Global Warming
and the daunting challenge of
Climate-Ecosystem Feedbacks

The University of Toronto

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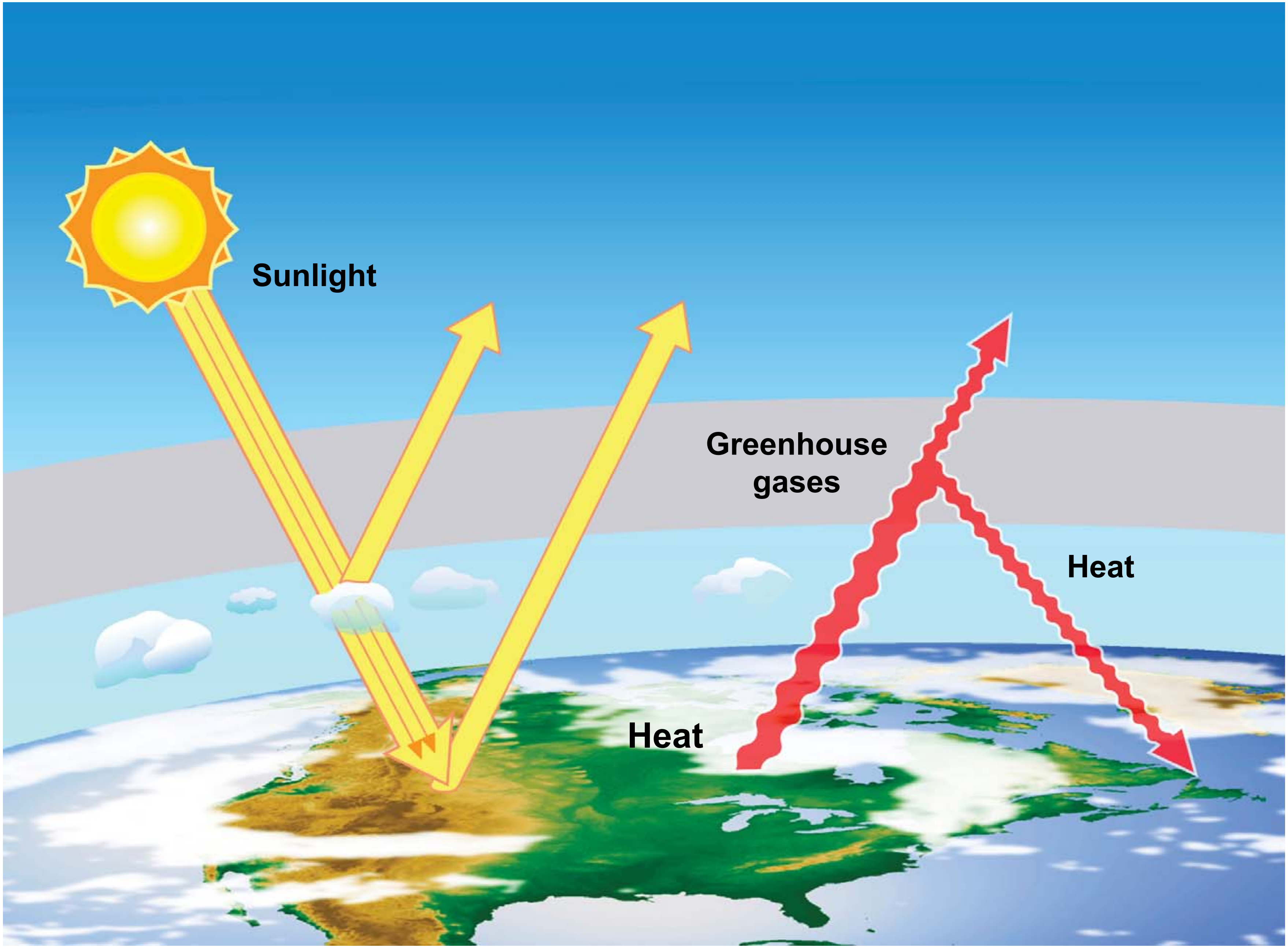
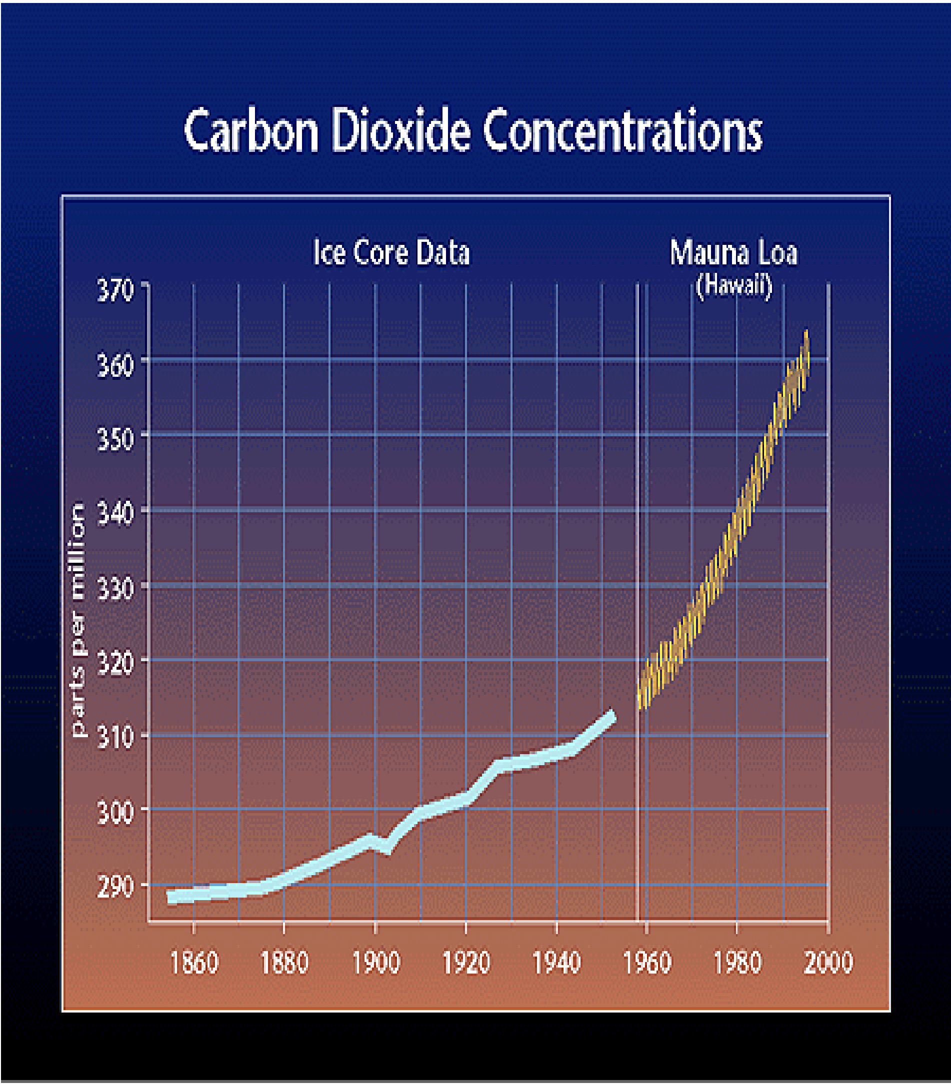
Outline of this talk

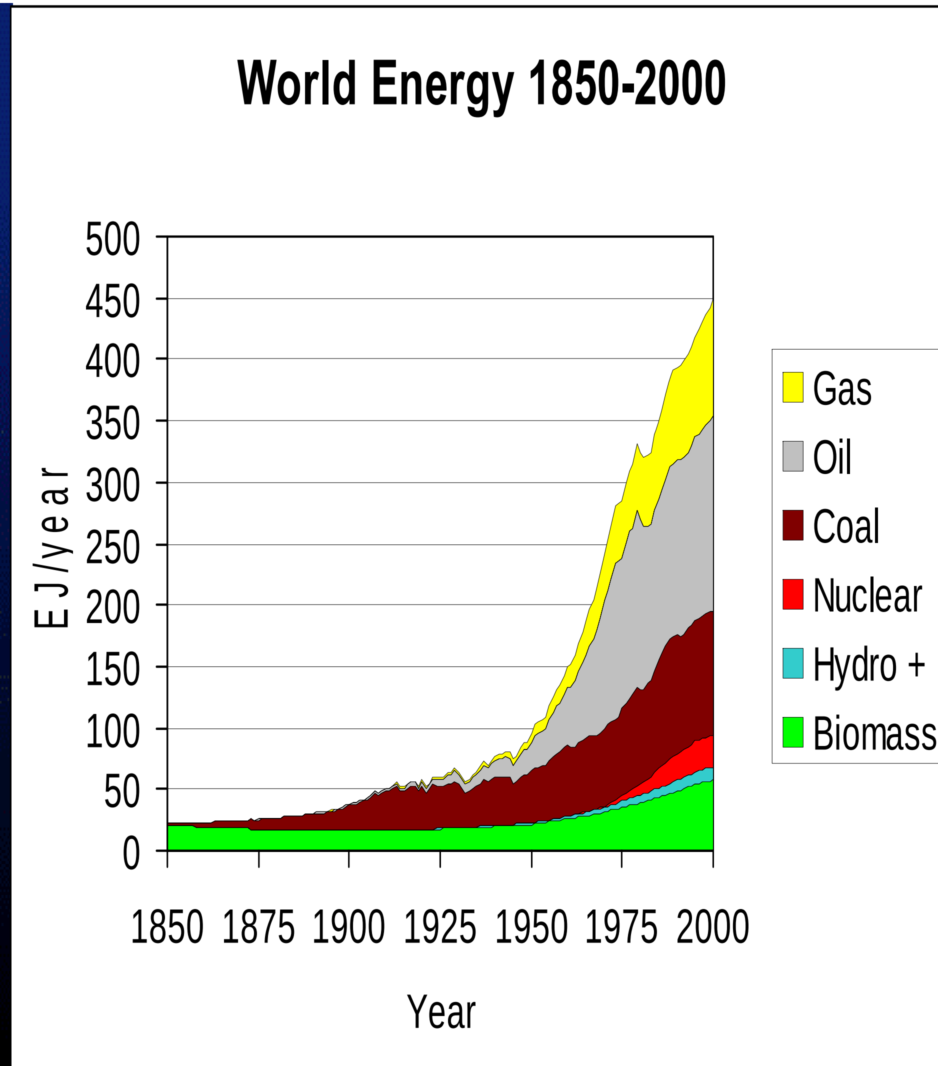
1. A quick overview of global warming

2. A global view of climate-ecosystem interactions and feedbacks

3. A local view: results from the RMBL meadow-warming experiment

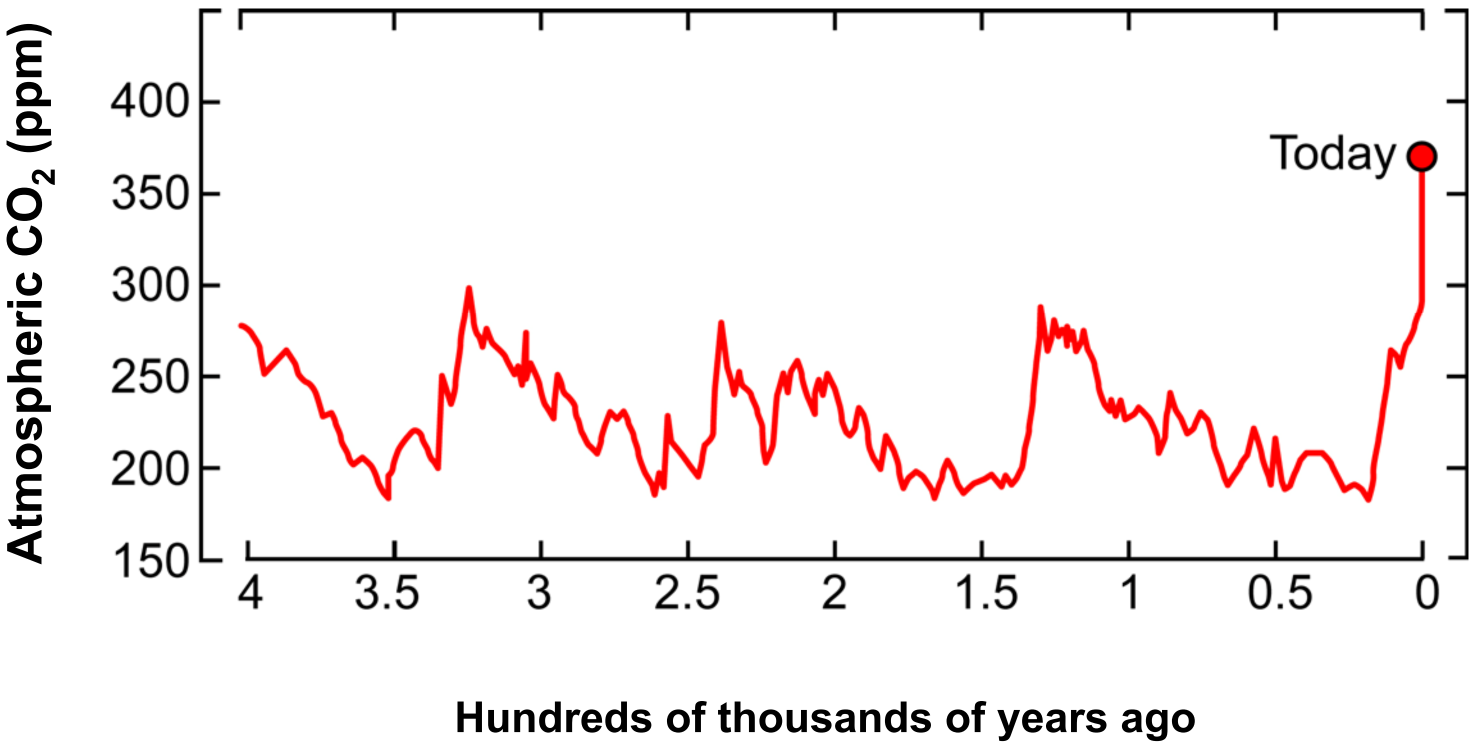

Sunlight
Greenhouse gases
Heat
Heat





The increase in atmospheric carbon dioxide is primarily due to world energy consumption and secondarily due to deforestation.

400,000 Years of Atmospheric Carbon Dioxide Data



What is the effect on global temperature of doubling the atmospheric concentration of carbon dioxide?

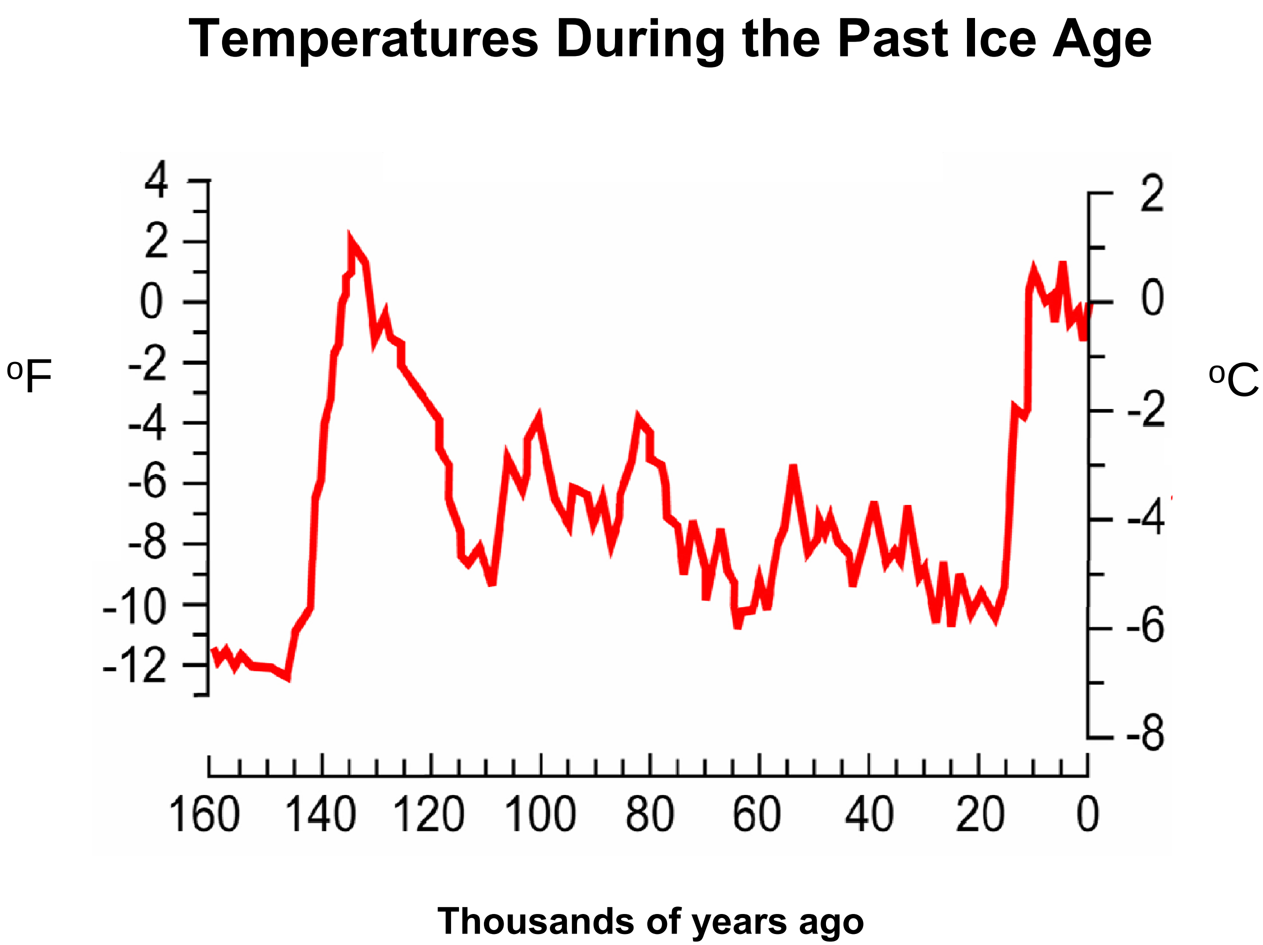
The direct effect of heat absorption by the CO_2: **+ 1 ^oC**

The indirect (feedback) effects: **+ 0.5 to 3.5 ^oC**

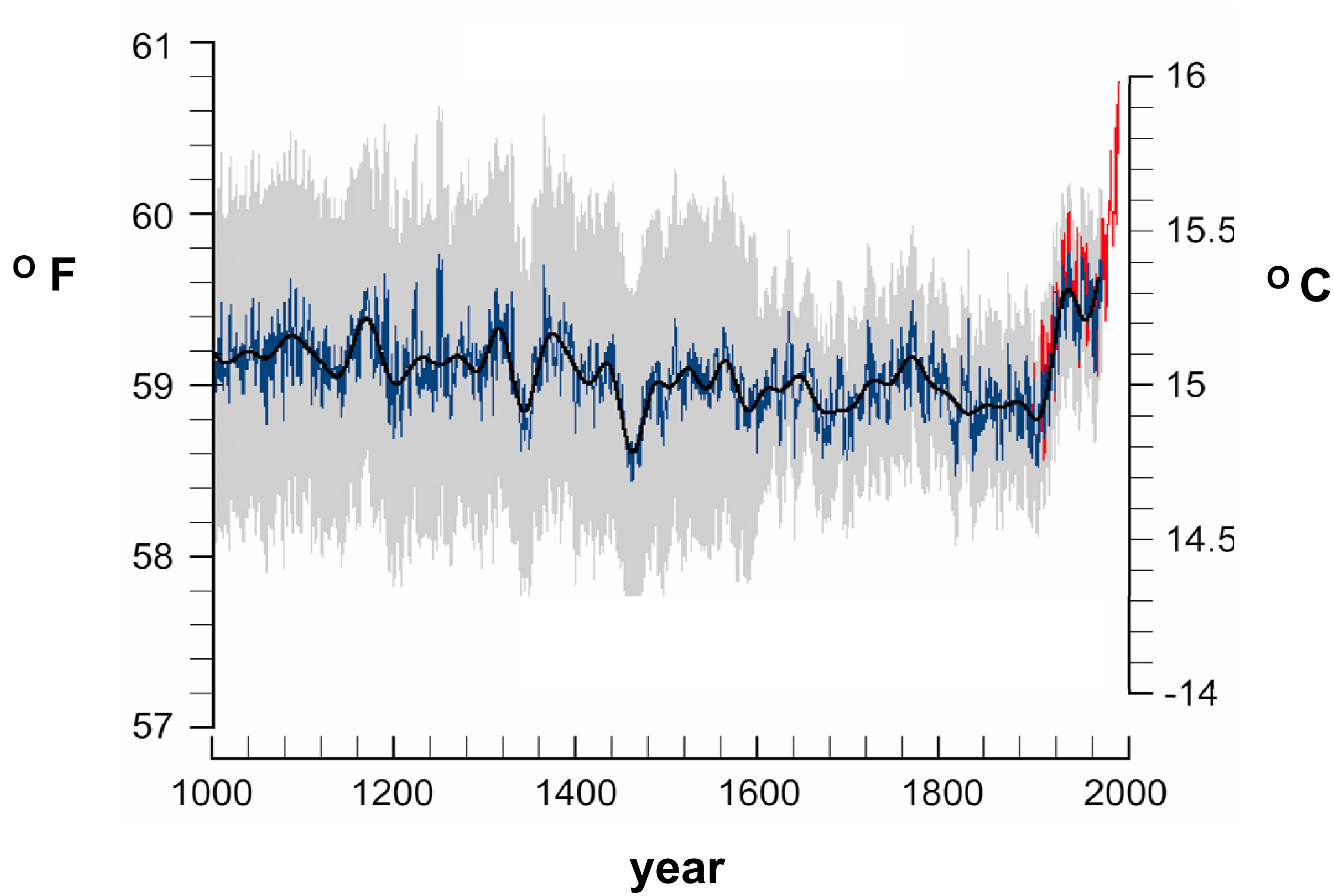
- melting ice and snow increases absorption of sunlight (ice-albedo effect)
- warmer air holds more water vapor, another greenhouse gas
- warmer air results in different cloud characteristics

TOTAL: **+ 1.5 to 4.5 ^oC**

Should we worry about +4 ^oC change?



1000 Years of Northern Hemisphere Temperature Data



Fingerprint of Global Warming

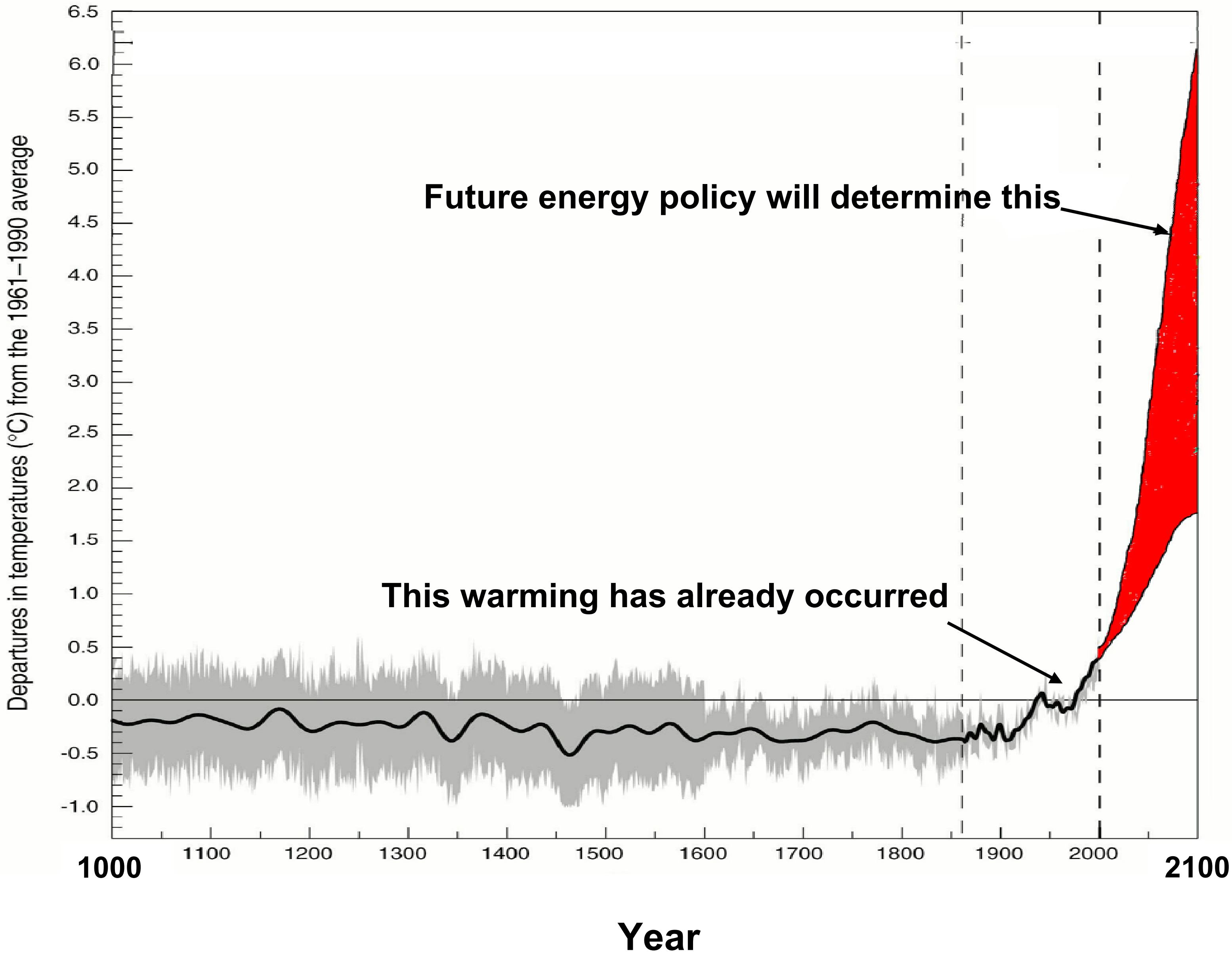
Models predict, and the data show that:

- Stratosphere cools as surface warms
- Temperature rises faster at night than day
- Temperature rises faster in winter than summer
- High latitudes warm more than low latitudes

If global warming were caused by a brightening sun, then the stratosphere would warm and temperature rise would be greatest in daytime

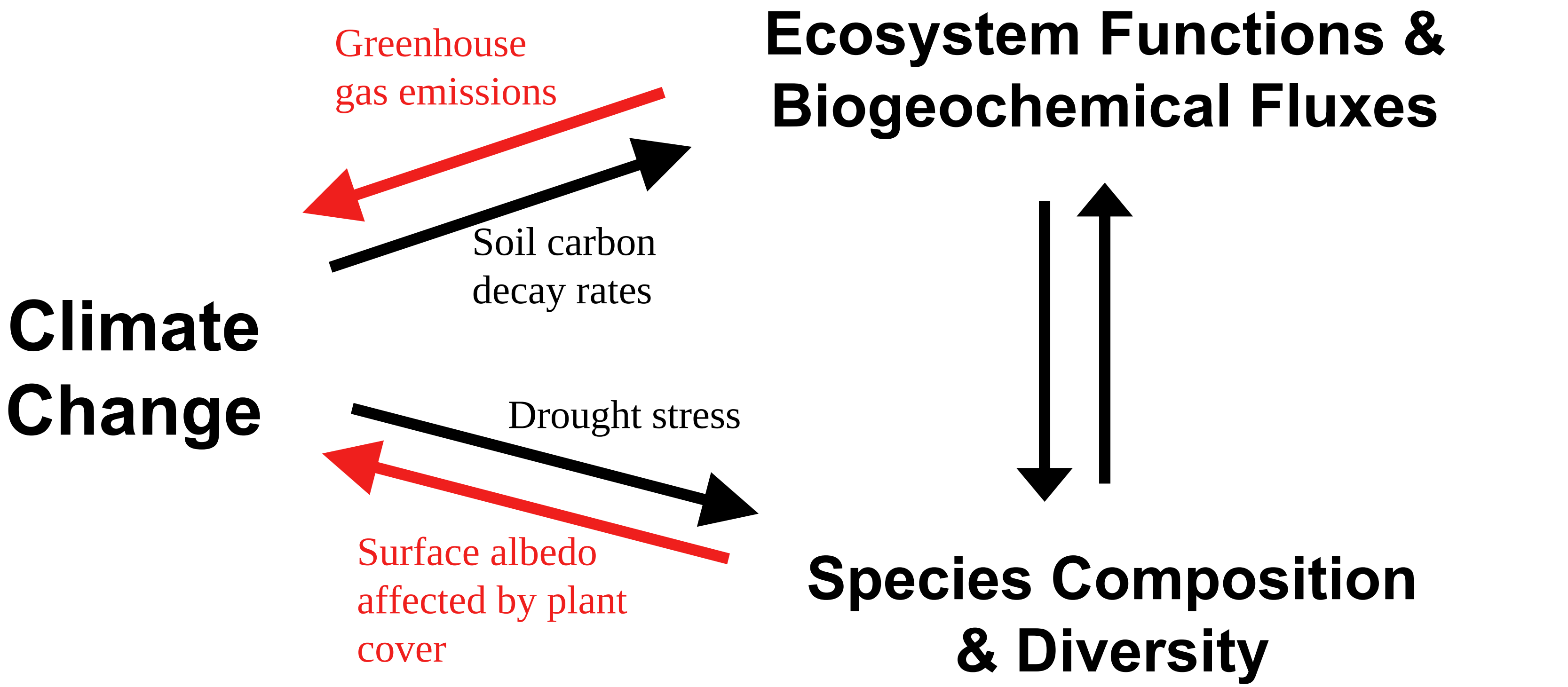
IMPACTS OF GLOBAL WARMING

- Threats to Food Production (Diminished Water Supplies)
- Human Health Impacts (Heat Waves, Infectious Disease)
- Wildfire
- Sealevel Rise
- Ecological Effects:
    - Extinction Episode Comparable to K-T Boundary
        - Spread of Invasive Species
        - Coral Bleaching



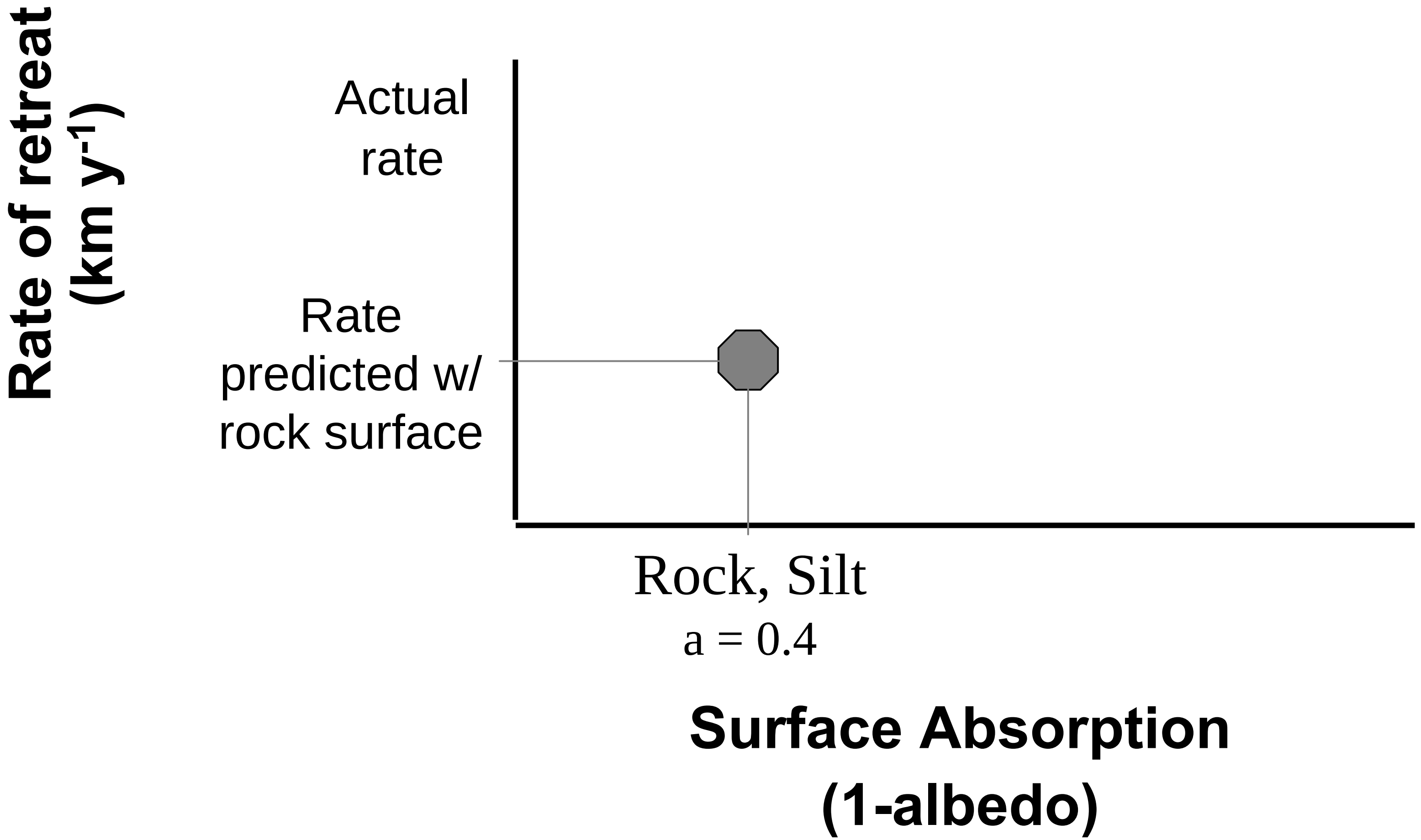
Departures in temperatures (°C) from the 1961–1990 average
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
Future energy policy will determine this
This warming has already occurred
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Year

Part 2: A global view of Climate-Ecosystem Feedbacks



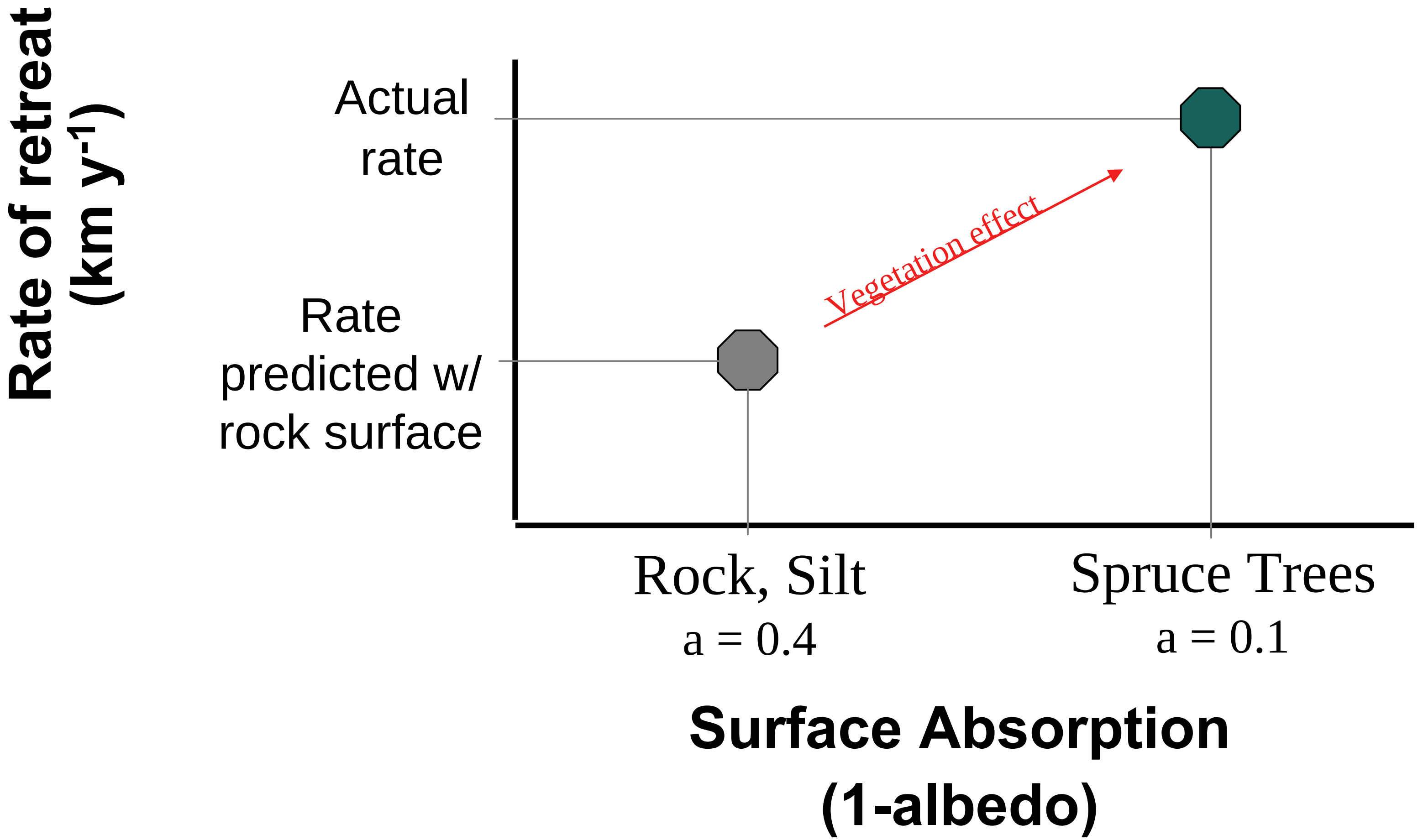
Retreat of N. American Ice Sheet

The model with rock and silt surface predicts slow retreat

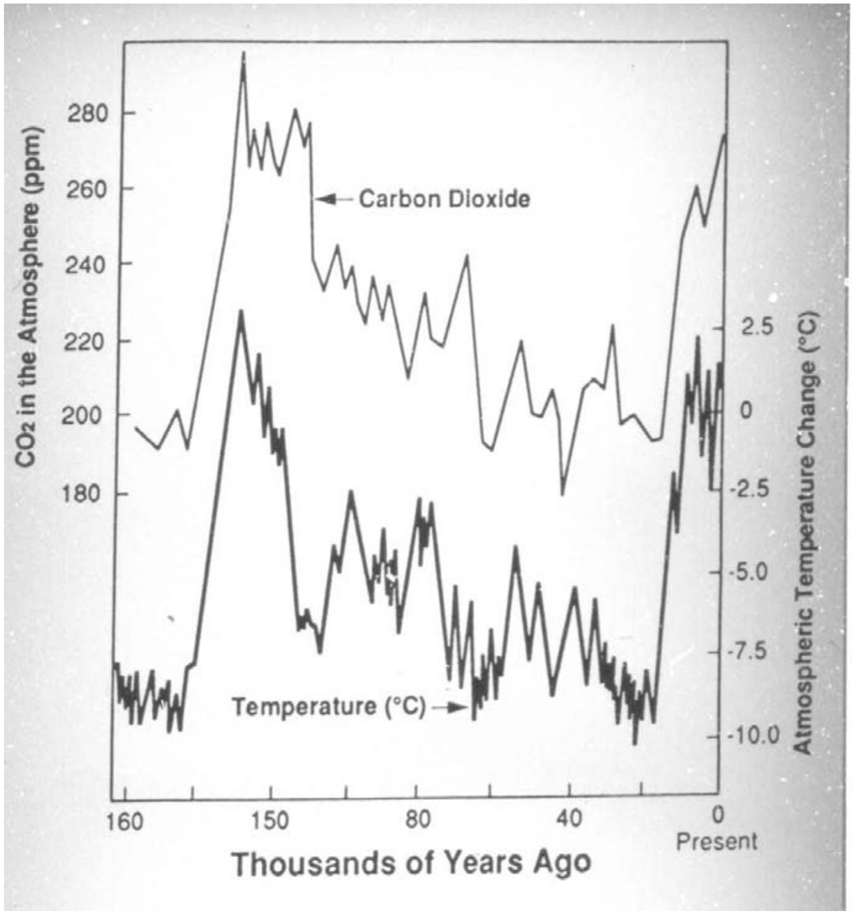


Retreat of N. American Ice Sheet

The model with spruce trees predicts actual rate



The Vostok core suggests feedback



Milankovitch Cycles are the time keeper but their magnitude is too weak to explain the huge climate variability

CO_2 release during slight warming must cause more warming!

And CO_2 uptake during slight cooling must cause more cooling.

This effect is not incorporated in our current climate models (GCM's)

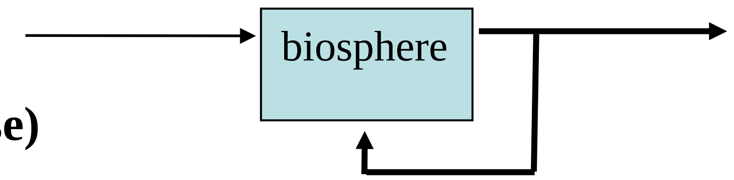
Slide 16

WB3 Wendy Brown, 2003-10-13

HOW DO WE QUANTIFY FEEDBACK?

Input Signal (I)

(e.g., direct warming effect of GHG increase)



Output Signal (O)

(e.g., full warming effect)

Gain Factor (g)

$$O = I + gI + ggI + gggI + \ldots$$

$$= I / (1 - g) \quad \text{if } g < 1$$

If $g < 0$: $O < I$, negative feedback

If $g > 0, g < 1$: $O > I$, positive feedback, stable

If $g > 1$: unstable positive feedback

$$g = \sum_{p_i} (\partial T/\partial p_i)(\partial p_i/\partial T)$$

e.g., $p_1(T)$ = albedo of land surface, which may change if warming induces a changes in dominant vegetation

FEEDBACK (CONTINUED)

$g < 0$: O < I, negative feedback
$g > 0$: O > I, positive feedback
$g > 1$: Unstable

Feedback process	Gain factor (g)
In current GCMs:	
water vapor	0.40 (0.28 - 0.52)
ice and snow	0.09 (0.03 - 0.21)
clouds	0.22 (-0.12 - 0.29)
total	0.71 (0.17 - 0.77)

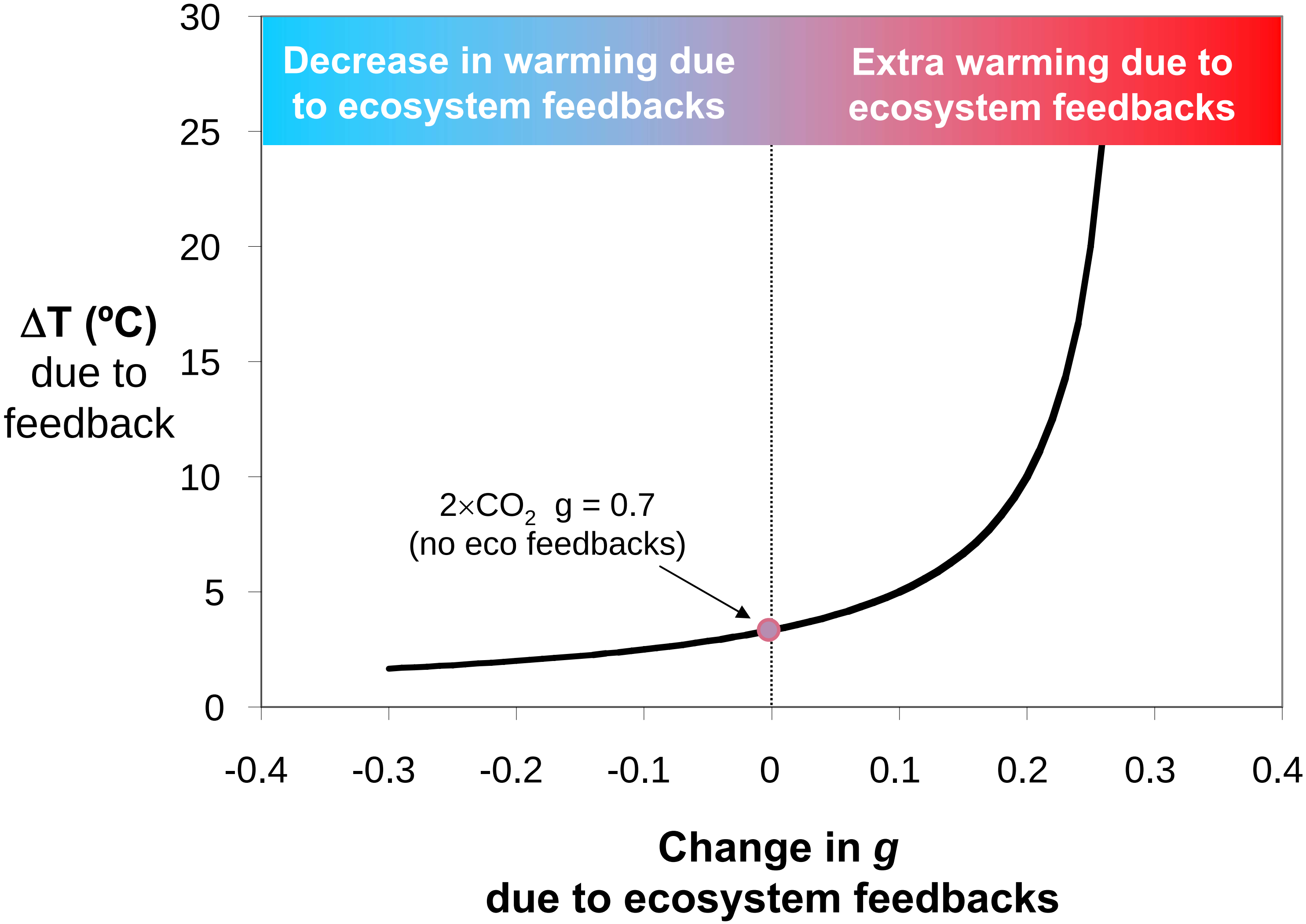
Climate change: ΔT=forcing effect/(1-g)

$$\Delta T = 1^{o}C/(1 - 0.71) = 3.^{o}C$$

Global Carbon Cycle

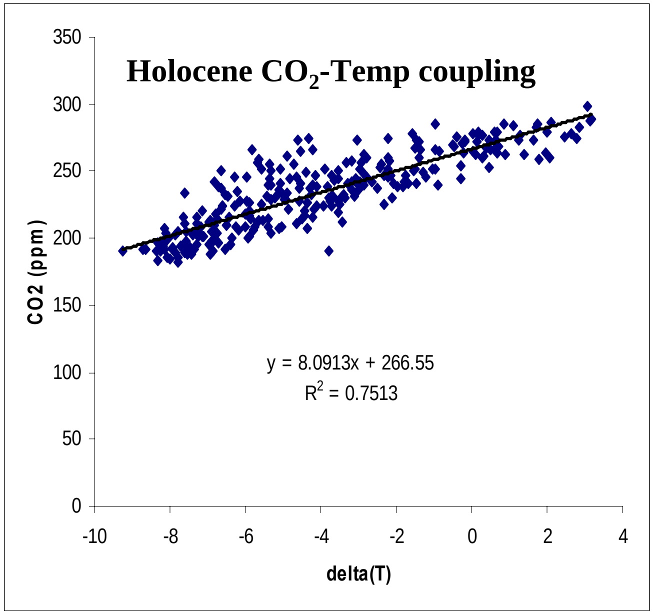
Small change in g causes large ΔT

Asymmetries



M.S. Torn, LBNL

An estimate of the carbon feedback from Vostok core data:



General Circulation Models

$$g_{CO2} = \frac{\partial T}{\partial CO_2} \bullet \frac{\partial CO_2}{\partial T} = \frac{4^o C}{275\,ppm(CO_2)} \bullet \frac{32\,ppm(CO_2)}{4^o C} = 0.12$$

1°C/(1 - .71) = 3.4°C

1°C/(1 - .71 – .12) = 6°C !!!

But where is the carbon coming from?

How can we learn about climate-ecosystem feedback?

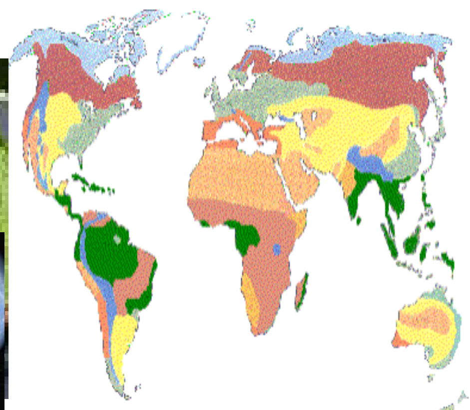
1. **Ecological correlations across different climates**
   - **natural climate variability in space (latitudinal, altitudinal)**
   - **natural inter-annual variability of climate**
   - **multi-decadal ecological trends synchronous with global warming trend**
   - **paleoclimatic variability, combined with pollen records and other ecological reconstructions**
2. **Climate manipulation experiments, with control,**

   allowing deduction of causal mechanisms
3. **Mathematical models**

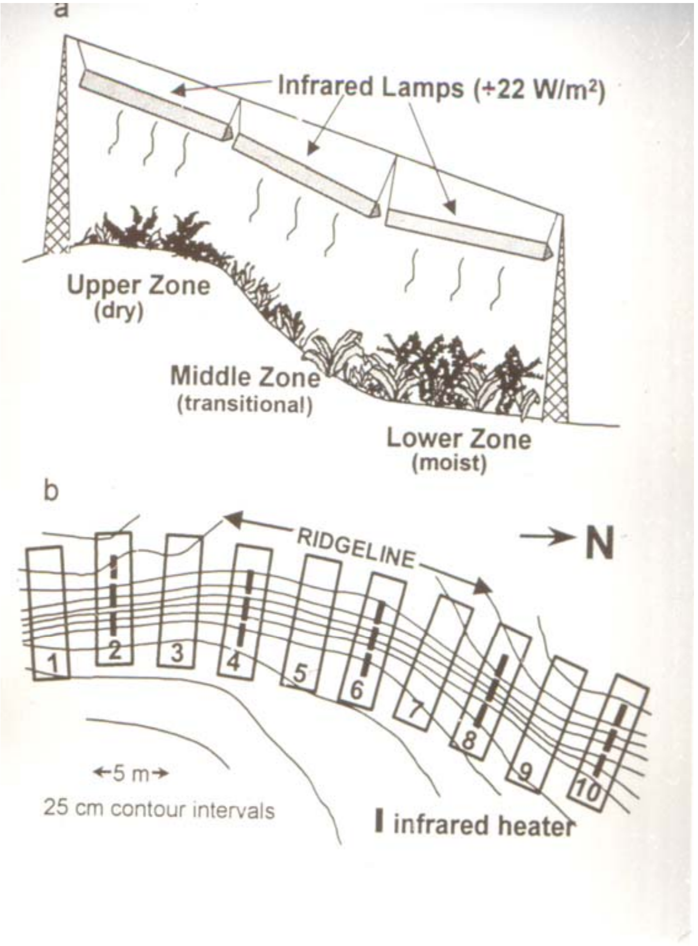
1. ***Applicable to large spatial scales, but potentially misleading.***
2. ***Confined to plot-scale, but capable of identifying mechanisms.***
3. ***Only as good as the observations!***

POSSIBLE LEVELS OF AGGREGATION IN GLOBAL MODELS

Planet	Biomes	Ecosystems	Community Patch
Single big leaf	Coarse Functional Groups	Functional Groups	Species assemblage
N=1	N ~ 10	N ~ 1000’s	N ~ millions



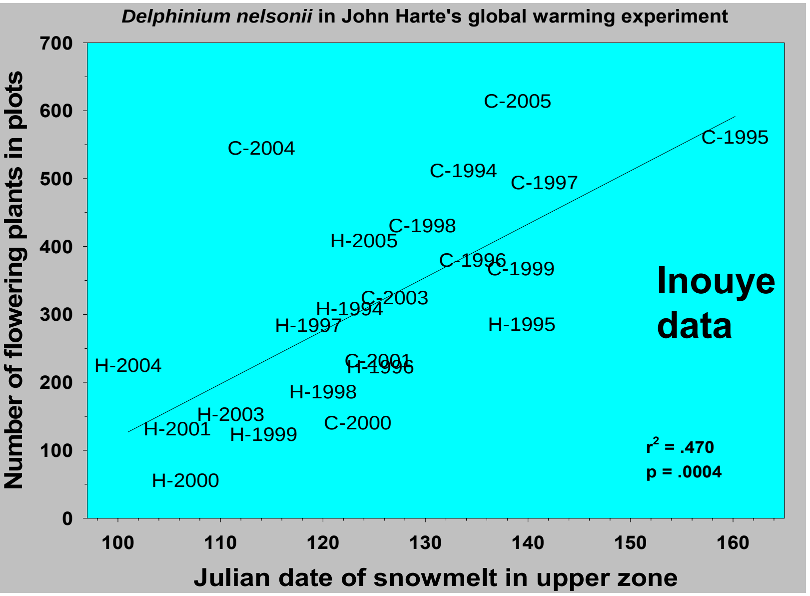
Part 3: A “longterm” warming experiment



Rocky Mt. Biological Laboratory, Gothic, Colorado

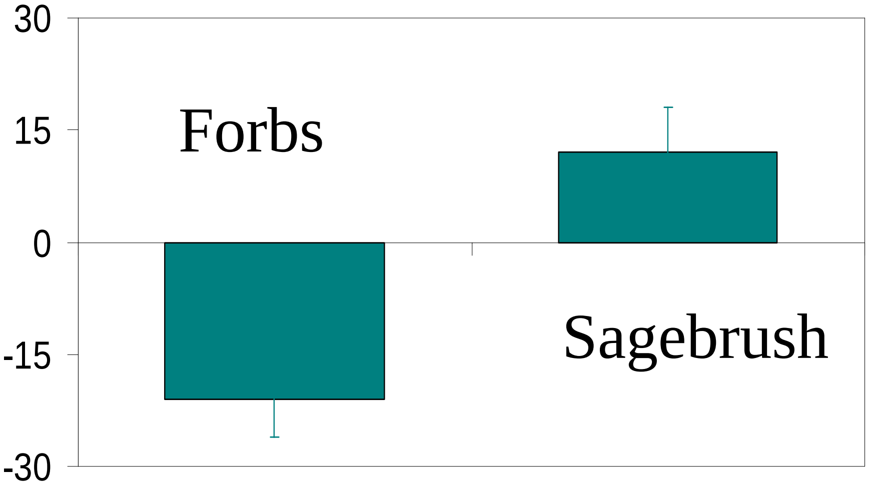
Infra-red heaters (22 W m^{-2}). Soil is warmer, drier; Earlier snowmelt

Warming Treatment Effect:
Forb Production Decreases.
Sagebrush Production Increases.



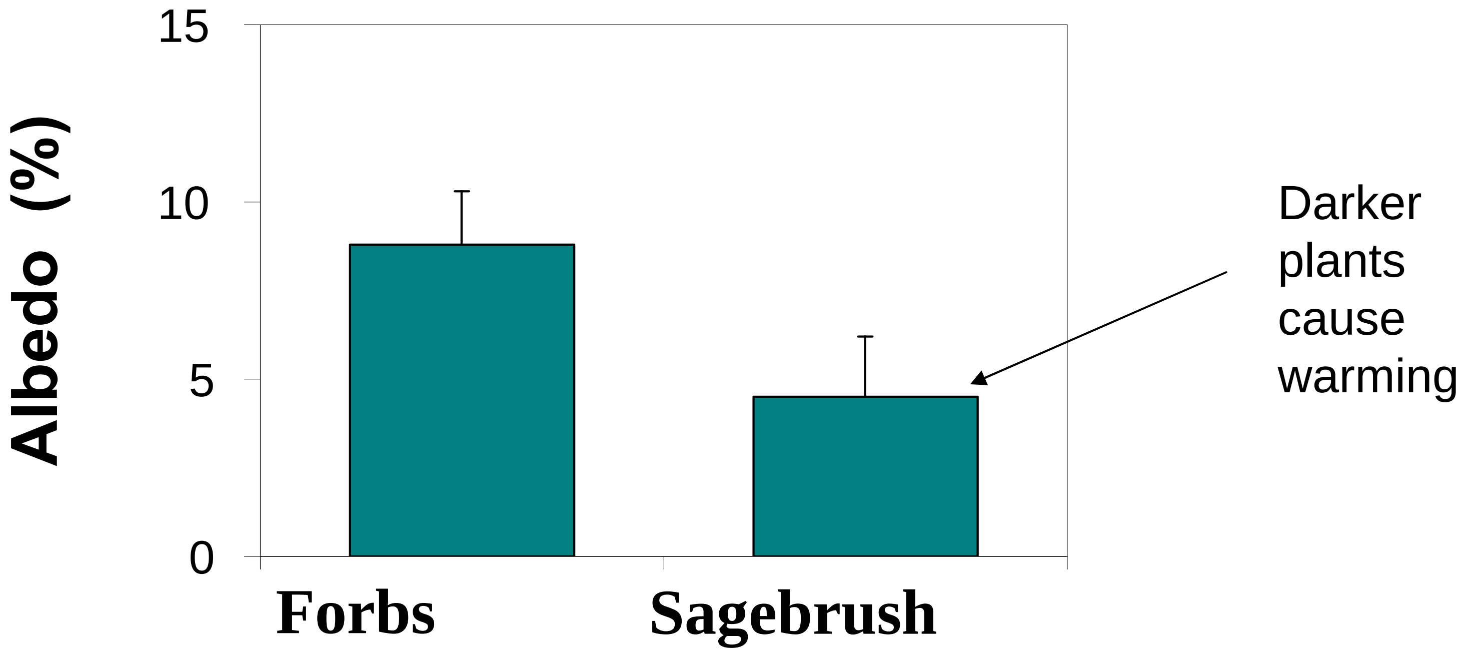
% Change in areal cover

$$\frac{(\text{Warming} - \text{Control})}{\text{Control}} \bullet 100\%$$



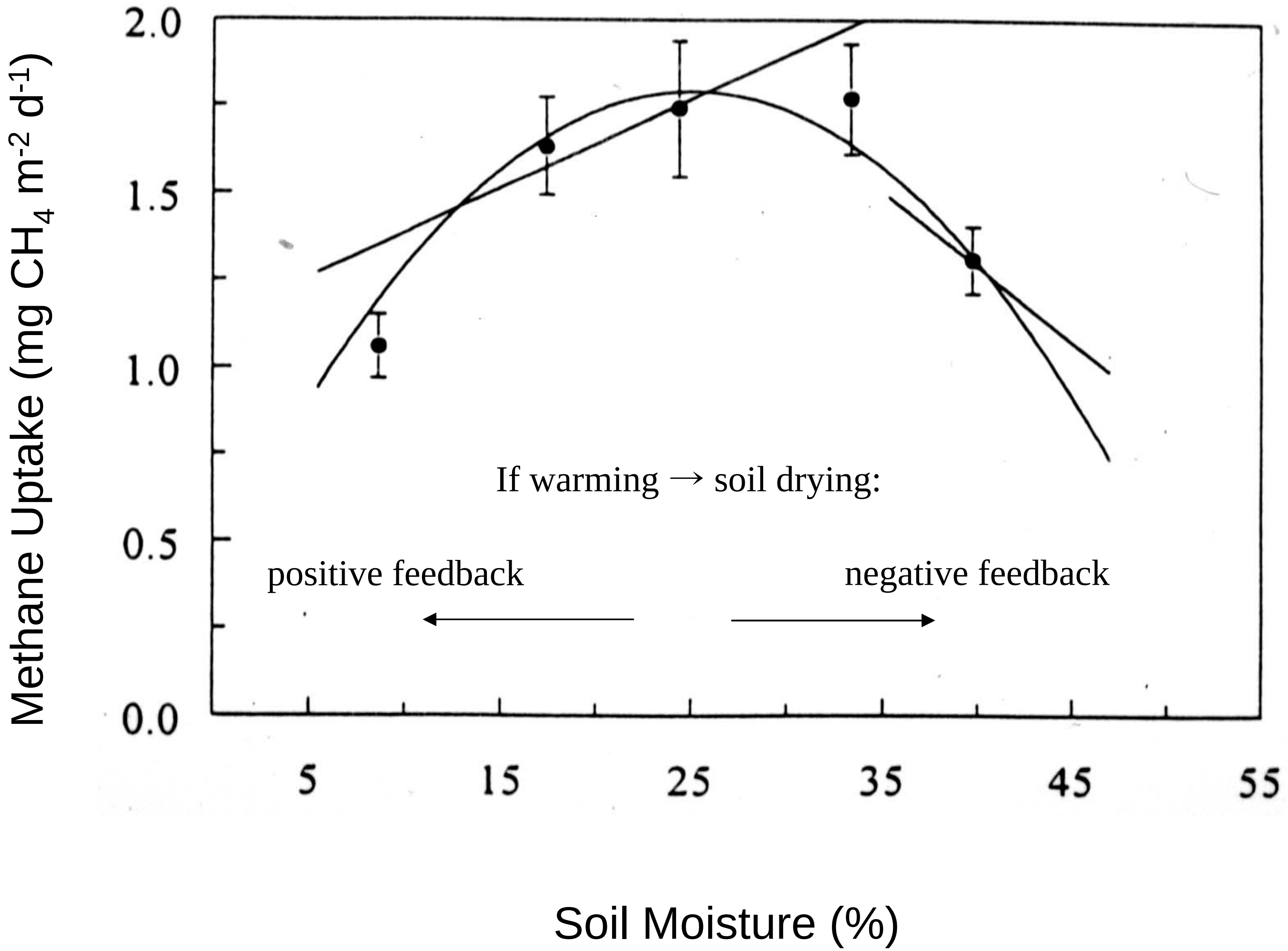
Harte and Shaw, *Science*, 1995

Feedback # 1: climate-induced change in species composition can alter late-spring surface albedo



A 20% change in regional plant cover will have an effect on <u>local</u> summertime climate that is comparable to that of 2 x CO_2

Feedback # 2: methane consumption influenced by soil moisture



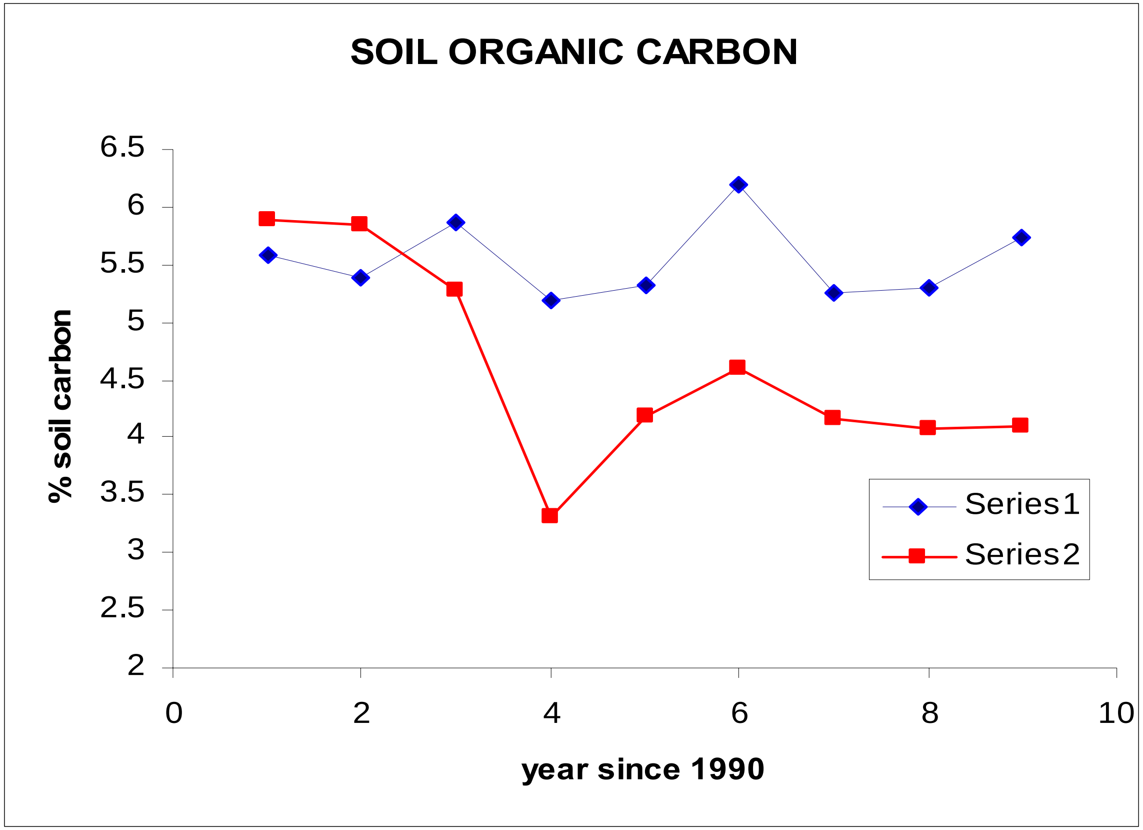
Torn and Harte, *Biogeochemistry, 1995*

Feedback # 3: warming can alter ecosystem carbon storage, and thus change atmospheric CO_2

Heated plot decline converts to:

~200-400 g C m^{-2}
(out of ~2300 total, 0-10cm)

Experimental warming reduces soil carbon!



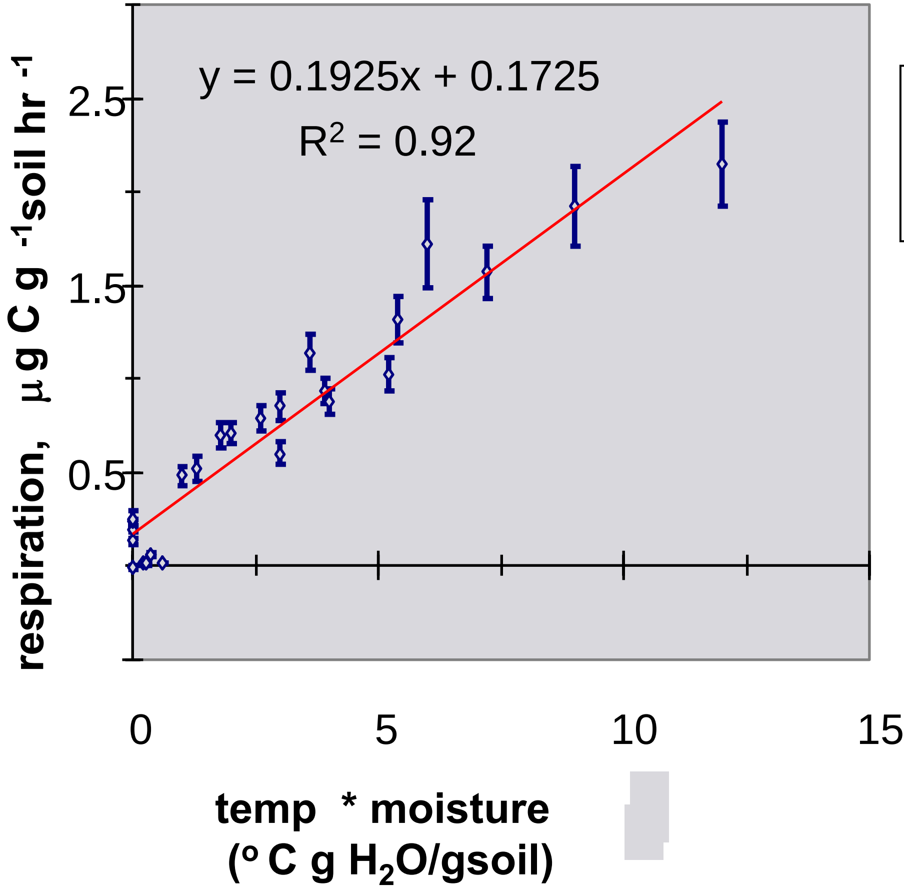
Question: What caused the decline in soil carbon?

Conventional answer: warming-induced enhancement of soil respiration

(Post et al. 1982; Raich and Schlesinger, 1992; Schimel et al. 1994; Trumbore et al., 1996)

What caused the decline in soil carbon?
→ **NOT** a heating-induced increase in soil respiration

Soil drying and soil warming have opposite effects (evidence from laboratory soil incubation)



<u>Full 5x5 factorial :</u>
0, 10, 13,18, 30 deg. C
2, 10, 20, 30, 40 %H2O

Thus,

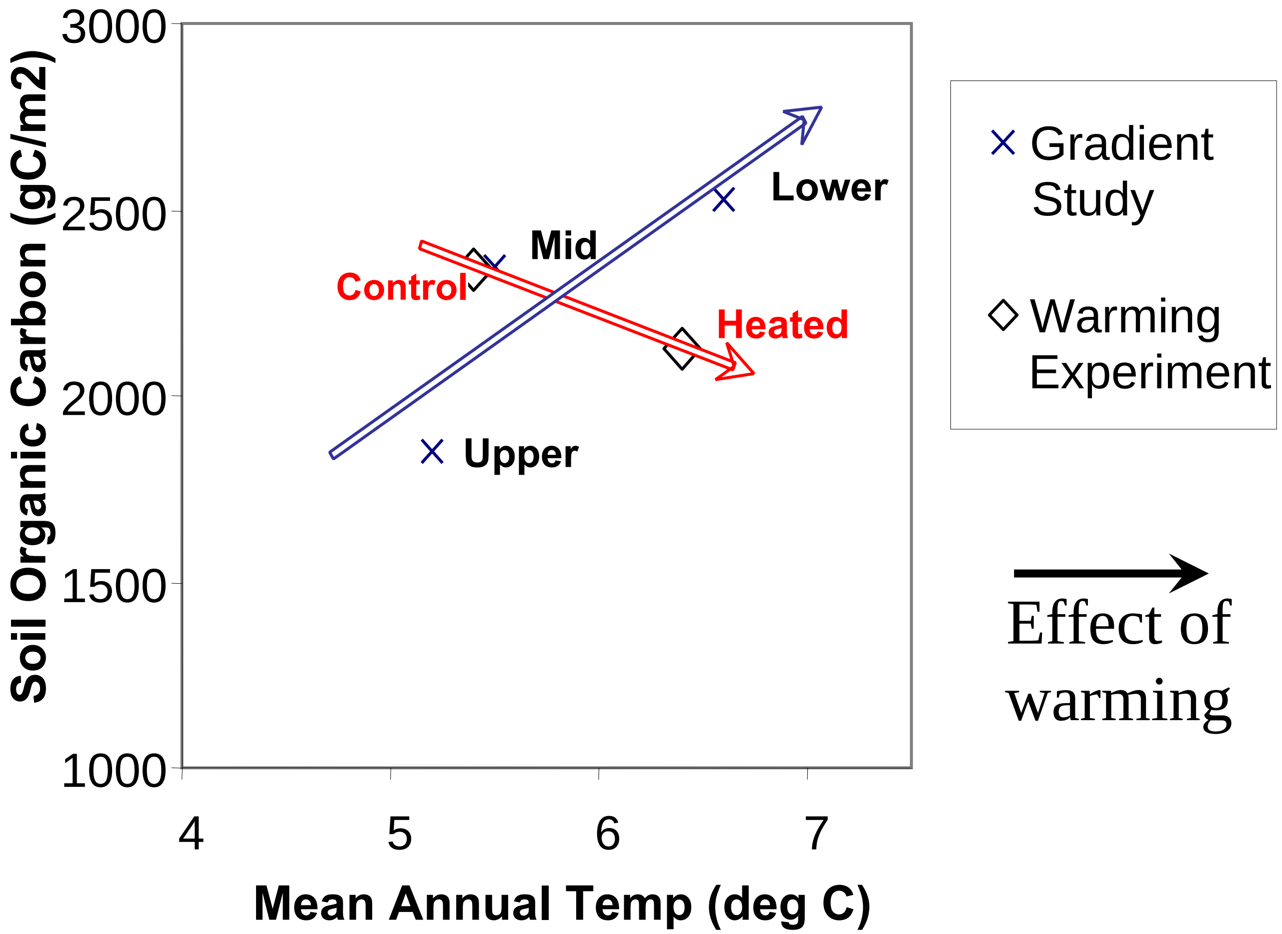
as T ↑, decomposition ↑

as M ↓, decomposition ↓

No overall effect!

Saleska et al., *Global Biogeochemical Cycles*, 2002

Approach 1: Simple space-for-time does NOT work here



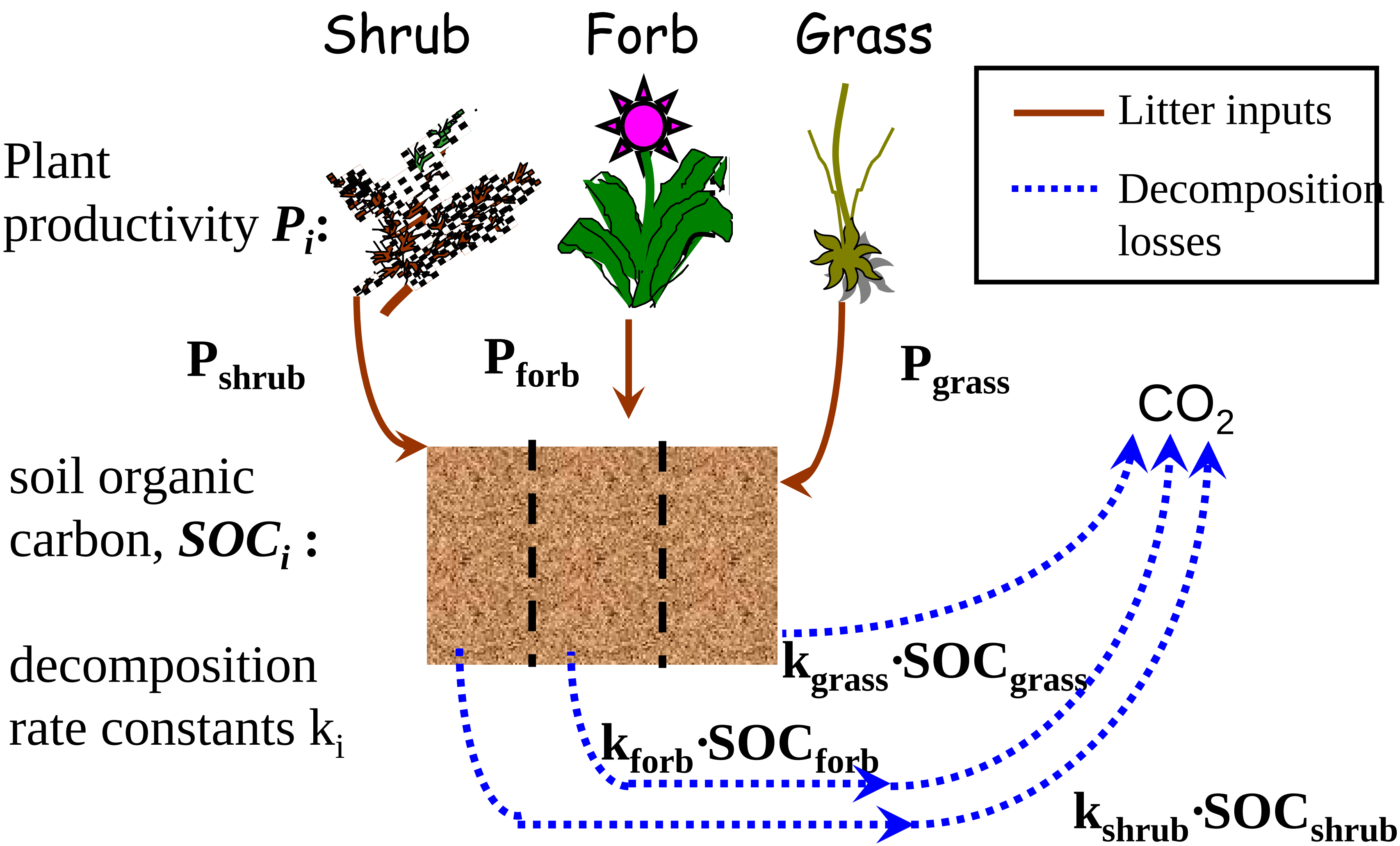
temp differences across space

temp difference expected at future time, in same space

Effect of warming

Dunne et al., 2004, *Ecology*

Approach 2: A Simple Model of the local carbon cycle



Can a simple mathematical model help make sense of this space-time mismatch?

Let C_i = soil carbon derived from vegetation-type i,

where i = forb, shrub, grass

$C = \Sigma_i C_i$

$$dC/dt = \Sigma_i dC_i/dt = \Sigma_i [P_i - k_i C_i]$$

P = net annual photosynthetic production of litter to soil

k = soil carbon decomposition rate constant

.

Under warming, $P_{forb}\downarrow$, $P_{shrub}\uparrow$, $P_{grass}\rightarrow$

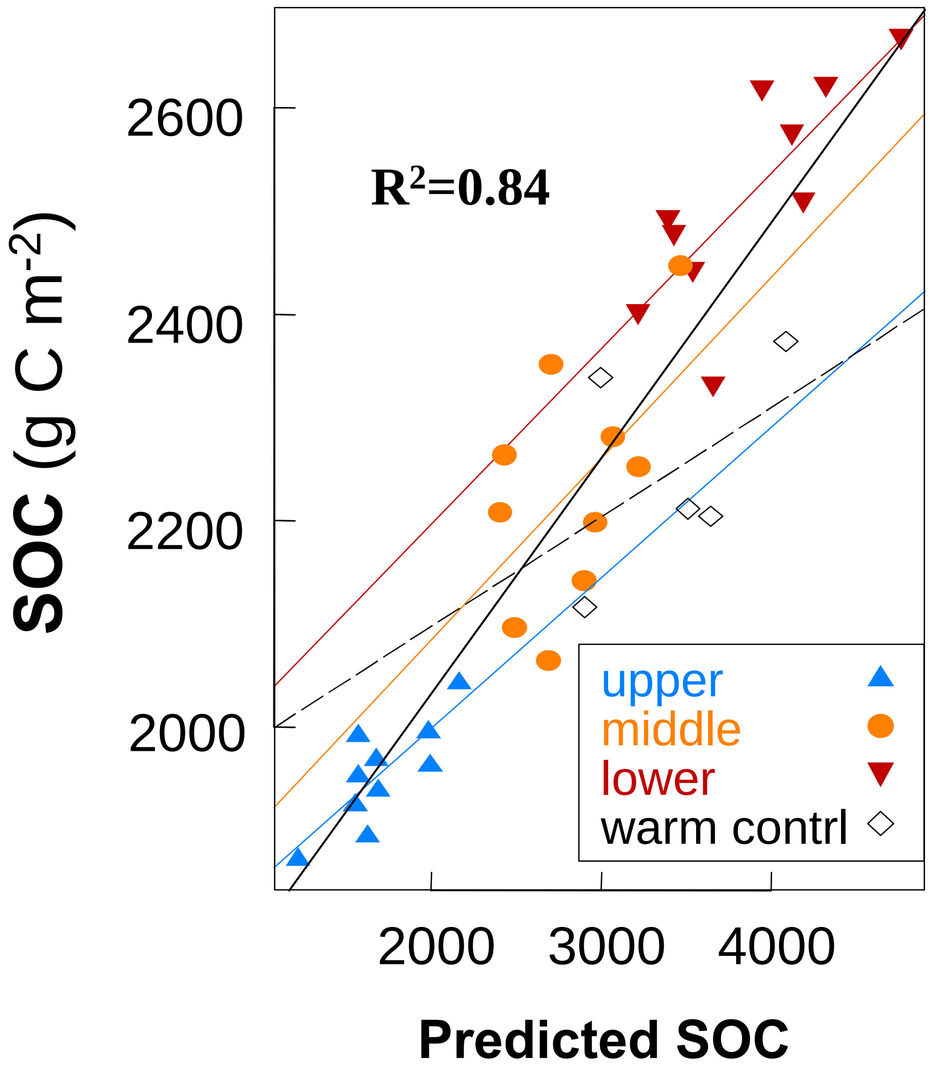
Key insight: $k_i = k_i$(Temp, Moisture, ***litter quality***)

factorial jar experiment determines T, M surface

chemical analysis of lignin;
k ~ nitrogen content/lignin content

At fixed T and M, $k_{forb} > k_{shrub} > k_{grass}$

Test of Simple Model for ambient Soil Organic Carbon



The <u>equilibrium solution</u> to the model accurately predicts <u>ambient</u> soil carbon levels across a climate gradient.

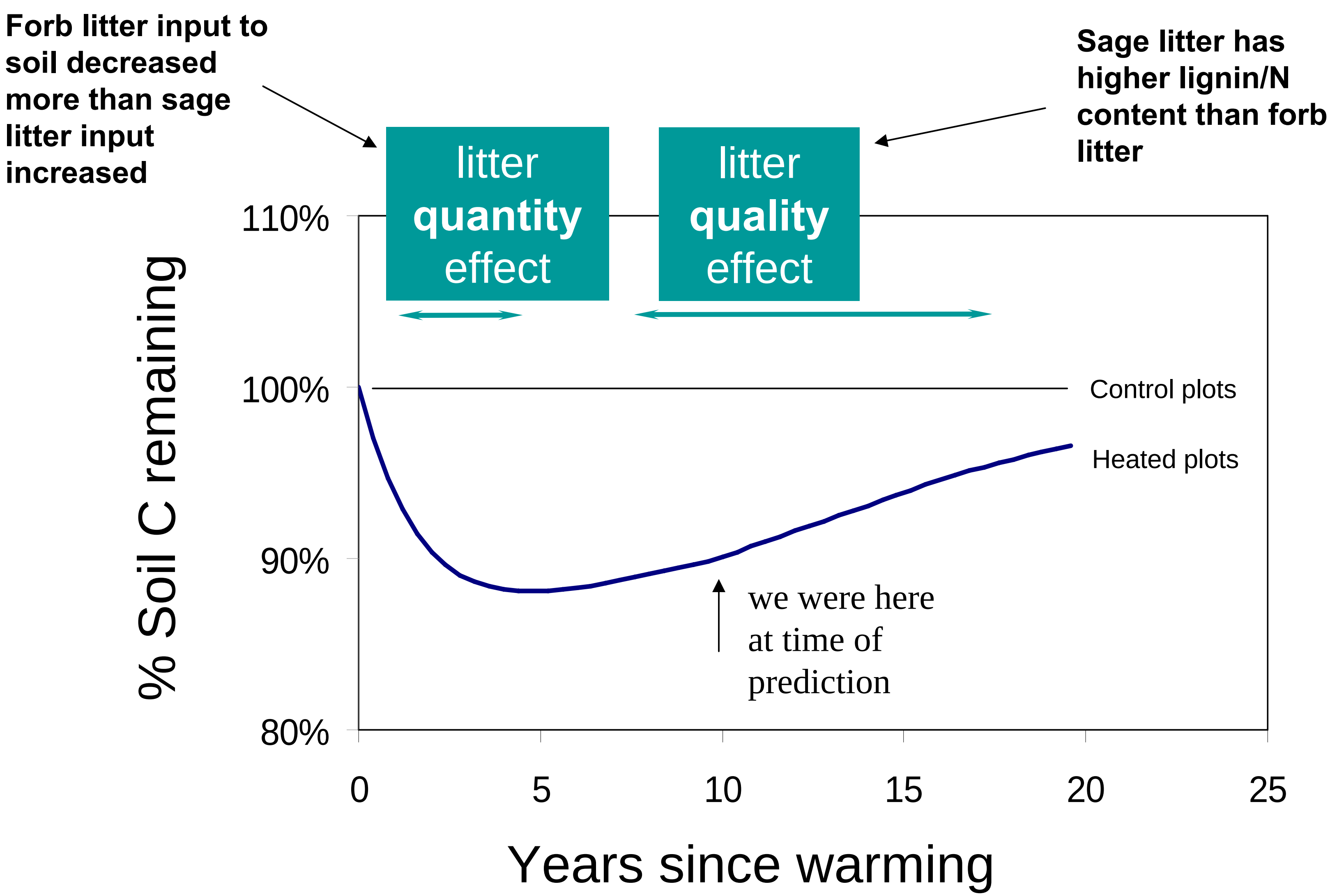
It fails to predict the transient response of carbon levels to heating.

So let's look at the dynamic solution to the differential equations…

Saleska et al., Global Biogeochemical Cycles, 2002

Dunne et al., Ecology, 2004

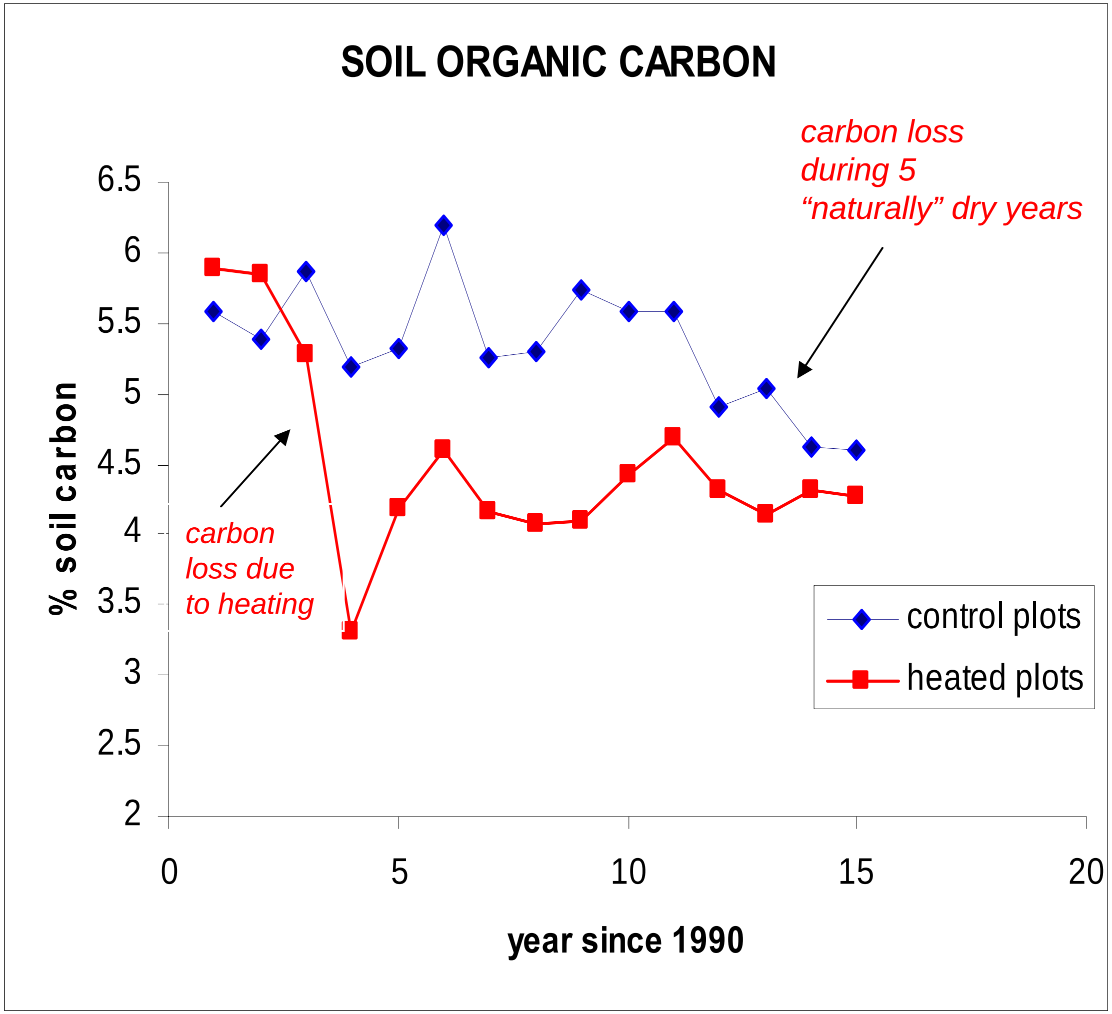
Change in species distribution causes transient loss and long-term gain of Soil C in heated plots

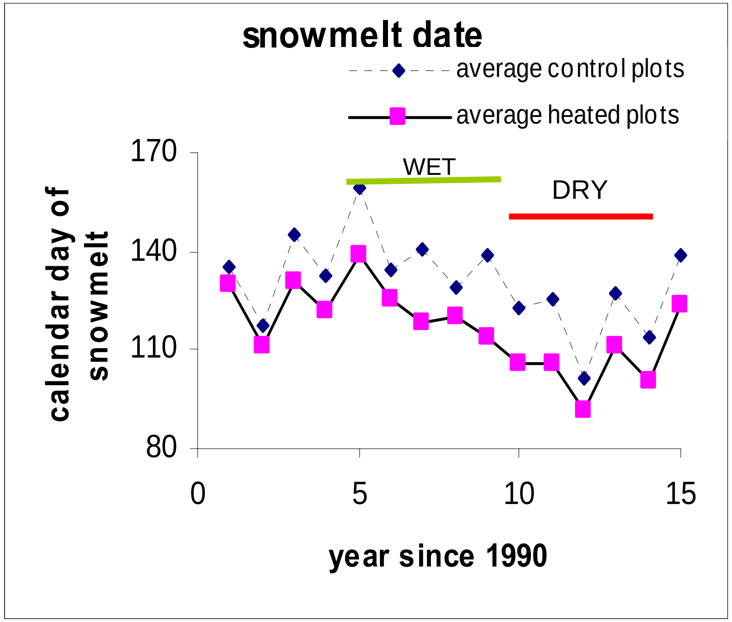


Something surprising has occurred in the past 5 years:

The heated and control plots carbon levels are converging as predicted, but not because the heated plots have recovered.

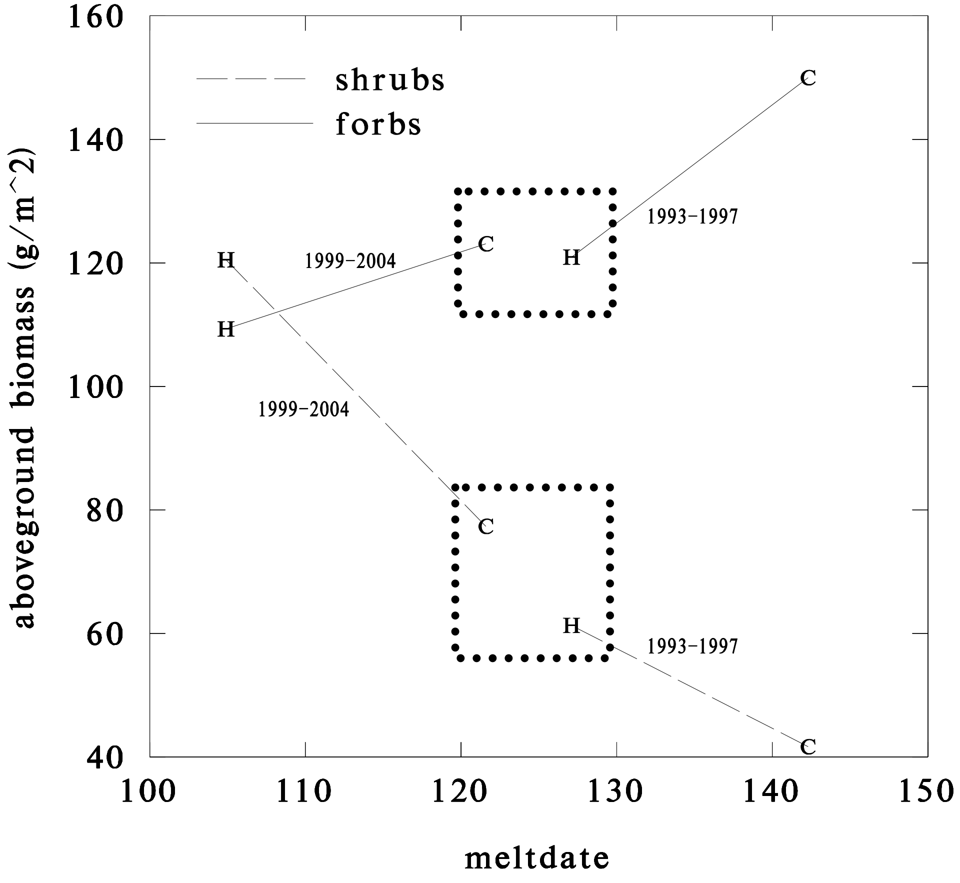
Starting in ~ 2000, the control plots are losing soil carbon, at ~ 1/3 the rate the heated plots did in 1991-1994!





Our model suggests that plant community composition/productivity controls soil carbon;

Above-Ground Biomass (AGB) of forbs and shrubs drives the model.



AGB in the control plots in 1999-2004

resembles

AGB in the heated plots in 1993-1997

Thus soil carbon in the control plots in 99-04 behaved like soil carbon in the heated plots in 93-97

Species matter!
Response to climate vs. effect on soil carbon turnover

Effect on Carbon turnover / **Response to Climate**	Medium lignin:N	Lower lignin:N
Shallow rooted (sensitive to drought)	Forb: *Erigeron speciosus*	Forb: *Delphinium nuttallianum*
Deep rooted (less sensitive to drought)	Forb: *Ligusticum porteri*	Forb: *Helianthella quinquinervis*

What is a sensible set of plant traits/categories?

Albedo

Contribution to NPP and thus carbon input to soil

Lignin:N of foliage

Sensitivity to climate change (e.g., rooting depth)

Transpiration rate

LAI or Shading of soil beneath plant

Canopy roughness

Categories: for each we might consider 3 levels: high, medium, low

Thus have $3^6 = 729$ plant categories.

Just based on on the RMBL experience: the first 4 above or $3^4 = 81$

The warming meadow contains about 75 plant species!

The feedback linkages in the meadow are very complex.

Yet we have not even begun here to look at:

- Other Habitats (tundra, desert, savannah, temperate forests, boreal forests, tropics, freshwater, marine …)
- Larger Spatial Scales (emergent phenomena?)
- Animals (grazers, pollinators, …)
- Other Climate Characteristics (extreme events, …)
- Carbon Dioxide increase (water efficiency, growth stimulation)
- Nitrogen Deposition (N addition can increase carbon storage)
- Land Use Changes (albedo, water exchange …)
- Invasive Species (carbon storage, albedo, water exchange)
- Genetic differences between populations (influences shifts in community composition)

Summary

- Analysis of the long-term climate record suggests that strong positive feedback operates in Earth's climate system.

- An ecosystem warming experiment provides further evidence for mechanisms that induce strong feedback responses.

- Current climate models do not incorporate these feedback effects and therefore are likely to be underestimating the magnitude of future warming.

- Developing a global-scale understanding of the sign and strength of these feedbacks is a huge challenge.