

A Global Overview of Drought and Heat-Induced Tree Mortality Reveals Emerging Climate Change Risks for Forests

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Also, I thank Rebecca Oertel, Andrew Goumas, Ángeles G. Mayor, and Megan Eberhardt Frank for literature review assistance; and Kay Beeley, Susana Bautista, and Jennifer Shoemaker for graphics support.

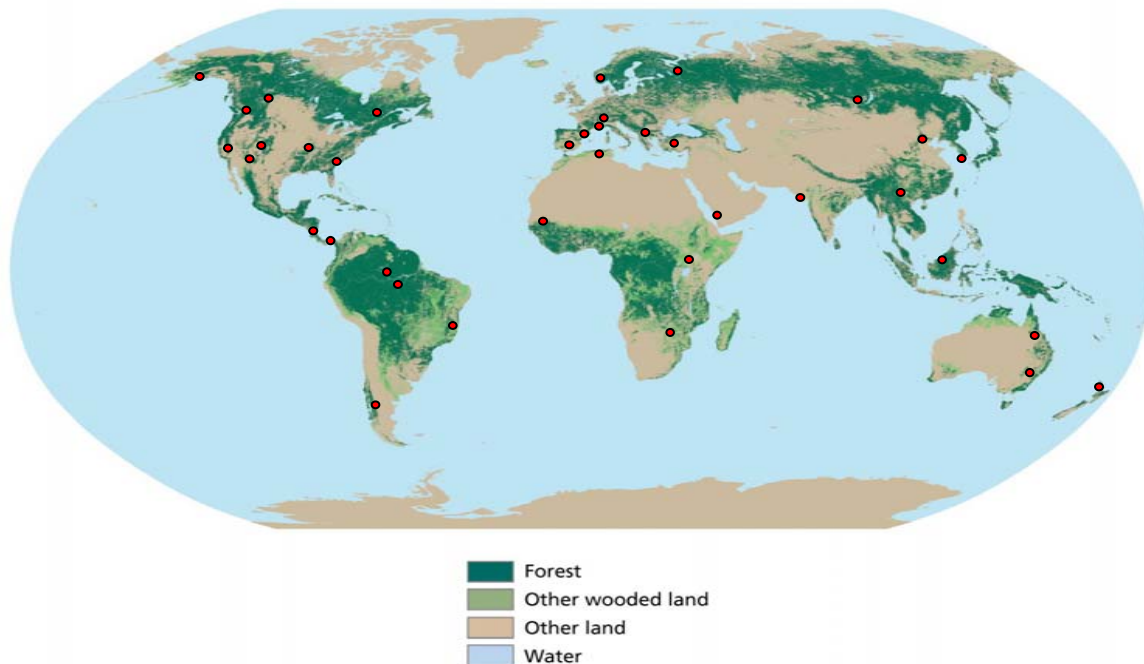
Support was provided by the U.S. Geological Survey, Biological Resources Discipline, Global Change Program, through the Western Mountain Initiative (WMI), a USGS research project.



This talk will:

- illustrate world-wide patterns of drought and heat-induced forest die-off, and “connect the dots” to reveal the potential for amplified tree mortality due to drought and heat in forests worldwide under climate change projections.

The world's forests



Allen 2009, Unasylva

© FAO 2006



Photo: CD Allen

Topics addressed:

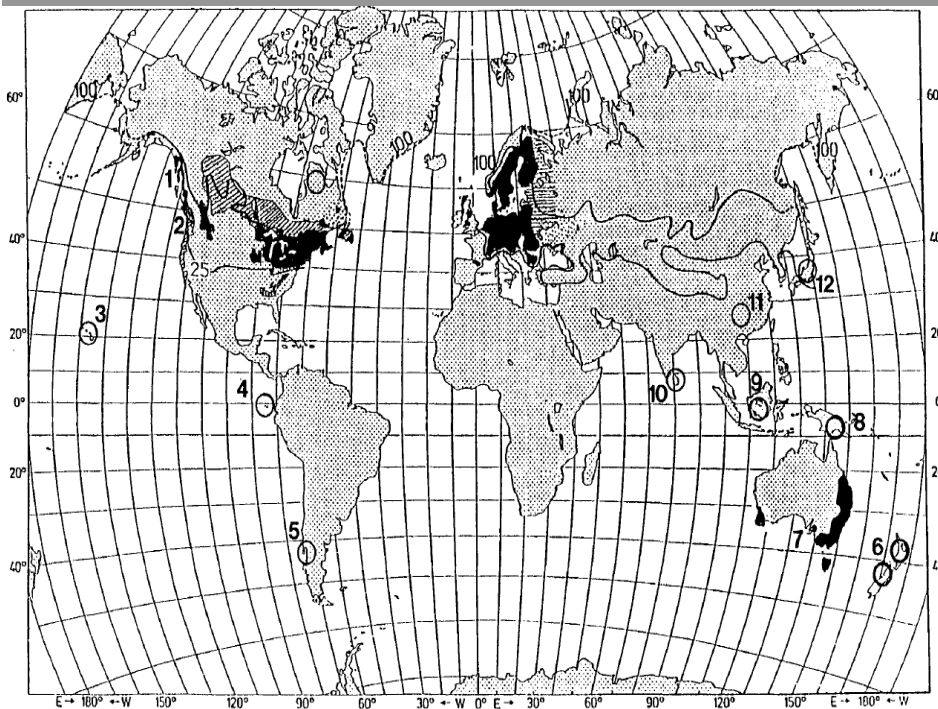
- Patterns of recent tree mortality and forest die-off in different continental regions.**
- Important processes involved in climate-induced forest mortality.**
- Key uncertainties and information gaps needed to more accurately project drought and heat-induced tree mortality.**

Forest decline and dieback have long been topics of global interest and concern, for example:

Decline and Dieback of Trees and Forests: A Global Overview.

1994. UN FAO Forestry Paper 120. W.M. Ciesla and E. Donaubauer. 90 pages.

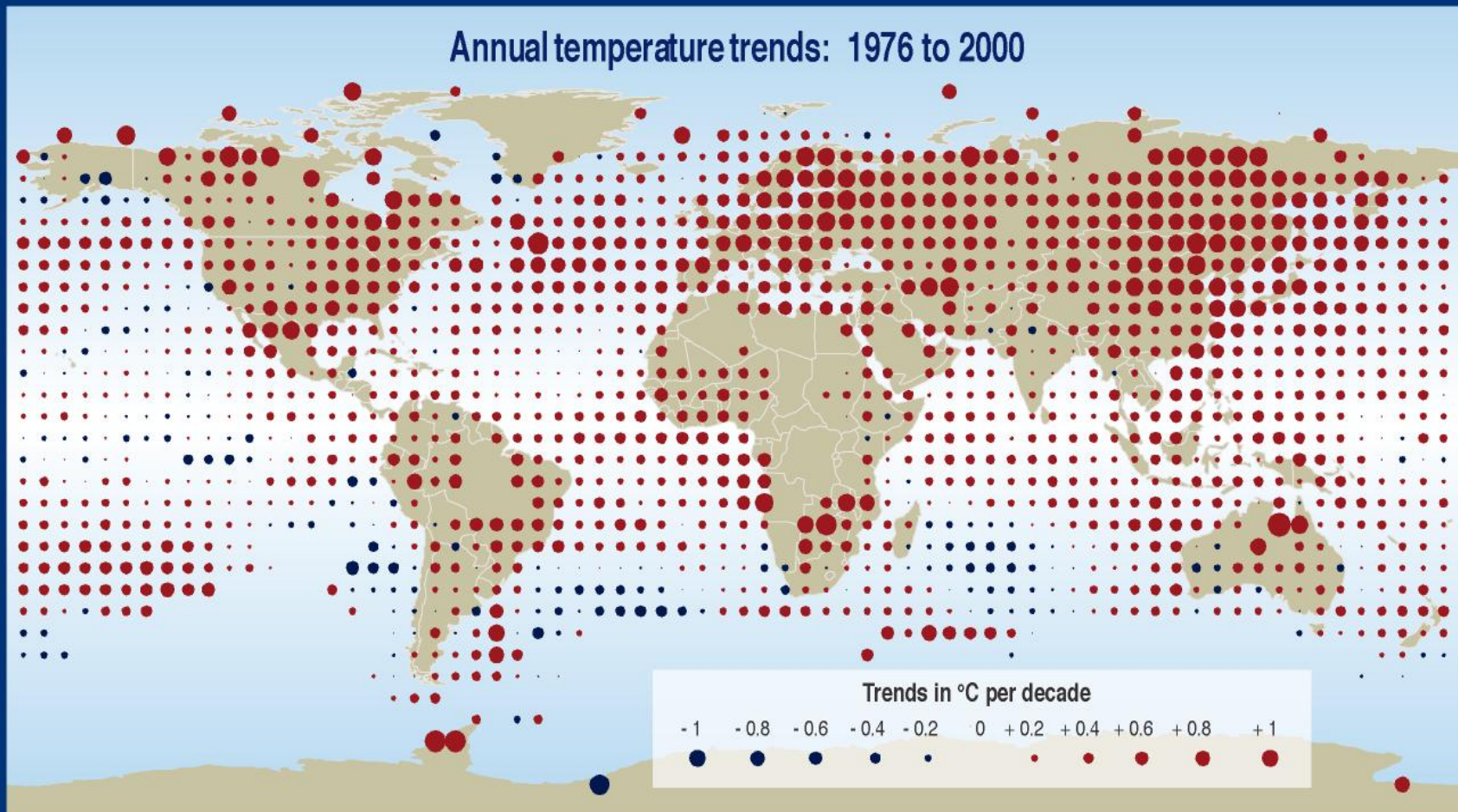
Extreme Climate Fluctuations as a Cause of Forest Dieback in the Pacific Rim. 1993. A. Auclair. *Water, Air, and Soil Pollut.* 66.



So is something new emerging re: forest dieback, related to ongoing global climate change?

Climate change trajectory – recent global warming observed

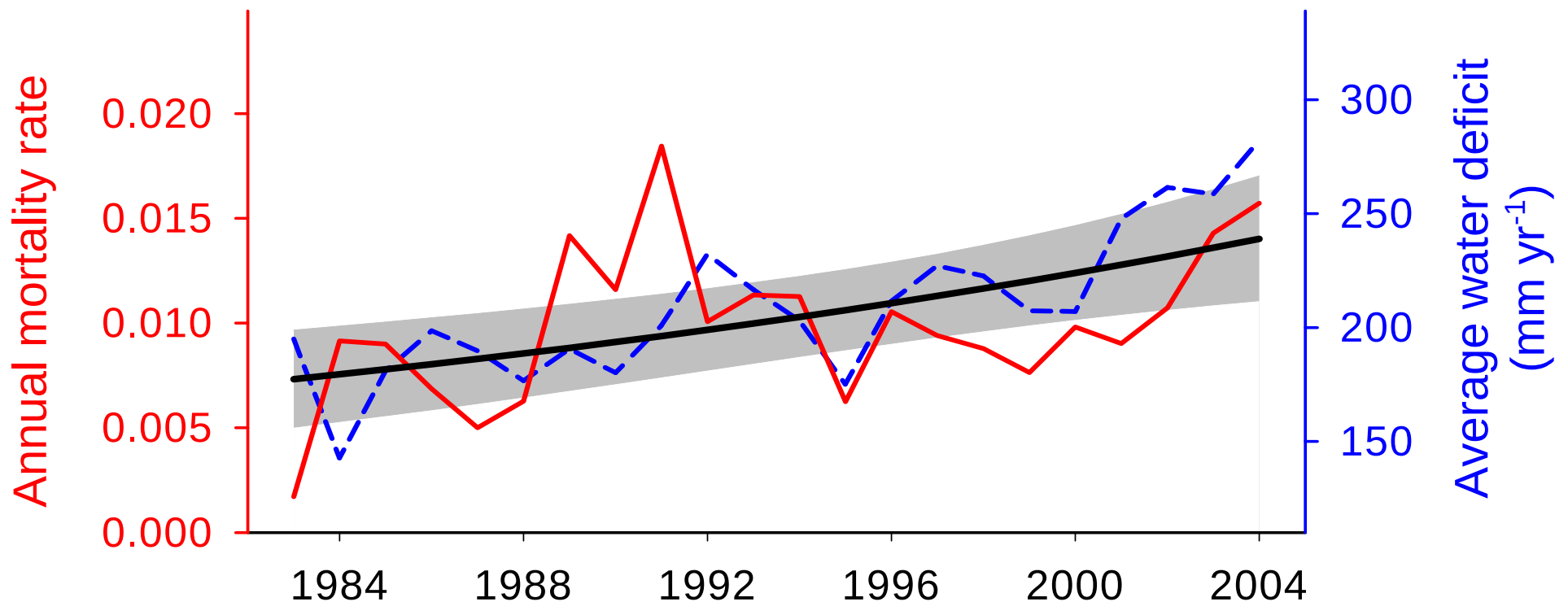
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SYR - FIGURE 2-6b

LETTER

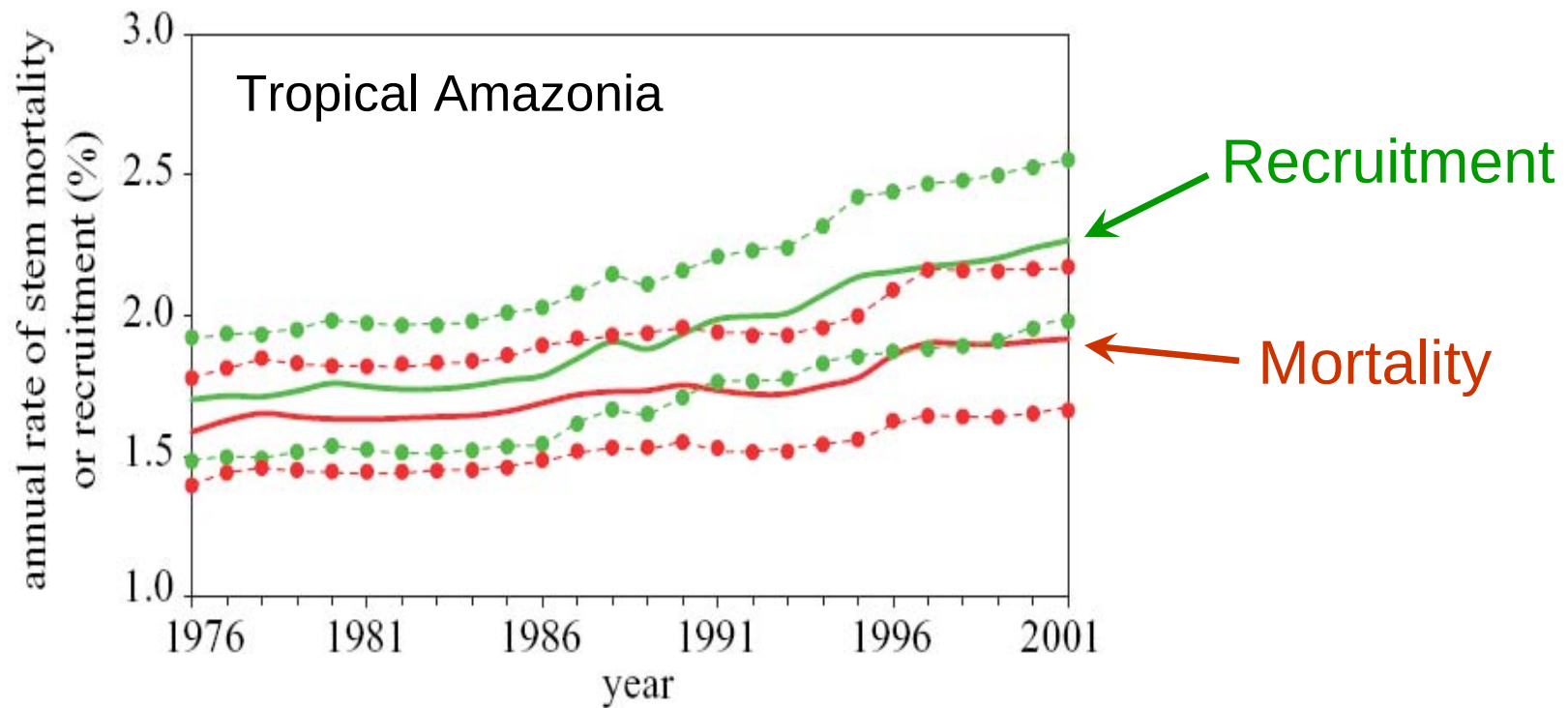
Apparent climatically induced increase of tree mortality rates in a temperate forest



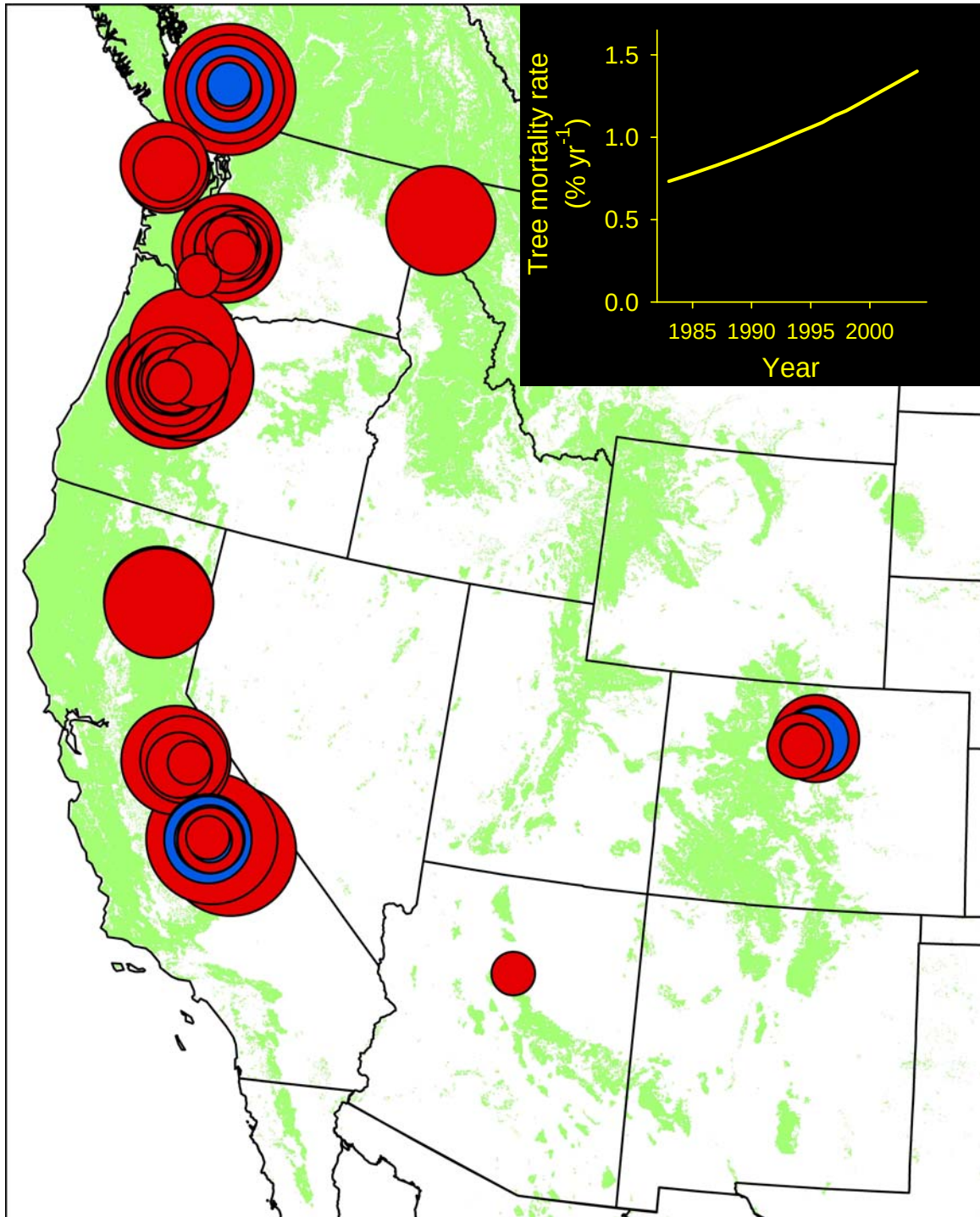
Background tree mortality rates in Sierra Nevada forests are increasing in parallel with temperature-driven increases in climatic water deficit (> 21,300 trees).

(van Mantgem and Stephenson, 2007, *Ecology Letters*)

Similar forest changes are in progress in
the **New World tropics**:



Phillips et al., *Phil. Trans. B*, 2004



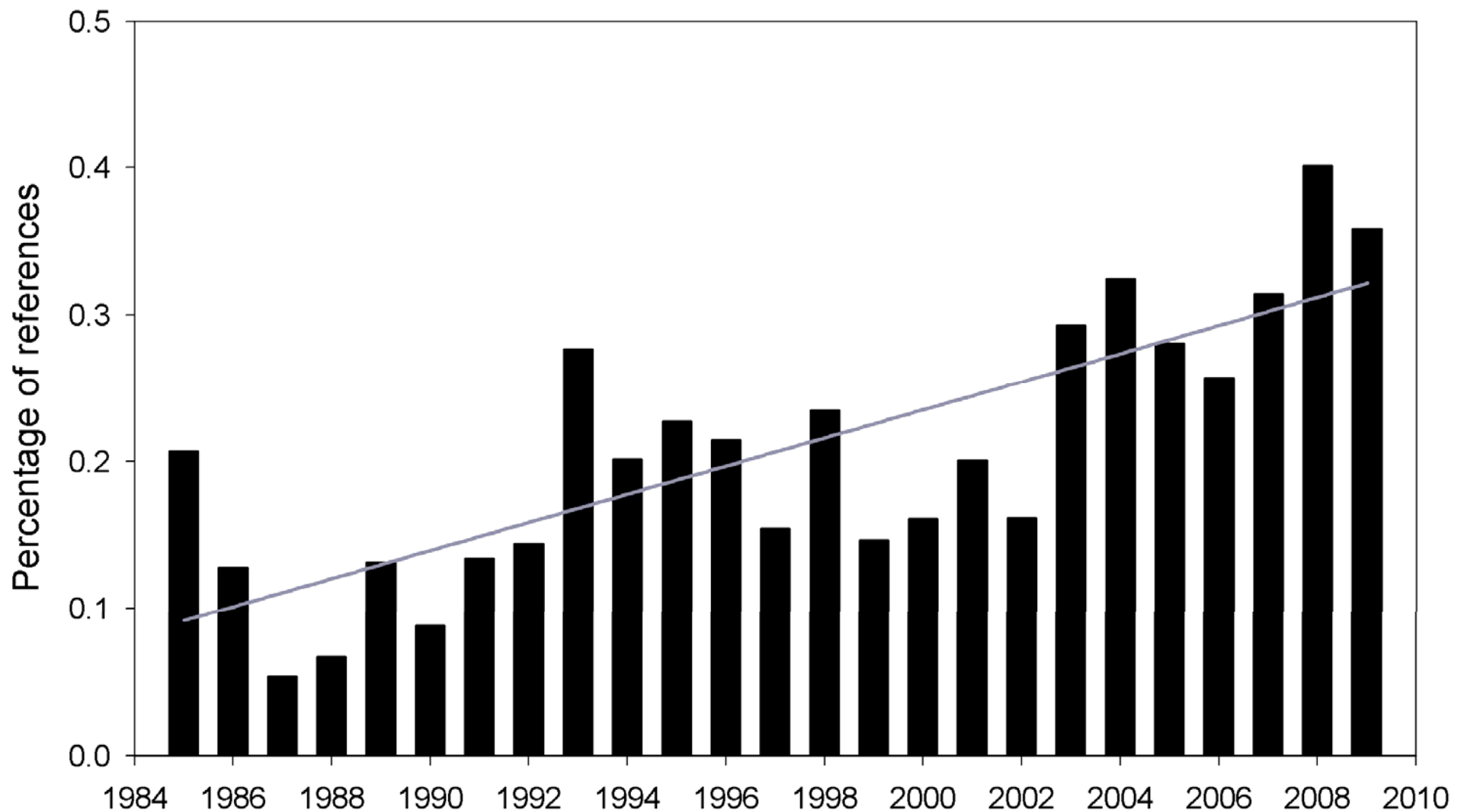
Background tree mortality rates have doubled since 1980 in western North America.

76 long-term forest plots.

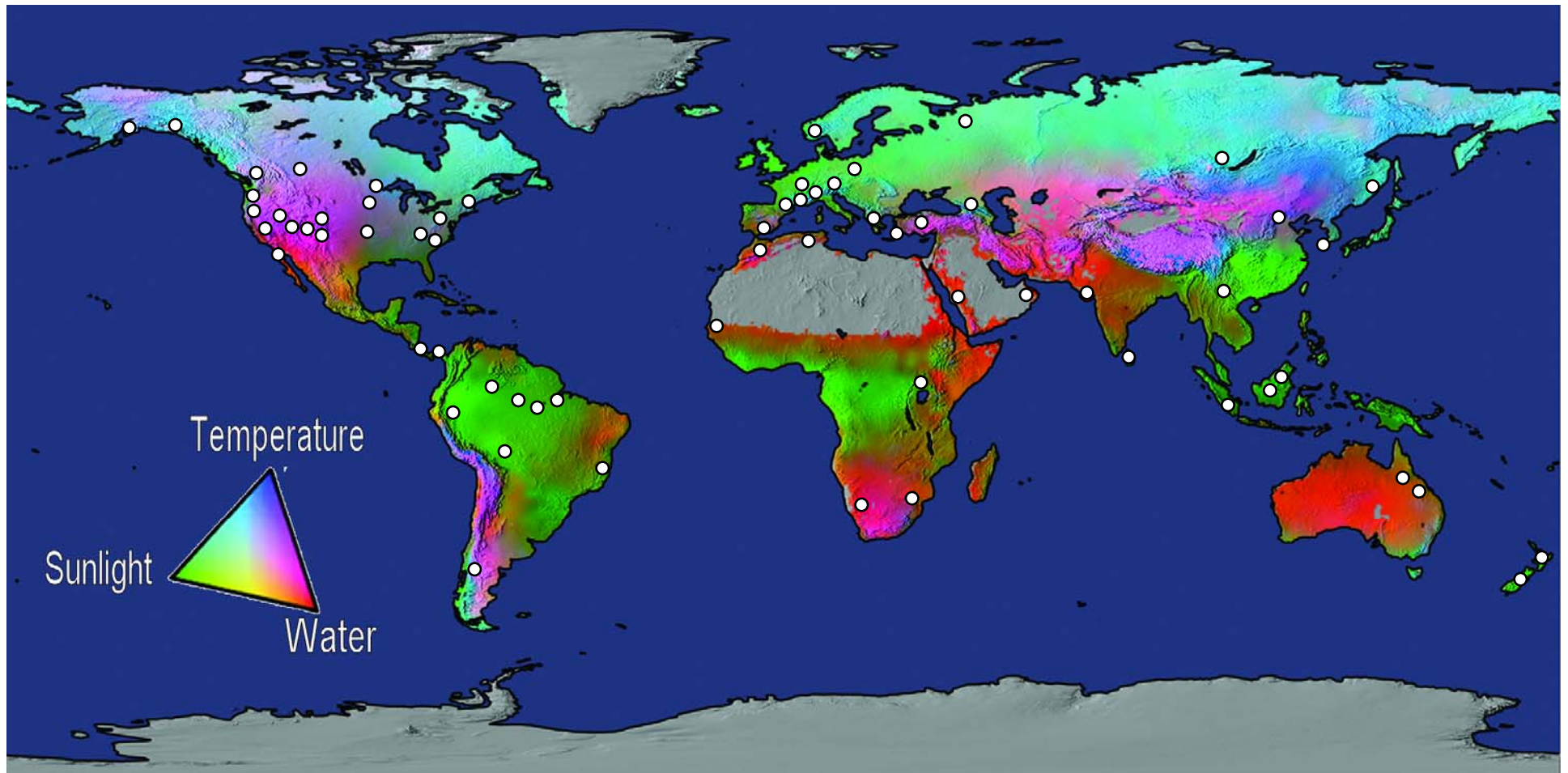
Red symbols
= increasing mortality rates;

blue dots
= decreasing mortality rates.

(van Mantgem et al., 2009, *Science*)



ISI Web of Science search of the trend in published reports of climate-related forest mortality in the scientific literature, for the years 1985–2009. Plotted bars show the percent of references using the topic words “forest AND mortality AND drought”, relative to all “forest” references. Line represents the linear regression model fitted to the data. (Allen et al., 2009)



White dots indicate documented localities with increased forest mortality related to climatic stress from drought and high temperatures.

Background: Potential limits to vegetation net primary production (Boisvenue and Running 2006).

Recent Examples of Documented Drought/Heat-Related Tree Mortality:

North America: Southwest: *Quercus gambelli*, *Juniperus deppeana*, *Juniperus monosperma*, *Pinus edulis*, *Pinus ponderosa*, *Pseudotsuga menziessi*, *Abies concolor*, *Pinus strobiformis*, *Abies lasiocarpa*, *Picea engelmanni*

Northern Rockies and British Columbia: *Pinus ponderosa*, *Pinus contorta*, *Picea engelmanni*, *Pinus albicaulis* Alaska: *Picea sitchensis*, other *Picea* sp.

Europe: Portugal, Spain, France, Italy, Greece; GDR, Switz.: multiple *Pinus* and *Quercus* sp., *Picea*, *Fagus*; Russia: *Picea*, *Pinus*

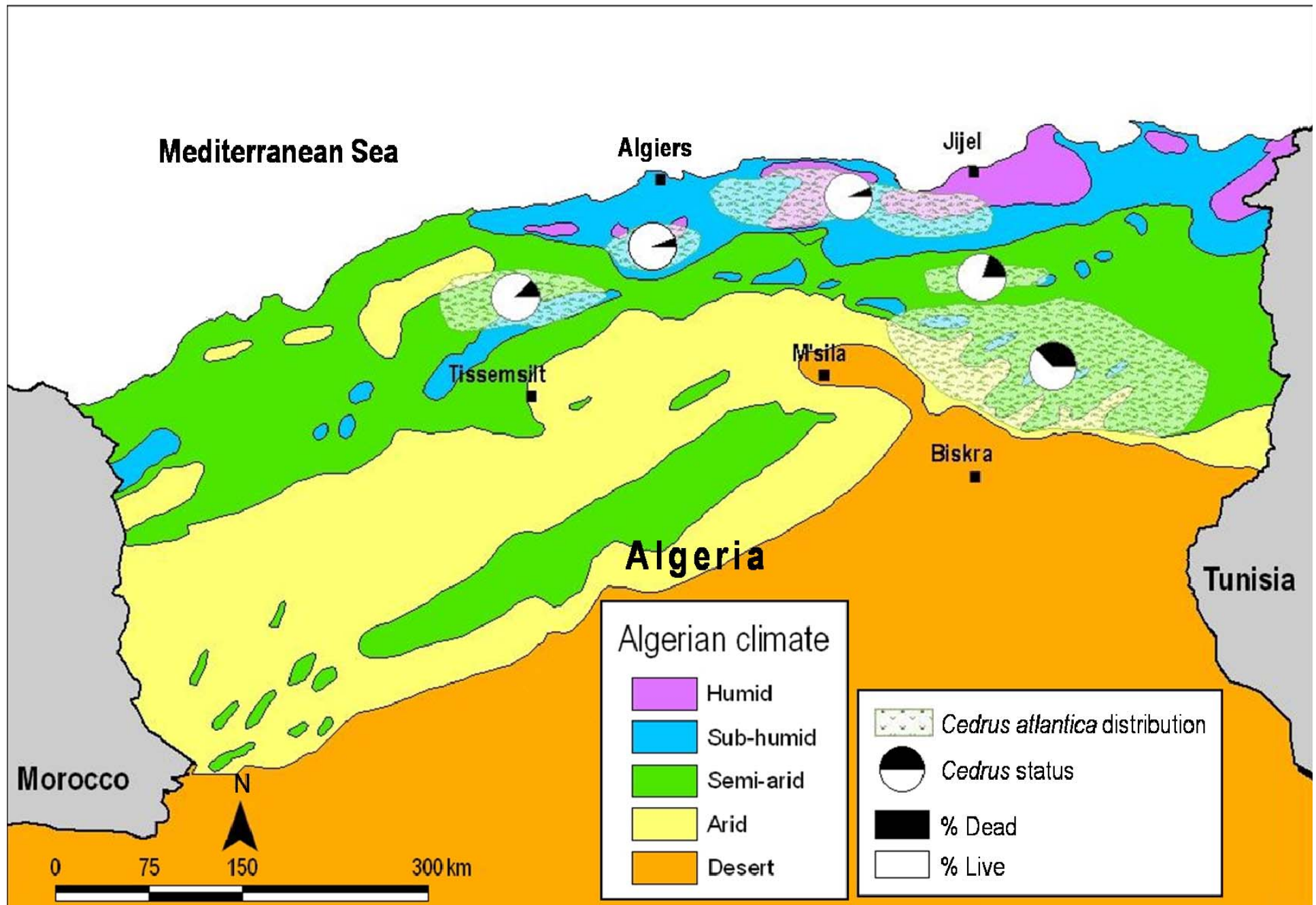
Asia: Borneo: dipterocarps; China: *Picea meyeri*, *Pinus* sp., N. Mongolia: *Pinus sylvestris*; Korea: *Abies koreana*; Turkey: *Pinus*, *Abies*, *Juniperus*; Russia: *Picea*, *Pinus*

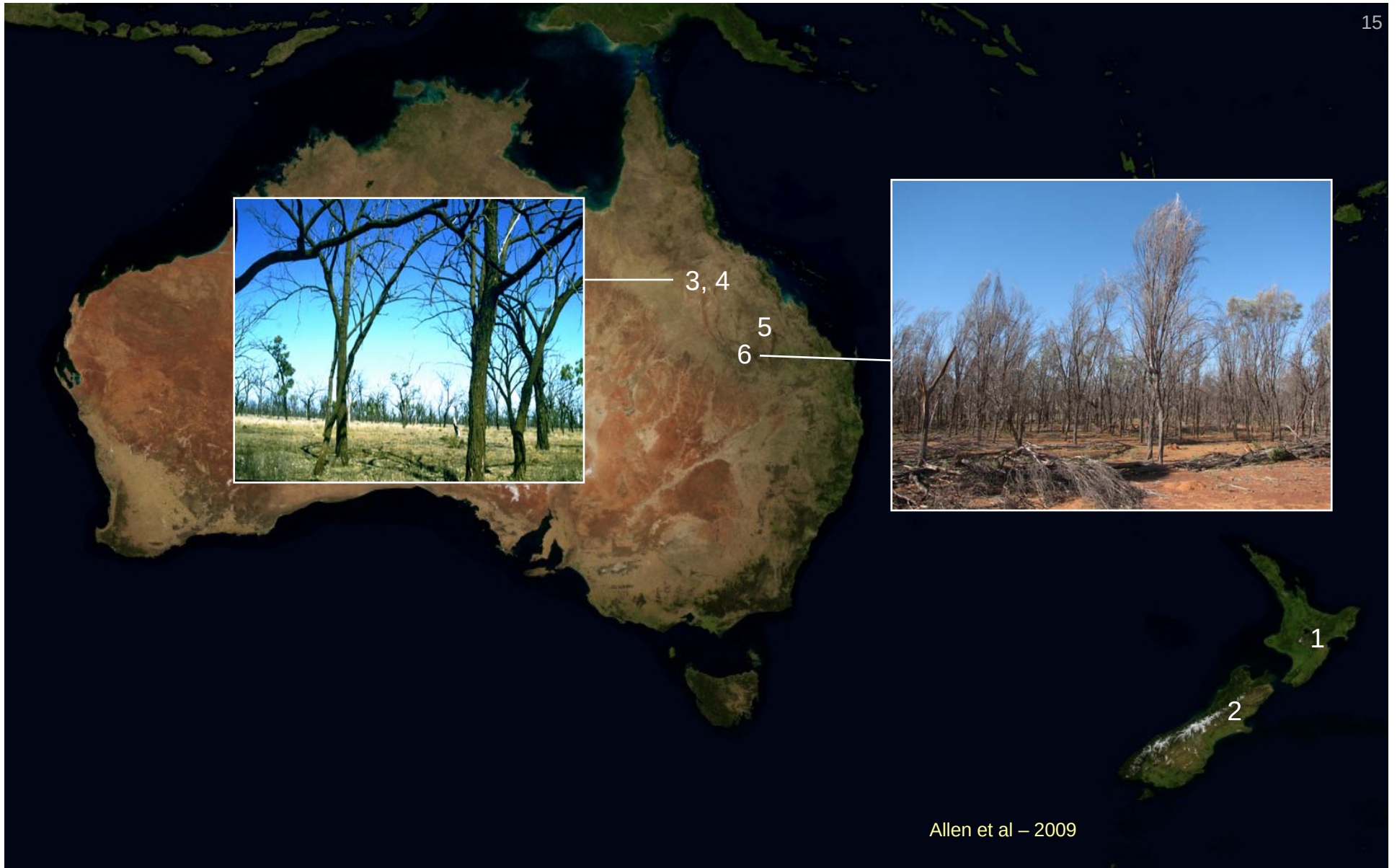
South America: Northern Patagonia (Argentina): *Nothofagus*, *Austrocedrus*
Amazon Basin: widespread mortality from 2005 drought, many spp.

Africa: West African Sahel: dieback of multiple forest sp., including *Prosopis africana*, *Boscia senegalensis*; Uganda: *Uvariopsis* and *Celtis* spp.; Namibia: *Aloe dichotoma*; Zimbabwe; Algeria, Morocco: *Cedrus atlantica*; South Africa: many spp.

Australasia: Queensland, New South Wales: multiple *Eucalypt* spp., *Acacia*.;
New Zealand: *Nothofagus*

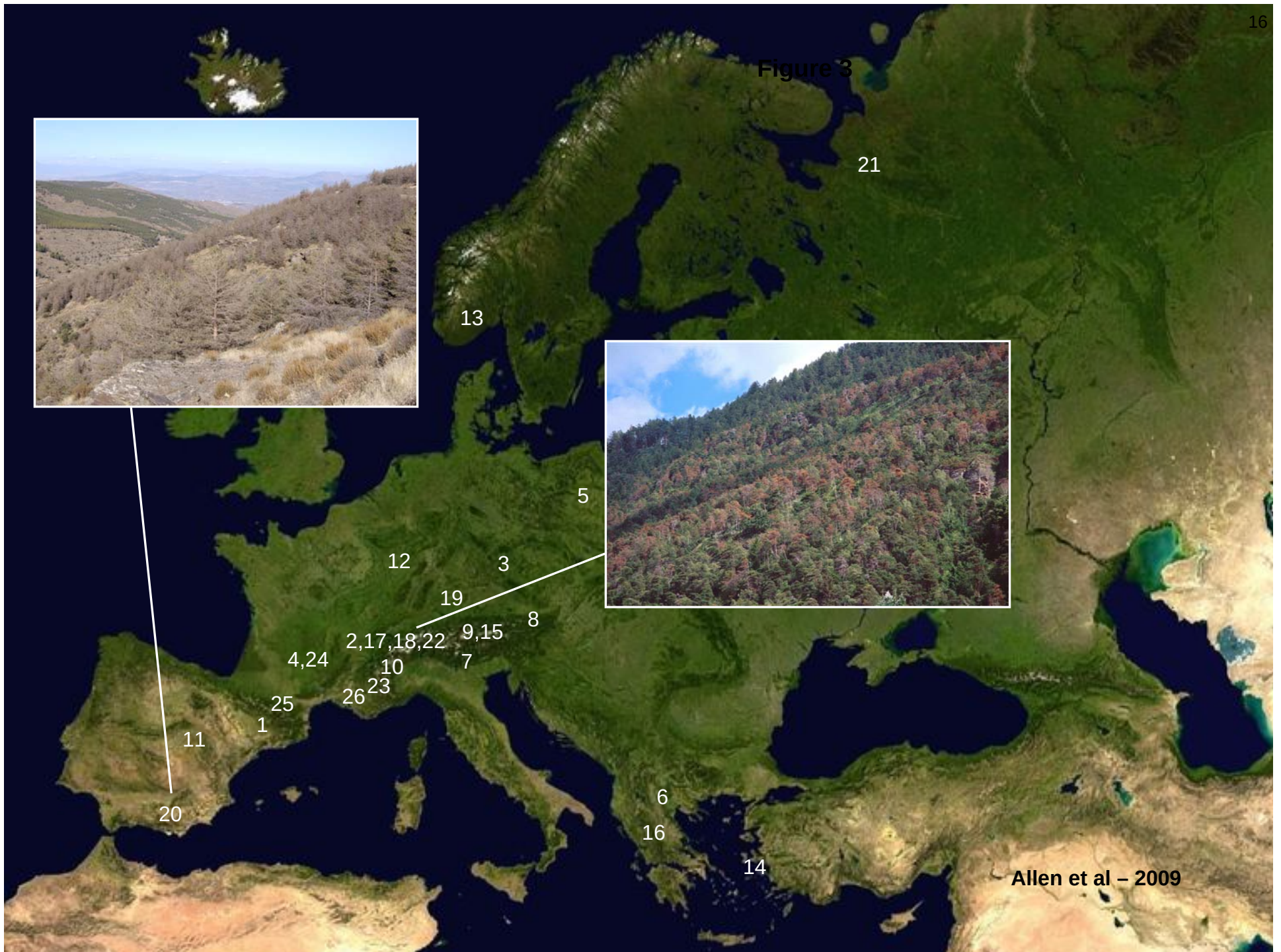


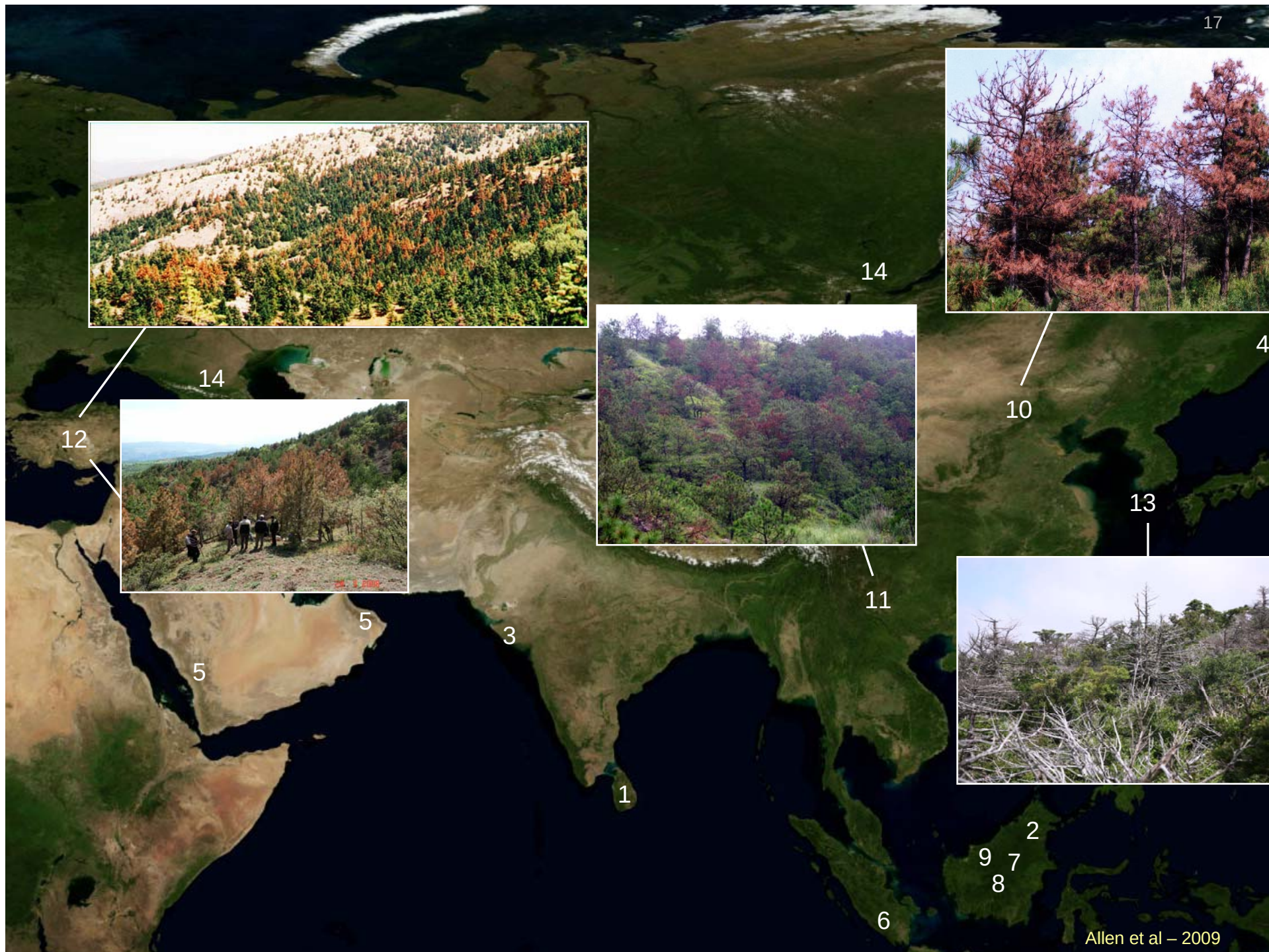




Allen et al – 2009

Figure 3







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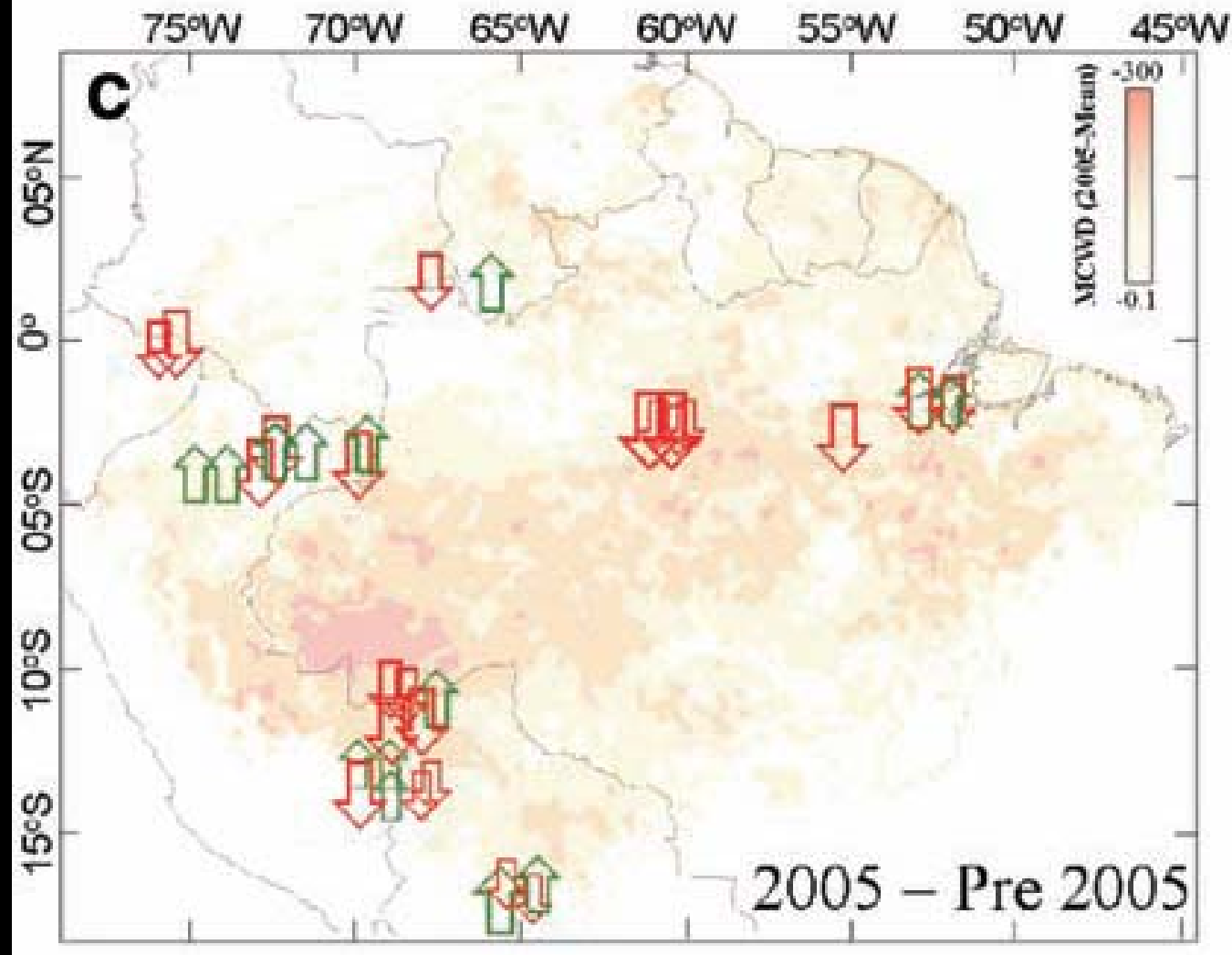
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Allen et al – 2009



Amazon Basin, difference in rates of change in aboveground biomass, 2005 versus pre-2005, for those plots monitored throughout. Colored shading in (C) indicates the intensity of the 2005 drought relative to the 1998–2004 mean as measured from space using radar-derived rainfall data.

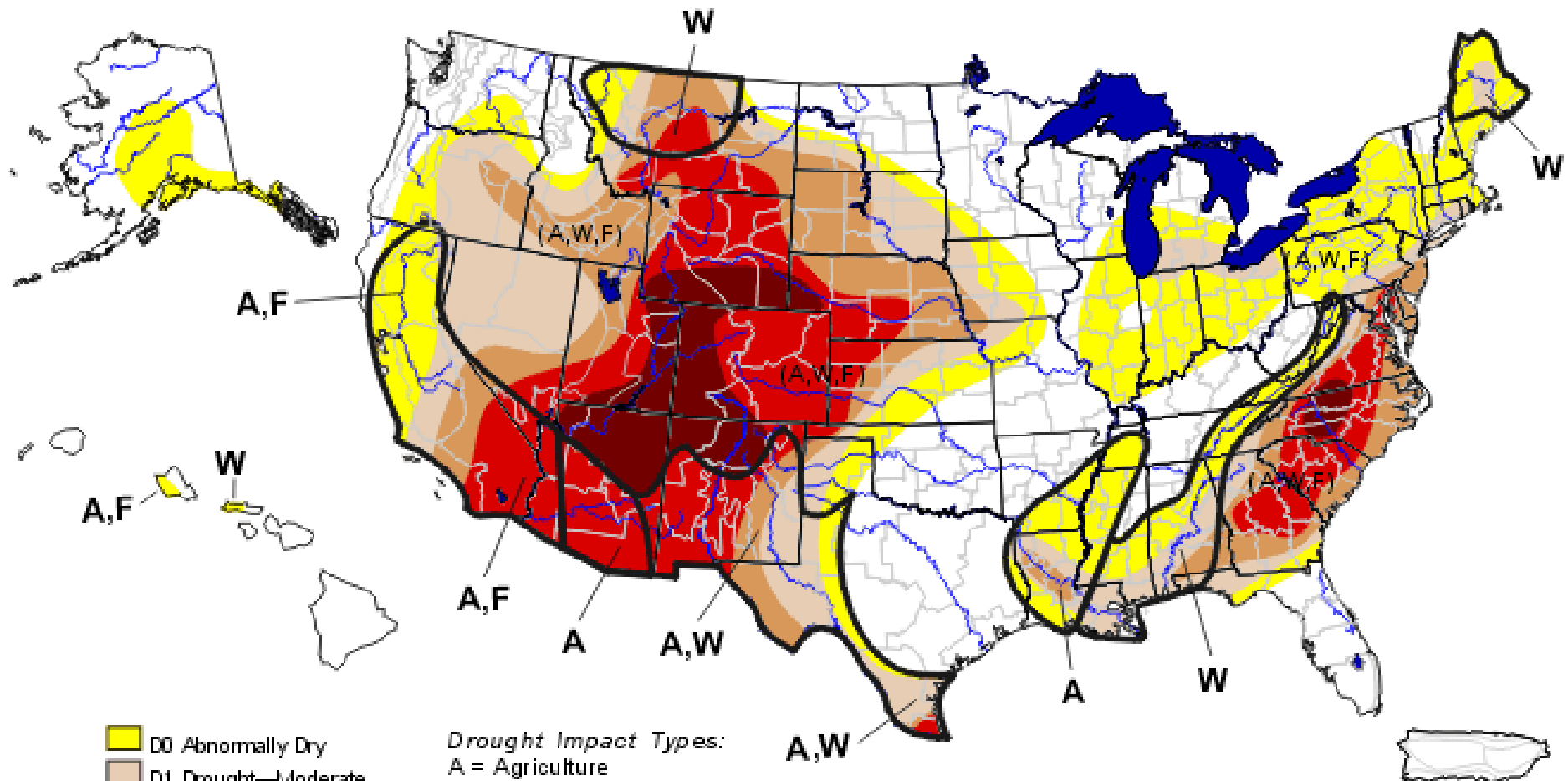
Phillips et al. 2009 – “Drought Sensitivity of the Amazon Rainforest”.



U.S. Drought Monitor

July 23, 2002

Valid 8 a.m. EDT



- D0 Abnormally Dry
- D1 Drought—Moderate
- D2 Drought—Severe
- D3 Drought—Extreme
- D4 Drought—Exceptional

Drought Impact Types:
 A = Agriculture
 W = Water (Hydrological)
 F = Fire danger (Wildfires)
 — Delineates dominant impacts
 (No type = All 3 impacts)

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

<http://drought.unl.edu/dm>

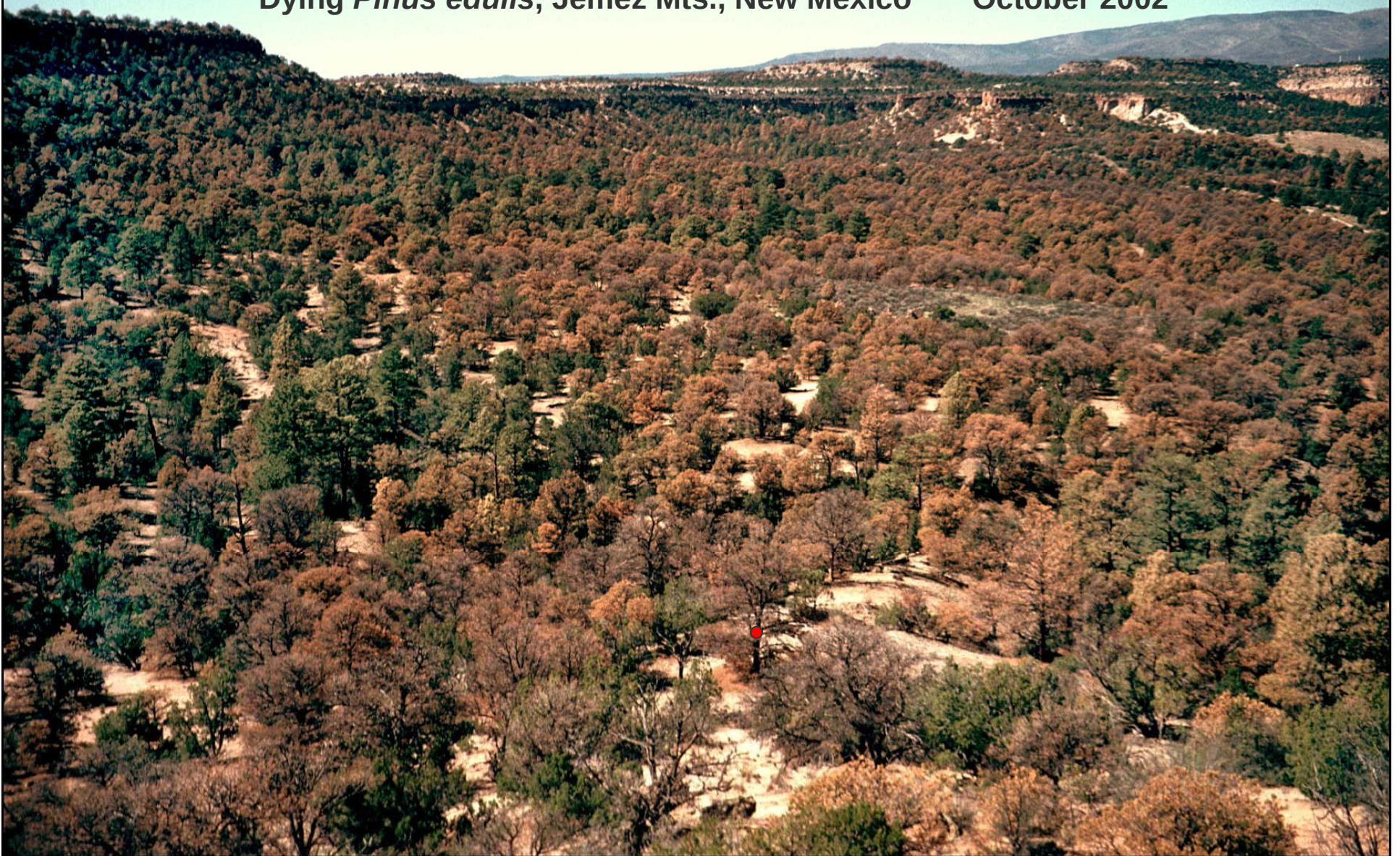


Released Thursday, July 25, 2002

Author: Brad Rippey, USDA

Dying *Pinus edulis*, Jemez Mts., New Mexico

October 2002



Trees are long-lived dominants, once established they have lots of inertia, tend to tolerate environmental stress and persist. So forests often are thought of as slow-changing, gradually adjusting to new climate conditions through competition and establishment.

Photo: CD Allen

Pinus skeletons, conversion to juniper woodlands, Jemez Mts.

May 2004



But, once thresholds of environmental stress are exceeded, rapid changes can occur through extensive forest die-off.

Photo: CD Allen

Dead *Pinus edulis*, Jemez Mts., New Mexico July 2004

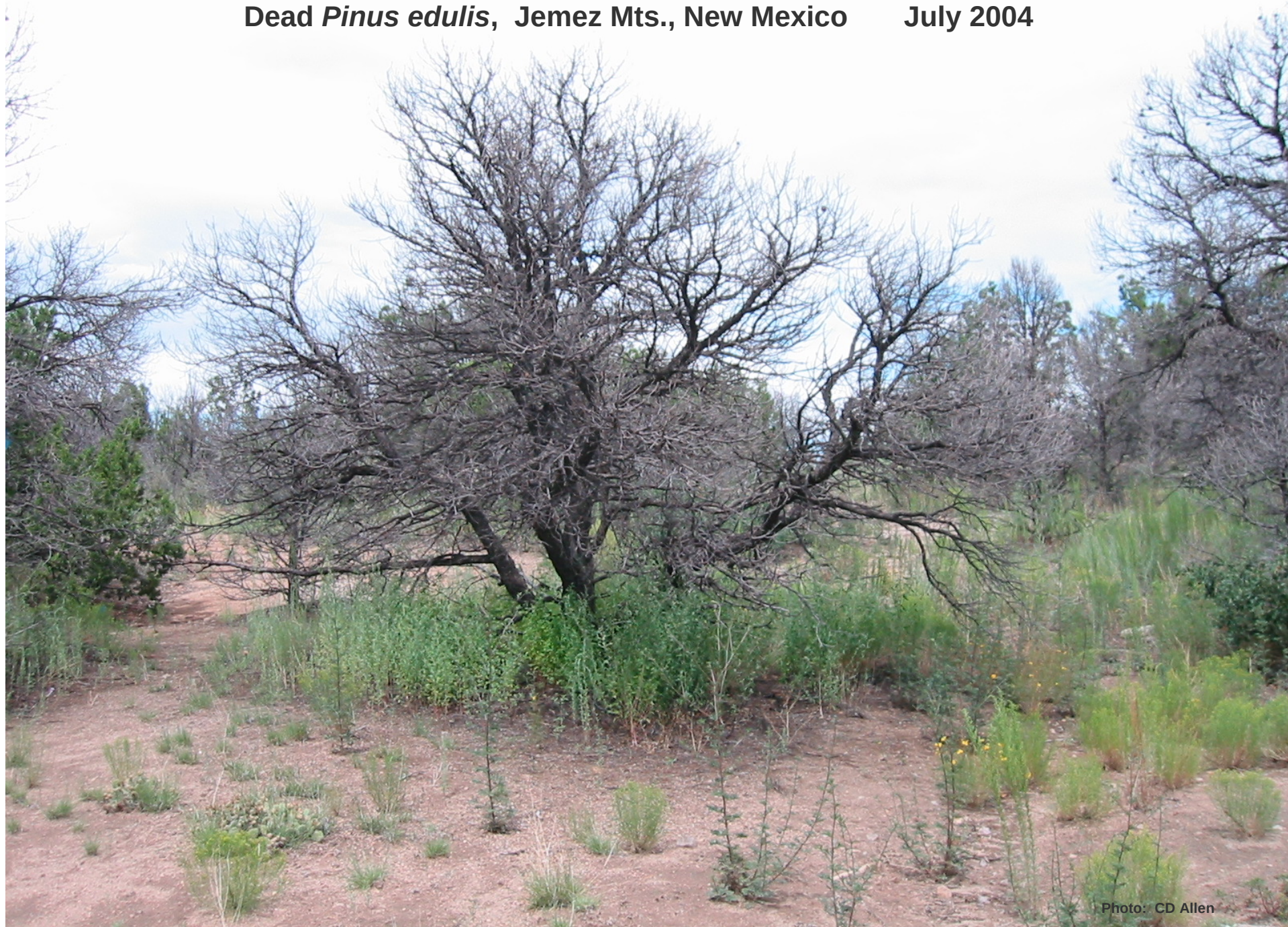
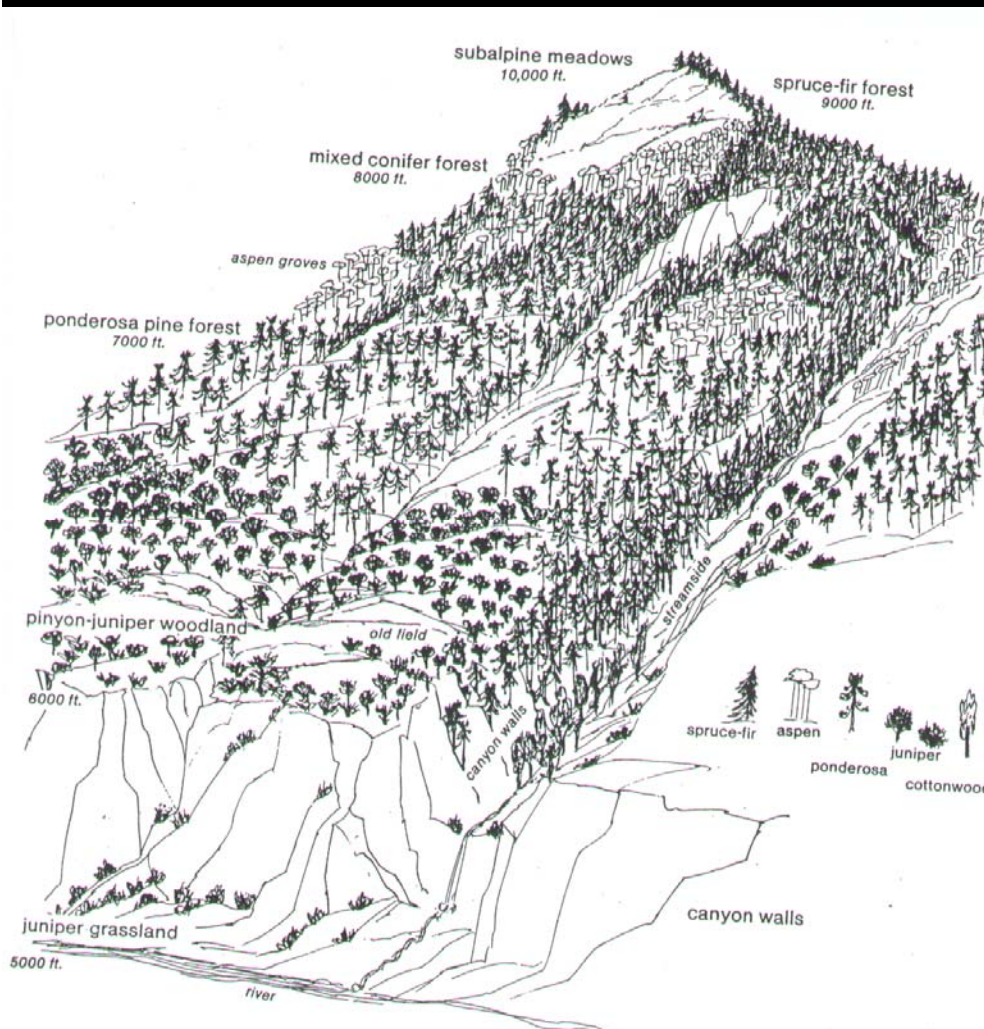


Photo: CD Allen

Substantial mortality of many tree, shrub, and grass species occurred across montane elevational gradients in the Southwest from 2002-2005.

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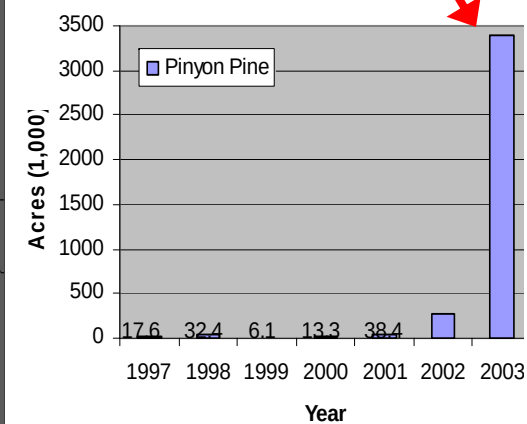
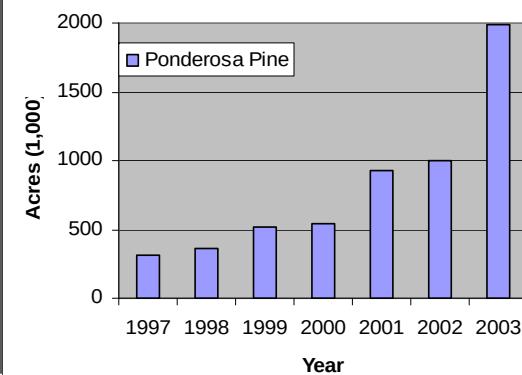


Photos: CD Allen

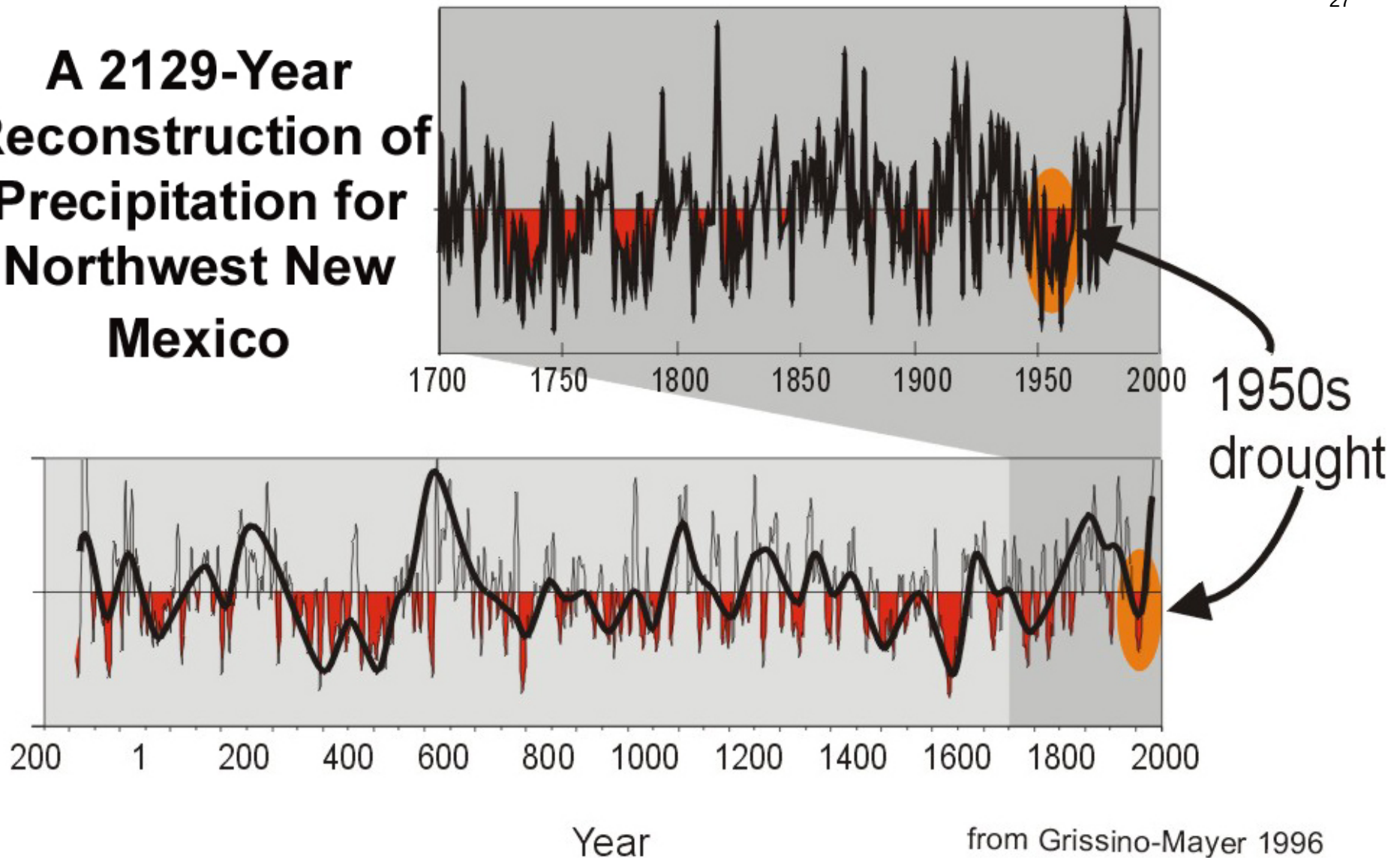
2000-2003 Mortality

■ Pinyon pine
■ Ponderosa pine

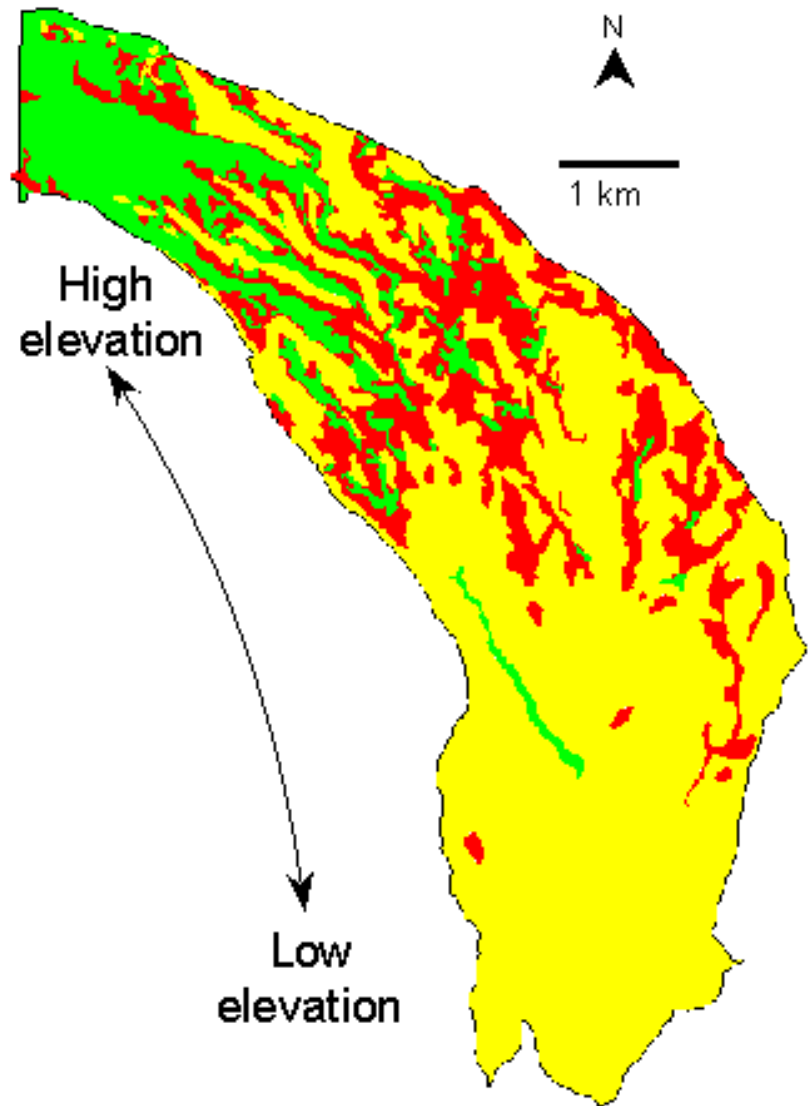
USFS aerial surveys for insect and disease, cumulative map of affected areas in Southwest US for 2000-2003.



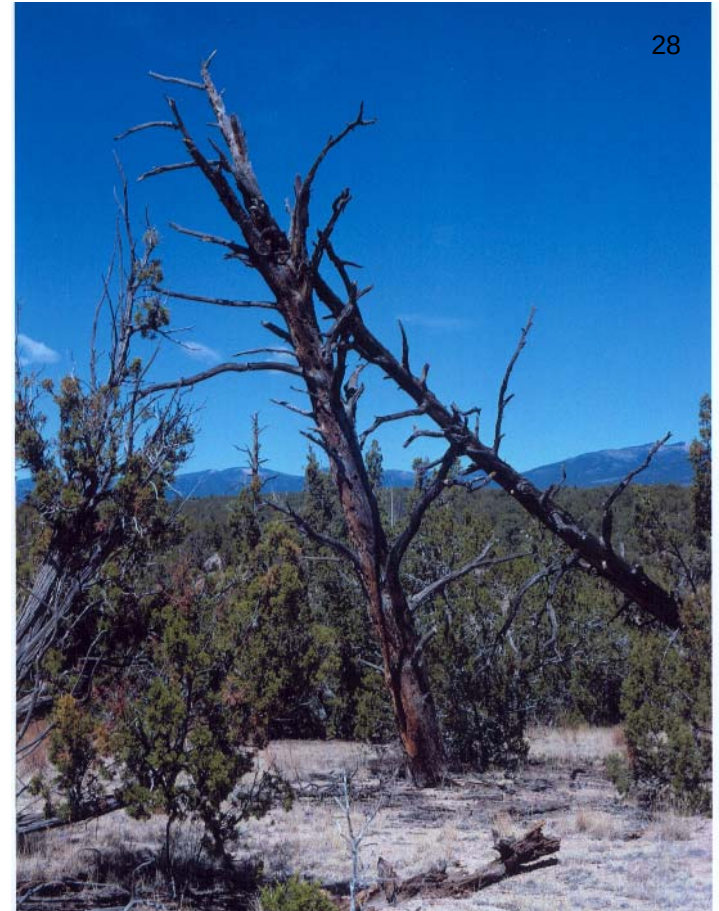
A 2129-Year Reconstruction of Precipitation for Northwest New Mexico



Tree-ring reconstructions clearly show how climate-driven drought is part of natural background. Red indicates periods of drought.



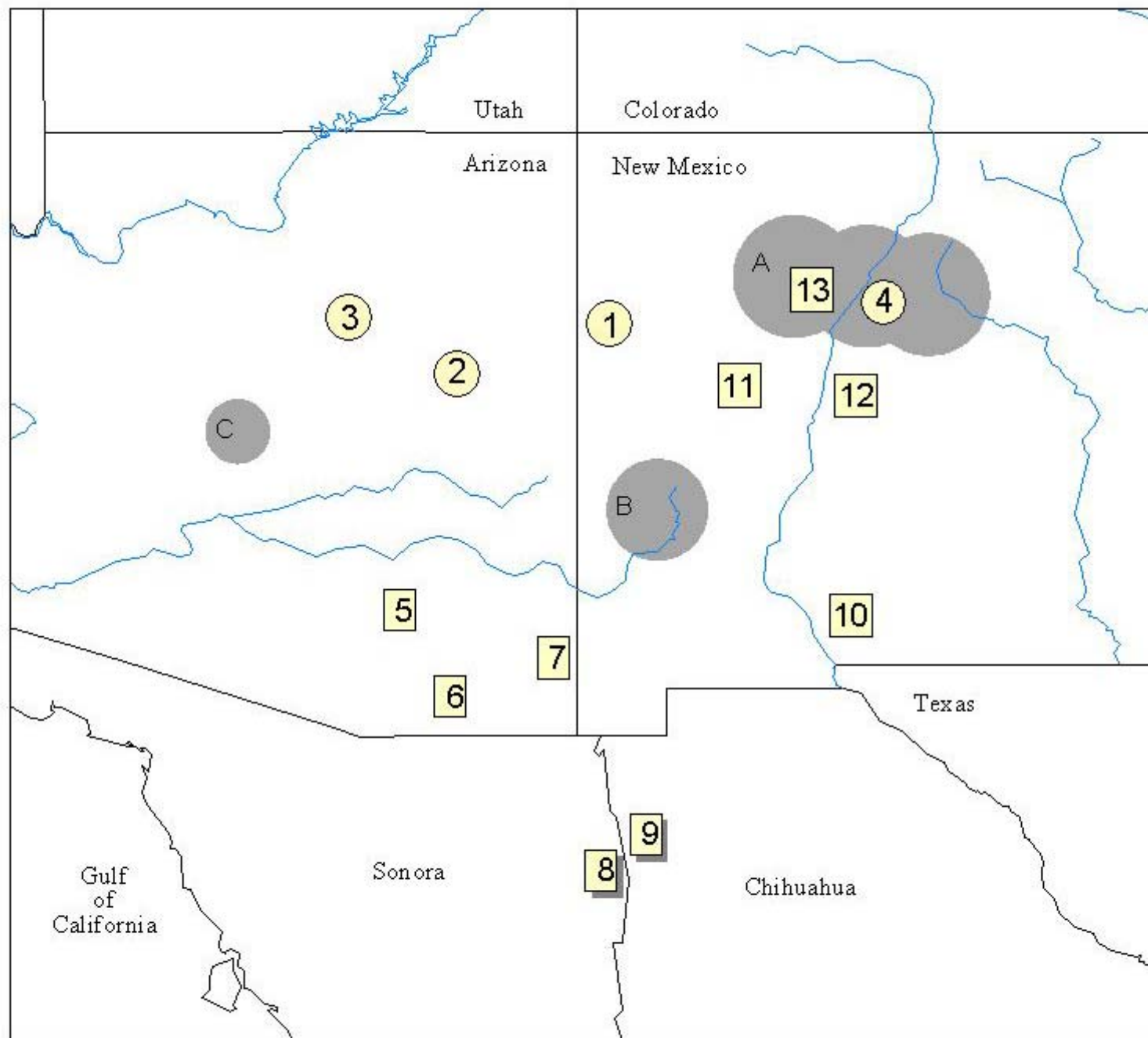
- Ponderosa pine forest
- Ecotone shift
- Piñon-juniper woodland



Allen and Breshears 1998, PNAS

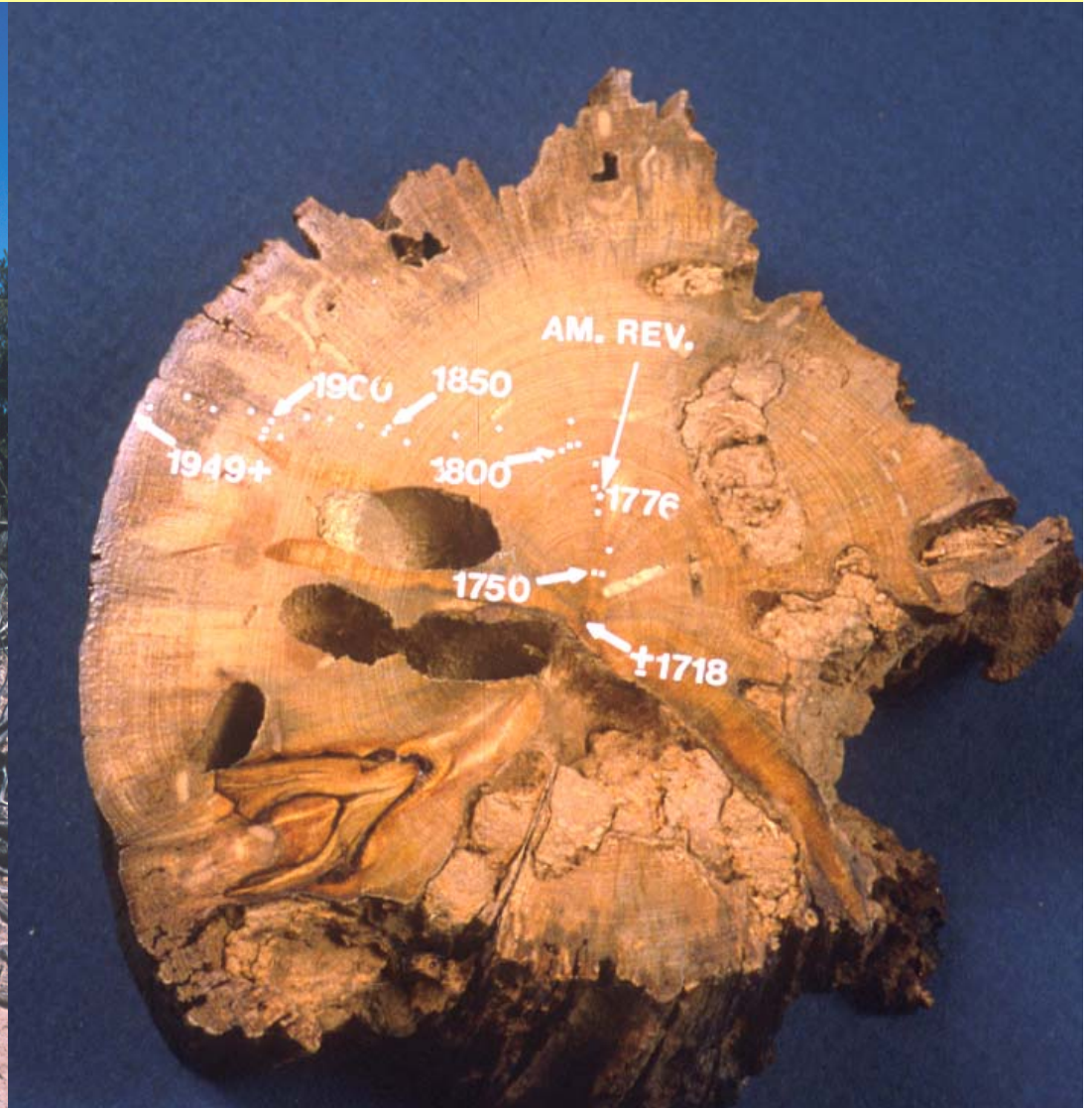
Evidence of 1950s dieback:

- remnant dead wood
- air photos
- documents



**Southwest
US and
Mexico
sites with
documentary
evidence of
substantial
forest
mortality
during the
1950s
drought.**

In 2001 we established two permanent plots, each 0.1 ha, and sampled and dated all live and dead pinyon. Most pinyon survived the 1950s drought.



Source: Tom Swetnam.



Jemez Mts. near Los Alamos, October 2002

Photo: CD Allen

Regional vegetation dieback: average 2002-2004 difference
from 1989-1999 base map

NDVI “green-ness”

Deviations from normal



Breshears et al. 2005, PNAS

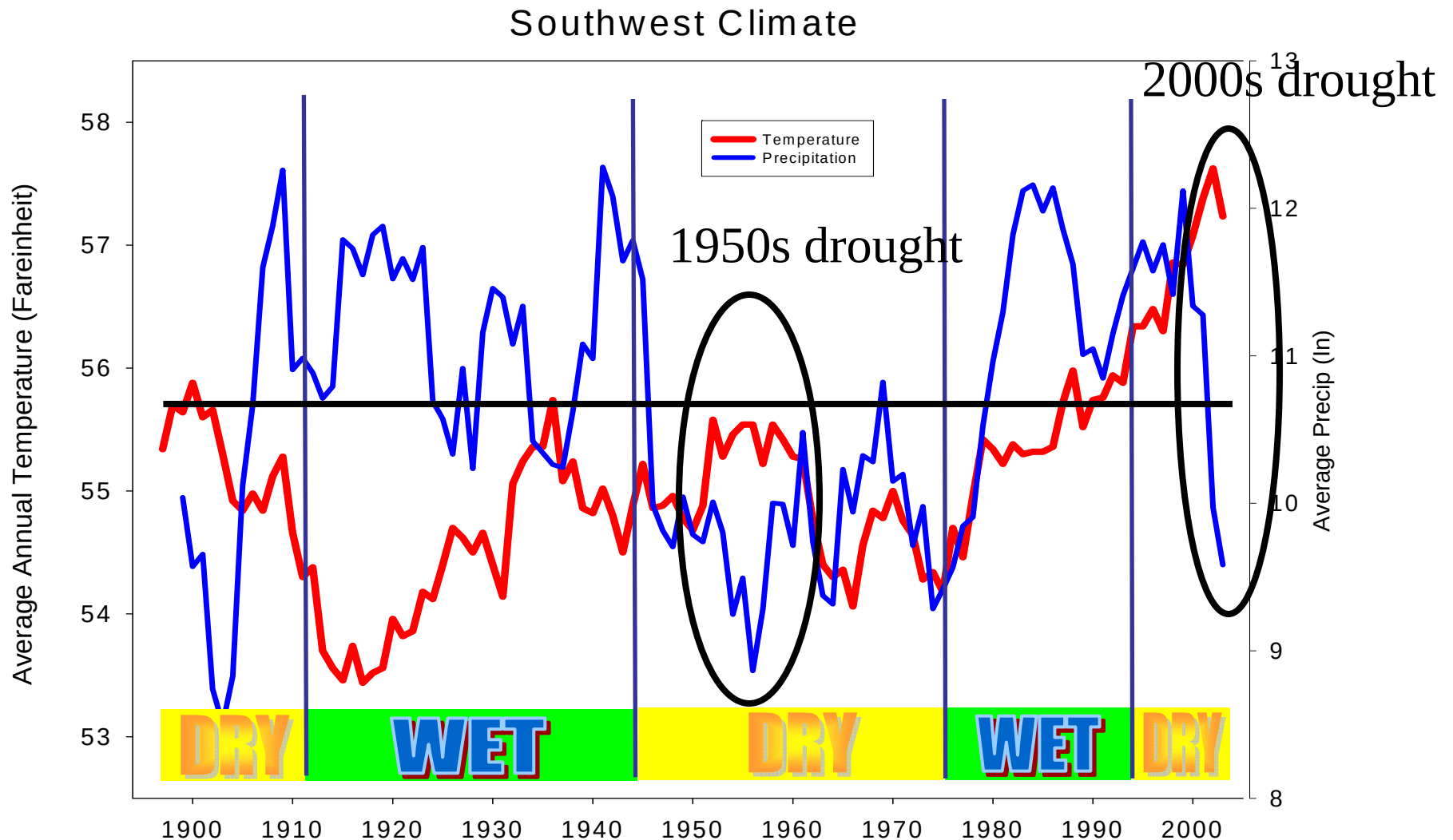
The die-off was reflected in changes in a remotely sensed index of vegetation greenness (NDVI = Normalized Difference Vegetation Index), extending over ~1,000,000 ha.

Regional vegetation die-off in response to global-change-type drought.

2005 -- *Proceedings of National Academy of Sciences USA* 102:15144-15148.

**David D. Breshears, Neil S. Cobb, Paul M. Rich, Kevin P. Price,
Craig D. Allen, Randy G. Balice, William H. Romme, Jude H. Kastens,
M. Lisa Floyd, Jayne Belnap, Jesse J. Anderson, Orrin B. Myers, and
Clifton W. Meyer**

The recent mortality event in the Southwest was probably more extensive than the 1950s event, and this may be due to the warmer conditions during the recent drought.

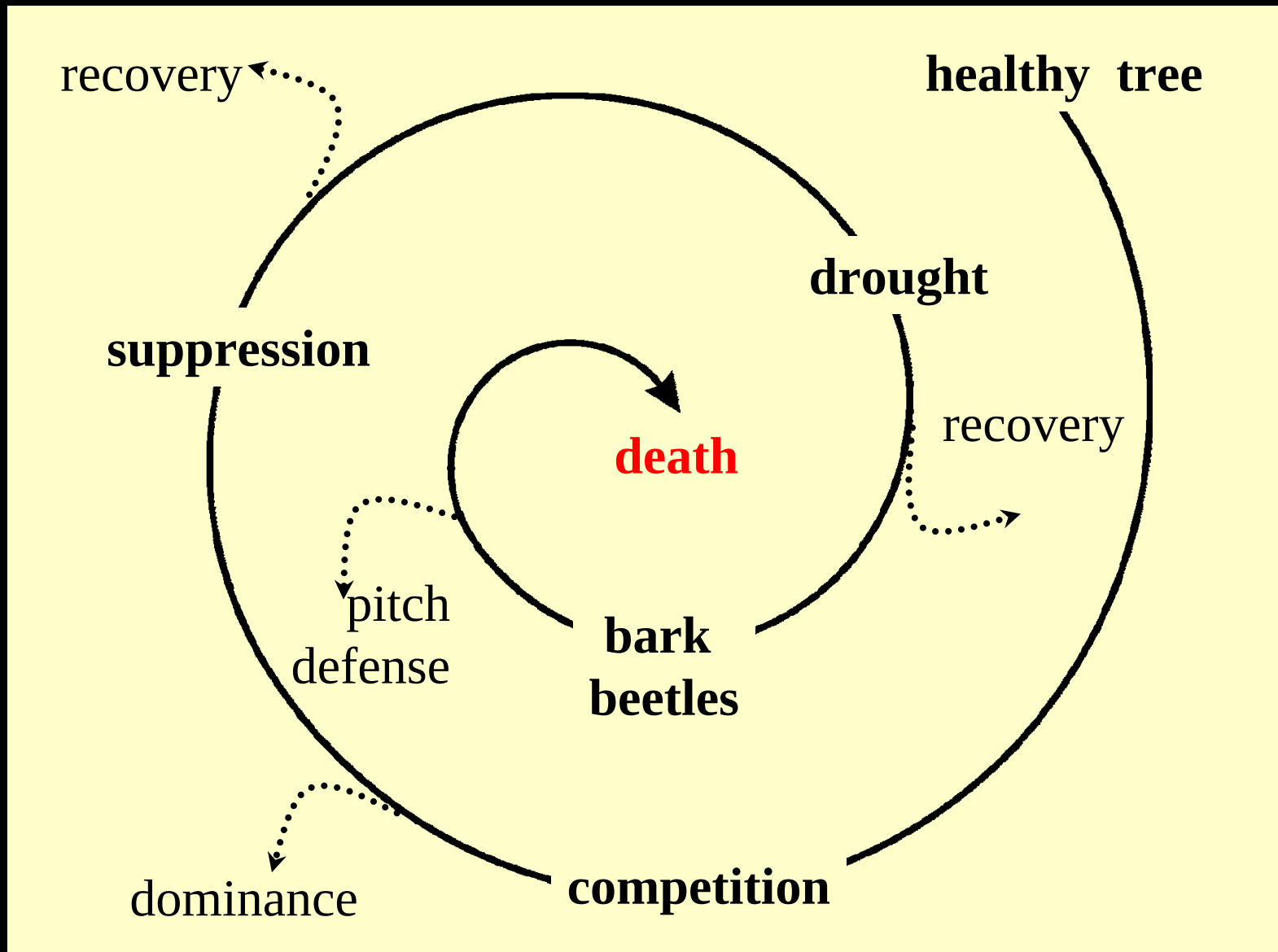


Breshears et al. PNAS 2005, and graphic from Neil Cobb

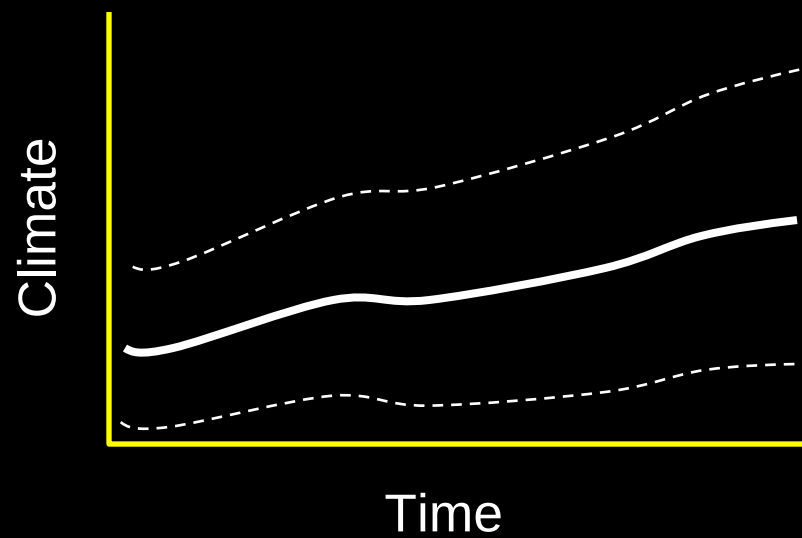
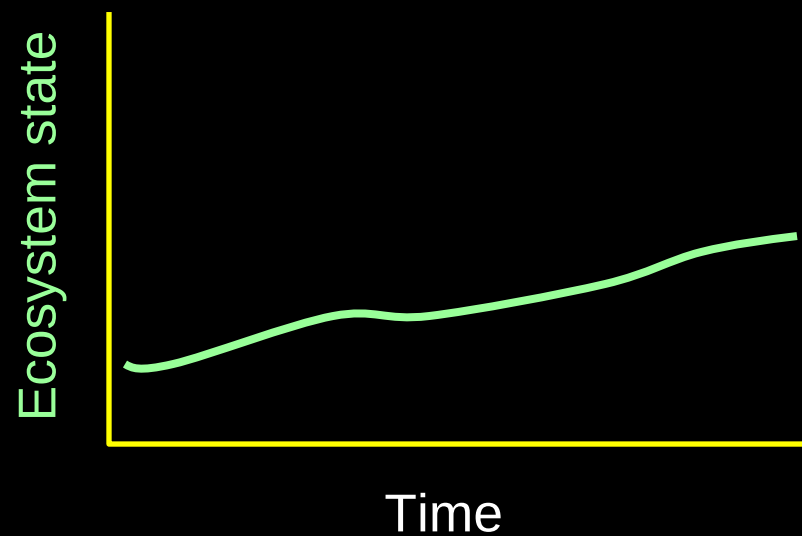
Climatic drivers of tree mortality include:

- *Drought*
- *High temperatures*
- *Synergy between moisture and temperature*
- *Multi-year cumulative stress, resultant poor tree growth, and low vigor*
- *Climate-amplified feedbacks with other mortality agents, such as insect outbreaks with changed population dynamics in climate-stressed forests*

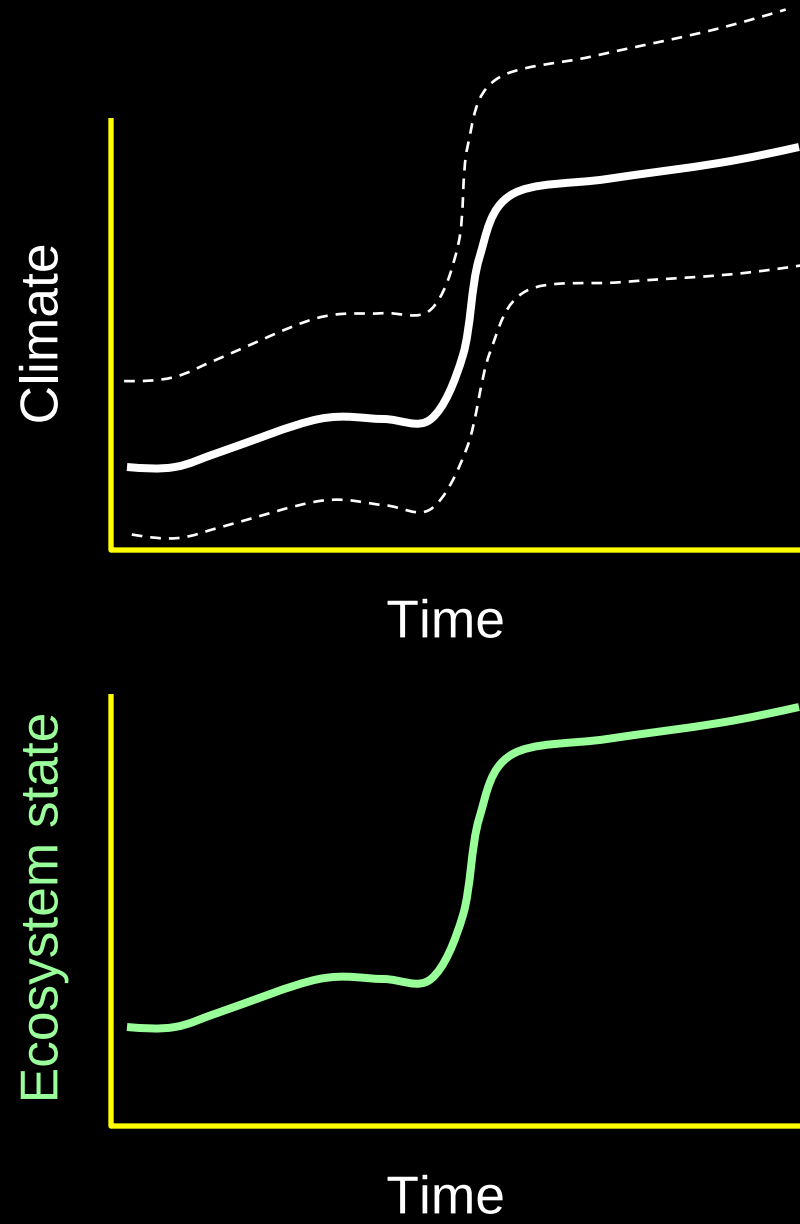
The decline spiral model of tree death: multiple factors, with inertia and lagged effects.



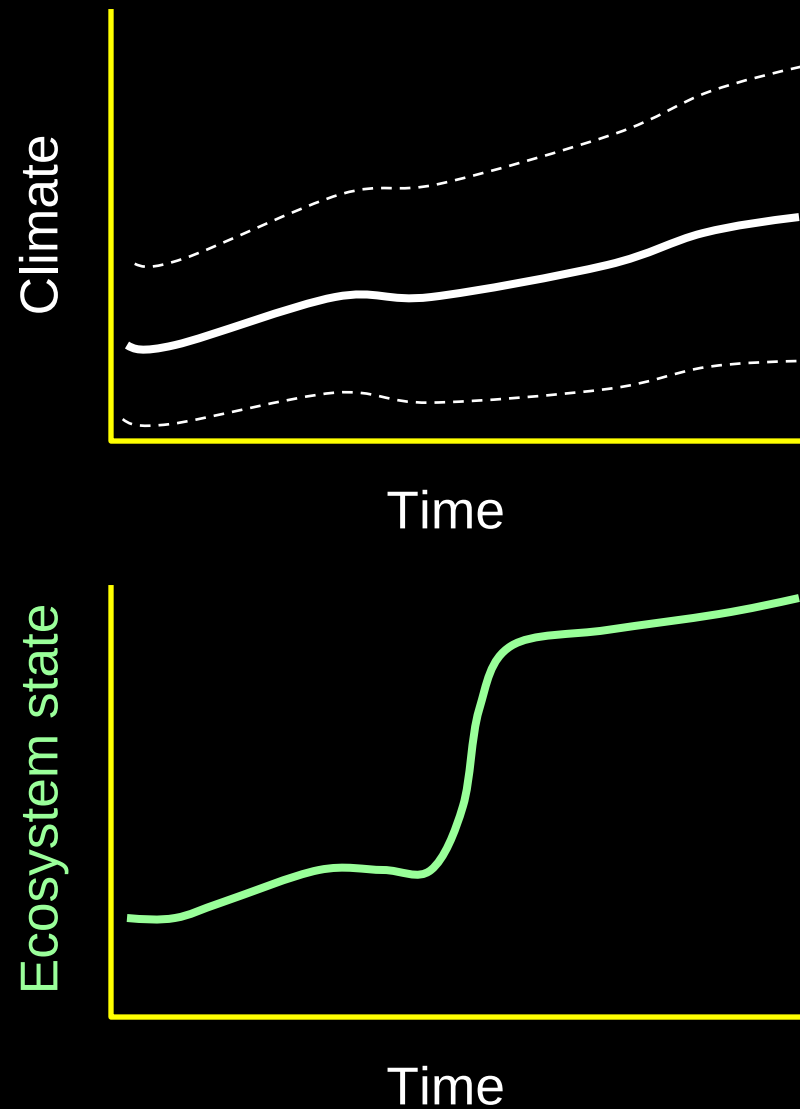
We usually think of gradual linear changes.



However, abrupt climatic change can lead to abrupt ecosystem change.



Gradual climatic change may also trigger abrupt ecosystem change (non-linear threshold response). Tree mortality can occur this way...



Some scientific uncertainties and knowledge gaps:

- Physiological thresholds of species-specific tree mortality.
- We don't really know specifically what it takes to kill most trees, the physiological responses to drought and heat stress in field conditions are hard to capture and predict, in part because they're non-linear.



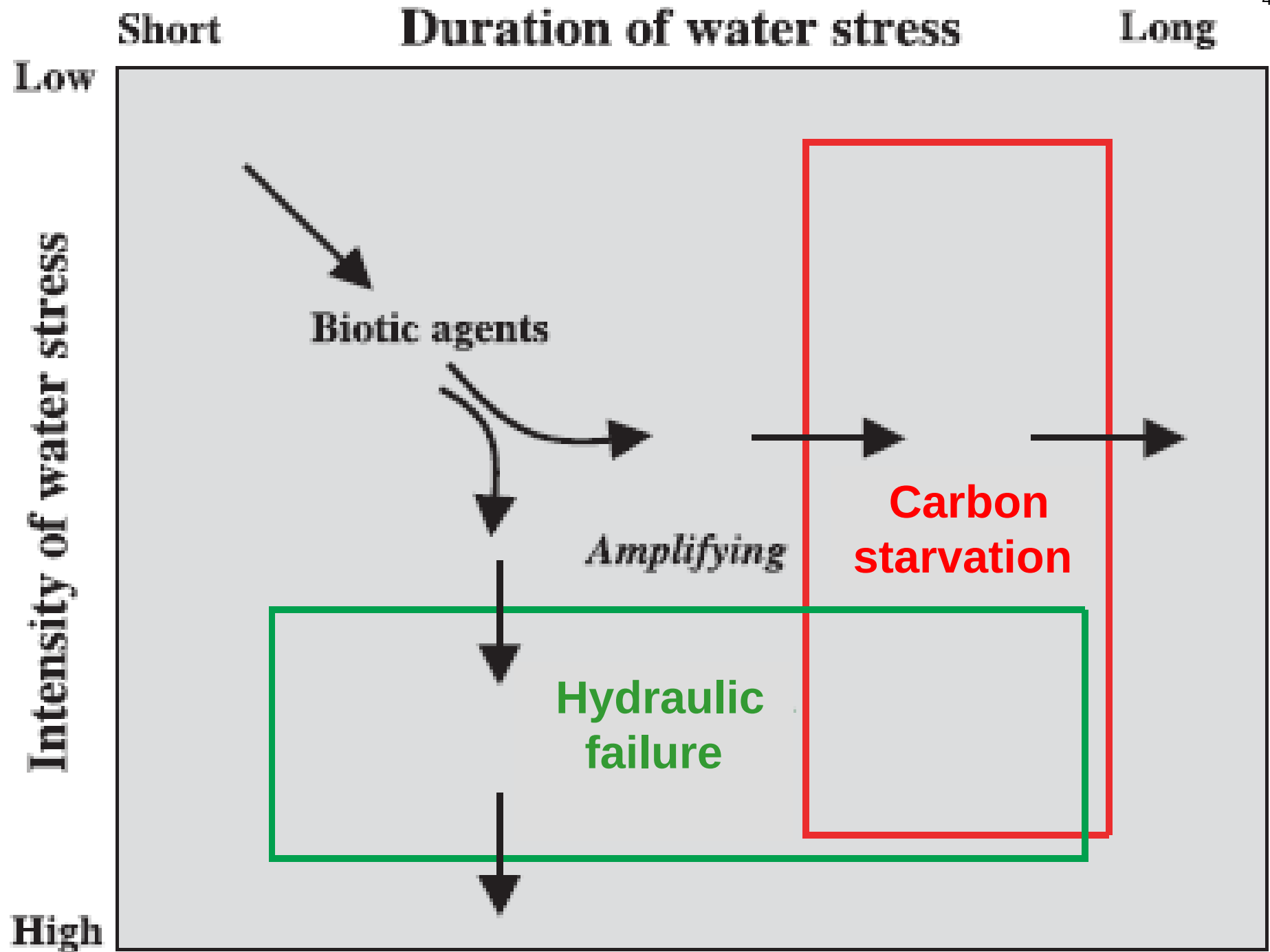
Photo: Nate McDowell

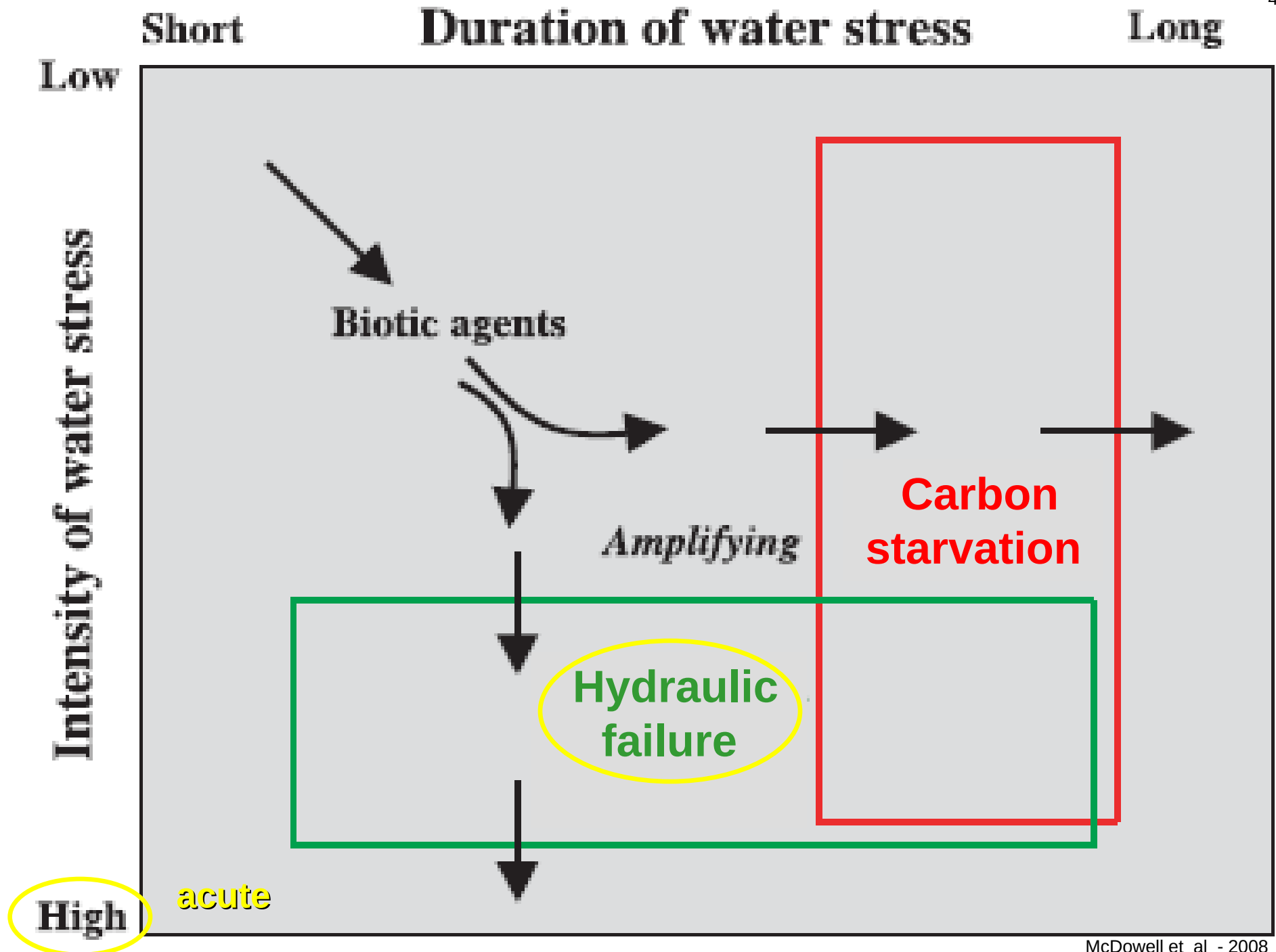
“Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global change-type drought.”

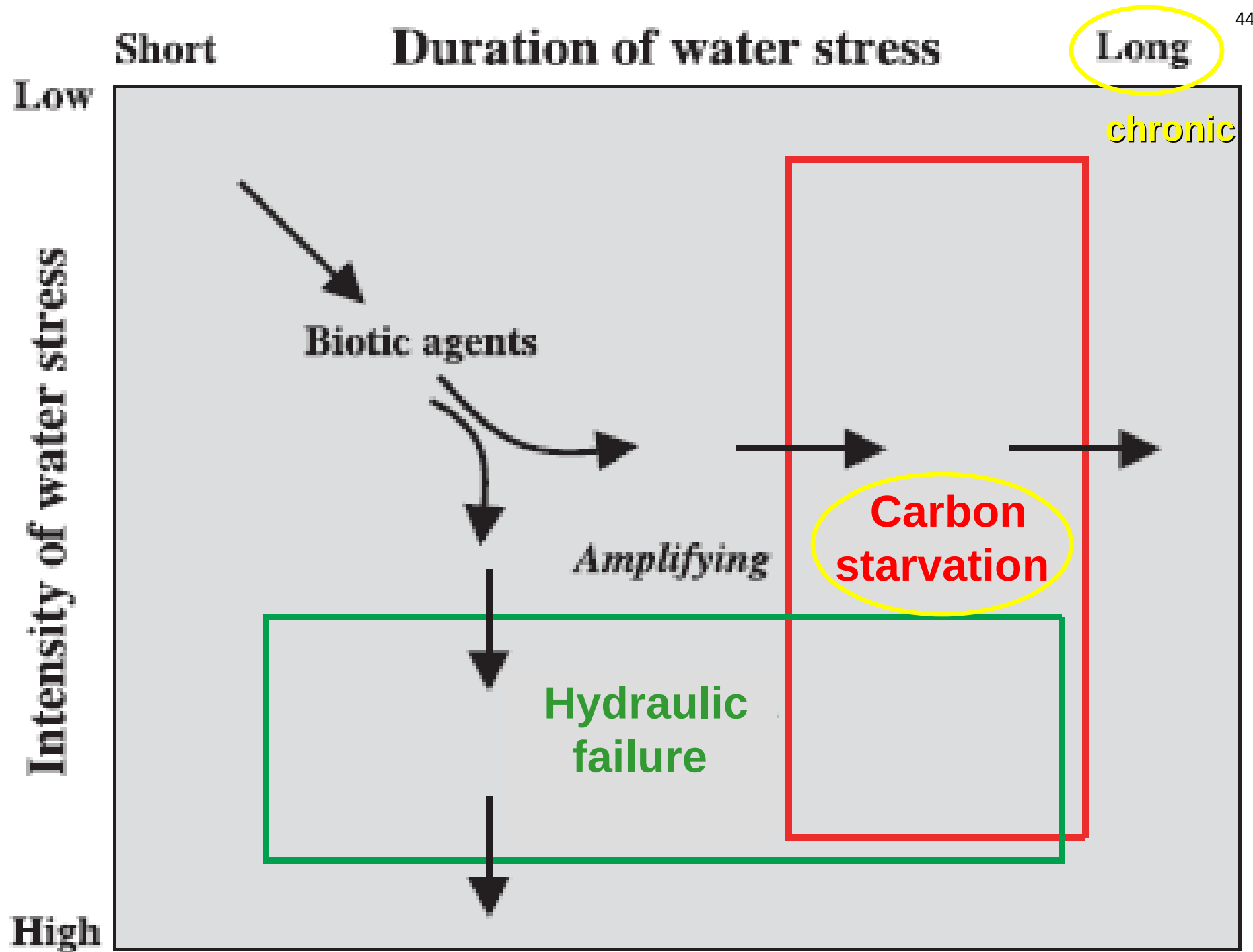
Adams et al. 2009, PNAS.

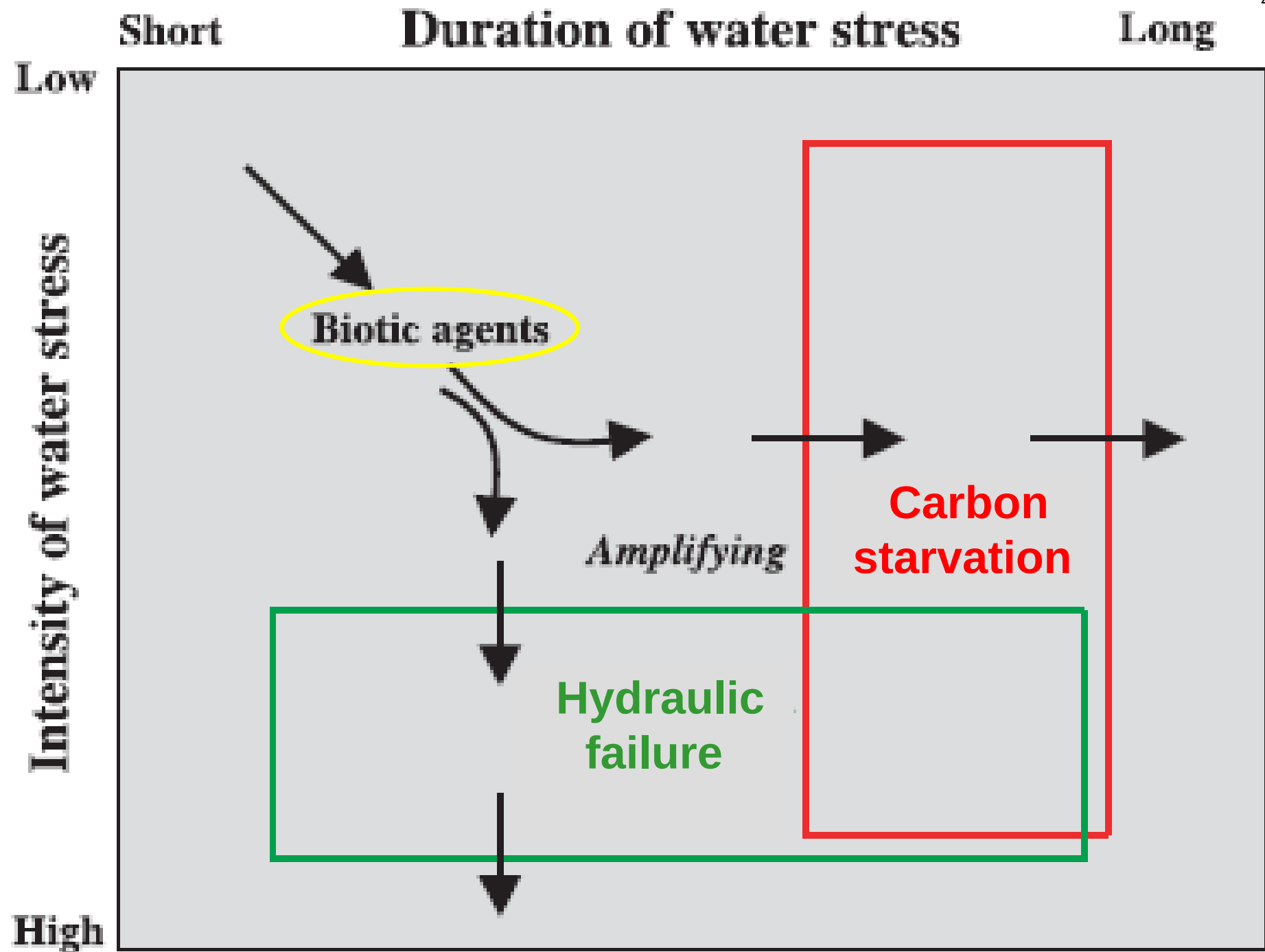


Experimental evidence from Biosphere II showing that *Pinus edulis* died 30% sooner under warmer condtions.

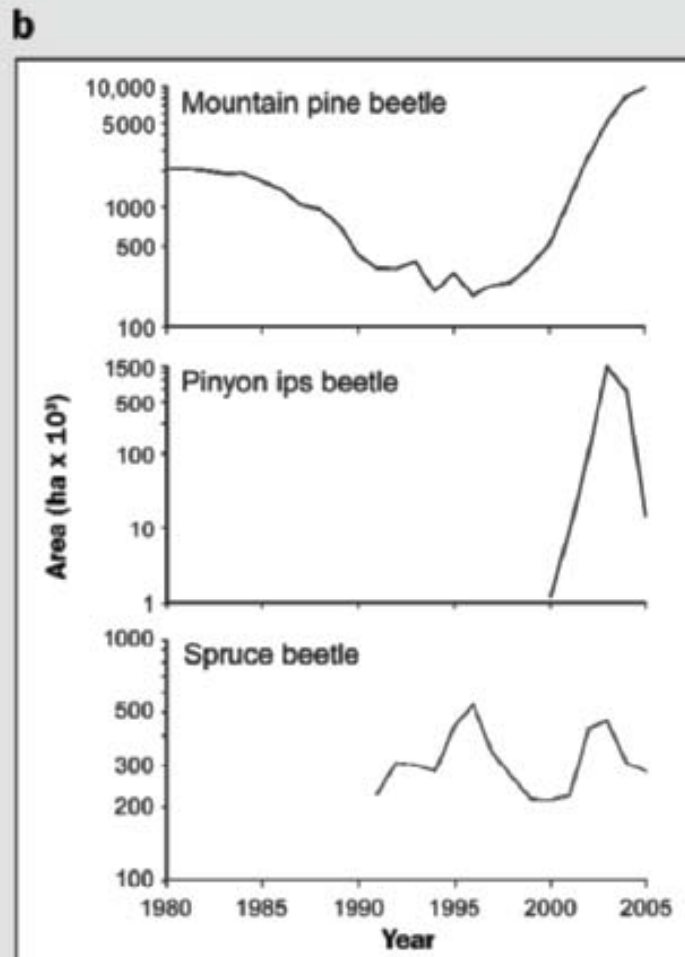




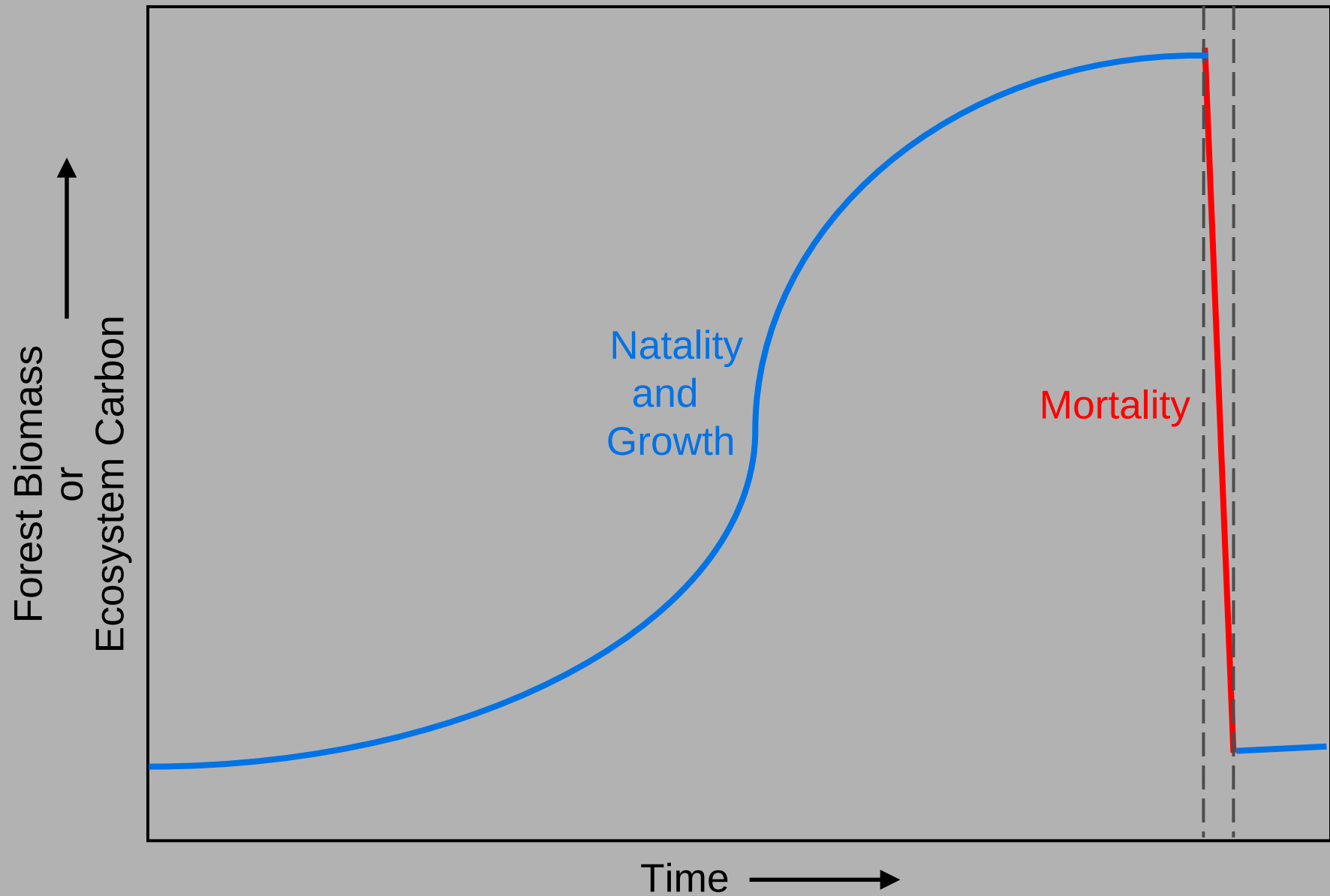




Bark beetles can act as “biotic amplifying agents”,
amplifying the magnitude of
climate-driven forest mortality.

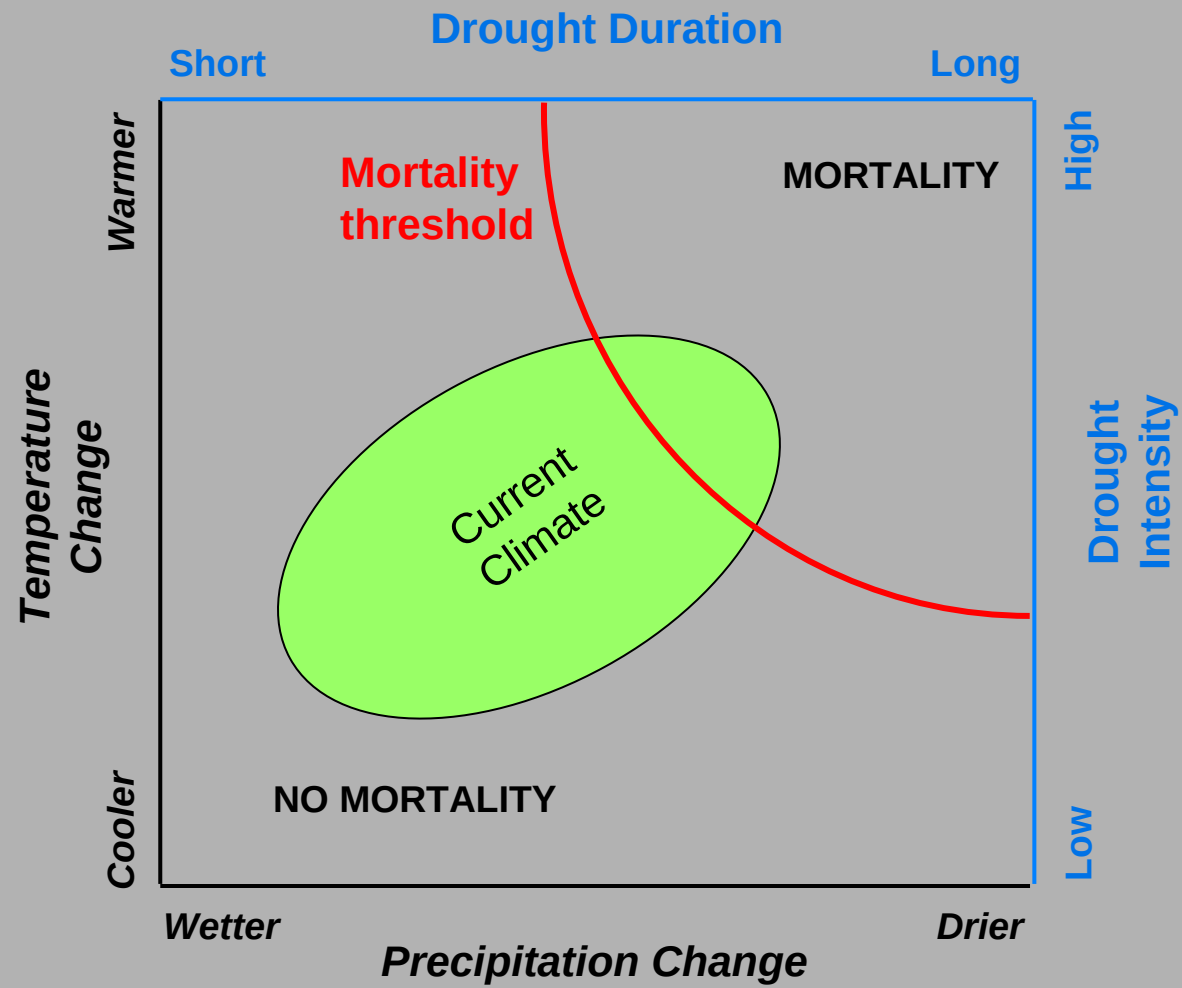


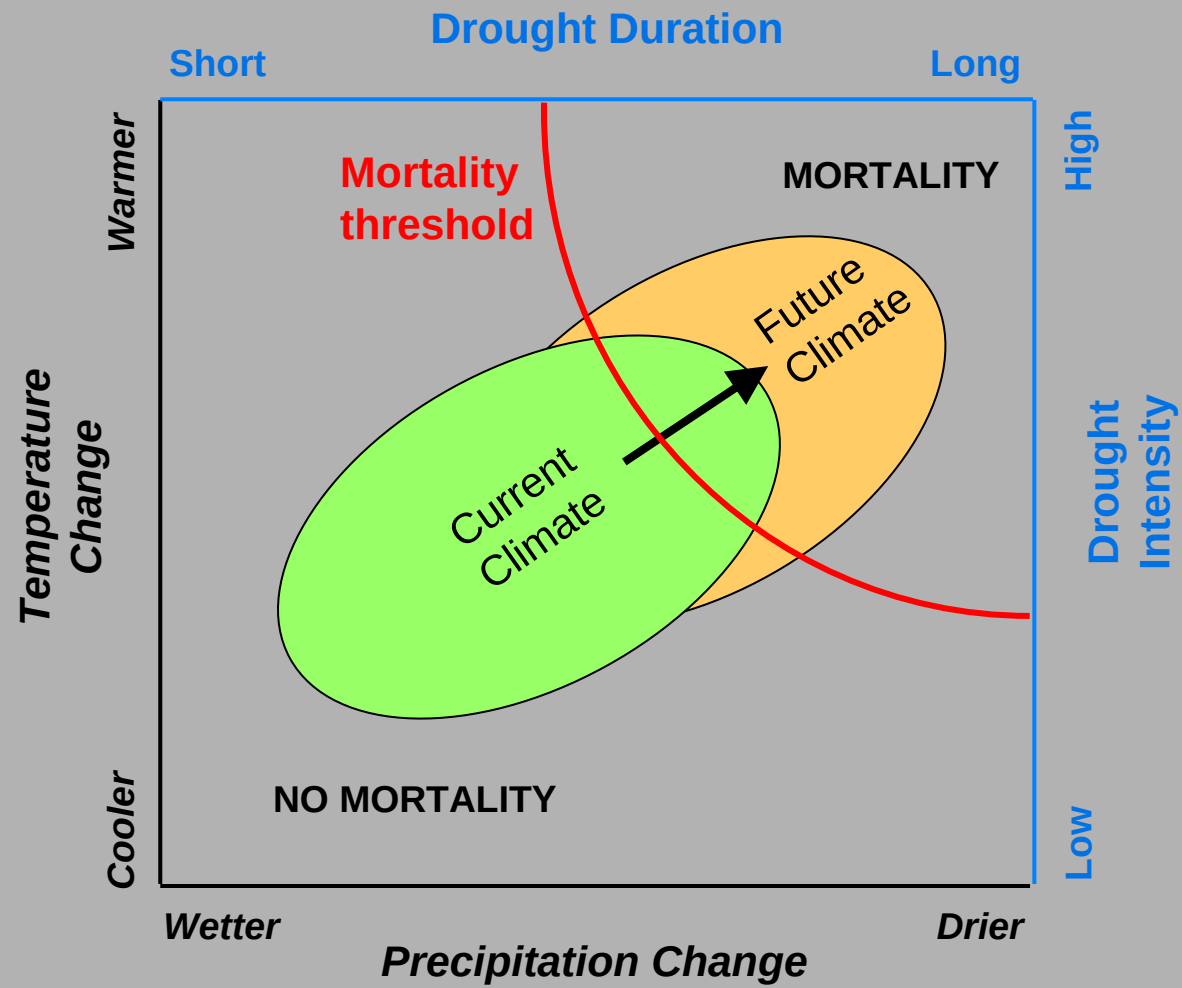
From: Raffa et al. 2008



Gradual increase from **natality**

Rapid loss from **mortality**





Science

11 January 2008 | \$10

50

Forest Dieback
Who's Listening?

AAAS

Science

11 January 2008 | \$10

51

Forest Dieback
Who's Listening?

AAAS

Almost no one, yet...

In major part because significant information gaps and scientific uncertainties still preclude accurate projection of climate-induced tree mortality.

Thus policy makers and the public not able to respond effectively yet.

Key information gaps and scientific uncertainties:

Accurate documentation of global forest mortality patterns and trends requires the establishment of a worldwide monitoring program.

Understanding the mechanisms by which climate change may affect forests requires quantitative knowledge of the species-specific physiological thresholds of individual tree mortality under chronic or acute water stress.

More accurate global vegetation maps are needed as essential inputs to calibrate and validate dynamic global vegetation models.

Spatially explicit documentation of environmental conditions in areas of forest die-off is necessary to link mortality to causal climate drivers, including precipitation, temperature, and vapor pressure deficit.

Mechanistic understanding of climate-induced tree mortality requires improved knowledge of belowground processes and soil moisture conditions.

The direct effects of climate on the population dynamics of almost all forest insect pests and other biotic disturbance agents remain poorly understood but are important to modeling climate-induced forest mortality.

Feedbacks between physiological stress (and tree mortality) driven by climate and other forest disturbance processes (e.g., insect outbreaks, fire) are poorly understood.

For example:
Interactions Among Climate-related disturbance processes

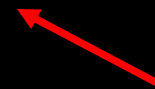
Fire

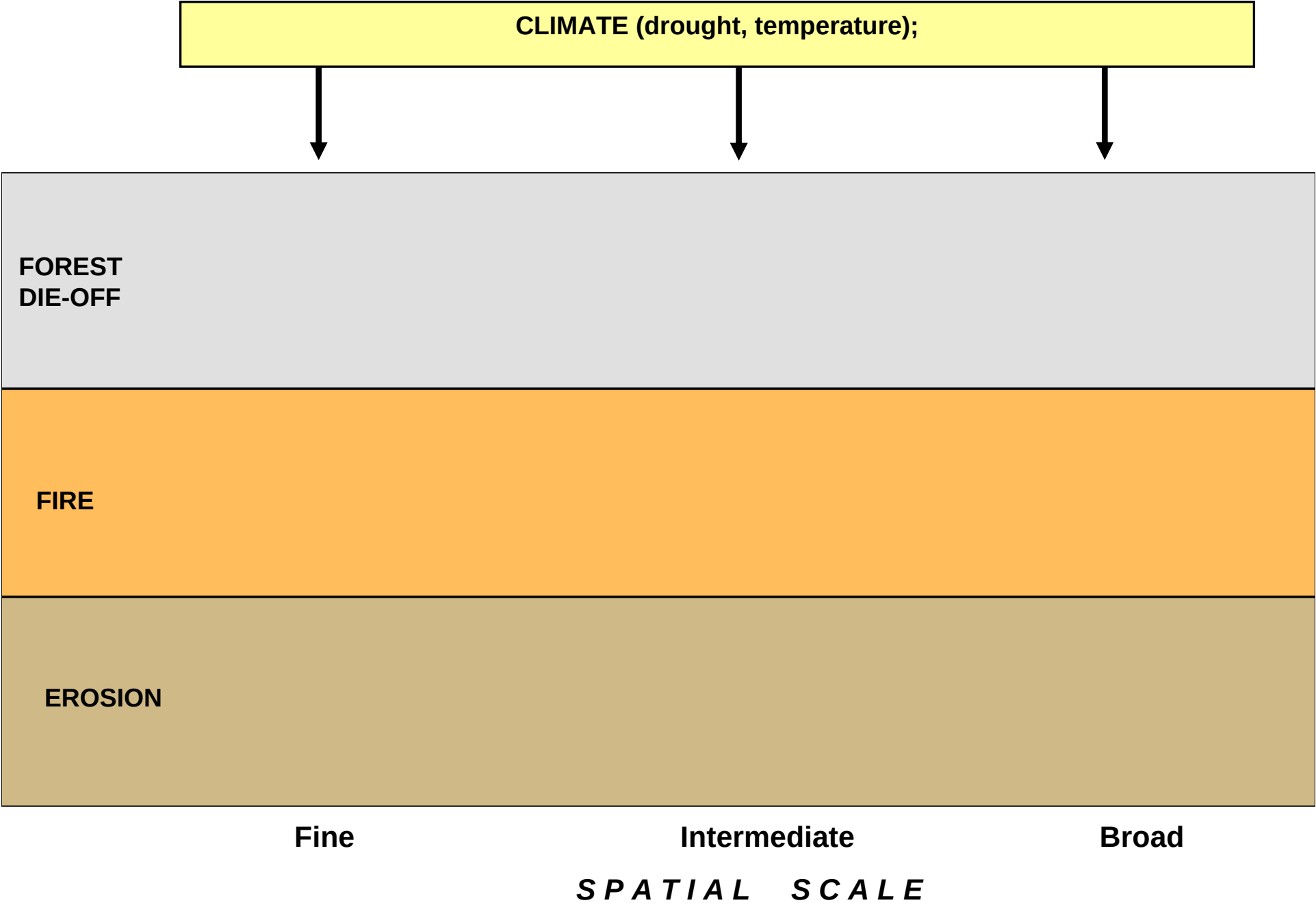


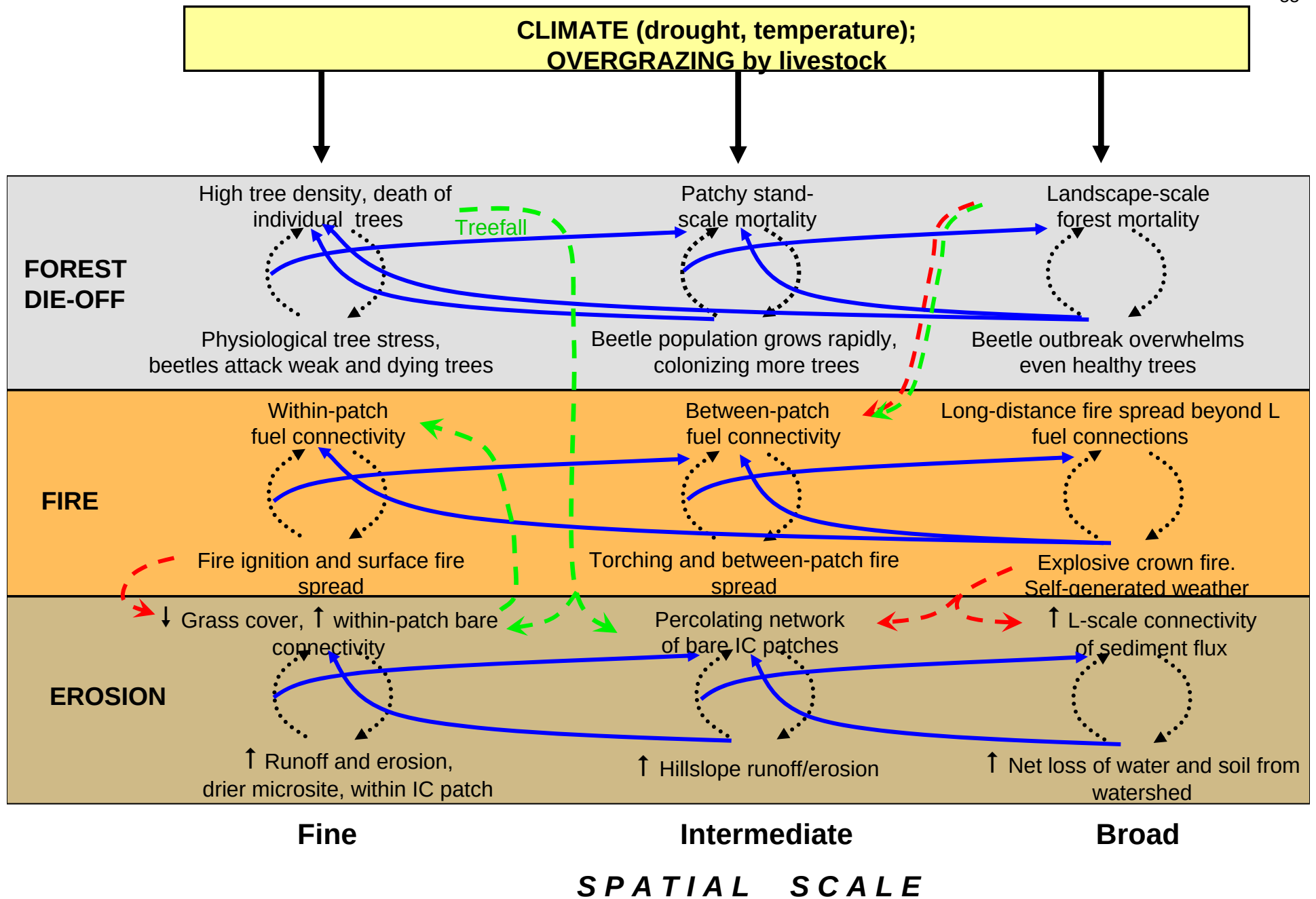
Erosion



Die-off







Interaction: Die-off and Fire

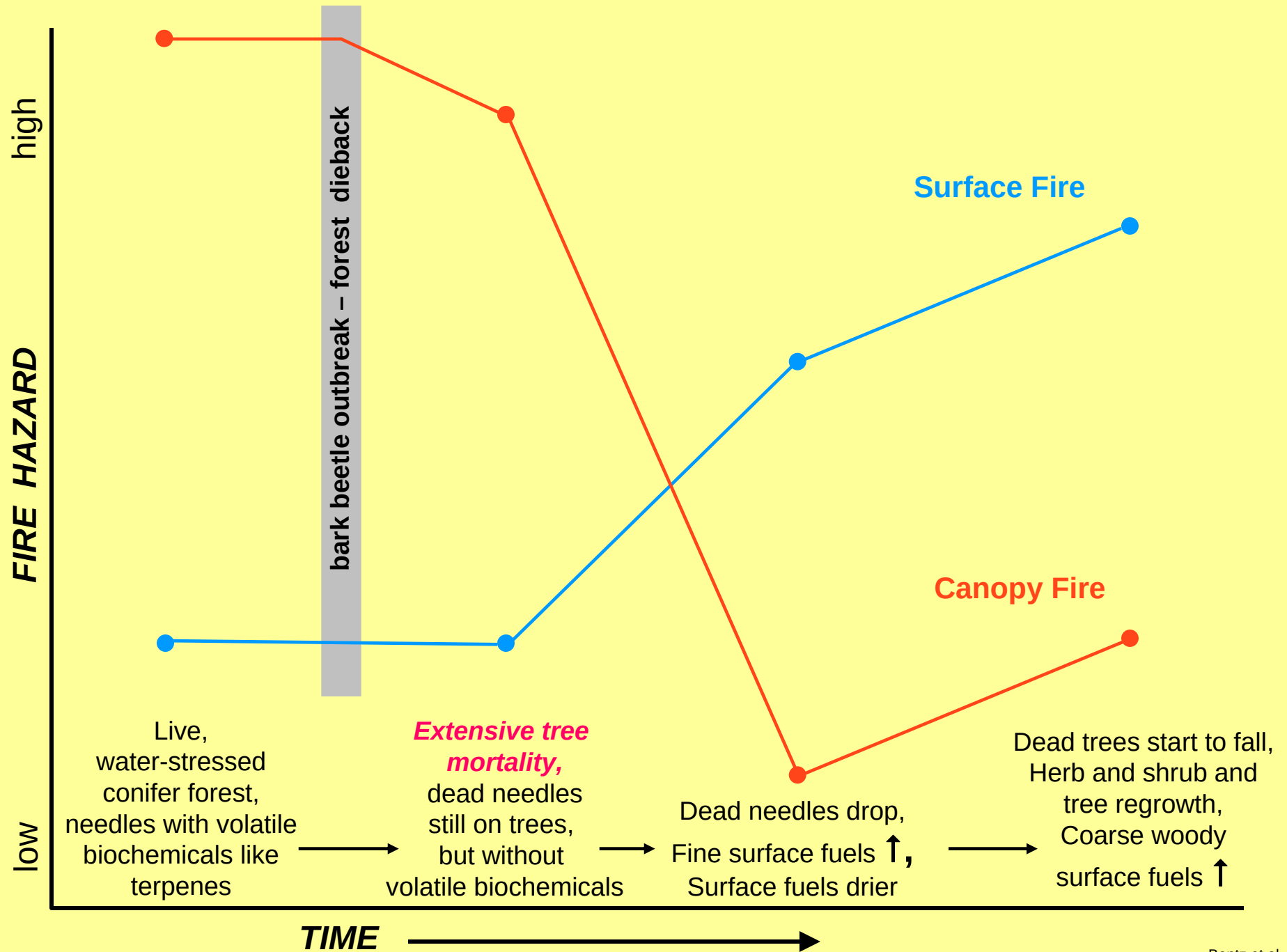
Active crown fires
burn explosively,
primarily in canopy
needles and twigs,
<1 cm diameter,

leaving scorched
trunks and branches
unconsumed.

So, crown fire risks
probably decrease
once dead needles
drop.

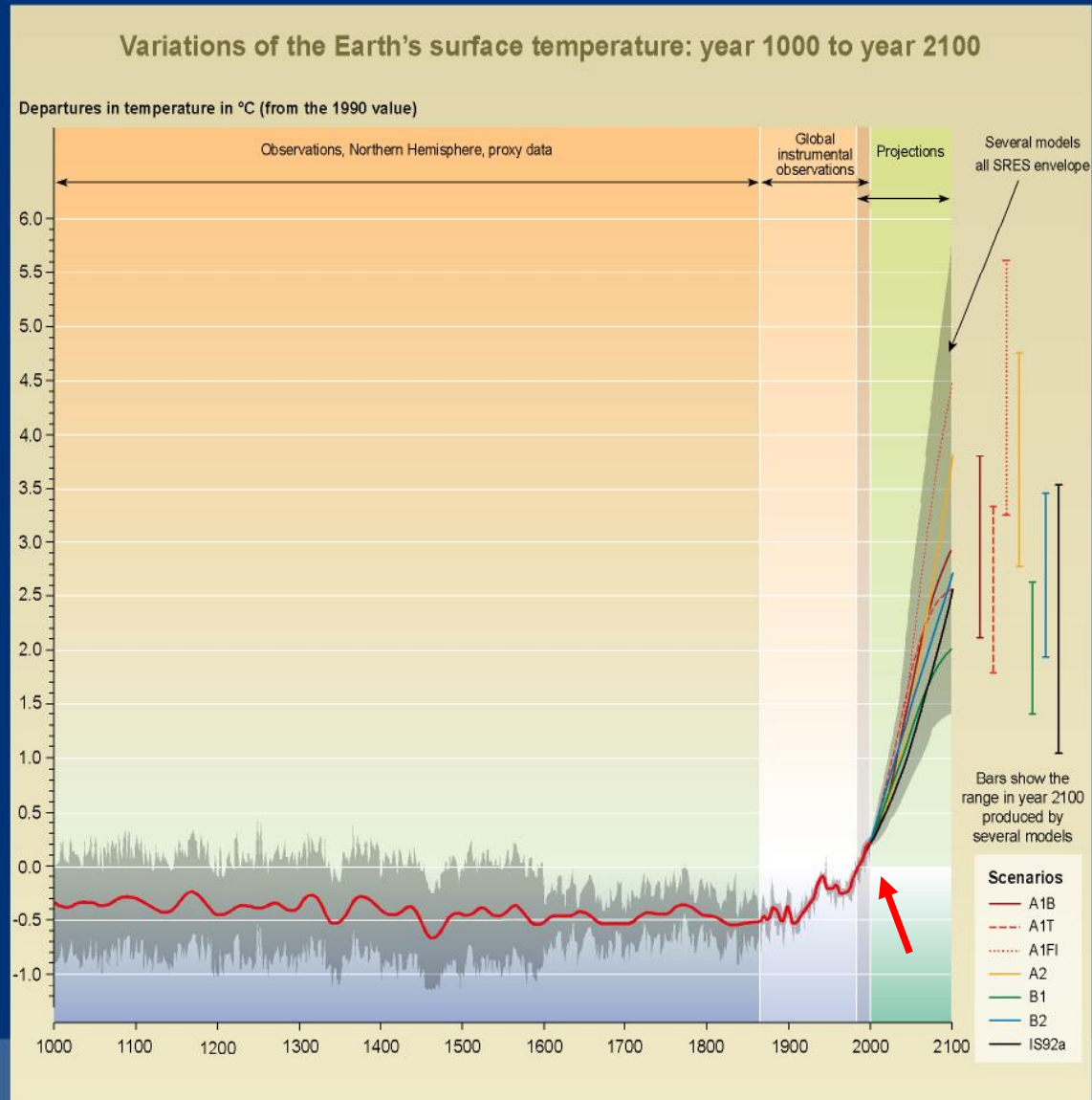
Post die-off

Post-crown
fire



Further rapid warming projected

58



SYR - FIGURE 9-1b

So:

**Forests globally are
vulnerable to climate-
induced tree mortality.**



Jemez Mts., New Mexico.

Photos: CD Allen



What's the good news ?



Photo: CD Allen

**Moderate levels of
forest die-off:**

**might be a
benefit for
many forests...**

- increased
resilience of
survivors**
- reduced crown
fire risk**
- easier to
prescribe burn**

Despite the risks and uncertainties, we can manage for more resilient forests.



65



Photos: CD Allen

Adaptation options still exist, including silvicultural practices, ranging from mechanical treatments and prescribed burning to changes in forest regeneration strategies.

You folks will be on the front lines of adaptation efforts.

Photos: CD Allen





People love trees and forests of all kinds, starting in their home landscapes.

If enough people see the risks to our forests soon enough it can help us overcome our societal inertia,

... and trigger the rapid restructuring of our economies and lifestyles in time to reduce CC impacts to forests and associated services that we value and need so much.

We need to continue to **learn**, and **act**, and expect **surprises**.

Think Globally, Act Locally
(and Regionally,
and Globally...)

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