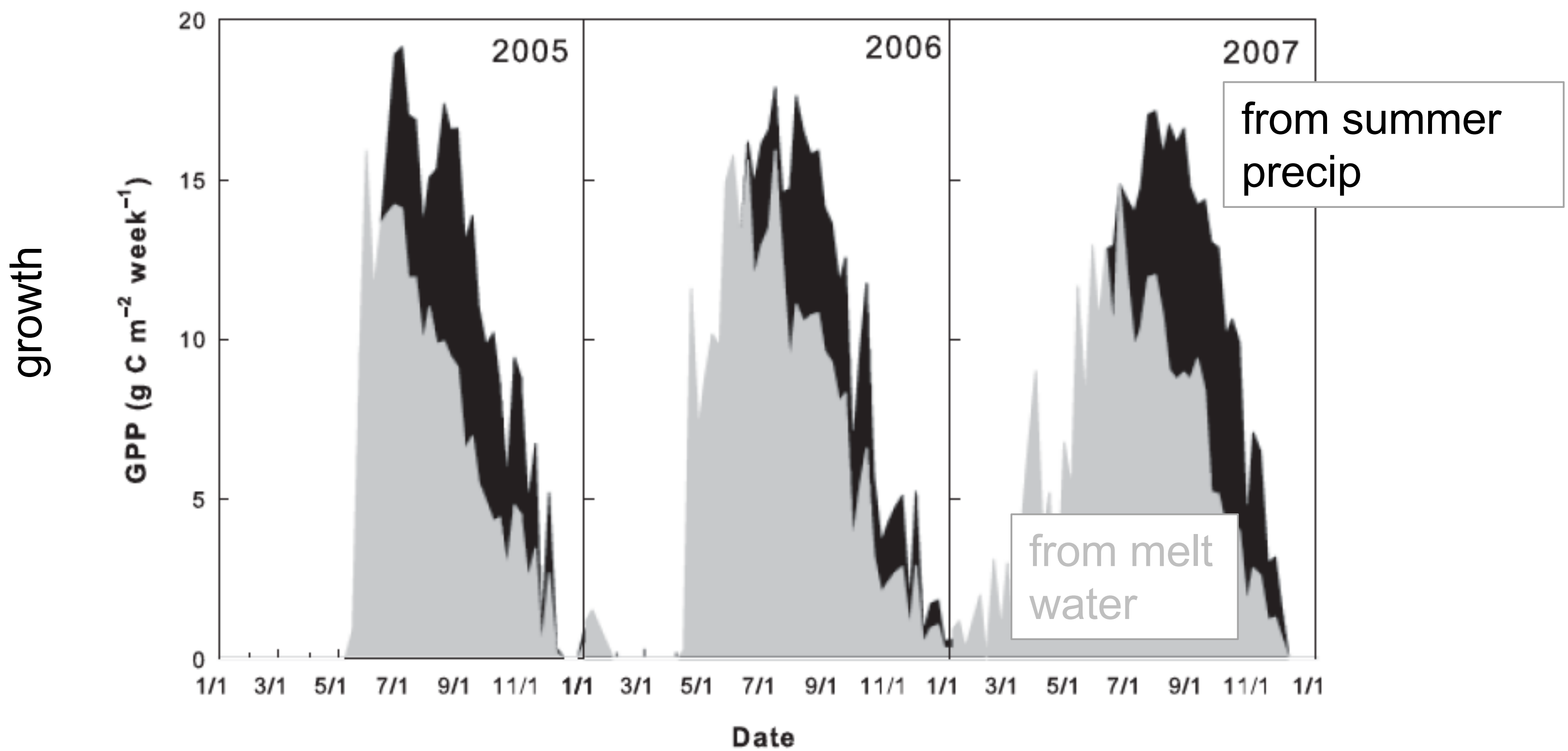
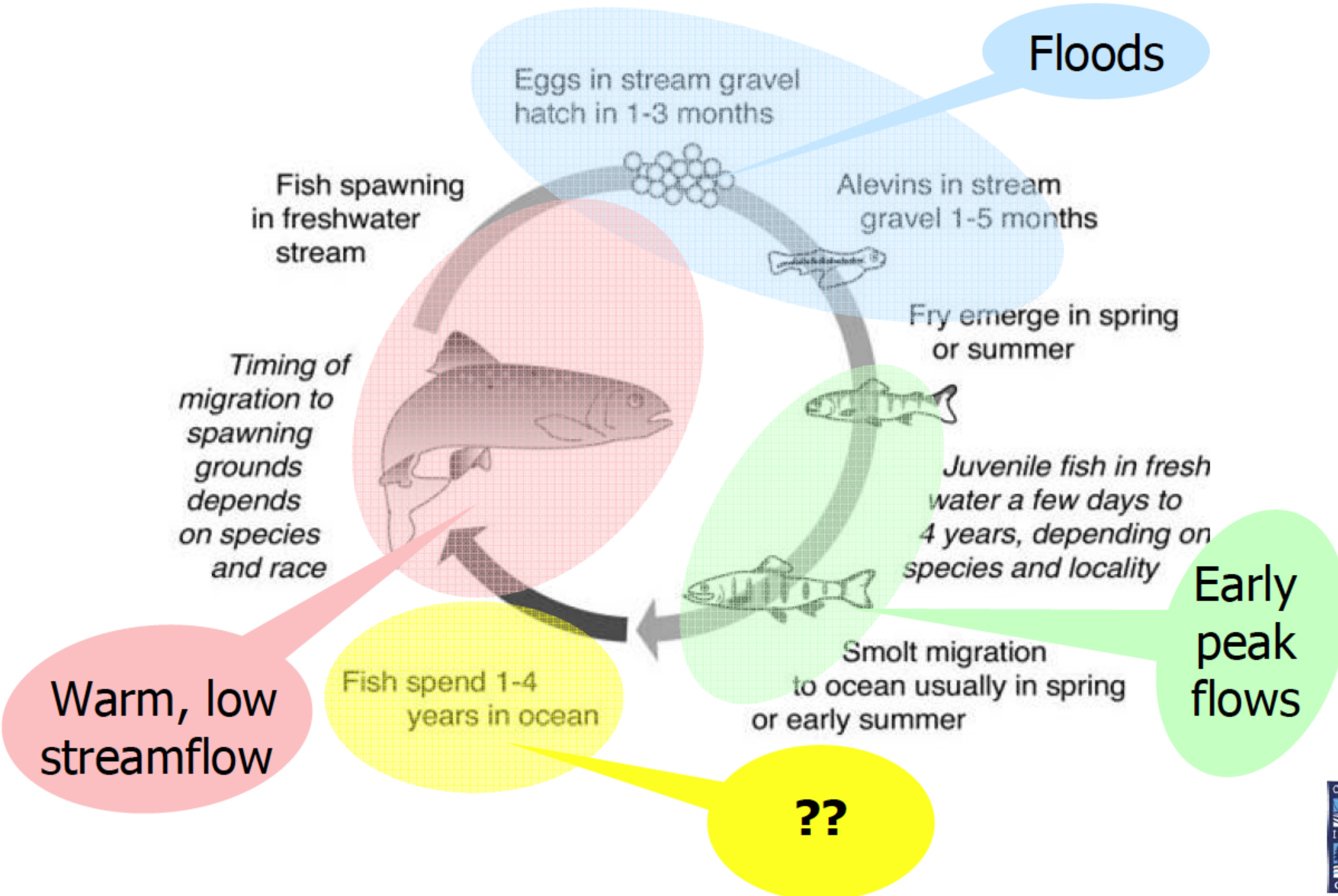


Fig. 7 Gross primary productivity (GPP) modeled using SIPNET for 2005, 2006, and 2007. Gray areas represent snow contributed GPP and black areas represent rain contributed GPP. Annual net ecosystem productivity (NEP) for each year is as follows: 2005 (88 gC m^{-2} yr^{-1}), 2006 (104 gC m^{-2} yr^{-1}), and 2007 (98 gC m^{-2} yr^{-1}).

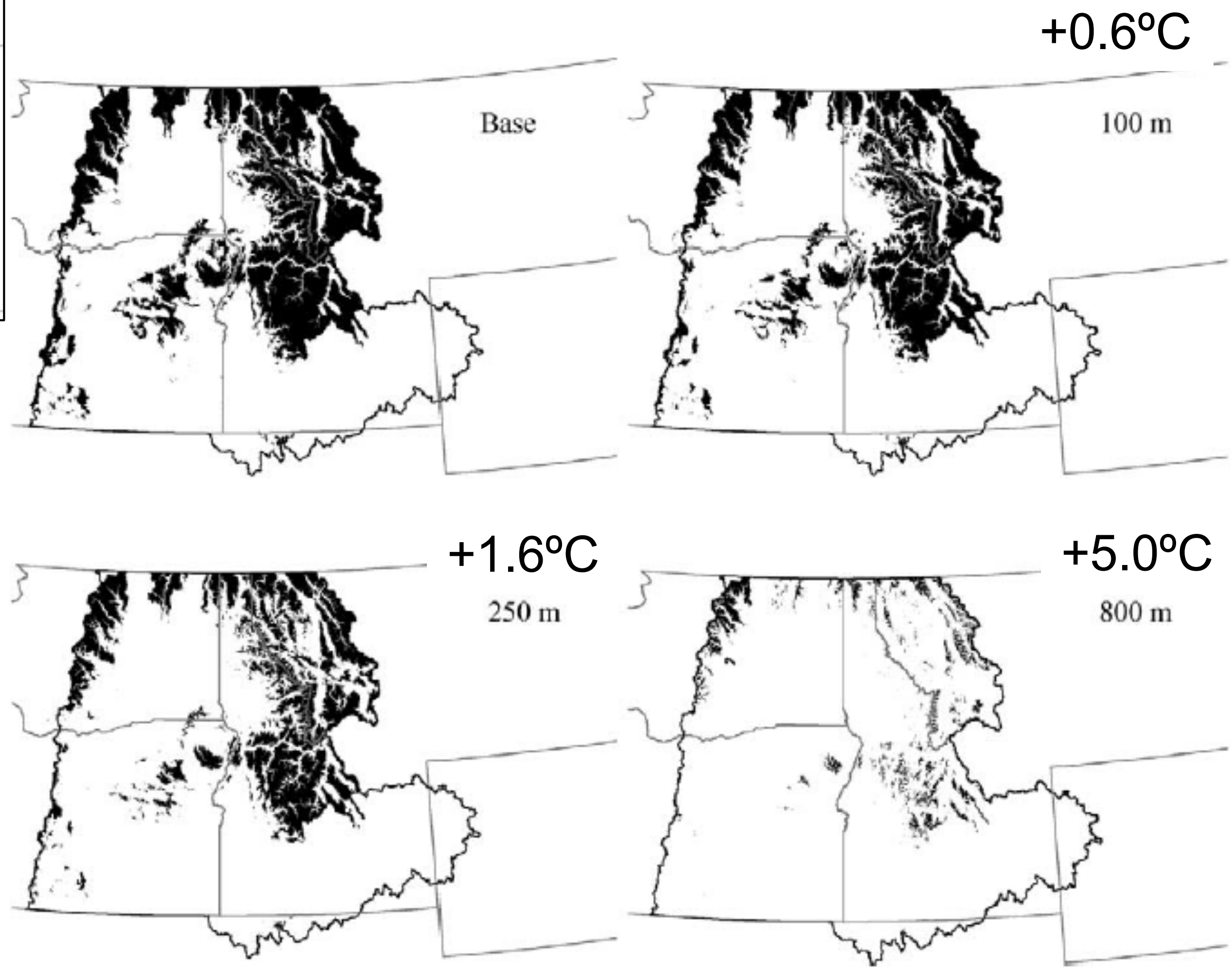
Hu et al., Global Change Biology, 2010

Salmon Impacted Across Full Life-Cycle



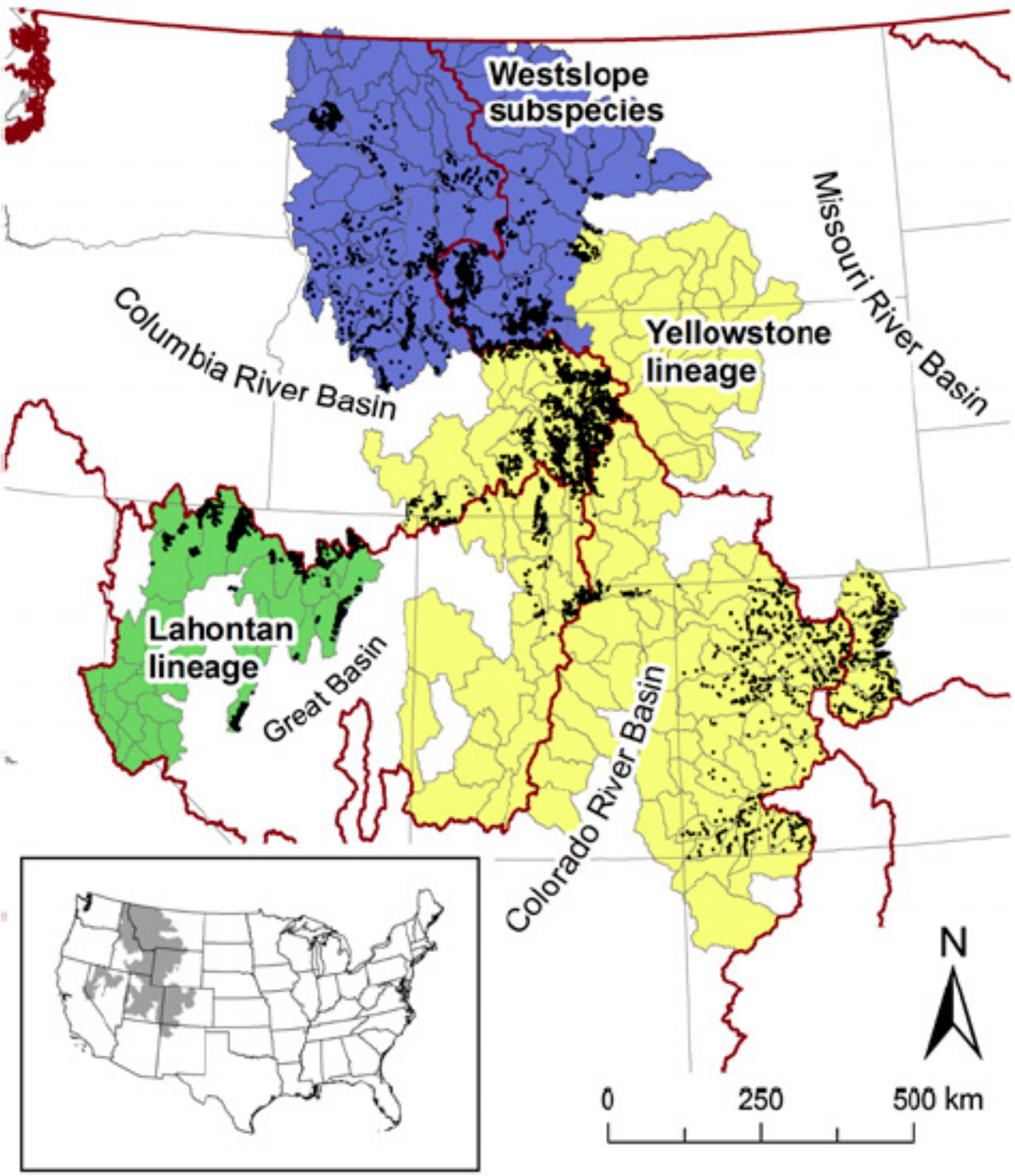
Source: Climate Impacts Group, University of Washington, www.cses.washington.edu/cig

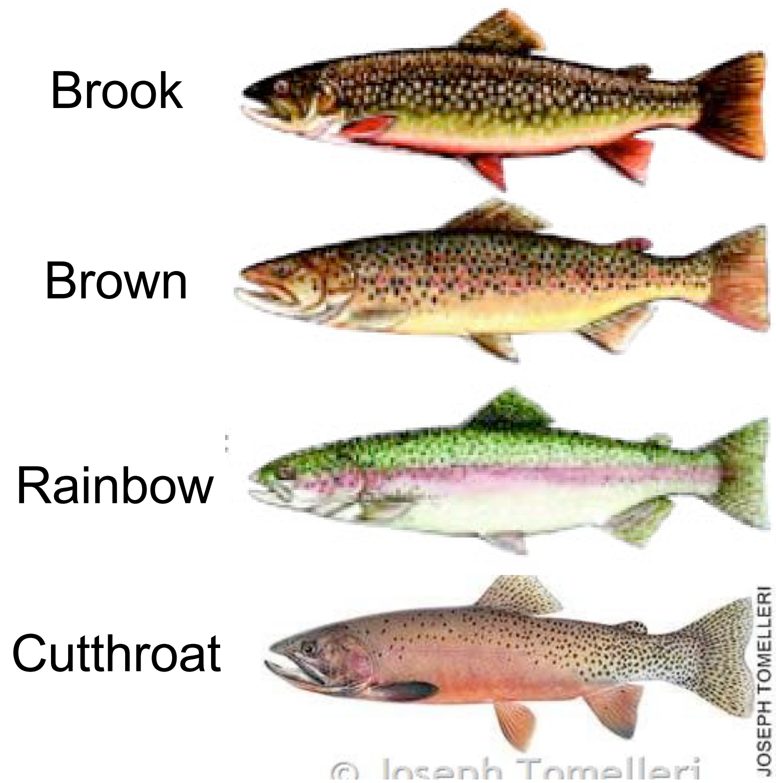
Predicted response of bull trout to warming



Rieman et al. 2007

Trout species respond differently to warming

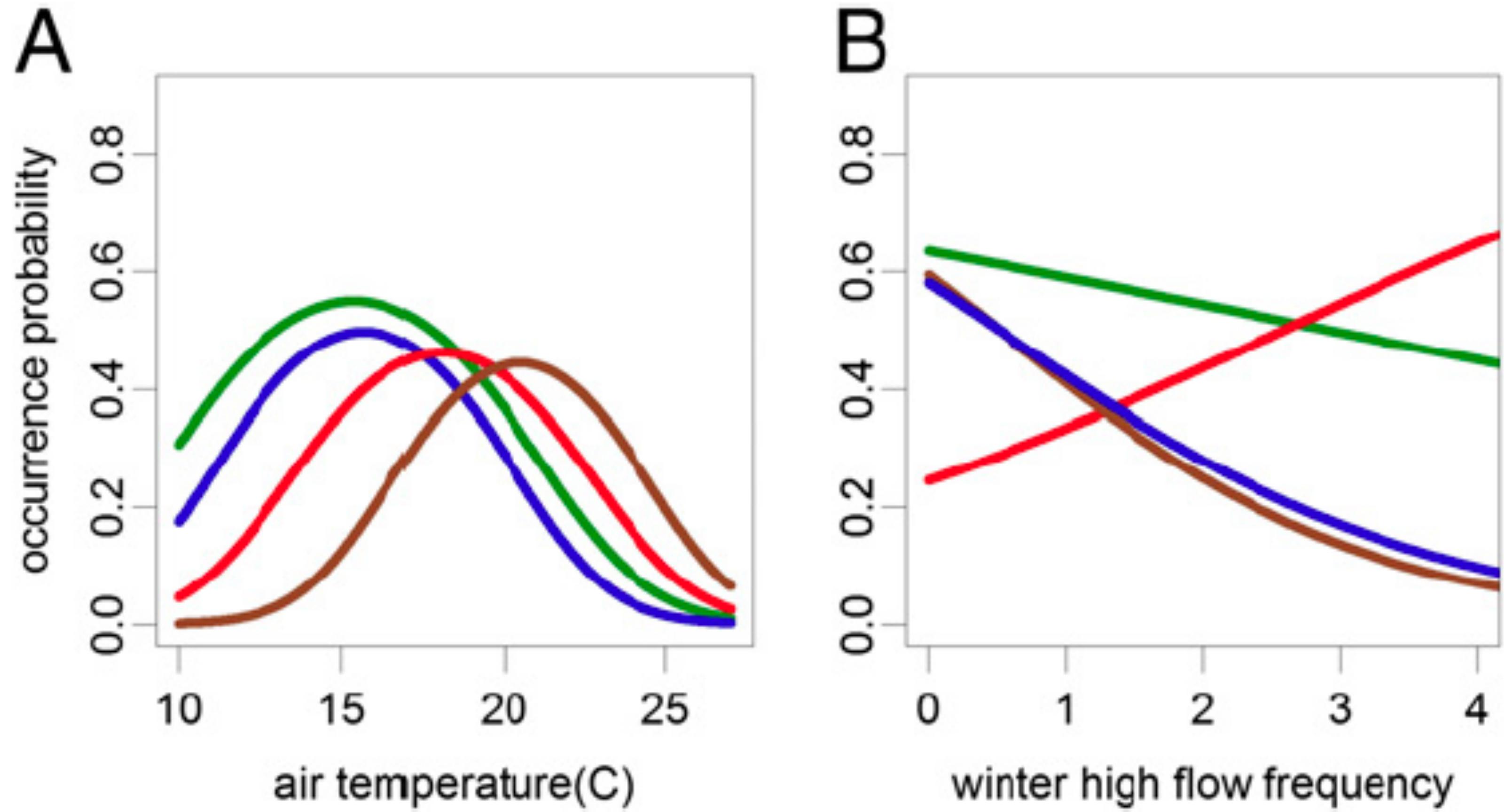




fishandboat.com/trout.htm;
fieldguide.mt.gov

Wenger et al. 2011

Species responses to air temperature, streamflow

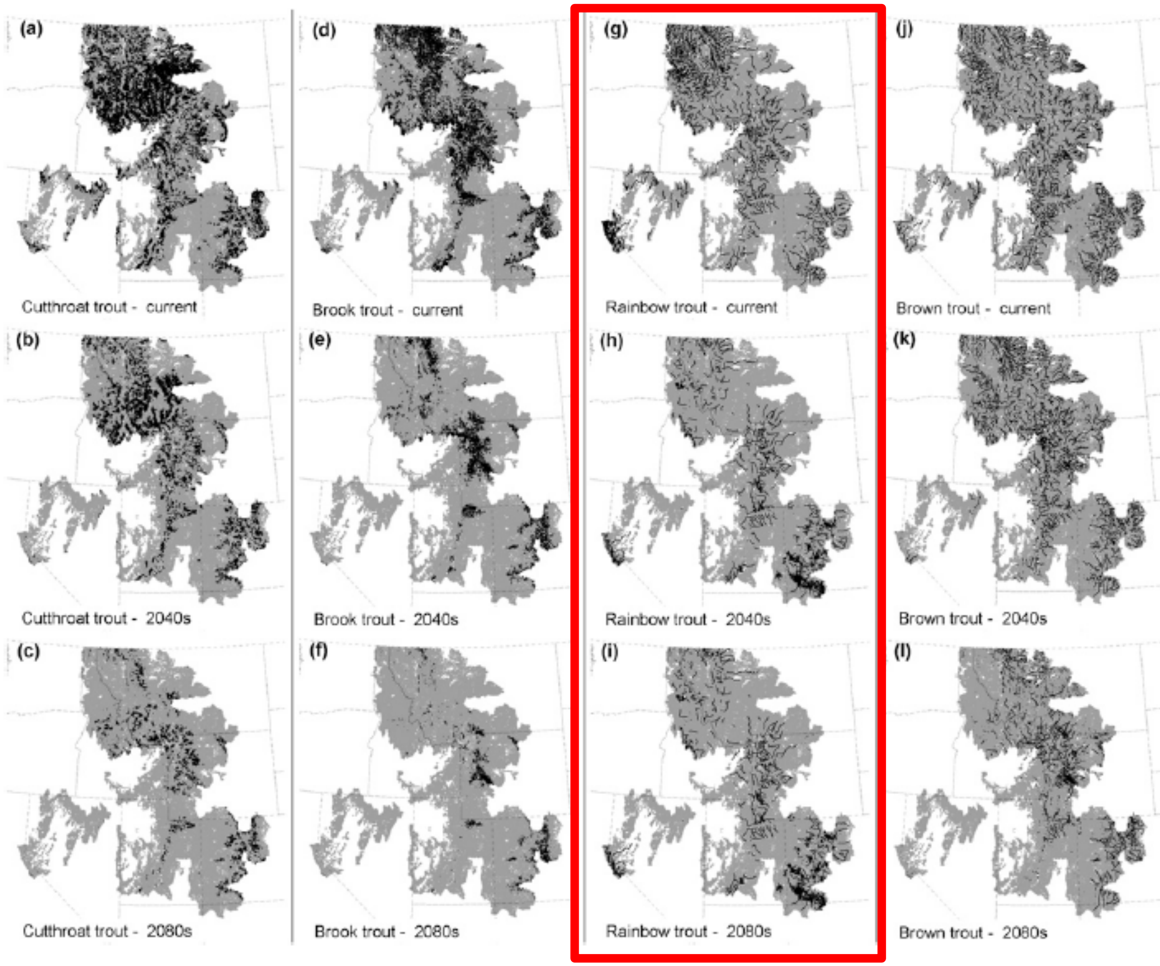


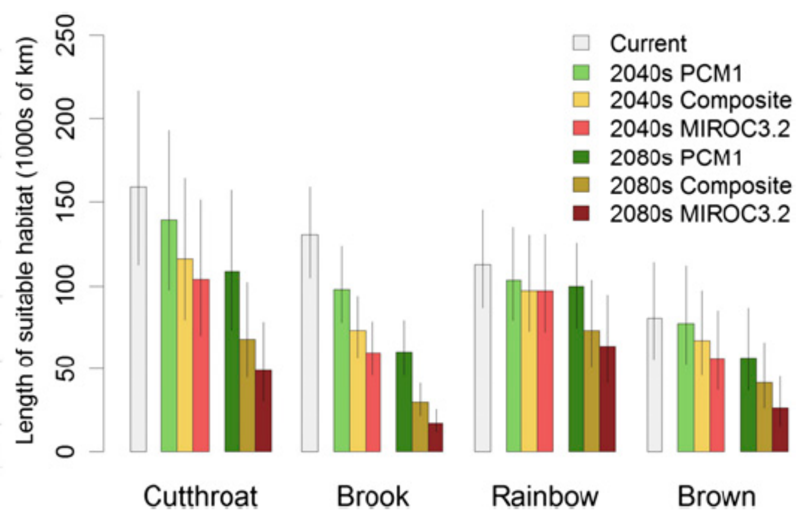
Brook **Brown** **Rainbow** **Cutthroat**

Wenger et al. 2011

Predictions using future climate projections

Overall: 47% decrease by 2080

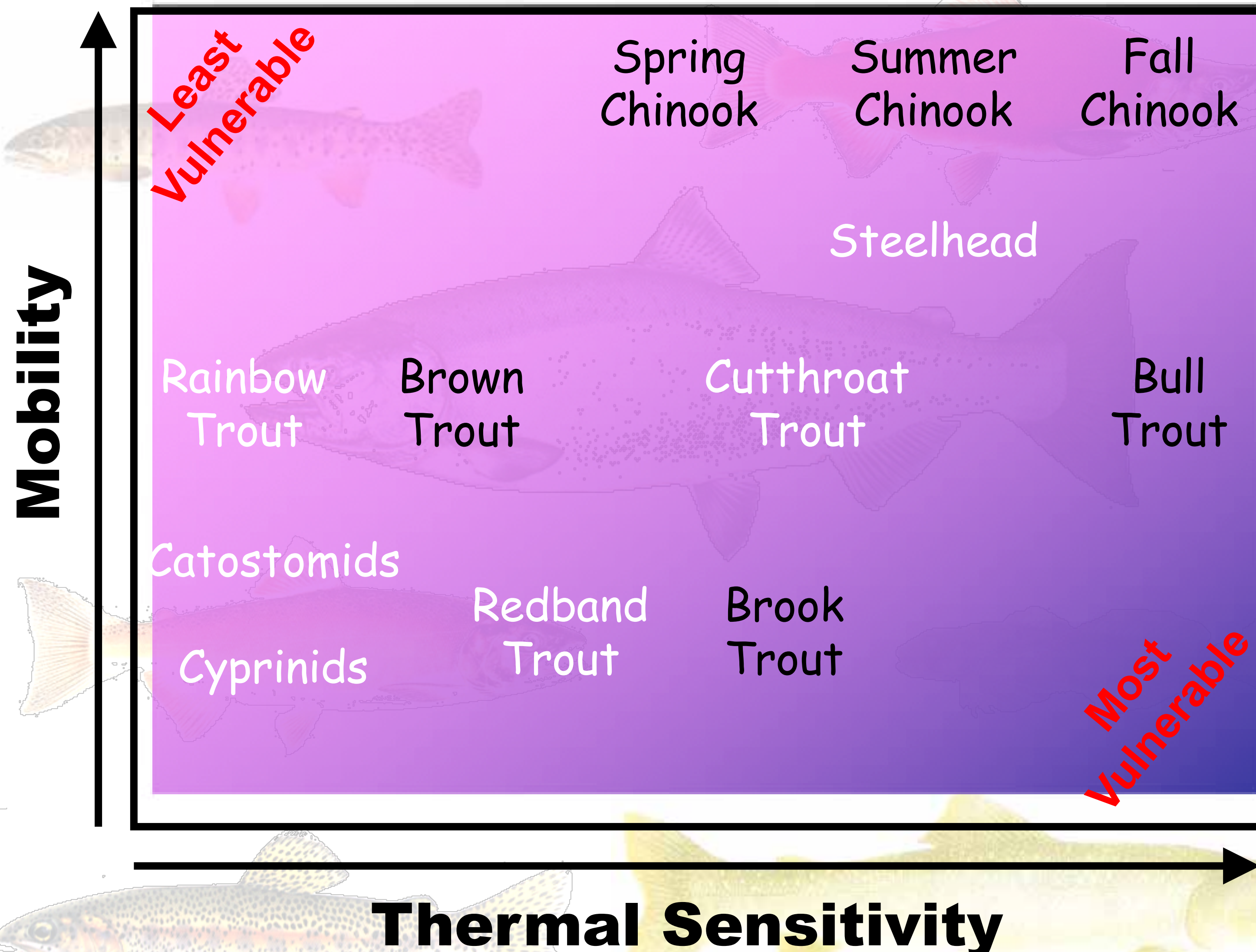




Wenger et al. 2011

Rainbow: negative T offset by flow changes that are beneficial (spring, not fall, spawners)

Vulnerability to Climate Change



Black = fall spawner

Slide courtesy D. Isaak, USDA FS

Cutthroat trout risk analysis that includes climate change

Factors influencing risk of losing cutthroat trout populations:
Adding climate change

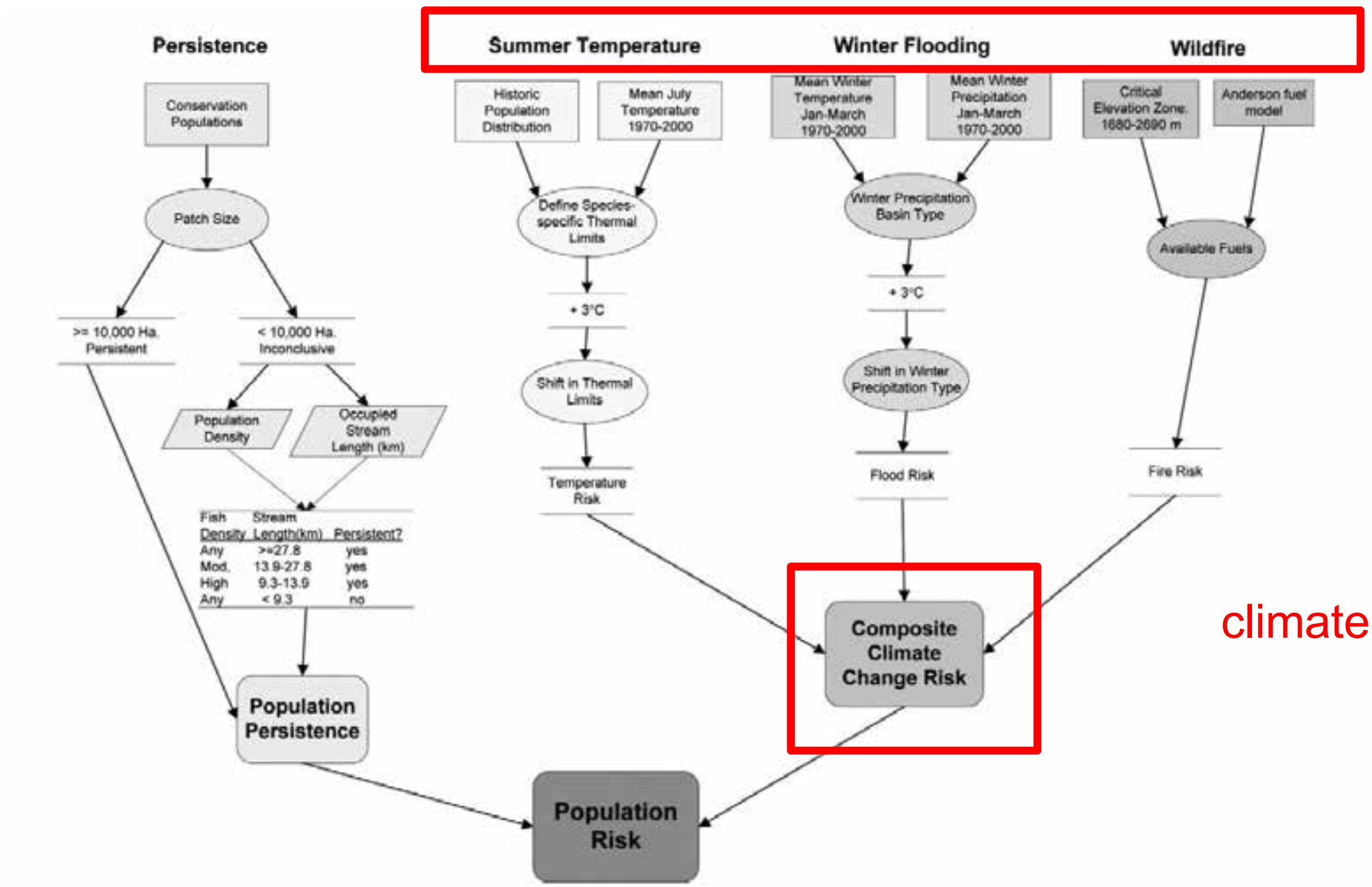


FIGURE 1.—Schematic showing how the current analysis of population persistence is influenced by climate change risk models to produce an overall description of population risk.

Williams et al., NAJ Fish. Manag., 2009

Cutthroat trout risk analysis that includes climate change

Factor 1: Summer temperature

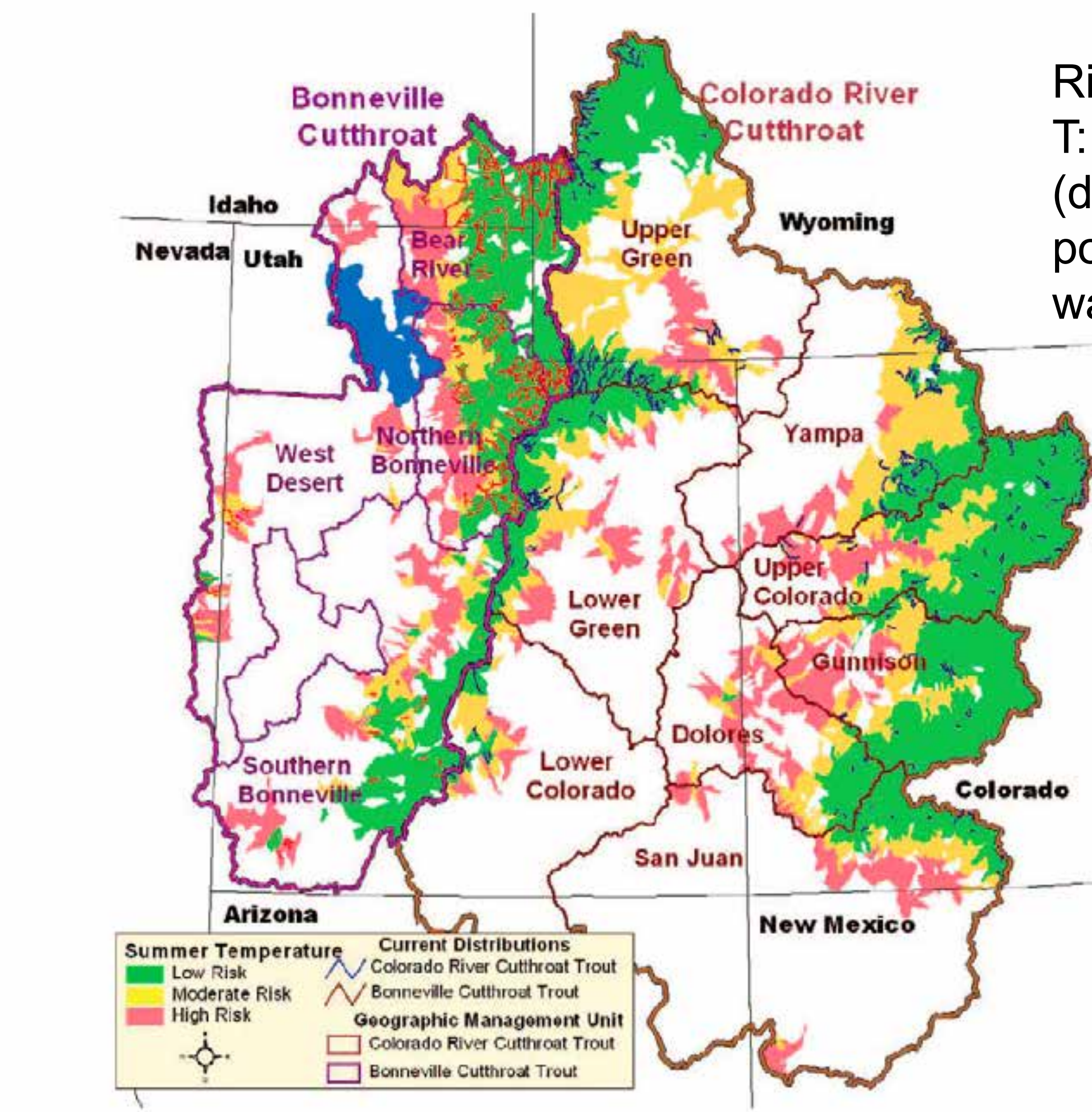


FIGURE 3.—Risk of increased summer temperature within the historic ranges of Bonneville cutthroat trout and Colorado River cutthroat trout, by subwatershed.

Risk of higher summer T: above 22º or 24ºC (depending on population) after 3ºC warming

Williams et al., NAJ Fish. Manag., 2009

Cutthroat trout risk analysis that includes climate change

Factor 2: Winter flooding

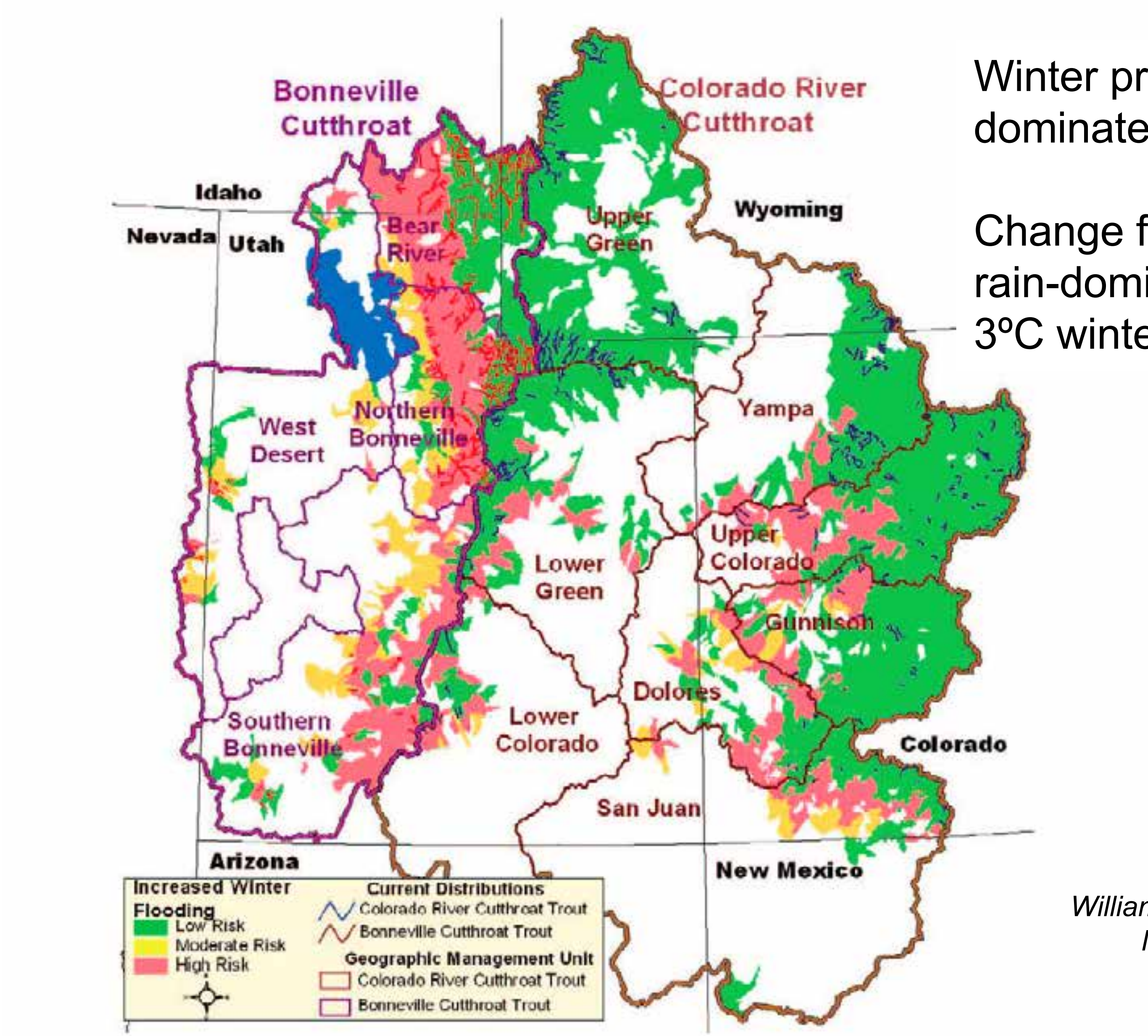


FIGURE 4.—Risk of increased winter floods within the historic ranges of Bonneville cutthroat trout and Colorado River cutthroat trout, by subwatershed.

Winter precip-dominated watersheds

Change from snow- to rain-dominated with 3ºC winter warming

Williams et al., NAJ Fish. Manag., 2009

Cutthroat trout risk analysis that includes climate change

Factor 3: Wildfire impacts

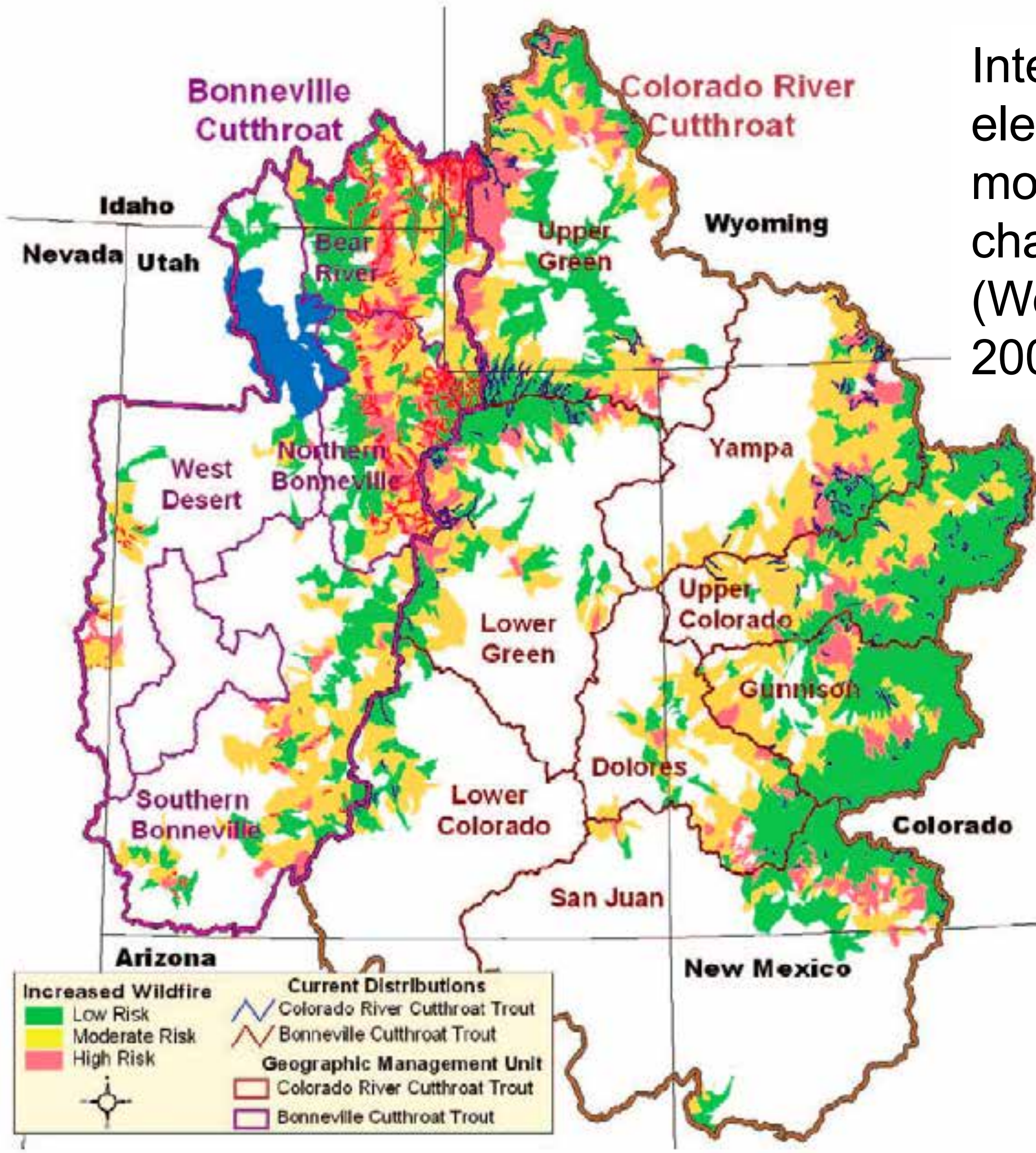


FIGURE 5.—Risk of increased wildfire within the historic ranges of Bonneville cutthroat trout and Colorado River cutthroat trout, by subwatershed.

Intermediate elevations may be more susceptible to changes in fire regime (Westerling et al., 2006)

Williams et al., NAJ Fish. Manag., 2009

Cutthroat trout risk analysis that includes climate change

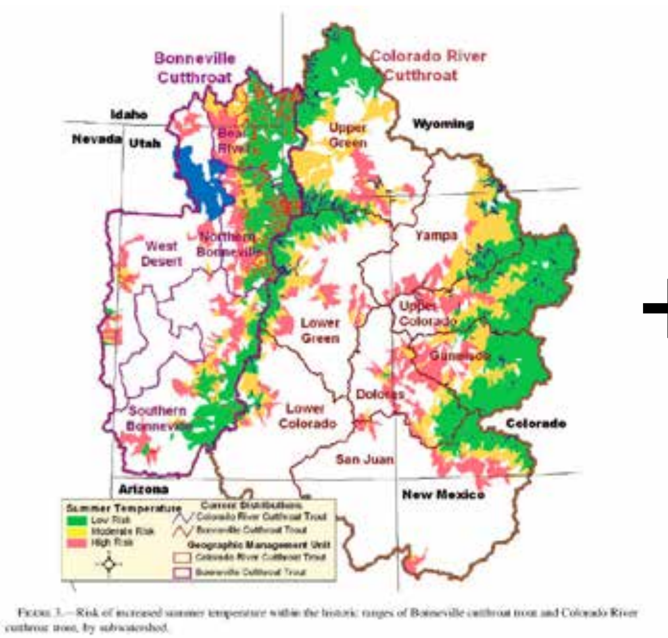
Composite risk = max of three climate risks

Bonneville subspecies: 73% in high risk

Colorado subspecies: 29% in high risk

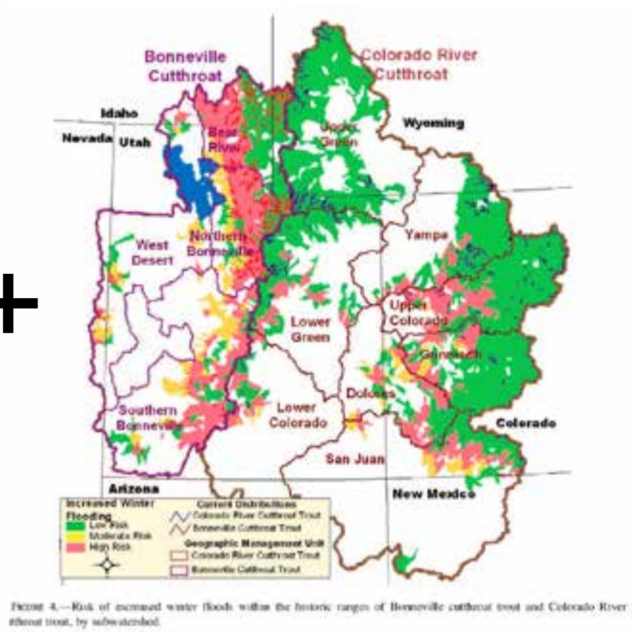
More change from flooding, fire than from summer warming

summer T



\+

winter flooding



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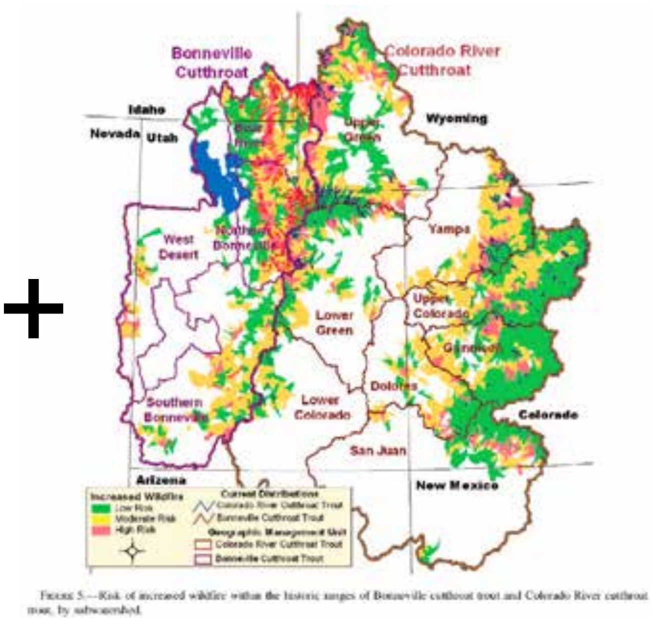
wildfire



Williams et al., NAJ Fish. Manag., 2009

Cutthroat trout risk analysis that includes climate change

Westslope subspecies: 65% in high risk

More change from flooding, fire than from summer warming

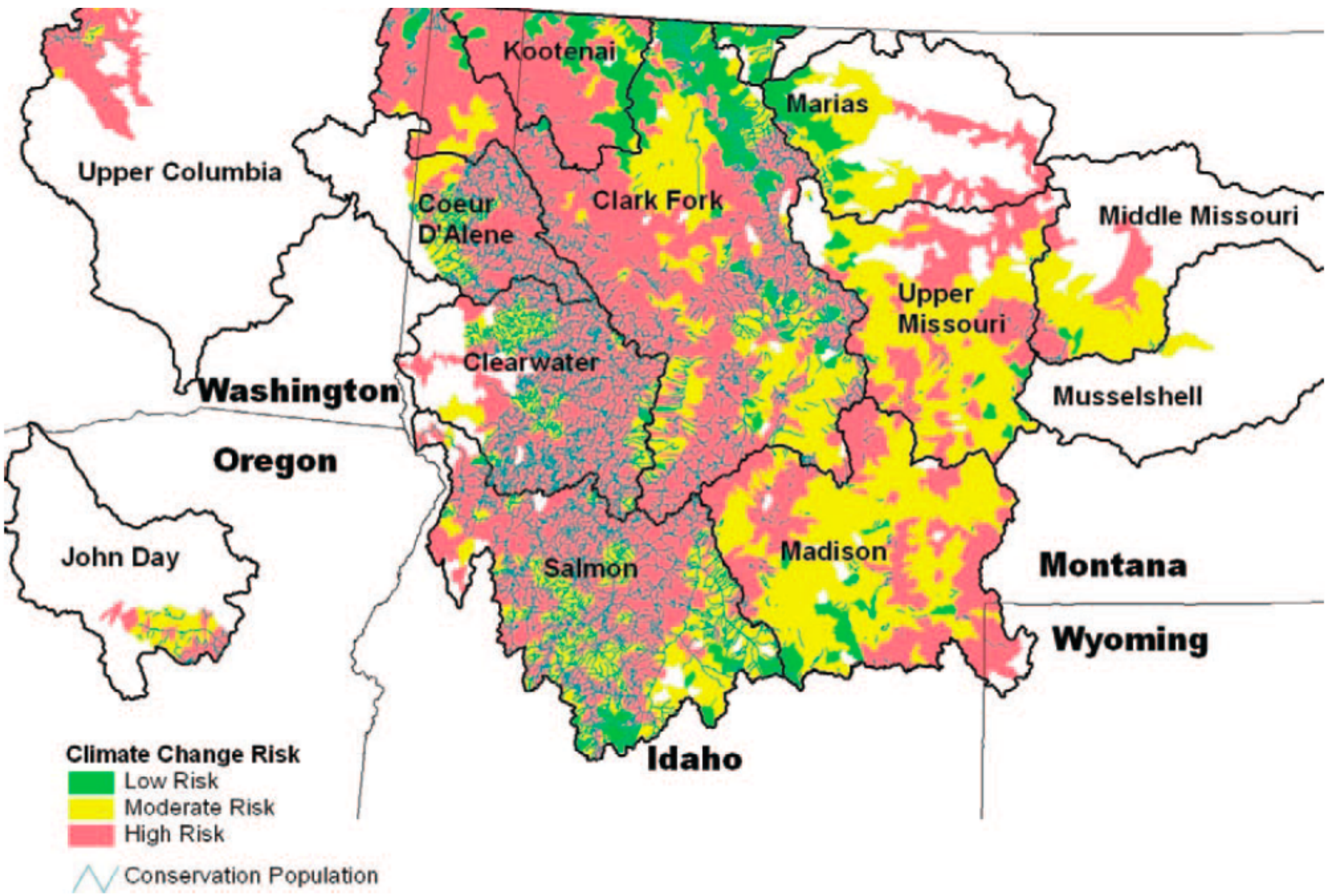


FIGURE 6.—Composite climate change risk for subwatersheds within the historic range of westslope cutthroat trout.

Williams et al., NAJ Fish. Manag., 2009

Coral bleaching

Hannah, 2011

Coral bleaching

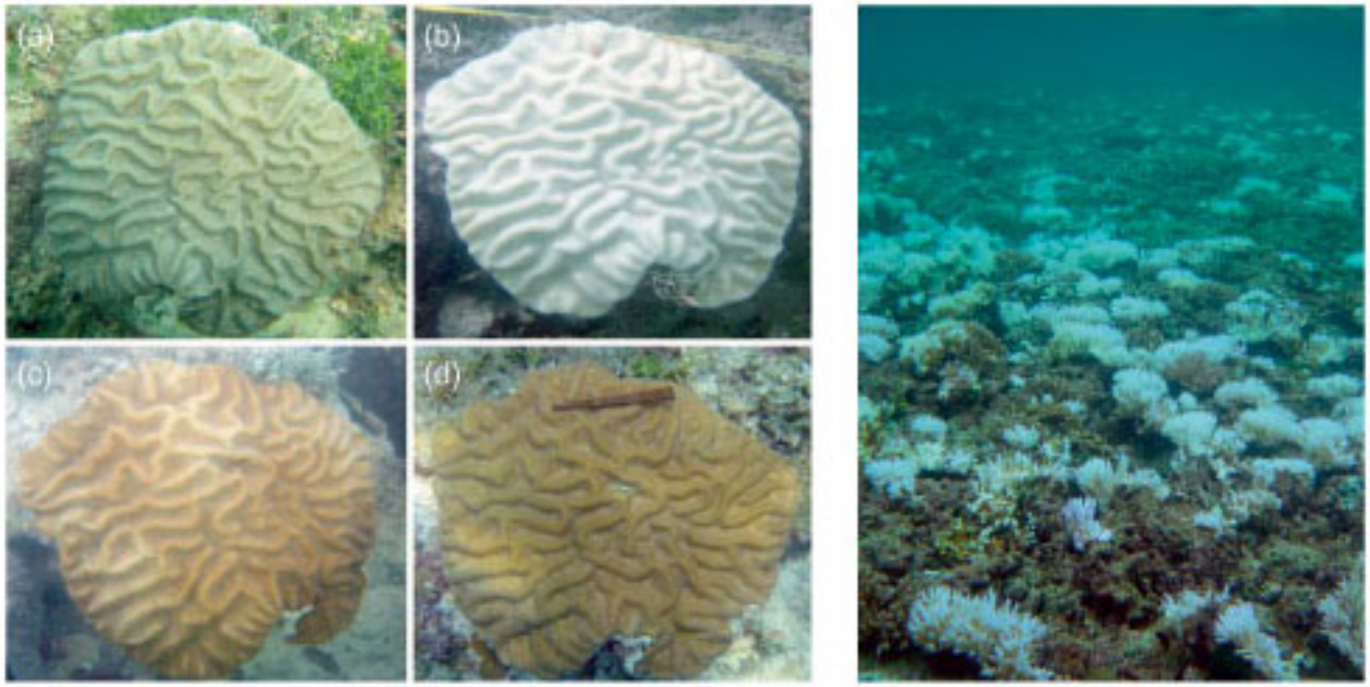
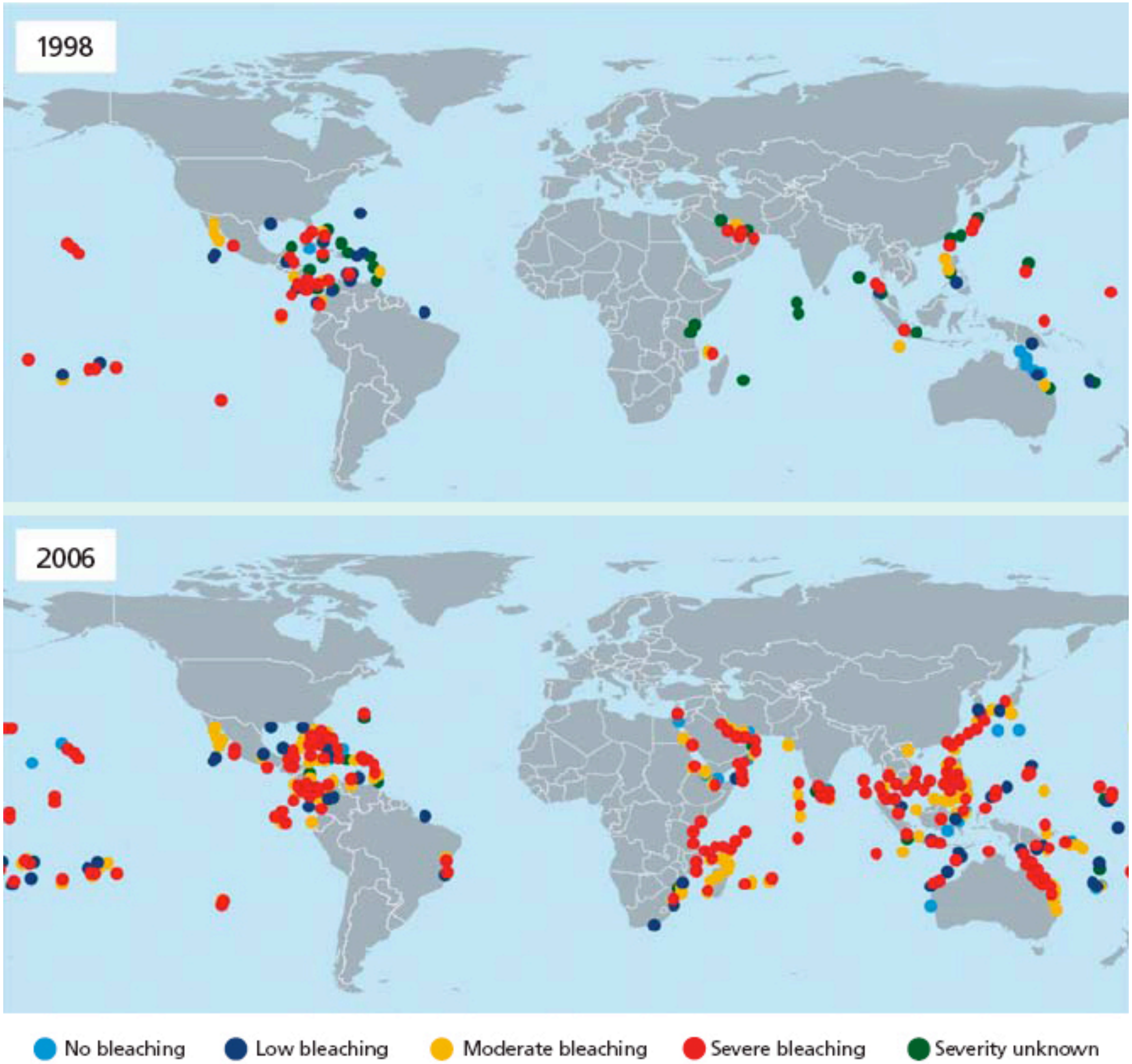


FIGURE 3.2 1997 – 1998: A Deadly Year for Corals.
The right panel shows corals bleached in the El Ni ñ o event of 1997 – 1998. The left panels show a single coral head pre- and postbleaching: (a) prebleaching, (b) bleached coral head, (c) partially recovered coral head, and (d) fully recovered postbleaching. *Left Source: Manzello et al., 2007; Right Source: Courtesy U.S. National Oceanic and Atmospheric Administration.*

Hannah, 2011

Coral bleaching



Marshall, Schuttenberg, 2006

Ocean acidification

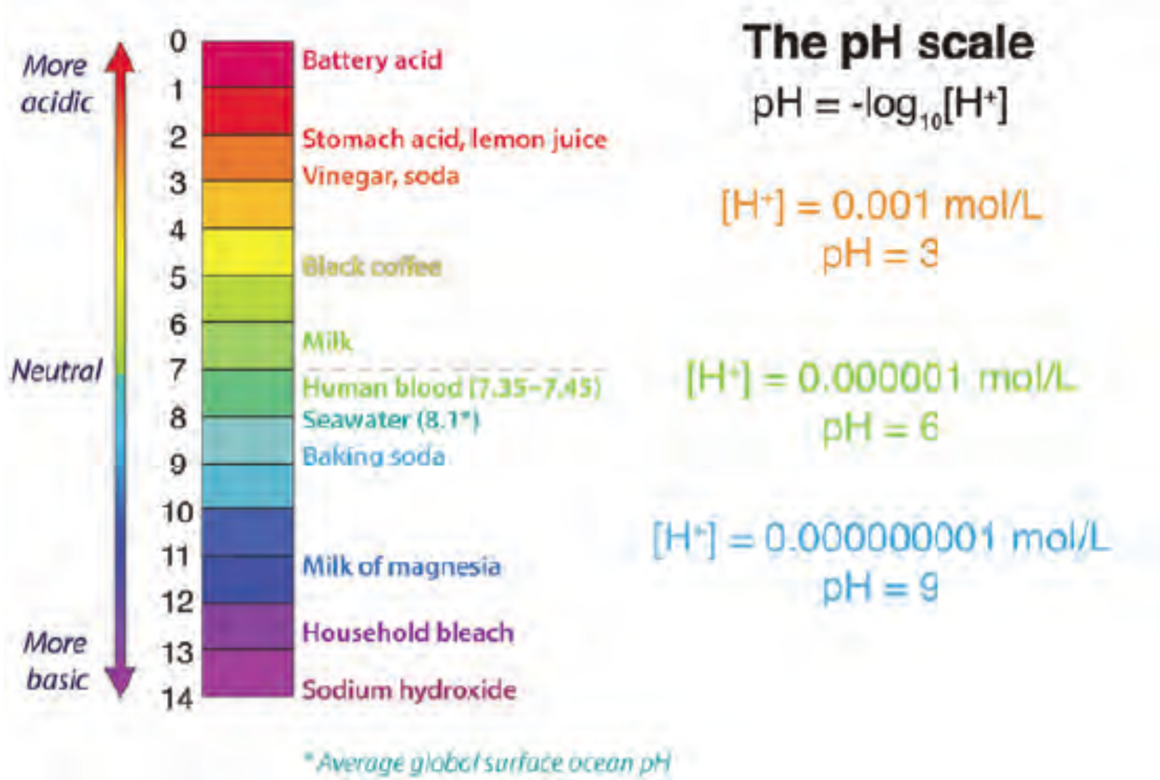
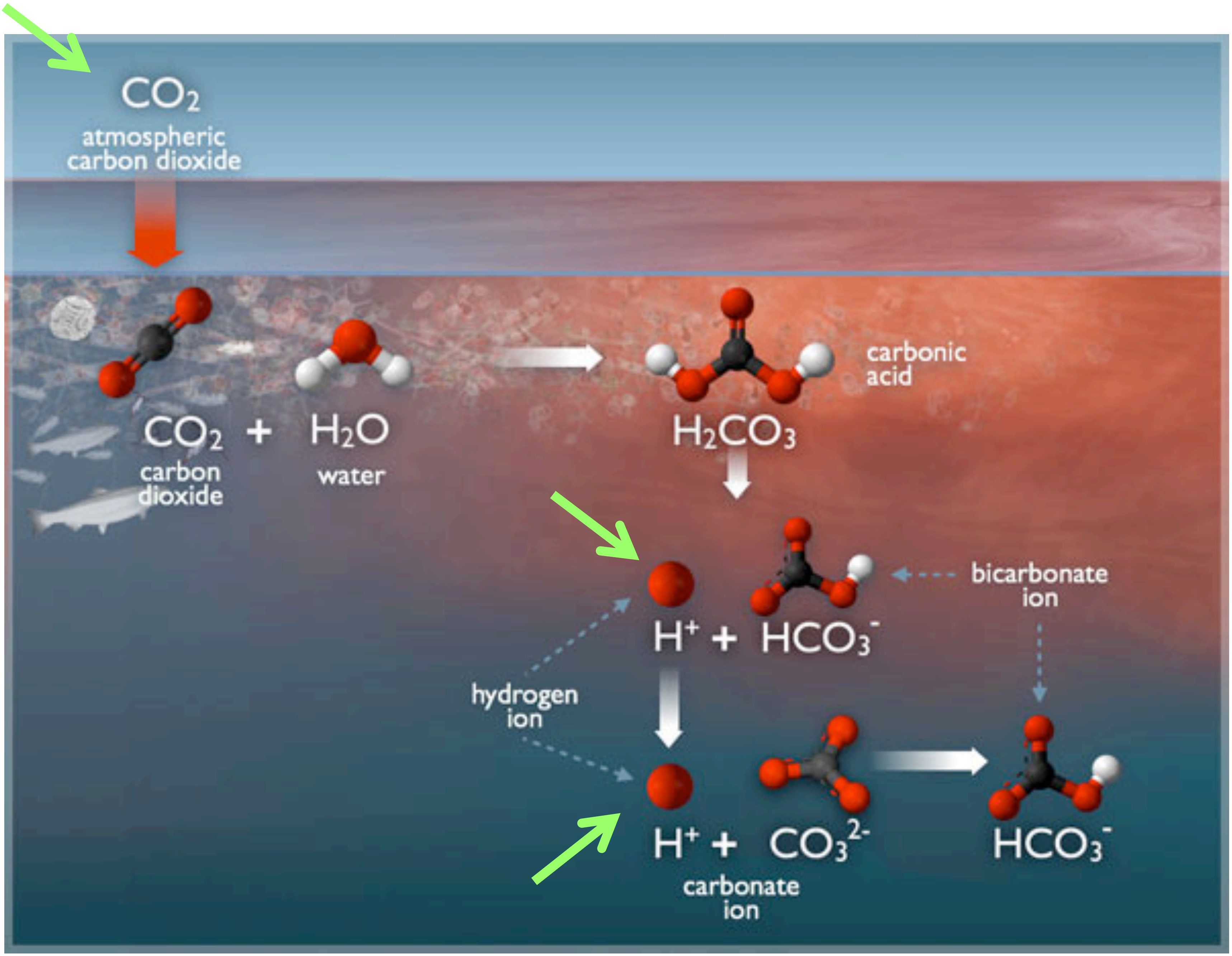


Figure 1.1 • Diagram of the pH scale, labeled with the average pH values for some common solutions, including seawater. pH is defined as the negative log of the hydrogen ion concentration in a solution. Neutral pH is 7.0, solutions that have pH values < 7.0 are acidic, and those that have pH values > 7.0 are basic. The term 'ocean acidification' refers to the direction of change toward more acidic conditions with increasing atmospheric CO_2 concentrations. Like the Richter scale, the pH scale is *logarithmic*. This means that a pH of 7 is *10 times more acidic* than a pH of 8.

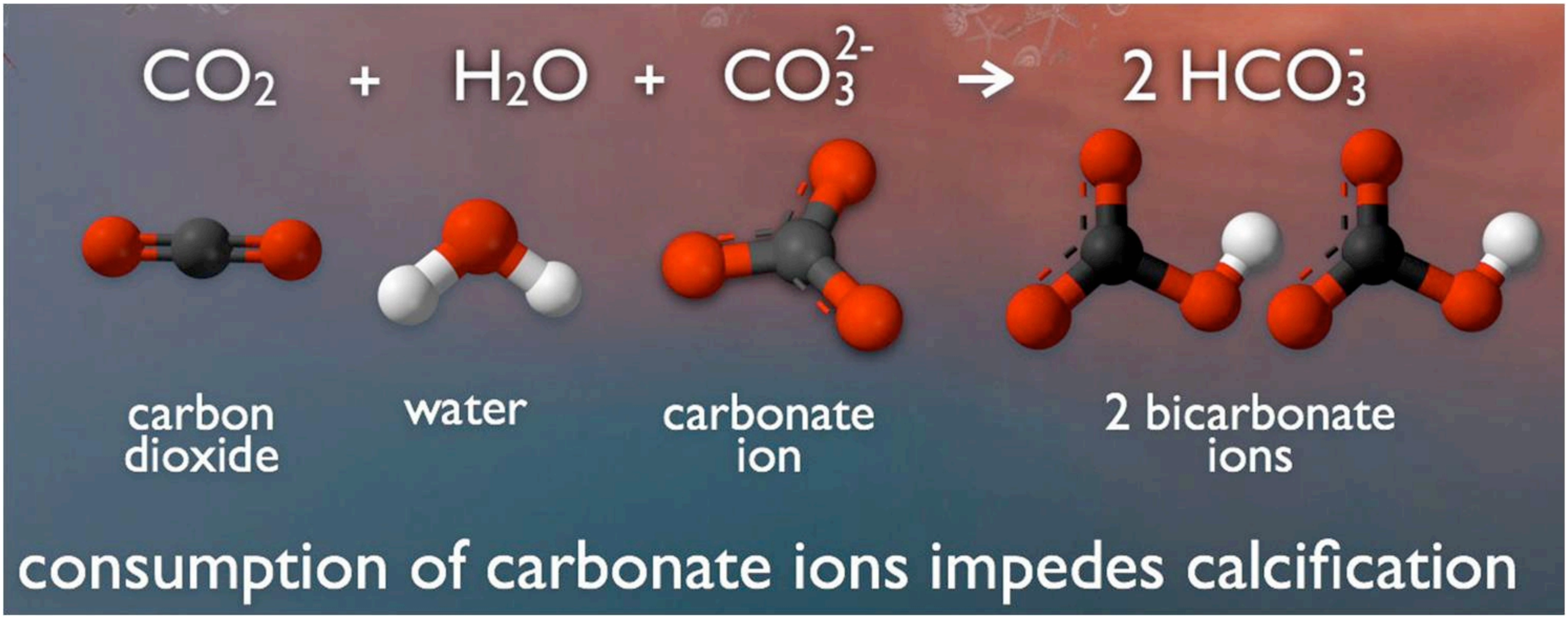
NOAA, State of Washington Report on Ocean Acidification, 2012

Inc. atm. CO2 leads to inc. H^+



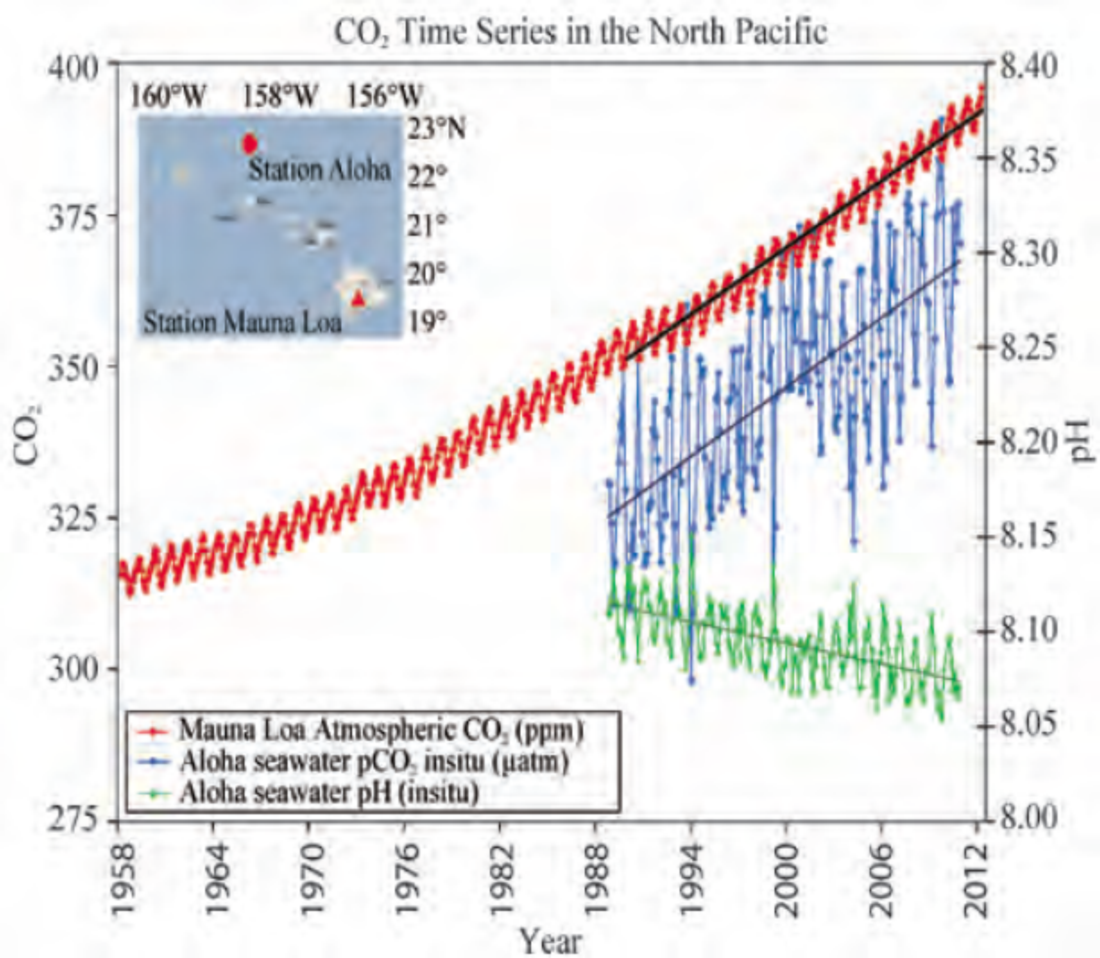
http://www.whoi.edu/OCB-OA/page.do?pid=112076

Inc. atm. CO2 leads to dec. carbonate ions



http://pmel.noaa.gov/co2/files/oareaction.jpg

Ocean acidification



Recent changes in atmospheric CO2, CO2 in seawater, and pH

Figure 1.3 • Time series of atmospheric CO_2 at Mauna Loa (in ppm; mole fraction in dry air) and surface ocean pH and pCO_2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean. Note that the increase in oceanic CO_2 over the last 19 years is consistent with the atmospheric increase within the statistical limits of the measurements. Mauna Loa data: Dr. Pieter Tans, NOAA/ESRL (http://www.esrl.noaa.gov/gmd/ccgg/trends); HOTS/ALOHA data: Dr. John Dore, University of Hawaii (http://hahana.soest.hawaii.edu).

NOAA, State of Washington Report on Ocean Acidification, 2012

Ocean acidification

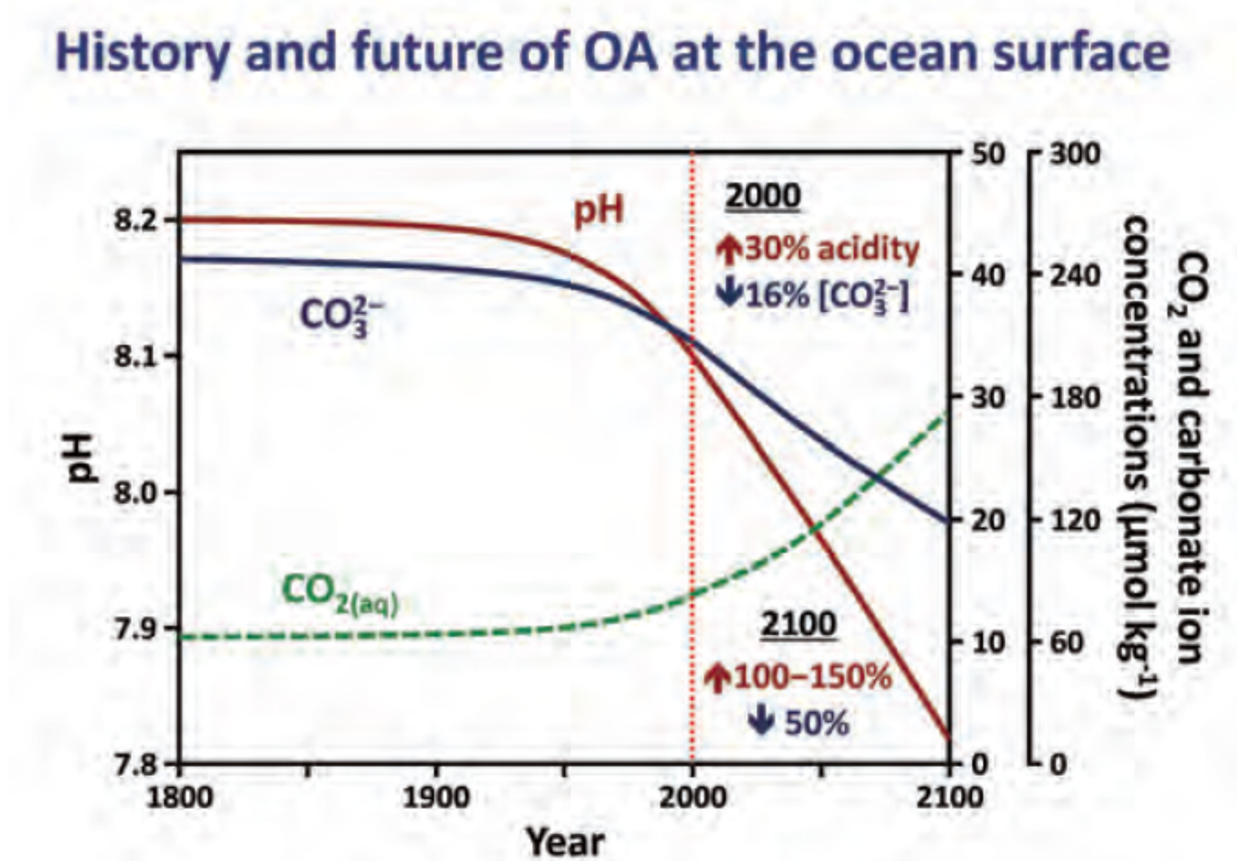
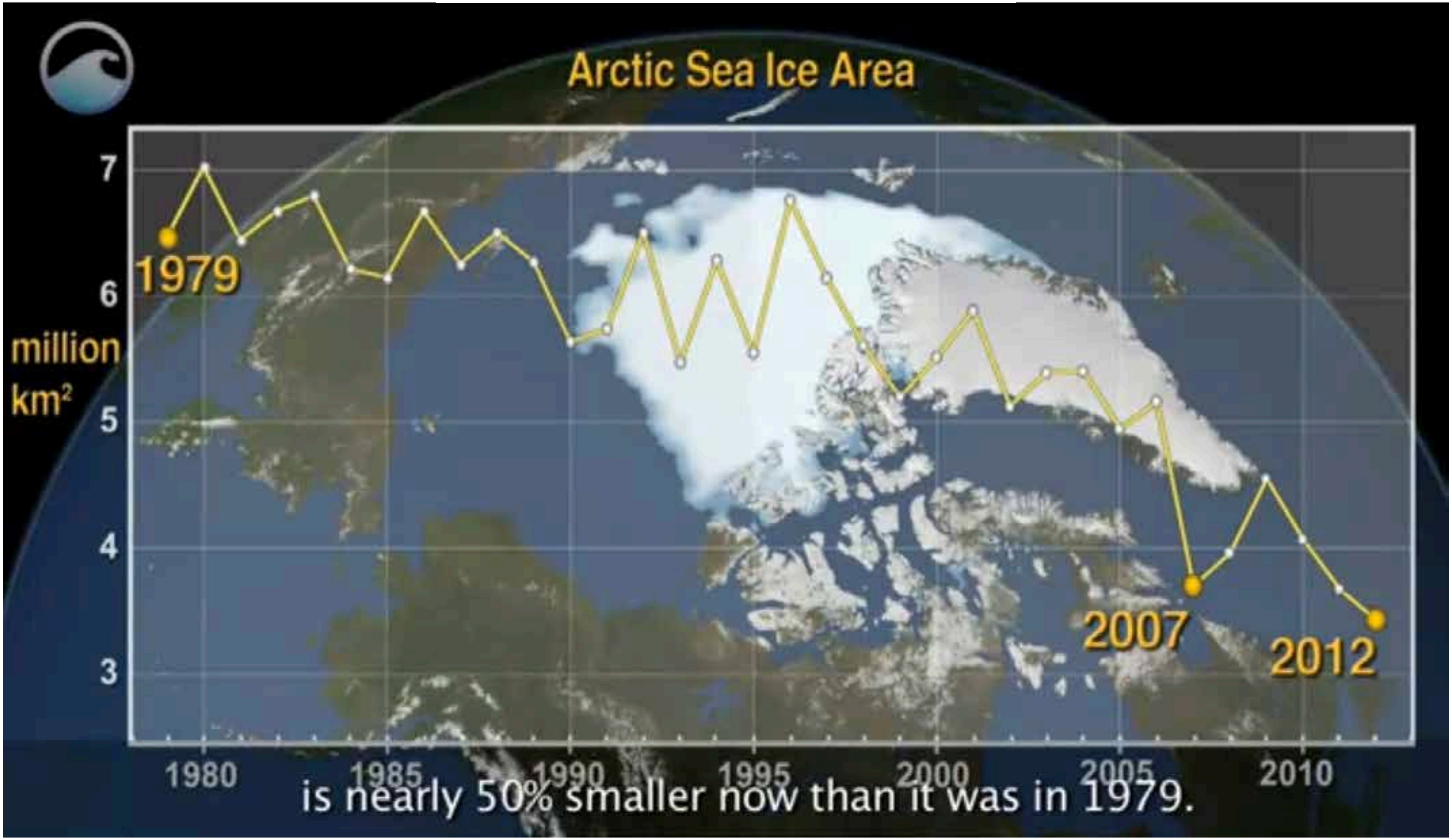


Figure 1.4 • Schematic diagram of the changes in pH, CO_3^{2-}, and $CO_{2(aqueous)}$ of the surface oceans under a high CO_2 emission scenario out to 2100 (after Wolf-Gladrow et al., 1999). The pH has declined by about 0.1 (equivalent to a hydrogen ion concentration increase of about 30%) since the beginning of the industrial era.

NOAA, State of Washington Report on Ocean Acidification, 2012

Arctic sea ice retreat

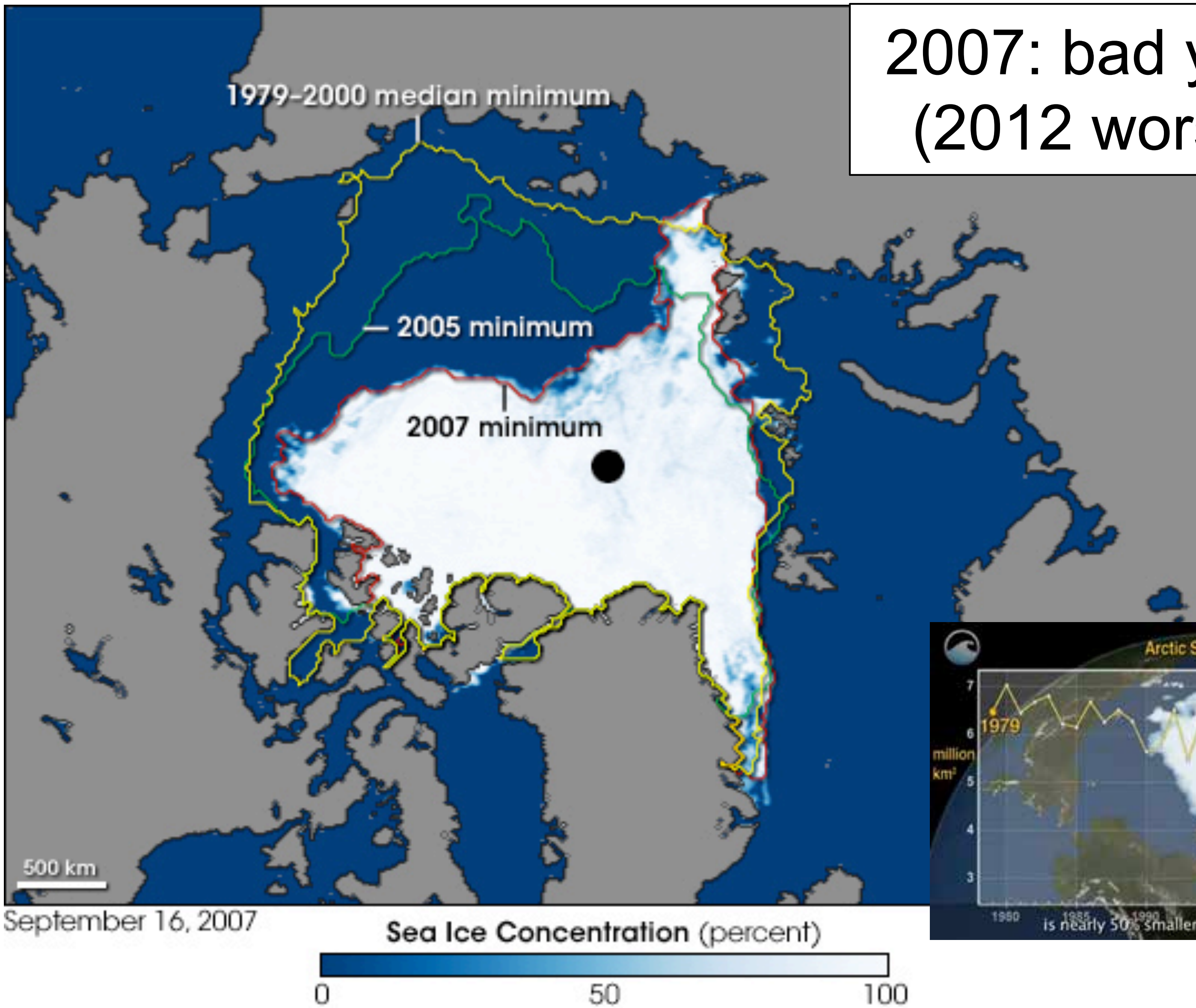
Extent in fall (minimum)

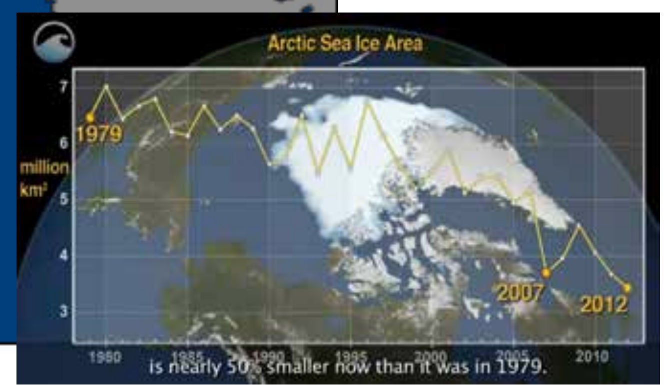


oceantoday.noaa.gov/welcome.html

Arctic sea ice retreat

2007: bad year
(2012 worse)

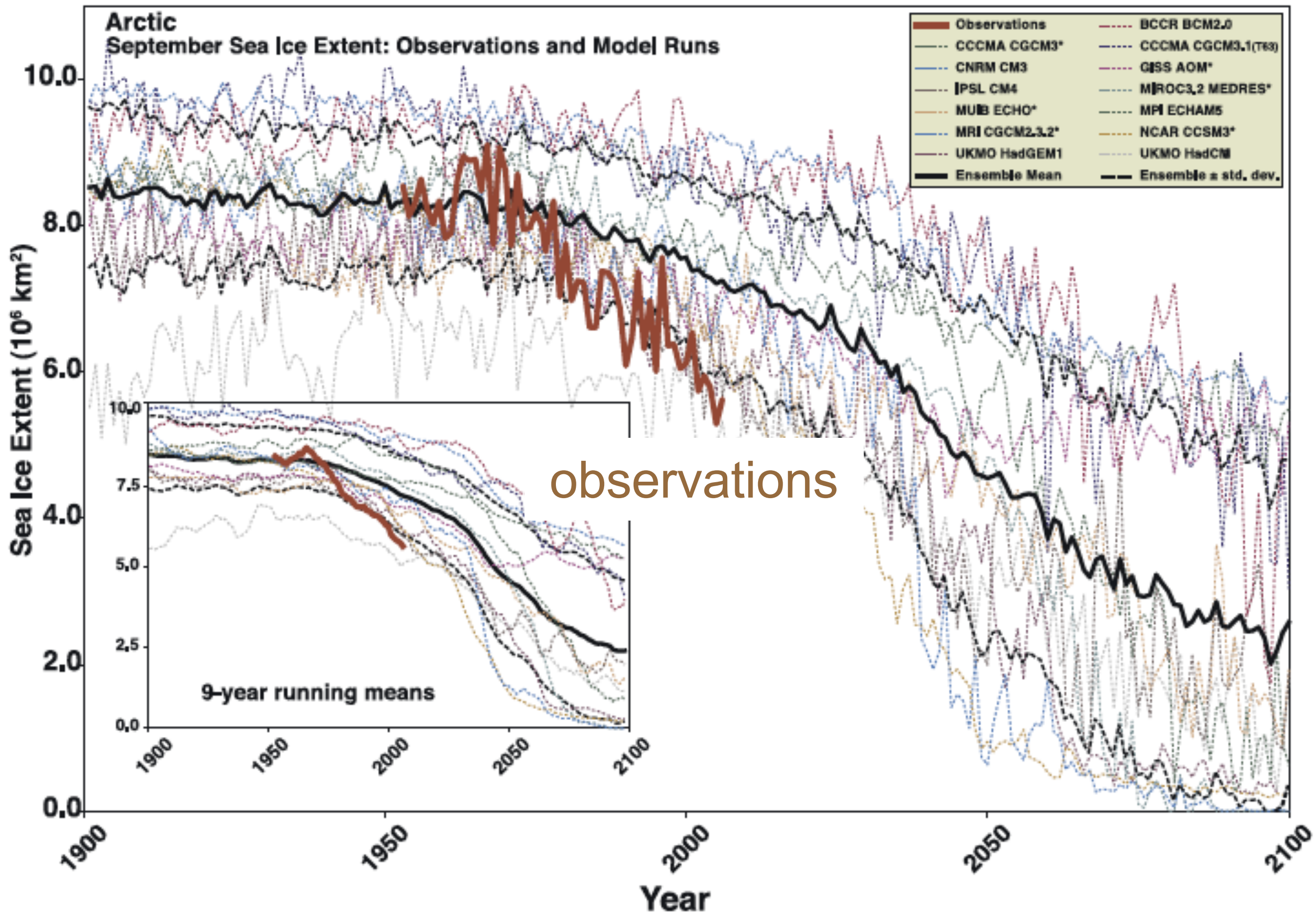




globalwarmingart.com

Arctic sea ice retreat

Models do not predict retreat as fast as observed (worrying)



multi-model mean

Figure 1. Arctic September sea ice extent ($\times 10^6$ km^2) from observations (thick red line) and 13 IPCC AR4 climate models, together with the multi-model ensemble mean (solid black line) and standard deviation (dotted black line). Models with more than one ensemble member are indicated with an asterisk. Inset shows 9-year running means.

Stroeve et al., GRL, 2007

Climate change effects on Antarctic food webs

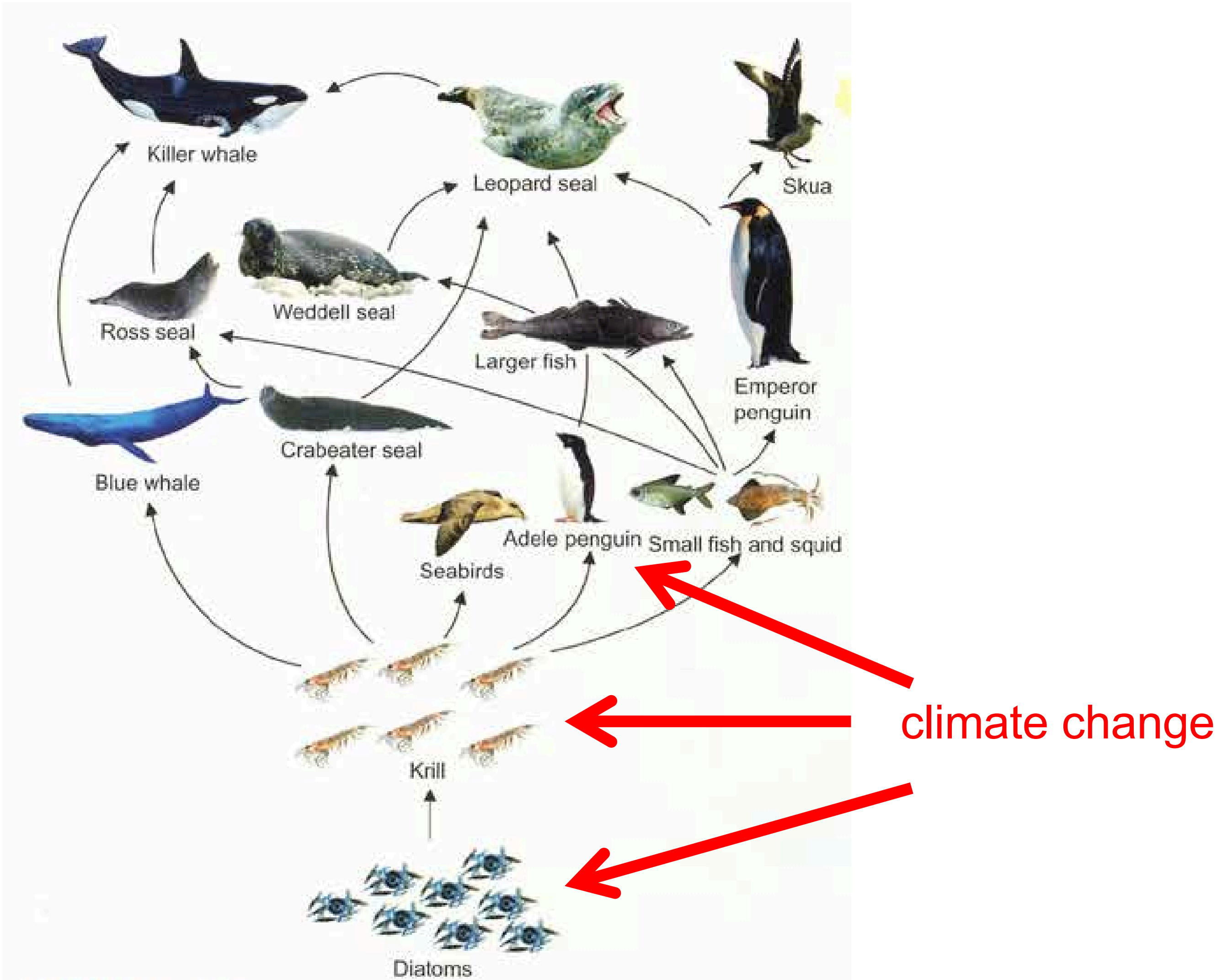


FIGURE 5.17 **Example of an Antarctic Food Web.**
Diatoms dependent on sea ice support a diverse food web, including great whales that feed directly on plankton and several food chains that have diatoms at their base.

Hannah, 2011