Forests and Climate Change: Forcings, Feedbacks and the Climate Benefits of Forests

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November 13, 2008

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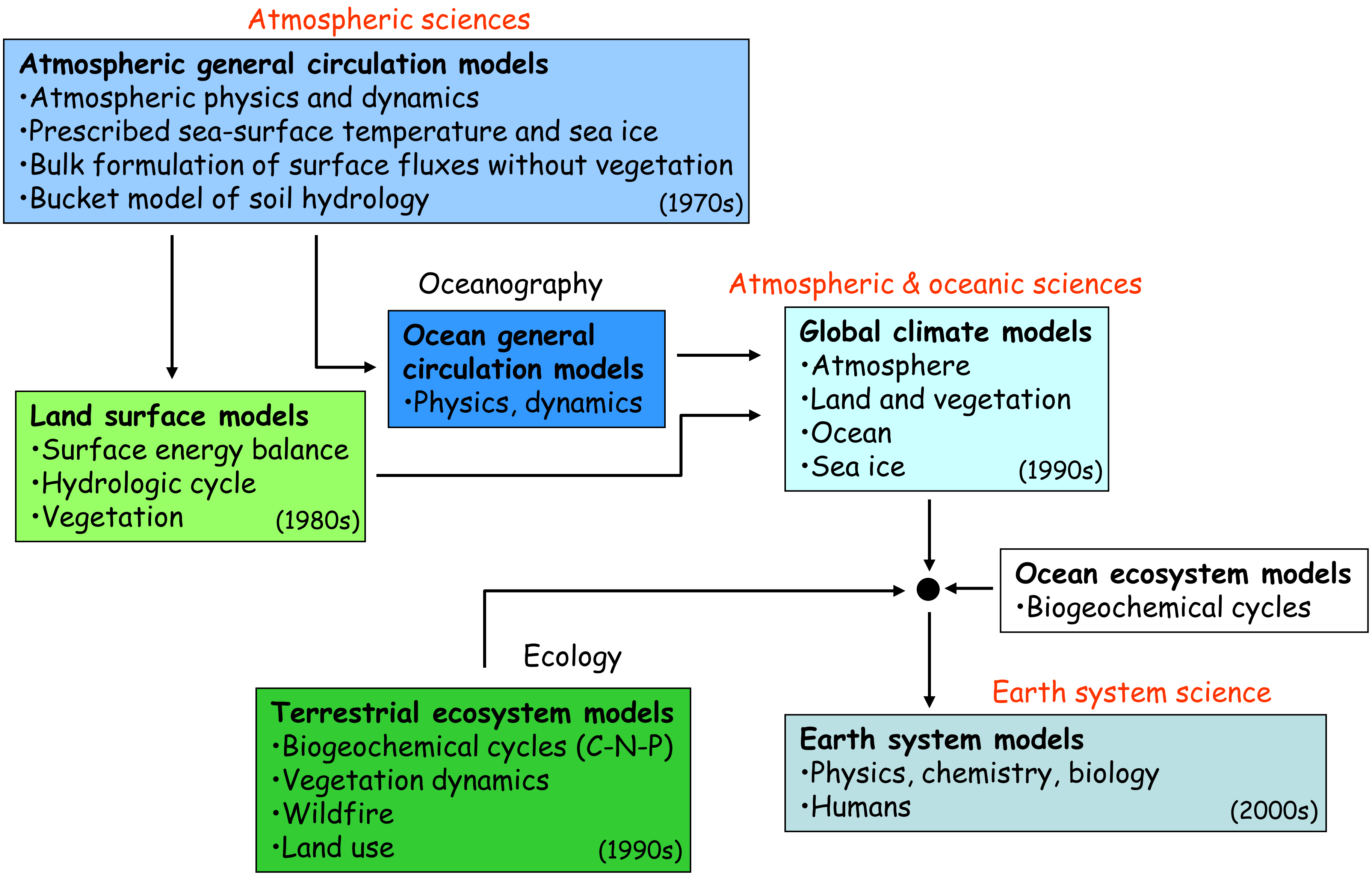
Evolution of climate science



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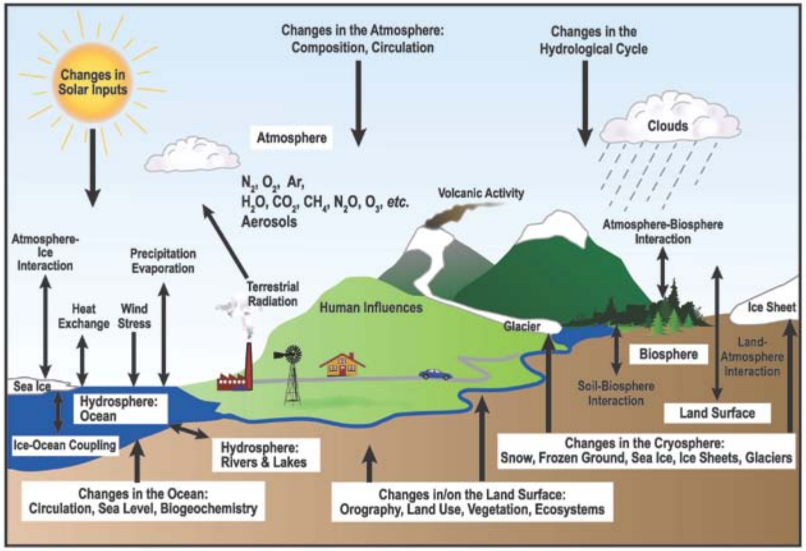
Our research

The land surface as the critical interface through which people affect, adapt to, and mitigate global environmental change

- Continued expansion of capability to simulate ecological, hydrological, and biogeochemical forcings and feedbacks in the earth system
- Increased emphasis on ability to conduct impacts, adaptation, and mitigation research
- Requires an integrated assessment modeling framework
  - Human systems (land use, urbanization, energy use)
  - Biogeochemical systems (C-N-P, trace gas emissions, constituent tracing, isotopes)
  - Water systems (water resource management, freshwater availability, water quality)
  - Ecosystems

    (disturbance, vulnerability, goods and services)



(IPCC 2007)

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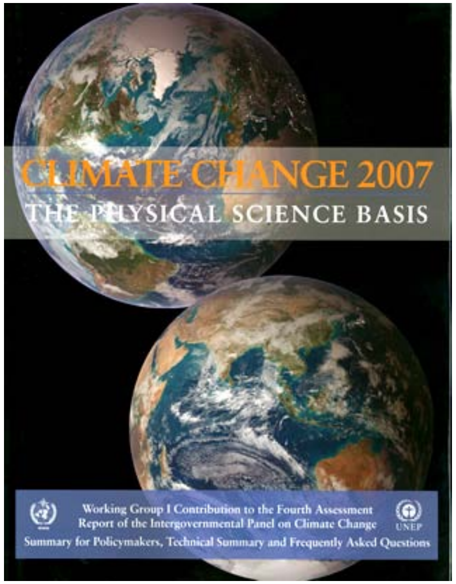
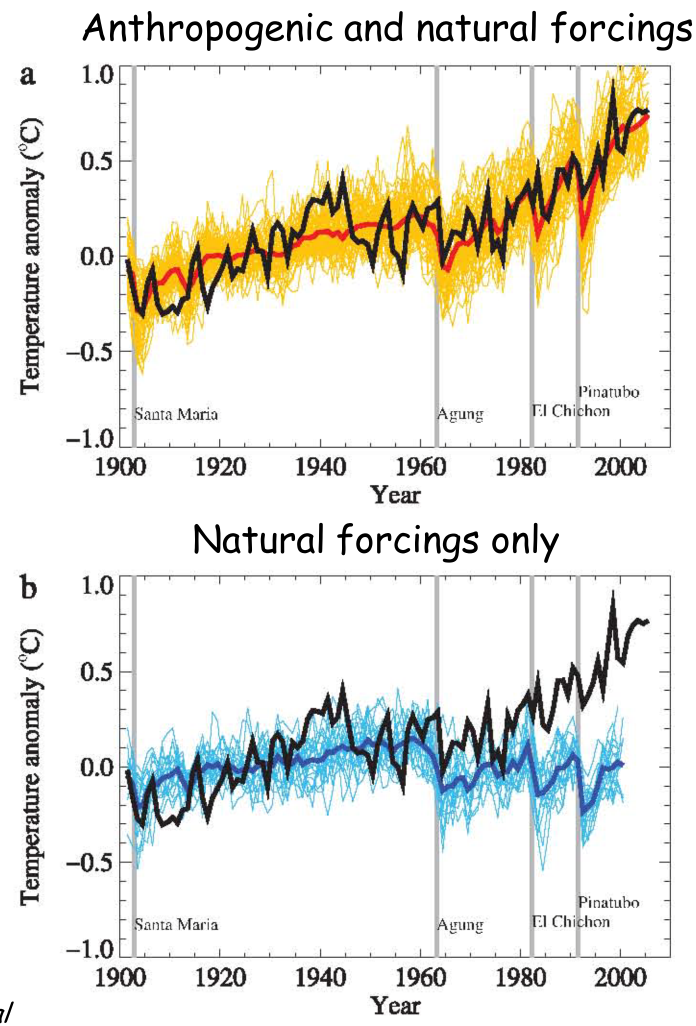
Climate of the 20th century





Anthropogenic forcings
Greenhouse gases
Sulfate aerosols
Black carbon aerosols
Ozone

Natural forcings
Solar variability
Volcanic aerosols

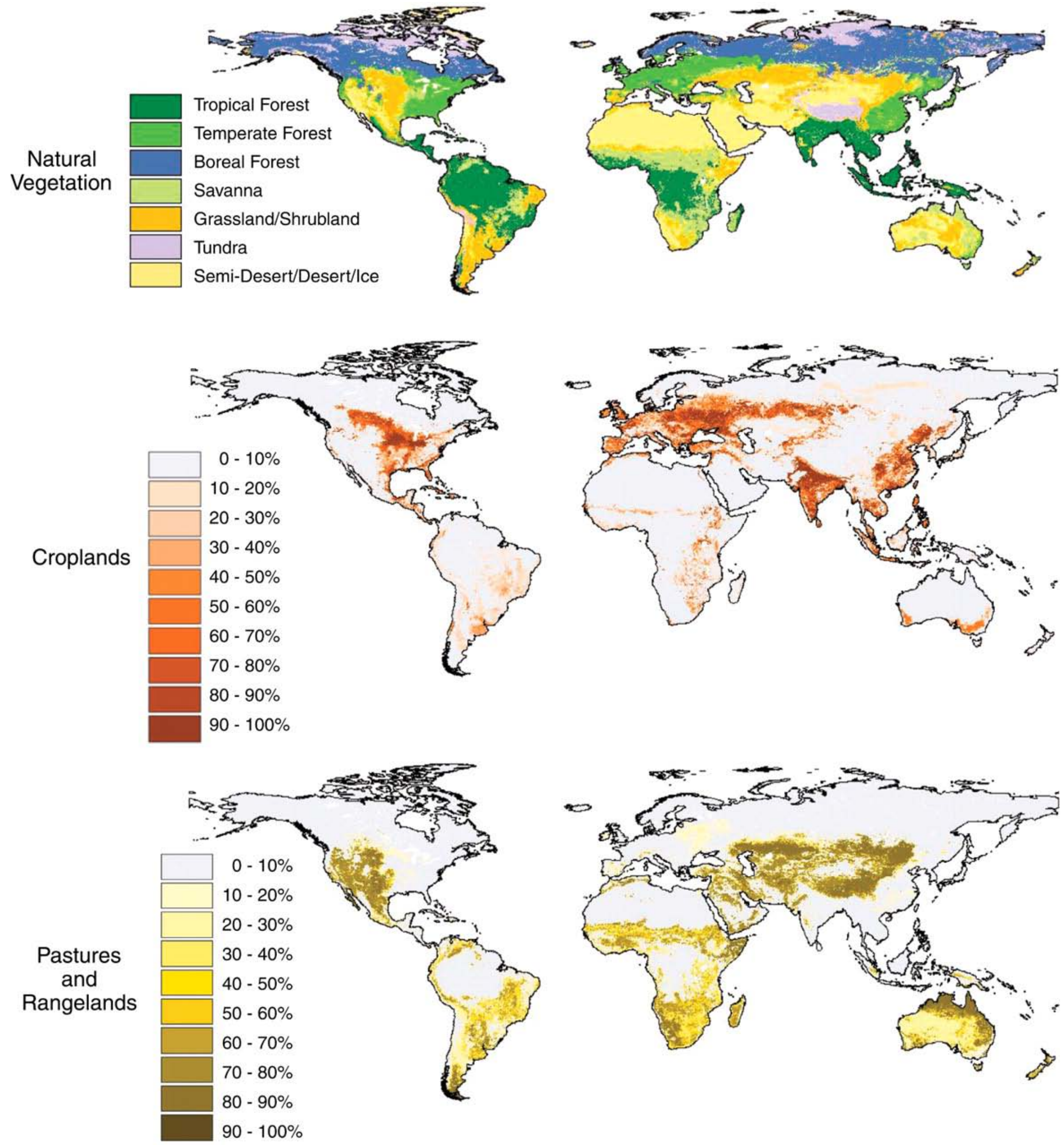
It is *extremely unlikely* (<5%) that the global pattern of warming during the past half century can be explained without external forcing, and *very unlikely* that it is due to known natural external causes alone

Hegerl et al. (2007) in *Climate Change 2007: The Physical Science Basis,* Solomon et al., Eds., 663-745

Anthropogenic land use

Agroecosytems

- Albedo
- Bowen ratio
- Infiltration/runoff
- Soil water holding capacity
- Atmospheric CO_2
- Nitrogen cycle
- Dust



Foley et al. (2005) Science 309:570-574

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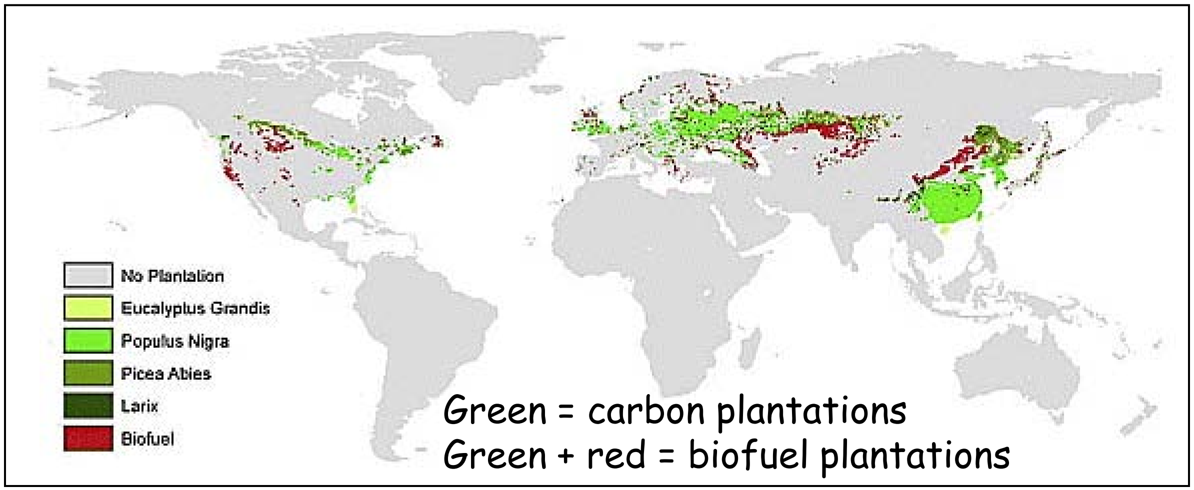
Land management mitigation policies

Reforestation might be chosen as an option for the enhancement of terrestrial carbon sequestration or biofuel plantations may be used as a substitute for fossil fuels

Maize/Poplar/Switchgrass

2100 land management, IPCC A1B scenario



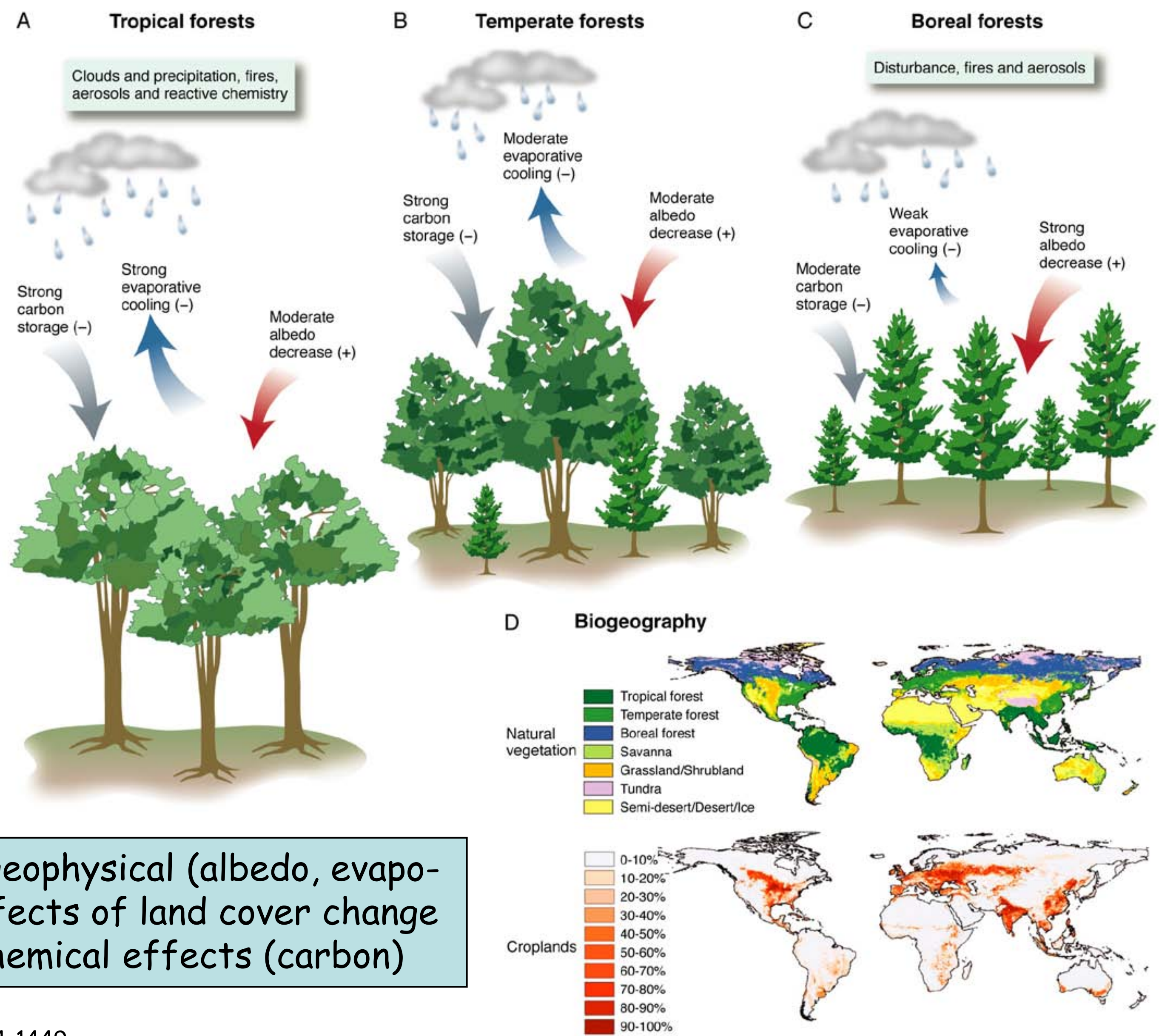
Excess agricultural land converted to carbon storage or biofuels

Carbon plantations and biofuel plantations reduce atmospheric CO_2, leading to cooling

Carbon plantations have lower albedo than biofuels, leading to warming

Schaeffer et al. (2006) GBC, 20, doi:10.1029/2005GB002581

Forests and climate change



Contrast the biogeophysical (albedo, evapo-transpiration) effects of land cover change with the biogeochemical effects (carbon)

Bonan (2008) Science 320:1444-1449

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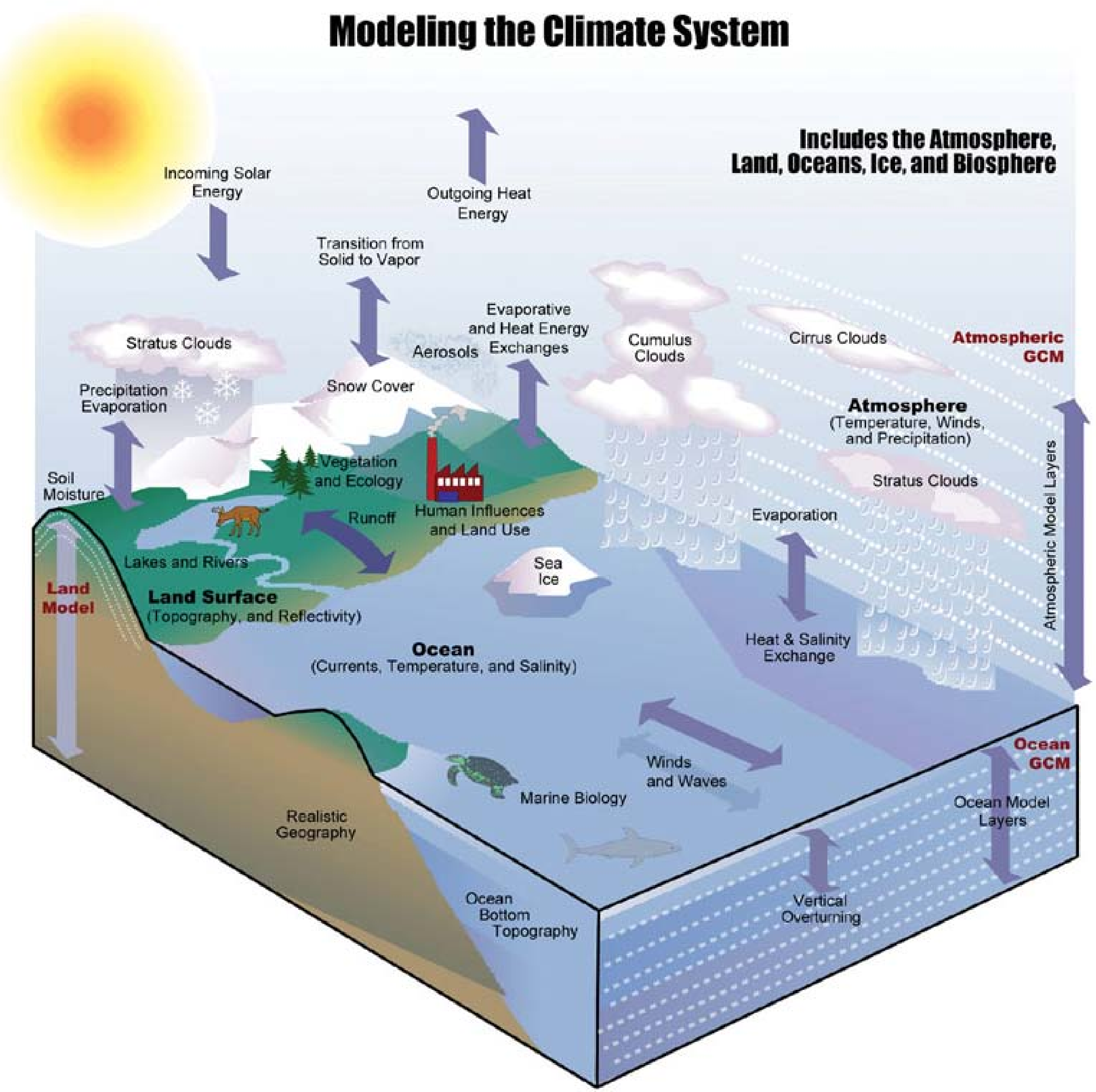
The climate system



Climate models use mathematical formulas to simulate the physical, chemical, and biological processes that drive Earth's climate

A typical climate model consists of coupled models of the atmosphere, ocean, sea ice, and land

Land is represented by its ecosystems, watersheds, people, and socioeconomic drivers of environmental change

The model provides a comprehensive understanding of the processes by which people and ecosystems affect, adapt to, and mitigate global change

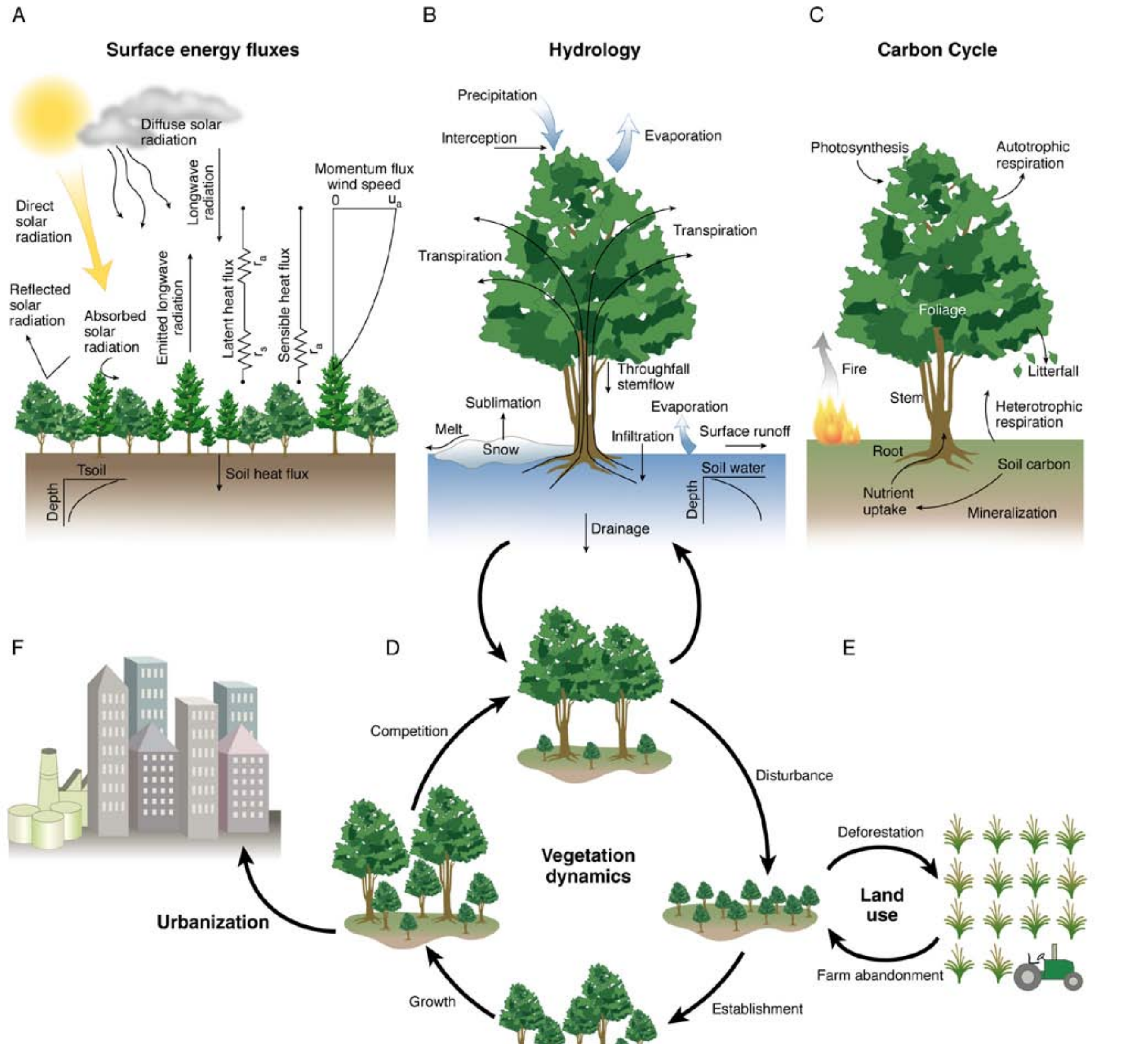
The Community Land Model

Fluxes of energy, water, and carbon and the dynamical processes that alter these fluxes

Oleson et al. (2004) NCAR/TN-461+STR

Oleson et al. (2008) JGR, 113, doi:10.1029/2007JG000563

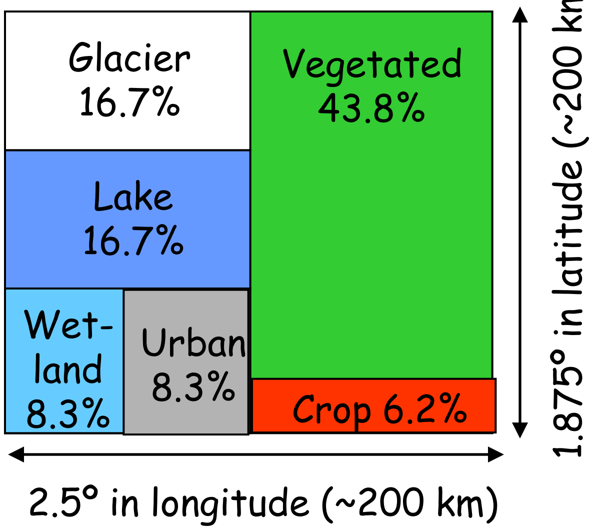
Stöckli et al. (2008) JGR, 113, doi:10.1029/2007JG000562



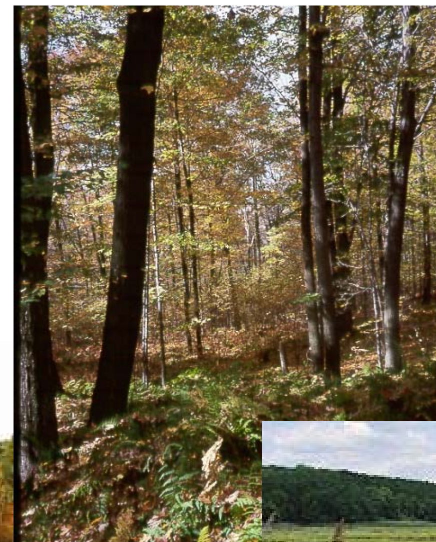
Bonan (2008) Science 320:1444-1449

Land surface heterogeneity

Subgrid land cover and plant functional types



CLM represents a model grid cell as a mosaic of up to 6 primary land cover types. Vegetated land is further represented as a mosaic of several plant functional types



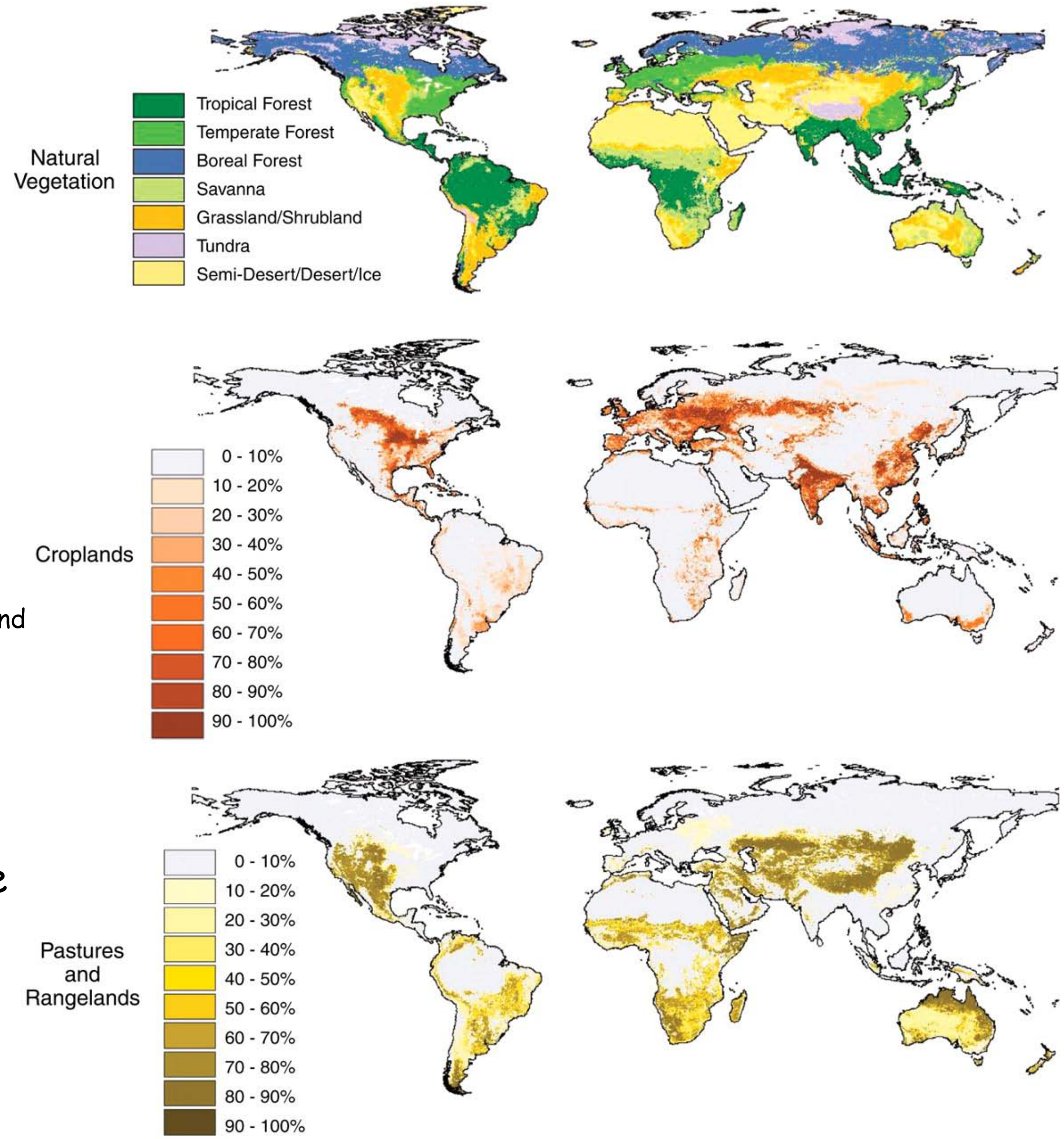
Bonan et al. (2002) GBC, 16, doi:10.1029/2000GB001360

Global land use

Local land use is spatially heterogeneous

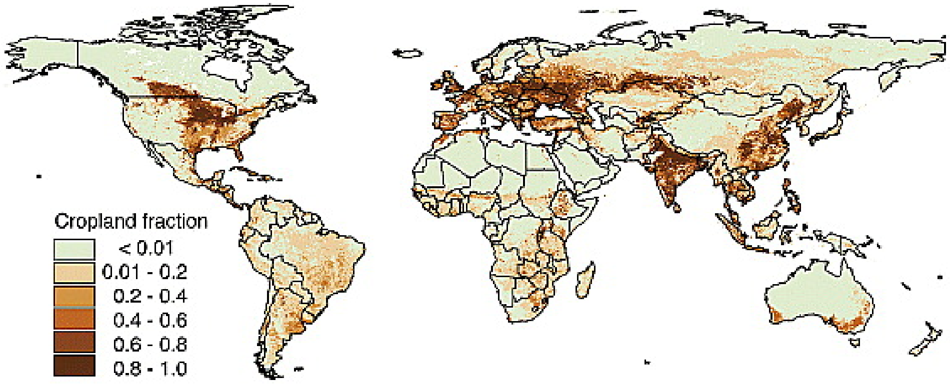
NSF/NCAR C-130 aircraft above a patchwork of agricultural land during a research flight over Colorado and northern Mexico

Global land use is abstracted to the fractional area of crops and pasture



Foley et al. (2005) Science 309:570-574

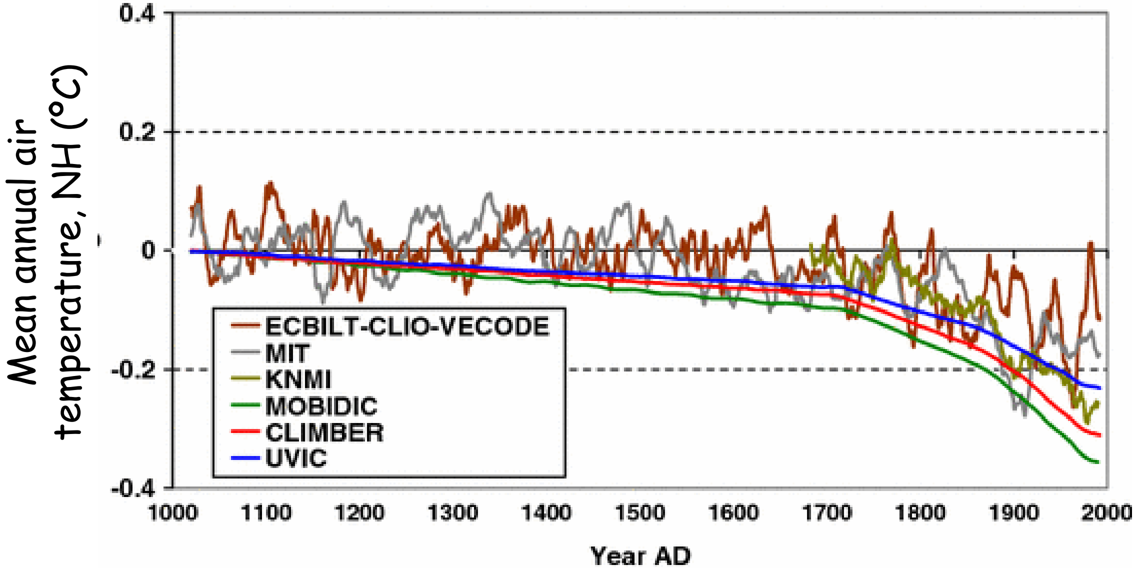
Land use forcing of climate



The emerging consensus is that land cover change in middle latitudes has cooled the Northern Hemisphere (primarily because of higher surface albedo in spring)

Northern Hemisphere annual mean temperature decreases by 0.19 to 0.36 °C relative to the pre-industrial era

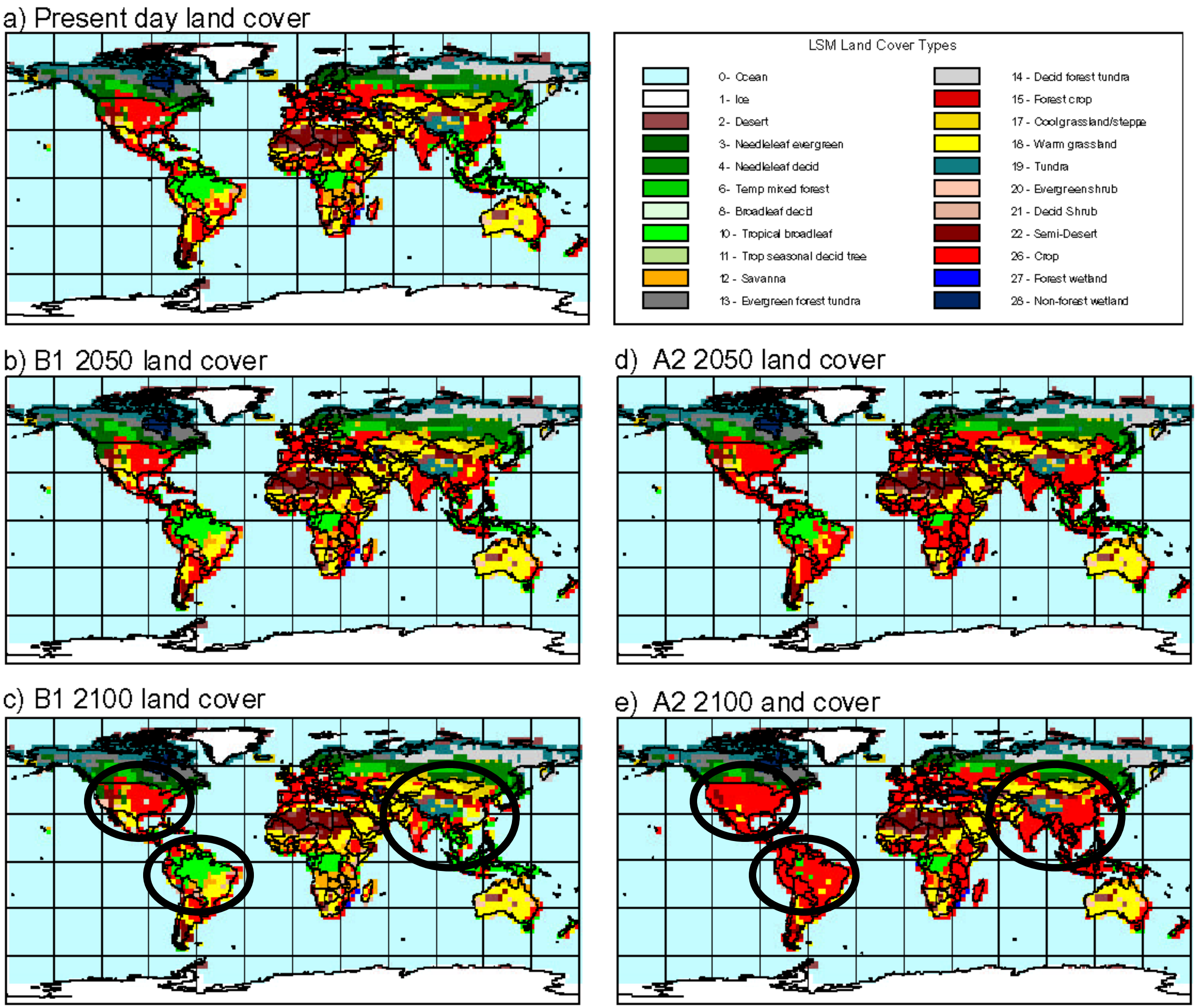
Comparison of 6 EMICs forced with historical land cover change, 1000-1992



Brovkin et al. (2006) Climate Dynamics 26:587-600

Future land cover change

Future IPCC SRES land cover scenarios for NCAR LSM/PCM



A2 – Widespread agricultural expansion with most land suitable for agriculture used for farming by 2100 to support a large global population

B1 - Loss of farmland and net reforestation due to declining global population and farm abandonment in the latter part of the century

Feddema et al. (2005) Science 310:1674-1678

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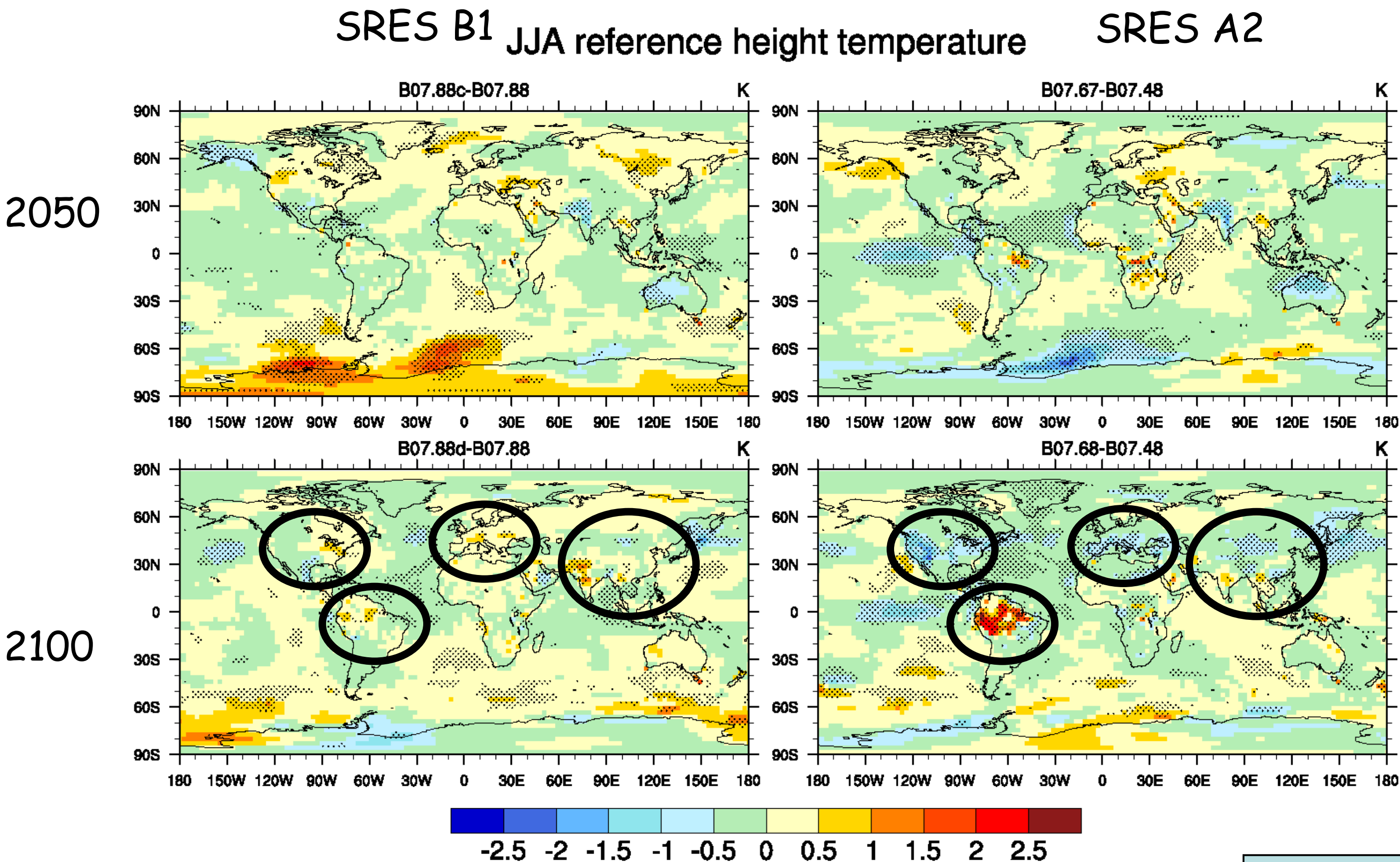
Future land cover change

Change in temperature due to land cover



Land use choices affect climate

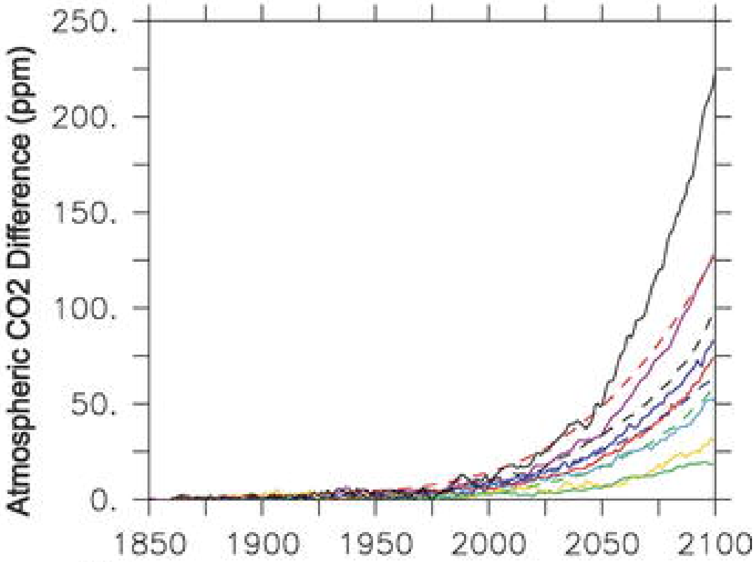
A2 – Widespread agricultural expansion with most land suitable for agriculture used for farming by 2100 to support a large global population

B1 - Loss of farmland and net reforestation due to declining global population and farm abandonment in the latter part of the century

Feddema et al. (2005) Science 310:1674-1678

Climate and carbon cycle

Effect of climate change on carbon cycle

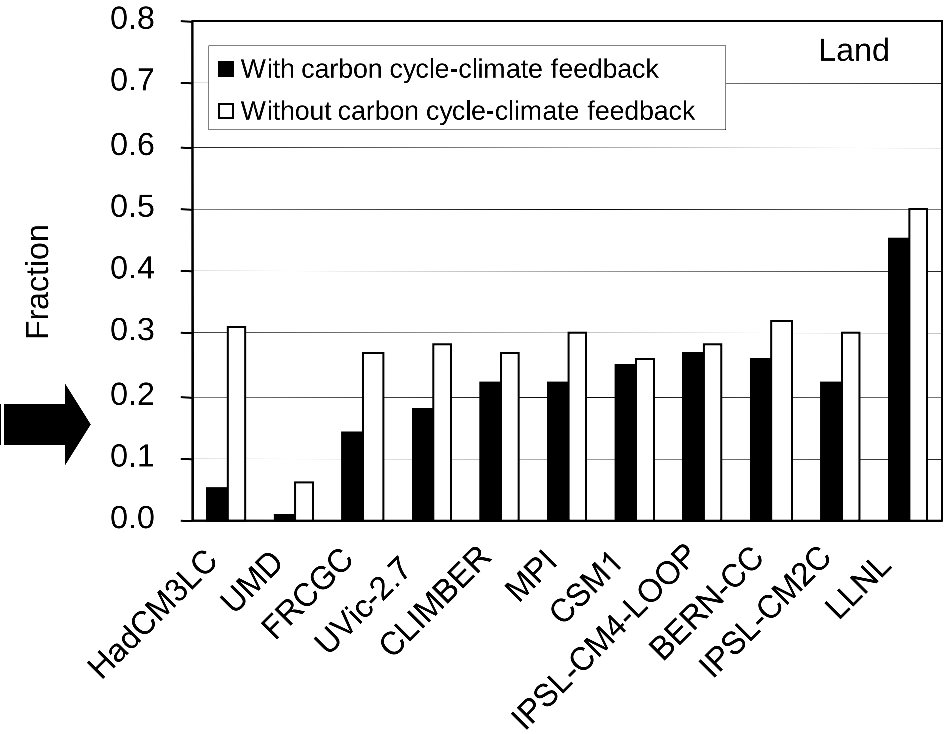


Climate-carbon cycle feedback

All models have a positive climate-carbon cycle feedback. The magnitude of this feedback ranges from 20 ppm to >200 ppm

Distribution at 2100 of cumulative anthropogenic carbon emissions

The amount of carbon stored in the atmosphere increases in each model compared with the comparable simulation without climate-carbon cycle feedback, while the land carbon storage decreases

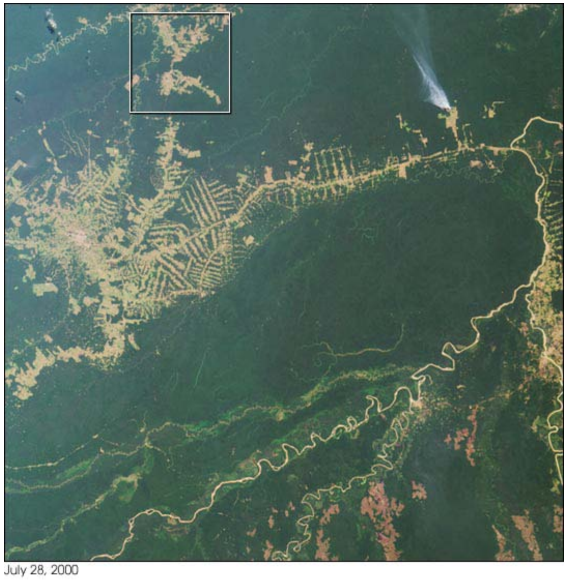


Friedlingstein et al. (2006) J Climate 19:3337-3353

Land use and carbon

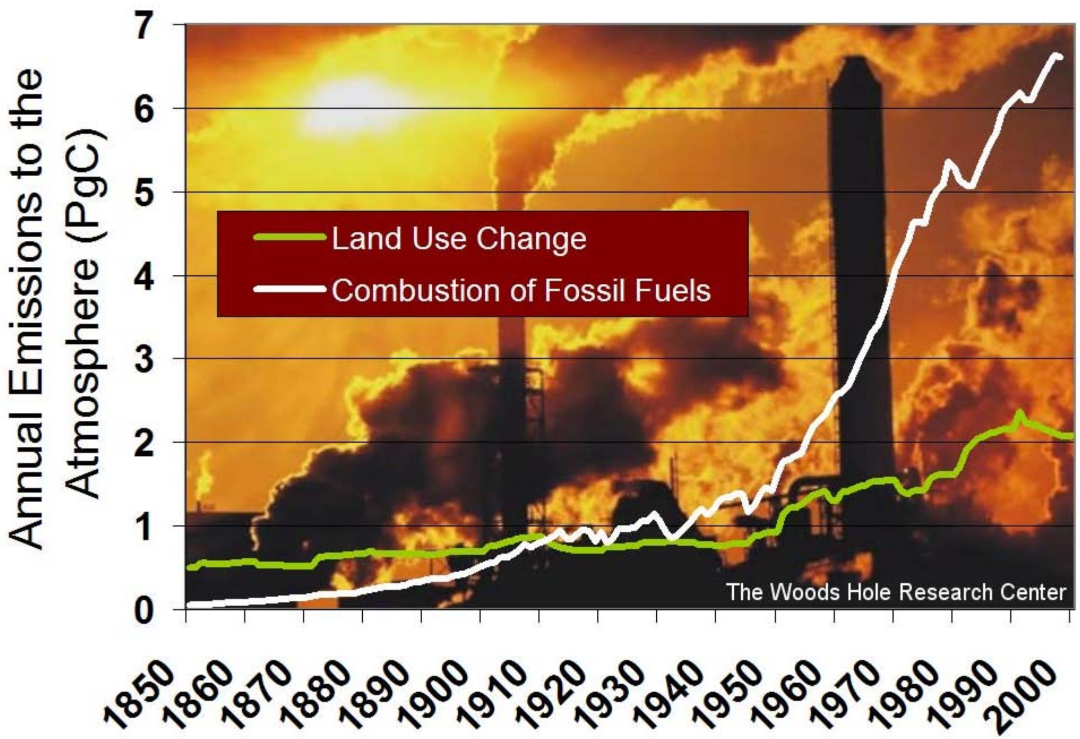
There is a net flux of carbon to the atmosphere from changes in land use

- Tropical deforestation releases carbon
- Temperate reforestation stores carbon



(NASA/GSFC/LaRC/JPL)

Settlement and deforestation surrounding Rio Branco, Brazil (10°S, 68°W) in the Brazilian state of Acre, near the border with Bolivia. The large image covers an area of 333 km x 333 km.



Integrated land cover change (2100)

Biogeophysical

A2 – cooling with widespread cropland

B1 – warming with temperate reforestation

Biogeochemical

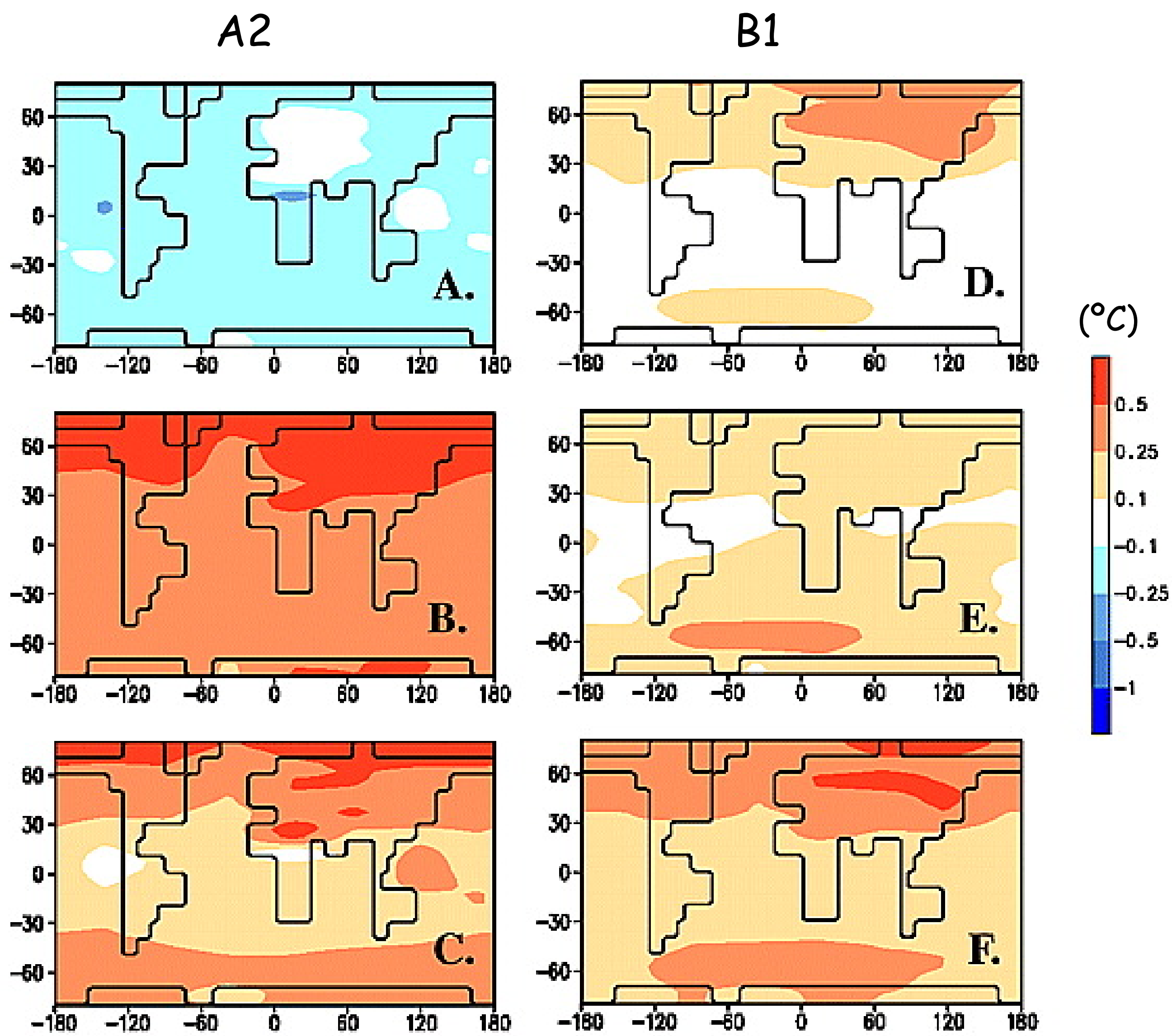
A2 – large warming; widespread deforestation

B1 – weak warming; less tropical deforestation, temperate reforestation

Net effect

A2 – BGC warming offsets BGP cooling

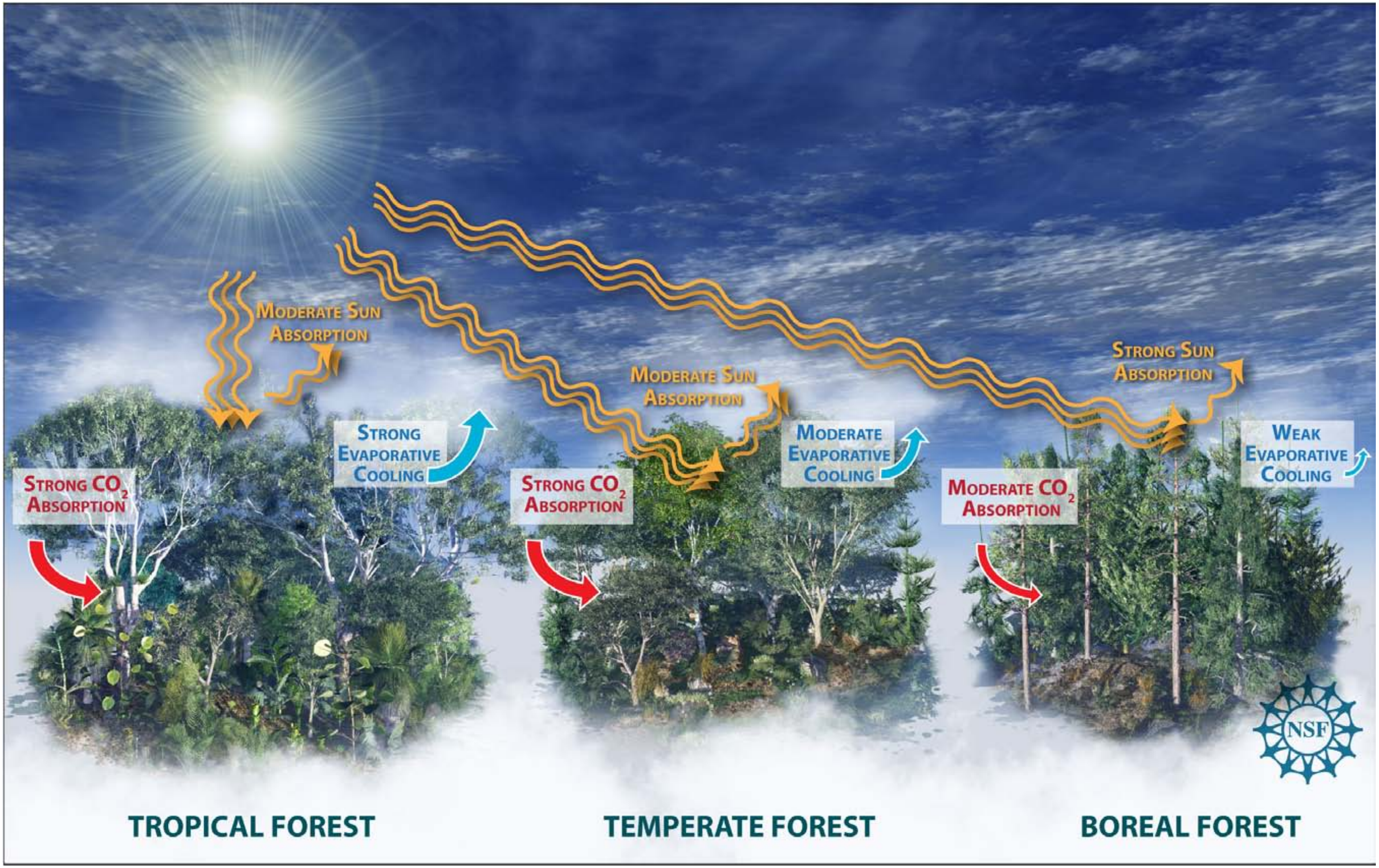
B1 – moderate BGP warming augments weak BGC warming



Sitch et al. (2005) GBC, 19, doi:10.1029/2004GB002311

Forests and climate change

Multiple competing influences of land cover change



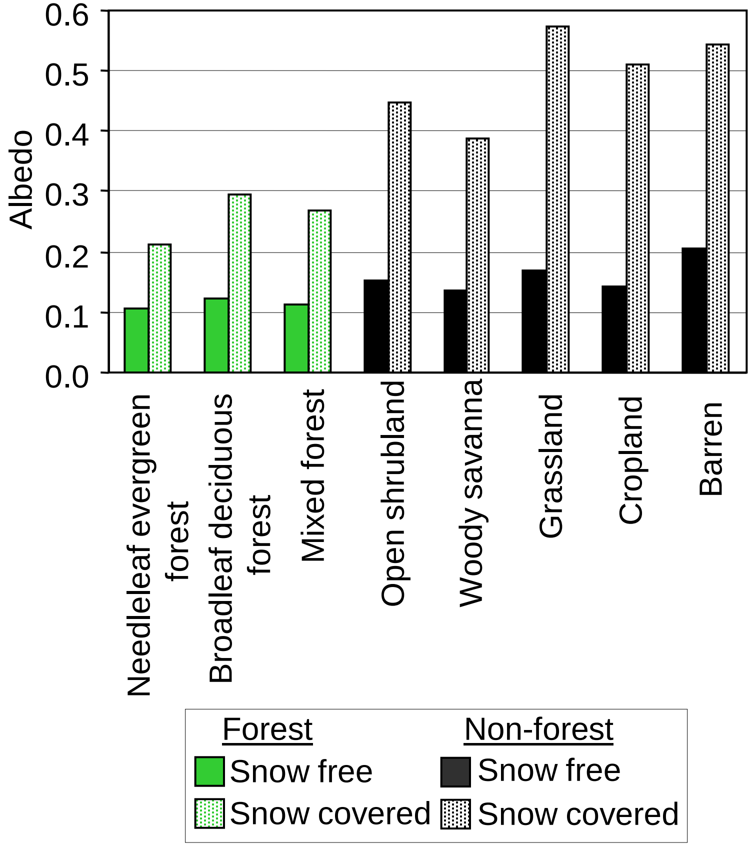
Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*

Vegetation masking of snow albedo

Forests have lower albedo during winter than other snow-covered land

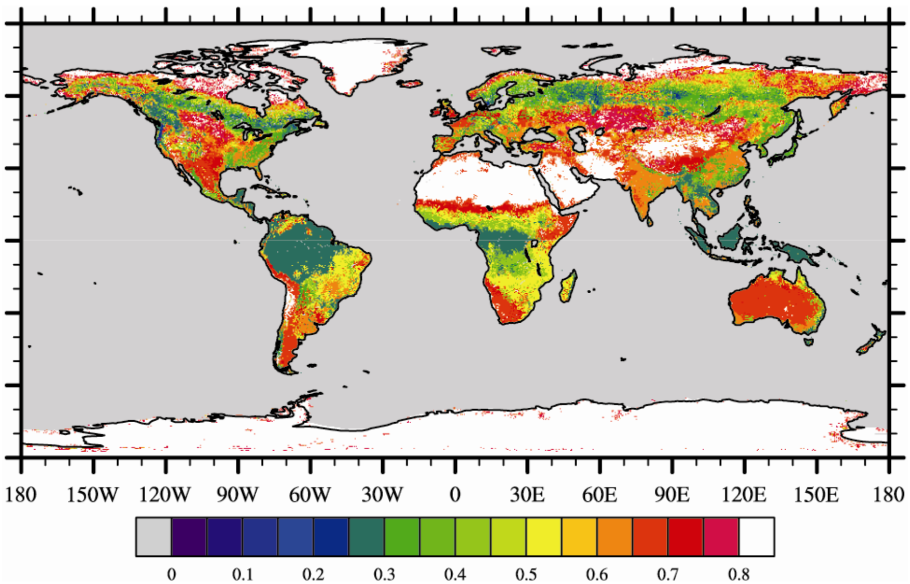
Broadband direct beam albedo (40° N and 50° N)



Jin et al. (2002) GRL, 29, doi:10.1029/2001GL014132

Colorado Rocky Mountains

Maximum albedo snow-covered land



Barlage et al. (2005) GRL, 32, doi:10.1029/2005GL022881

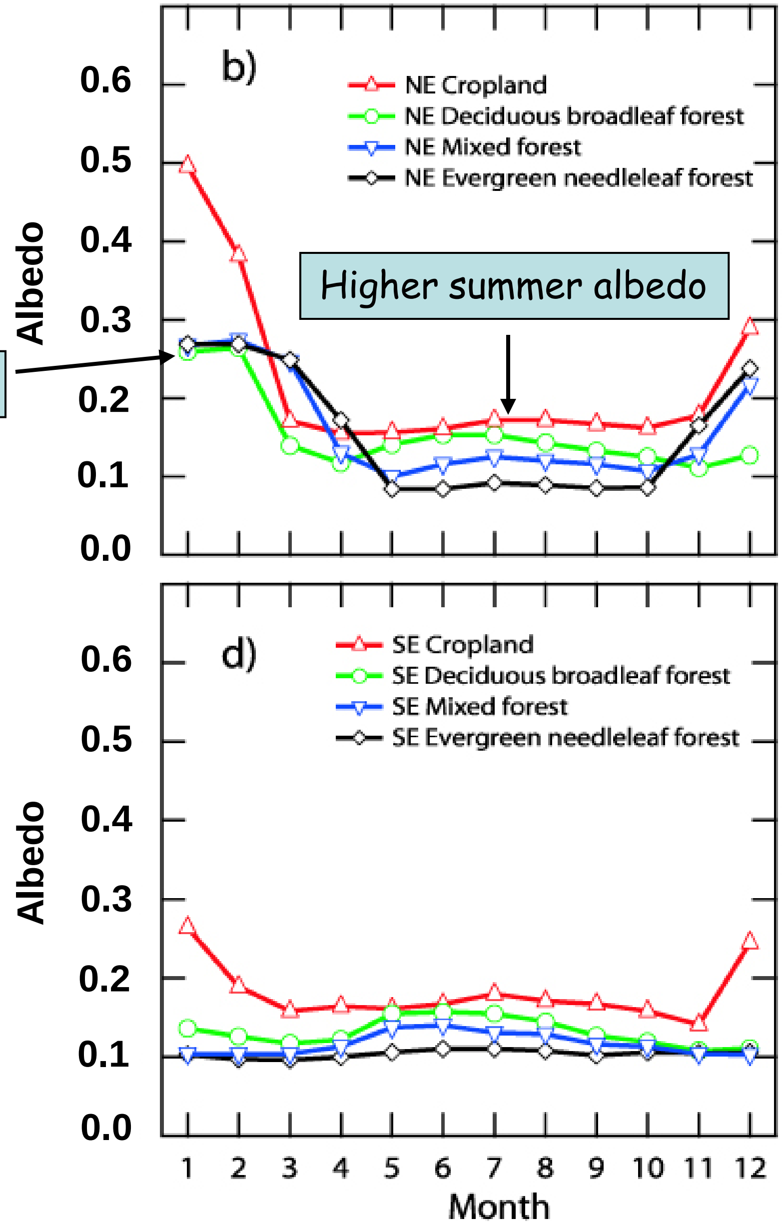
Cropland increases surface albedo

Monthly shortwave surface albedo for dominant US land cover types in the Northeast (b) and Southeast (d)

Jackson et al. (2008) Environ Res Lett, in press

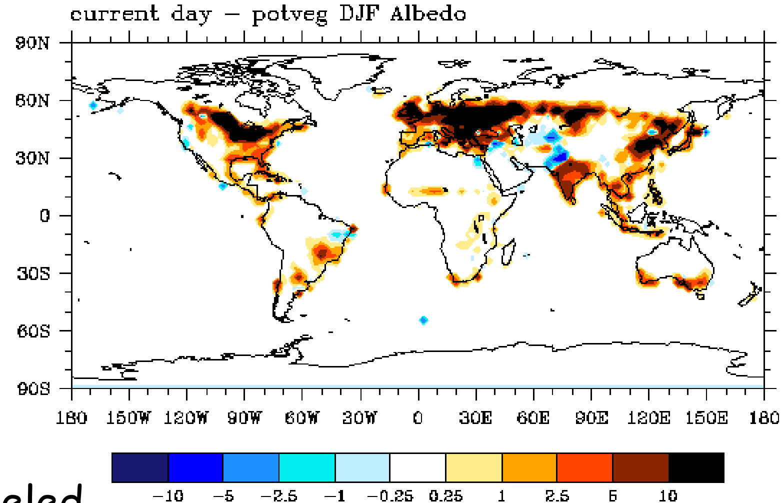
Forest masking

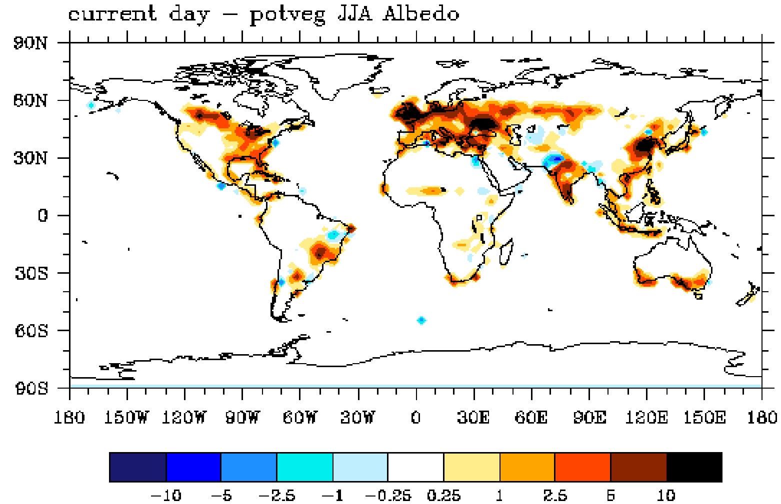
Cropland has a high winter and summer albedo compared with forest



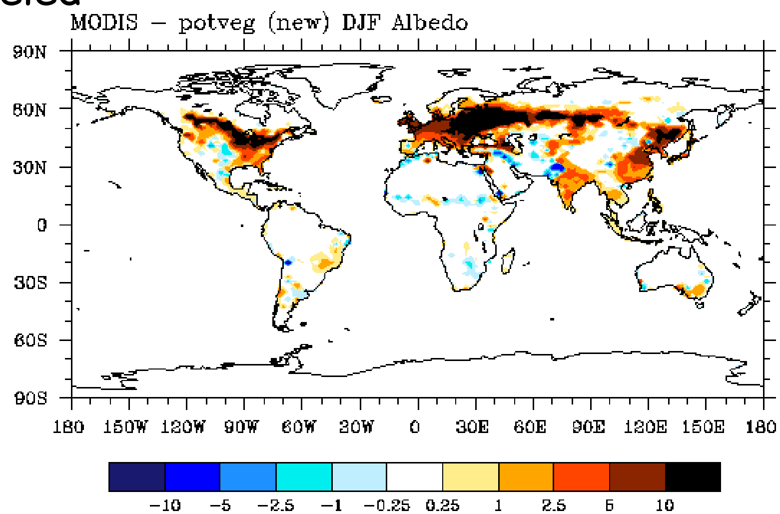
Albedo land use forcing

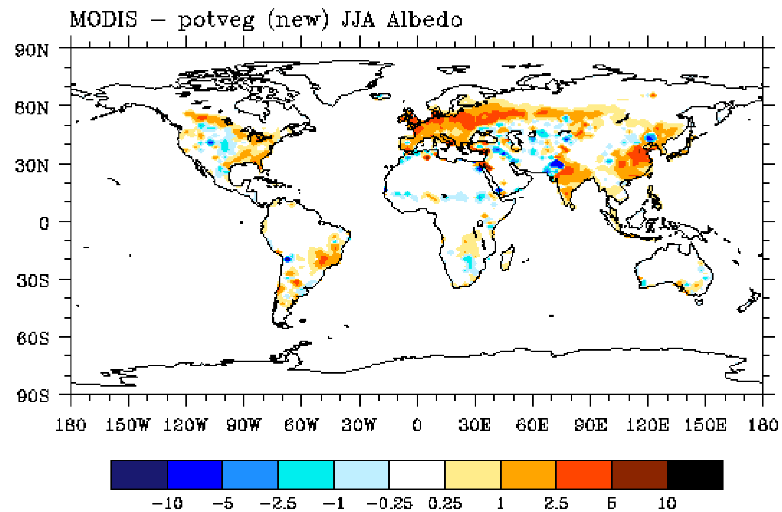
Expected





Modeled





Units are Δalbedo $\times$ 100

Peter Lawrence (NCAR), unpublished

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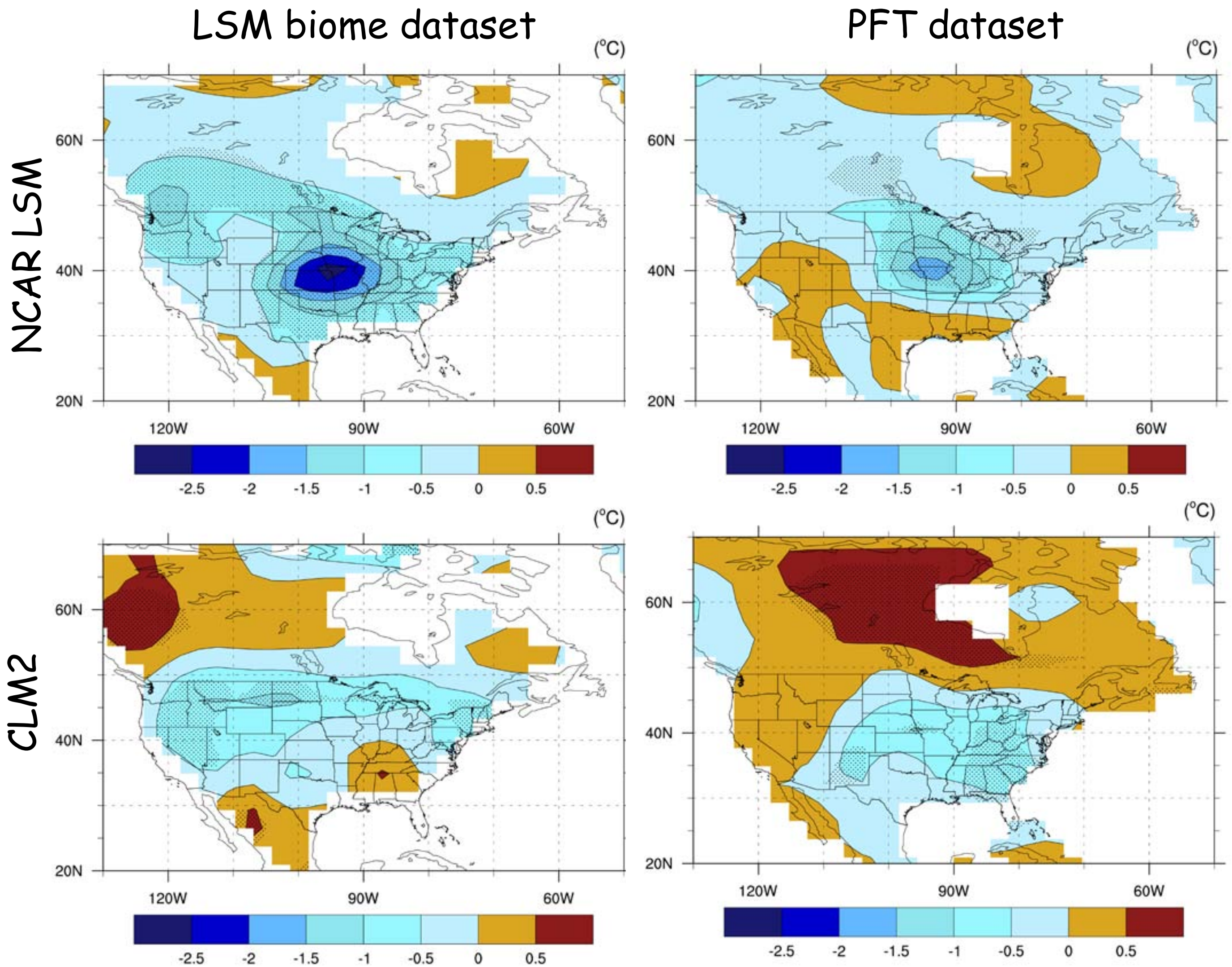
Temperate deforestation cools climate

Summer air temperature difference (present day – natural vegetation)



Four paired climate simulations with CAM2 using two land surface models

- NCAR LSM
- CLM2

and two surface datasets

- Biome dataset without subgrid heterogeneity
- Dataset of plant functional types with subgrid heterogeneity

Conclusion
Magnitude of cooling associated with croplands is sensitive to surface datasets and model physics

Oleson et al. (2004) Climate Dynamics 23:117-132

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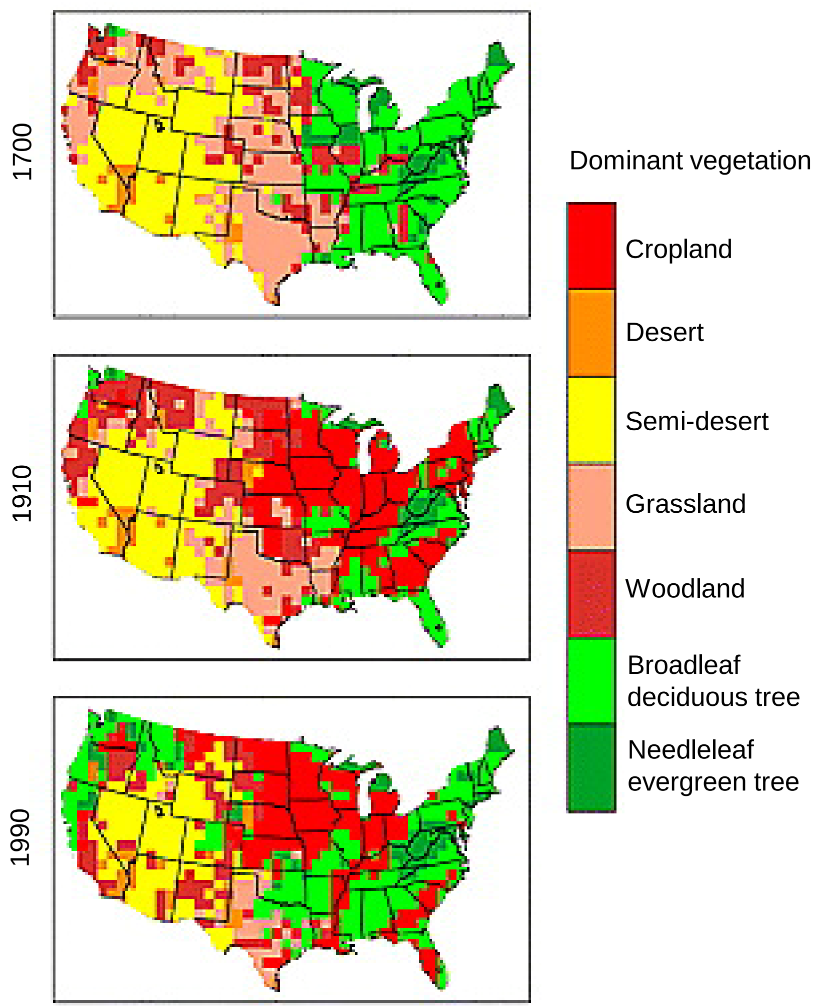
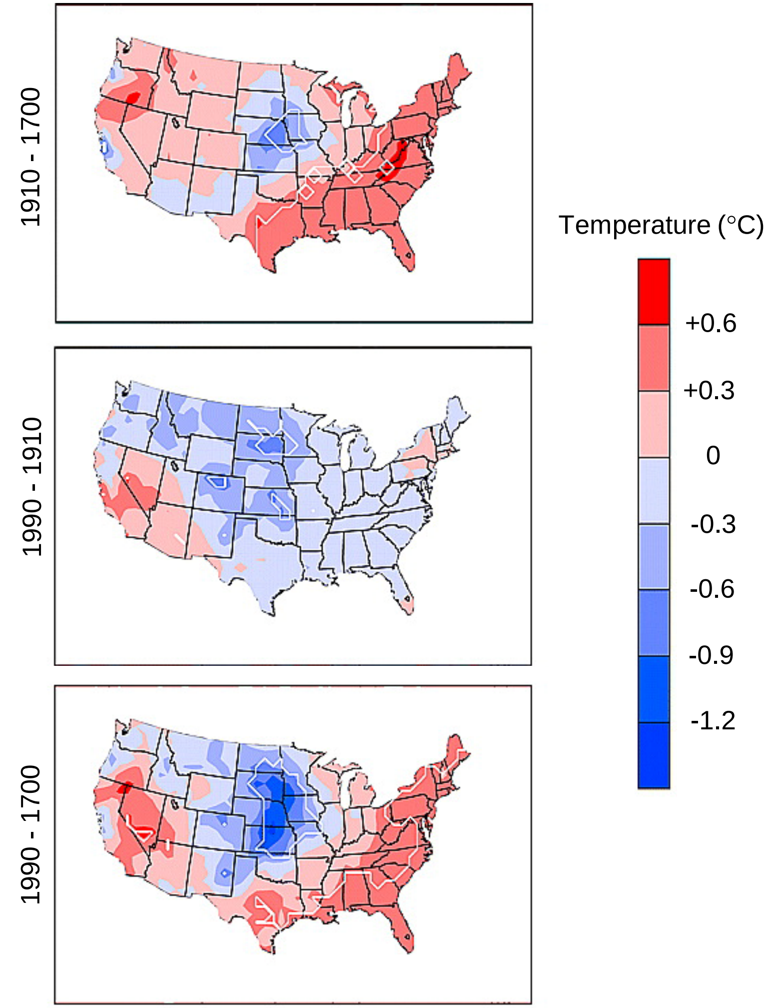
Temperate deforestation warms climate

Regional climate model
RAMS with LEAF-2

Land cover



July temperature difference

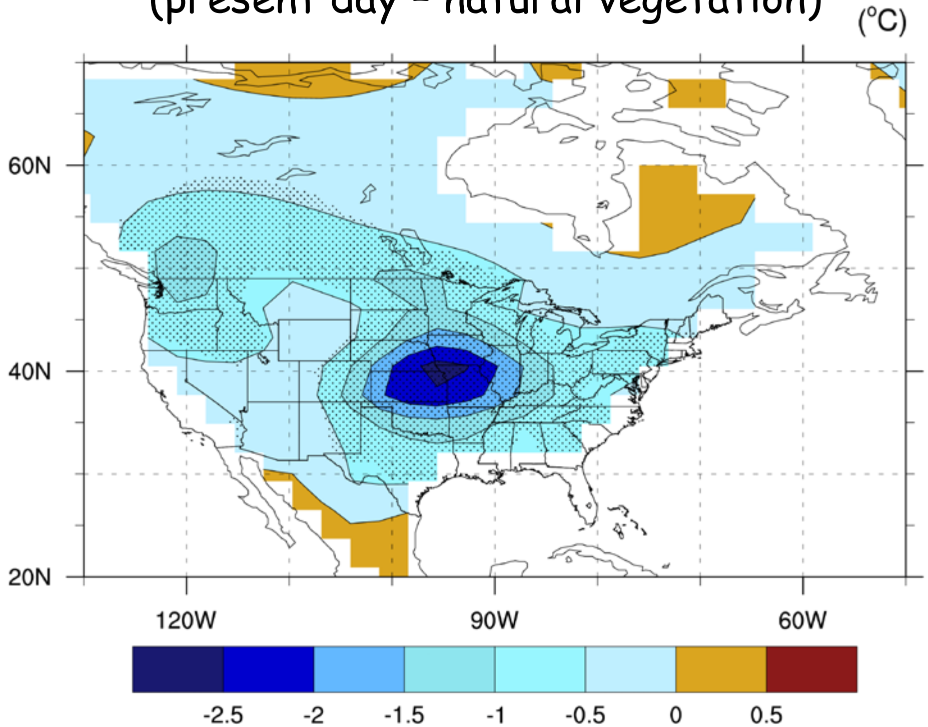


Grass → crop: Increased ET
Forest → crop: Increased albedo, reduced z0, reduced ET (rooting depth)

Baidya Roy et al. (2003) JGR, 108, doi:10.1029/2003JD003565

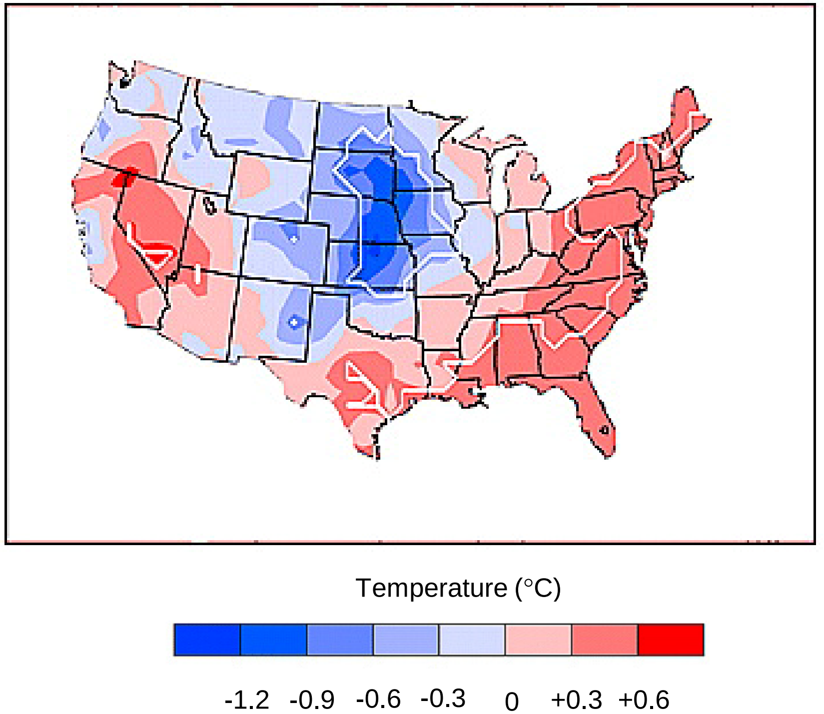
Temperate deforestation – two views

Summer (JJA) temperature difference
(present day – natural vegetation)



Oleson et al. (2004) Climate Dynamics 23:117-132

July temperature difference
(1990 – 1700)

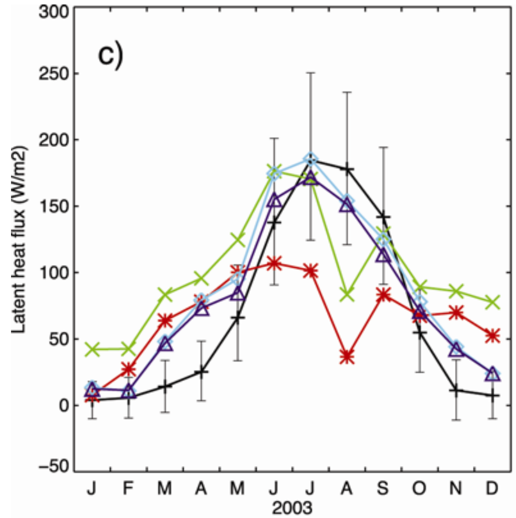


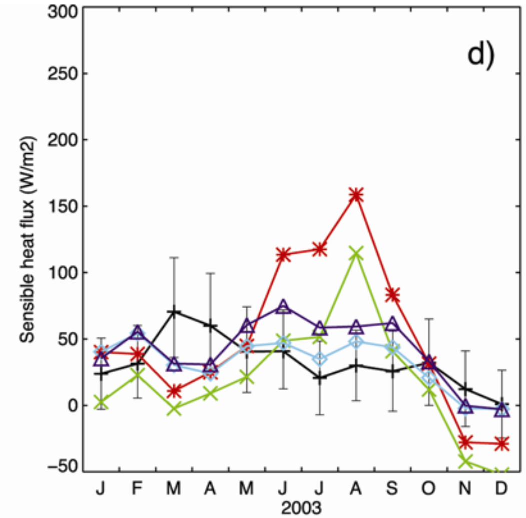
Baidya Roy et al. (2003) JGR, 108, doi:10.1029/2003JD003565

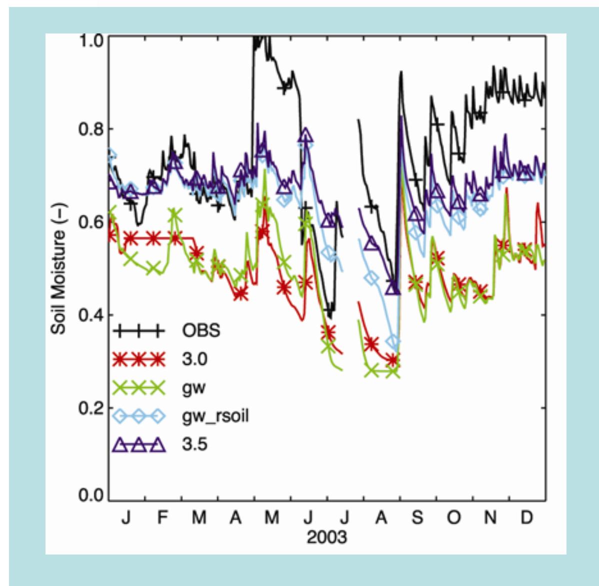
Two contrasting model-generated hypotheses of how deforestation affects climate

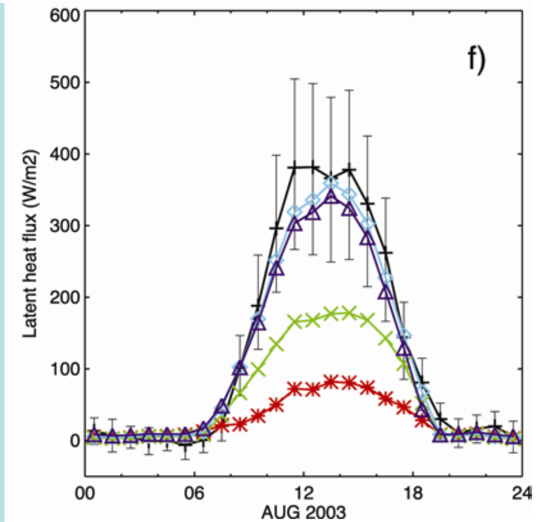
Flux tower measurements

Morgan Monroe State Forest, Indiana





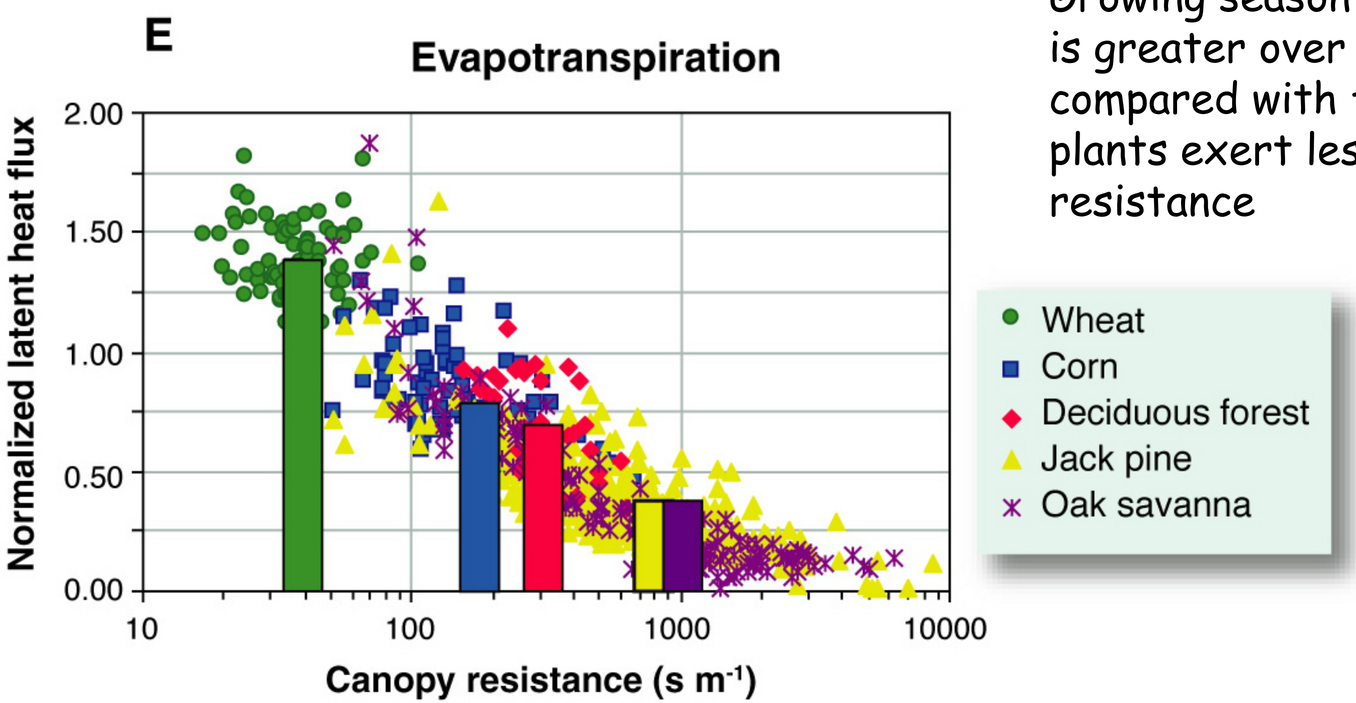




CLM3 – dry soil, low latent heat flux, high sensible heat flux
CLM3.5 – wetter soil and higher latent heat flux

Stöckli et al. (2008) JGR, 113, doi:10.1029/2007JG000562

Crop latent heat flux



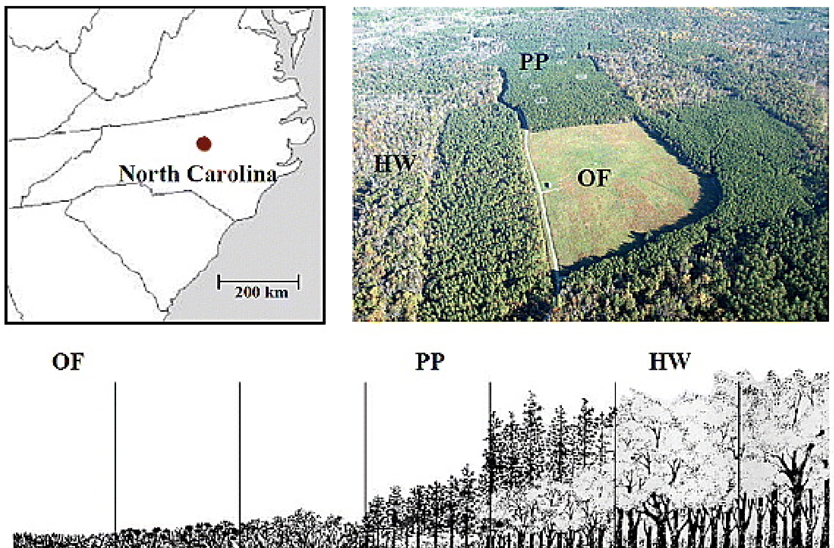
Bonan (2008) Science 320:1444-1449

Growing season evaporative cooling is greater over watered crops compared with forests and these plants exert less evaporative resistance

Evapotranspiration normalized by its equilibrium rate in relation to canopy resistance for wheat, corn, temperate deciduous forest, boreal jack pine conifer forest, and oak savanna. Shown are individual data points and the mean for each vegetation type.

Original data from: Baldocchi et al. (1997) JGR 102D:28939-51; Baldocchi & Xu (2007) Adv. Water Resour. 30:2113-2122

Reforestation cools climate



(http://www.nicholas.duke.edu/forest/forest/succession.htm)

Annual mean temperature change

	OF to PP	OF to HW
Albedo	+0.9°C	+0.7°C
Ecophysiology and aerodynamics	-2.9°C	-2.1°C

Forest
- Lower albedo (+)
- Greater leaf area index, aerodynamic conductance, and latent heat flux (-)

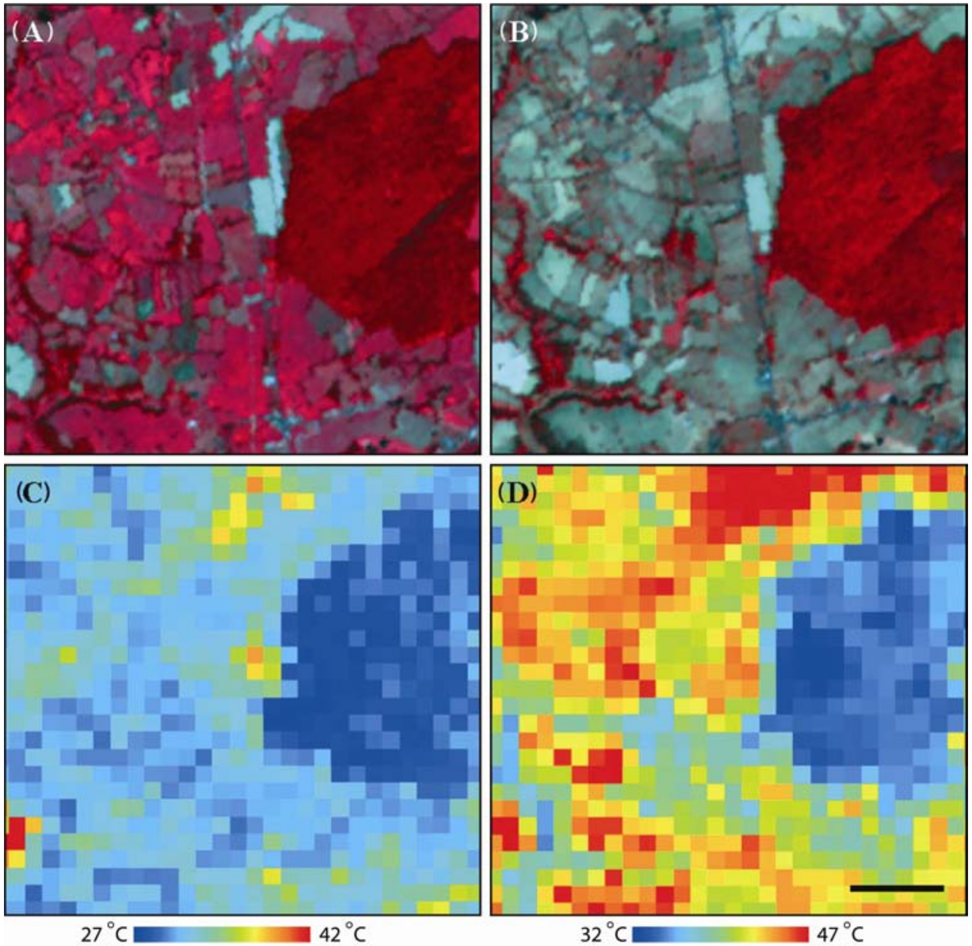
Juang et al. (2007) GRL, 34, doi:10.1029/2007GL031296

Soil water affects the Δforest-crop

Central France

1 August 2000 — 10 August 2003

Surface reflectance



Surface temperature

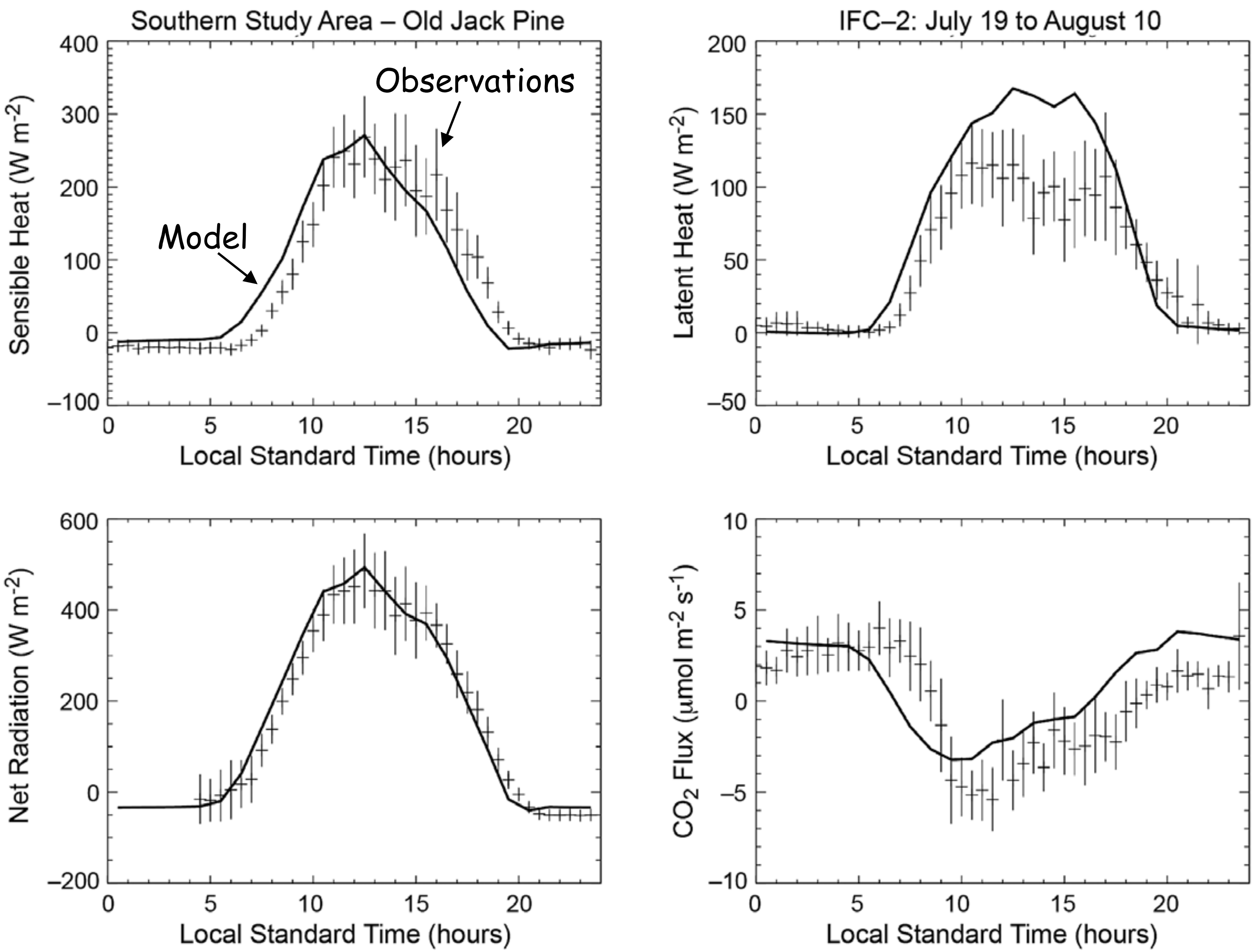
	2000	2003	Change
Forest			
NDVI	0.87	0.87	0
Albedo	0.19	0.17	-0.02
T_R (°C)	29	40	+11
Crops			
NDVI	0.81	0.43	-0.37
Albedo	0.22	0.22	0
T_R (°C)	30	54	+24
Barren			
NDVI	0.27	0.29	+0.02
Albedo	0.24	0.22	-0.02
T_R (°C)	47	58	+11

Scale bar indicates 500 m

Zaitchik et al. (2006) Int J Climatol 26:743-769

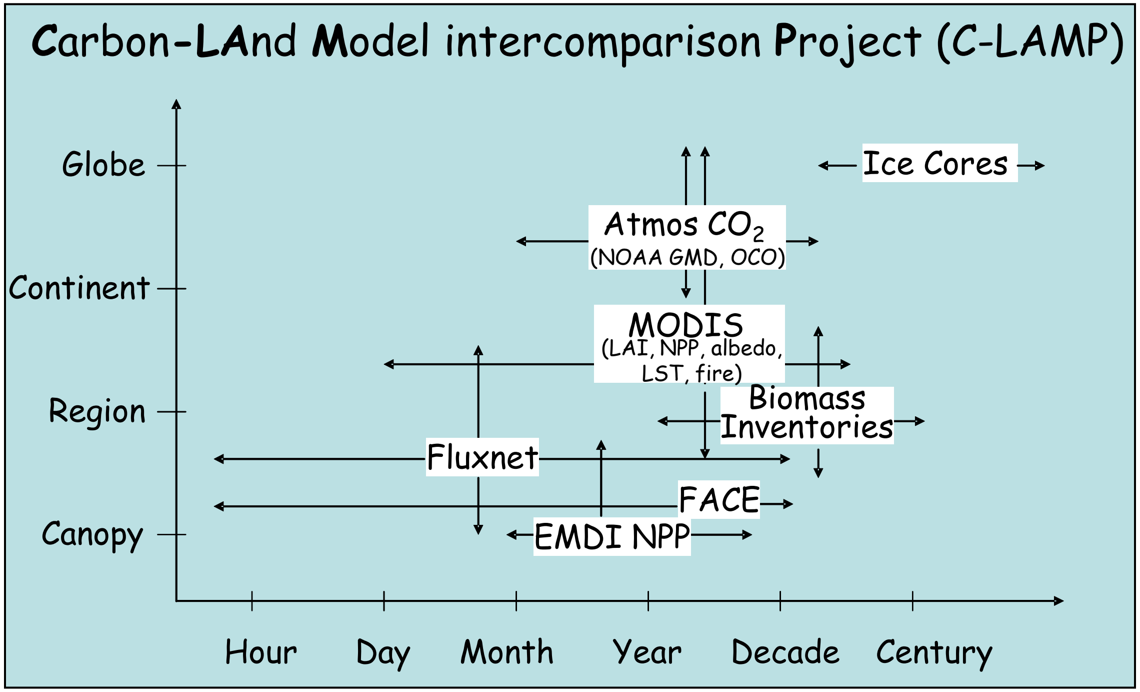
Carbon model validation with tower fluxes

Boreal Ecosystem Atmosphere Study (BOREAS)



Bonan et al. (1997) JGR 102D:29065-75

Multi-scale carbon cycle evaluation



"Systematic assessment of terrestrial biogeochemistry in coupled climate-carbon models"

James T. Randerson, Forrest M. Hoffman, Peter E. Thornton, Natalie M. Mahowald, Keith Lindsay, Yen-Hui Lee, Cynthia D. Nevison, Scott C. Doney, Gordon Bonan, Reto Stocki, Steven W. Running, and Inez Fung

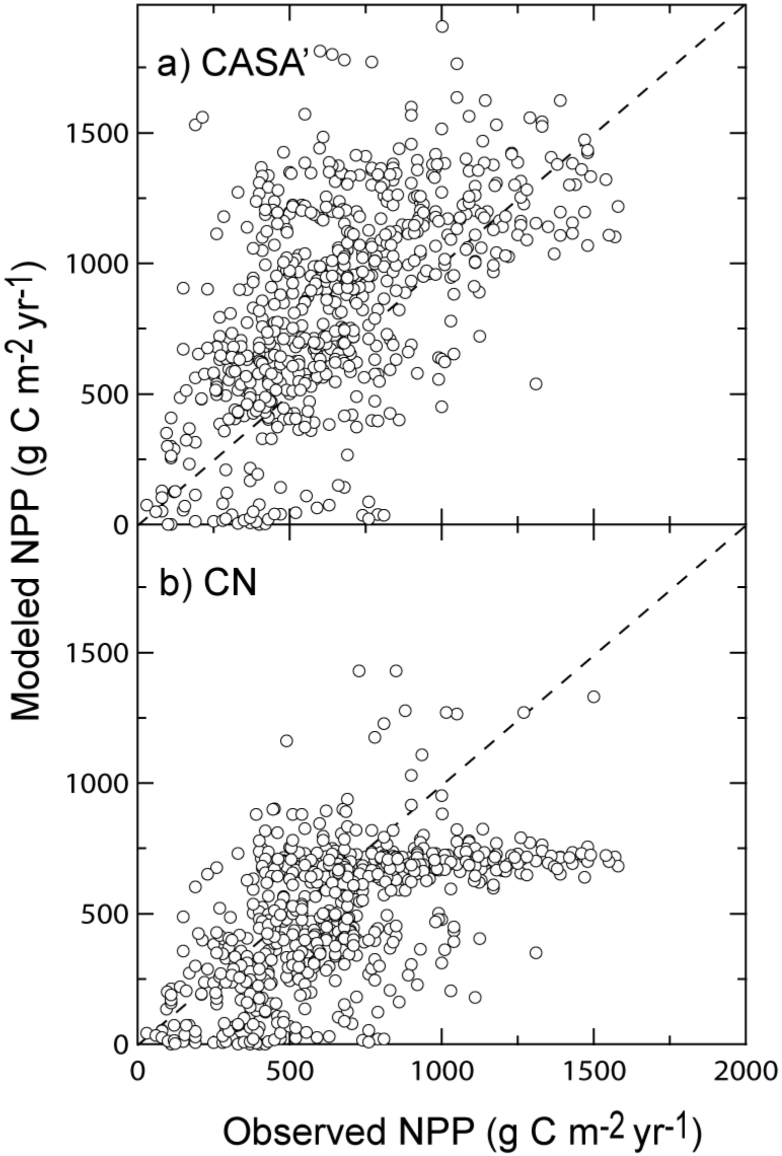
Submitted to Global Change Biology

Annual net primary production

Ecosystem Model-Data Intercomparison (EMDI) compilation of observations

- Class A (81 sites)
- Class B (933 sites)

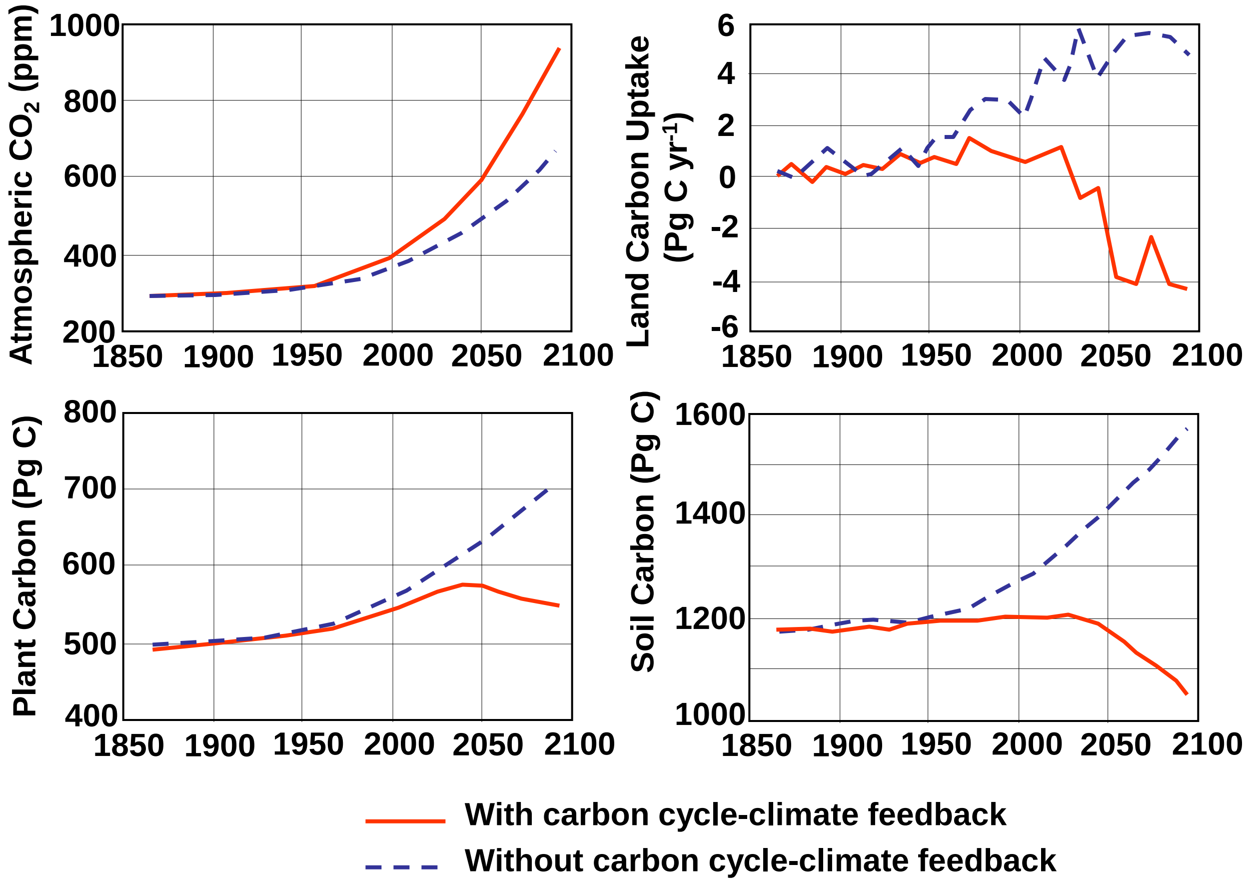
NPP extracted for each model grid cell corresponding to a measurement location



Randerson et al. (2008) GCB, submitted

Prevailing modeling paradigm

CO_2 fertilization enhances plant productivity, offset by decreased productivity and increased soil carbon loss with warming

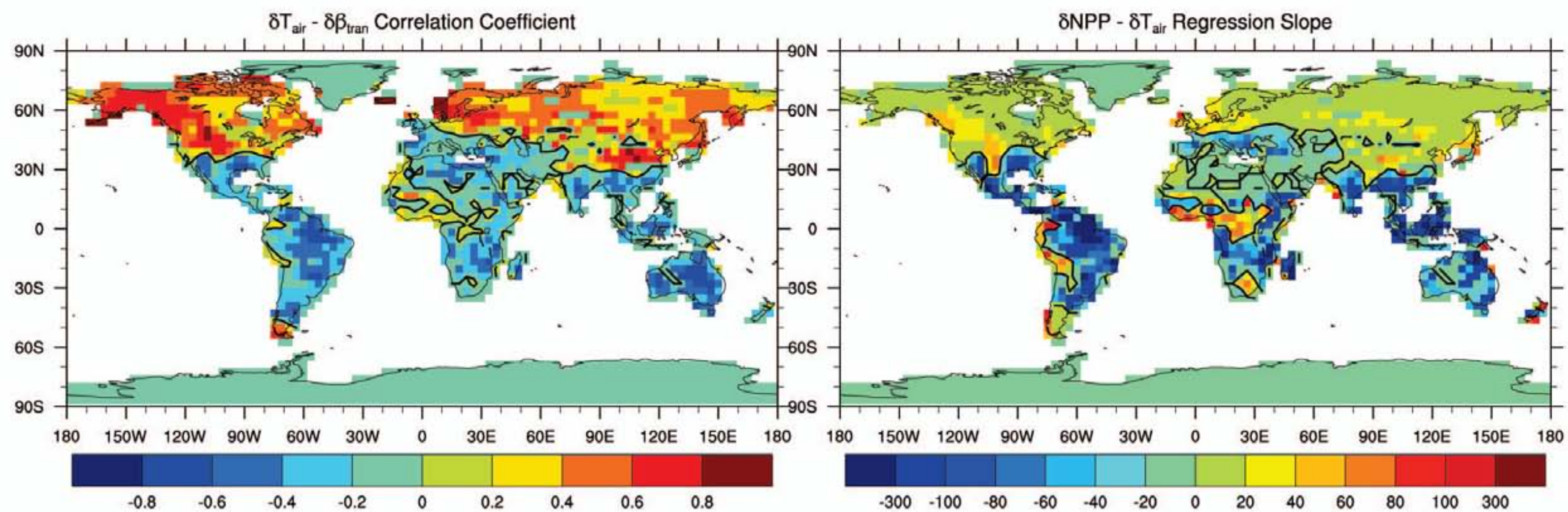


Cox et al. (2004) Theor Appl Climatol 78:137-156

Geography of carbon cycle feedback

Correlation of air temperature with soil moisture

Correlation of NPP with air temperature



Correlation coefficient

kg C m^{-2} yr^{-1} per °C

Low latitudes
Negative correlation: warming leads to drier soil in warm regions

Middle to high latitudes
Positive correlation: warming leads to wetter soil in cold regions

Low latitudes
Negative correlation: NPP decreases with warming because of soil desiccation

Middle to high latitudes
Positive correlation: NPP increases with warming because of more favorable climate

Fung et al. (2005) PNAS 102:11201-11206

N fertilization

Carbon cycle-climate feedback in response to increasing atmospheric CO_2 and warming, with and without nitrogen

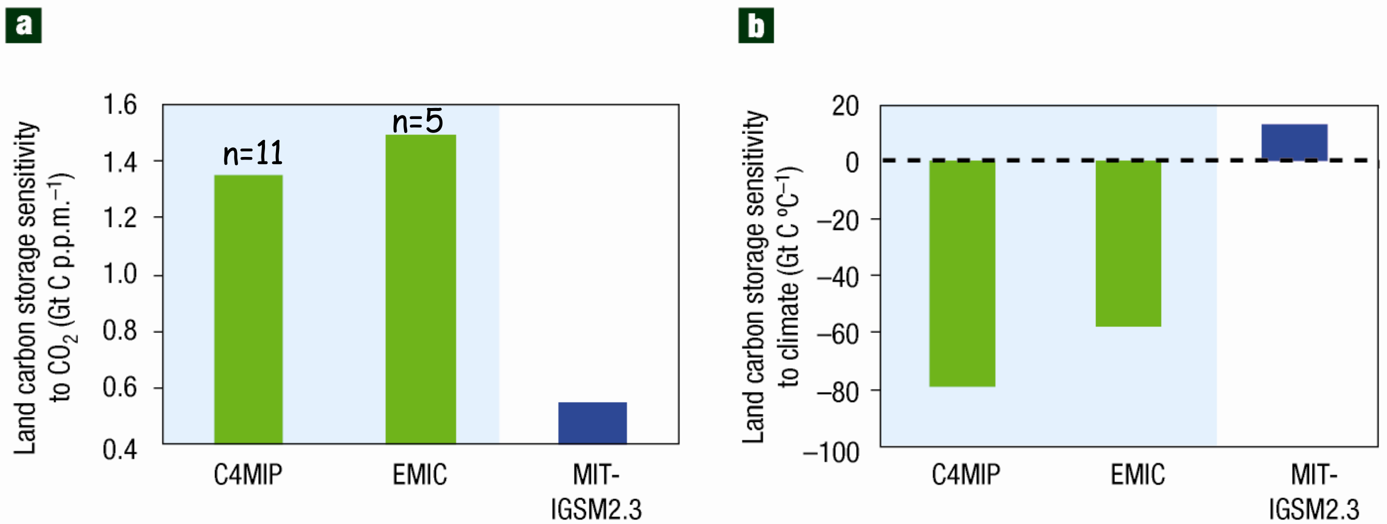
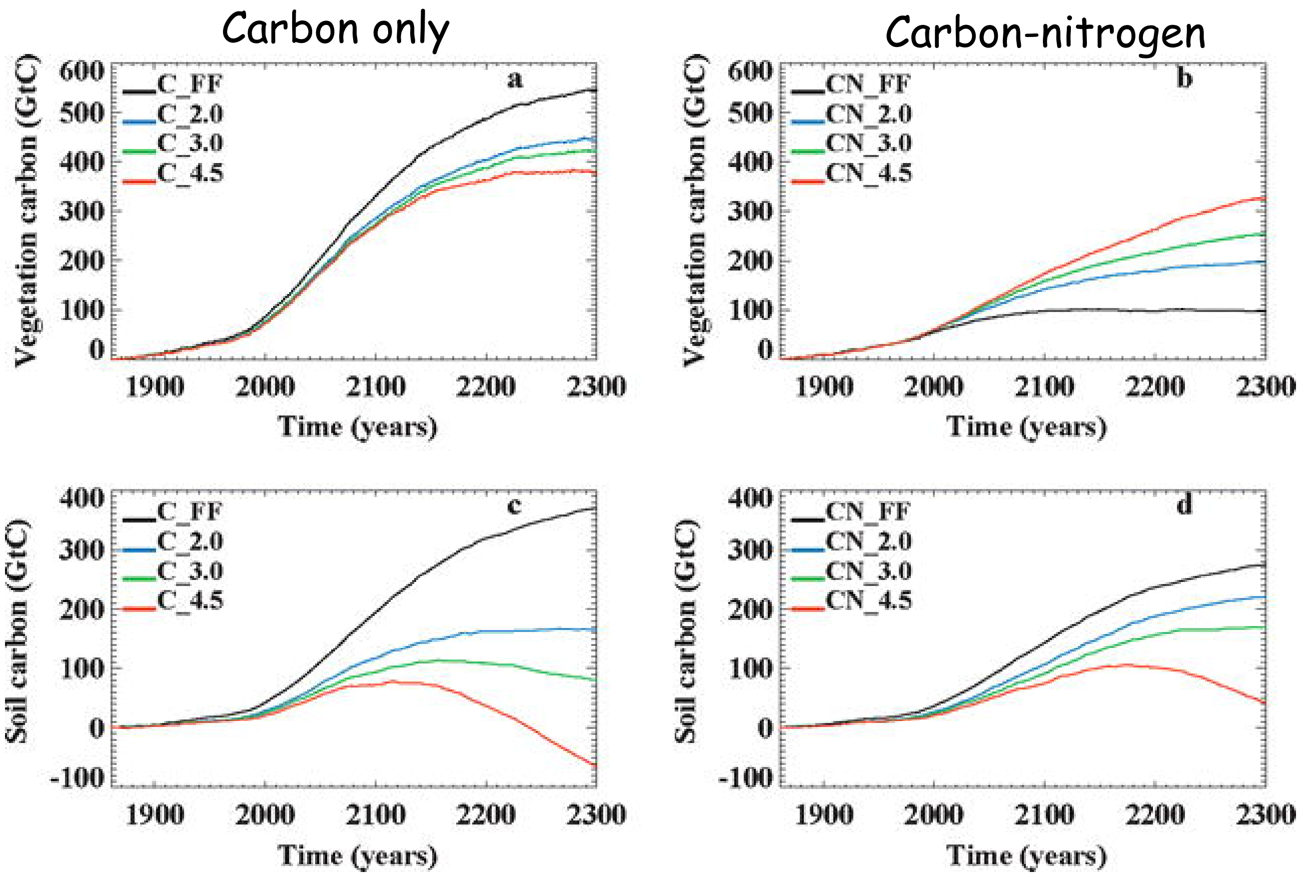


Figure from Bonan (2008) Nature Geoscience 1:645-646

Carbon-nitrogen interactions significantly reduce net terrestrial carbon uptake, even though, at least for small to moderate climate warming, enhanced nitrogen availability stimulates plant growth and changes the sign of the carbon cycle-climate feedback from positive to negative

Sokolov et al. (2008) J Climate 21:3776-3796

N fertilization



- Nitrogen limitation reduces the CO_2 fertilization effect
- Greater N mineralization with warming stimulates plant growth
- Overall, terrestrial carbon sequestration is reduced, but climate warming increases carbon sequestration in a negative, rather than a positive feedback

Sokolov et al. (2008) J Climate 21:3776-3796

NCAR
National Center for Atmospheric Research
Boulder, Colorado

Comparison with FACE experiments

Experiment	Latitude (°N)	CO_2 initial	CO_2 final	CN			CASA'		
				Initial NPP	final NPP	Beta	Initial NPP	final NPP	Beta
DukeFACE	35.6	283.2	364.1	661	733	0.43	1091	1241	0.55
AspenFACE	45.4	283.2	364.1	358	397	0.43	524	595	0.54
ORNL-FACE	35.5	283.2	364.1	828	901	0.35	1090	1248	0.58
POP-EUROFACE	42.2	283.2	364.1	235	253	0.30	397	453	0.56
Mean:						**0.38**			**0.56**

Observed mean β: **0.60**
CN model mean β: **0.38**
CASA′ model mean β: **0.56**

Observed NPP increase (376 -> 550ppm): 23%
CN predicted (376 -> 550ppm): 14%
CASA′ predicted (376 -> 550ppm): 21%

$$\beta = \frac{\left(\frac{NPP(f)}{NPP(i)} - 1\right)}{\ln\left(\frac{CO_2(f)}{CO_2(i)}\right)}$$

$$NPP(t) = NPP(i) \cdot \left[\beta \cdot \ln\left(\frac{CO_2(t)}{CO_2(i)}\right) + 1\right]$$

Randerson et al. (2008) GCB, submitted

Integrate ecological studies with earth system models

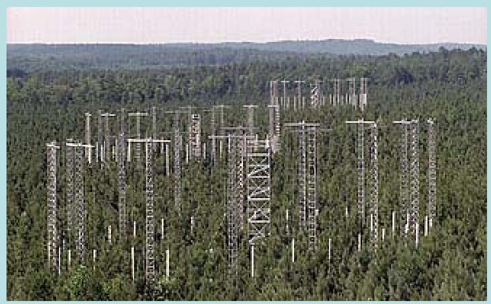
Environmental Monitoring

Eddy covariance flux tower
(courtesy Dennis Baldocchi)

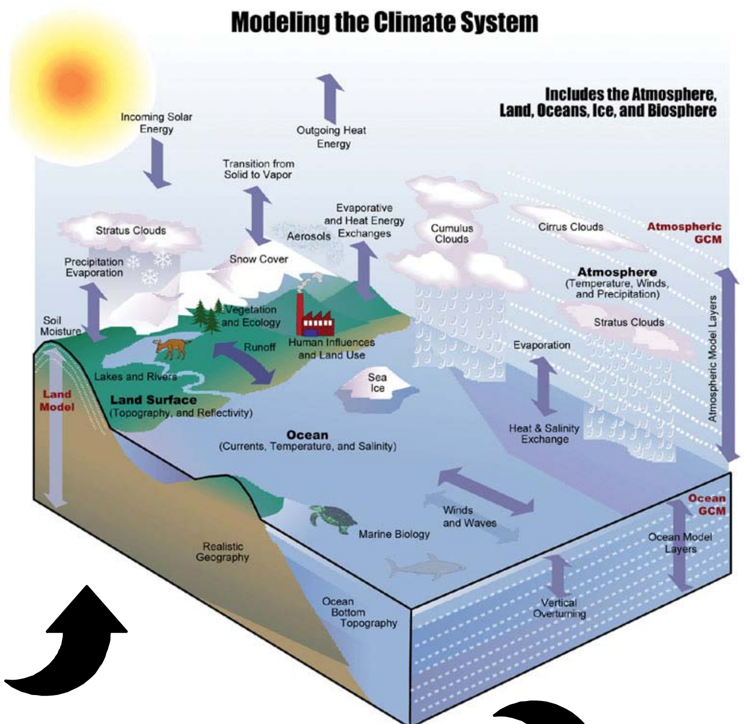
Hubbard Brook
Ecosystem Study

Experimental Manipulation

Soil warming, Harvard Forest



CO_2 enrichment, Duke Forest



Planetary energetics
Planetary ecology
Planetary metabolism

Test model-generated hypotheses of earth system functioning with observations

Colonial Americans and forests

Thomas Cole – "View from Mount Holyoke, Northampton, Massachusetts, after a Thunderstorm (The Oxbow)", 1836

Conveys the views Americans at that time felt toward forests. The forest on the left is threatening. The farmland on the right is serene.

American deforestation – Colonial views

"For some years it has been a general remark in the United States, that very perceptible partial changes in the climate took place, which displayed themselves in proportion as the land was cleared" (Constantin-François Volney, 1803)

Plate 5.4. The first six months. (Orsamus Turner, *A Pioneer History of the Holland Purchase of Western New York.*)

Plate 5.5. The second year. (Turner, *Pioneer History of the Holland Purchase.*)

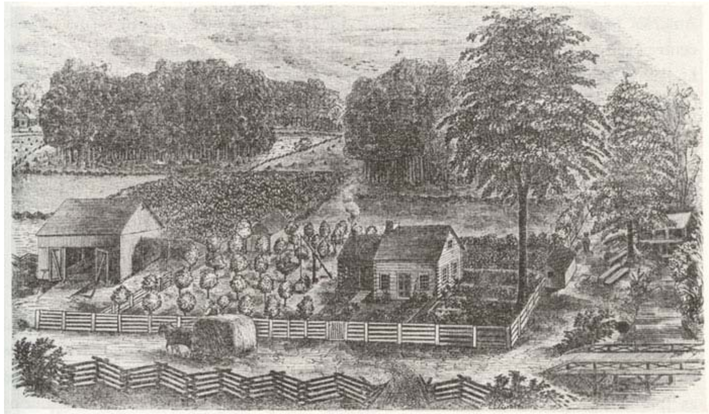


Plate 5.6. Ten years later. (Turner, *Pioneer History of the Holland Purchase.*)

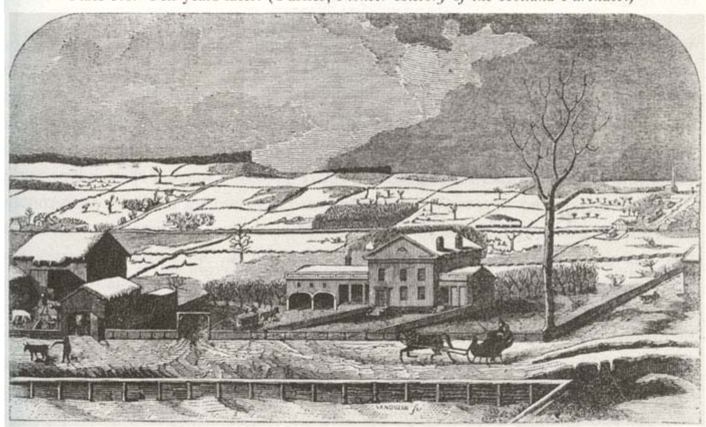


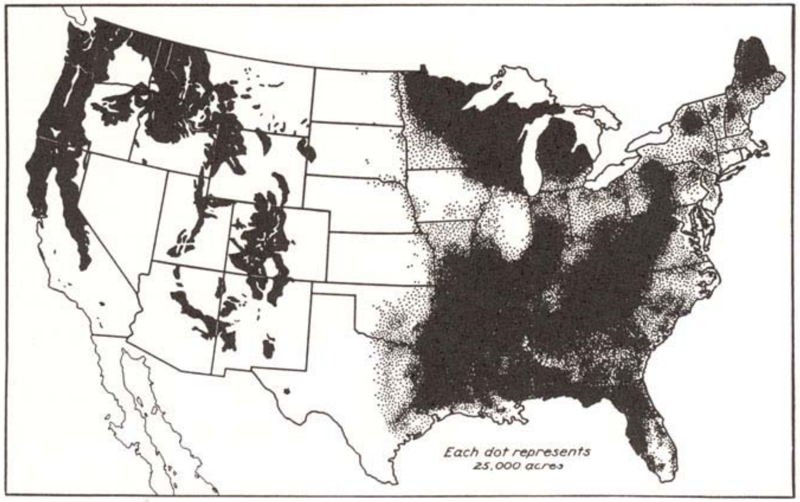
Plate 5.7. The work of a lifetime. (Turner, *Pioneer History of the Holland Purchase.*)

Williams (1989) Americans and their Forests (Cambridge Univ. Press)

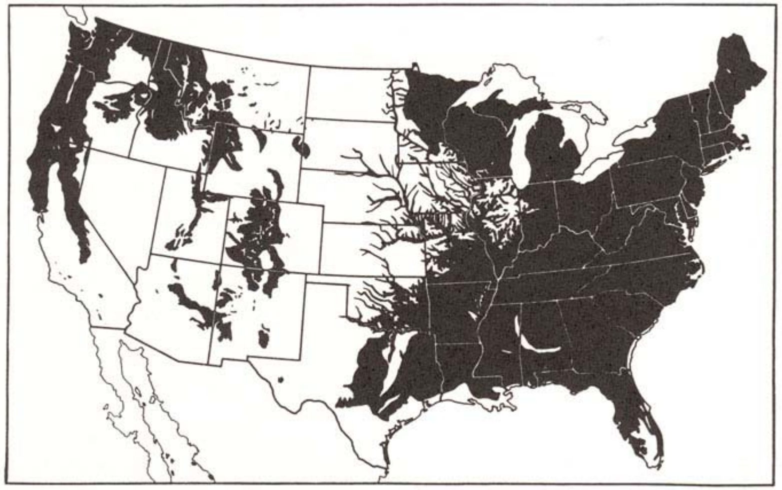
American deforestation – Colonial views

"The statements so frequently advanced, although unsupported by measurements, that since the first European settlements in New England, Pennsylvania, and Virginia, the destruction of many forests on both sides of the Alleghanys [*sic*], has rendered the climate more equable, – making the winters milder and the summers cooler, – are now generally discredited" (Alexander von Humboldt, 1807)

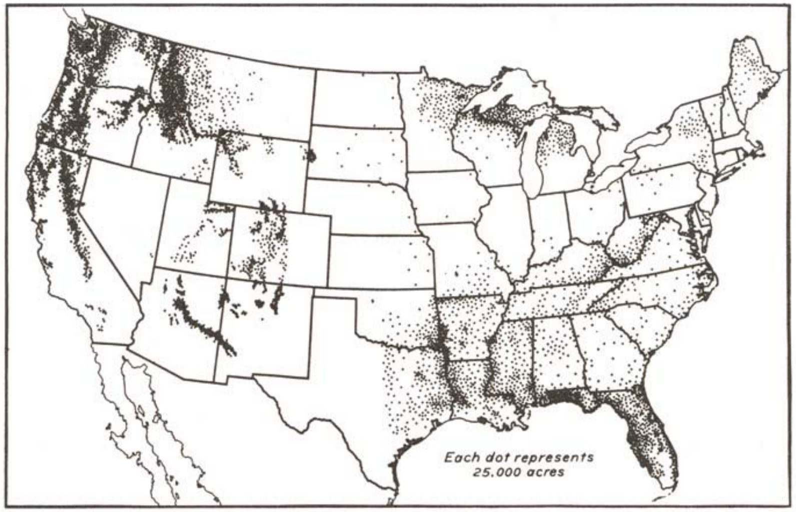
1850



Area of old-growth forest, 1620

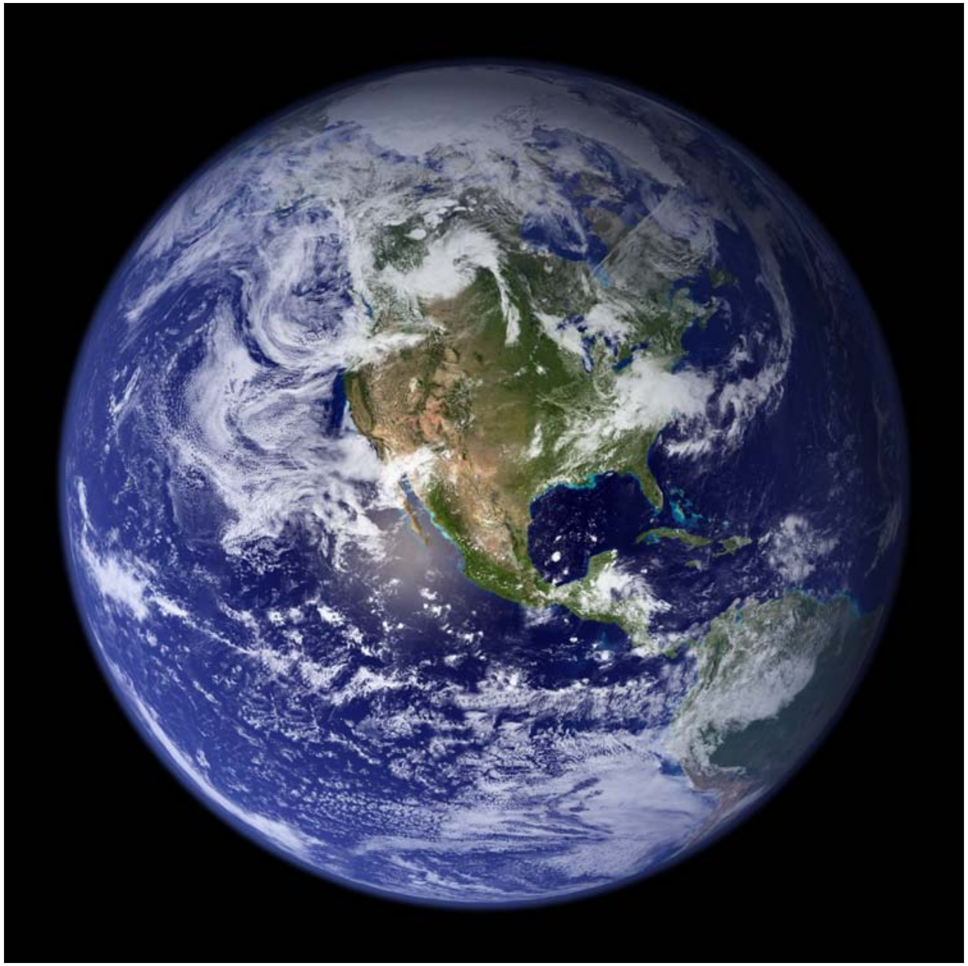


1920



Williams (1989) Americans and their Forests (Cambridge Univ. Press)

Concluding thoughts



(NASA Goddard Space Flight Center)

The picture that has emerged from observational studies and some 20 years of climate-vegetation modeling is that terrestrial vegetation is a crucial determinant of our weather and climate

- Around our homes
- In our towns and cities
- On our planet

We need to recognize the value of vegetation in improving our climate

Landscape design/urban planning – greenspaces

How do we use the science of ecology and meteorology to plan for a sustainable future?