Ecological Consequences of Climate Extremes :

Impacts of Drought-Induced Forest Mortality on Forest Carbon Sinks

Changhui Peng, CEF, UQAM

(www.crc.uqam.ca)

Co-auhors: Zhiha Ma, Weifeng Wang, QiuAn Zhu, etc…

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

Topics Outline

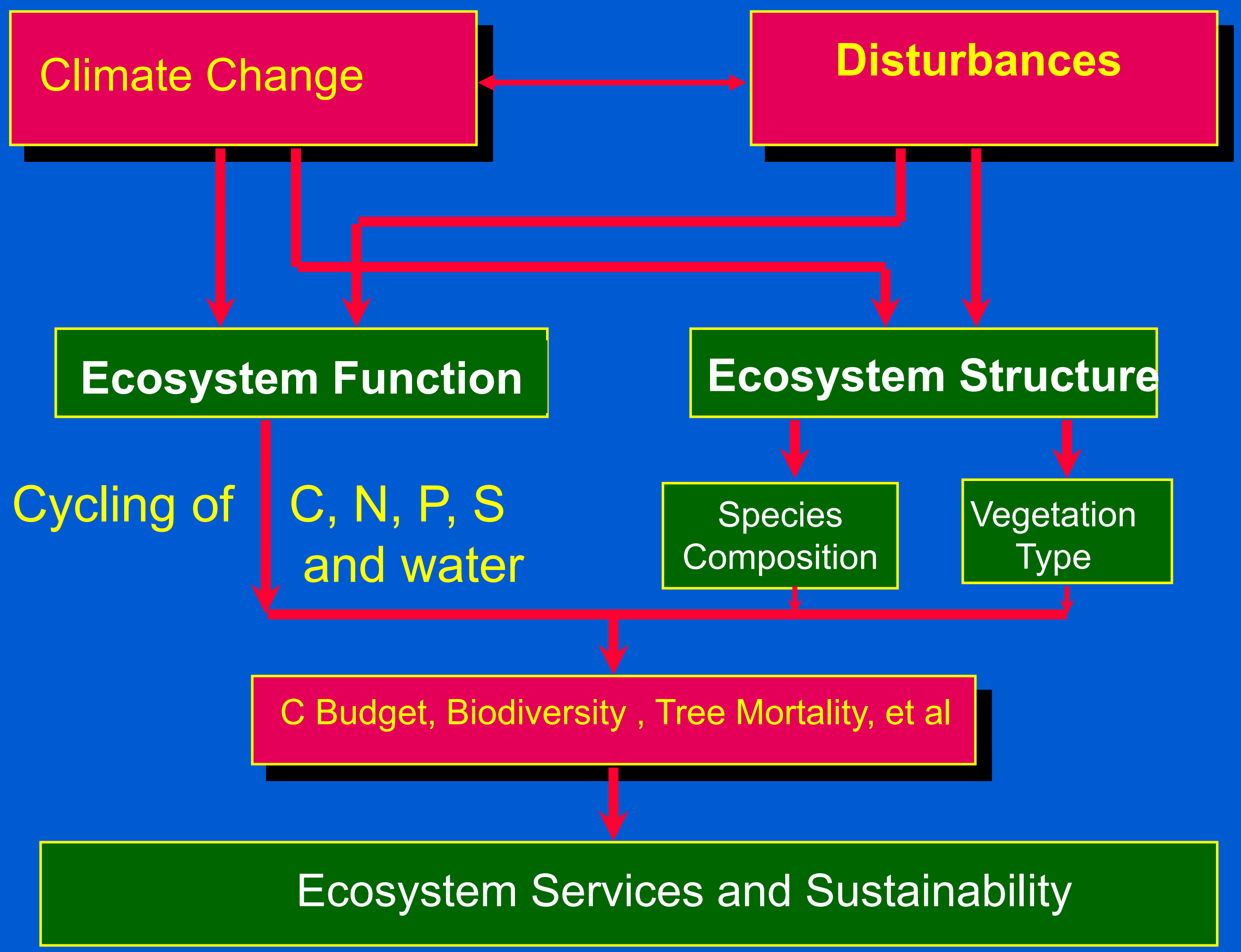
I. Introduction and Overview

II. One Case Study:

- Boreal forest mortality, growth, and carbon sink in Canada

III. Causes, Consequences, and Ongoing Challenges

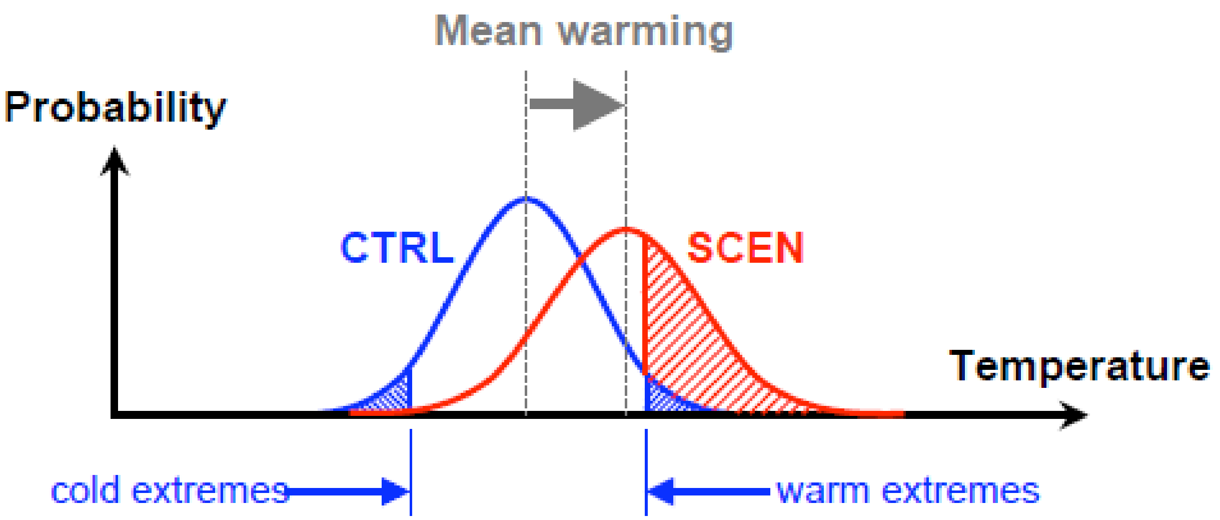
Interactions of Climate Chang & Forest Ecosystems



(modified from Peng et al., 2001)

Extreme events

Extreme events defined



Extreme events are defined in statistical terms, as events that deviate strikingly from the statistical mean.

Climate change implies changes in frequency of extremes.

Generally needs to account for changes of the whole statistical distribution (i.e. mean, variability, skewness, etc)

Schär, ETH Zürich

12-day heatwave, 3-14 Aug, 2003

Maximum Temperature, Aug 10

Excess Mortality:

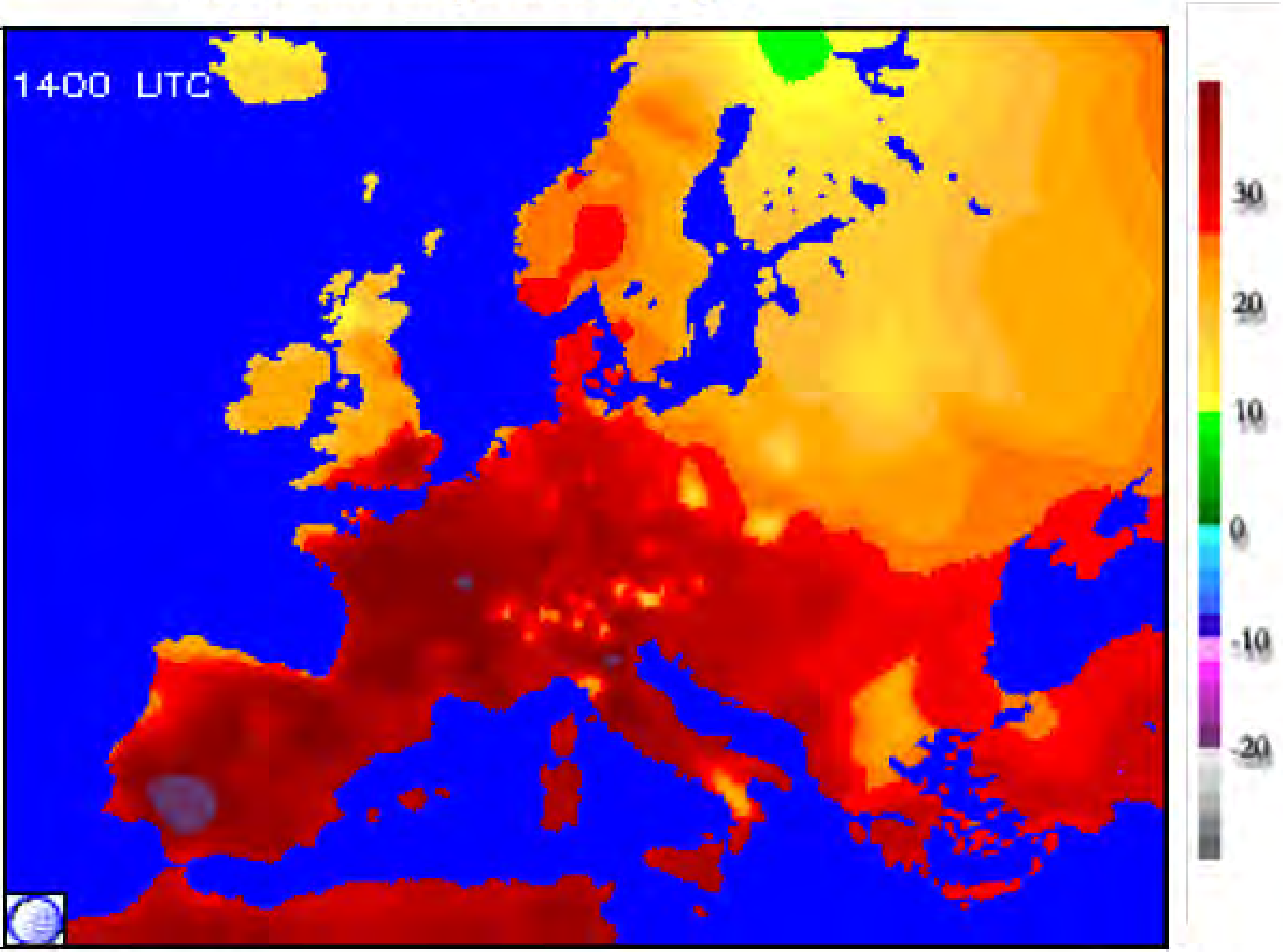
France:
14,800

Italy:
10,000

Spain & Portugal:
5,000

Etc.

Total =
35,000



Slide attributed to Tony McMichael

Texas 2011

JJA 2011 Hottest
On record

Some towns in western Texas went more than 60 straight days over 100F

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]

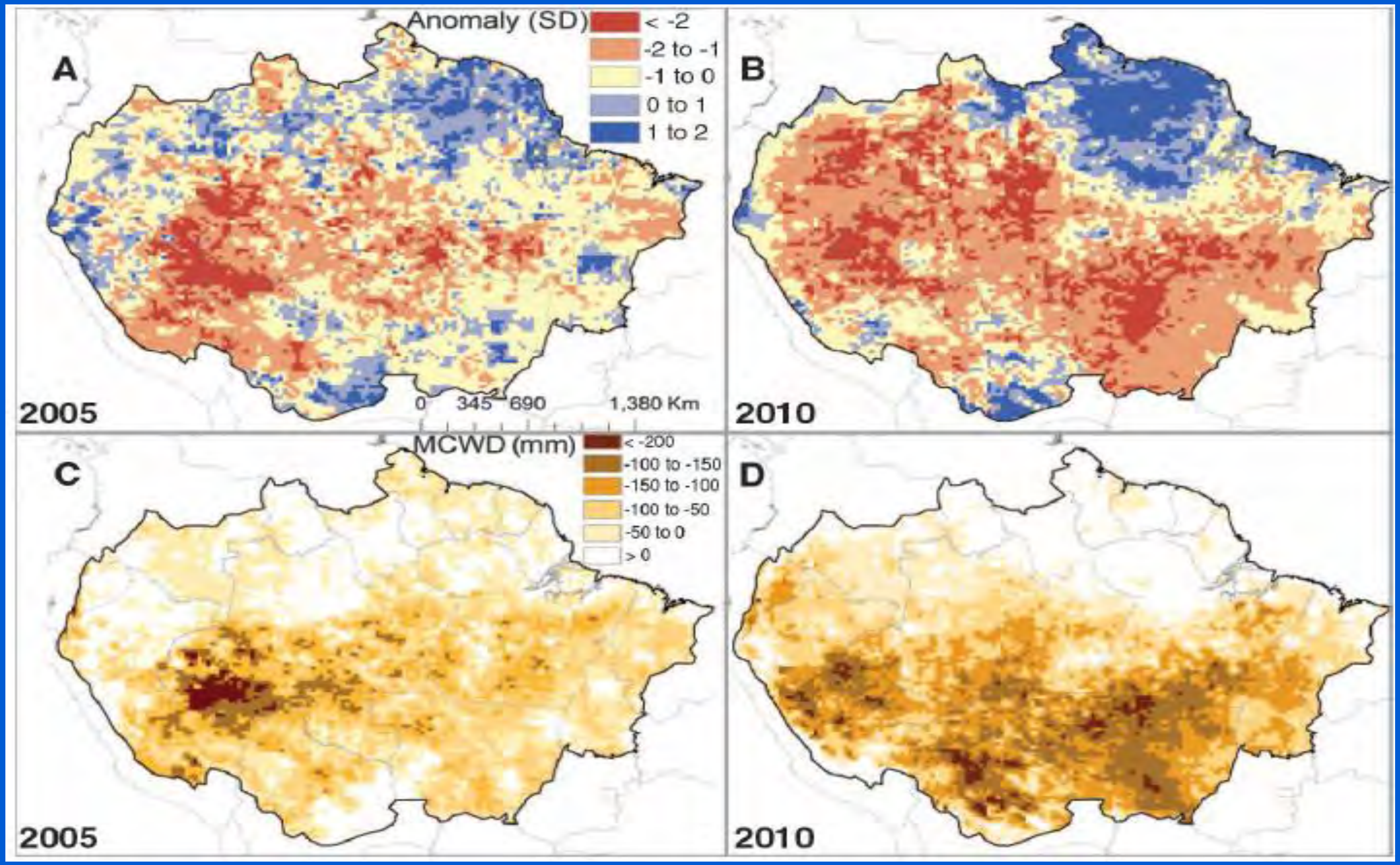


Fig. 1. (A and B) Satellite-derived standardized anomalies for dry-season rainfall for the two most extensive droughts of the 21st century in Amazonia. (C and D) The difference in the 12-month (October to September) MCWD from the decadal mean (excluding 2005 and 2010), a measure of drought intensity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

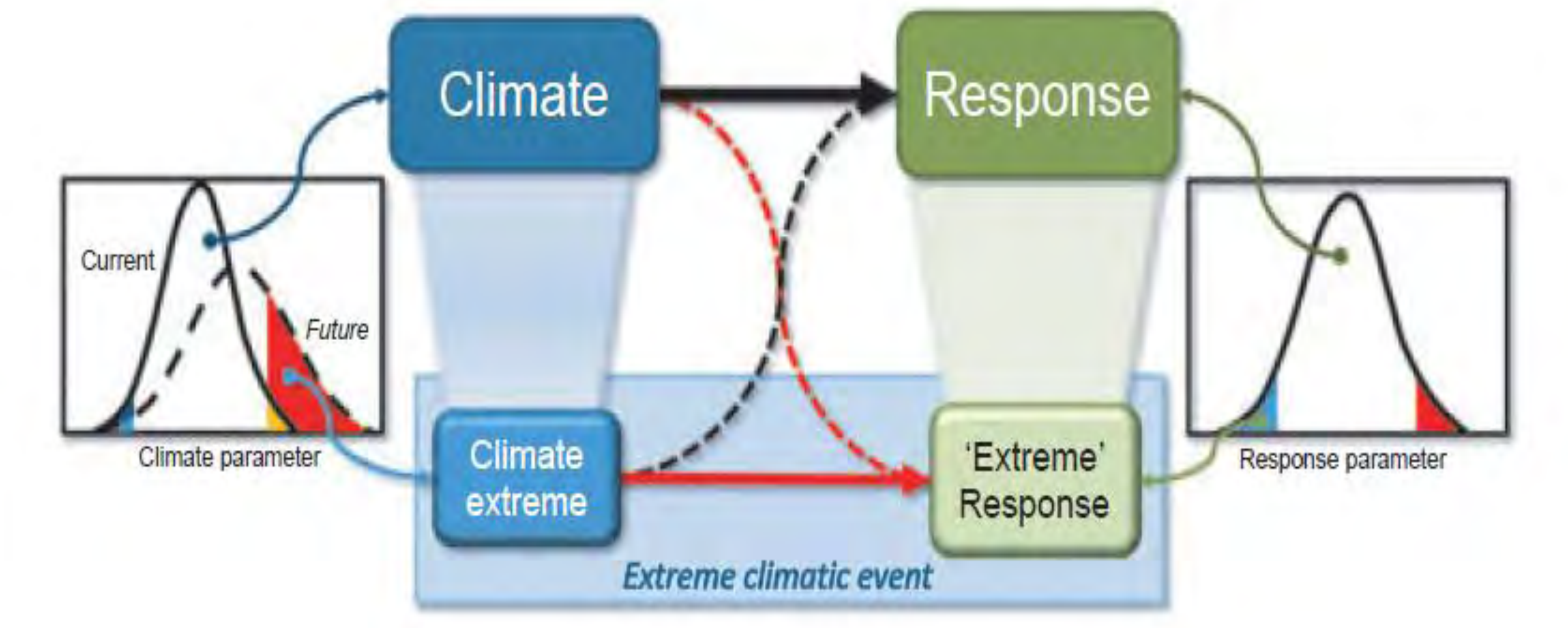
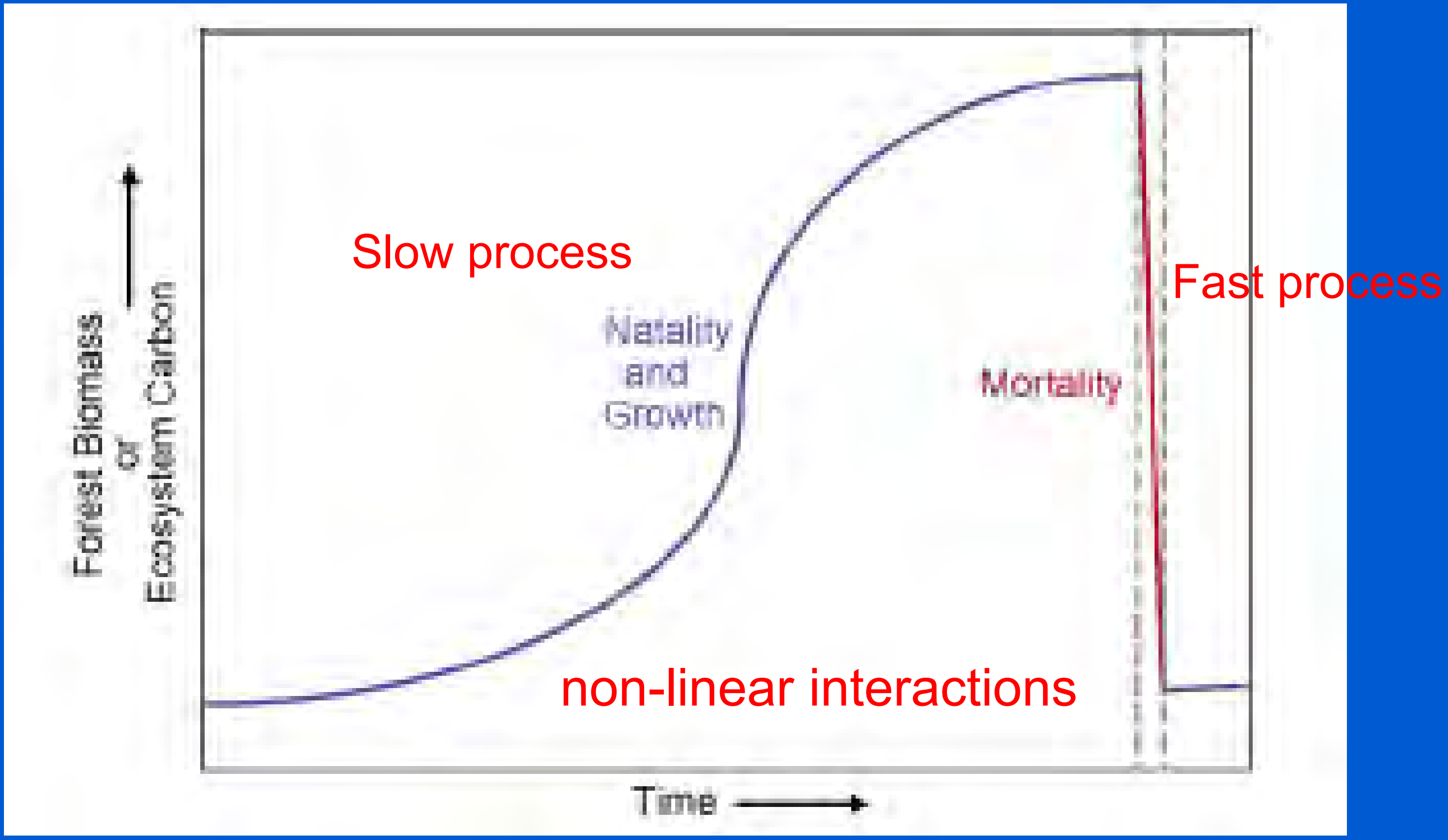


Fig. 1. Conceptual representation of an extreme climatic event. Climate variability can evoke a range of ecological responses (small to extreme, distribution on the right). Changes in climate means or variability may result in a response that is well within the range of variability for a system (solid black arrow) or one that is extreme (i.e. exceeds this range, dashed red arrow). Similarly, climate extremes (represented by tails of the distribution on the left) may (solid red arrow) or may not (dashed black arrow) result in an ecological response that is outside the typical or normal range of variability for a system. Here, an 'extreme climatic event' is defined synthetically as involving extremeness in both the climate driver and the ecological response.

(Melinda Smith, 2011. JE)

$$\frac{dBiomass}{dt} = \textbf{Growth - Mortality}$$



Allen et al., 2010

Environmental Factors Controlling Forest Growth and Death

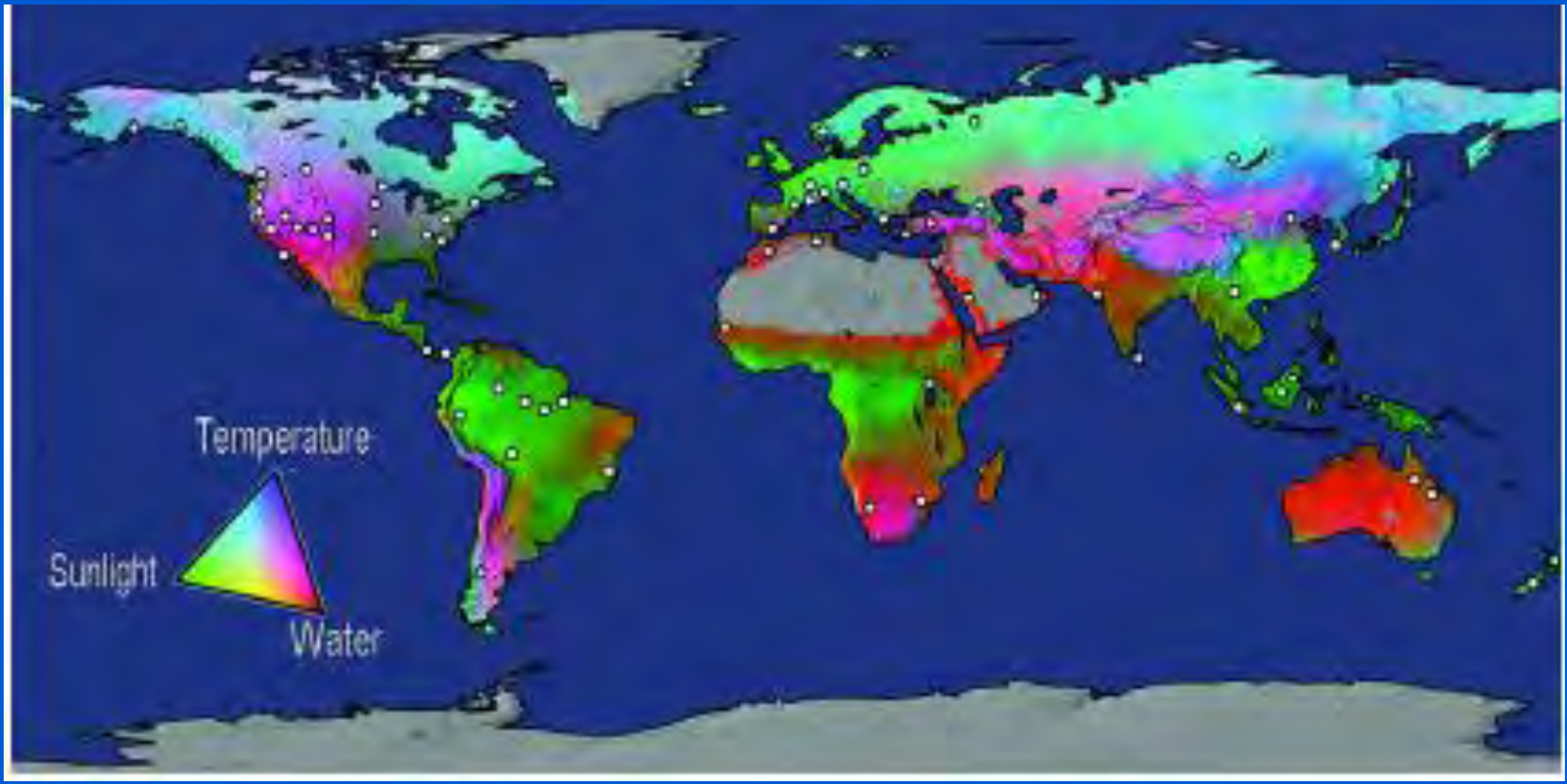
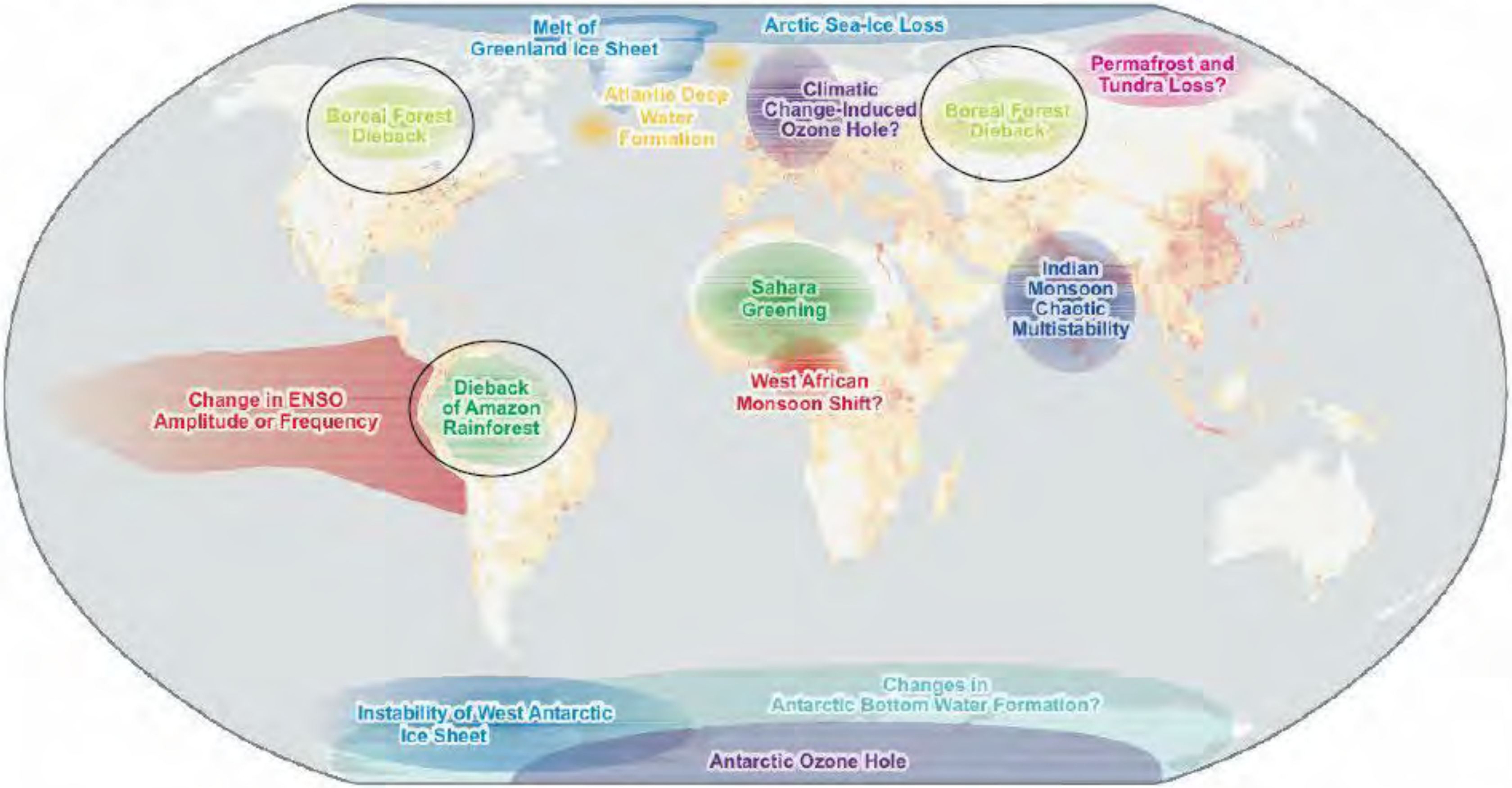


Fig. 1. White dots indicate documented localities with forest mortality related to climatic stress from drought and high temperatures. Background map shows potential environmental limits to vegetation net primary production (Boisvenue and Running, 2006).

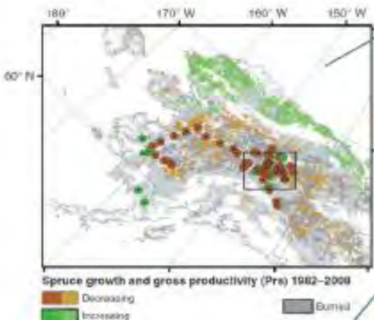
Mortality is expected to be a major tipping point in the climate system



Drought impacts on terrestrial systems are **widely accepted** to be large tipping points that will cause positive climate feedbacks (IPCC 2007, 2009)

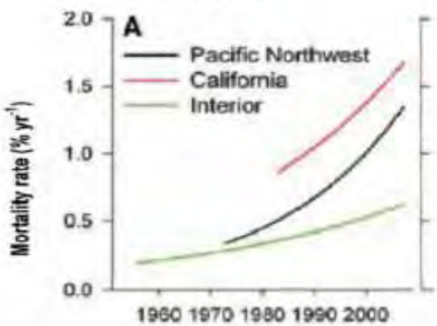
Forest mortality is accelerating globally due to drought and heat

Beck et al. *Eco Let.* 2011



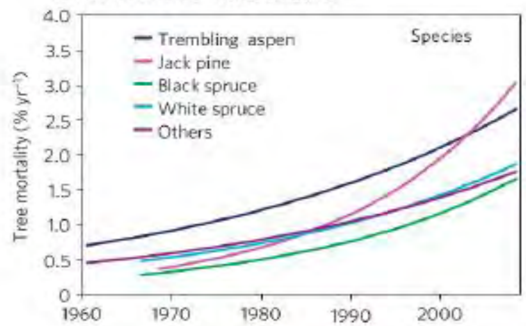
McDowell et al. 2011

Western USA



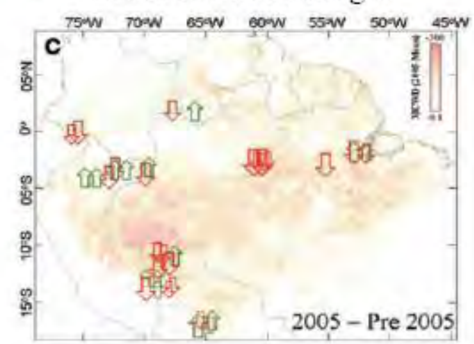
Van Mantgem et al. *Science* 2011

Canada boreal forests



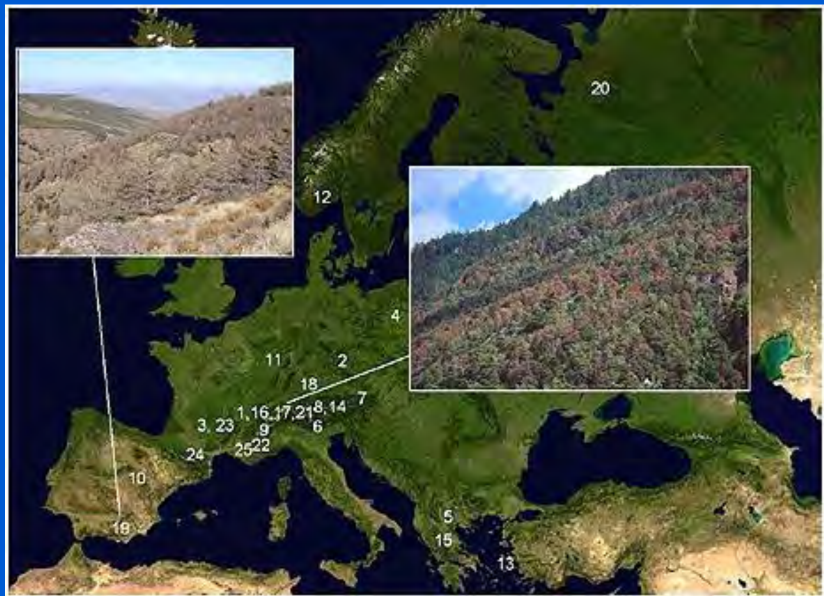
Peng et al. *Nature Climate Change* 2011

Amazon 2005 drought

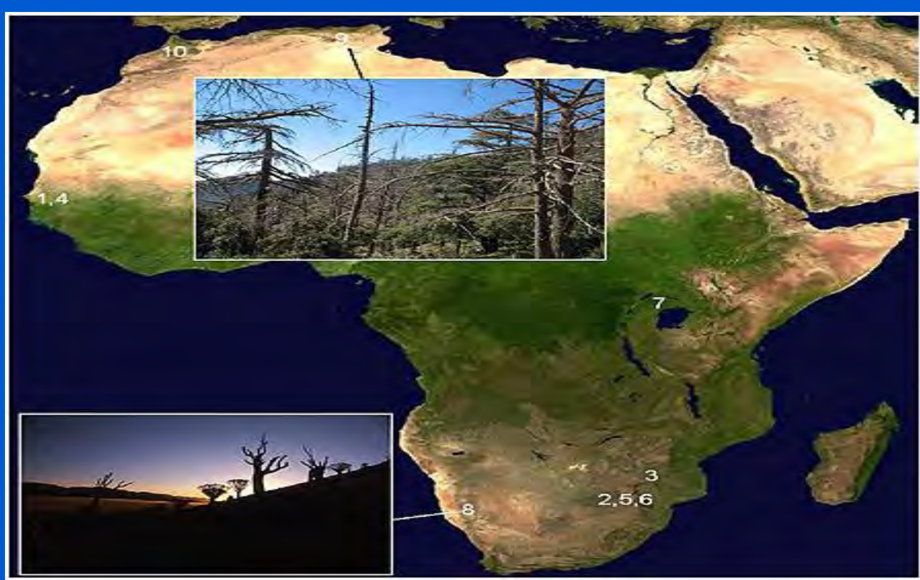


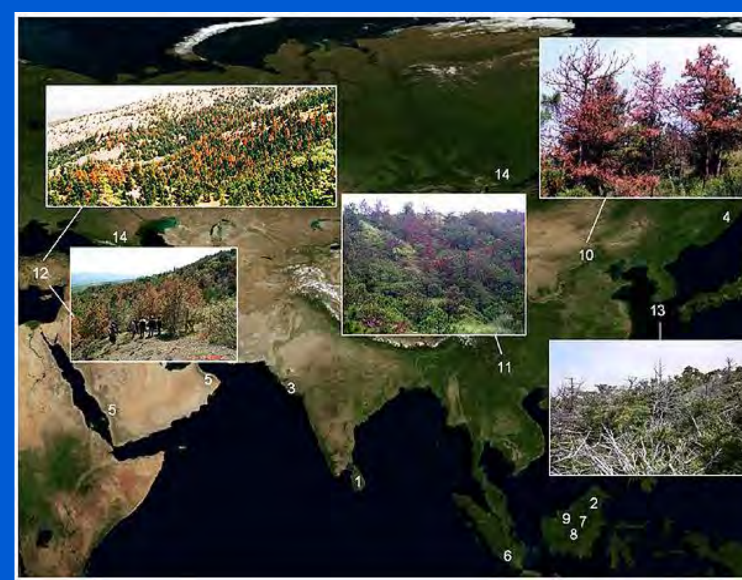
Phillips et al. *Science* 2009

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).





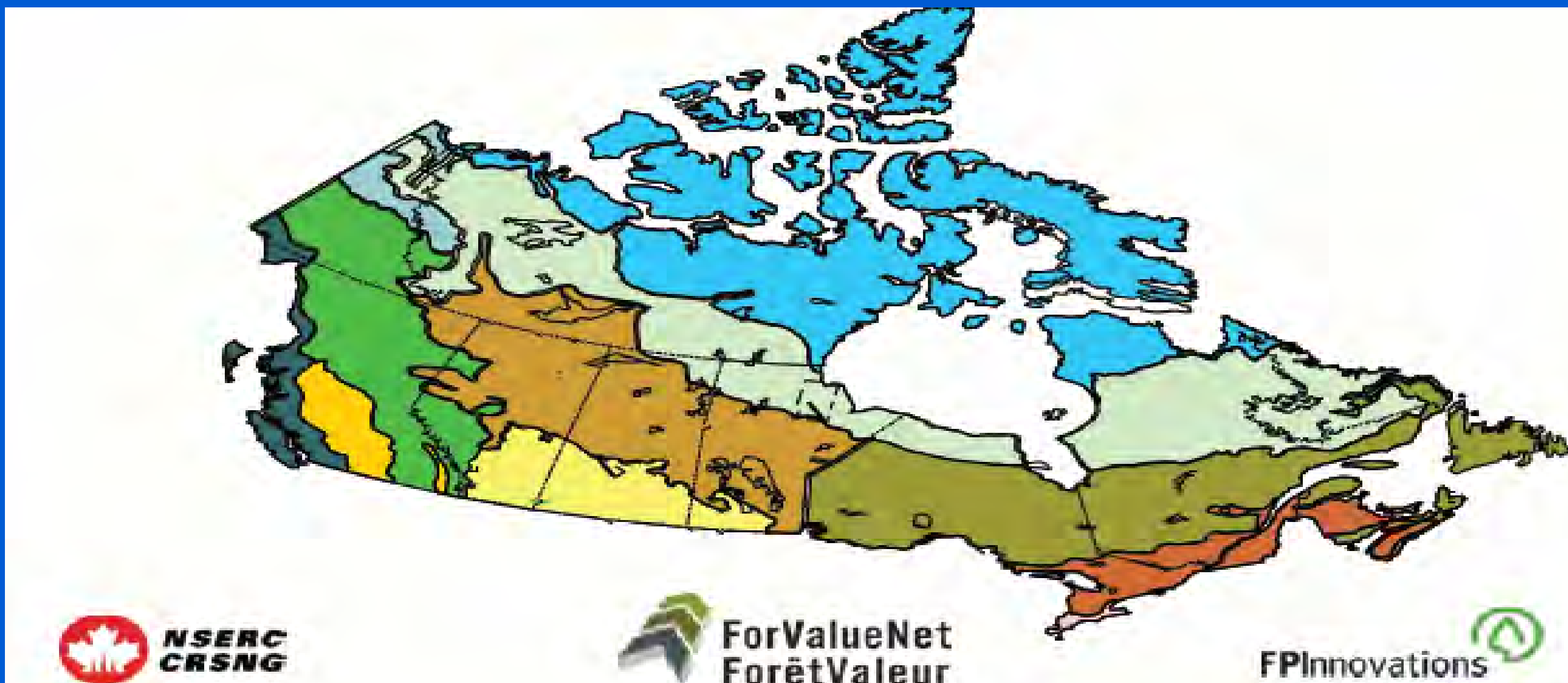
nature climate change

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]



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.)

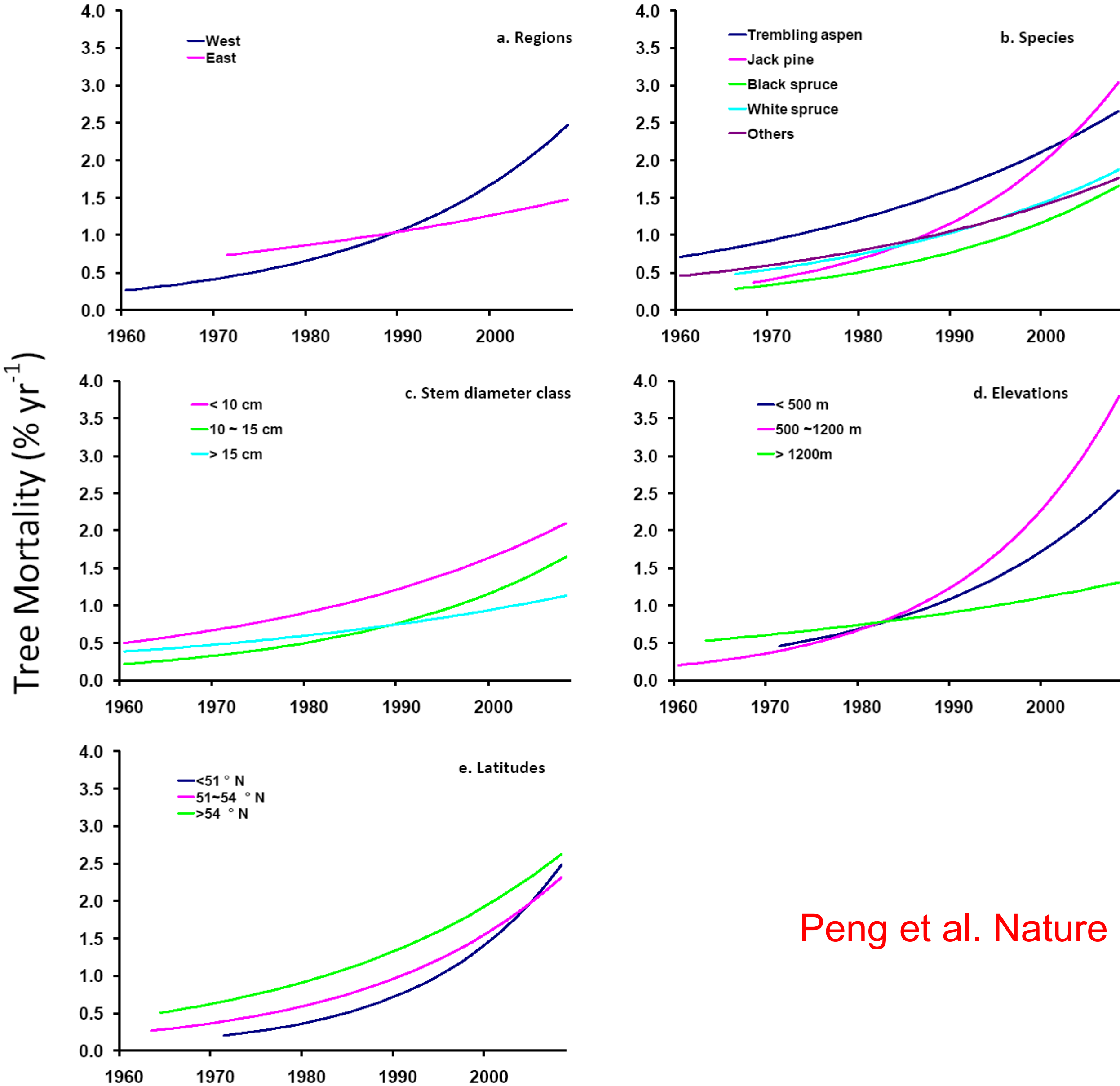
Total 22,425 living trees and 74,556 observations

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

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)



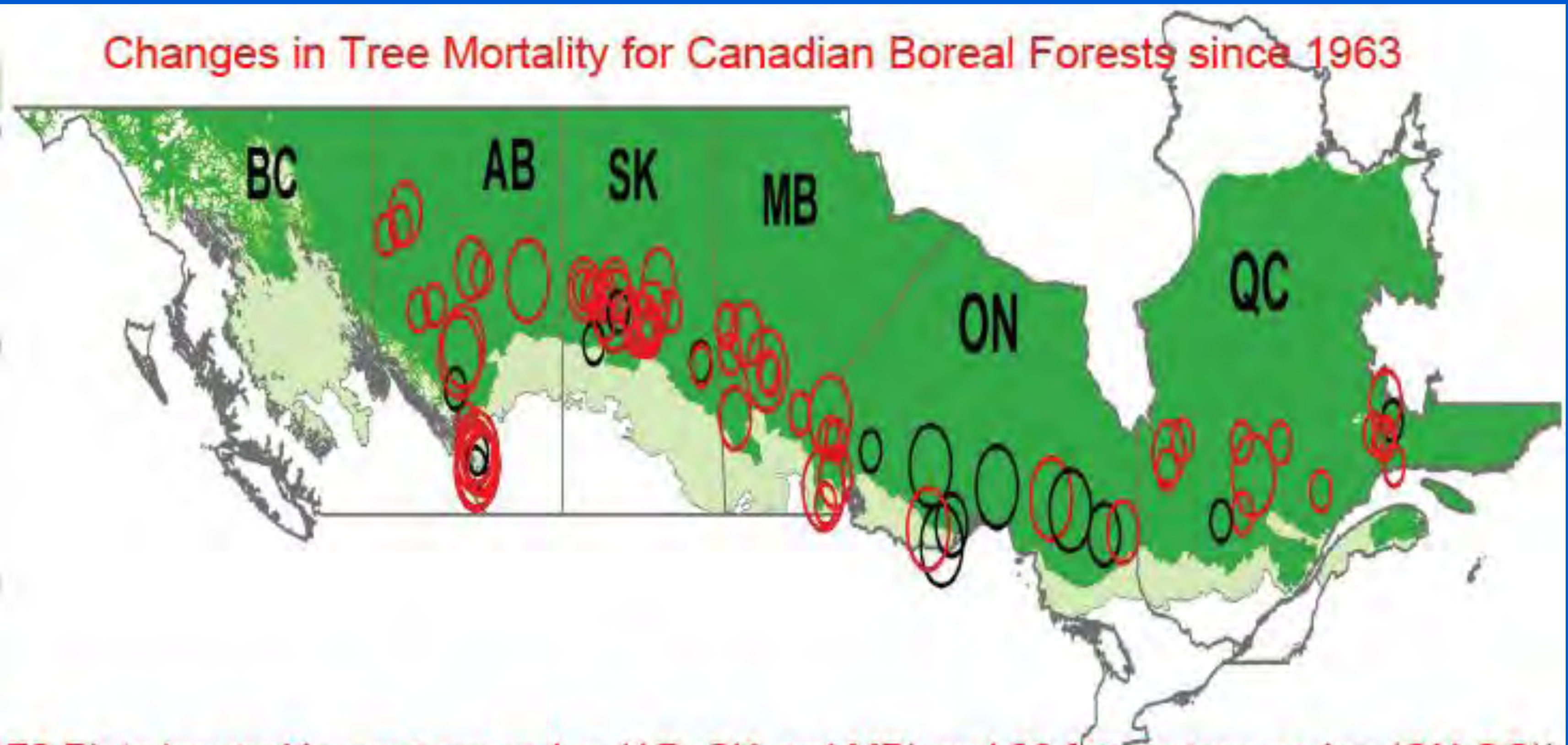
Peng et al. Nature CC,(2011)

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	<0.0001	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)

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 $year^{-1}$)

Main findings (1):

(1) 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 (**about 4.9%**) than in eastern regions (**about 1.9%**).

(2) 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)

Spatial and temporal changes in the tree growth rates in the boreal forest of Canada under a changing climate

Zhihai Ma[1], Changhui Peng[1,2*], Qiuan Zhu[2], Jianwei Liu[3], Xia Xu[4,1], Xiaolu Zhou[1]

Submitted

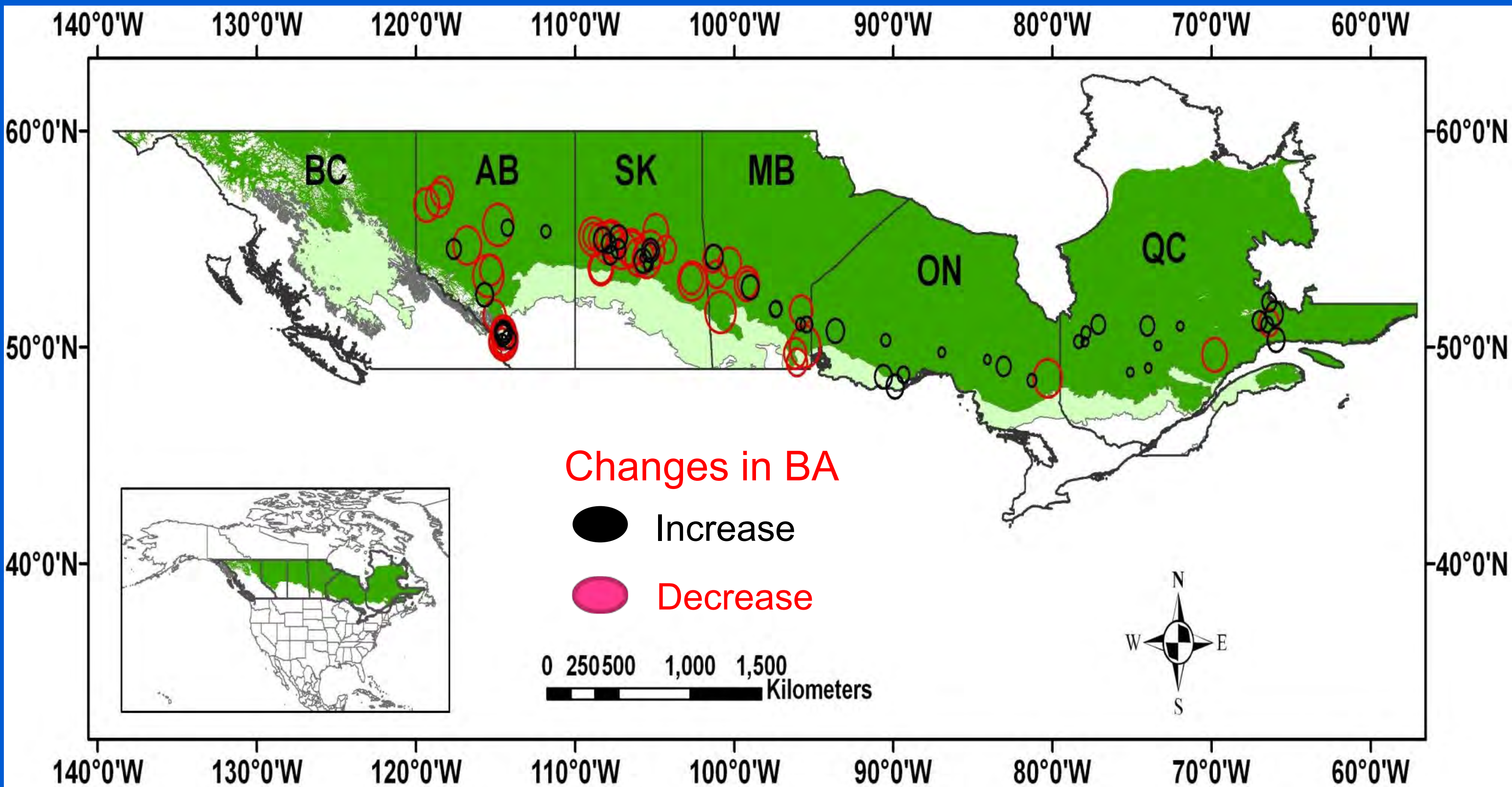


Table 1. Individual tree growth rates for all five provinces investigated.

Province‡	Individual tree growth rate	Tree Number 1 §	Tree Number 2 §	Percentage*
AB	Decrease Increase Constant	3745 2171 70	5986	63% 36% 1%
SK	Decrease Increase Constant	1774 1218 41	3033	59% 40% 1%
MB	Decrease Increase Constant	1705 1186 28	2919	58% 41% 1%
ON	Decrease Increase Constant	389 844 19	1252	31% 67% 2%
QC	Decrease Increase Constant	345 756 9	1110	31% 68% 1%

‡ AB = Alberta; SK = Saskatchewan; MB = Manitoba; ON = Ontario; QC = Quebec.
§ Tree Number 1 represents the number of trees with decreasing, increasing, and constant growth rates. Tree Number 2 represents the number of trees for each province.
* Percentages were calculated as (Tree Number 1/Tree Number 2)*100%.

Main findings (2):

Growth rates for about 60% individual trees in western Canada (Alberta, Saskatchewan, and Manitoba) were found to be decreasing.

Conversely, growth rates for approximately 70% individual trees in eastern Canada (Ontario and Quebec) were found to be increasing.

(Ma, Peng et al., 2013, submitted, GEB)

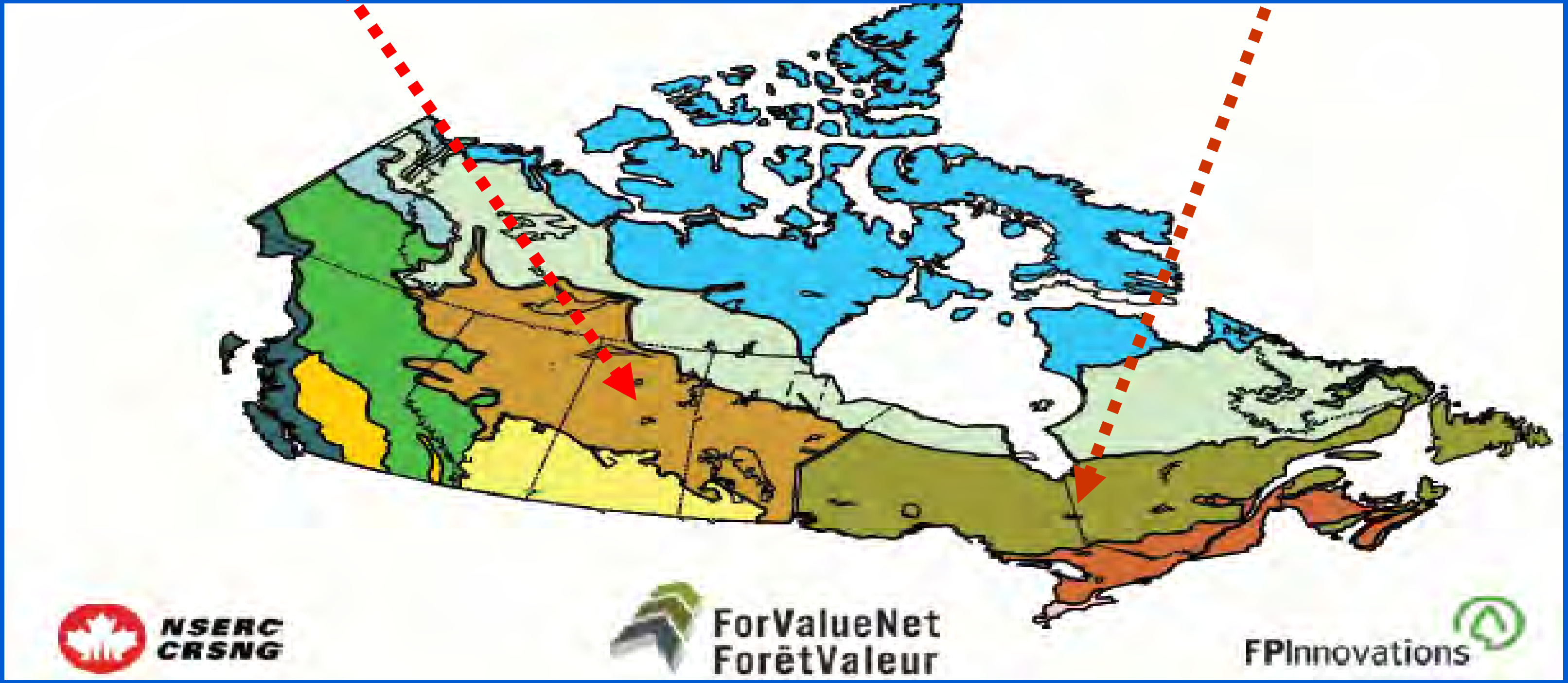
+ Mortality
- Growth

Biomass
Carbon Sink?

$$\frac{dBiomass}{dt} = \textbf{Growth - Mortality}$$

+ Mortality
+ Growth

Biomass
Carbon Sink?



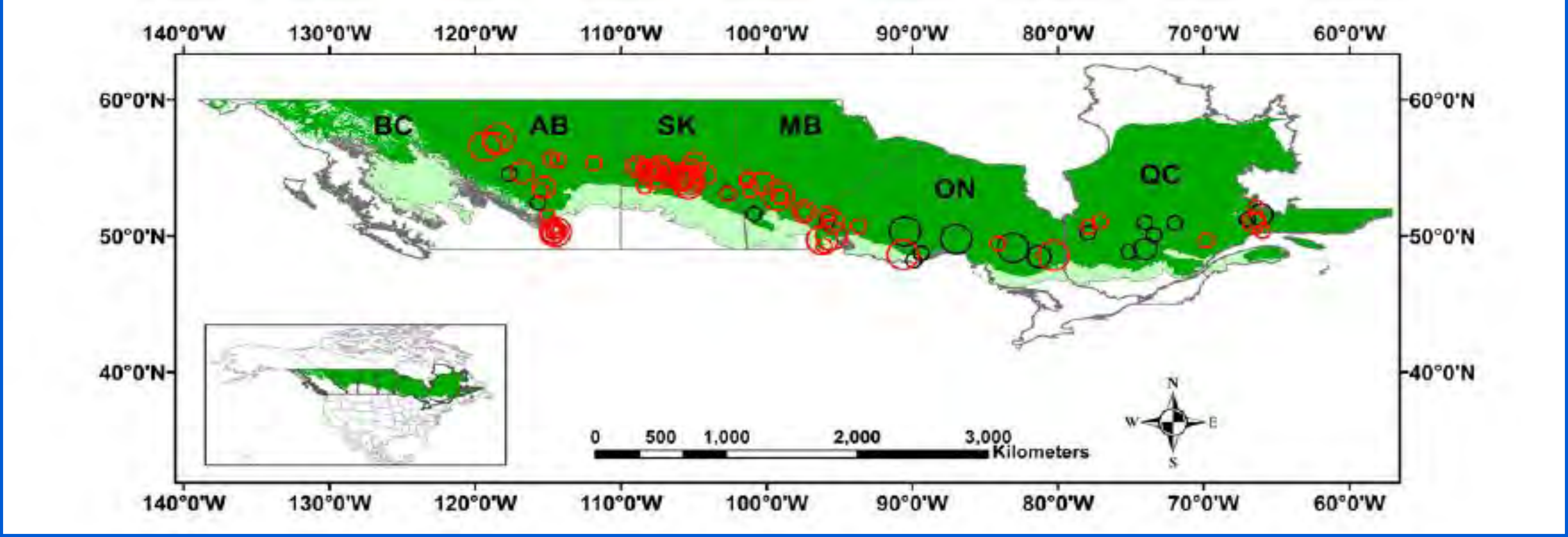
PNAS

Regional drought-induced reduction in the biomass carbon sink of Canada's boreal forests

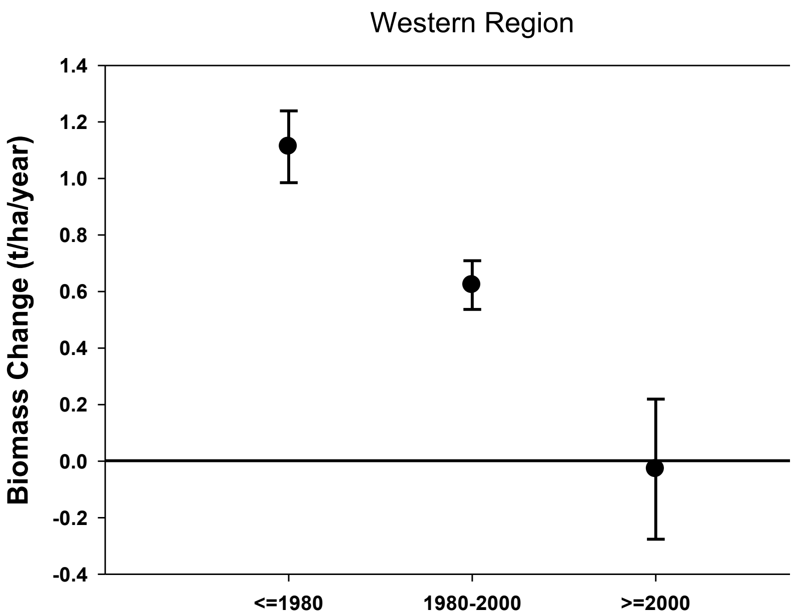
Zhihai Ma[a,1], Changhui Peng[a,b,1,2], Qiuan Zhu[b], Huai Chen[b], Guirui Yu[c], Weizhong Li[b], Xiaolu Zhou[a], Weifeng Wang[a], and Wenhua Zhang[a]

[a]Department of Biology Sciences, Institute of Environment Sciences, University of Quebec, Montreal, QC, Canada H3C 3P8; [b]Laboratory for Ecological Forecasting and Global Change, College of Forestry, Northwest Agriculture and Forestry University, Yangling, Shaanxi 712100, People's Republic of China; and [c]Institute of Geographic Science and Natural Resources Research, Chinese Academy of Science, Beijing 100101, People's Republic of China

Edited by Steven C. Wofsy, Harvard University, Cambridge, MA, and approved December 28, 2011 (received for review July 18, 2011)



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



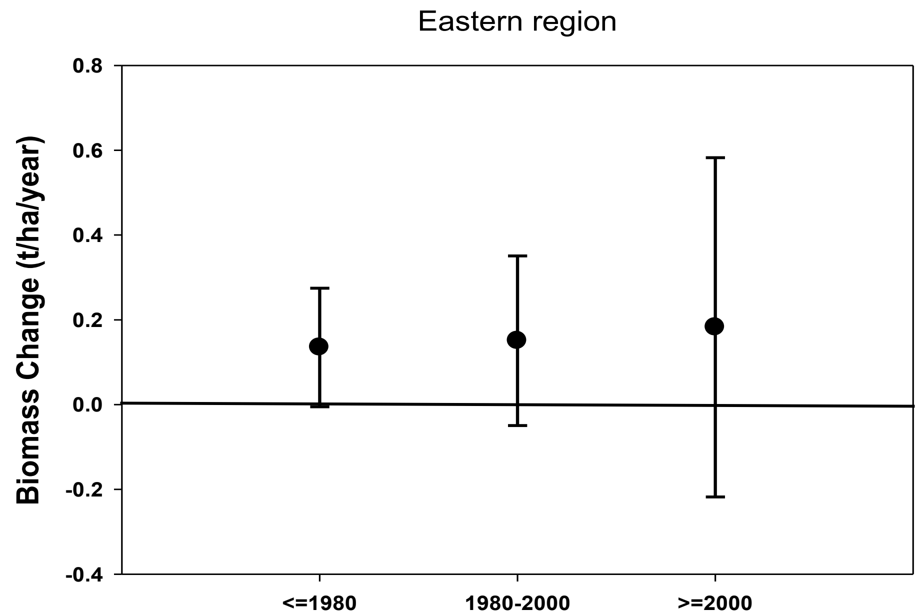
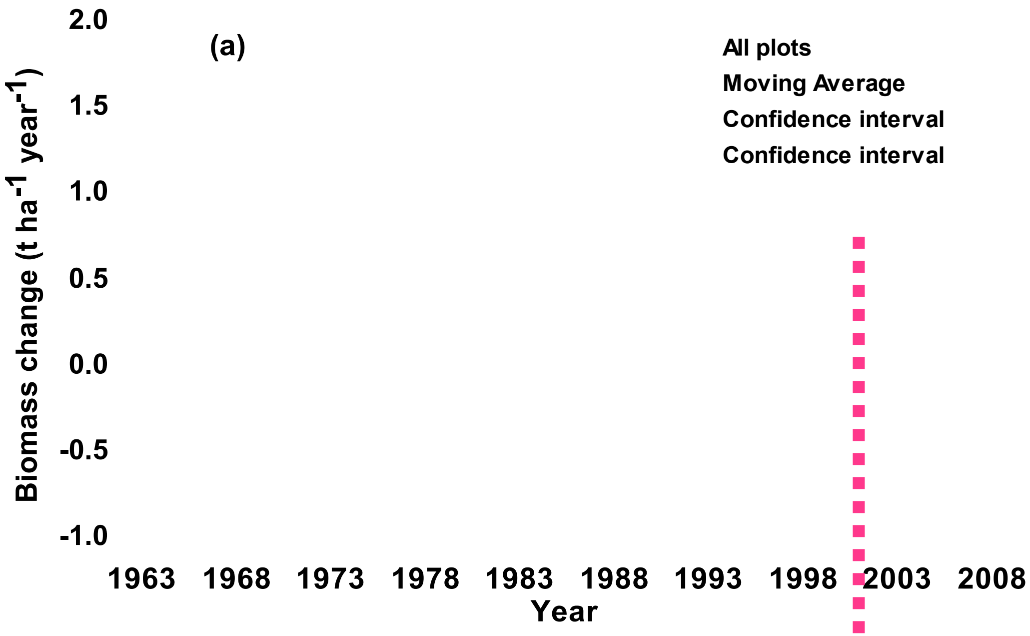


Table 1. Fixed effects of the linear mixed models (*SI Appendix*, Eq. S1) describing trends in the rate of biomass change

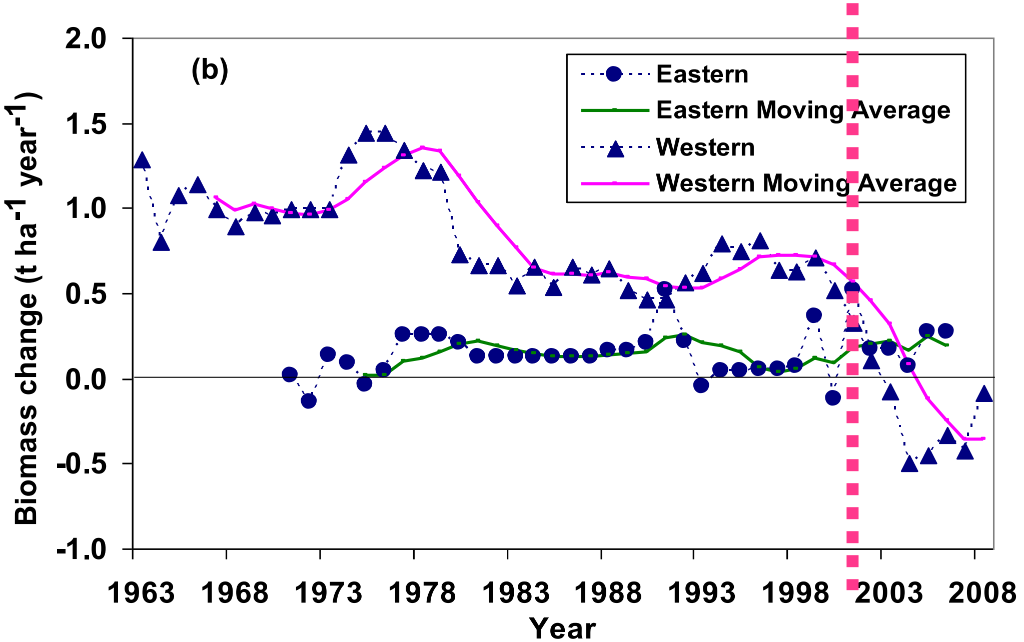
Data	Model	β_1	SE	*P*	*n*
All plots	Trend in rate of biomass change	−0.0514	0.0105	<0.0001	96
Western region	Trend in rate of biomass change	−0.0694	0.0117	<0.0001	70
Eastern region	Trend in rate of biomass change	0.0061	0.0229	0.7922	26

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)



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



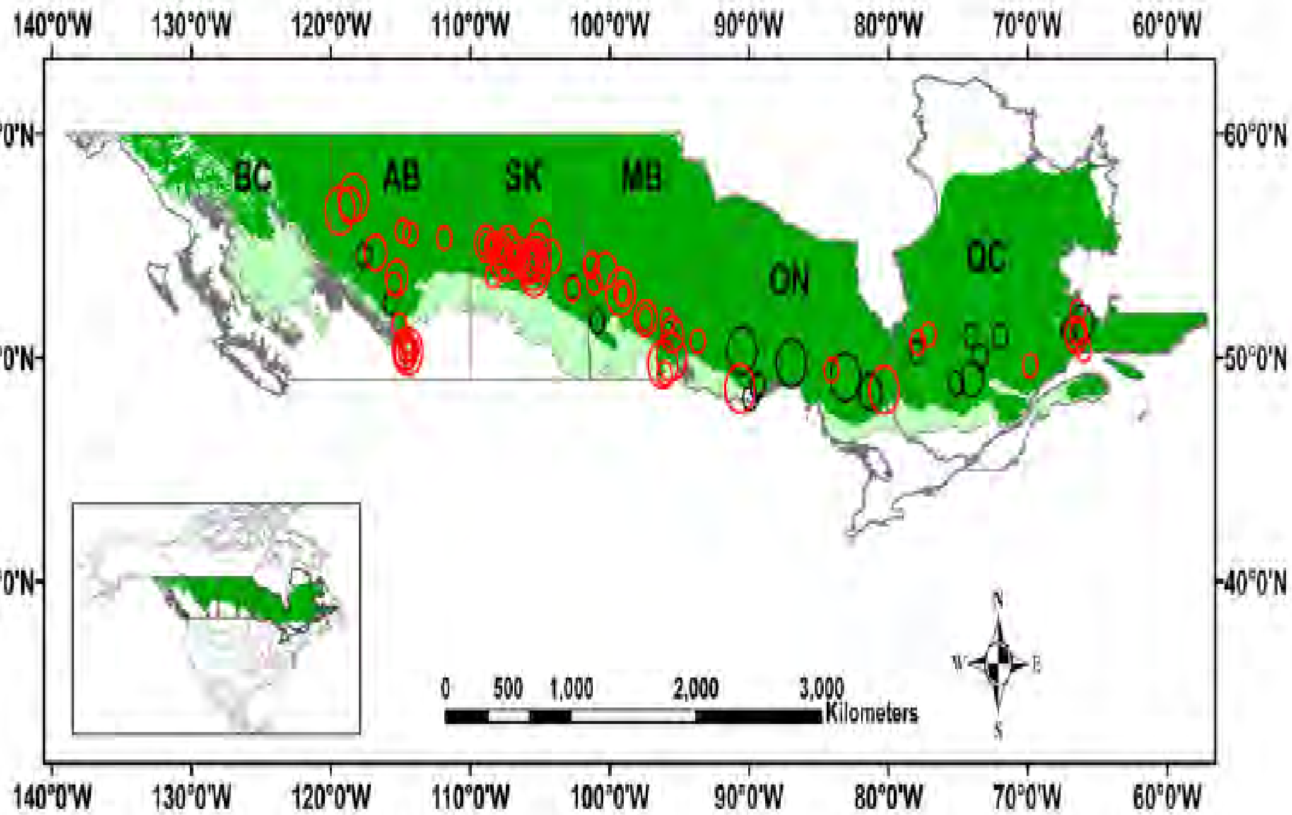


Fig. 1. Locations of the 96 forest plots in Canada's boreal forest. The red and black circles represent plots with respectively decreasing and increasing rates of biomass change. The size of the circle is proportional to the plot-specific slope of the ordinary least-squares regression for the rate of biomass change as a function of the calendar year. Thus, the circle size reflects the rate of annual change in biomass. The background colors of green and light green represent the boreal and hemiboreal regions, respectively. In total, 80 plots (83% of the 96 forest plots) were located in the boreal region and 16 (17%) were located in the hemiboreal region. A total of 70 plots were located in the western region (Alberta, Saskatchewan, and Manitoba) and 26 were located in the eastern region (Ontario and Quebec). In total, 89% of the plots (62/70) in the western region and 46% of the plots (12/26) in the eastern region experienced decreasing rate of biomass change. The shapefiles defining Canada's boreal and hemiboreal zones were developed by J. P. Brandt of Natural Resources Canada (*SI Appendix*, ref. S16) and were obtained from the agency's Web page (http://canadaforests.nrcan.gc.ca/download; accessed December 23 2011).

Method for tracking changes in moisture:

Climate Moisture Index (CMI)

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

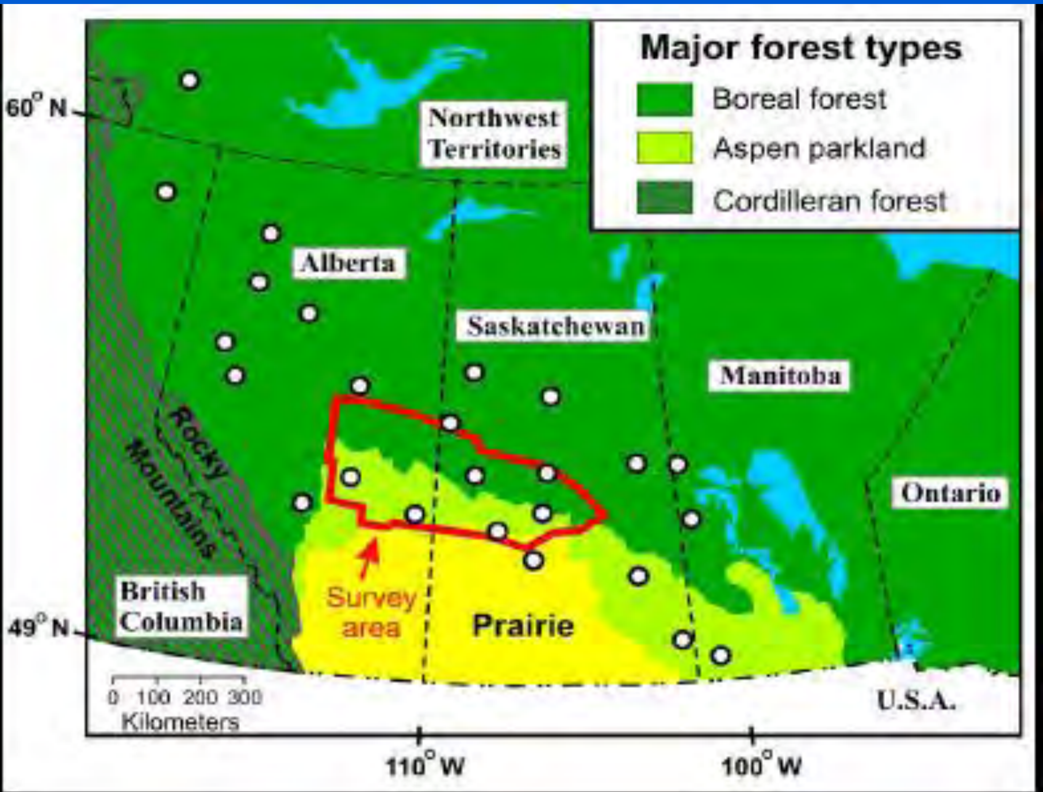
CMI = P – PET

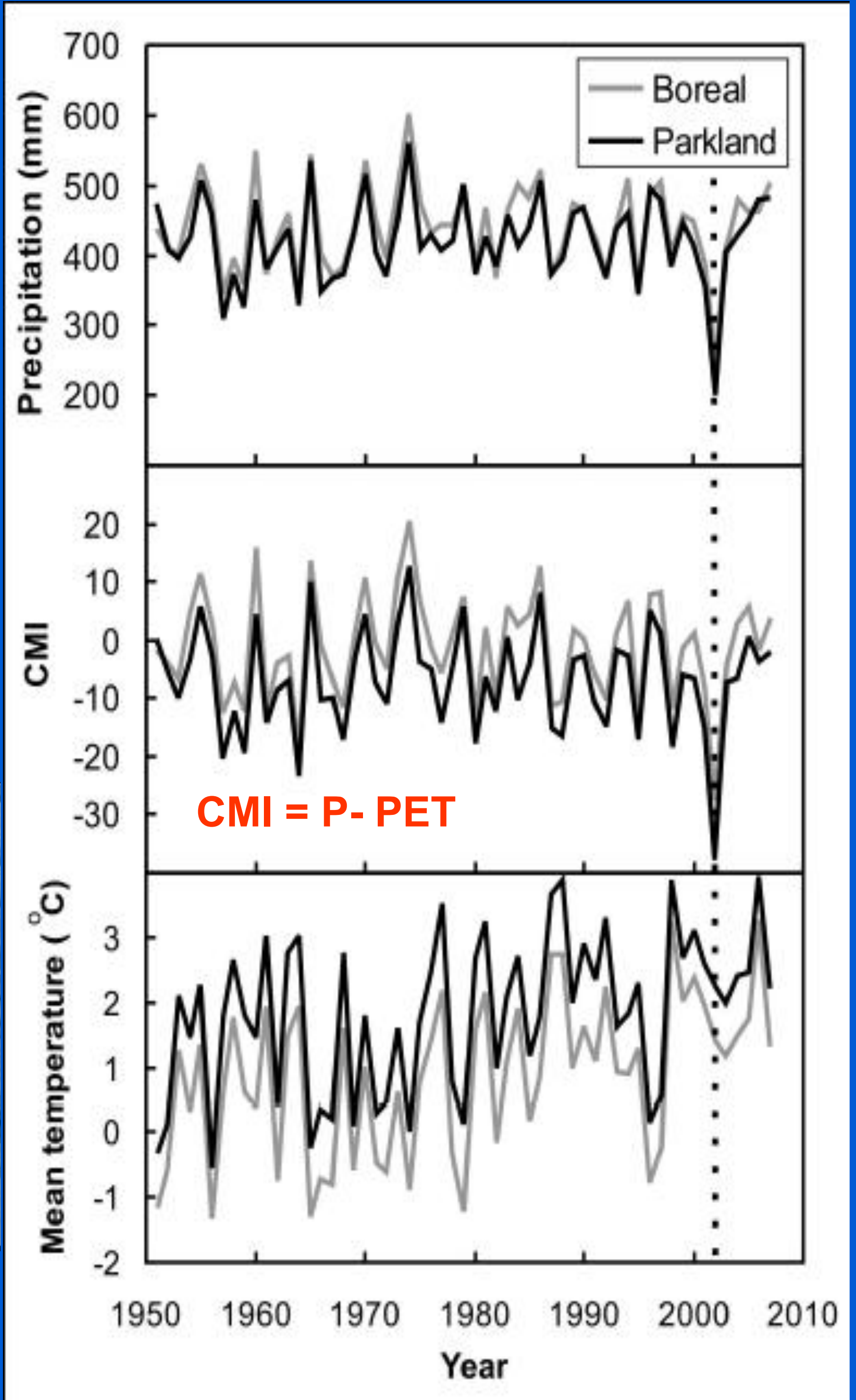
(units in cm/year)

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

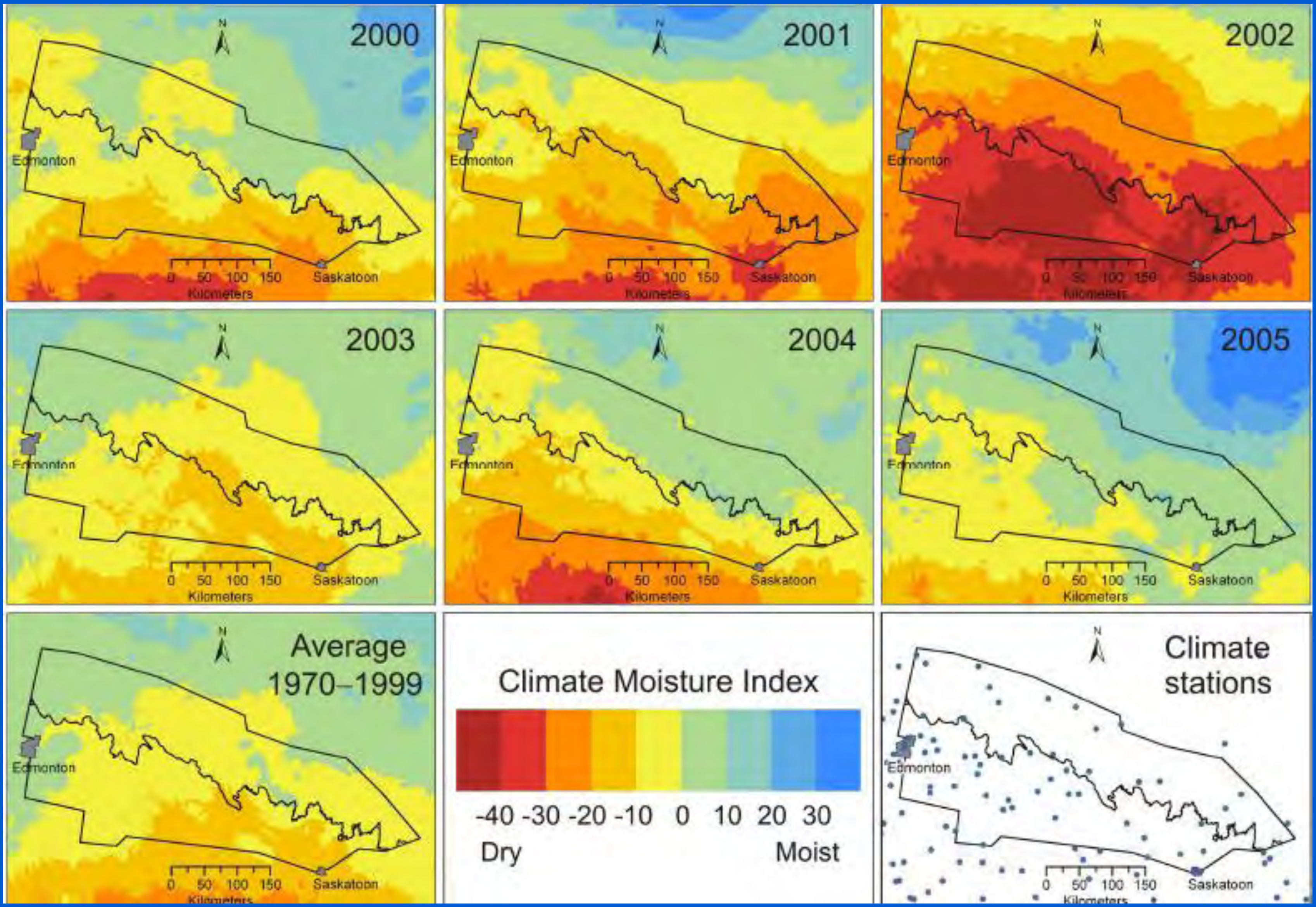
PET is annual potential evapotranspiration
loss of water vapour from a well-vegetated landscape, estimated from monthly temperature (mean daily max and min)

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

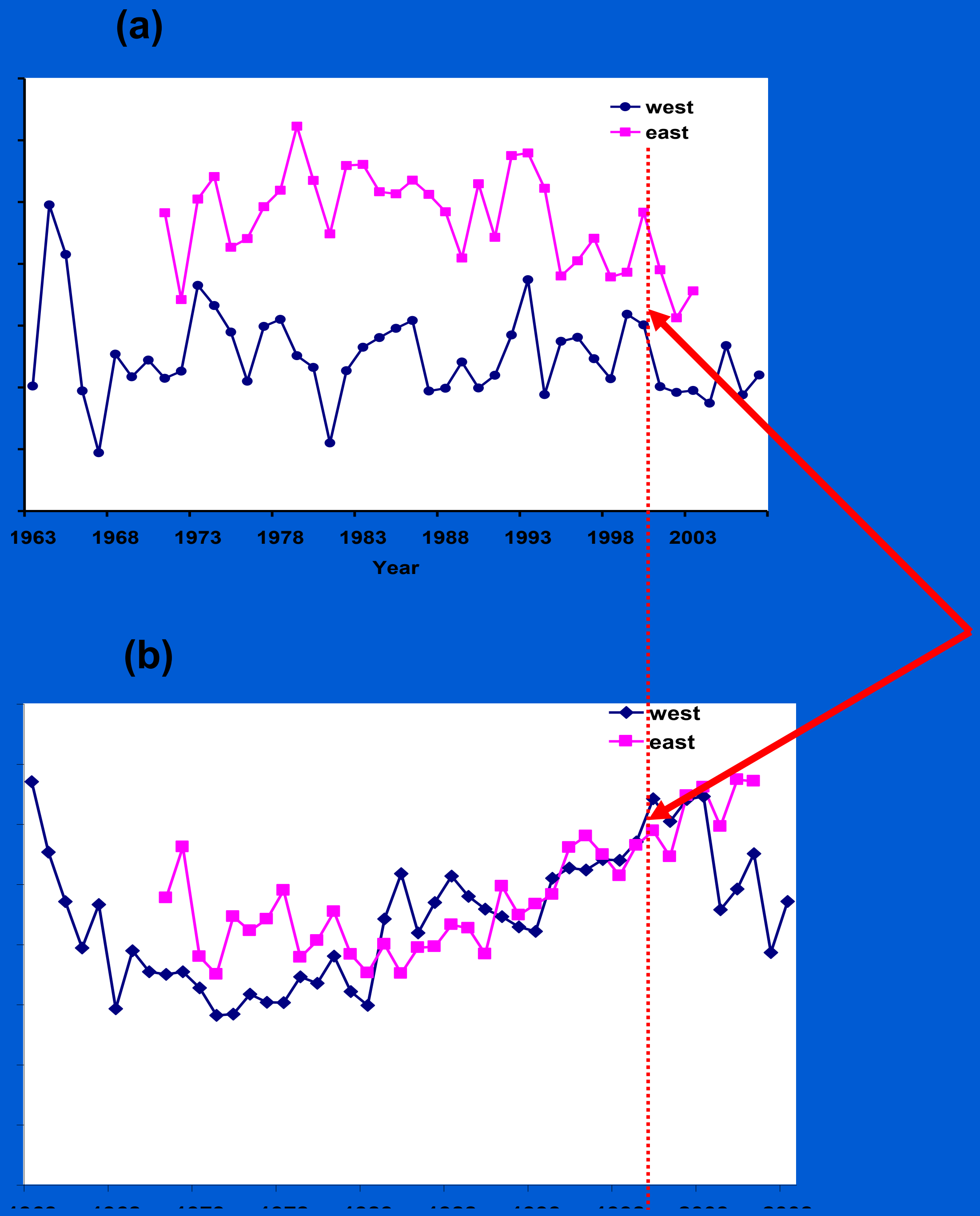




(Michaelian, Hogg et al, 2011, GCB)


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

Growth CMI



After 2000

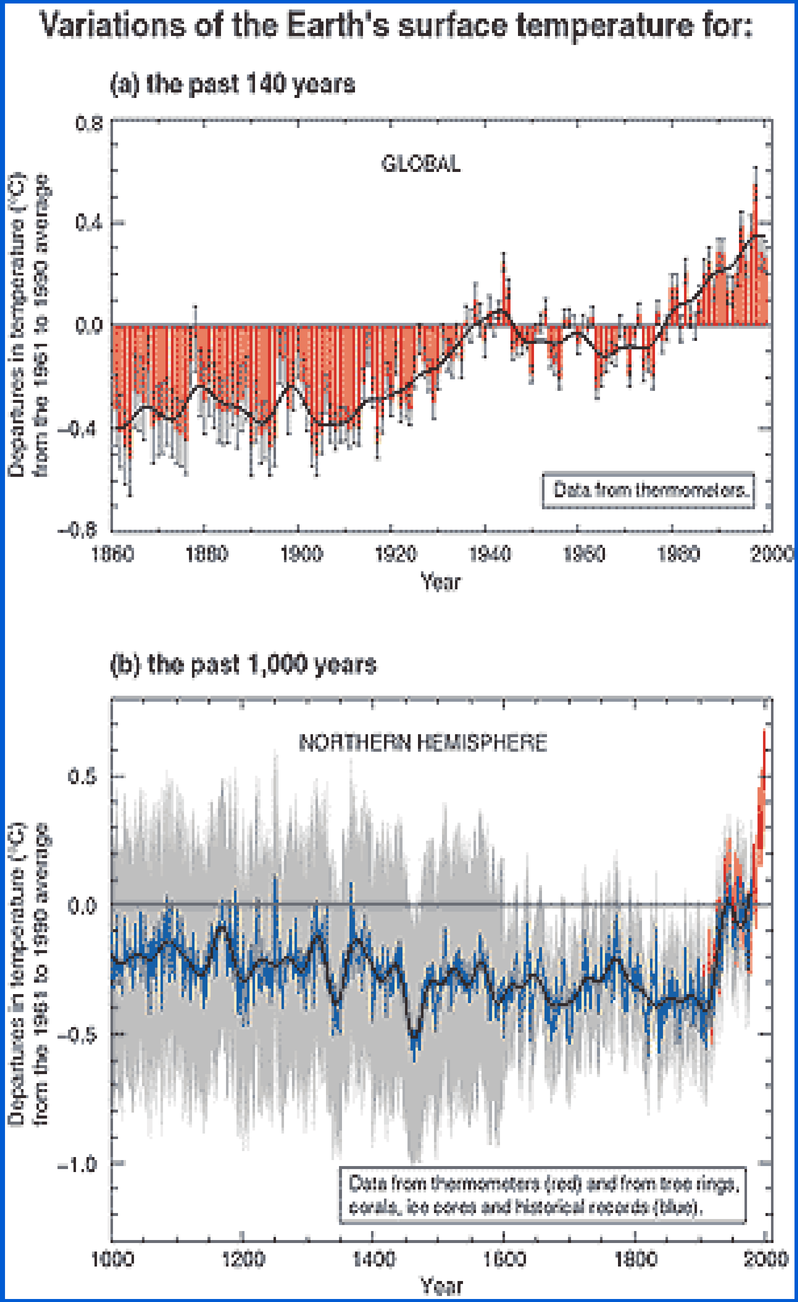
Solar Radiation

Main findings (3):

- 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).

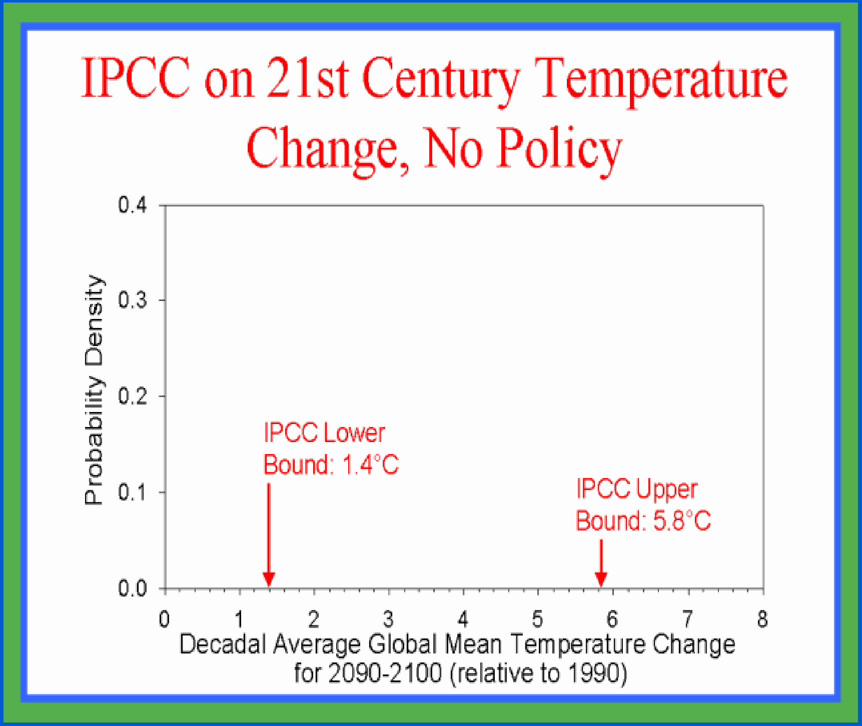
- Our results revealed that recent climate change, and especially drought-induced water stress, is the dominant cause of the observed reduction in the biomass carbon sink, suggesting that western Canada's boreal forests may become net carbon sources if the climate change–induced droughts continue to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

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



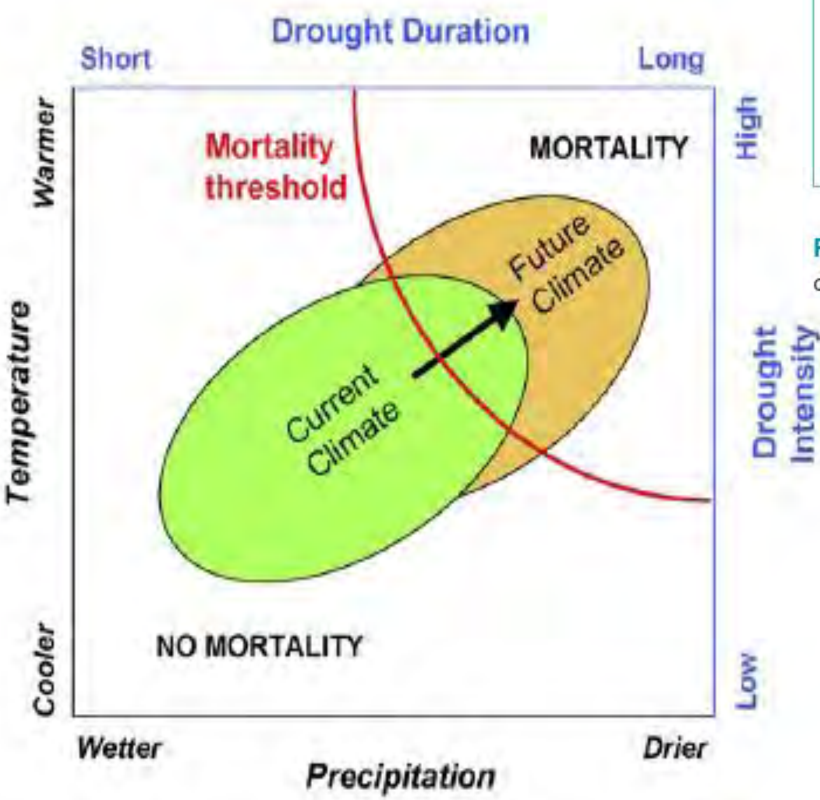
"Global warming continues"

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



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

Allen et al., 2010, FEM



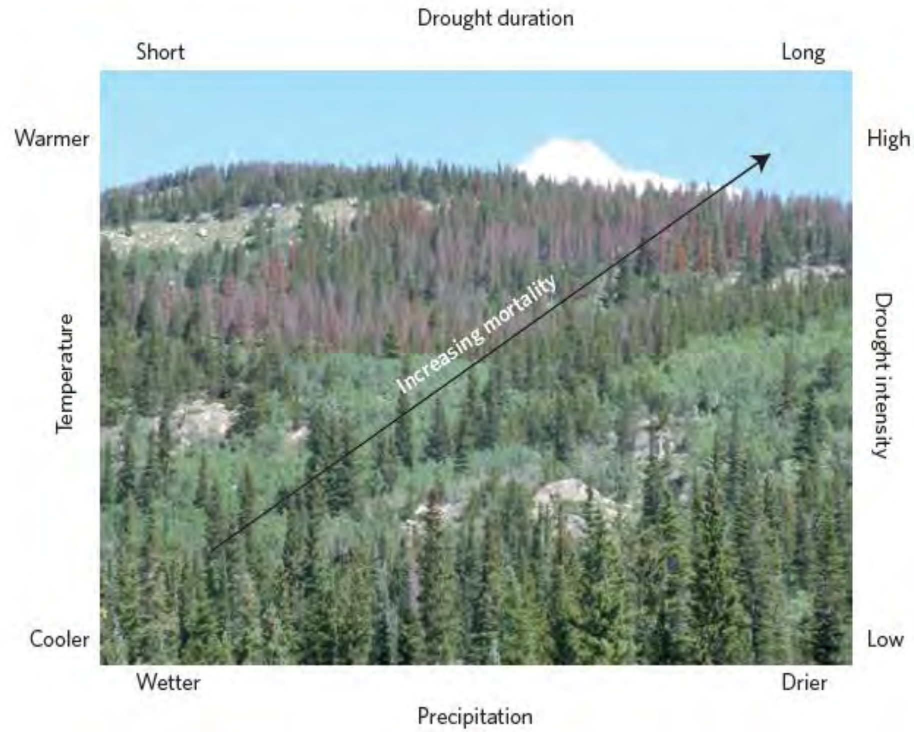


Figure 1 | Conceptual schematic showing how tree mortality might vary with temperature, drought duration and intensity, and precipitation. Figure adapted with permission from ref. 2, © 2010 Elsevier.

(Birdsey and Pan, 2011, Nature CC)

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

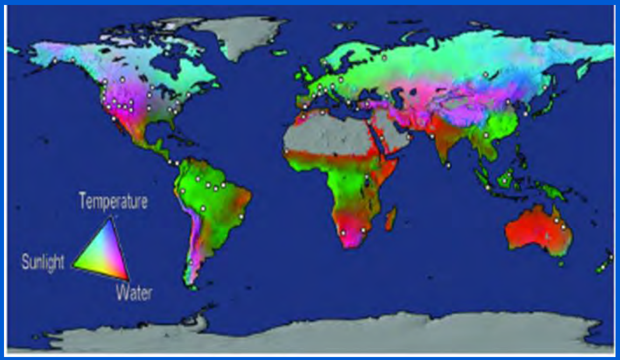
- Lacking the ability to predict mortality and die-off of tree species and forest types based on specific combinations of climatic events and their interactions with biotic stressors and place-specific site conditions.

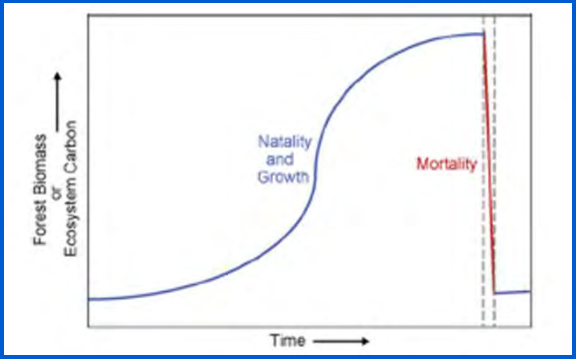
Research Needs and Ongoing Challenges:

- 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).

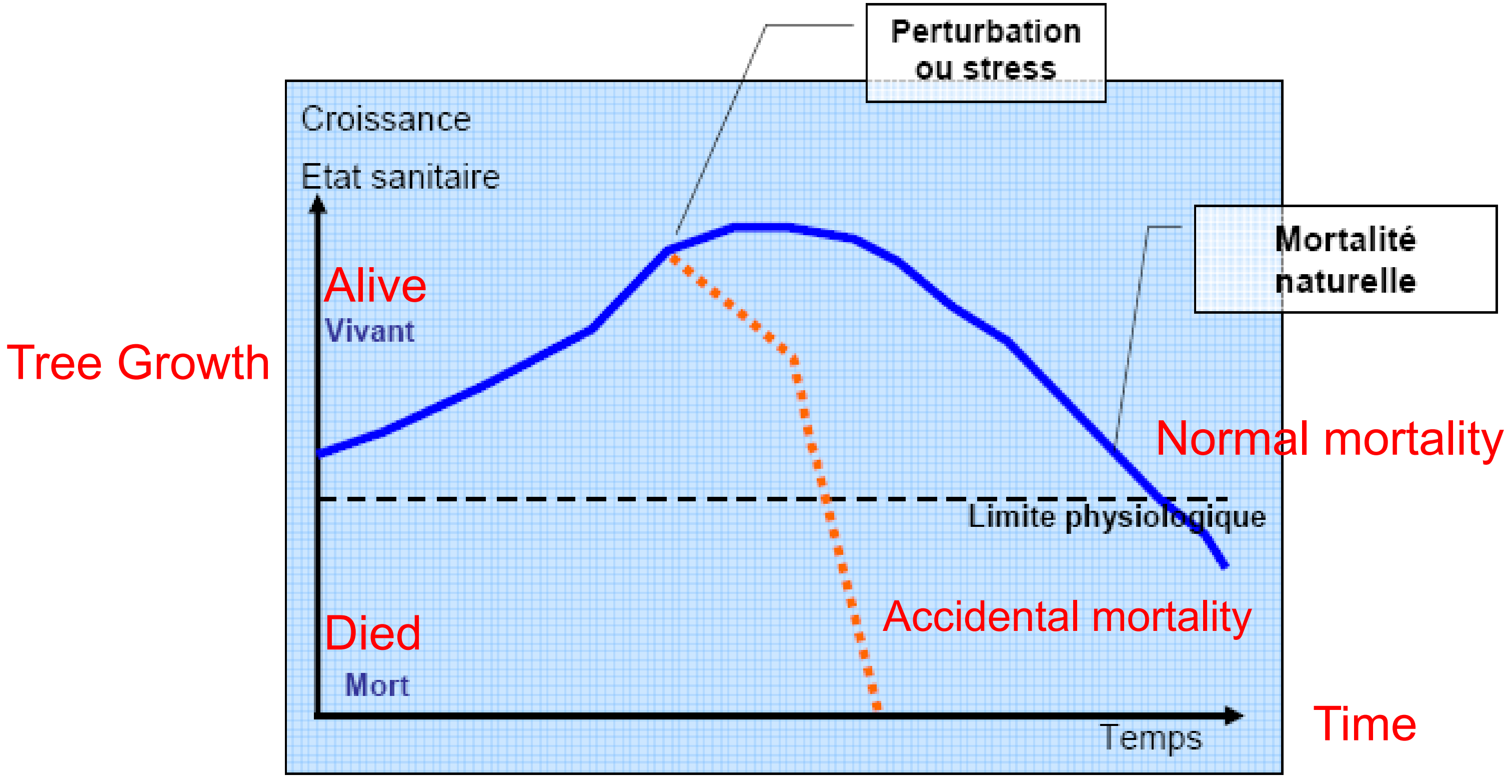




Why tree died quickly under disturbance or stress ?

Pourquoi les arbres meurent-ils ?

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



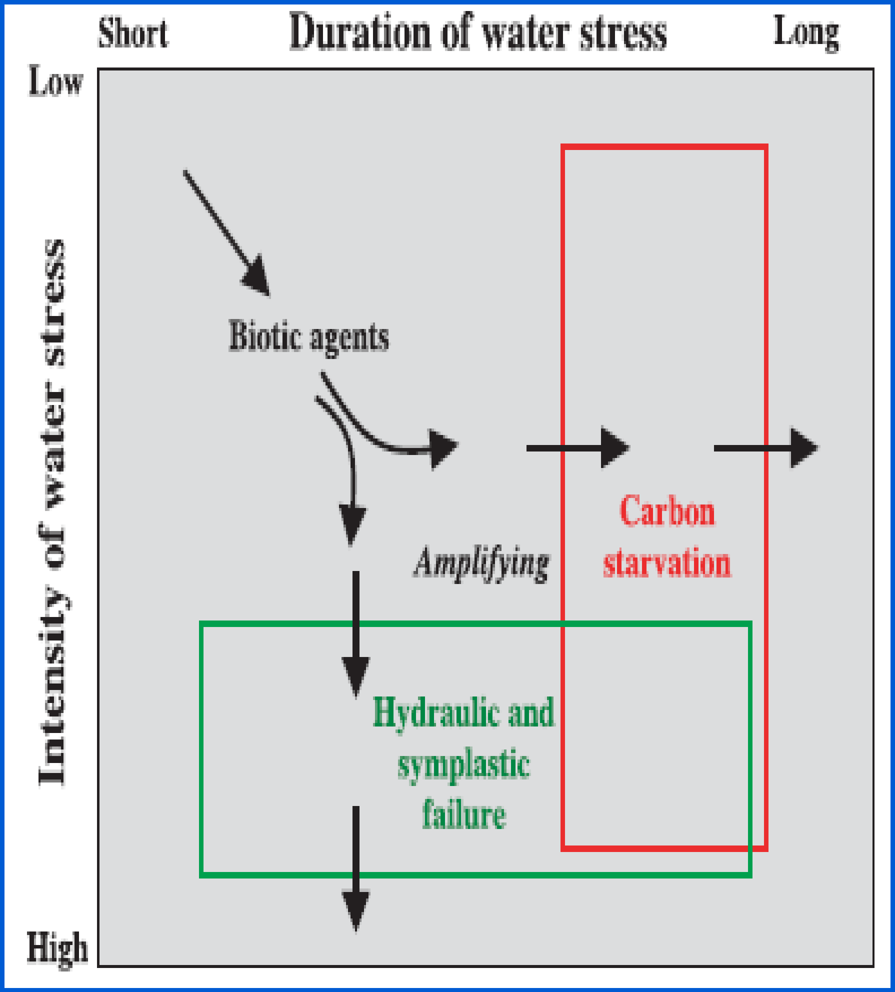
Mechanisms of Tree Mortality

Three hypothesized mechanisms underlying mortality.

- Carbon starvation

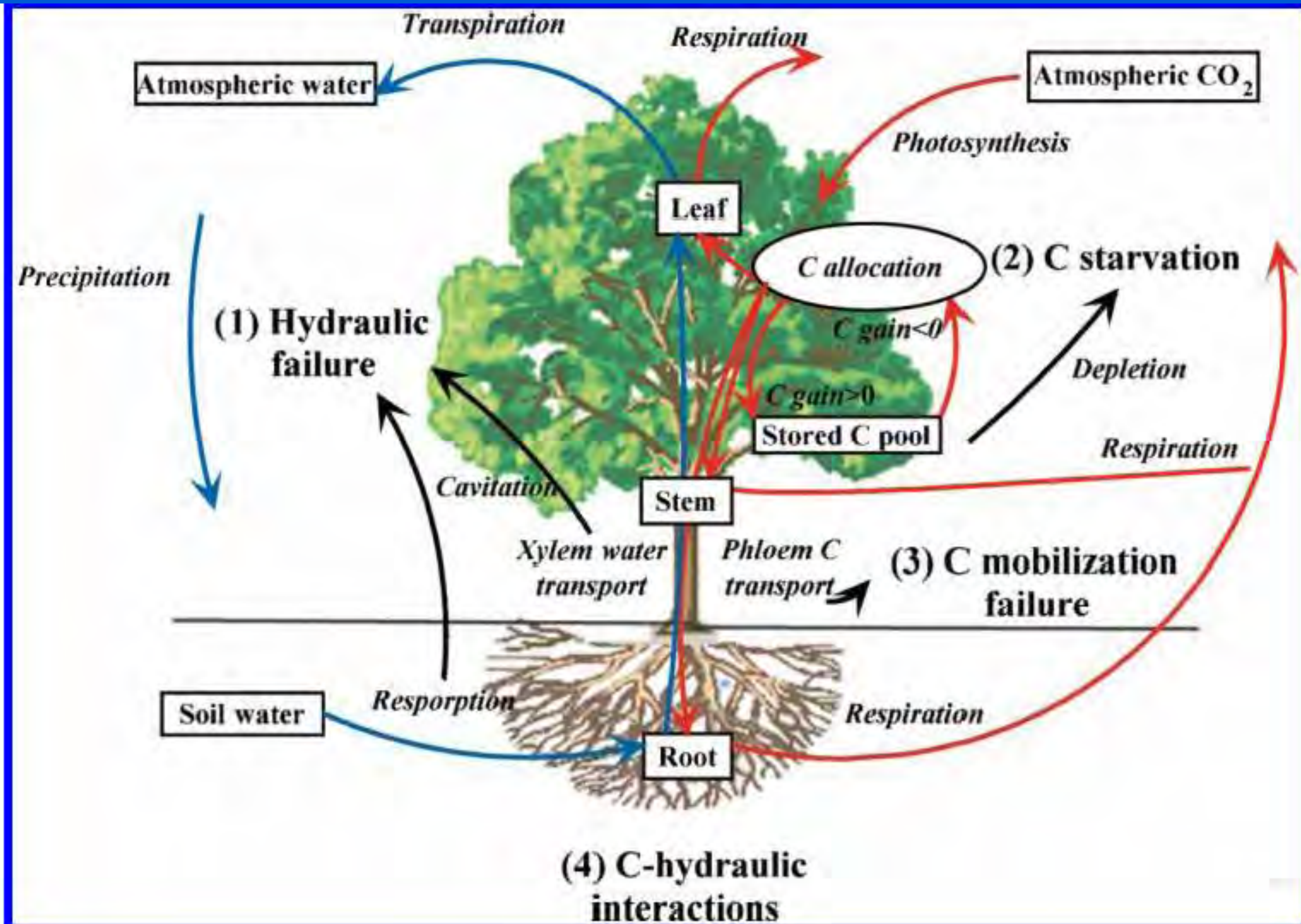
- Hydraulic failure

- Biotic agents (such as insects and pathogens)

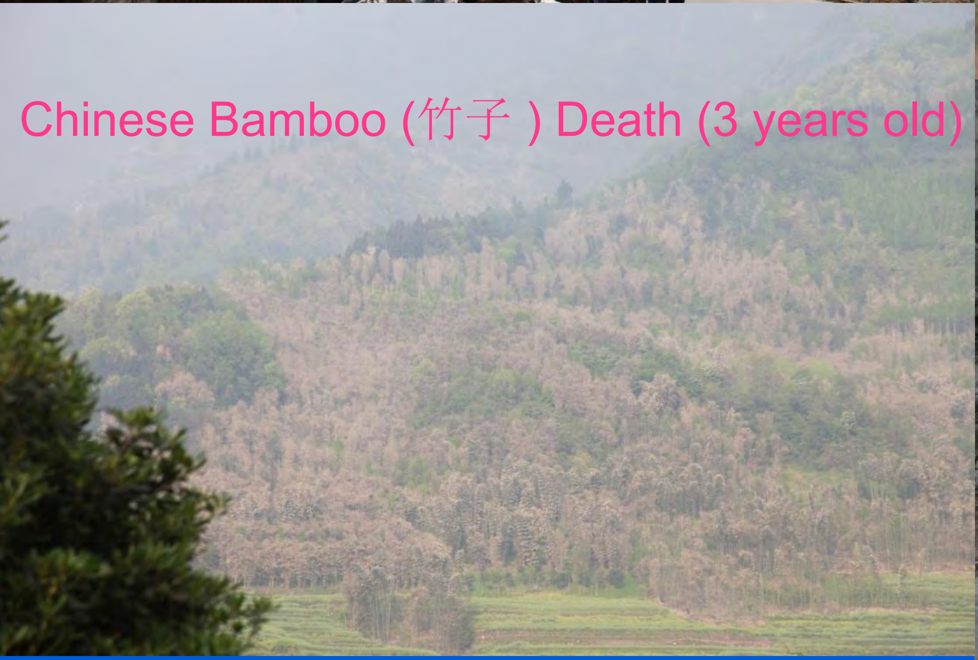


Theoretical relationship, based on the hydraulic framework, between the temporal length of drought (duration), the relative decrease in water availability (intensity)

(Nate McDowell et al. 2008)



(Wang et al. 2012, ER)



(Ya-An, Chengdu, China, April 20, 2011, Photo by Changhui Peng)

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.

4) Phillips, O.L., Aragao, L.E.O.C et al., 2009. Drought sensitivity of the Amazon rainforest. *Science*, 323(5919): 1344–1347.

5) McDowell, N.G., et al. 2011. The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends Ecol. Evol.* 26(10): 523–532.

6). Van Mantgem et al. 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323: 521-524.

7). Wang, WF, Peng, Ch et al. 2012. Drought-induced tree mortality: ecological consequences, causes, and modeling. *Environ. Rev.* 20: 109–121 (2012)

Acknowledgments

- NSERC Strategic Network (ForValuenet),
- NSERC Discovery Grant
- Forest Management Branch of Alberta Ministry of Sustainable Resource Development, Saskatchewan Renewable Resources Forestry Branch, Forestry Branch of Manitoba, Ontario Terrestrial Assessment Program, and Ministère des Ressources Naturelles et de la Faune du Québec, and our colleagues (P. Comeau, J. Liu, V. LeMay, S. Huang, J. Parton, K. Zhou)

Merci Beaucoup ! **Open for Questions?**