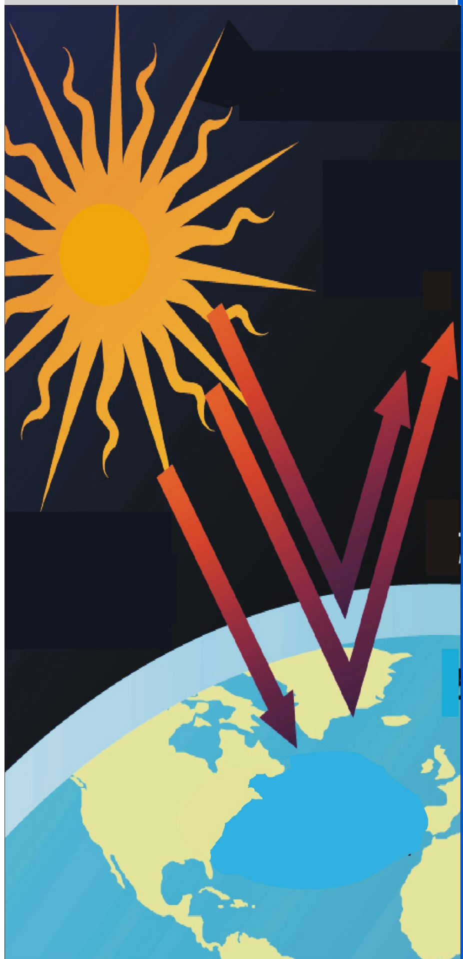

Ecological Consequences of Climate Extremes :

Impacts of Drought-Induced Forest Mortality on Forest Carbon Sinks

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University of Quebec at Montreal (UQAM). Montreal, Canada

Laboratoire de modélisation écologique et de science du carbone (Eco-MSC)
Ecological Modelling and Carbon Science Laboratory (Eco-MCS)

Topics Outline

I. Introduction and Overview

II. Global Patterns (Case Studies):

- Increase tropic forest mortality in Amazon
- Increase temperate forest mortality in West USA
- Increase boreal forest mortality in West Canada

III. Causes, Consequences, and Ongoing Challenges

Extreme events

12-day heatwave, 3-14 Aug, 2003

Maximum Temperature, Aug 10

Excess Mortality:

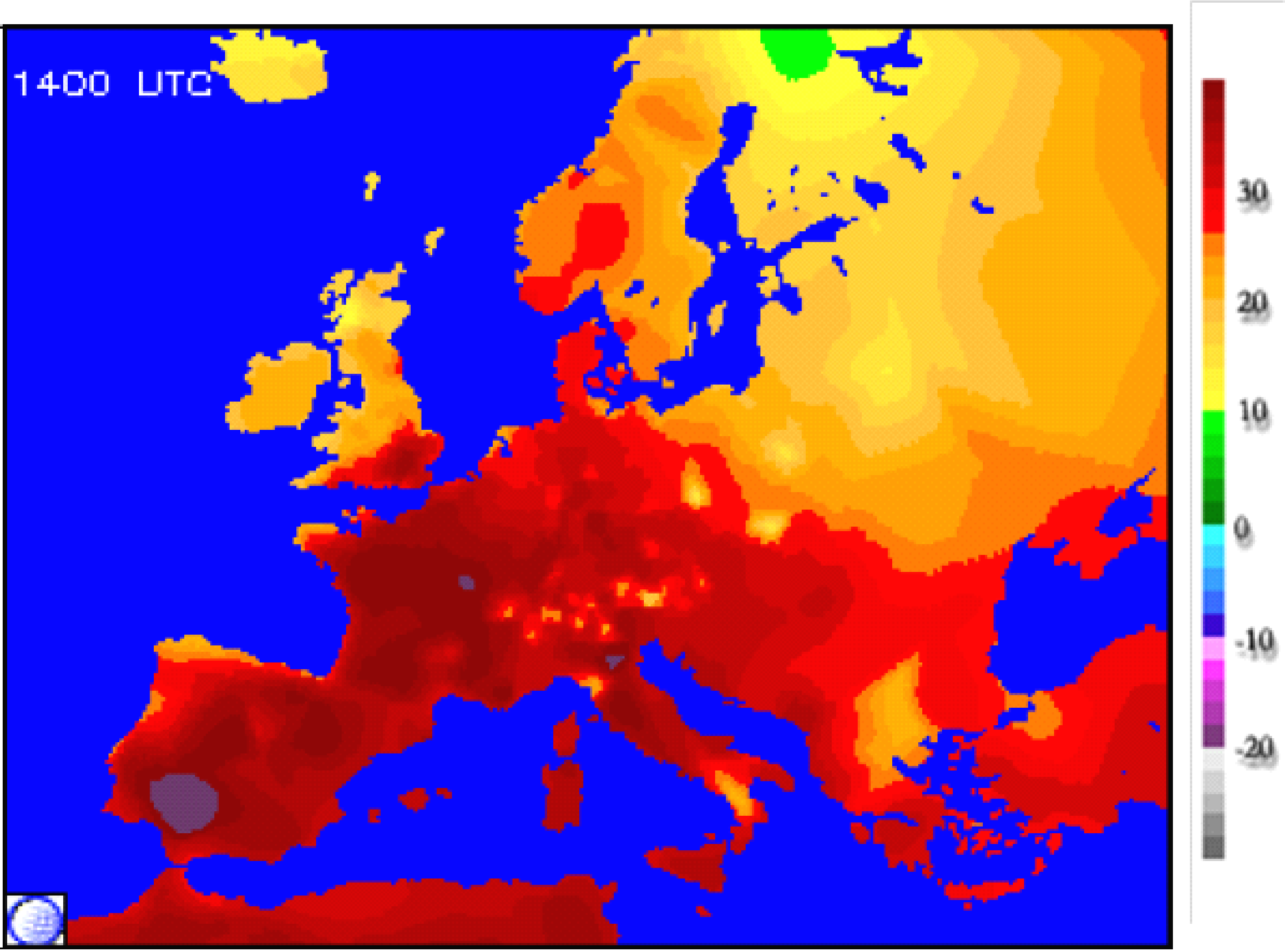
France: 14,800

Italy: 10,000

Spain & Portugal: 5,000

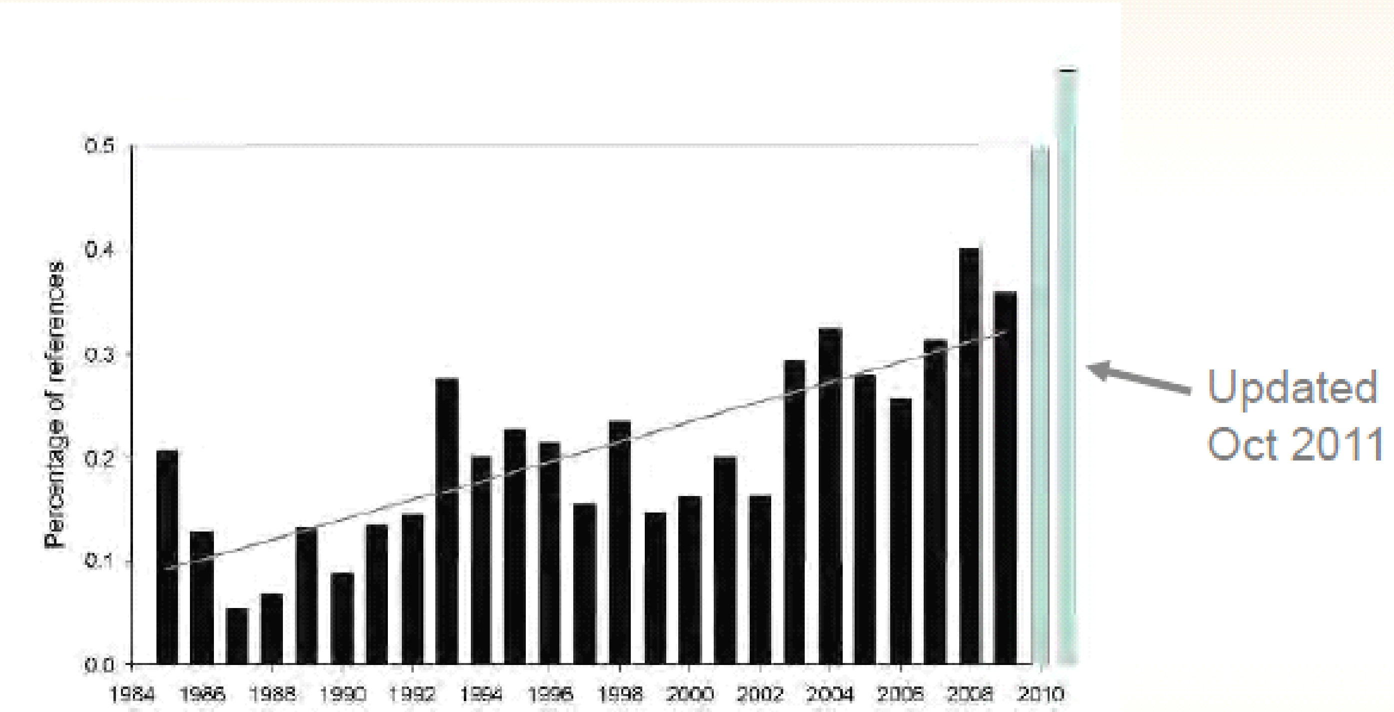
Etc.

Total = 35,000



Slide attributed to Tony McMichael

Drought-induced forest decline: An emerging global change issue

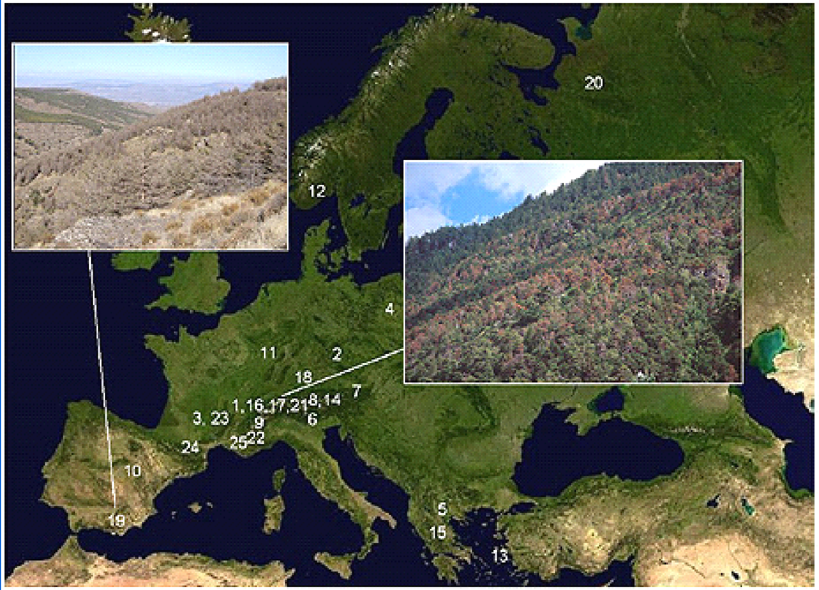


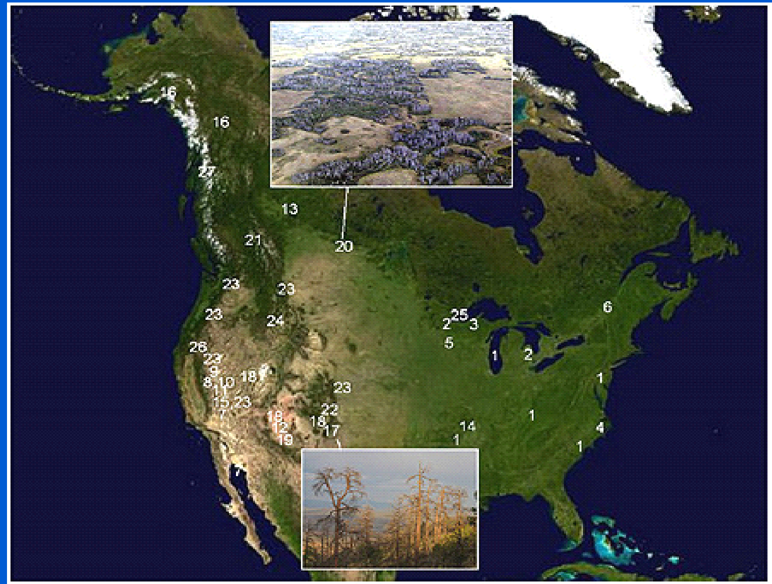
Increase in % of papers on forests reporting on drought & mortality (Allen et al. 2010):

A very preliminary indicator in the absence of a global monitoring system for forests!

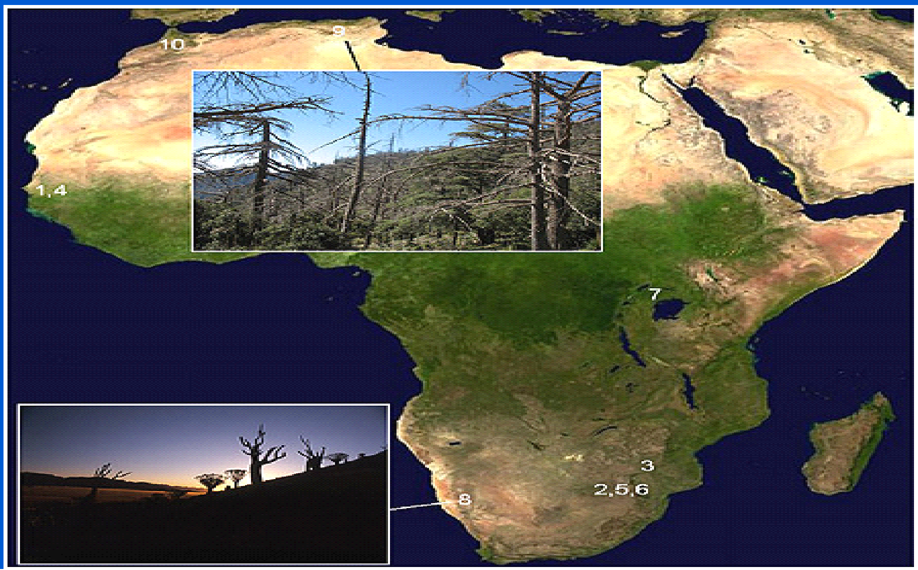
Examples of drought-induced forest decline

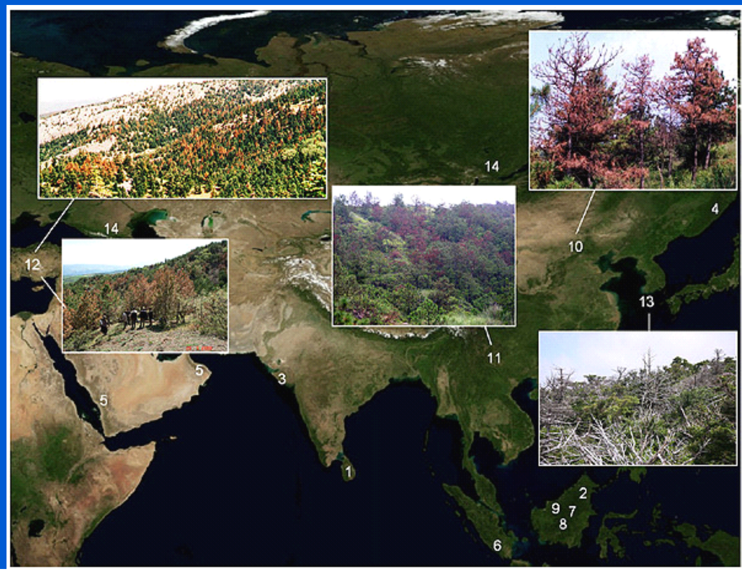
Global Observations and Patterns of Tree Mortality





>150 references with 88 examples of forest mortality driven by climatic water/heat stress since 1970 (Allen et al, 2010).





Chinese Bamboo (竹子) Death (photo by Changhui Peng)

美国8年前预测中国大旱 气候研究战略警醒中国

在2004年7月7日出版的官方《人民日报》科技版上，- 有一篇题为“2010年中国气候突变 美秘密报告引关注”的报导。

这份题为《气候突变的情景及其对美国国家安全的意义》的报告，由美国全球商业网络咨询公司（GBN）于2003年10月发布于其公司网站上。报告是美国国防部出资10万美元委托该公司完成的。

报告用上百字篇幅对中国当前的气候做了如下预言：

“中国南部地区在2010年前后将发生持续整整10年的特大干旱。2010年以后，中国北方水患不断，南方一片干旱…’

An Abrupt Climate Change Scenario and Its Implications for United States National Security

October 2003

By Peter Schwartz and Doug Randall

气候突变的情景及其对美国国家安全的意义

彼得 •施瓦兹和达哥 •兰德尔

2003 年 10 月

The effects of the drought are more devastating than the unpleasantness of temperature decreases in the agricultural and populated areas. With the persistent reduction of precipitation in these areas, lakes dry-up, river flow decreases, and fresh water supply is squeezed, overwhelming available conservation options and depleting fresh water reserves. The Mega-droughts begin in key regions in Southern China and Northern Europe around 2010 and last throughout the full decade. At the same time, areas that were relatively dry over the past few decades receive persistent years of torrential rainfall, flooding rivers, and regions that traditionally relied on dryland agriculture.

Environmental Factors Controlling Forest Growth and Death

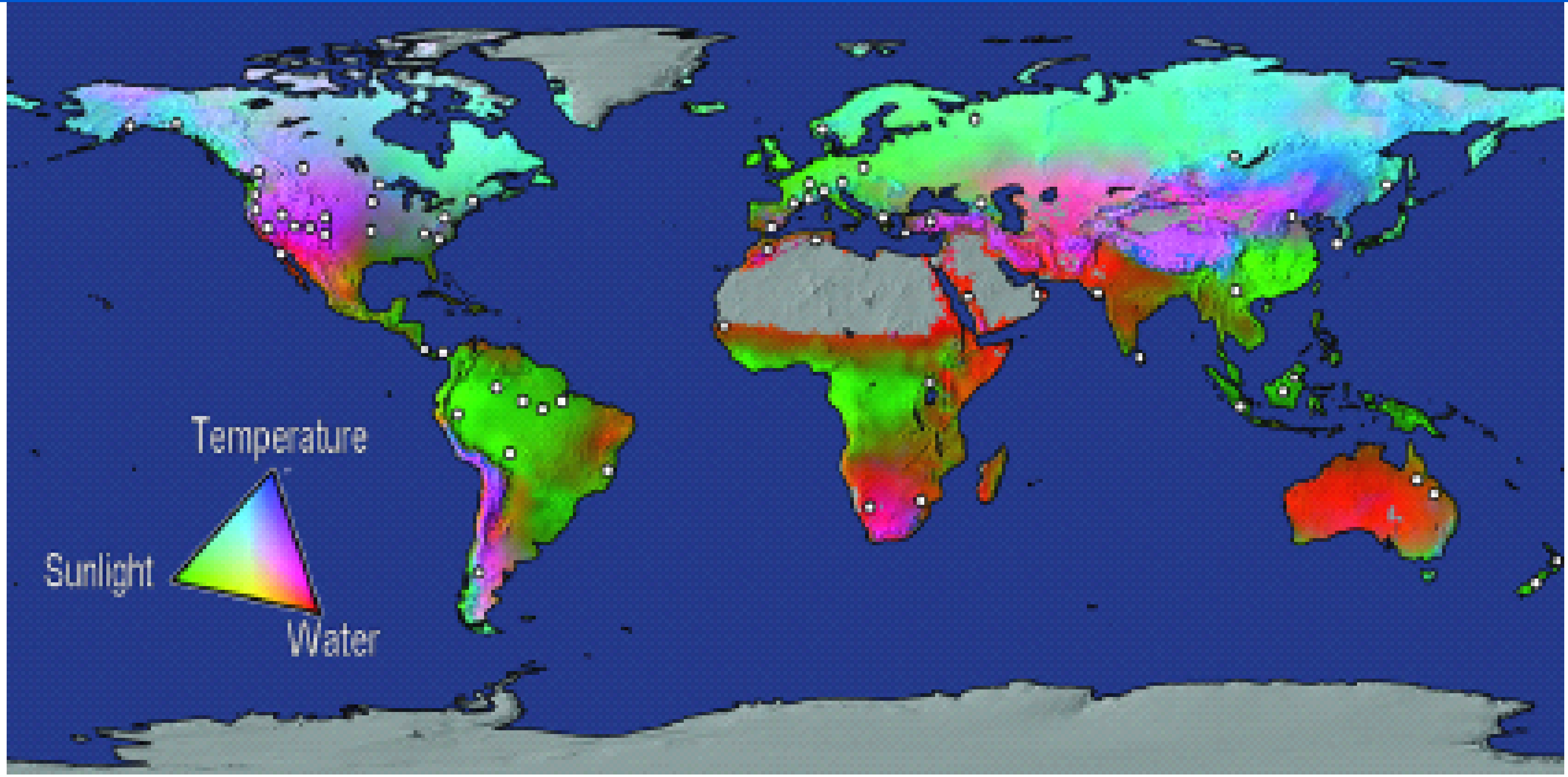
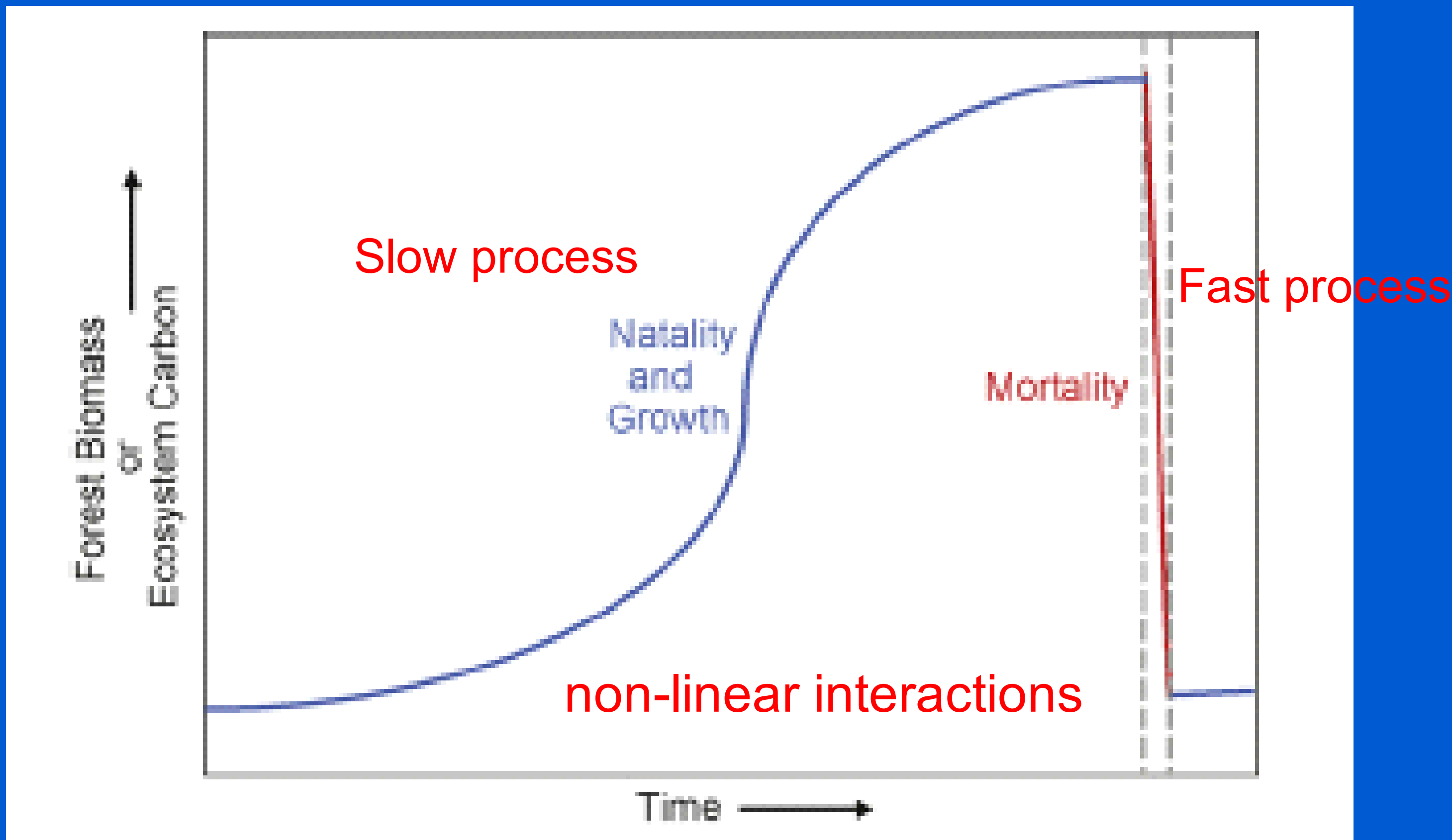


Fig. 1. White dots indicate documented localities with forest mortality related to climatic stress from drought and high temperatures. Background map shows potential environmental limits to vegetation net primary production (Boisvenue and Running, 2006).

$$\frac{d\mathit{Biomass}}{dt} = \textbf{Growth - Mortality}$$

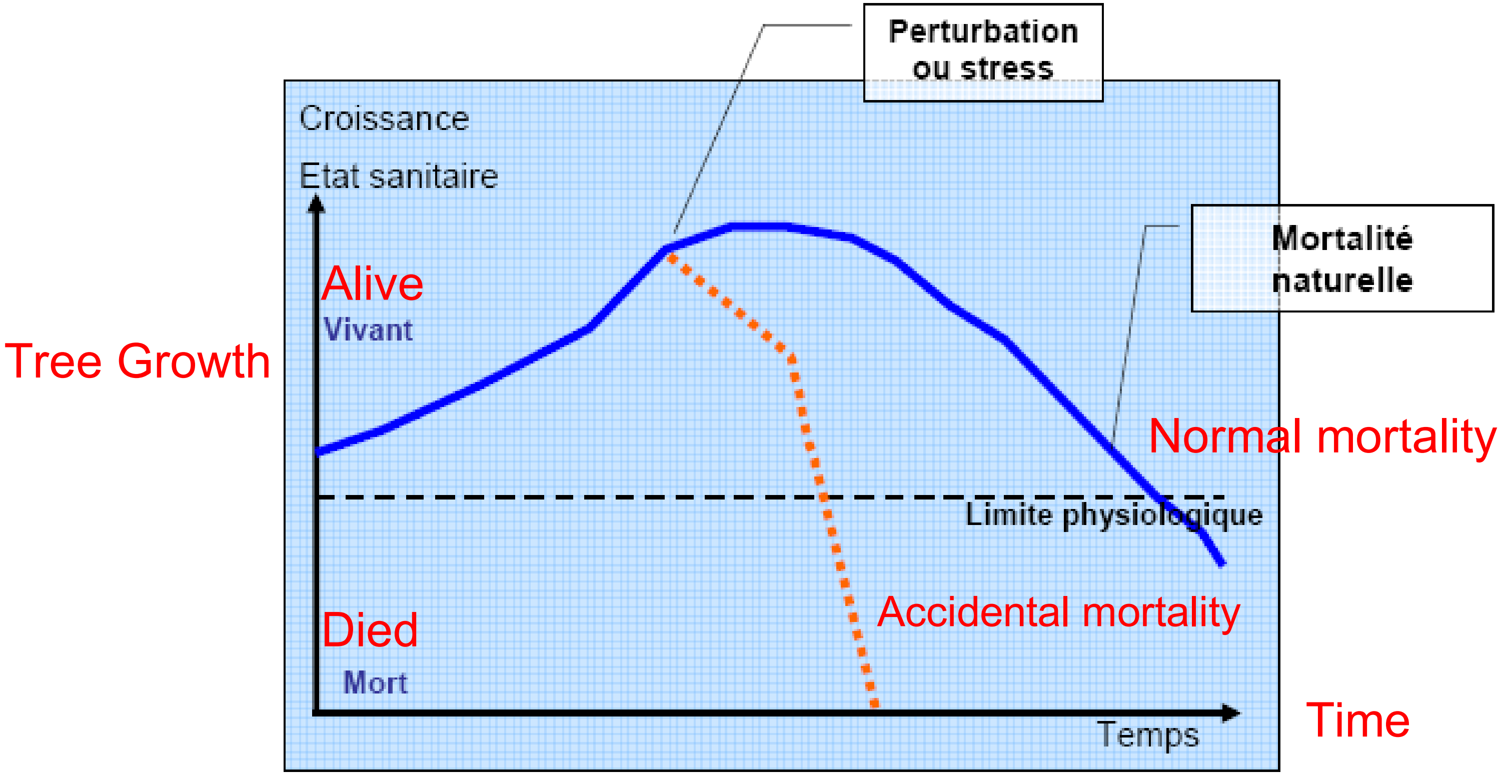


Allen et al., 2010

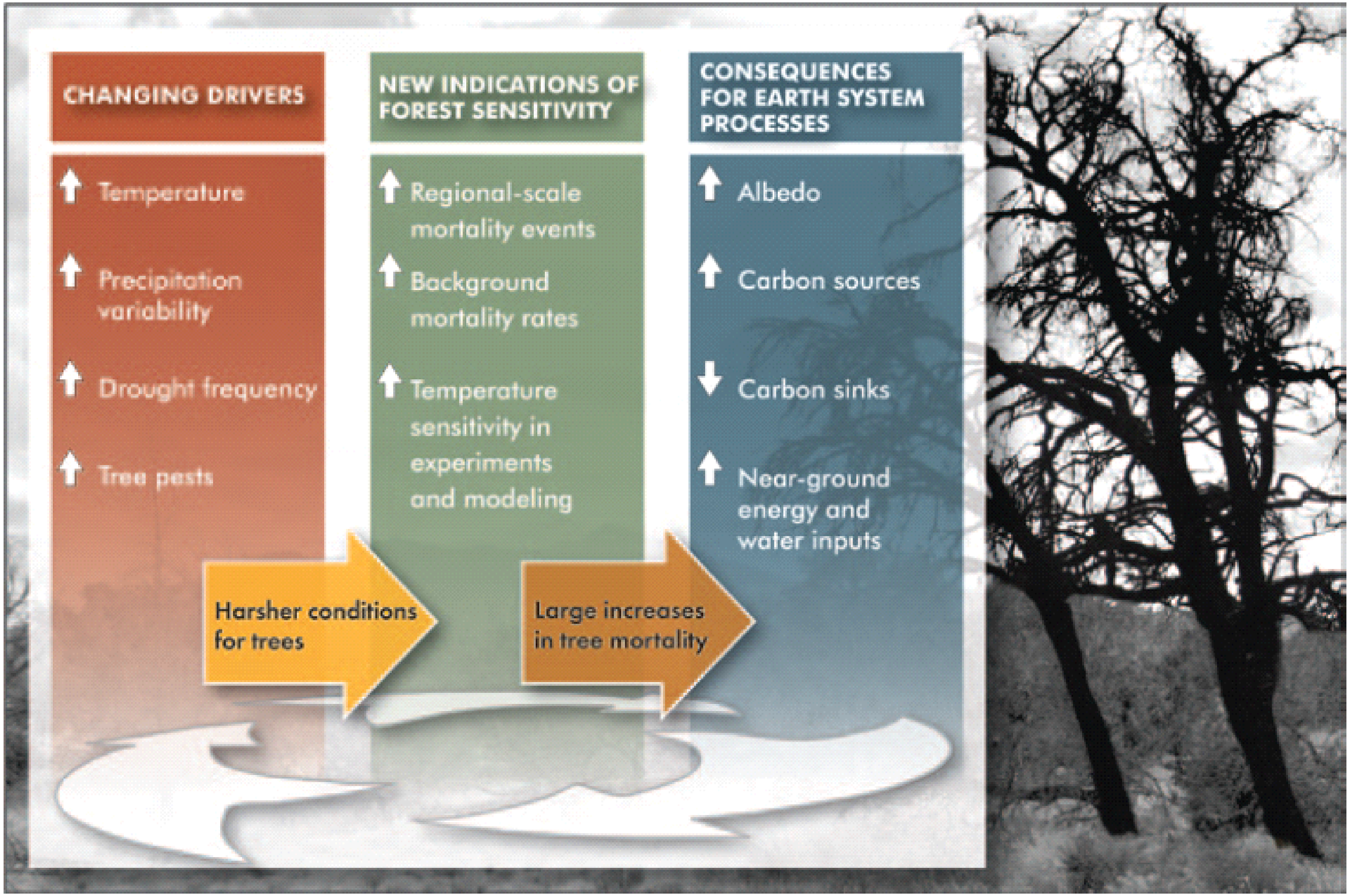
Why tree died quickly under disturbance or stress ?

Pourquoi les arbres meurent-ils ?

Un processus complexe et multifactoriel :
des facteurs *favorisants, déclenchant, aggravants*

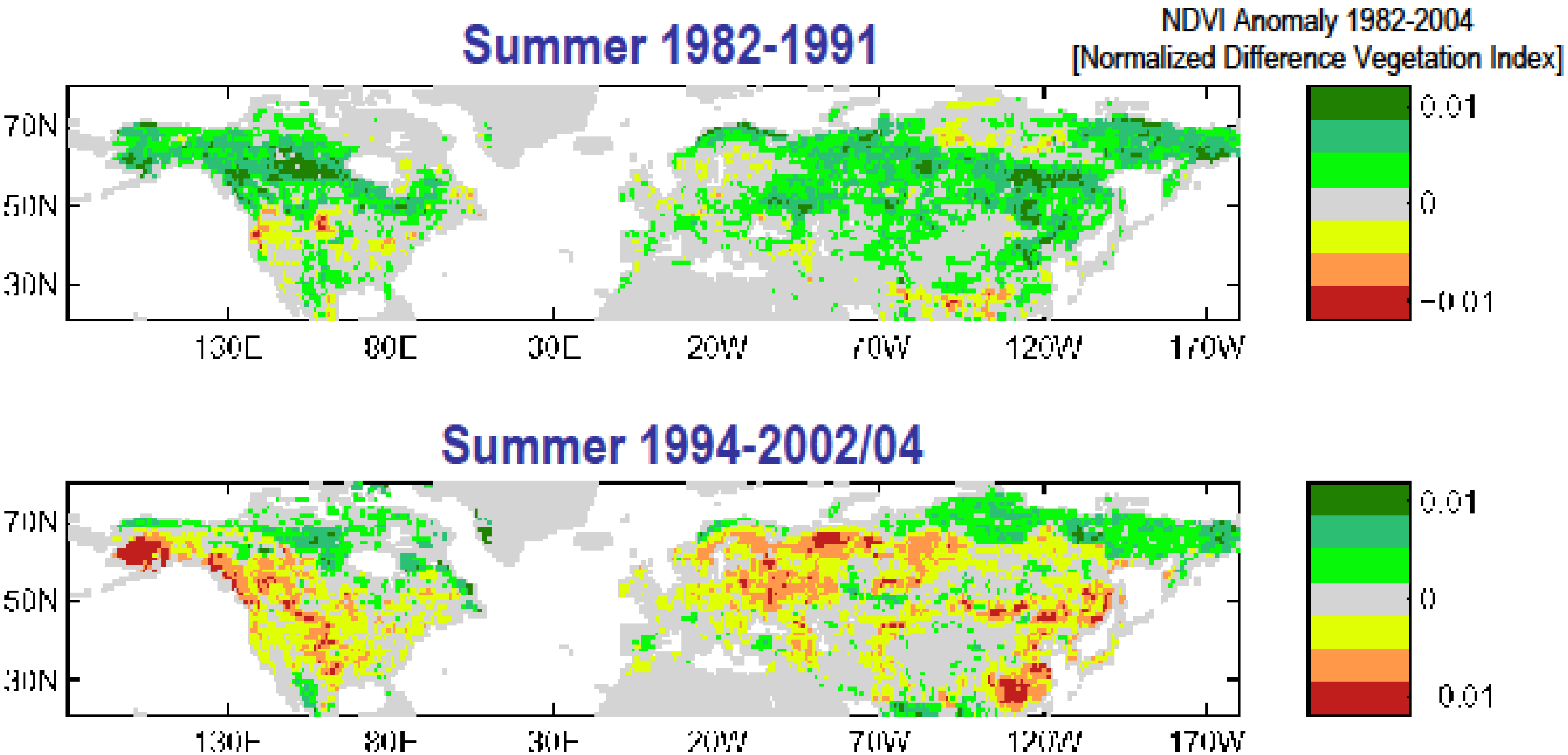


Consequences of Climate-Induced Tree Mortality



干旱减弱北半球中纬度地区 碳汇

A number of major droughts in mid-latitudes have contributed to the weakening of the growth rate of terrestrial carbon sinks in these regions.



Angert et al. 2005, PNAS; Buermann et al. 2007, PNAS; Ciais et al. 2005, Science

New Phytologist
Research

Drought–mortality relationships for tropical forests

Oliver L. Phillips[1], Geertje van der Heijden[1], Simon L. Lewis[1], Gabriela López-González[1], Luiz E. O. C.

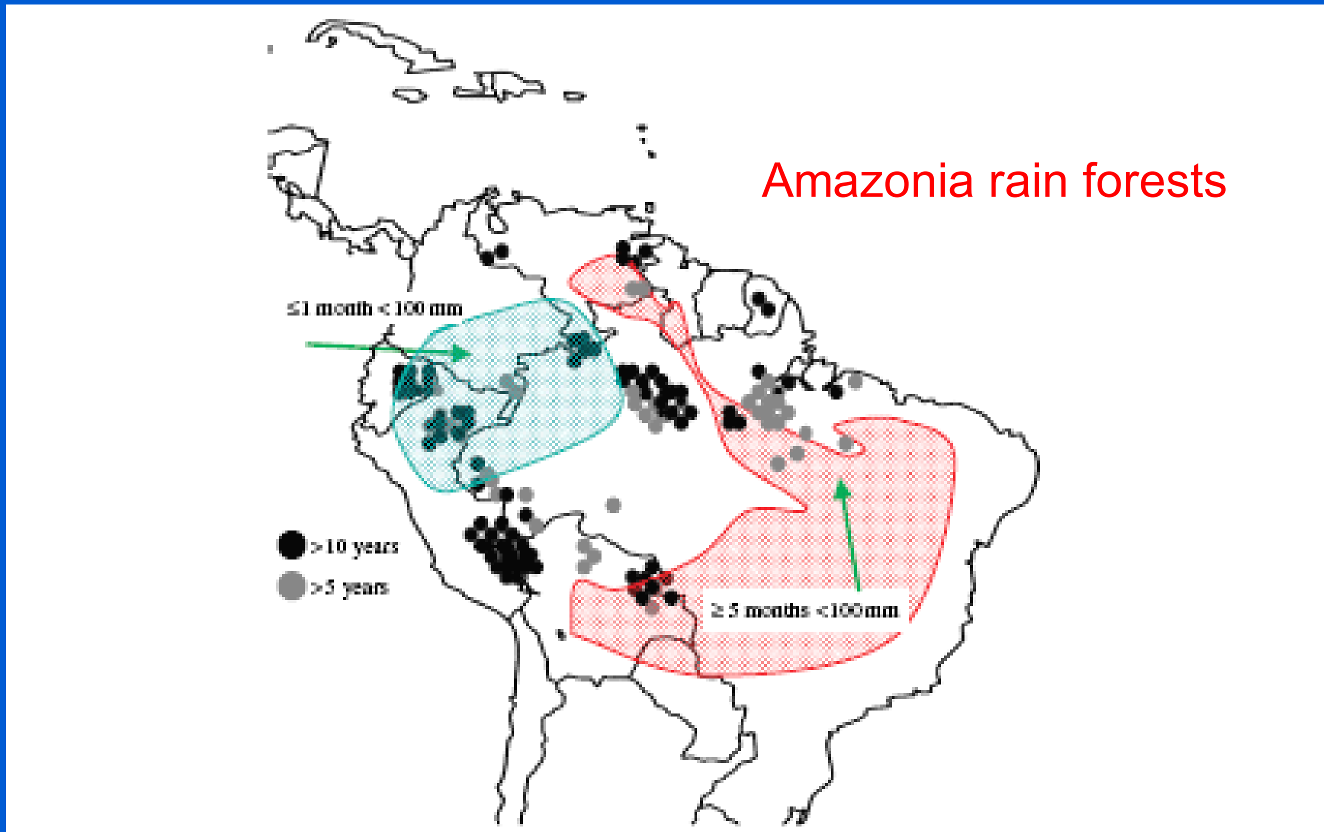
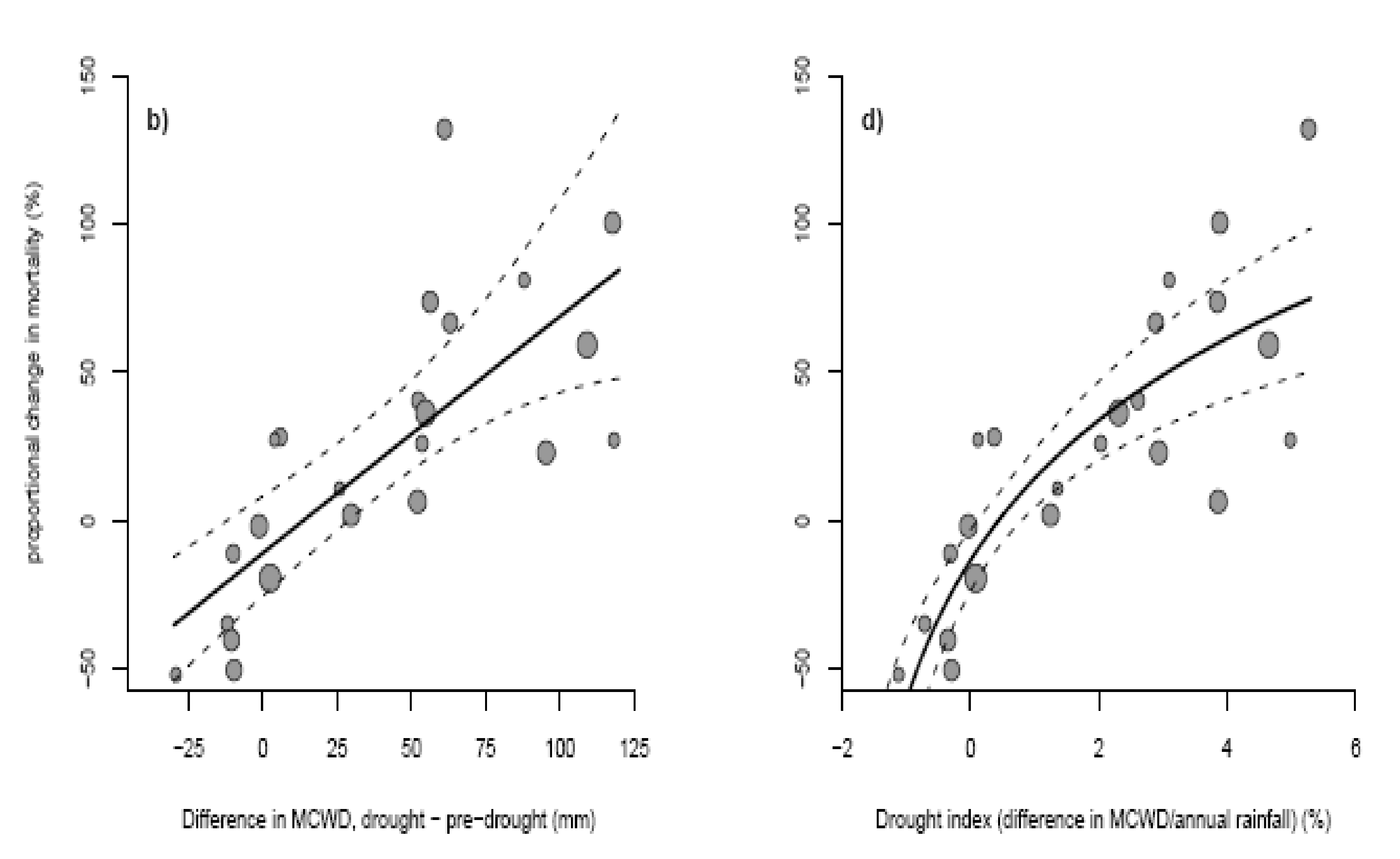


Figure 1. Plot locations. Symbols represent approximate locations of each plot: grey circles for plots monitored for 5–10 years and black circles for those with more than 10 years of monitoring (Phillips et al, 2008)

Change (%) in Mortality



MCWD (maximum climatic water deficit)

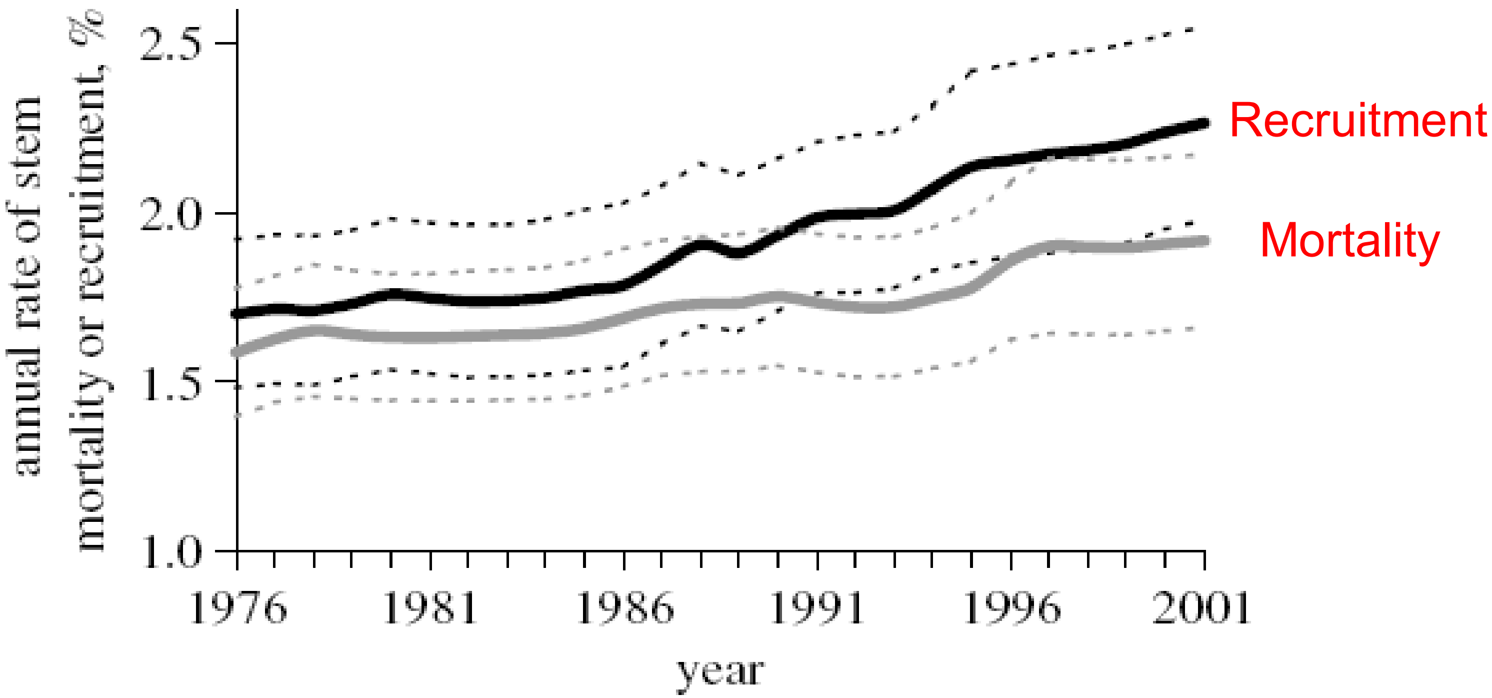
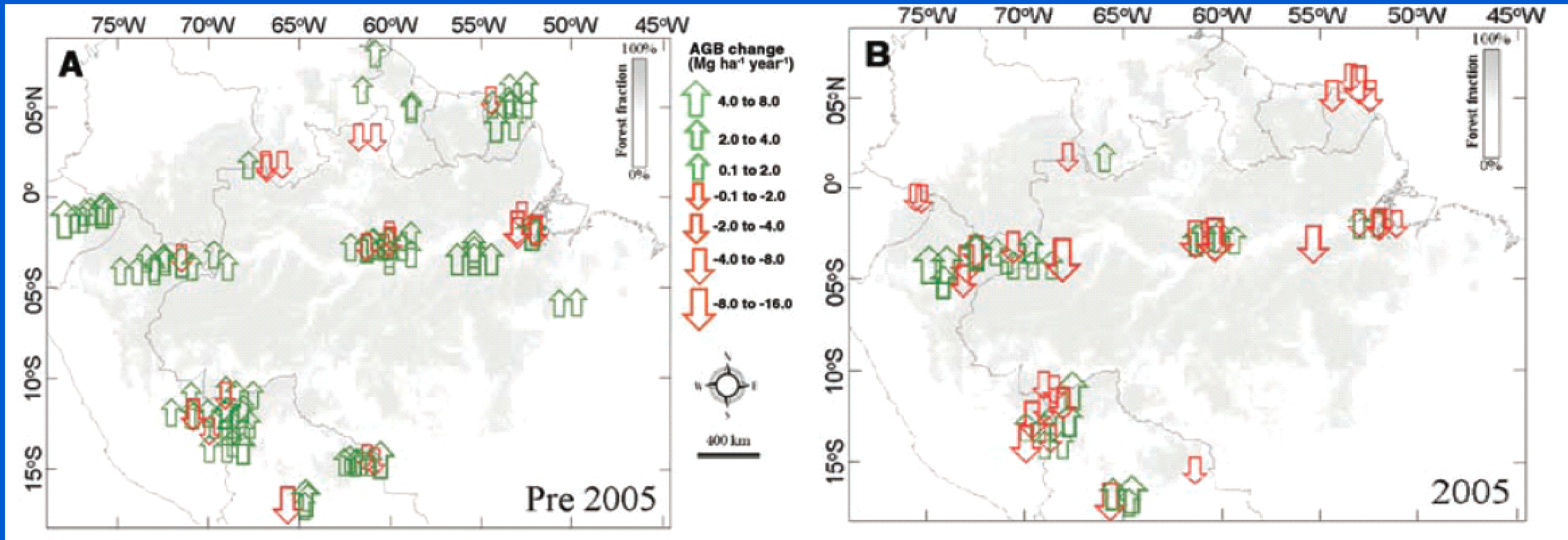
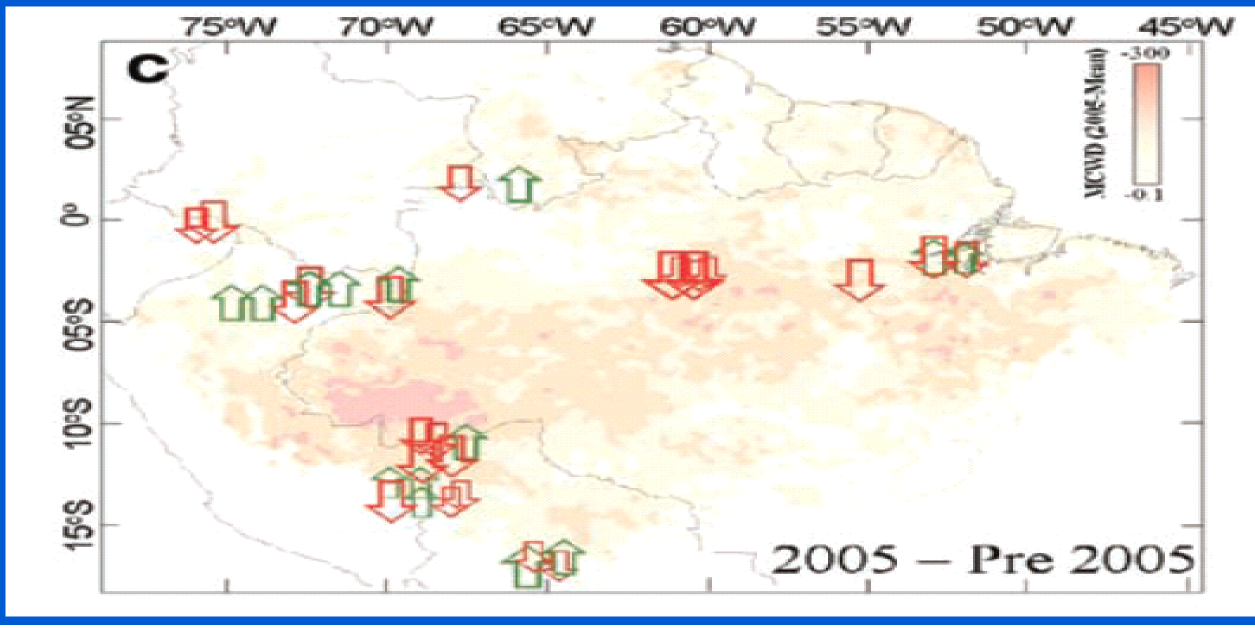


Figure 4. Mean and 95% CIs for stem recruitment and mortality rates against calendar year, for plots across Amazonia. Black lines indicate recruitment and grey lines indicate mortality; solid lines are means and dotted lines are 95% CIs. Rates were corrected for the effects of differing census-interval lengths, for site-switching and possible 'majestic-forest bias' (Phillips *et al.* 2004). All trends hold if these corrections are not applied.

Drought effects (2005) on Aboveground biomass of Amazon Rainforests





(Phillips et al, 2009, Science)

BREVIA

(4 FEBRUARY 2011 VOL 331 SCIENCE)

The 2010 Amazon Drought

Simon L. Lewis,[1*†] Paulo M. Brando,[2,3*] Oliver L. Phillips,[1]
Geertje M. F. van der Heijden,[4] Daniel Nepstad[2]

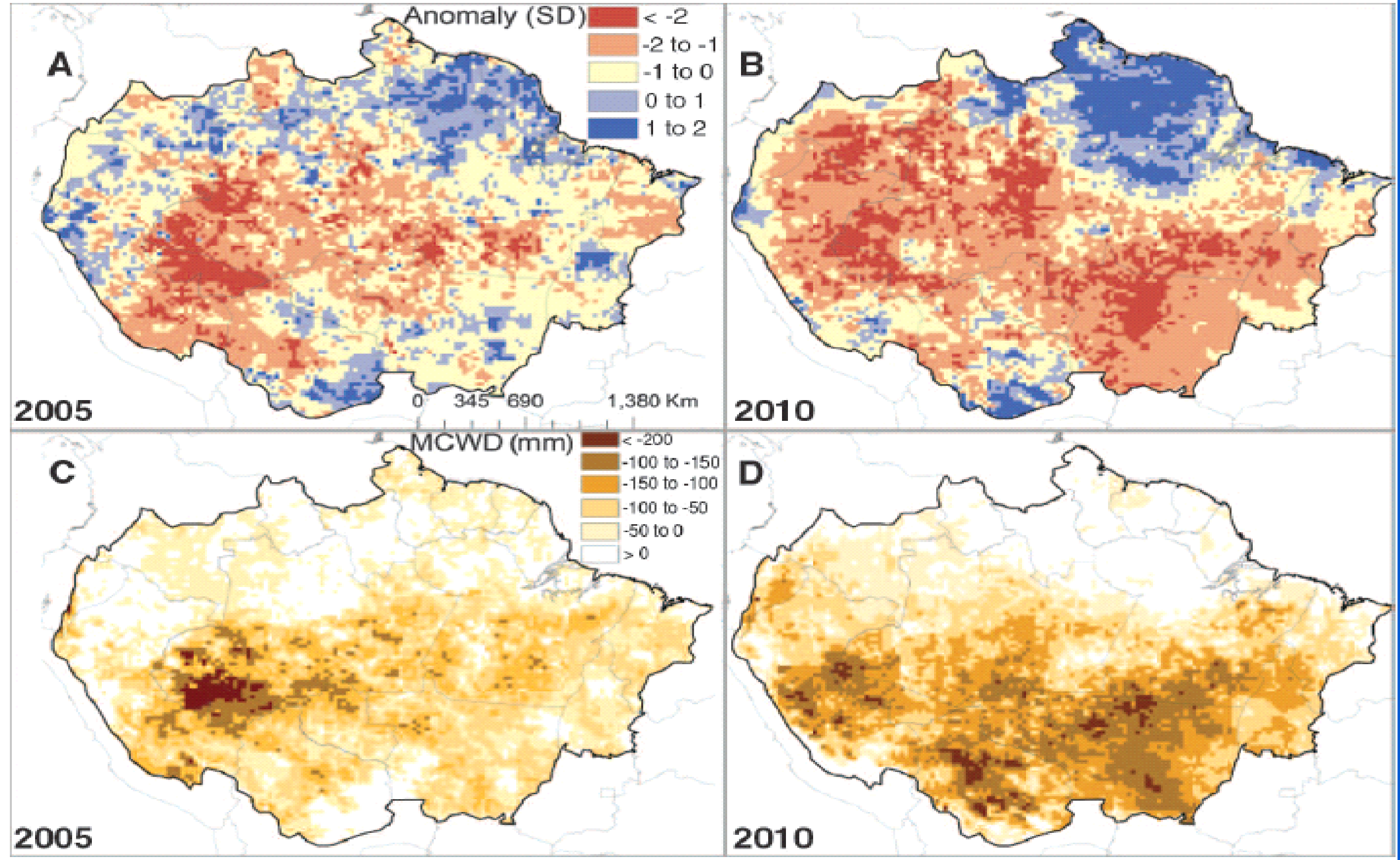
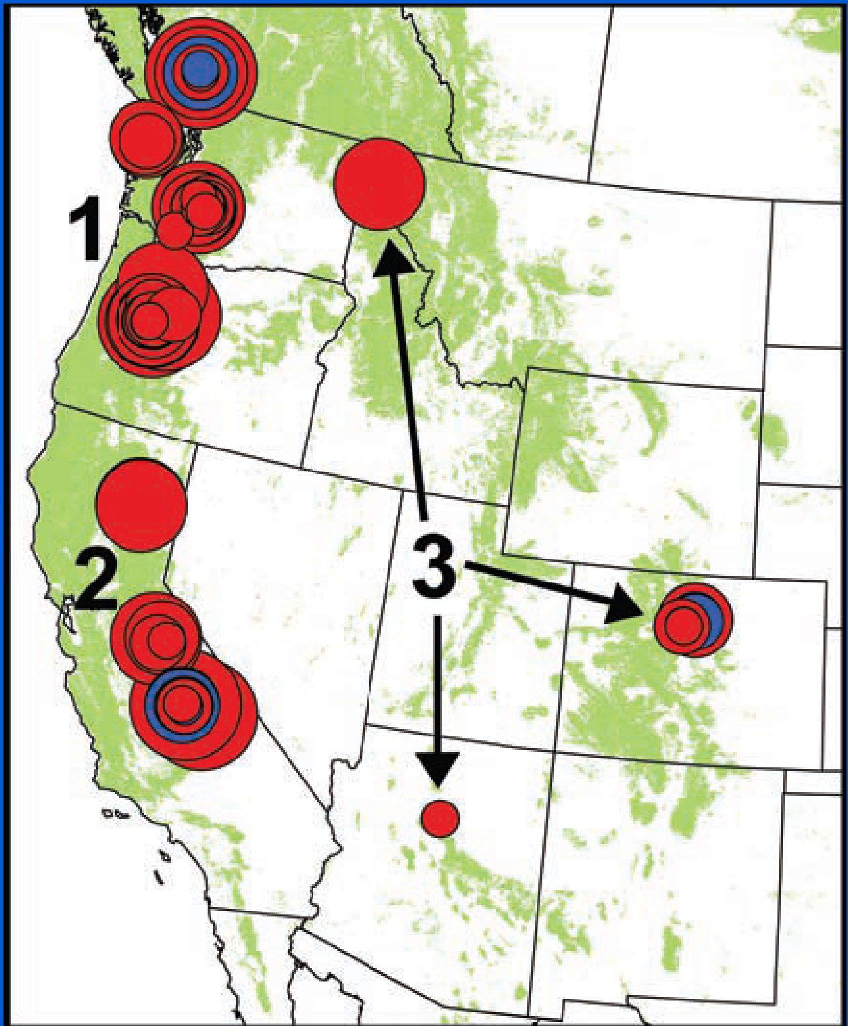


Fig. 1. (A and B) Satellite-derived standardized anomalies for dry-season rainfall for the two most extensive droughts of the 21st century in Amazonia. (C and D) The difference in the 12-month (October to September) MCWD from the decadal mean (excluding 2005 and 2010), a measure of drought intensity that correlates with tree mortality. (A) and (C) show the 2005 drought; (B) and (D) show the 2010 drought.

Fig. Locations of the 76 forest plots in the western United States and southwestern British Columbia



.

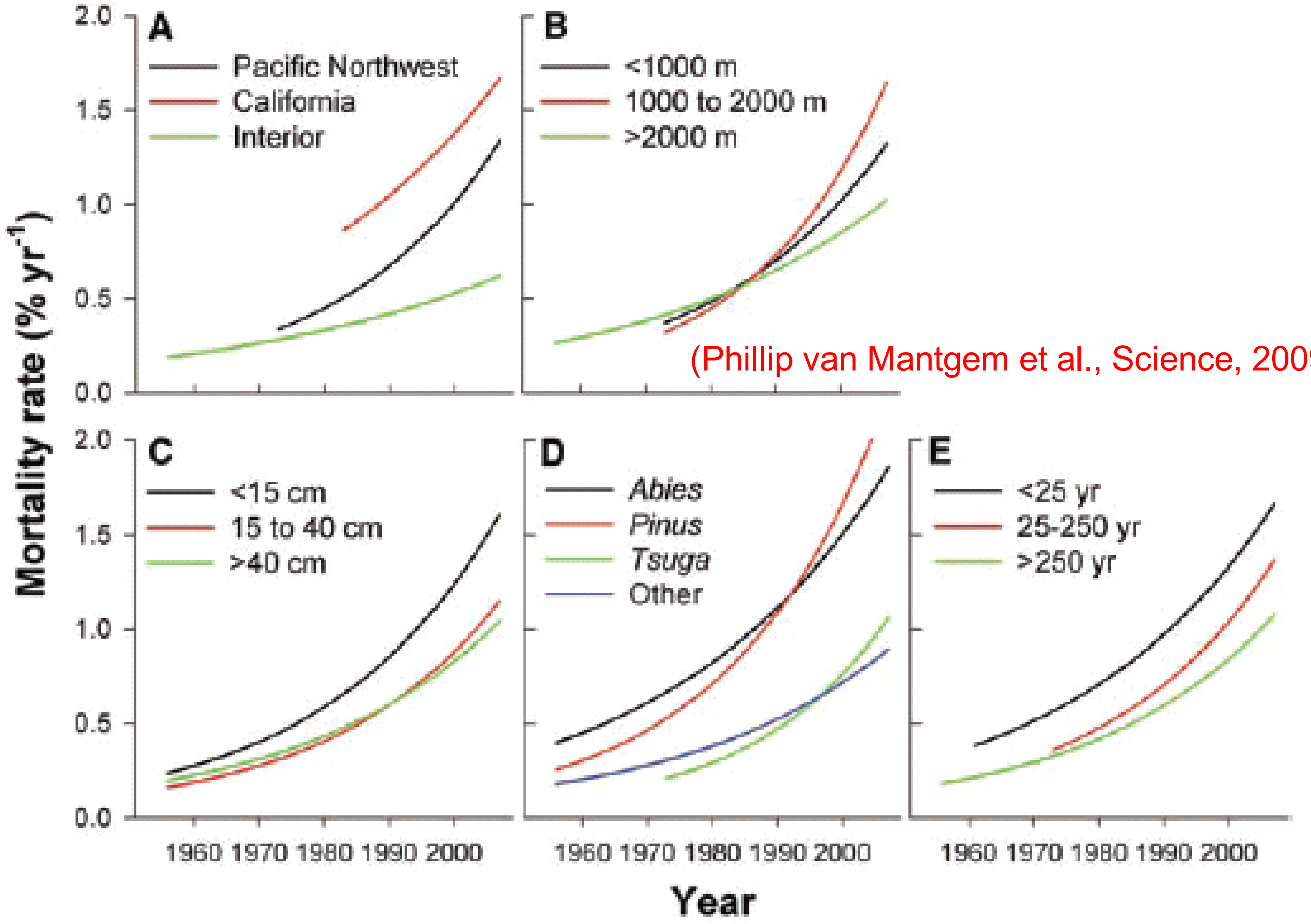
Red and blue symbols indicate, plots with increasing or decreasing mortality rates.

Symbol size: change in mortality rate
Smallest: <0.025 year−1;
Largest : >0.100 year−1;

Numerals indicate 3 groups of plots: region:
(1) Pacific Northwest,
(2) California,
(3) interior.

Forest cover is shown in green.

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



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

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.

Table 1. Fixed effects of generalized nonlinear mixed models describing mortality rate trends (*10*); *a* is the estimated annual fractional change in mortality rate (*10*) and *n* is the number of forest plots used in the model.

Model	Data	*a*	SE	*P*	*n*
Mortality trend	All plots	0.039	0.005	<0.0001	76
Mortality trend by region	Pacific Northwest	0.042	0.006	<0.0001	47
	California	0.028	0.009	0.0050	20
	Interior	0.024	0.009	0.0319	9
Mortality trend by elevation class	<1000 m	0.038	0.007	<0.0001	33
	1000 to 2000 m	0.050	0.010	<0.0001	20
	>2000 m	0.027	0.006	0.0003	23
Mortality trend by stem diameter class	<15 cm	0.039	0.006	<0.0001	61
	15 to 40 cm	0.040	0.006	<0.0001	76
	>40 cm	0.033	0.007	<0.0001	76
Mortality trend by genus	*Abies*	0.031	0.010	0.0025	62
	Pinus	0.044	0.010	<0.0001	37
	Tsuga	0.049	0.009	<0.0001	47
	All other genera	0.032	0.008	<0.0001	64
Mortality trend by fire return interval	<25 years	0.033	0.008	0.0009	15
	25 to 250 years	0.040	0.006	<0.0001	32
	>250 years	0.036	0.010	0.0008	29

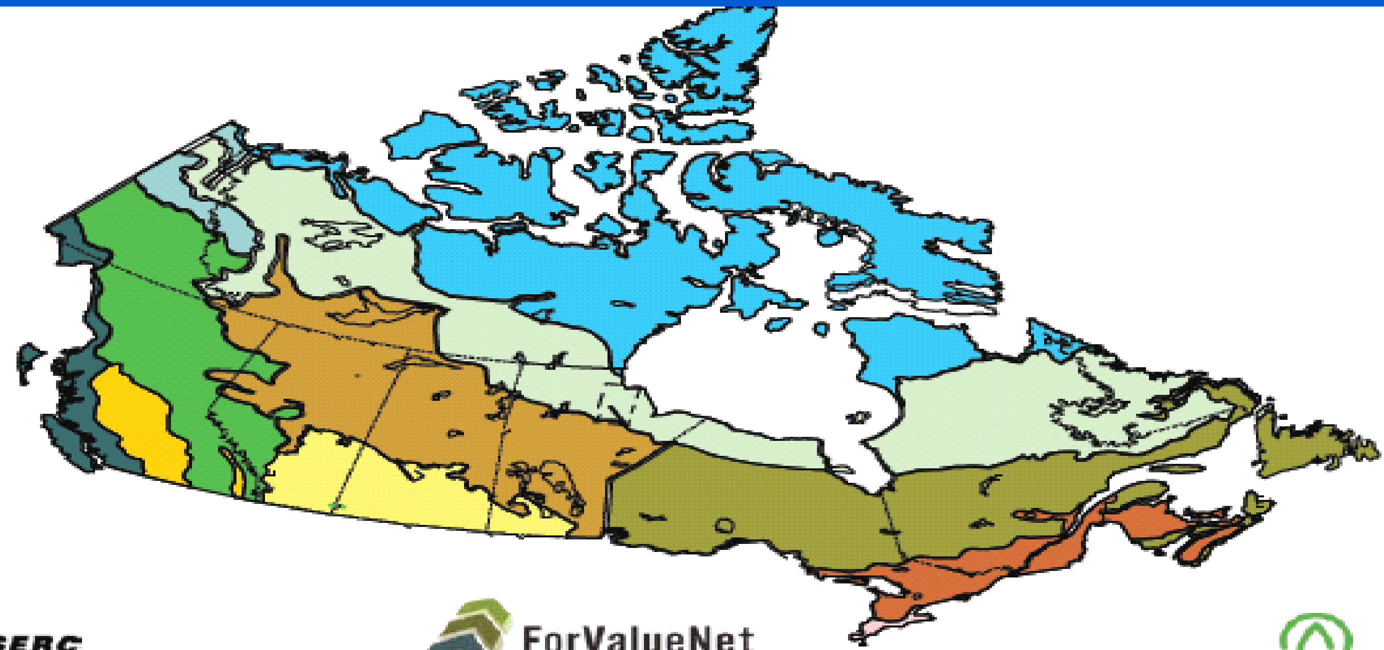
nature climate change

LETTERS

PUBLISHED ONLINE: 20 NOVEMBER 2011 | DOI: 10.1038/NCLIMATE1293

A drought-induced pervasive increase in tree mortality across Canada's boreal forests

Changhui Peng[1,2]*, Zhihai Ma[1], Xiangdong Lei[1,3], Qiuan Zhu[1,2], Huai Chen[1,2], Weifeng Wang[1], Shirong Liu[4], Weizhong Li[1,2], Xiuqin Fang[1] and Xiaolu Zhou[1]



NSERC CRSNG

ForValueNet ForêtValeur

FPInnovations

Data Sources and selection:

Total > 16,000 permanent sample plots (PSPs) available:

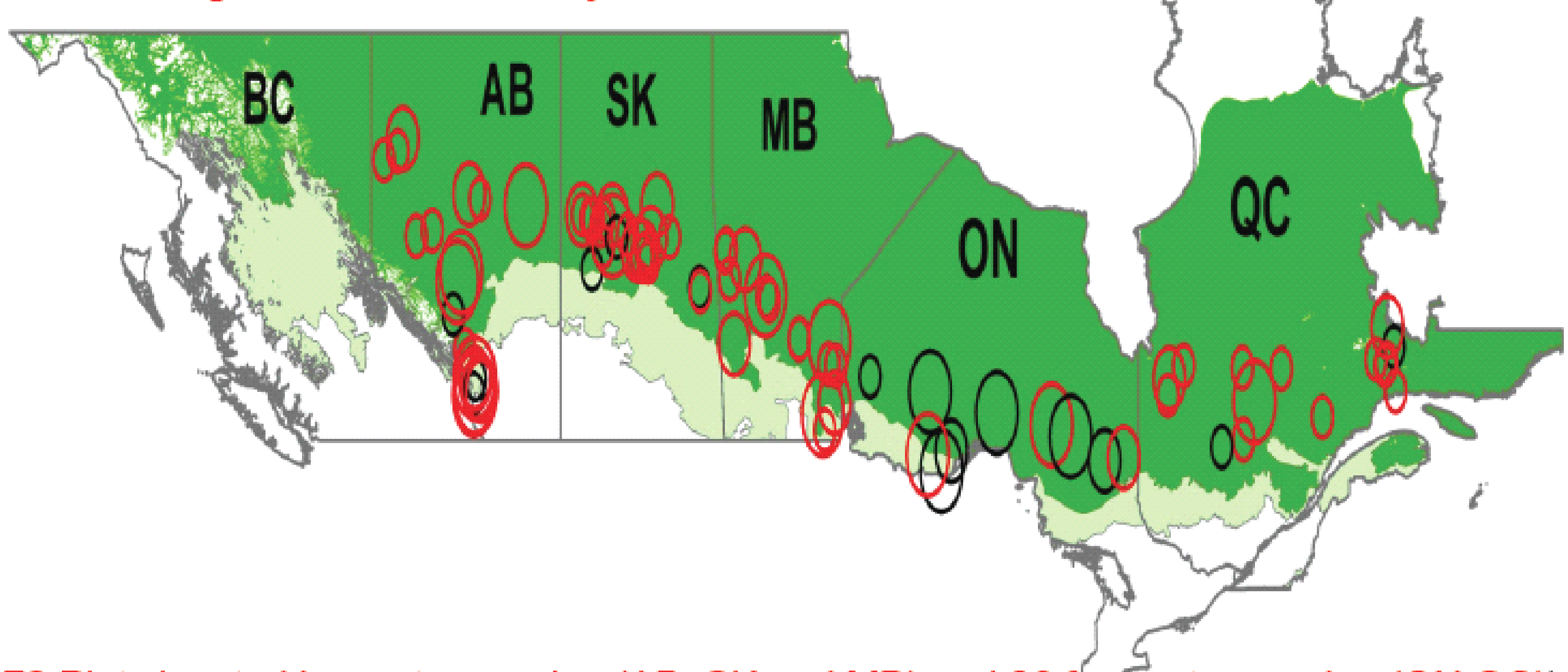
(Including Alberta (580 plots), Saskatchewan (2426), Manitoba (368), Ontario 4000), and Quebec (12 000)

Selected Total 96 PSPs with following 6 criteria：

1)Natural forest stands (without forest managements, fire, flood, storm, or insect disturbances)
2) 3 consecutive censuses on both recruitment and mortality rates
3)> 10 years of observations between their first and last census
4) Stand age was ≥ 80 years (assuming mature forests)
5) with a large enough number of live trees (≥ 80)
6) with spatial location (long. ,lati.)

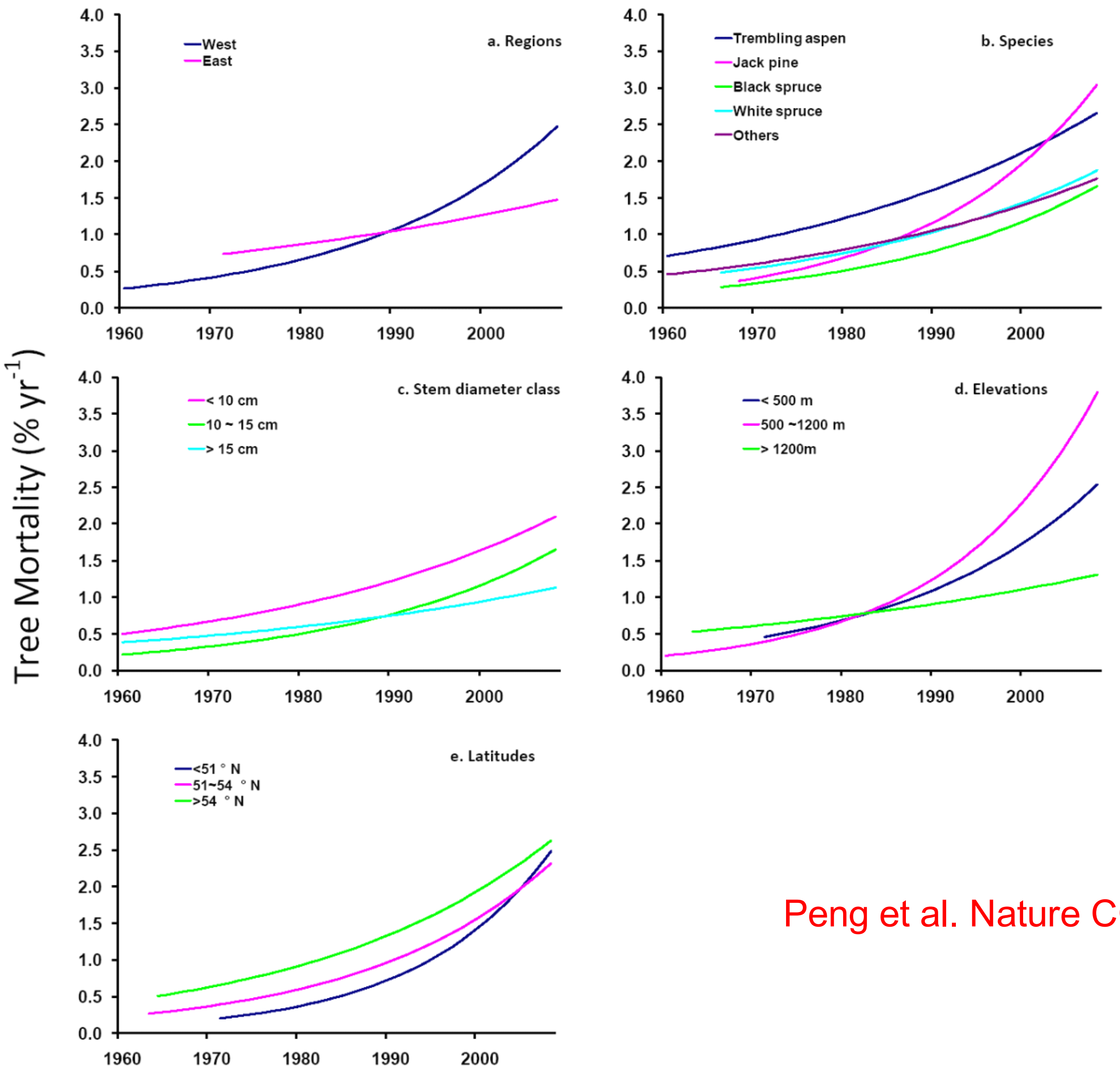
(Peng et al., Nature Climate Change, 2011)

Changes in Tree Mortality for Canadian Boreal Forests since 1963



70 Plots located in western region (AB, SK and MB) and 26 for eastern region (ON,QC))

The red and black circles represent plots with increasing and decreasing mortality rate respectively. Circle size corresponds to annual fractional change in mortality rates (smallest symbol, <0.05 year^{-1}; largest symbol, >0.1 year^{-1}; medium symbol, 0.05~0.1 year^{-1})

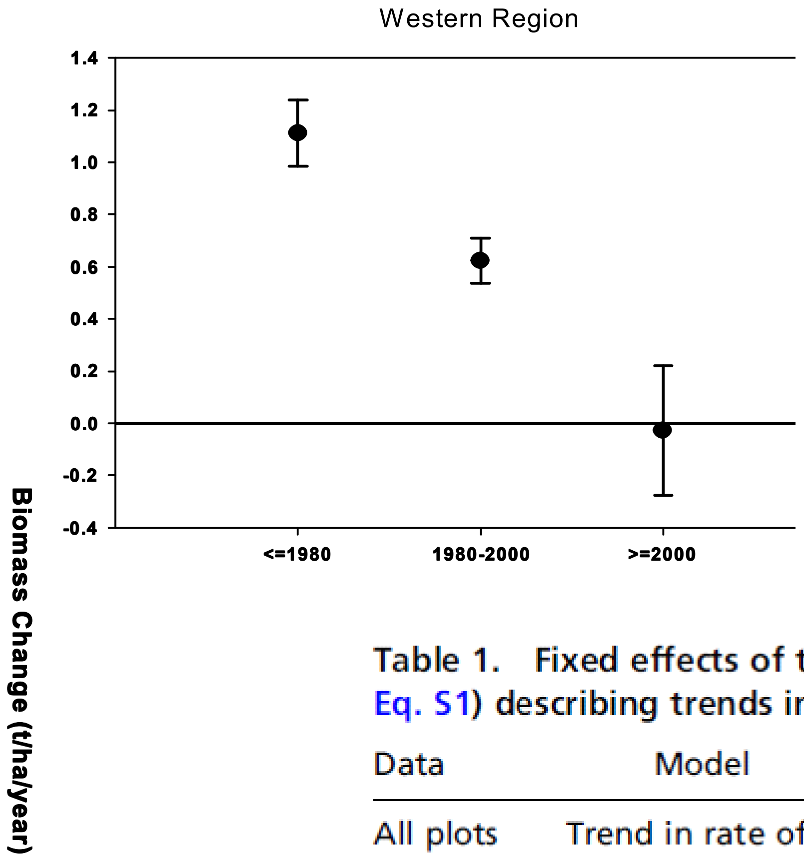


Peng et al. Nature CC,(2011)

Main findings (1):

We found that tree mortality rates increased by an overall average of 4.7% per year from 1963 to 2008, with higher mortality rate increases in western regions than in eastern regions (about 4.9 and 1.9% per year, respectively). The water stress created by regional drought may be the dominant contributor to these widespread increases in tree mortality rates across tree species, sizes, elevations, longitudes, and latitudes. Western Canada appears to have been more sensitive to drought than eastern Canada.

(Peng et al., Nature Climate Change, 2011)



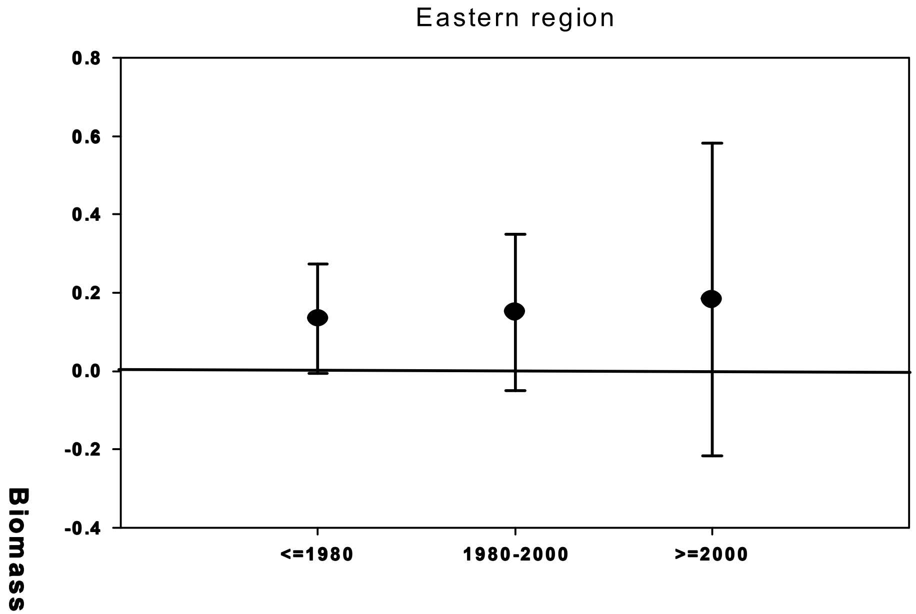
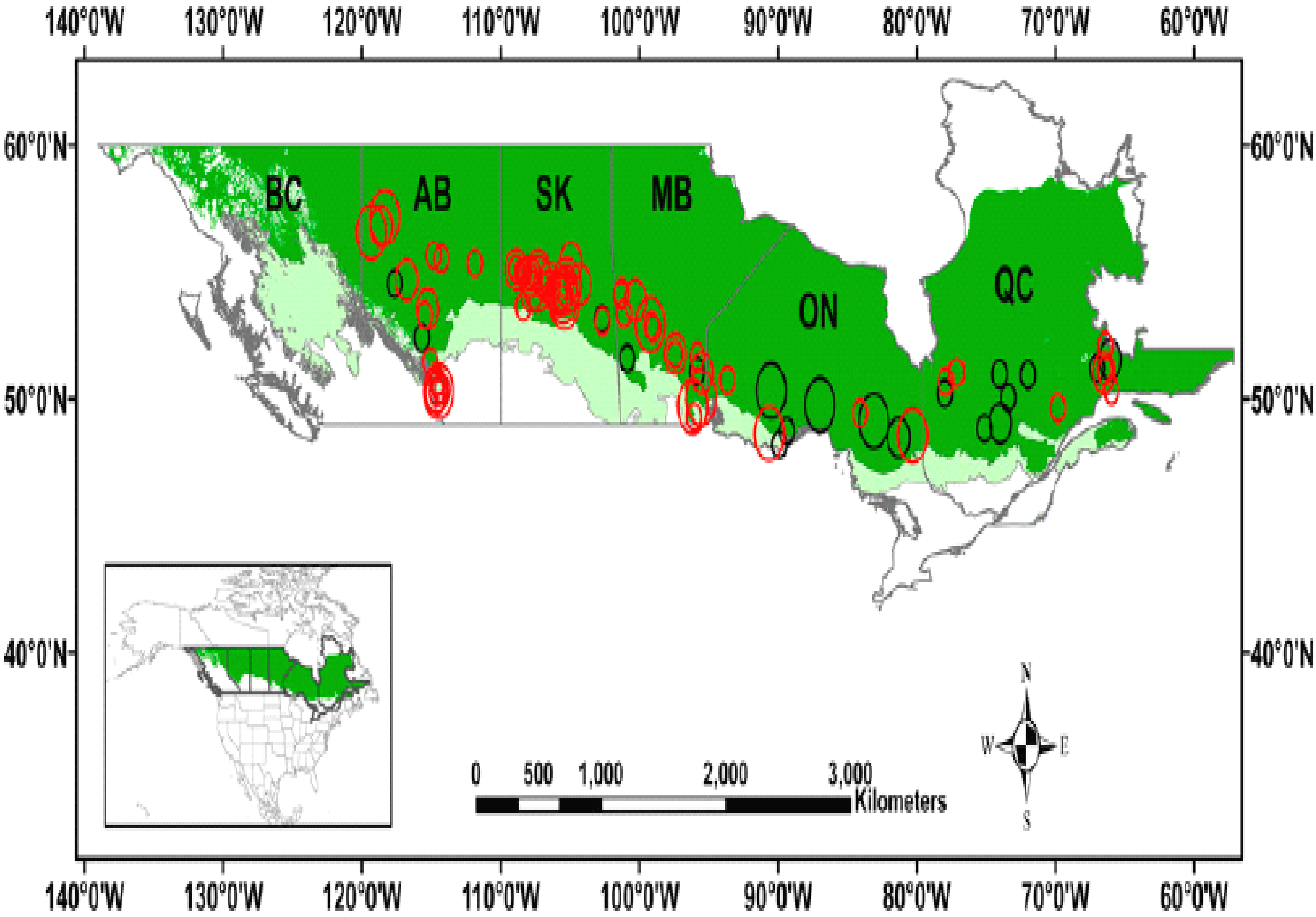


Table 1. Fixed effects of the linear mixed models (*SI Appendix*, Eq. S1) describing trends in the rate of biomass change

Data	Model	β_1	SE	*P*	*n*
All plots	Trend in rate of biomass change	−0.0514	0.0105	<0.0001	96
Western region	Trend in rate of biomass change	−0.0694	0.0117	<0.0001	70
Eastern region	Trend in rate of biomass change	0.0061	0.0229	0.7922	26

β_1 is the slope and represents the annual rate of change in biomass ($t\ ha^{-1}\ year^{-1}\ year^{-1}$), *n* is the number of forest plots used in the model, and *P* is the significance level for the model's fixed effects based on a *t* test. The dataset used for fitting the linear mixed models is not the dataset to estimate the average trend dot values in Fig. 2*A*.

(Ma, Peng et al., PNAS, 2012)


140°0'W
130°0'W
120°0'W
110°0'W
100°0'W
90°0'W
80°0'W
70°0'W
60°0'W
60°0'N
50°0'N
40°0'N
BC
AB
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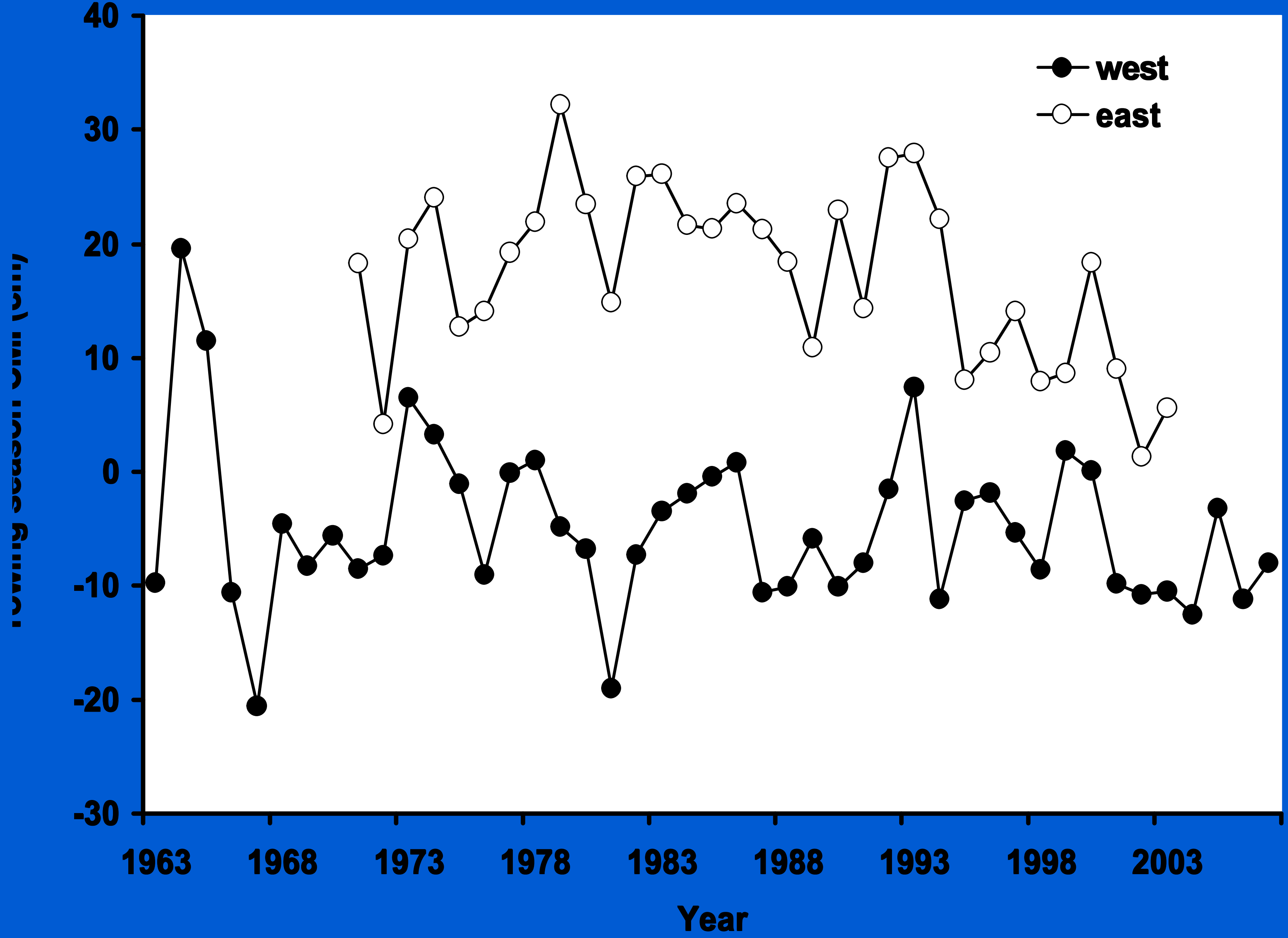
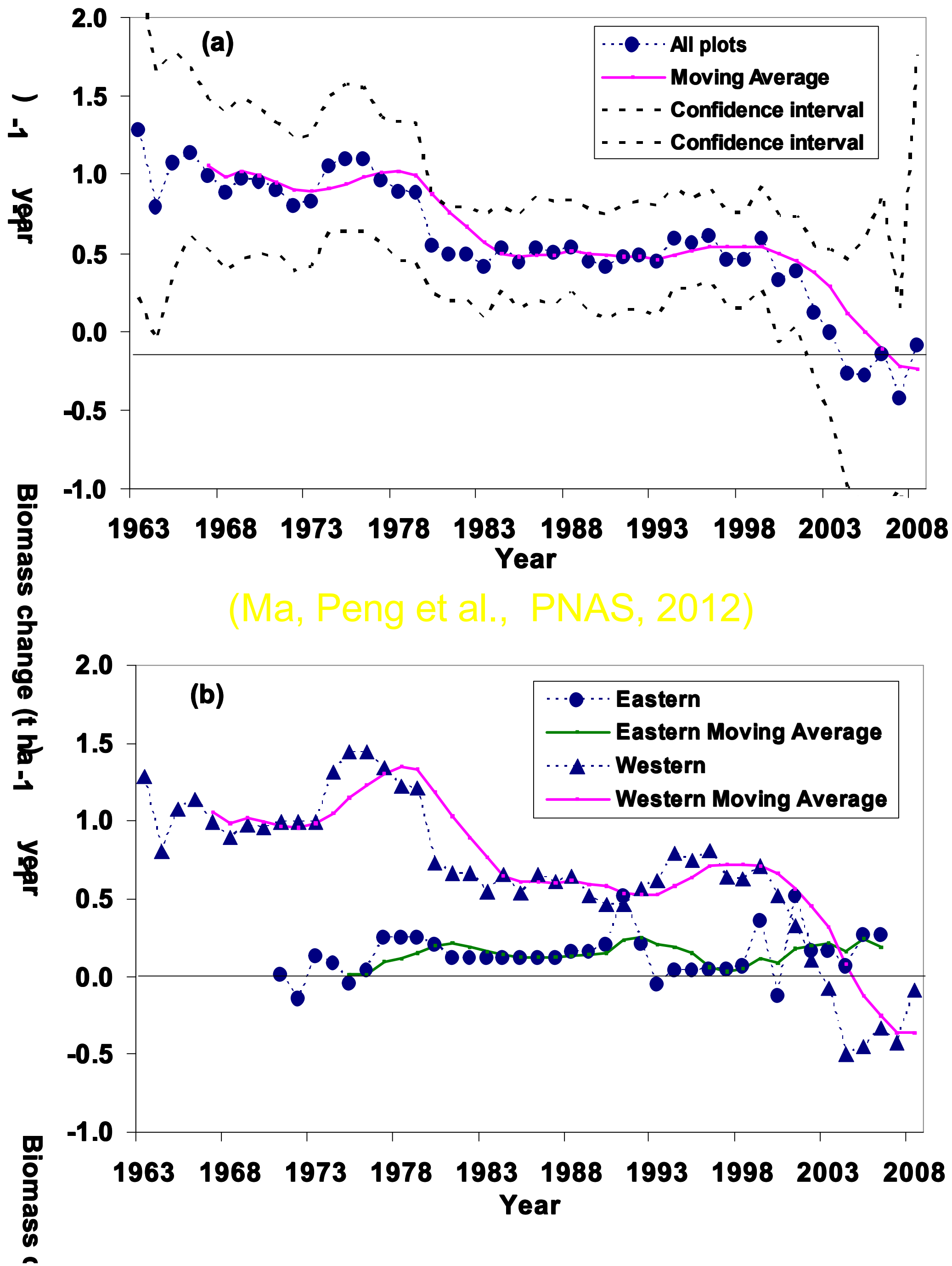


Figure S3. Comparison of averaged climate moisture index (CMI) for growing season from May to September between Western Canada (west) and Eastern Canada (east) since 1963.



(Ma, Peng et al., PNAS, 2012)

Main findings (2):

- We found that in recent decades, the rate of biomass change decreased significantly in western Canada (Alberta, Saskatchewan, and Manitoba), but there was no significant trend for eastern Canada (Ontario and Quebec).

- Our results revealed that recent climate change, and especially drought-induced water stress, is the dominant cause of the observed reduction in the biomass carbon sink, suggesting that western Canada's boreal forests may become net carbon sources if the climate change–induced droughts continue to intensify.

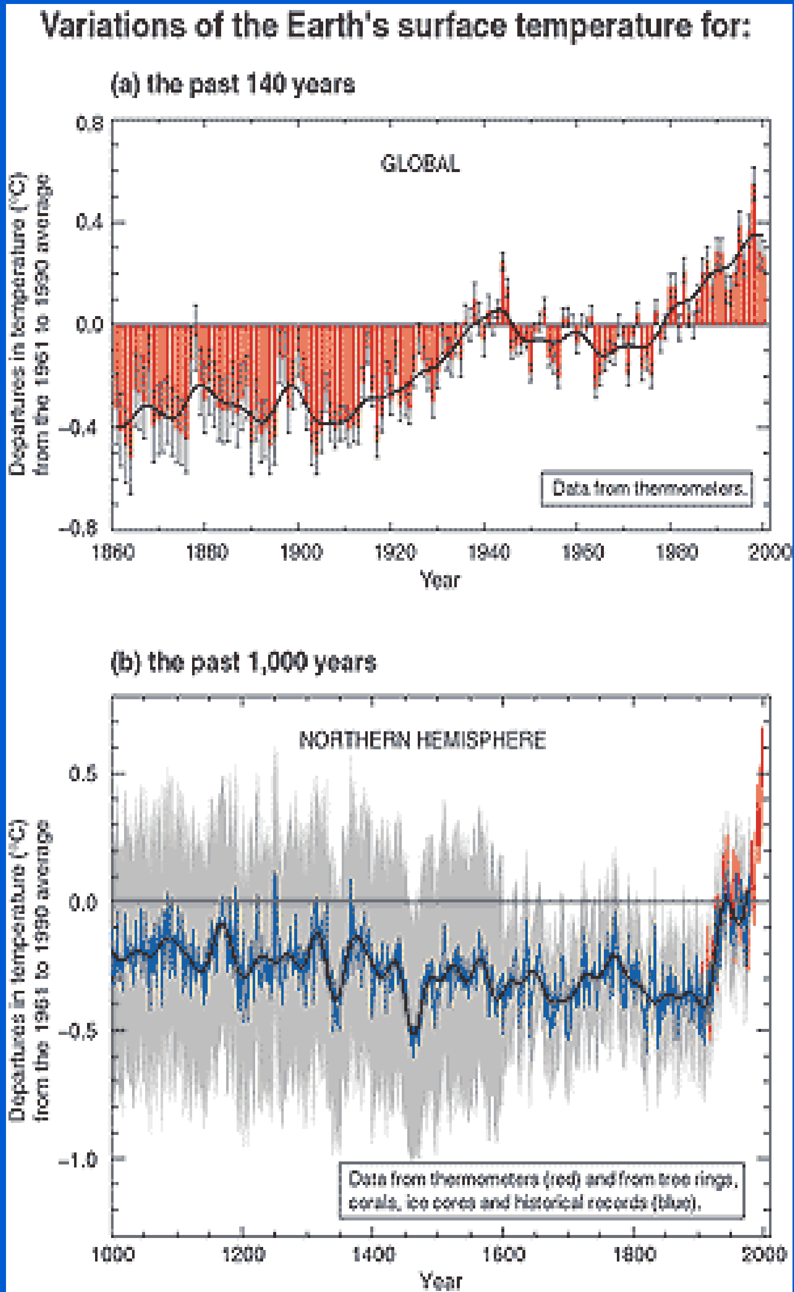
(Ma, Peng et al., *PNAS*, 2012)

Observational evidence to support the idea of a reduction of carbon sinks caused by drought in northern terrestrial ecosystems

- Two major droughts(2005 and 2010) in a decade may largely offset the net gains of ~0.4 Pg C year−1 in intact Amazon forest aboveground biomass in nondrought years. (Lewis et al. Science, 2011)

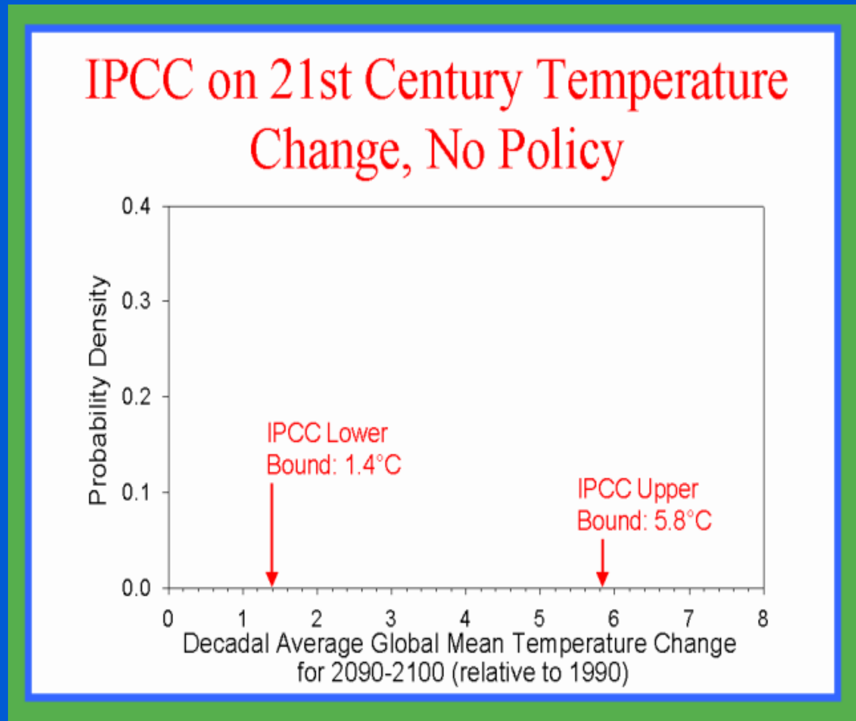
- Droughts in 2002 and 2006 reduced the U.S. carbon sink by ~ 20% (0.12 Pg C year−1) relative to a normal year. (Disturbances including wildfires and hurricanes reduced carbon uptake or resulted in carbon release at regional scales (Xiao et al, A. F.M. 151: 60-69, 2011)

- Decrease in biomass in Canadian boreal forest is equivalent to a net decrease in the carbon sink of 7.89±3.22 Mt C $year^{-1}$, which is equivalent to about 3.9% of Canada's total annual carbon emission (Peng et al., Nature CC, Ma et al., PNAS, 2011)

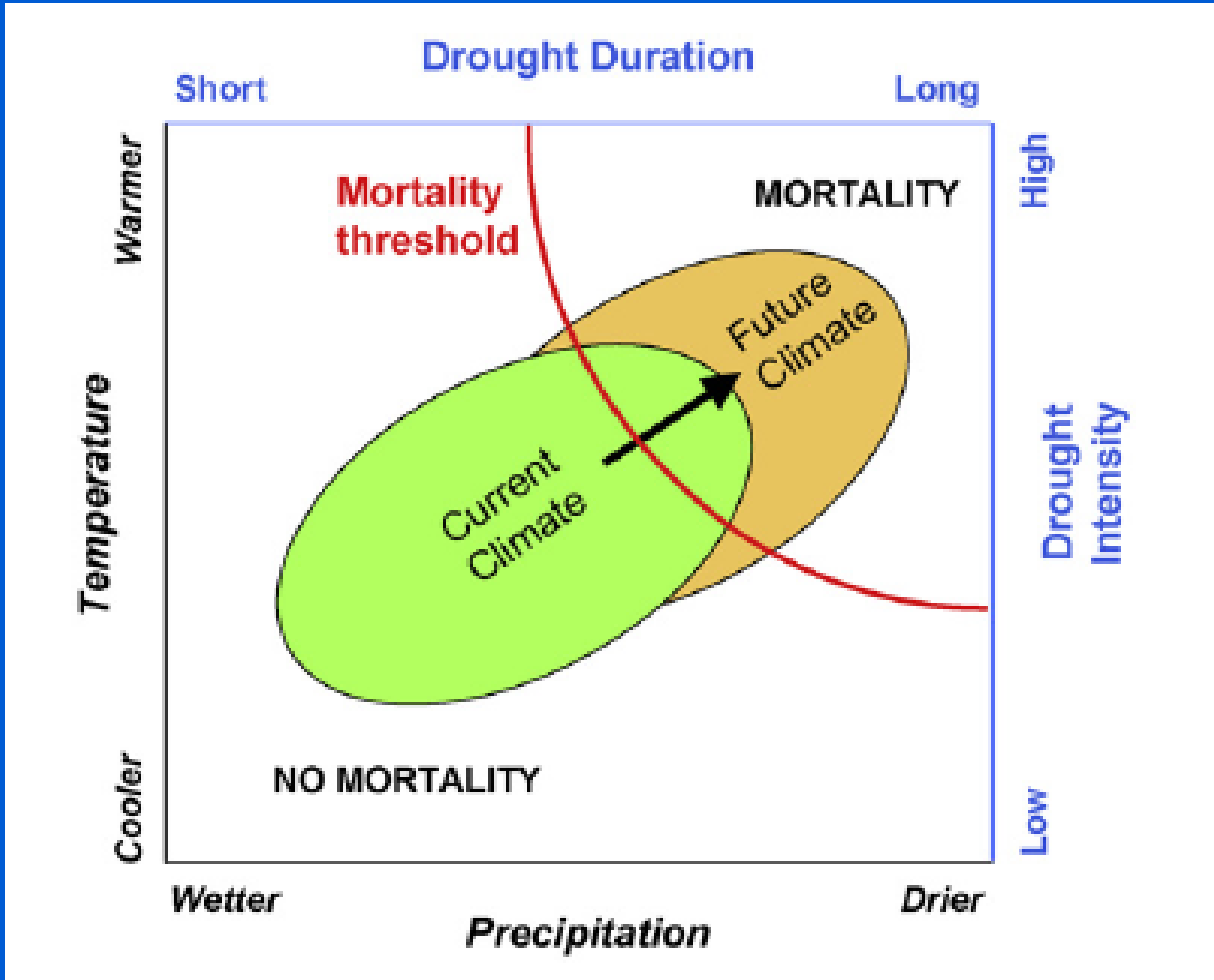


"Global warming continues"

(Hansen et al., 2002; *Science,* 295, 275)



IPCC Third Assessment Report (TAR)
WMO, (2001)



Allen et al., 2010

Current limitations and Uncertainties

- Despite many national and even regional forest monitoring efforts, there is an absence of adequate global data on forest health status

- Lacking a fundamental mechanistic understanding of mortality at all spatial scales, from the level of individual trees, through forest stands, to regional landscapes.

- Lacking adequate knowledge of the feedback and non-linear interactions between climate-induced forest stress, insect outbreaks and fire, that can cause widespread forest mortality

- Lacking the ability to predict mortality and die-off of tree species and forest types based on specific combinations of climatic events and their interactions with biotic stressors and place-specific site conditions.

Research Needs and Ongoing Challenges:

- An improved network of observations, both ground-based and remotely sensed, is needed to document tree mortality annually

- Improved experiments assessing mechanisms of tree mortality in relation to climate drivers are needed for more biomes

- Efforts on modelling tree mortality (both observations and experiments must be linked to modeling efforts to improve forecasts).

Box 1. An example of a multi-factor climate extremes field experiment designed to identify thresholds of extreme ecological response.

(Established in May 2010 in USA, 6x24 m in size– two climate extremes – severe drought and heat waves) (Melinda Smith, 2010)

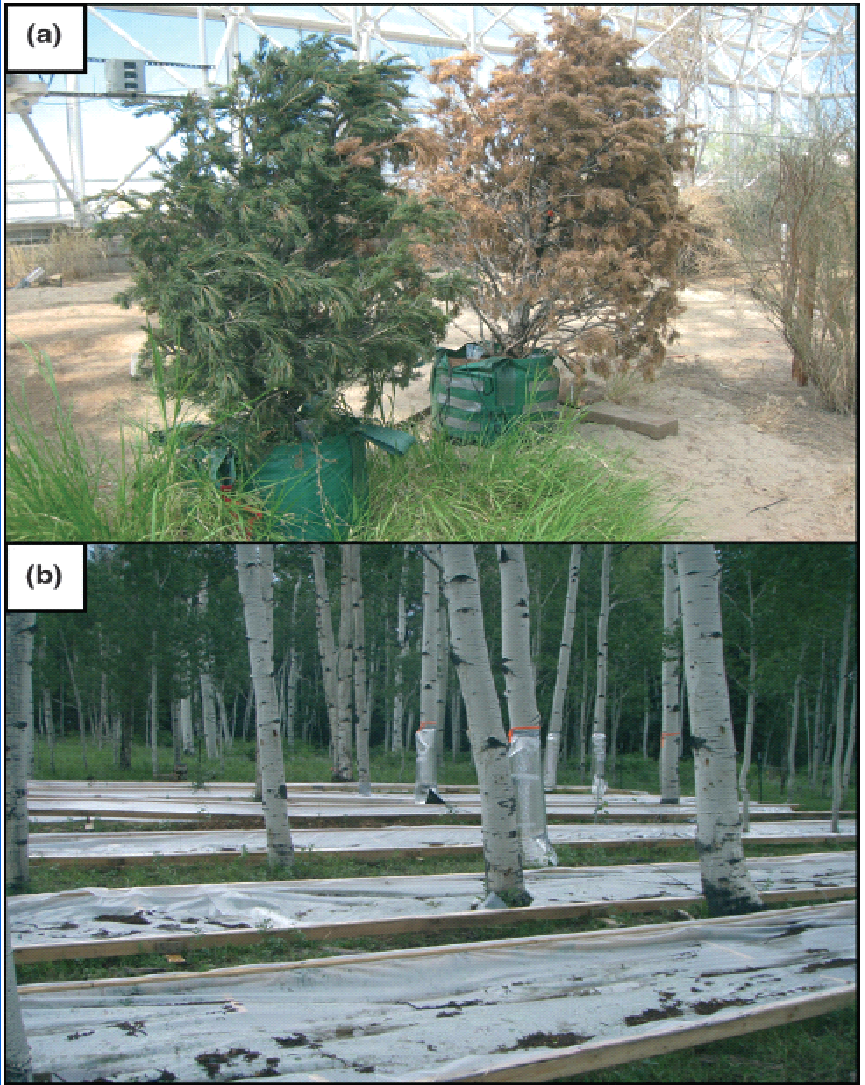


Fig. 1 Photographs of tree drought mortality research presented at the 2011 annual Ecological Society of America meeting. (a) Watered and unwatered piñon pine trees near the end of a drought experiment inside the biosphere 2 glasshouse. (b) A rain-out shelter field drought manipulation in an aspen forest in southwest Colorado. (c) Eucalyptus saplings in a glasshouse drought experiment at the University of Western Sydney, Australia.

96th Annual Meeting, Ecological Society of America in Austin, Texas, August 2011

Zeppel et al 2011, NP

Table I. Plant mortality algorithms from a selection of the most commonly used DGVMs, listed approximately in order of progressive increase in mechanistic detail, with example models cited in the references

Mortality algorithms	Description
Productivity dependence	No explicit concept of mortality; plant biomass reduced via declining productivity [88]
Background rate	Mortality is set at a constant, invariant rate (approximately 1–2% yr^{-1}). This does not allow climate to drive variation in mortality [89–91]. In [12,92], background mortality increases as wood density decreases relative to the community maximum
Climate tolerance	Death occurs if the 20-year average climate exceeds predefined monthly climatic tolerances [93–96]
Size threshold	Death occurs if trunk diameter > 1.0 m [96].
Age threshold	Death increases as stand age approaches the plant functional type-specific maximum [84]
Heat stress threshold	Mortality is a function of the number of days per year in which the average temperature exceeds a threshold temperature, and the number of degrees (°C) by which this threshold is exceeded [84,92–97]
Negative productivity	Death occurs if annual net productivity < 0.0 g [93–96]
Shading/competition	Mortality increases as a function of canopy cover [12,92–97]
Growth efficiency threshold	Mortality occurs when biomass increment per unit leaf area falls below a quantitative threshold that varies between models [86,93–96,98]
Carbon starvation	Mortality is a function of carbohydrate storage per unit leaf biomass [12]

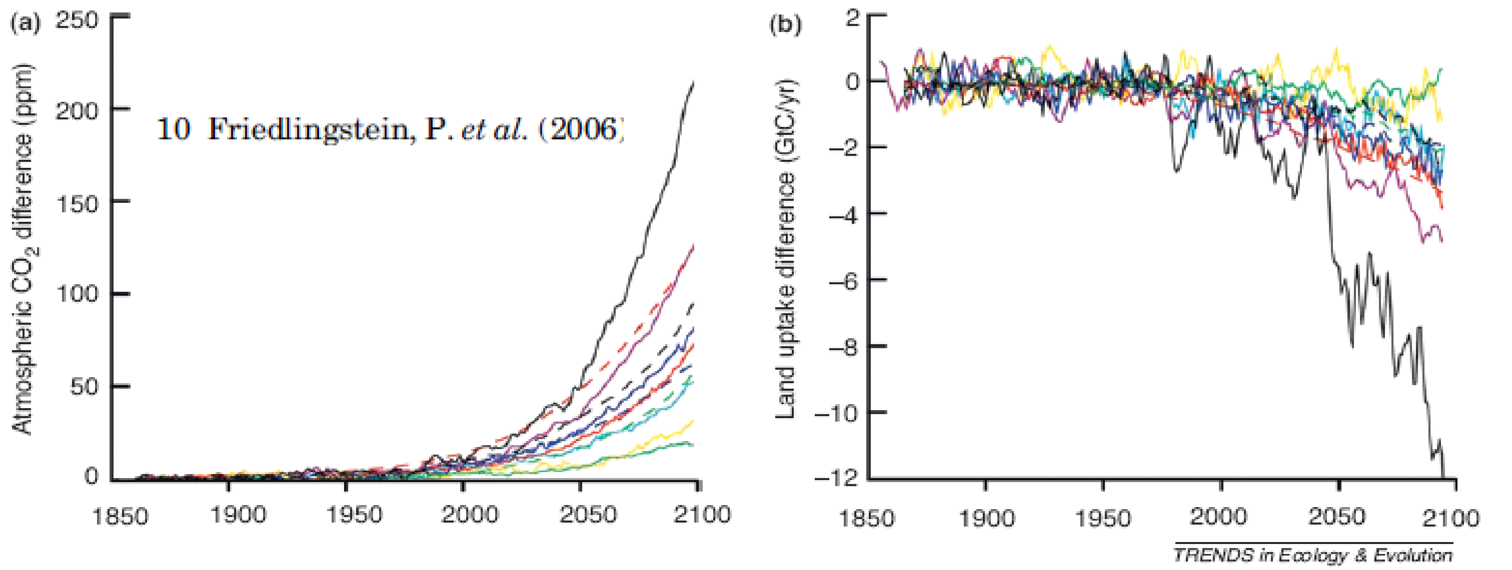


Figure I. Dynamic global vegetation models all simulate a net rise in future atmospheric CO_2 **(a)**, owing to a decline in land carbon uptake **(b)**. The models have wide divergence owing, in part, to the variety of mortality algorithms used [10–12]; see Table I for details on algorithms. Adapted from [10]).

McDowell et al., (2011, TREE)

(Ya-An, Chengdu, China, April 20, 2011)

Key References for further Reading:

1) Allen, C.D., et al. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management,* **259,** 660-684.

2). Peng, C., Ma, Z., et al. 2011. A drought-induced pervasive increase in tree mortality across Canada's boreal forests. *Nature Clim. Change* **1**: 467-471.

3). Ma, Z., Peng, C. et al. 2012. Regional drought-induced reduction in the biomass carbon sink of Canada's boreal forests. *PNAS.* 109(7): 2423–2427.

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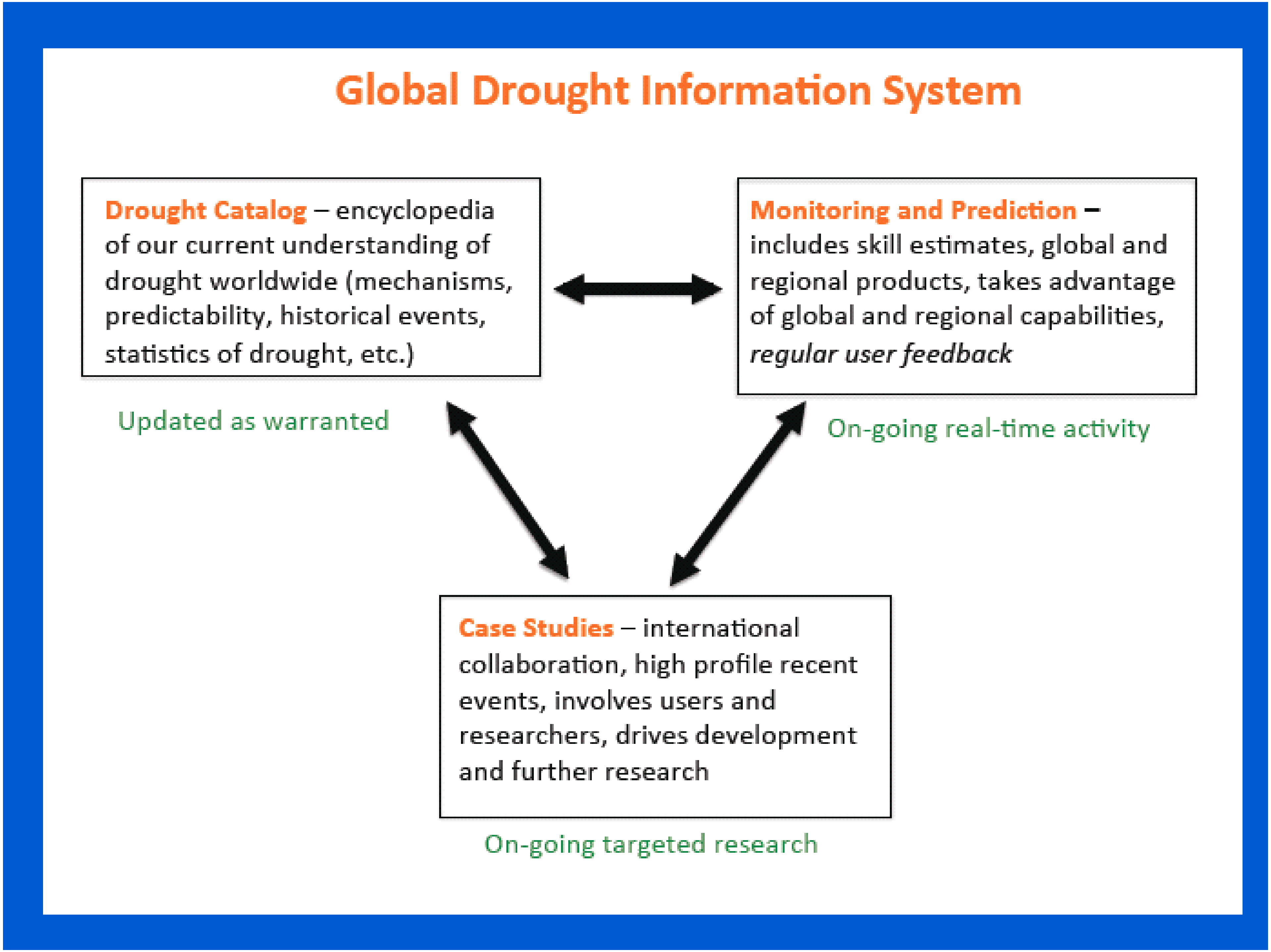
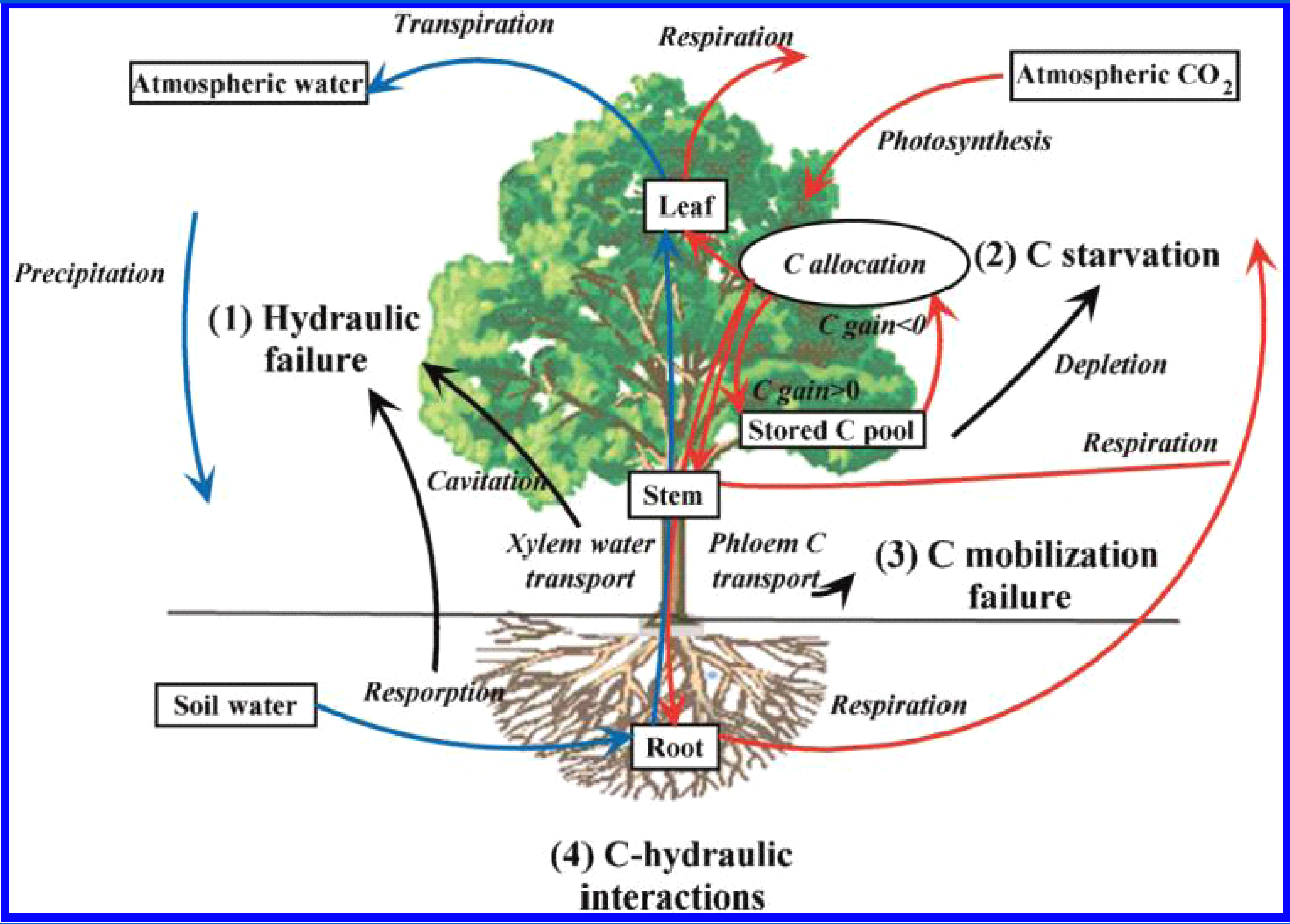
Thank you !
Open for Questions?


Global Drought Information System
Drought Catalog – encyclopedia of our current understanding of drought worldwide (mechanisms, predictability, historical events, statistics of drought, etc.)
Updated as warranted
Monitoring and Prediction – includes skill estimates, global and regional products, takes advantage of global and regional capabilities, regular user feedback
On-going real-time activity
Case Studies – international collaboration, high profile recent events, involves users and researchers, drives development and further research
On-going targeted research



(Wang et al. 2012), ER

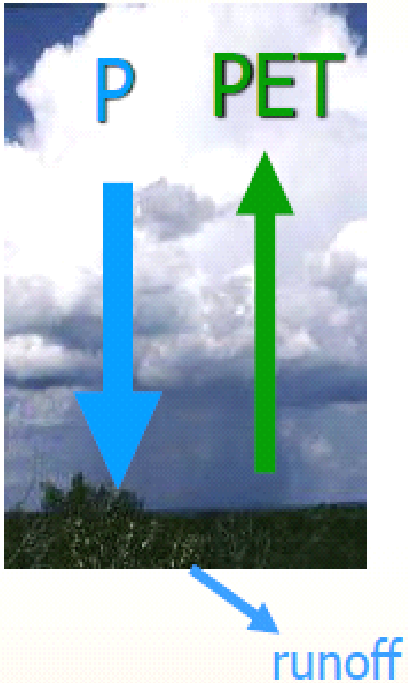
Method for tracking changes in moisture:

Climate Moisture Index (CMI)

Hogg (1997) Agric. For. Meteorol. 84: 115-122

$$CMI = P - PET$$

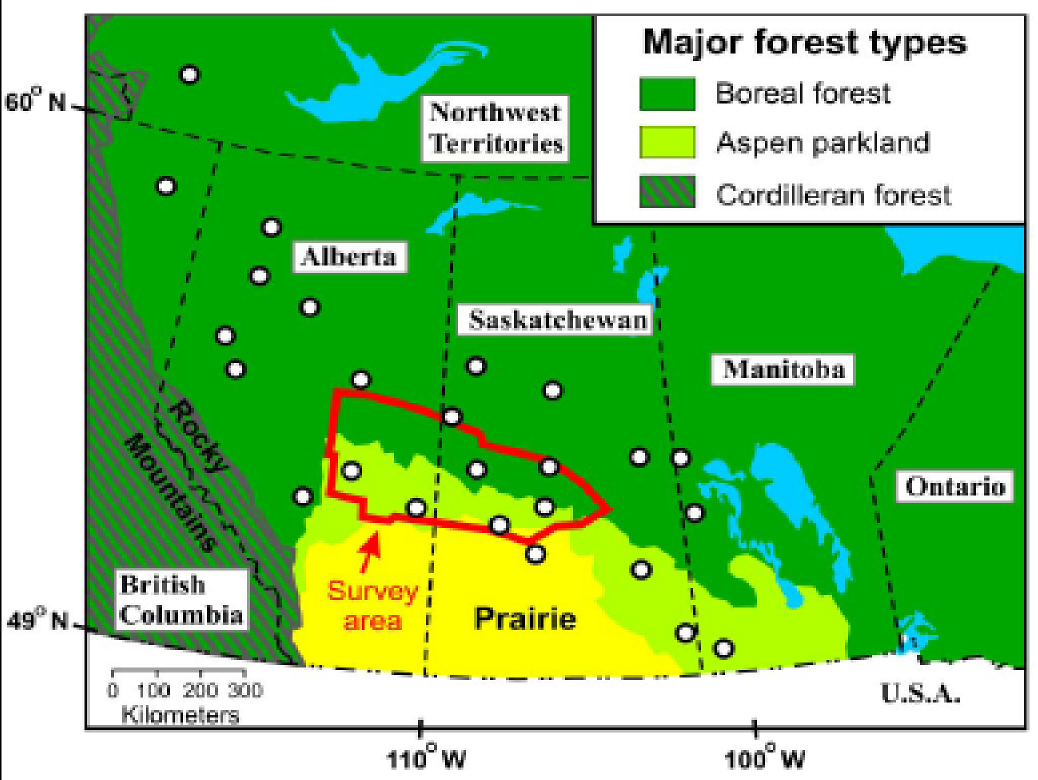
(units in cm/year)

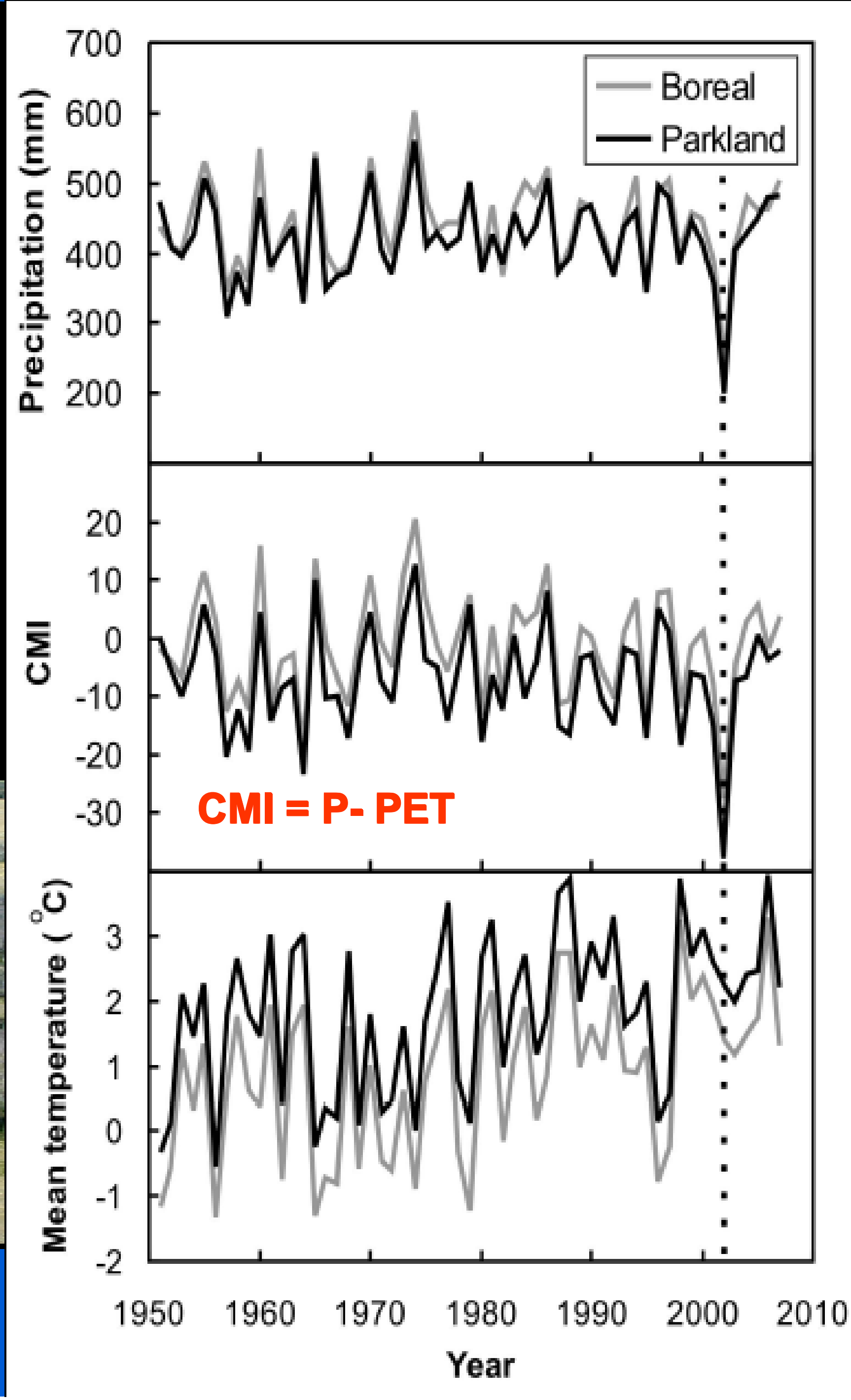


P is mean annual precipitation
includes water input as both rain and snow

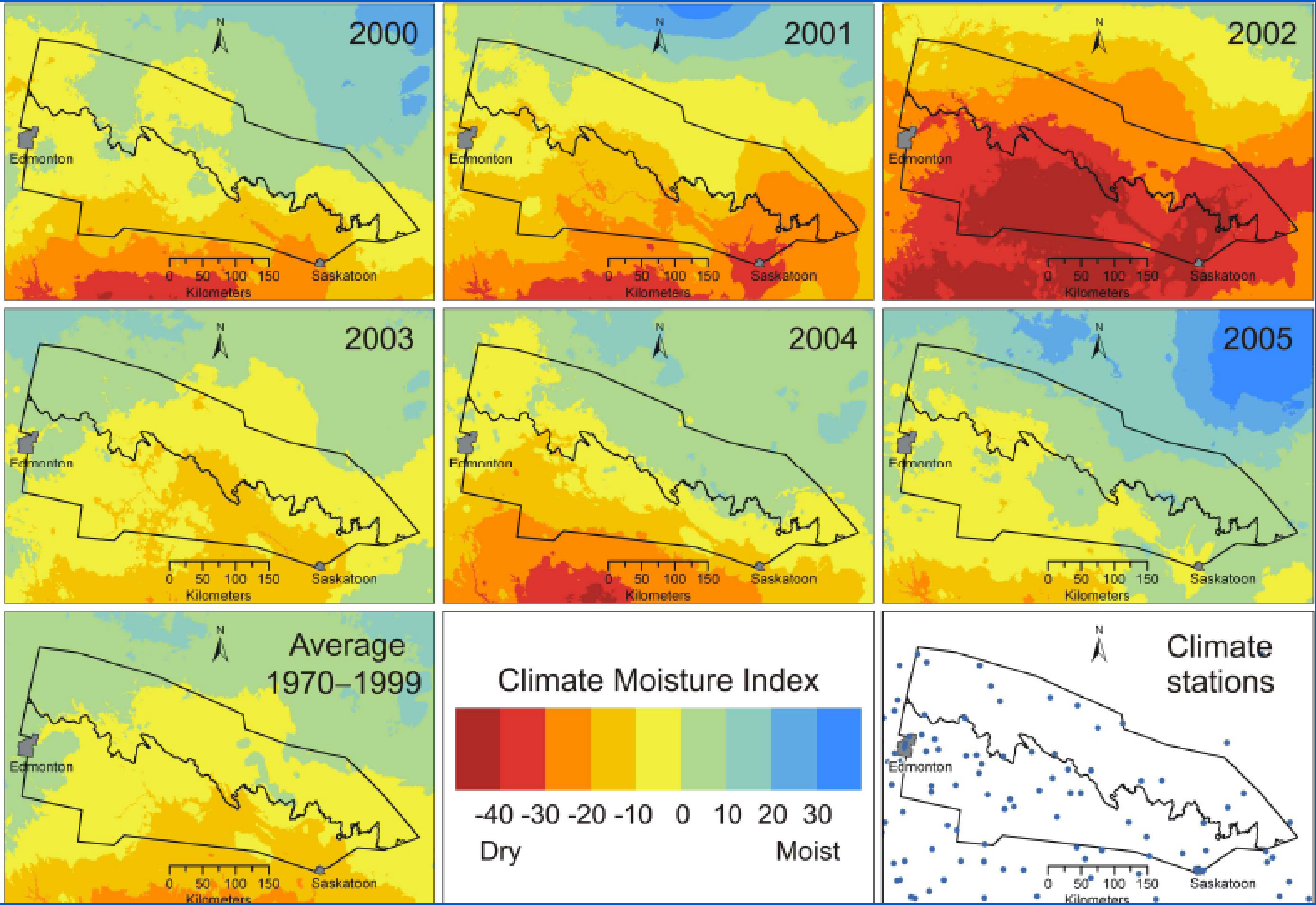
PET is annual potential evapotranspiration
loss of water vapour from a well-vegetated landscape,
estimated from monthly temperature (mean daily max and min)

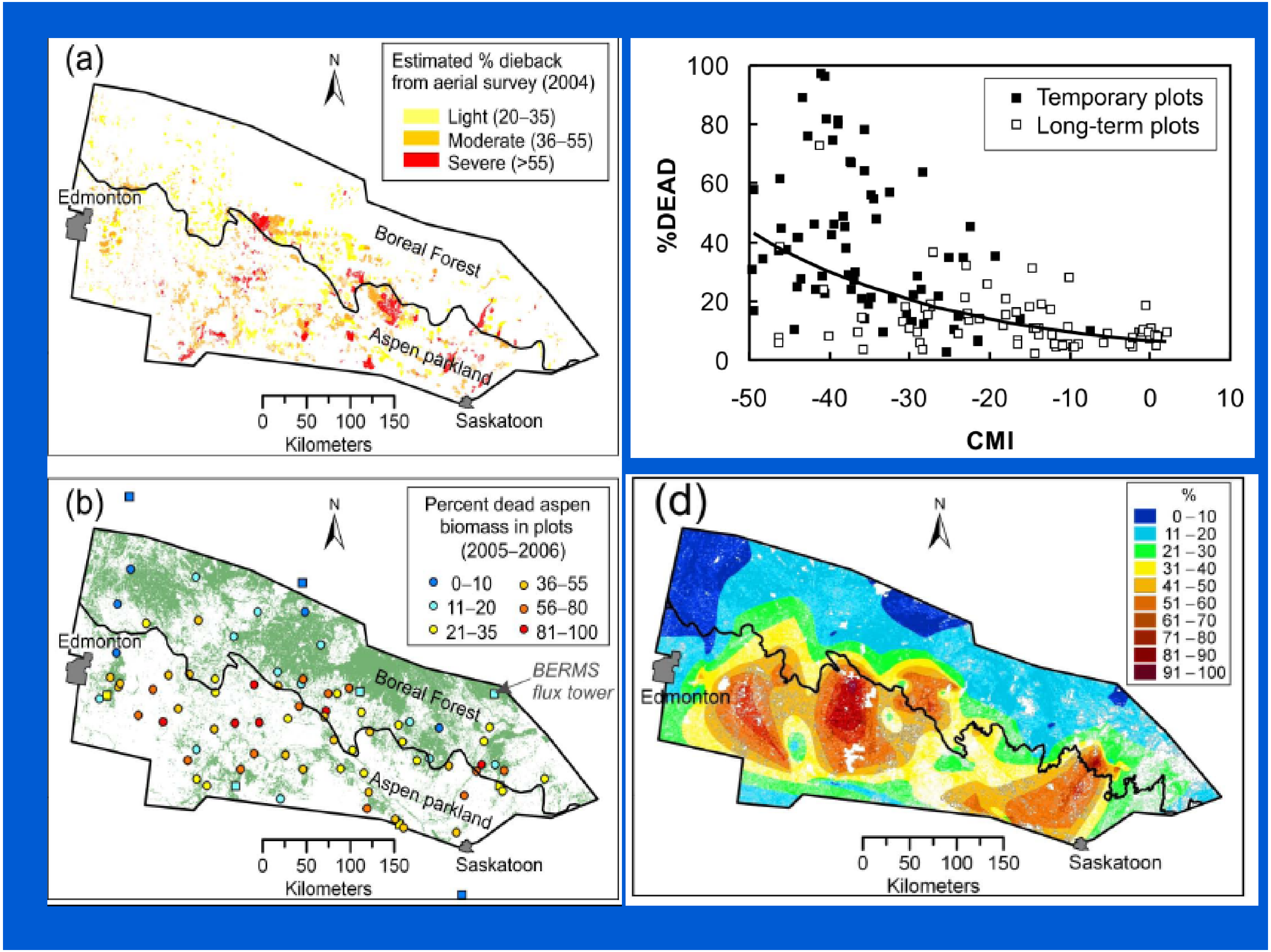
Note: The CMI provides a simple index for assessing moisture variation & drought severity in remote forested regions where long-term climate data are typically limited to temperature and precipitation



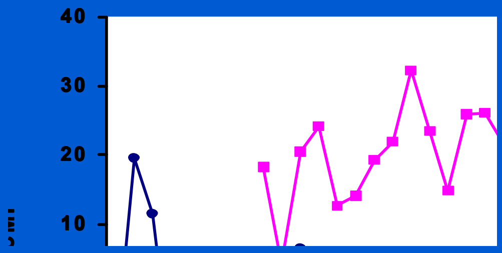


(Michaelian, Hogg et al, 2011, GCB)


2000
2001
2002
2003
2004
2005
Average
1970–1999
Climate stations
Edmonton
Saskatoon
0 50 100 150
Kilometers
N
Climate Moisture Index
-40 -30 -20 -10 0 10 20 30
Dry
Moist


(a)
Estimated % dieback from aerial survey (2004)
Light (20–35)
Moderate (36–55)
Severe (>55)
N
Edmonton
Boreal Forest
Aspen parkland
Saskatoon
0 50 100 150
Kilometers
100
80
60
40
20
0
%DEAD
-50 -40 -30 -20 -10 0 10
CMI
Temporary plots
Long-term plots
(b)
Percent dead aspen biomass in plots (2005–2006)
0–10
11–20
21–35
36–55
56–80
81–100
BERMS flux tower
(d)
%
0 – 10
11 – 20
21 – 30
31 – 40
41 – 50
51 – 60
61 – 70
71 – 80
81 – 90
91 – 100

(a)



(b)

Table 1. Fixed effects in the generalized nonlinear mixed models describing annual tree mortality rate trends; *a* is the estimated annual change in mortality rate (% year^{-1}) and *n* is the number of forest plots used in the model.

Model	Data	β	*a* = exp(β) – 1	Std. error	*P*	*n*
Overall mortality trend	All	0.0458	0.0469	0.002	<0.0001	96
Mortality trends by longitude (region)	West (119°W to 97°W)	0.0476	0.0488	0.002	<0.0001	70
	East (94°W to 65°W)	0.0191	0.0193	0.008	0.0227	26
Mortality trends by latitude	<51°N	0.0686	0.0710	0.006	<0.0001	38
	51°N to 54°N	0.0489	0.0501	0.003	<0.0001	24
	>54°N	0.0380	0.0387	0.003	<0.0001	34
Mortality trends by elevation	< 500 m	0.0469	0.0480	0.005	<0.0001	35
	500 to 1200 m	0.0625	0.0645	0.003	<0.0001	26
	> 1200 m	0.0204	0.0206	0.003	<0.0001	35
Mortality trends by species	Trembling aspen	0.0280	0.0284	0.006	<0.0001	21
	Jack pine	0.0537	0.0552	0.017	0.0132	10
	Black spruce	0.0425	0.0434	0.004	<0.0001	45
	White spruce	0.0329	0.0334	0.005	<0.0001	21
	Others	0.0286	0.0290	0.004	<0.0001	31
Mortality trends by diameter class	< 15 cm	0.0304	0.0309	0.003	<0.0001	94
	15 to 20 cm	0.0428	0.0437	0.005	<0.0001	74
	> 20 cm	0.0229	0.0232	0.005	<0.0001	50

Peng et al. Nature CC (2011)

Table 2: Fixed effects in the generalized nonlinear mixed-effects models describing the relationship between annual tree mortality and climatic variables. *n* is the number of forest plots used in the model.

	Models of tree mortality as a function of	β	**Std. error**	***P***	***n***
All plots	Annual mean temperature (°C)	0.3761	0.0217	<0.0001	96
	Annual climate moisture index (*CMI*)	-0.0318	0.0043	**Data**	96
	Annual moisture index (*AMI*)	0.0018	0.0002	<0.0001	96
West	Annual mean temperature (°C)	0.4445	0.0280	<0.0001	70
	Annual climate moisture index (*CMI*)	-0.0602	0.0049	<0.0001	70
	Annual moisture index (*AMI*)	0.0023	0.0002	<0.0001	70
East	Annual mean temperature (°C)	0.0969	0.0554	0.0428	26
	Annual climate moisture index (*CMI*)	0.0083	0.0063	0.2020	26
	Annual moisture index (*AMI*)	-0.0009	0.0006	0.1307	26

Peng et al. Nature CC (2011)

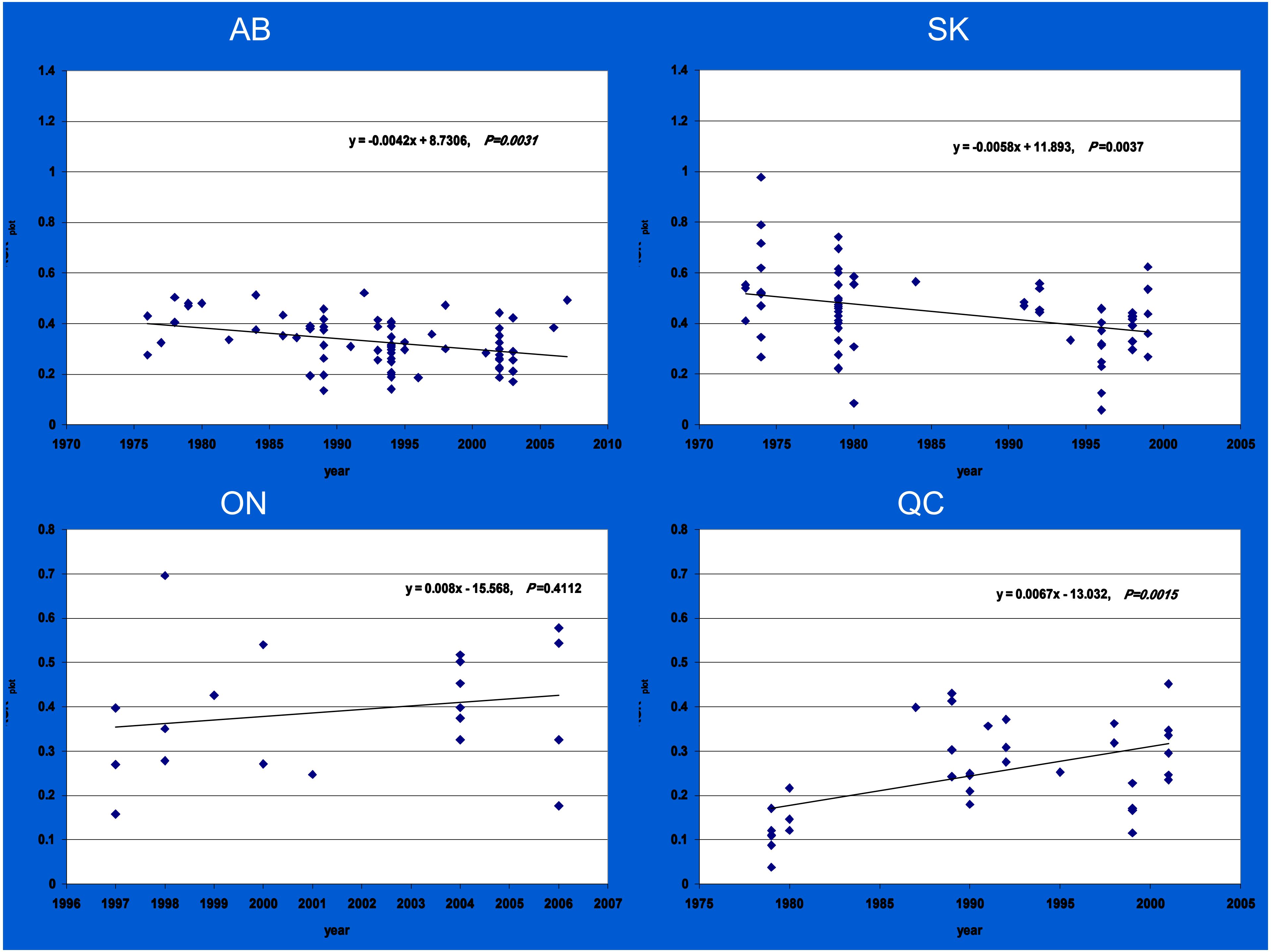
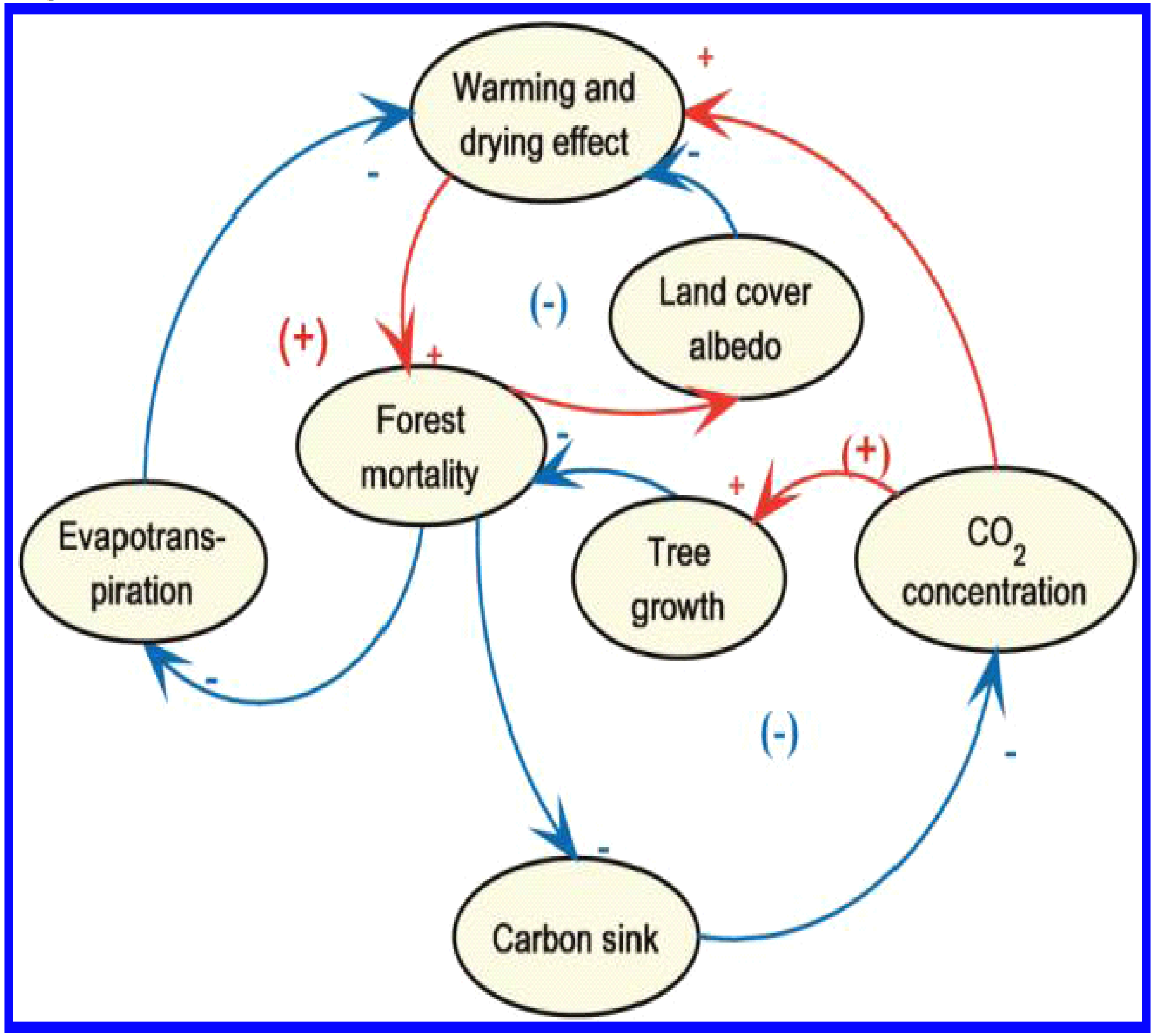

AB
y = -0.0042x + 8.7306, P=0.0031
SK
y = -0.0058x + 11.893, P=0.0037
ON
y = 0.008x - 15.568, P=0.4112
QC
y = 0.0067x - 13.032, P=0.0015
year

Fig. 2. Causal loop diagram of how drought-induced forest mortality affects earth system feedbacks between ecosystems and the climate sys tem in energy, carbon, and water cycles. Red arrows with plus marks and blue arrows with minus marks represent a cause-and-effect relationship in which the two variables change in the same and opposite directions, respectively. Symbols(+) and (–) represent positive and negative feedbacks, respectively.



（Wang et al. 2012)