Problems and Prospects at the Intersection of Ecology and Climate

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Main Points:

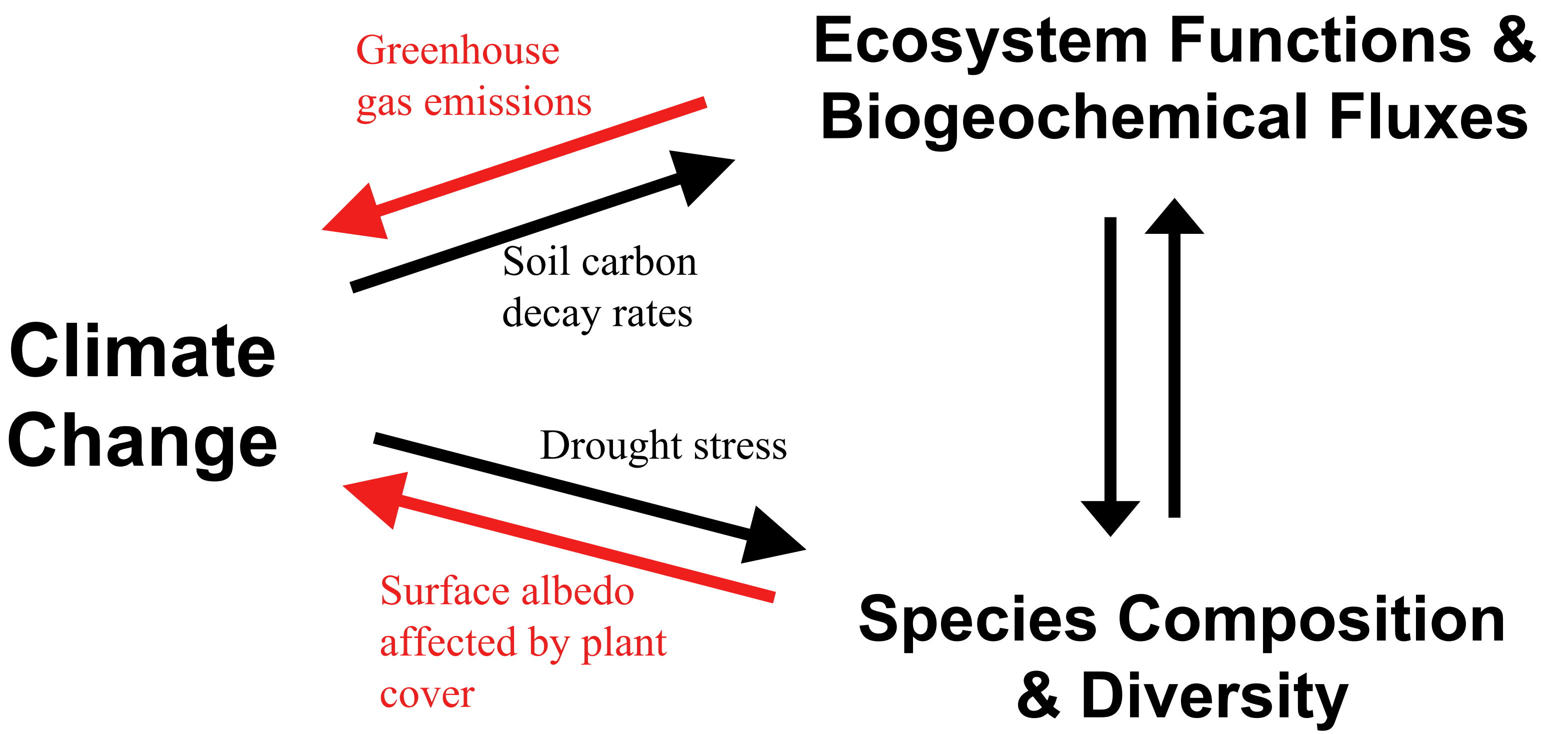
1. Paleo data, modern observations, ecosystem manipulation experiments, and models all suggest that ecosystems respond to climate change in ways that generate large feedbacks not currently included in our climate models.

2. Many “missing feedbacks” appear to be positive…”the warming feeds the warming”. They induce very asymmetric, fat-tailed uncertainties into predictions.

3. In Earth system science there are fundamental knowledge gaps that impede our ability to quantify ecological feedbacks to climate change.

Why do climatologists need to know about ecosystems?

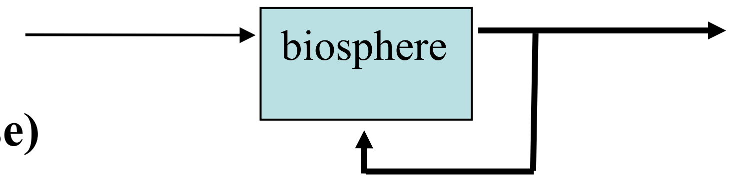
Climate-Ecosystem Feedbacks



HOW DO WE QUANTIFY FEEDBACK?

Input Signal (I)

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



Output Signal (O)

(e.g., full warming effect)

Feedback Factor (f)

$$O = I + f\,I + ff\,I + fff\,I + \ldots = g\,I$$

g = gain factor $= 1/(1-f)$

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

If $f < 0$: $O < I$, **negative feedback**

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

If $f > 1$: **unstable positive feedback**

g can be calculated!

$$f = \Sigma\,(\partial T/\partial p_i)\,(\partial p_i/\partial T)$$

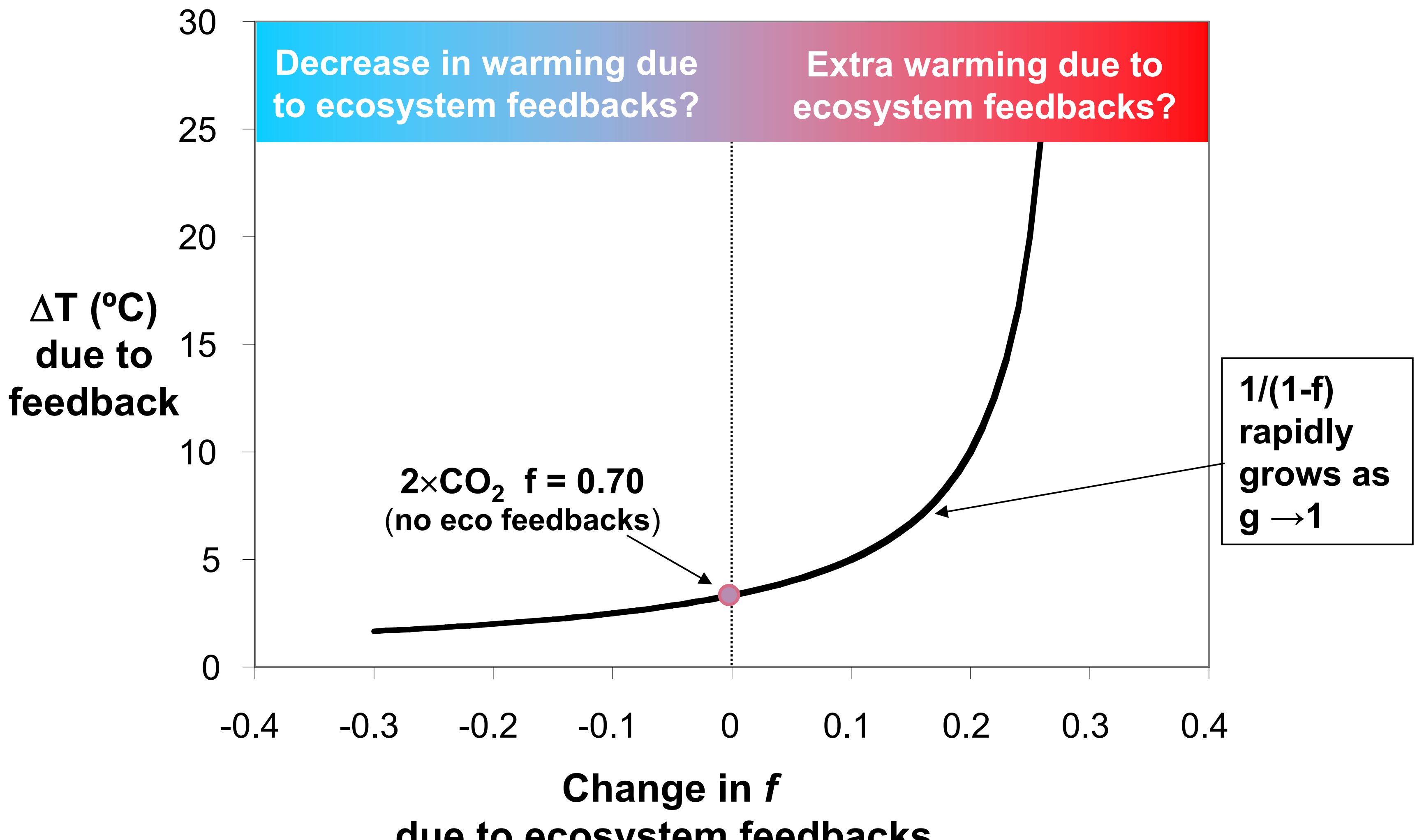
e.g., $p_1(T)$ **= albedo of land surface, which may change if warming induces a changes in dominant vegetation**

Role of feedback for 2 x CO_2

Climate change: $\Delta T = 1.2\ ^oC / (1-f)$

Feedback processes in current climate models	feedback factor (f)	T_{lower}	T_{upper}
water vapor + ice-albedo + clouds	0.2 - 0.74	$1.2^oC/(1 - 0.2) = 1.5^oC$	$1.2^oC/(1 - 0.74) = 4.6^oC$

Small change in f causes large ΔT asymmetry



Torn & Harte, GRL, 2006

Why do climatologists need to know about ecosystems?

1. Earth's carbon budget: ecosystems are a big player

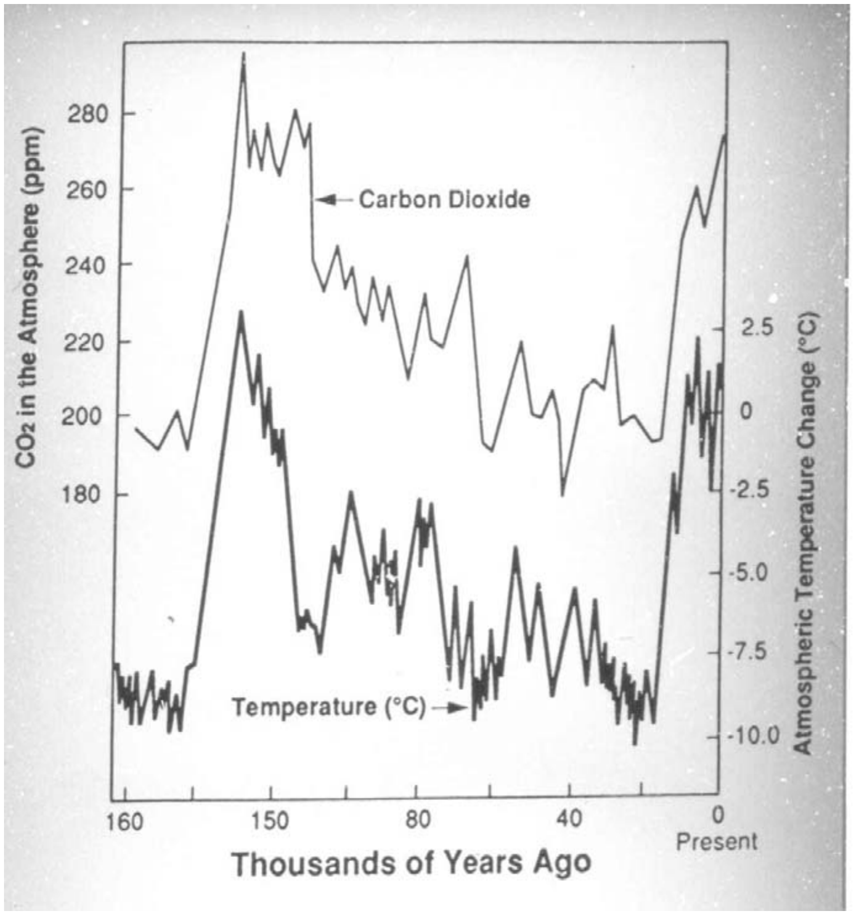
STOCKS

atmosphere:	~ 800 Gt(C)	(CO_2, + 3.5 Gt(C)/year)
living plants	~ 700 Gt(C)	(~ 99% on land)
organic matter in soils	~ 2000 Gt(C)	(down to 1 meter)
in the oceans	~ 45,000 Gt(C)	(mostly HCO_3^-)

Gross FLOWS to and from ATMOSPHERE

primary production	~ 125 Gt(C)/year	(2/3 terrestrial)
plant respiration	~ 50 Gt(C)/year	
decomposition of organics	~ 75 Gt(C)/year	(2/3 terrestrial)
physical exchange w/seawater	~ 75 Gt(C)/year	
fossil fuel burning	~ 6.5 Gt(C)/year	
deforestation	~ 1.5 Gt(C)/year	

The Vostok core data imply CO_2 and CH_4 feedback



Milankovitch mechanisms are the forcing, and thus the **time keeper**, but their magnitude is too weak to explain the **magnitude** of the huge climate variability

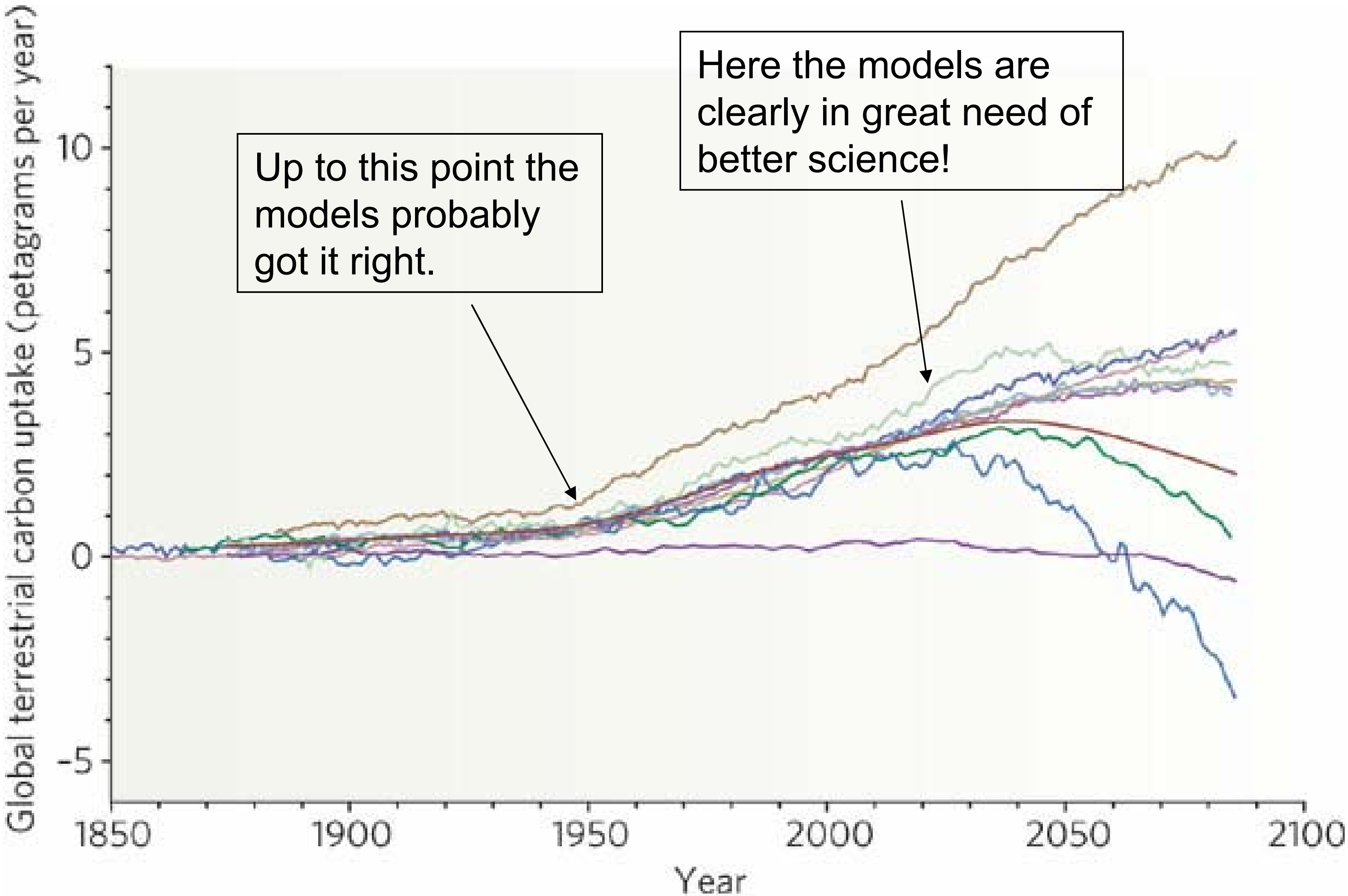
CO_2 release during slight warming must cause more warming!

And CO_2 uptake during slight cooling must cause more cooling.

This feedback is not incorporated in our current GCM's and suggests that future warming may be worse than we think

Slide 8

WB3 Wendy Brown, 10/13/2003



Comparison of estimated global terrestrial carbon uptake in different models of the carbon-cycle–climate system.

Martin Heimann & Markus Reichstein
Nature 451, 289-292(17 January 2008)

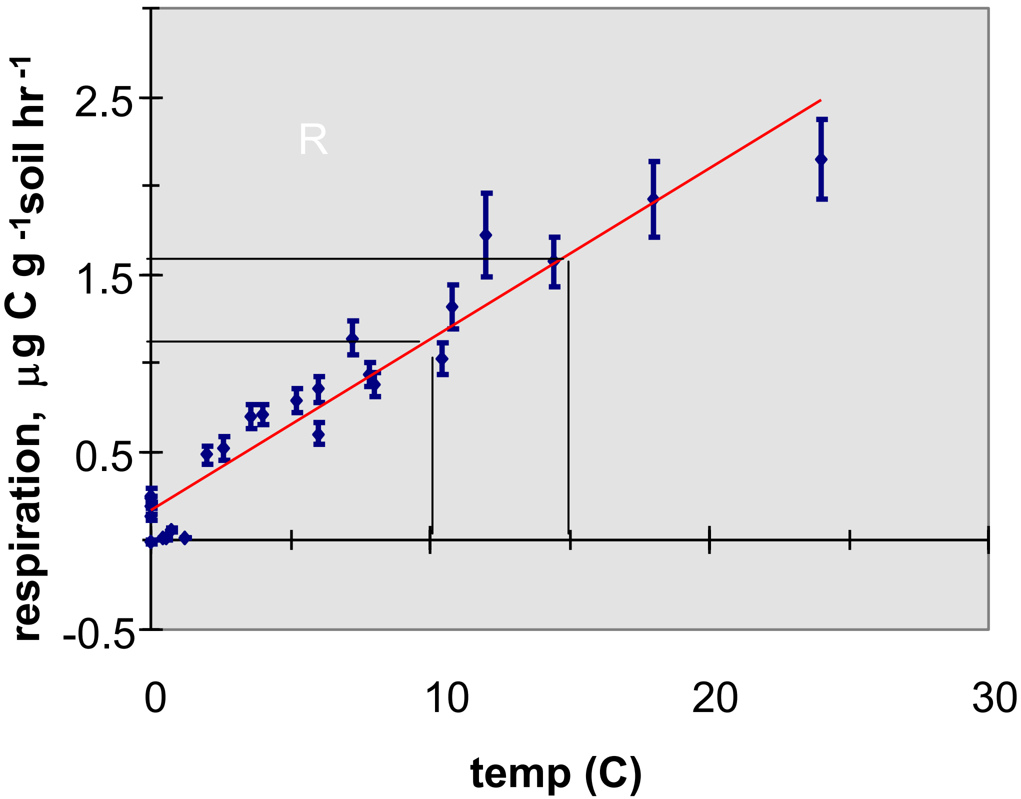
Small climate changes can hugely alter local carbon budgets

If decomposition and respiration exceeds photosynthesis by just **5%**, that results in a net flow to the atmosphere of .05 x 75Gt(C)/year

= 3.75 Gt(C)/year which ~ current rate of increase of atmospheric C.

!

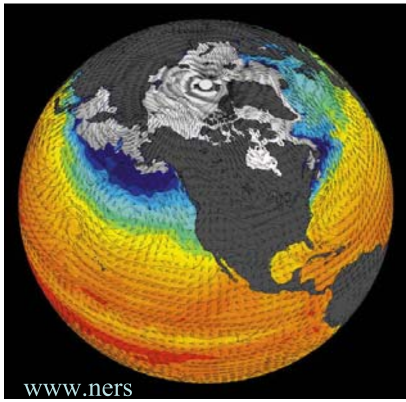
Soil organic matter decomposition:



a 5°C rise in soil temperature can cause a 50% rise in soil decomposition rate!

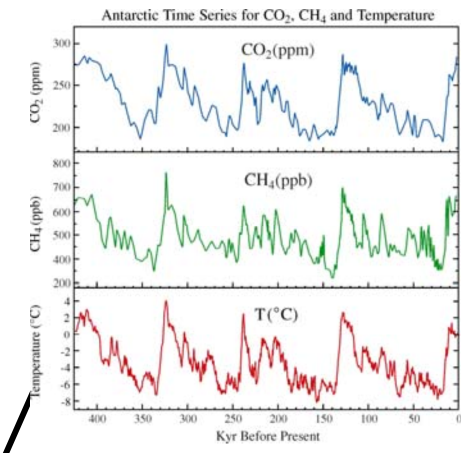
Major caveat: soil moisture also matters!

Calculating the Missing Greenhouse Gas Feedbacks



www.nersc.gov

GCM Output



Ice Core Data

Input Signal, ΔT_i → ***Temperature*** → **Output Signal, ΔT**

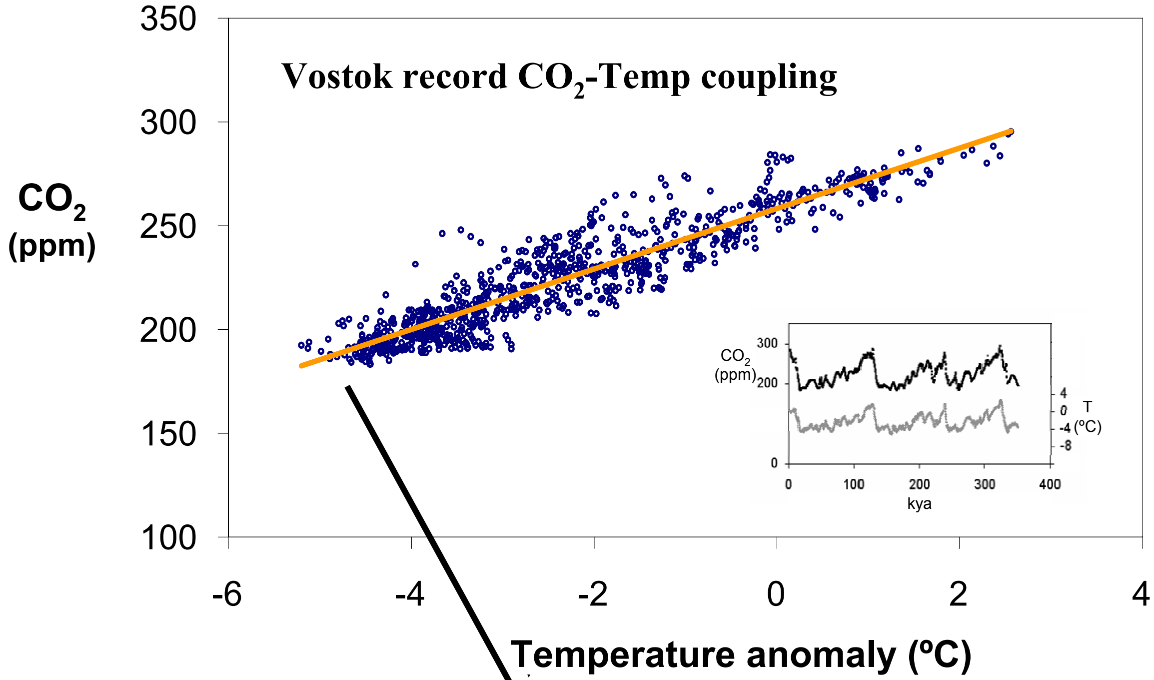
Full warming

atm CO_2

Output = Input/(1-f)
f = feedback factor
F > 0 is positive feedback

Torn & Harte, GRL, 2006

An estimate of the carbon feedback from Vostok core data:



Forcing from GCM

$$f_{CO_2} = \frac{\partial T}{\partial CO_2}\frac{\partial CO_2}{\partial T} = \frac{1.2^o C}{275\,ppm(CO_2)}\frac{14.6\,ppm(CO_2)}{^oC} = 0.064$$

Torn and Harte, *Geophysical Research Letters*, 2006
(see also Scheffer, Brovkin and Cox, same issue)

Ice core data tell us how greenhouse gases respond to temperature change:

The combined CO_2 and CH_4 data from Vostok suggest that f_{GHG} ~ 0.07 →

$$f_{lower} = 0.20 + 0.07 = 0.27$$

$$f_{upper} = 0.74 + 0.07 = 0.81$$

As f → 1, the feedback effect ~ 1/(1-f) gets huge!

at the lower limit

1.5°C

↓ **0.15° additional warming**

1.65°C

at the upper limit

4.6°C

↓ **1.7° additional warming**

6.3°C !!!

Two reasons for concern about the feedback effects not in our current models:

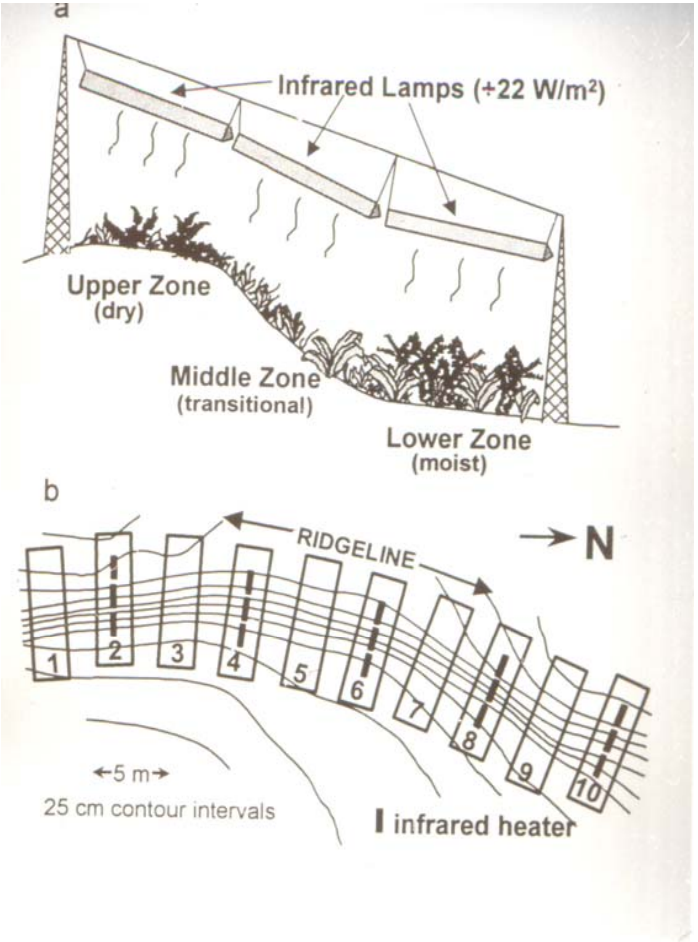
- **The "missing" feedbacks are mostly positive.** (Lashof et al., *Ann. Rev. Energy and Env.* 2002)
- **Positive feedbacks exert an asymmetric effect on warming-- the upper limit expands much more than the lower. It is intrinsic to positive feedback that it exerts this asymmetry in the range of uncertainty.**

But where are the carbon and the methane coming from?

And can we assume that the mechanisms causing this feedback over the paleoclimate temperature range will still operate in the future climate?

And what other feedbacks to climate change may be lurking in the biosphere?

A "longterm" warming experiment



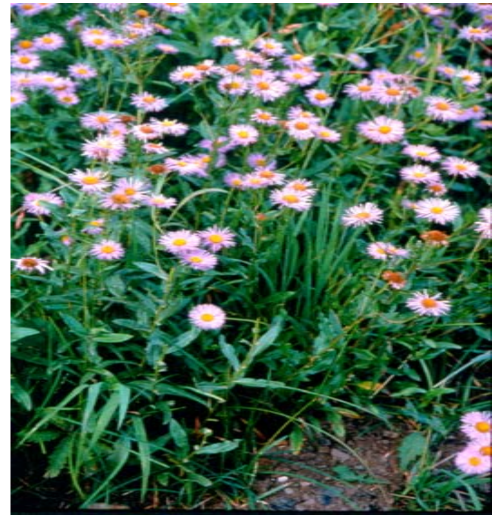
The Rocky Mountain Biological Laboratory (RMBL) Gothic CO (9600')

Infra-red heaters (22 W m^{-2}). Soil is warmer (+ 2°C), drier (-15% gravimetric).

Experiment begun in1990; heaters on day and night, year around.

The UC Berkeley long-term climate-warming experiment in the Colorado Rockies

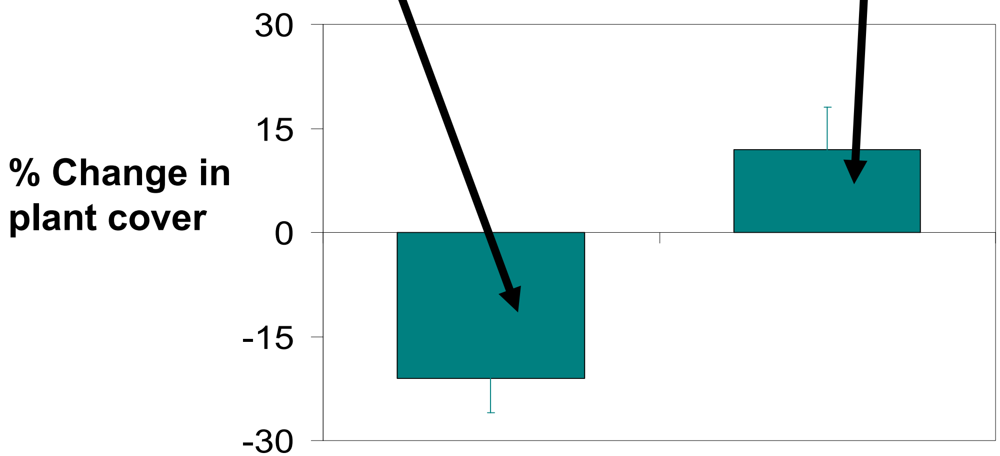
:



forbs (e.g. daisies)

→

sagebrush



Harte and Shaw, Science, **1995**

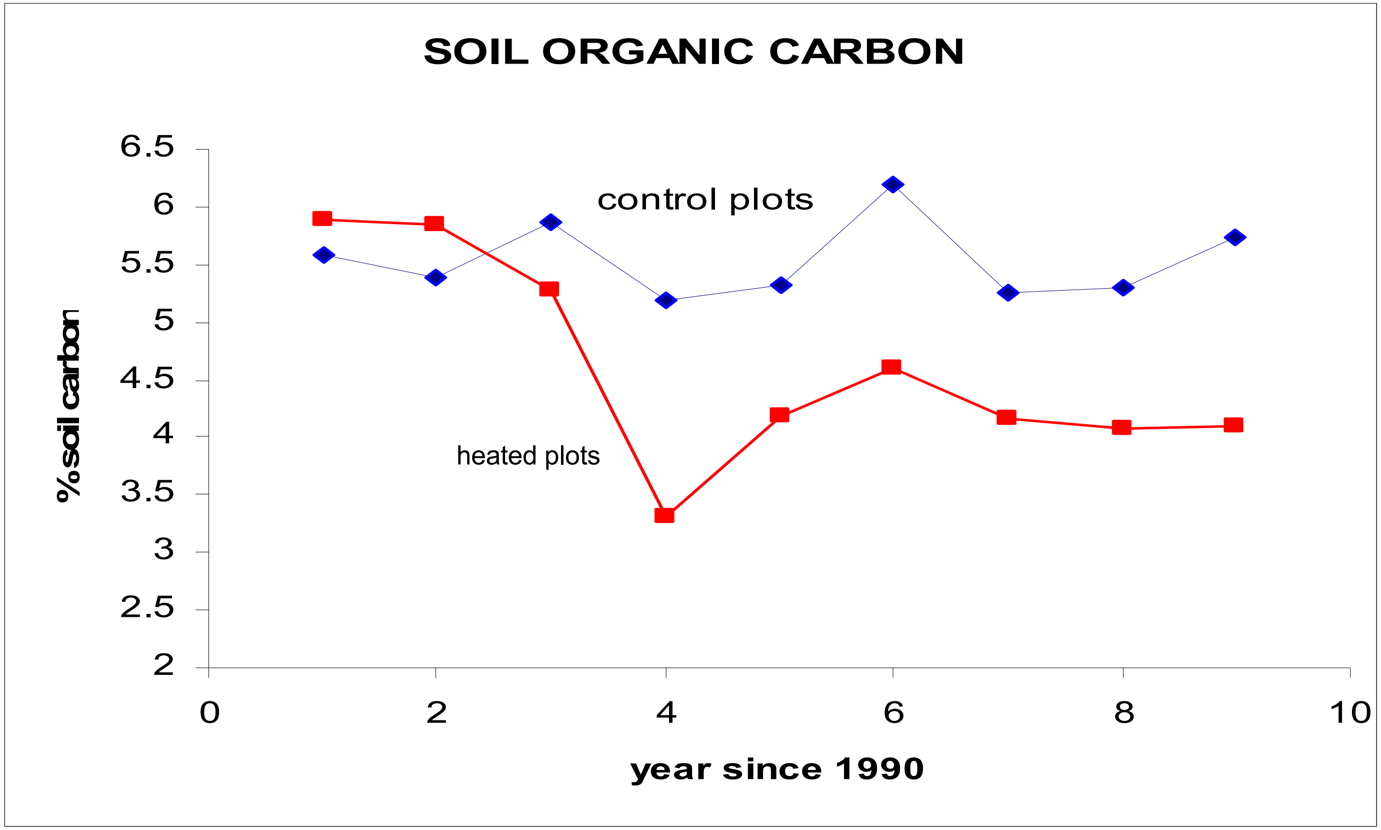
Also a 3-fold reduction in flowering success of shallow-rooted forbs in heated plots

Carbon Feedback: 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)

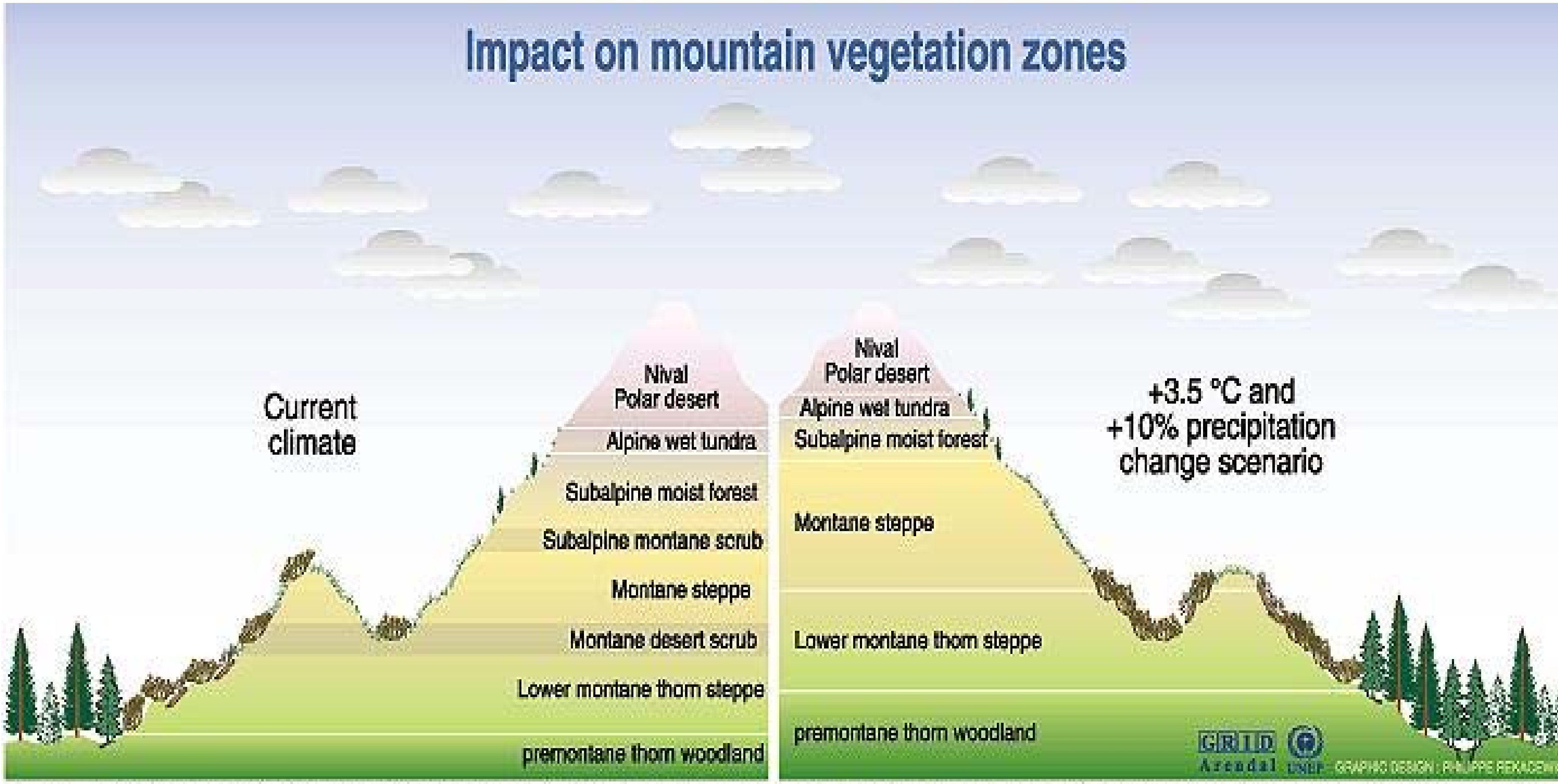
Experimental warming reduces soil carbon!



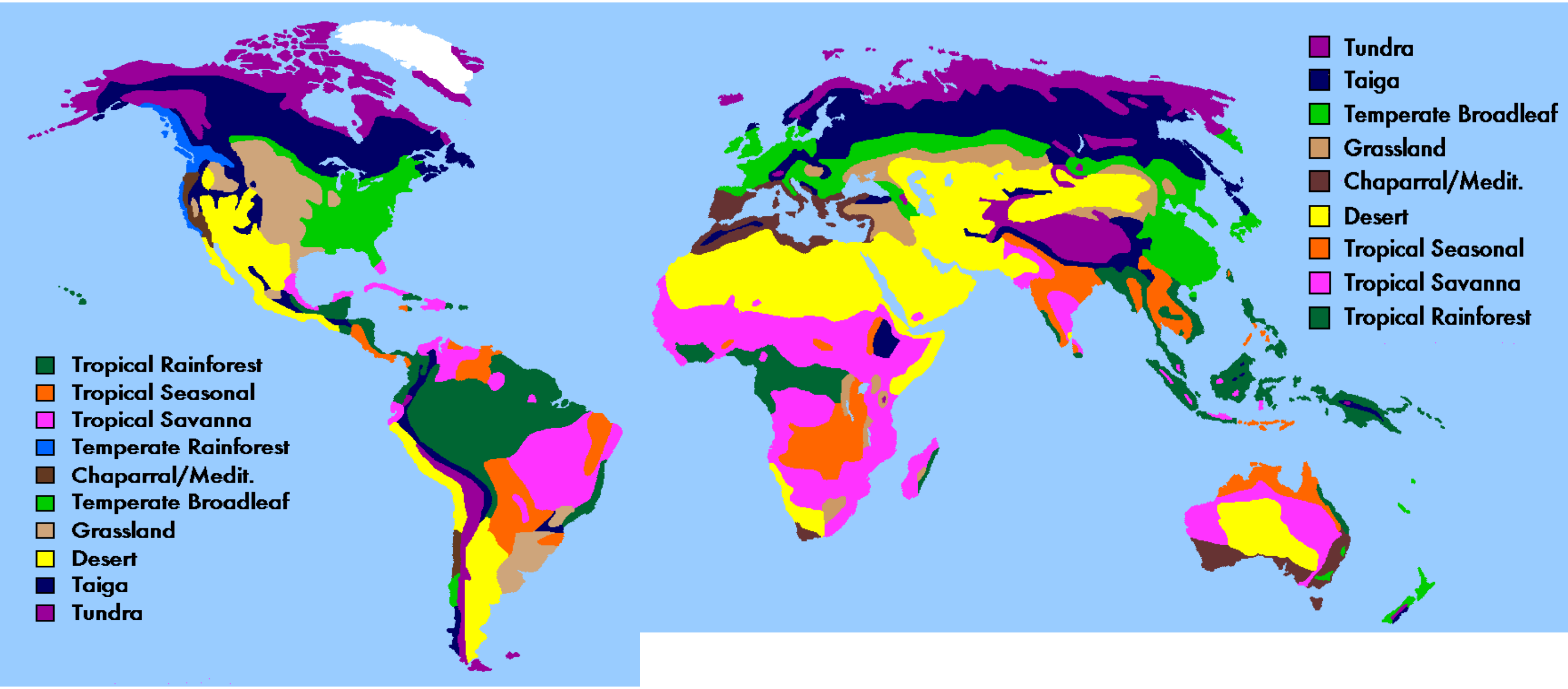
Why do climatologists need to know about ecosystems?

1. Earth’s carbon budget: ecosystems are a big player

2. Earth’s albedo: vegetation is a big player



Sources: Martin Benitson, Mountain environments in changing climates, Routledge, London, 1994; Climate change 1995, Impacts, adaptations and migration of climate change, contribution of working group 2 to the second assessment report of the Intergovernmental panel on climate change (IPCC), UNEP and WMO, Cambridge press university, 1996.



Tundra
Taiga
Temperate Broadleaf
Grassland
Chaparral/Medit.
Desert
Tropical Seasonal
Tropical Savanna
Tropical Rainforest
Tropical Rainforest
Tropical Seasonal
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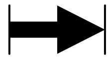
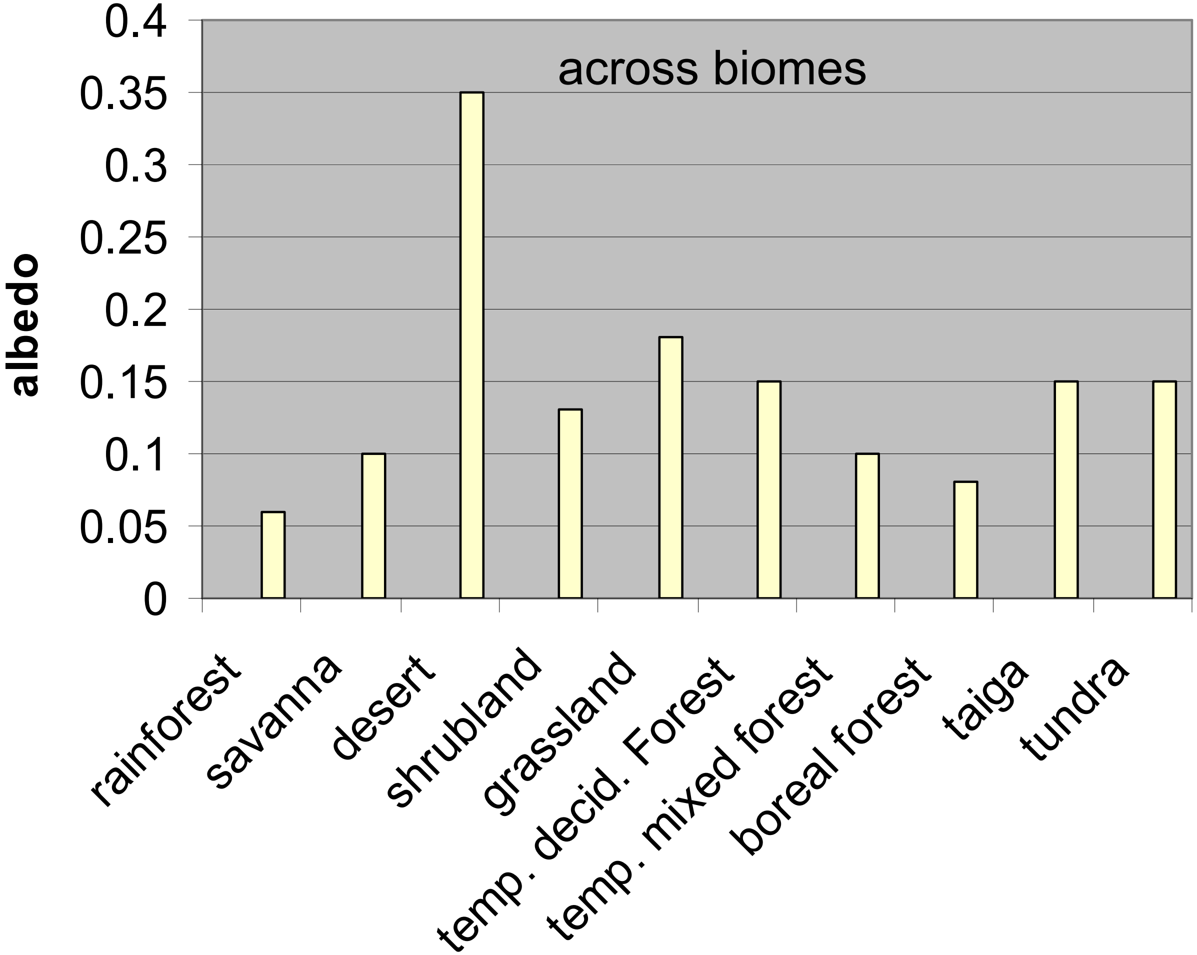
Temperate Broadleaf
Grassland
Desert
Taiga
Tundra

ALBEDO OF VEGETATION

 **= direction and approximate magnitude of shift in biome type under climate change this century**



within biomes

The albedos of adjacent biomes differ by anywhere from 0 to 0.25. Therefore shifts in vegetation cover can result in regional changes in albedo within that range.

(e.g., savanna turning to desert or boreal forest extending into taiga or tundra)

But some transitions will result in **increases in albedo** and others in **decreases in albedo.**

Back of Envelope Estimate of Magnitude of Effect

Suppose 4°C global warming results in a total albedo <u>shift</u> of -0.05 over 20% of the land area of Earth.

This corresponds to an approximate contribution to the feedback factor, f, of:

$$\mathbf{f_{biome\ albedo}} =$$

$$(\partial T/\partial a) \cdot (\partial a/\partial R_s) \cdot (\partial R_s/\partial \text{biome albedo}) \cdot (\partial \text{biome albedo}/\partial T)$$

(R_S = *Earth's land surface albedo*)

$$= (-65) \cdot (0.28 \cdot 0.3) \cdot (0.20) \cdot (-0.05) = +0.05$$

rad-only model | **clouds dominate** | land fraction | land fraction | Δ albedo

Now add up the f's from CO_2 and CH_4 feedback (f = +0.07) and hypothetical but possible vegetation-albedo feedback(f = +.05):

f_{lower} = 0.20 + 0.12 = 0.32 ⟶ T_{lower} = 1.2/(1 - 0.32) = 1.8^{o} C

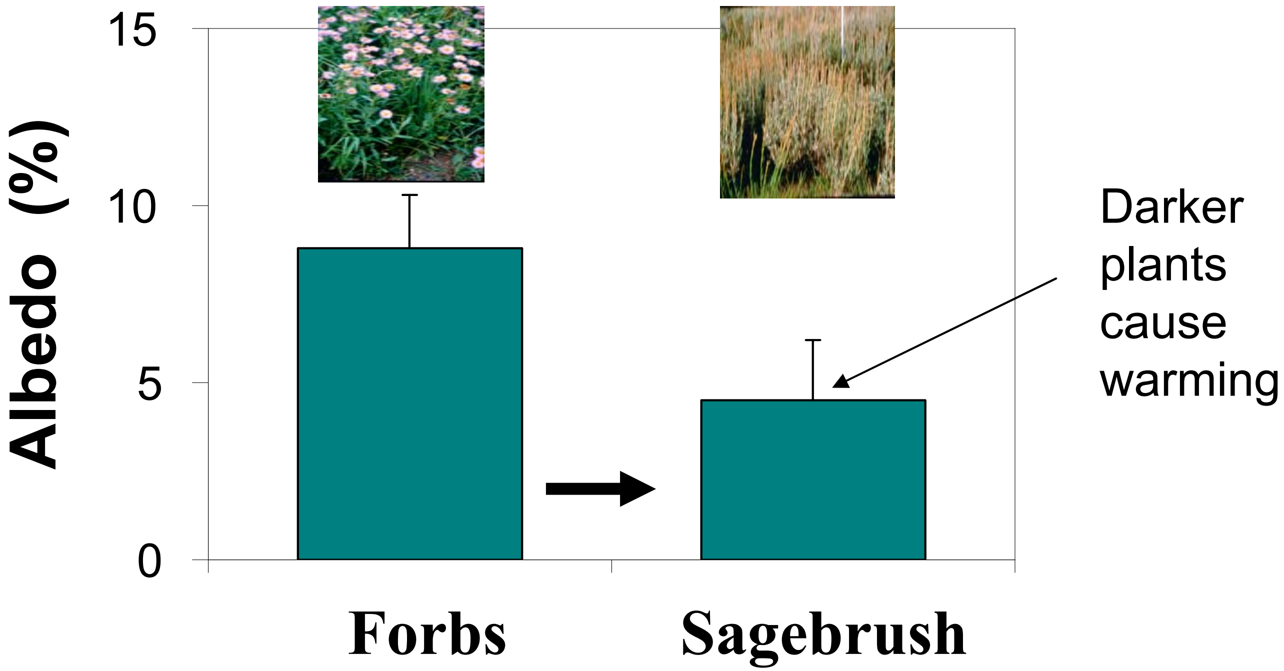
f_{upper} = 0.74 + 0.12 = 0.86 ⟶ T_{upper} = 1.2/(1 – 0.86) = **8.6^{o} C**

A shift in albedo of 0.05 over 40% of the land surface would push the upper limit to **+13^{o} C!**

The take-home message isn't that this <u>will</u> happen;

It is that we need to understand better how vegetation communities will respond to climate change because it plausibly could happen.

Albedo Feedback : 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 2 x CO_2 forcing

Why do climatologists need to know about ecosystems?

1. Earth's carbon budget: ecosystems are a big player

2. Earth's surface albedo: vegetation is a big player

3. There are many other ecosystem-mediated feedbacks to climate

a. Via the hydrocycle:

The conventional feedbacks in GCMs stem from the 3 phases of water:

ice, vapor, clouds

But ecosystems influence **soil moisture, LH, cloudiness,**

b. Forest Fires ⟶ CO_2, particulates, surface albedo

c. N_2O and CH_4 flux to atmosphere; strongly regulated by soil moisture

d. Surface roughness

e. HC particulates from plants

f. Sulfides from the sea

What will burning of, or spread of, boreal forests do to Arctic cloud cover?

How can we learn about climate-ecosystem feedback?

1. **Compare ecological and climatic patterns across space and time**

- **Gradient analysis (latitudinal, altitudinal)**
- **Inter-annual variability of climate**
- **Decadal to century trends**
- **Paleoclimatic variability**

Large scales but correlations only

2. **Climate manipulation experiments,**

Small scales but can deduce mechanisms

3. **Mathematical models**

Only as good as the data that drive them

The Gaping Hole in our Knowledge:

We don’t know how to predict the direct response of vegetation, and of the pollinators and herbivores and pathogens that interact with vegetation, to climate change

Specific Issues:

a. How do we scale up from field experiments?
b. What is the appropriate level of resolution of models?
c. How useful is the Climate-Envelope concept?

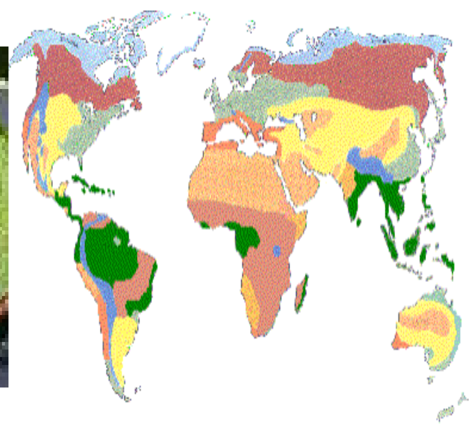
The challenge of scaling up from experiments

The feedback linkages in the subalpine meadow are many and complex.
Yet ecologists have only begun to look experimentally
at feedback effects of warming.

•Other habitats	Tropical and temperate forests? Marine?
•Larger space/time scales	Emergent phenomena? Role of grazers, pollinators, pathogens that are difficult to study with small-scale field experiments)
•Synergies with other global changes	N- deposition [as fertilizer and as acid] invasive species, land use changes air pollution deforestation

POSSIBLE LEVELS OF RESOLUTION IN GLOBAL CLIMATE-ECOSYSTEM 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



certainly too crude

?

we hope we don't have to go to this level of disaggregation

But 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*

We need to know whether and how species might re-locate in response to climate change.

Do they move or do they die?

Bio-climate Models Rely on the Climate-Envelope Concept:

Each species has a set of temperature/precipitation parameters, which are determined from where it is now found and which determine where it will be found in the future.

Yes, but:

- **Assumption of unlimited dispersal**
- **Disregard for phenotypic variation**

Using IBIS, a climate-ecosystem model developed by Jon Foley, and assuming 5 alternative assumptions about <u>plant dispersability</u>, we modeled ecosystem-mediated carbon and energy flux feedbacks.

Mean total global carbon storage (Pg-C) in plants and soil for each IBIS simulation (4 x CO_2 forcing)

Dispersal Scenario	Biomass Carbon (Gt(C))	Soil Carbon (Gt(C)
control climate and vegetation	715	1688
all plants free to disperse	561	972
no dispersal	274	810
dispersal only within grid cell	405	819
grasses and shrubs free to disperse, not trees	390	1001
dispersal only to adjacent grid cells	485	980

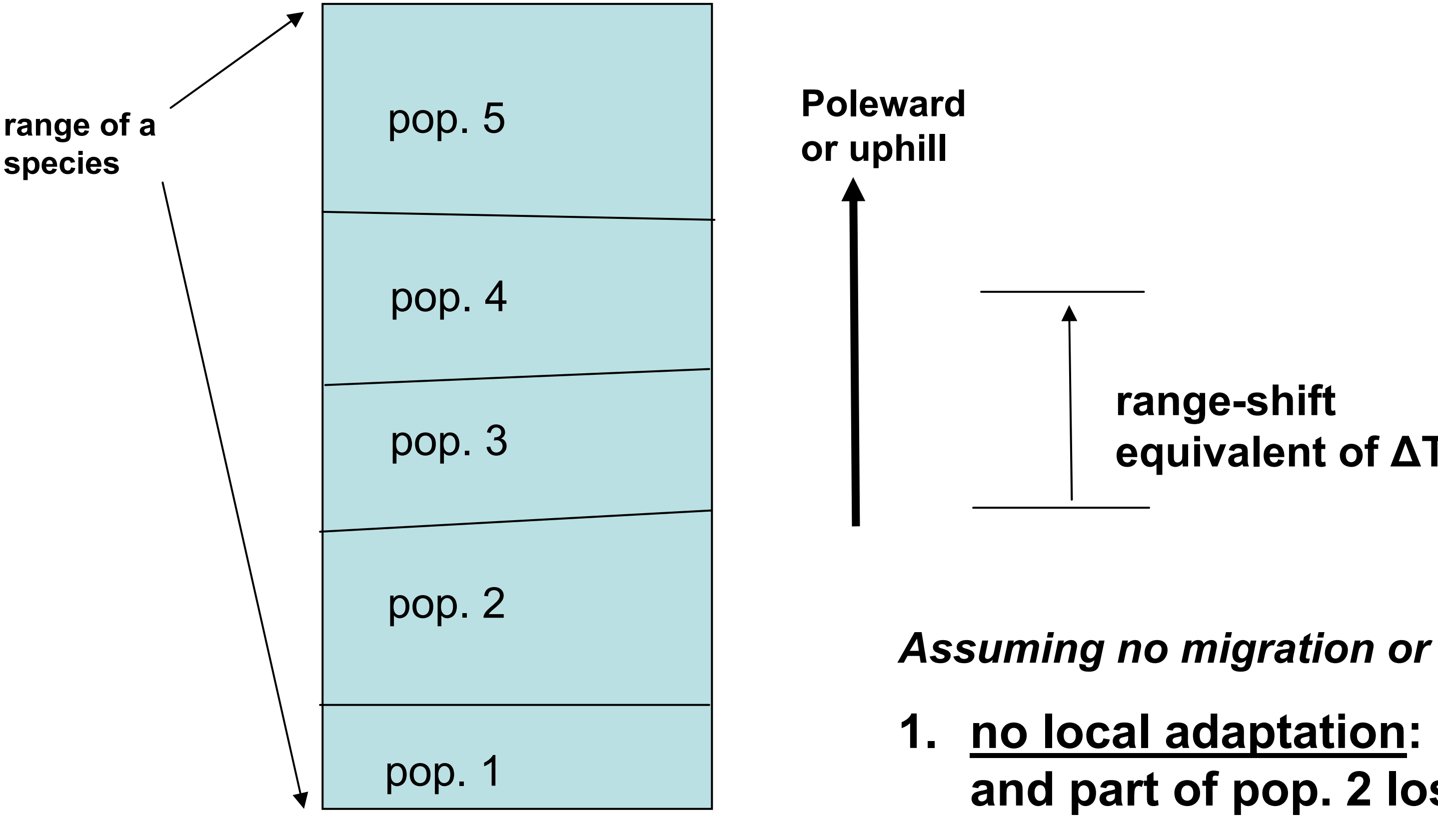
P. Higgins and J. Harte, *BioScience, 2006*

These <u>differences</u> between dispersal scenarios amount to hundreds of Gt(C) in the atmosphere!

They also amount to albedo differences equivalent to $f_{\text{biome albedo}} \sim 0.05$

Phenotypic Variability across a Species Range

a simple illustration of why it matters:



Assuming no migration or dispersal:

1. **<u>no local adaptation</u>: only pop. 1 and part of pop. 2 lost**
2. **<u>local adaptation</u>: every population lost and species goes extinct!**

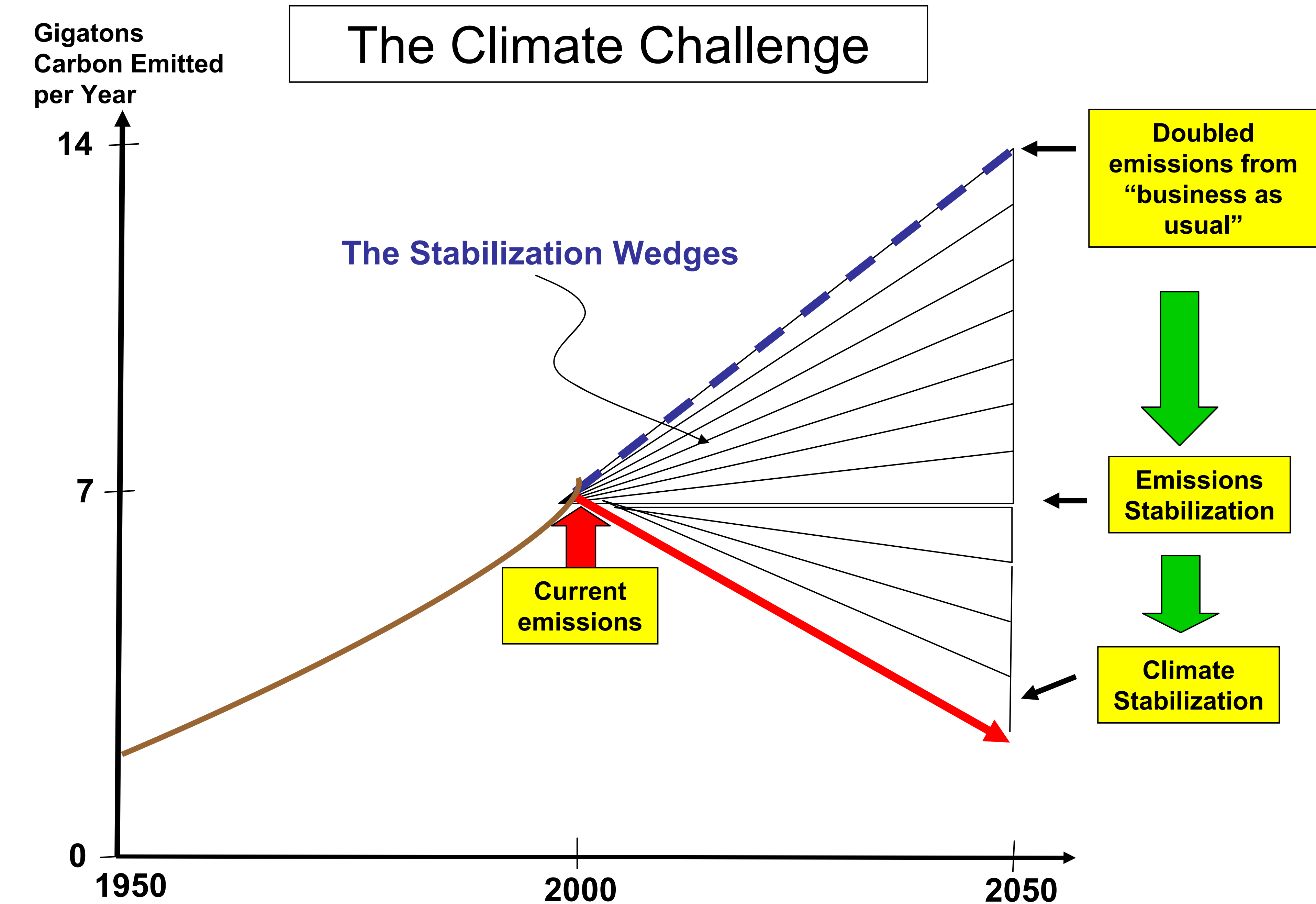
D. Jensen, PhD thesis, UC Berkeley, showed that option 2 is more appropriate for white fir in the CA Sierra; but Perkins et al., show no effect for subalpine fir in the Rockies

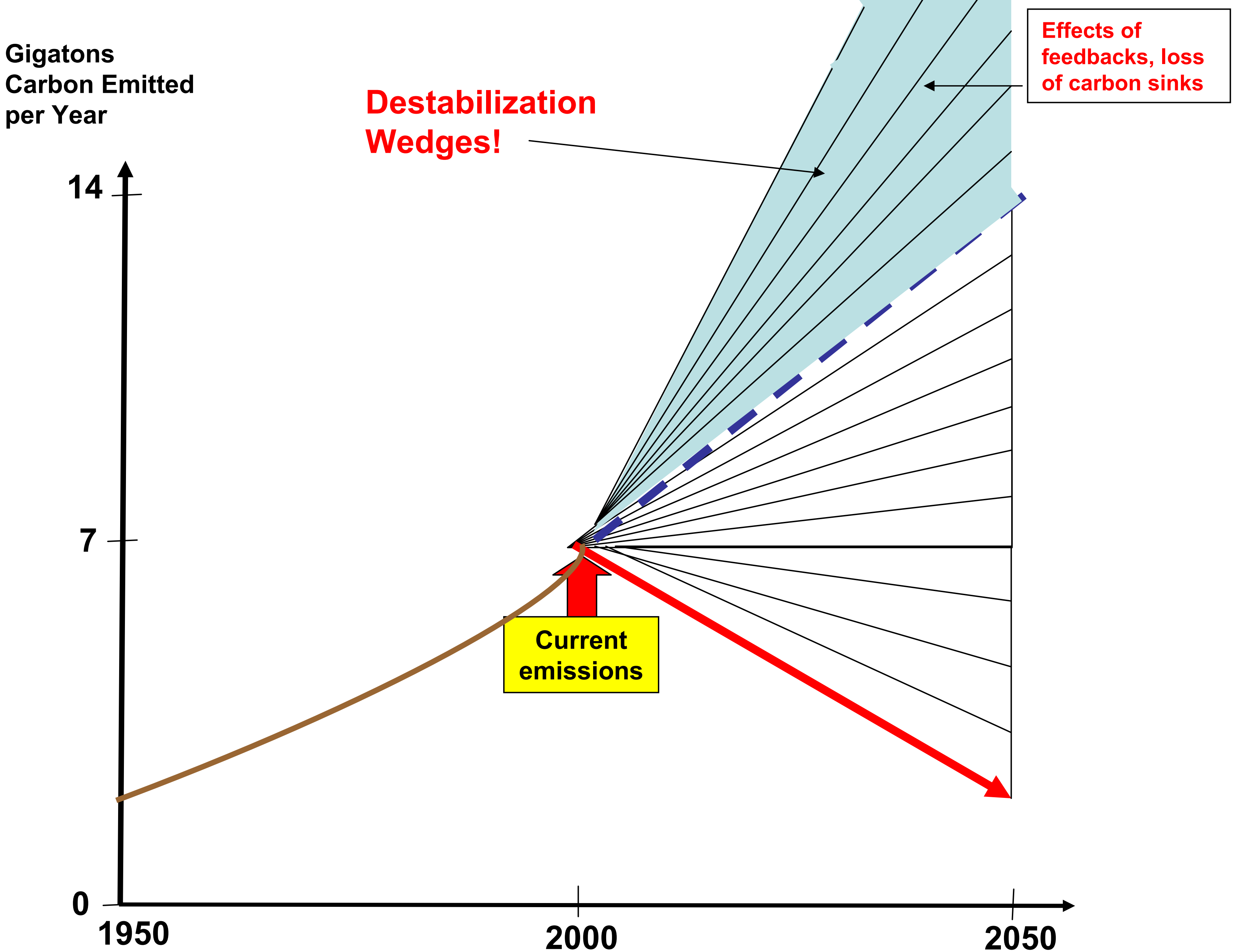
Main Points:

1. Ecosystems respond to climate change in ways that can potentially cause large feedbacks to the climate system. Paleo data, modern observations, ecosystem manipulation experiments, and models all suggest that there are large feedbacks not currently included in our climate models

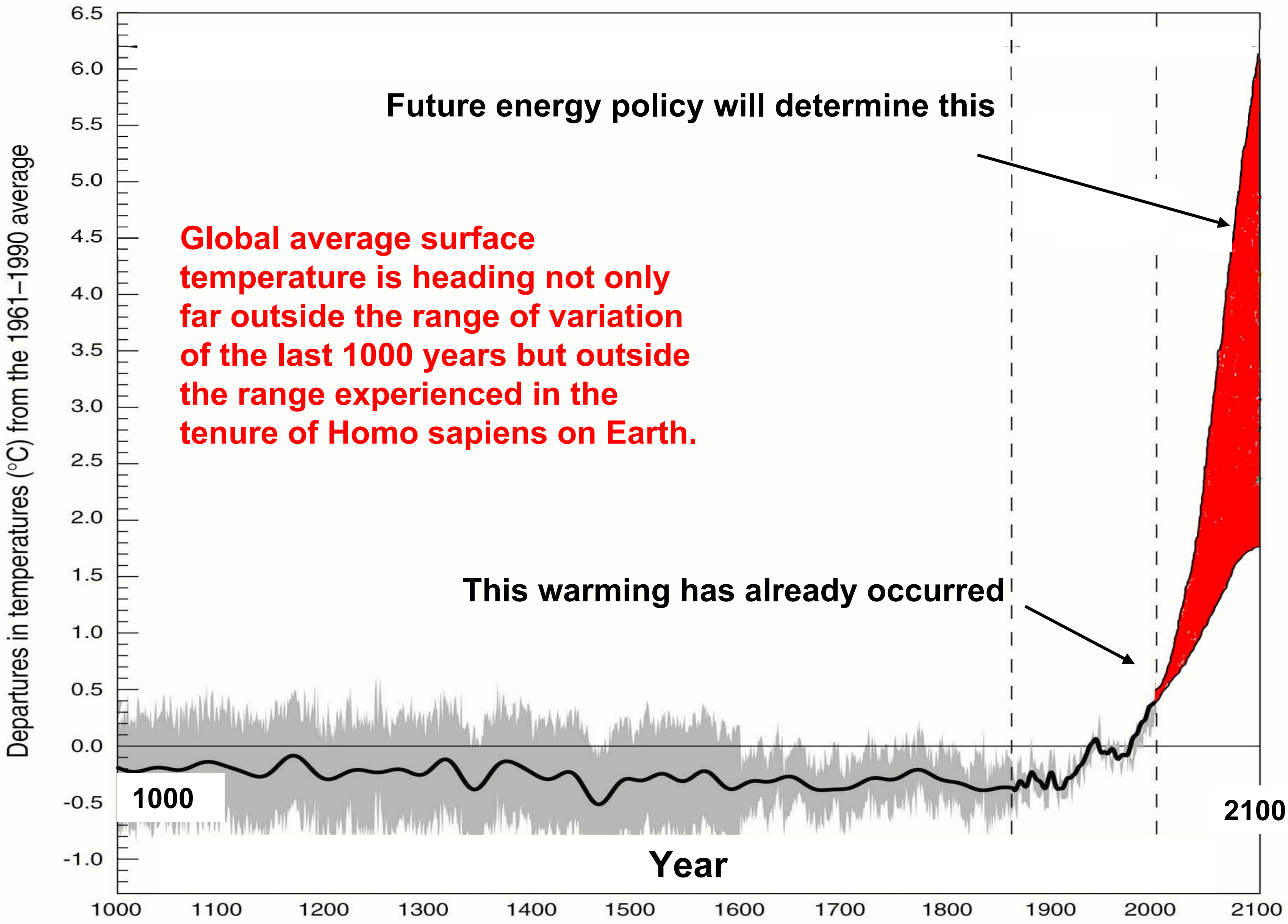
2. Many of the "missing feedbacks" appear to be positive…"the warming feeds the warming". These feedbacks can induce very asymmetric, fat-tailed uncertainties into our model predictions.

3. In both biogeochemistry and population biology there are fundamental knowledge gaps that impede our ability to quantify ecological feedbacks to climate change.


The Climate Challenge
Gigatons Carbon Emitted per Year
14
7
0
1950
2000
2050
The Stabilization Wedges
Doubled emissions from "business as usual"
Emissions Stabilization
Climate Stabilization
Current emissions


Gigatons
Carbon Emitted
per Year
Destabilization
Wedges!
Effects of
feedbacks, loss
of carbon sinks
14
7
0
Current
emissions
1950
2000
2050

Maybe Preventing Global Warming is Easier than Understanding it???

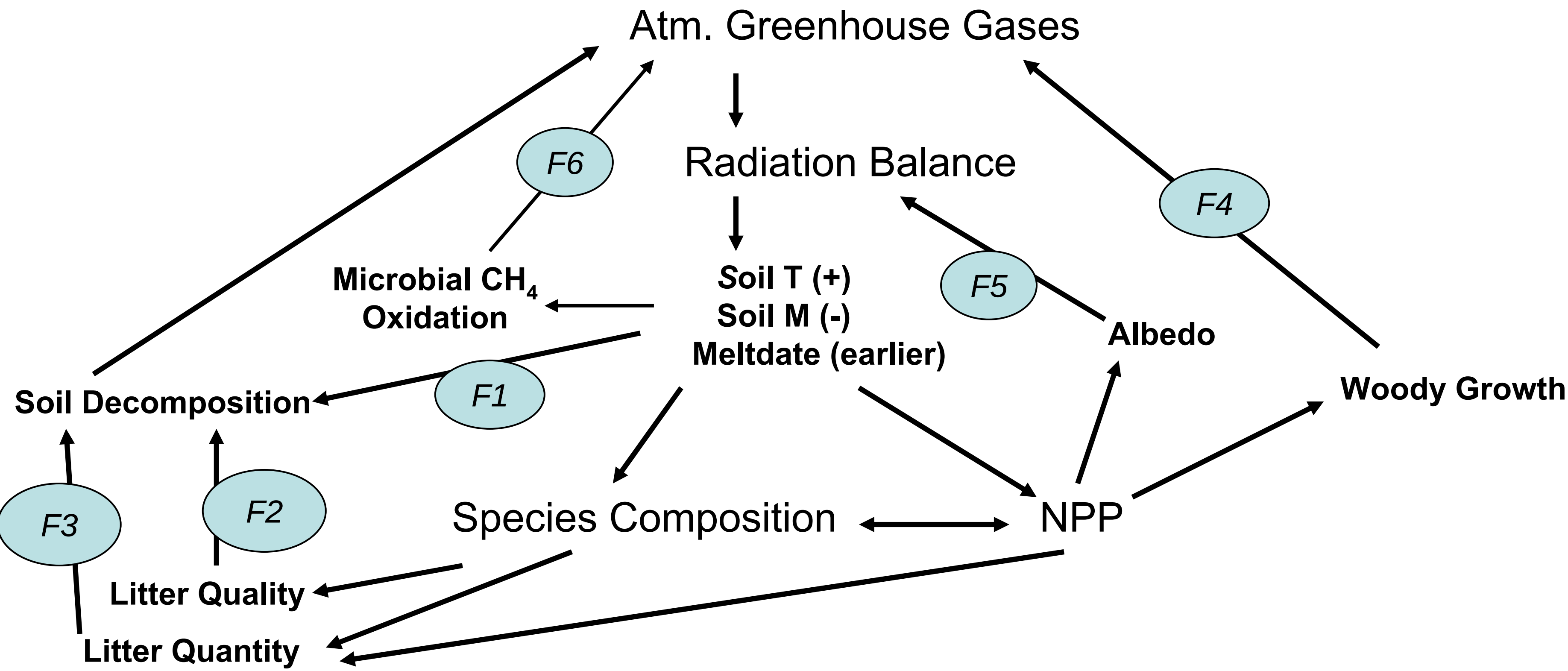


Thanks to the National Science Foundation, the U.S. Departments of Energy and Agriculture, and the Miller and Guggenheim Foundations for support of my research.

Thanks to over 40 students and postdocs for working with me over the past 20 years on this stuff.

And thank you for your attention!

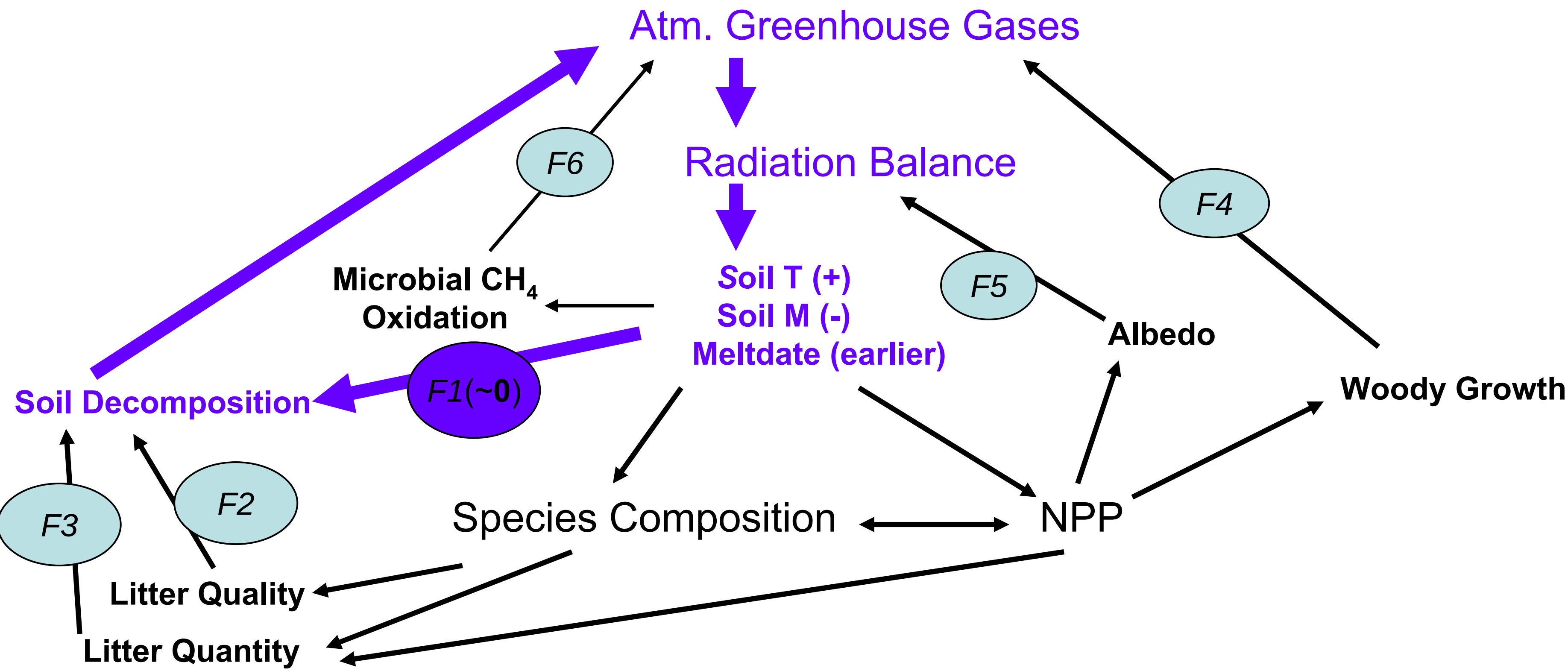
ECOLOGICAL FEEDBACKS to CLIMATE



There are 6 distinct feedback loops analyzable from the meadow-warming experiment.

They influence net GHG fluxes and surface albedo.

ECOLOGICAL FEEDBACKS to CLIMATE



F1: T,M → decomposition (~ 0)

F2: meltdate → forb/shrub → litter quality

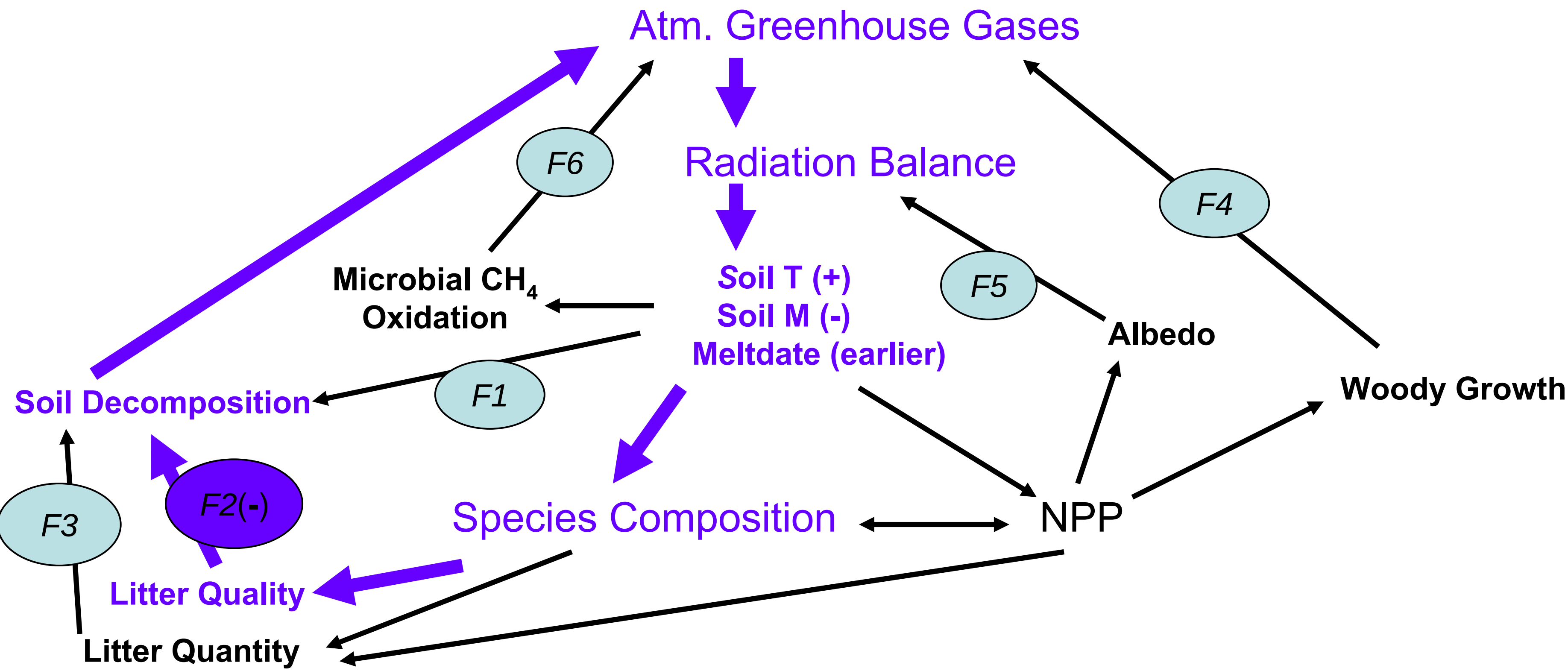
F3: meltdate → forb/shrub → litter quantity

F4: meltdate → woody growth

F5: meltdate → forb/shrub → albedo

F6: soil M → microbial oxidation of CH_4

ECOLOGICAL FEEDBACKS to CLIMATE



F1: T,M → decomposition

F2: meltdate → forb/shrub → litter quality (-)

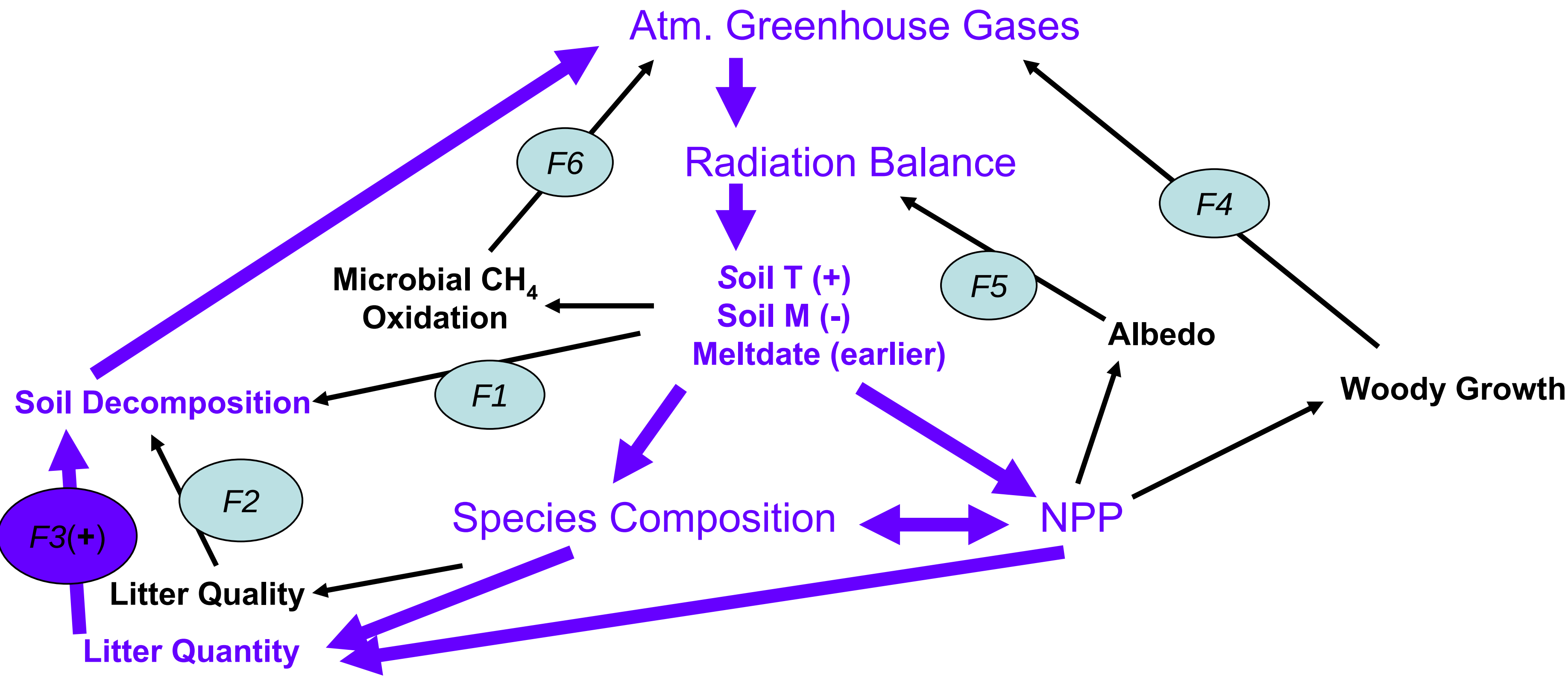
F3: meltdate → forb/shrub → litter quantity

F4: meltdate → woody growth

F5: meltdate → forb/shrub → albedo

F6: soil M → microbial oxidation of CH_4

ECOLOGICAL FEEDBACKS to CLIMATE



F1: T,M → decomposition

F2: meltdate → forb/shrub → litter quality

F3: meltdate → forb/shrub → litter quantity (+)

F4: meltdate ⟶ woody growth

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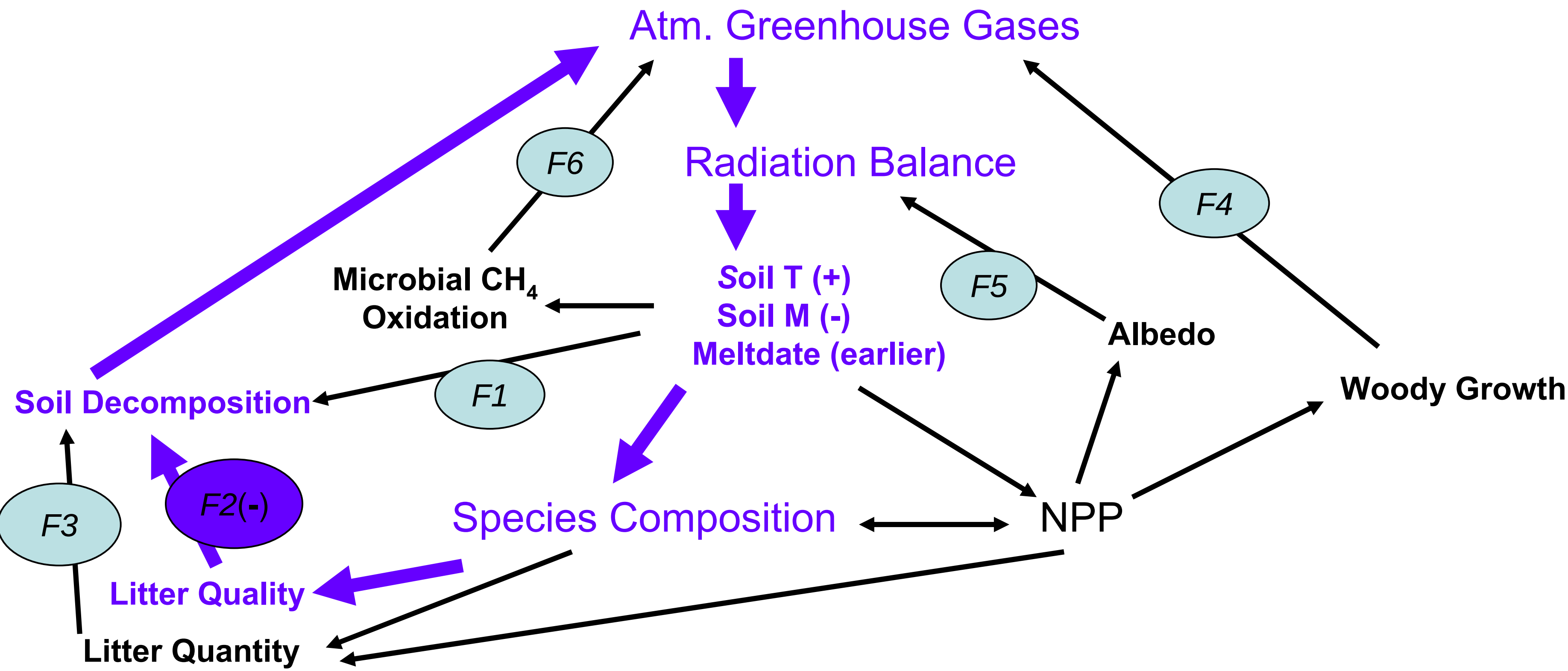

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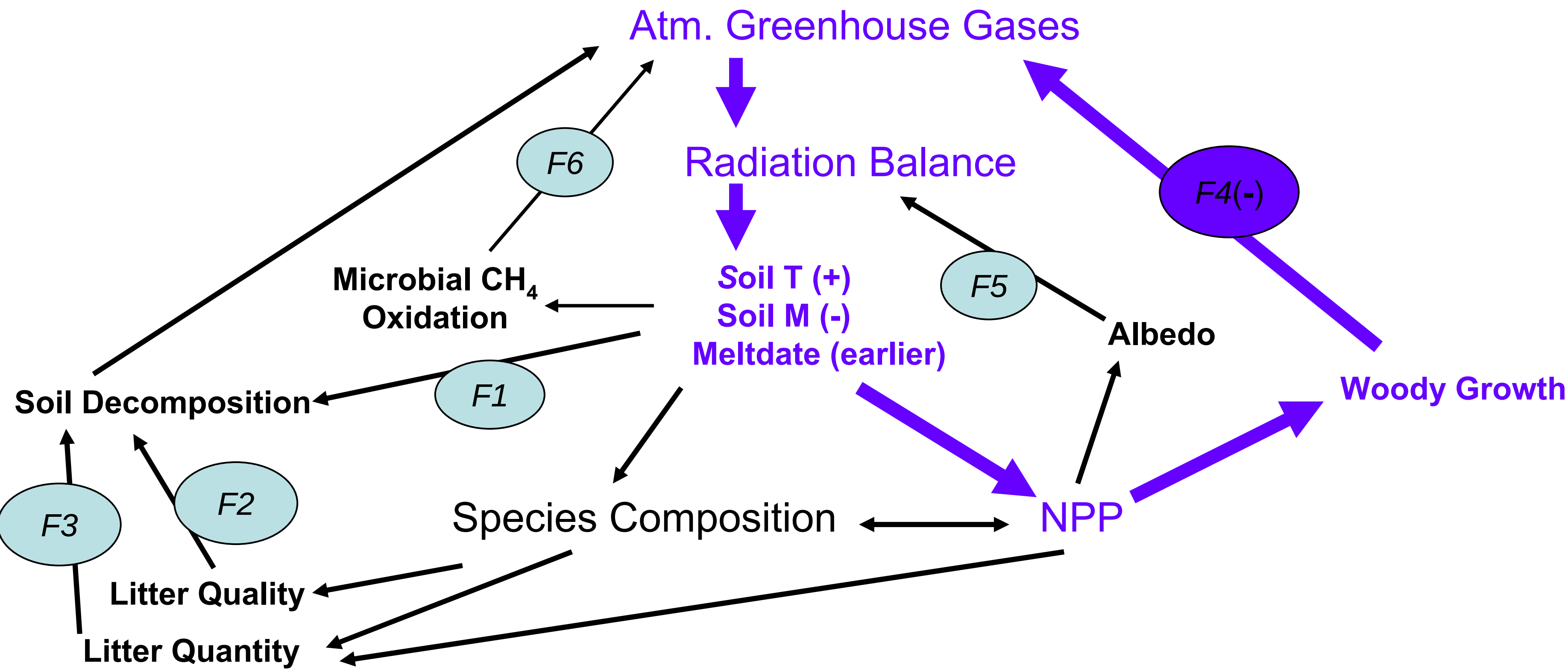

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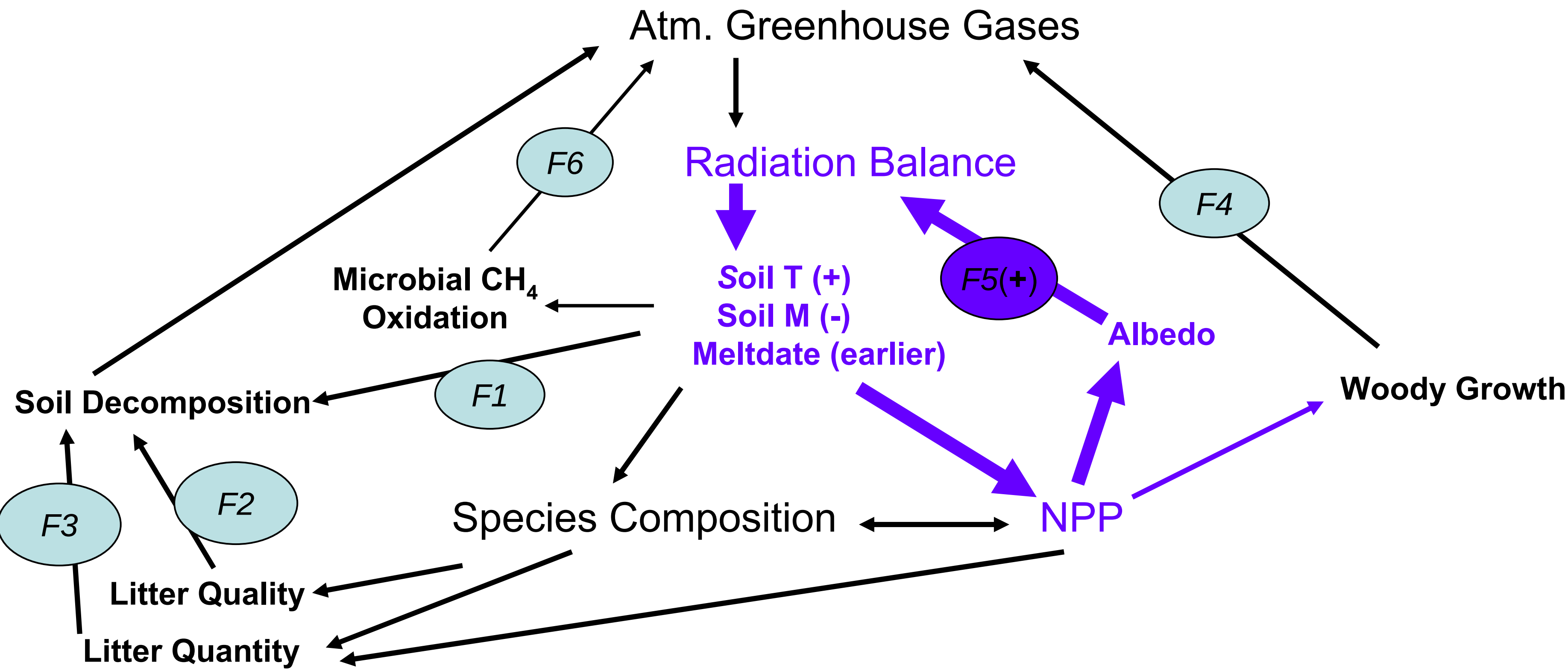

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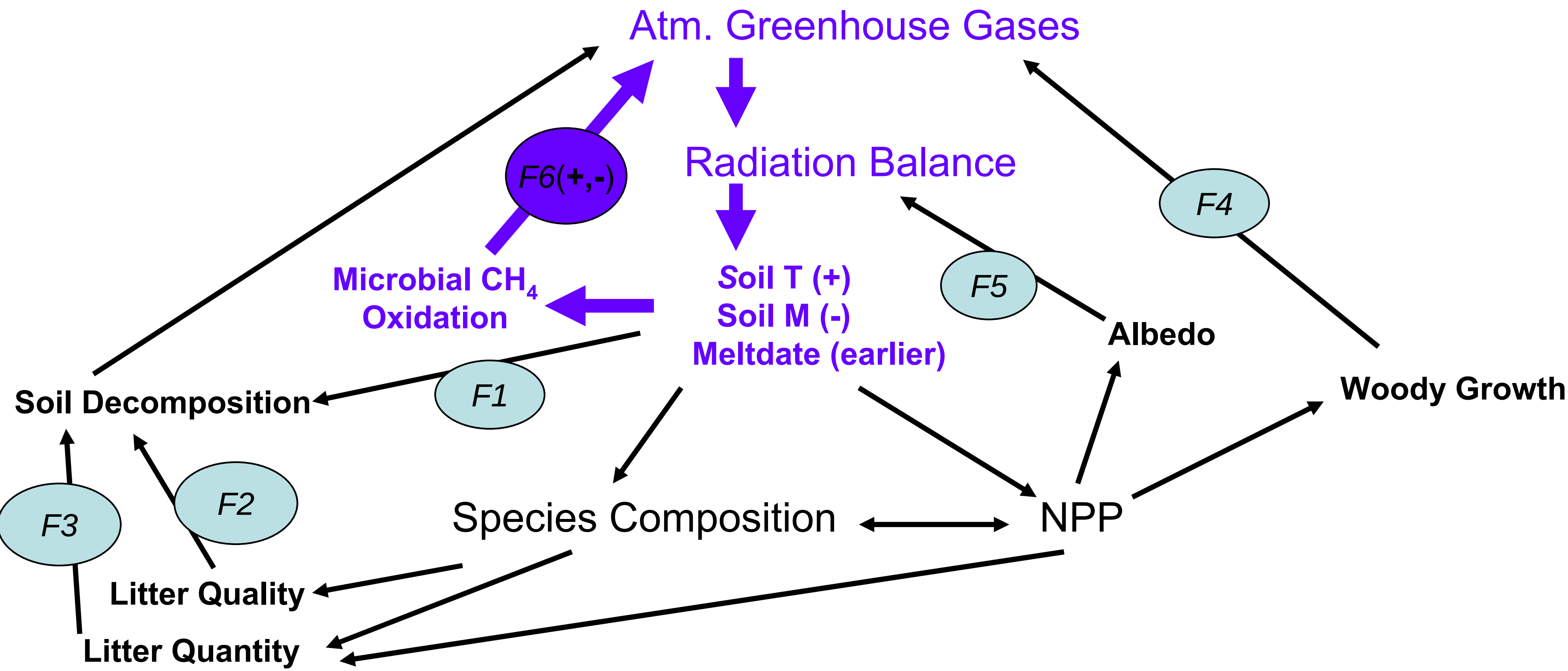
ECOLOGICAL FEEDBACKS to CLIMATE



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F2: meltdate → forb/shrub → litter quality

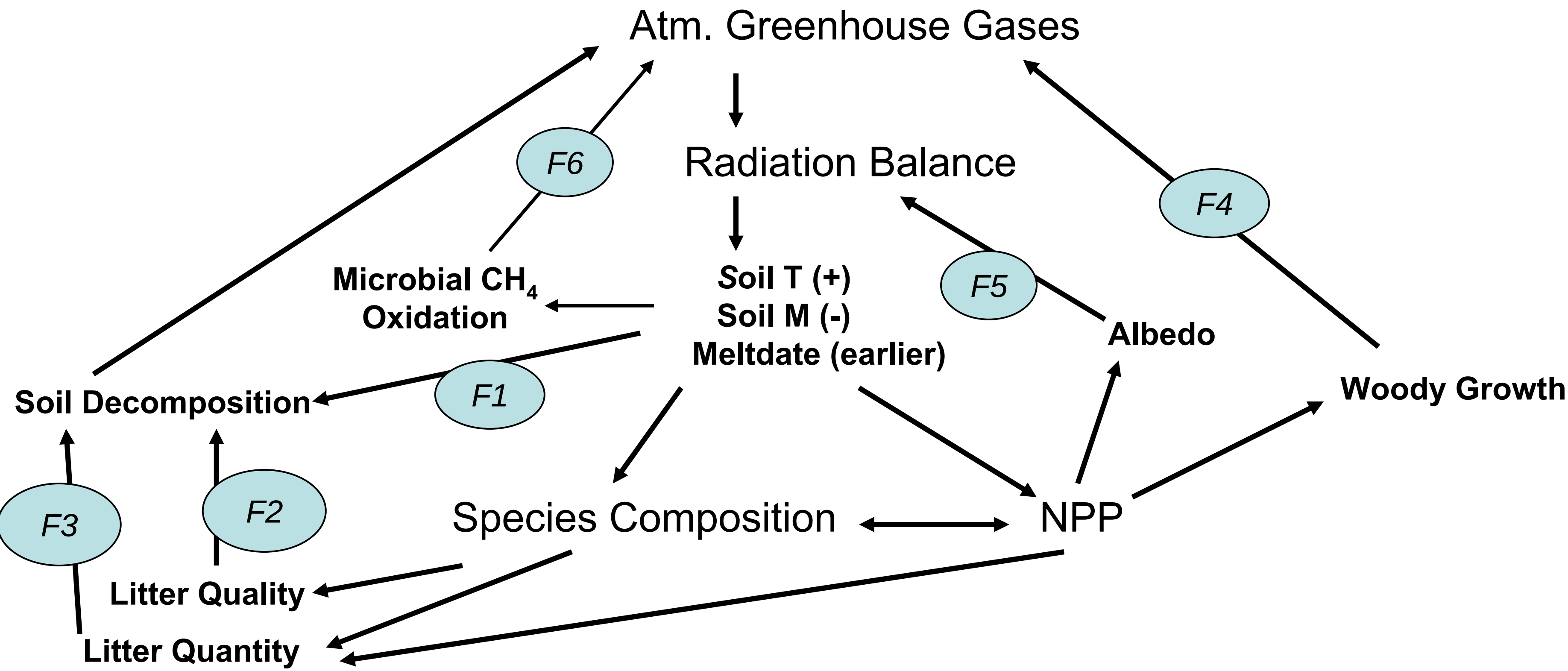
F3: meltdate → forb/shrub → litter quantity

F4: meltdate → woody growth

F5: meltdate → forb/shrub → albedo

F6: soil M → microbial oxidation of CH_4 (+,-)

ECOLOGICAL FEEDBACKS to CLIMATE



Magnitudes and Overall Sign of Feedbacks:

SHORT-TERM **(years to decade):** ***F3*(+) > *F5*(+) > F4(-) > *F2*(-), *F6* (+) > *F1* ~ 0;** **(+)**

LONG-TERM **(decade to century):** ***F5*(+), *F2* (-) > *F3*(+), *F4*(-), *F6*(+) > *F1* ~ 0;** **(?)**

Metrics of Temporal Variability

Consider a river with instantaneous flow Q. Over a long period flow data reveal a mean <Q> and a variance σ^2_Q.

But if your concern is with the viability of a population of fish in the river, those flow metrics may not be very informative.

Consider xQy, where x is days, y is years. *It is the lowest x day flow that can be expected to recur on average every y years.*

Thus an $_7Q_5$ of 100 cfs means that on average every 5 years you can expect to see a flow as low as 100 cfs for 7 consecutive days.

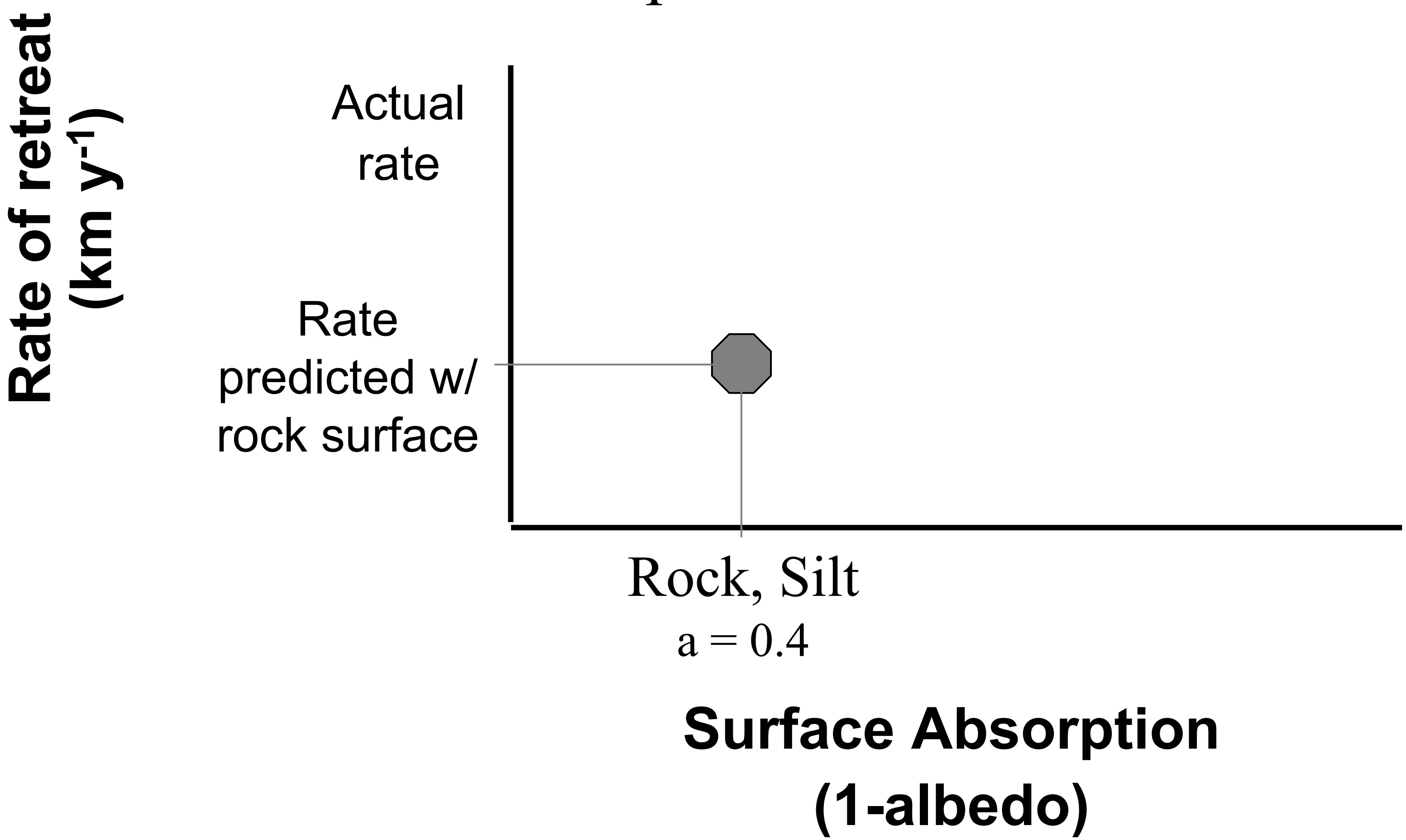
A <u>prolonged</u> rather than a brief low flow can be bad for fish because it can cause oxygen levels to fall below a critical value.

A <u>frequently-recurring</u> low flow can be bad for fish because the "multiple whammy" can wreck havoc with demographics.

- What will global warming, or an upstream dam, due to the **xQy** value of a river?
- What x and y are most useful?
- Are there other, better metrics?

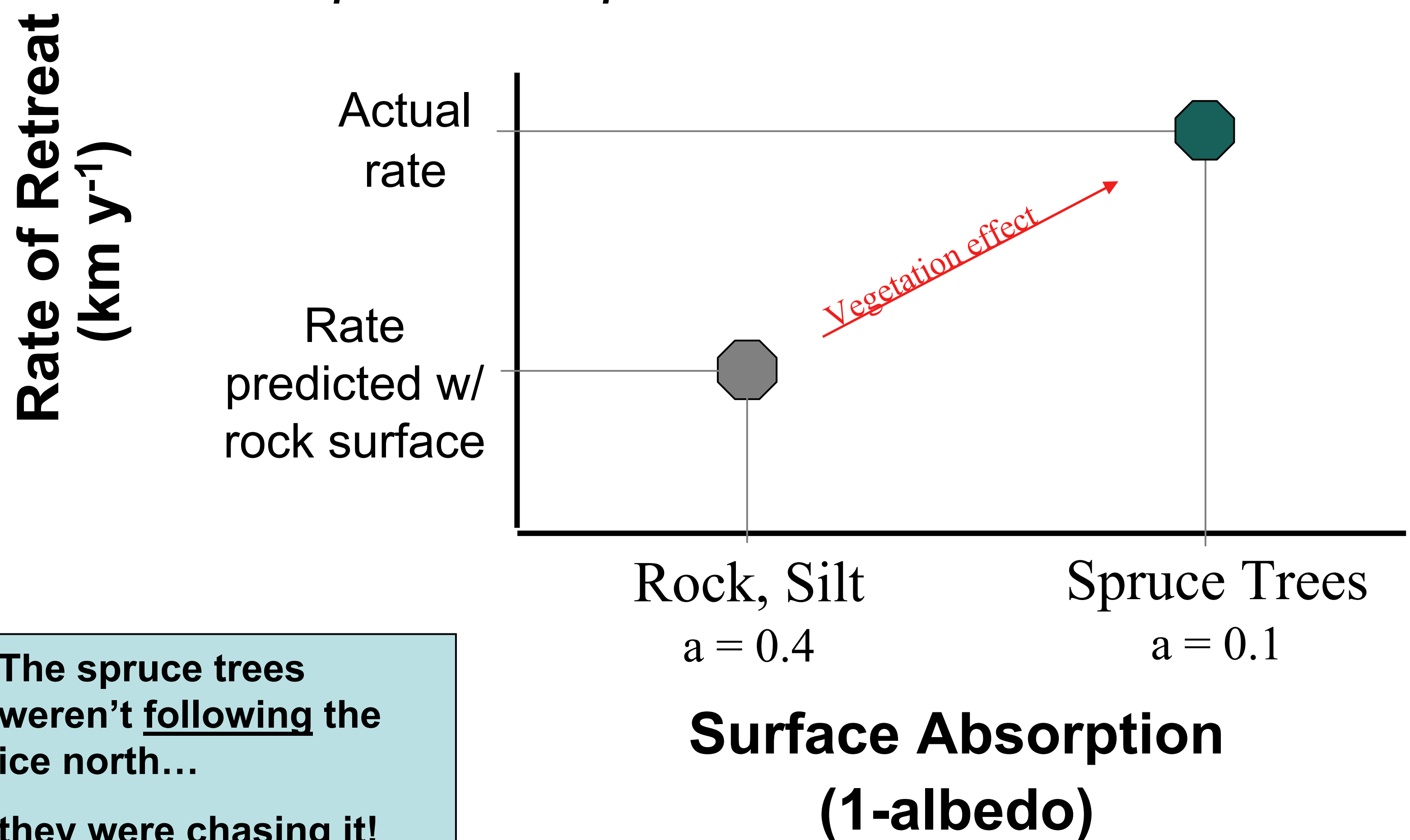
Retreat of N. American Ice Sheet

Models with rock and silt surface predicts slow retreat



Retreat of N. American Ice Sheet: Evidence for vegetation-mediated feedback

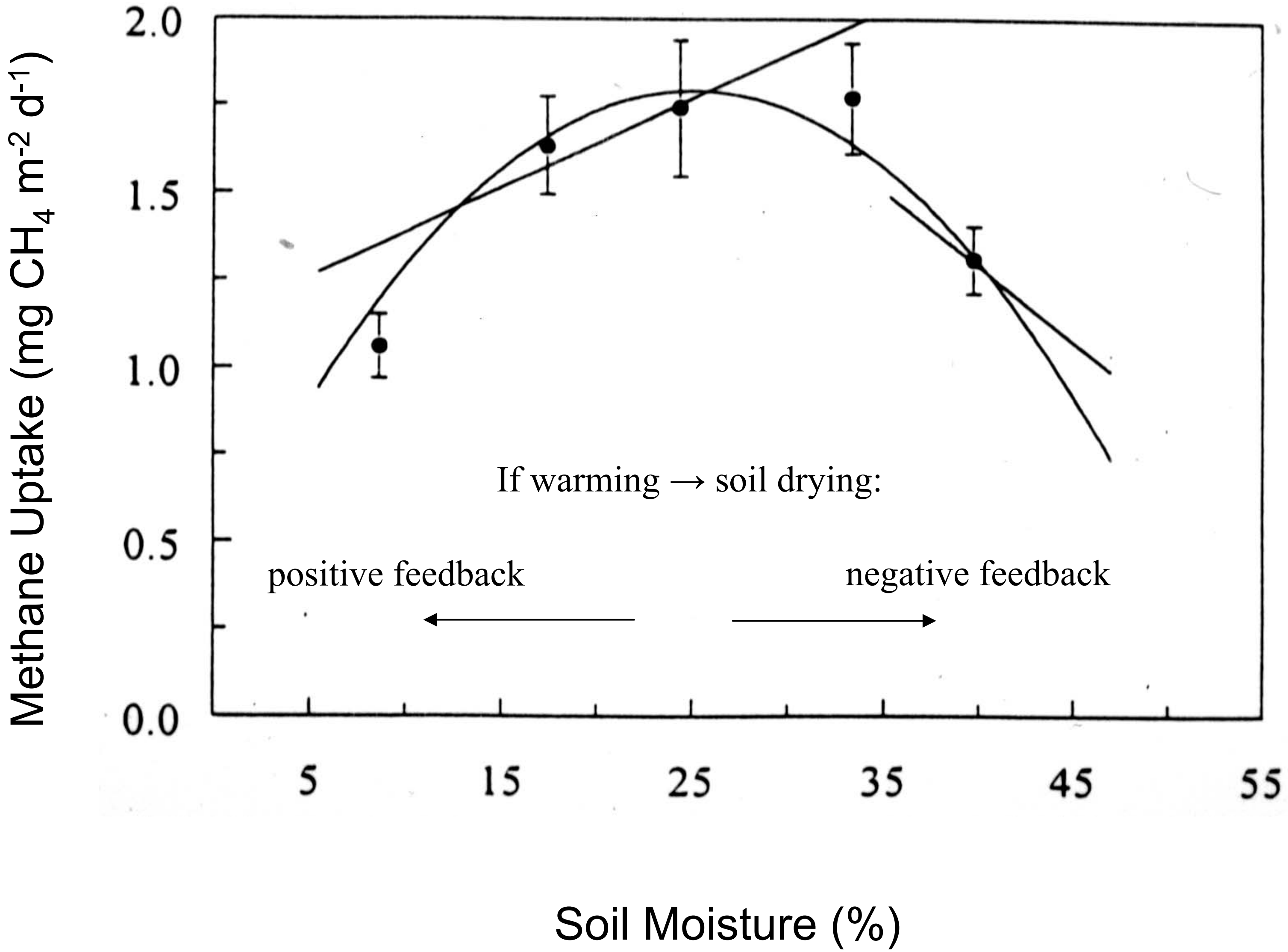
Models without spruce trees cannot predict actual rate of retreat of continental ice sheet



The spruce trees weren't <u>following</u> the ice north…

they were <u>chasing</u> it!

Feedback # 2: methane consumption influenced by soil moisture



Torn and Harte,
Biogeochemistry, 1995

We can’t just think about the threat of global warming in isolation: The sinister side of synergy