Co-evolution of Climate and Life

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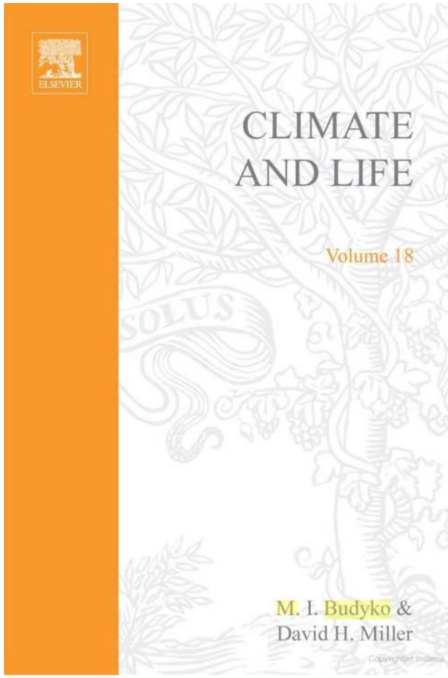
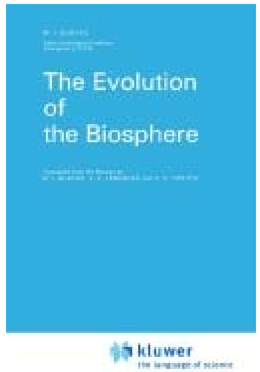
Thomas Cole – "View from Mount Holyoke, Northampton, Massachusetts, after a Thunderstorm (The Oxbow)", 1836

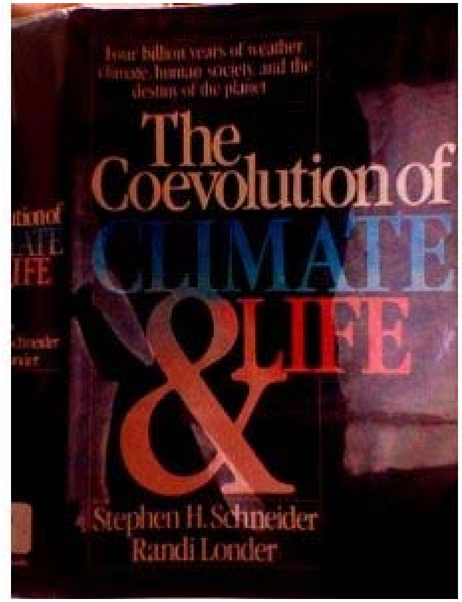
NCAR is sponsored by the National Science Foundation

A compelling topic …

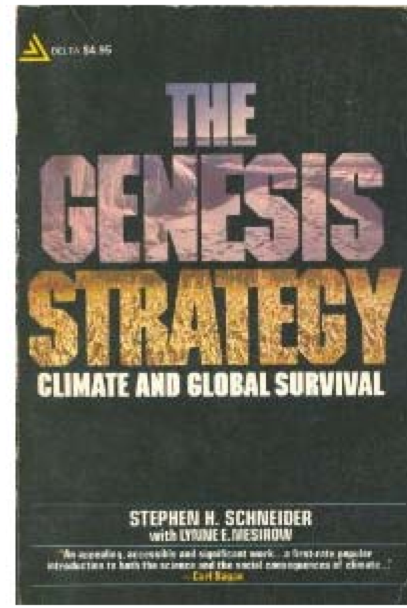


Mikhail Budyko

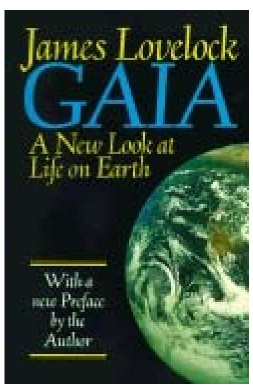


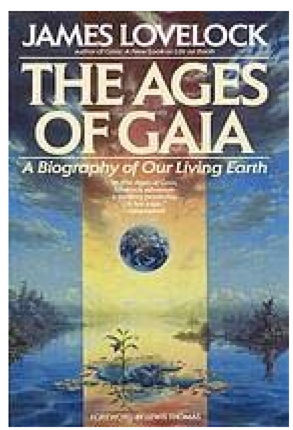


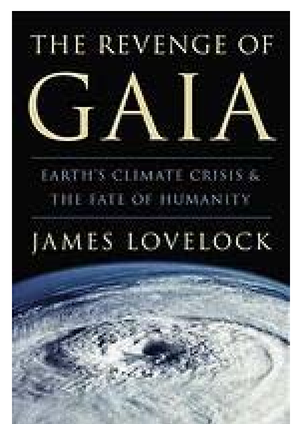
Stephen Schneider



James Lovelock







Outline of talk

1. Introduction

2. Key ecosystem processes that affect climate
   Albedo, evapotranspiration, carbon-nitrogen biogeochemistry

3. Paleoclimate examples
   Boreal forest, North Africa

4. Anthropogenic climate change (20th and 21st centuries)

5. Earth system models

6. Carbon cycle and climate
   Concentration–carbon feedback (CO_2 fertilization)
   Climate–carbon feedback (temperature)
   Nitrogen cycle

7. Land use and land cover change

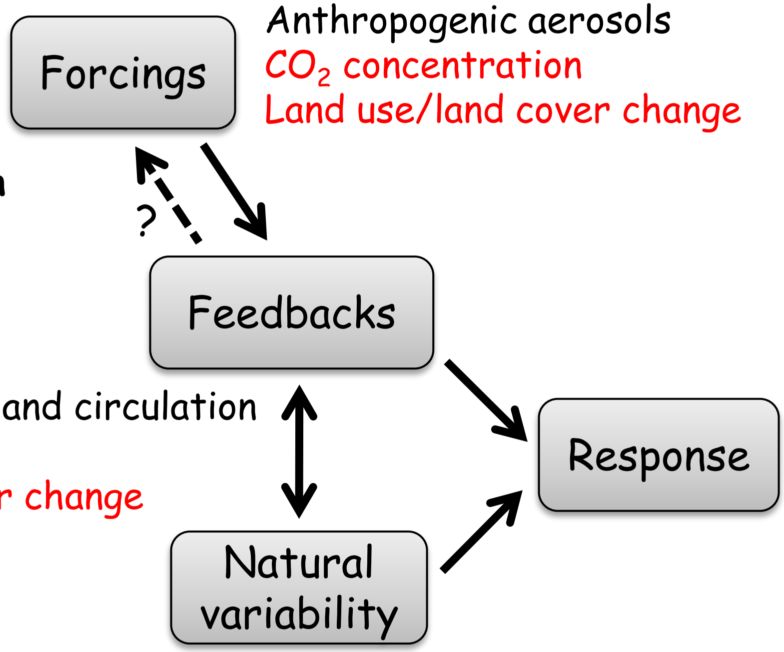
7a. Biogeochemical	*7b. Biogeophysical*
Land use carbon flux	Albedo and evapotranspiration

8. Conclusions

Understanding Earth's climate system

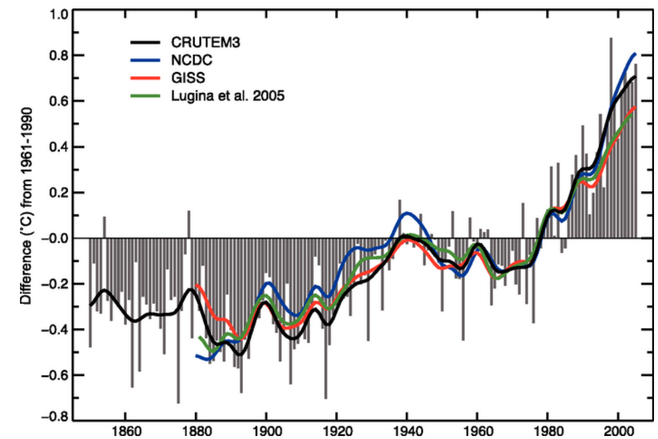
External drivers of system change
Solar irradiance
Volcanic aerosols
Anthropogenic aerosols
CO_2 concentration
Land use/land cover change

Amplify or dampen system response
Water vapor
Clouds
Ice albedo
Ocean heat uptake and circulation
Carbon cycle
Land use/land cover change

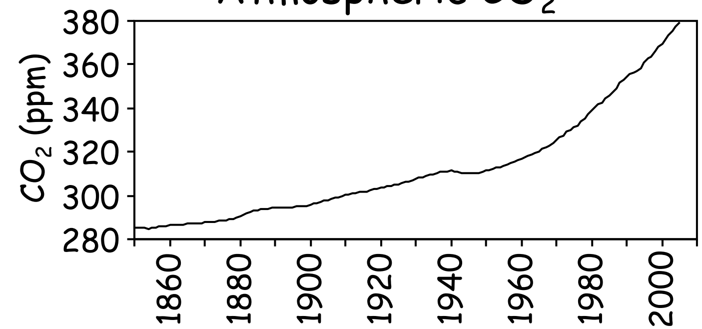


El Niño-Southern Oscillation

Global temperature

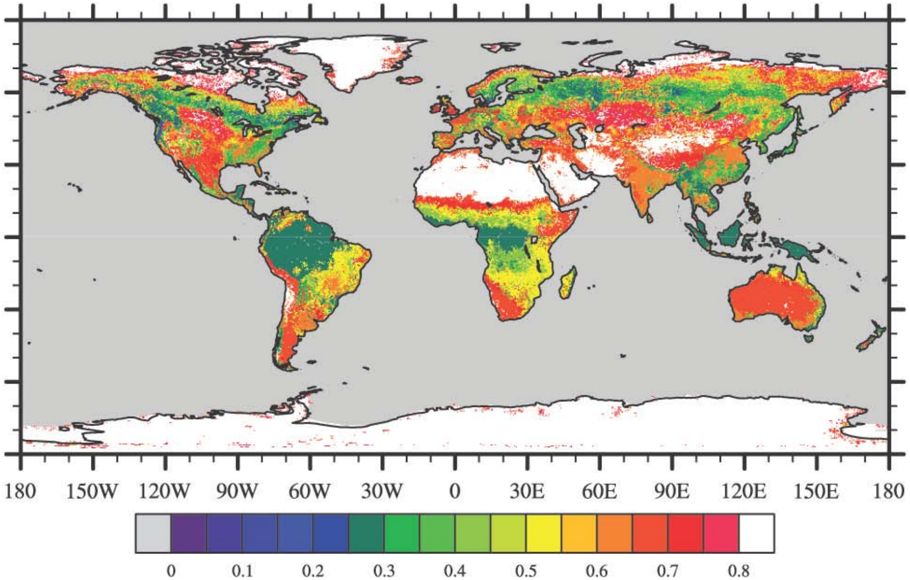


Atmospheric CO_2



Surface albedo

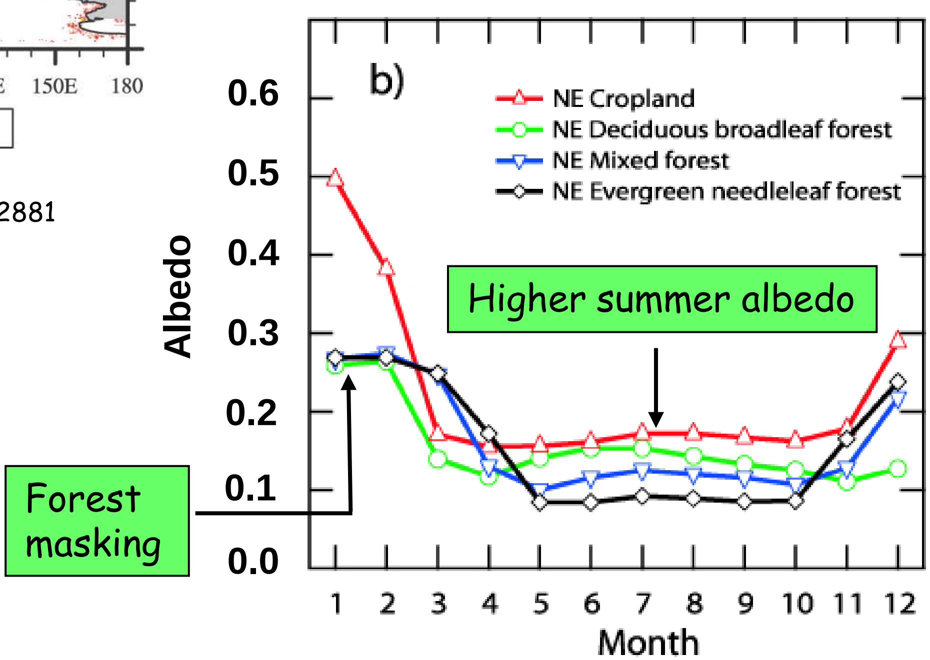
Maximum snow-covered albedo



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

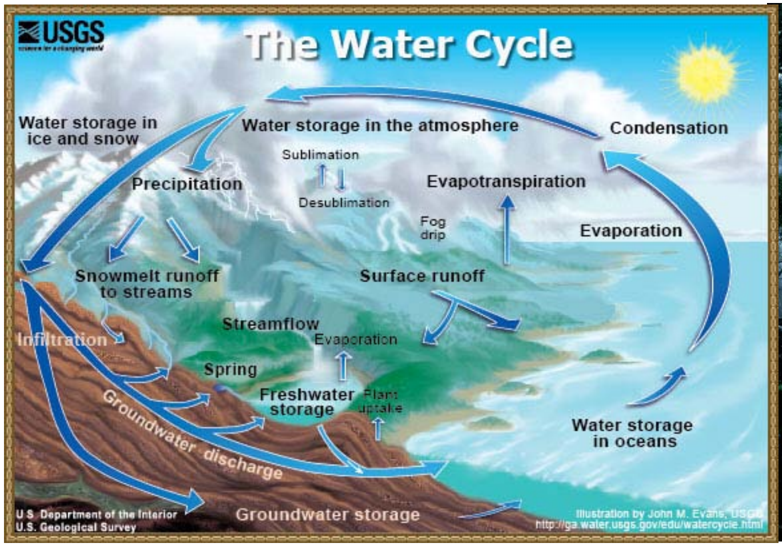
- Albedo varies among vegetation
- Higher albedo = less solar radiation absorbed at surface

Monthly surface albedo by land cover type in NE US



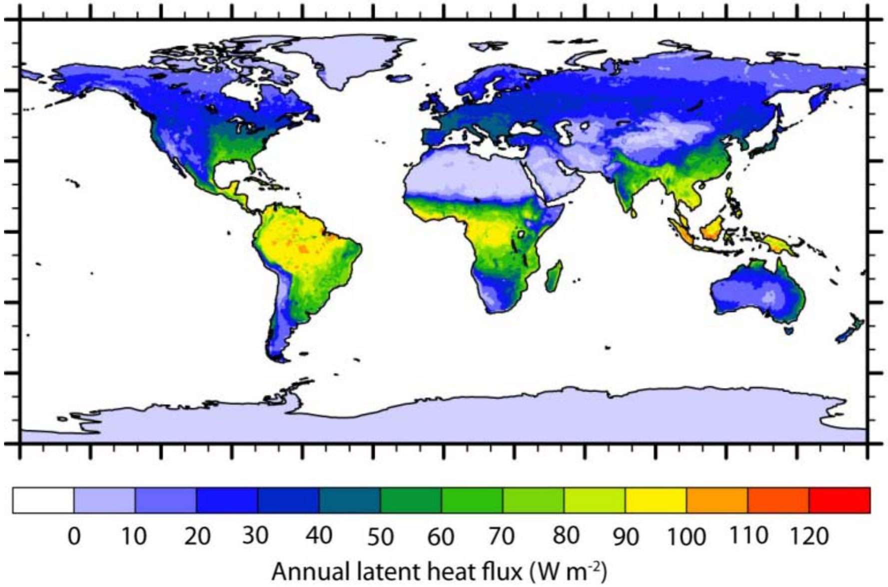
Jackson et al. (2008) Environ Res Lett, 3, 044006 (doi:10.1088/1748-9326/3/4/044006)

Evapotranspiration



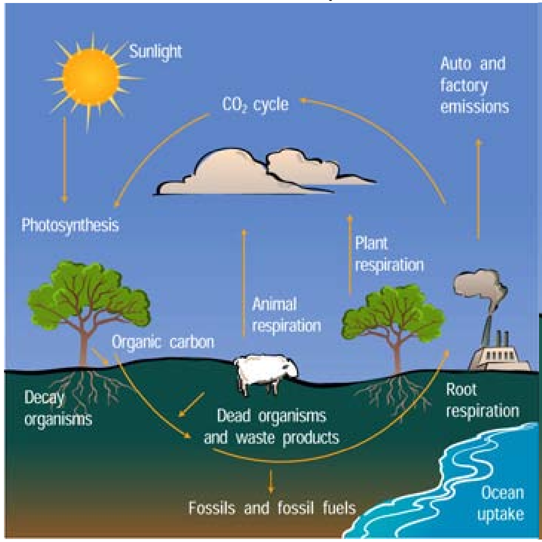
- ET varies among vegetation
- High ET cools surface climate locally
- But ET contributes water vapor (greenhouse gas)

Annual evapotranspiration

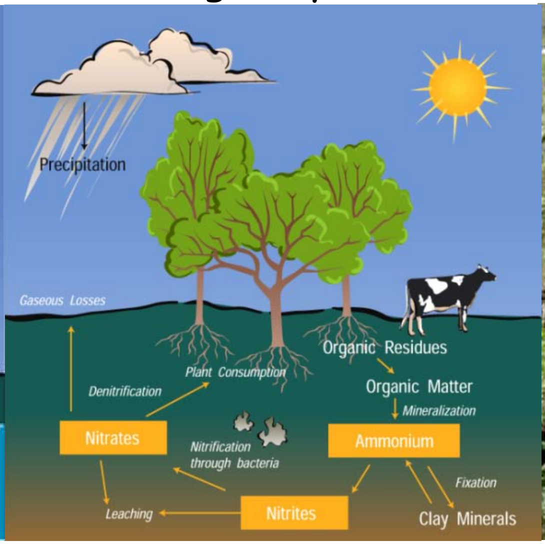


Biogeochemical cycles

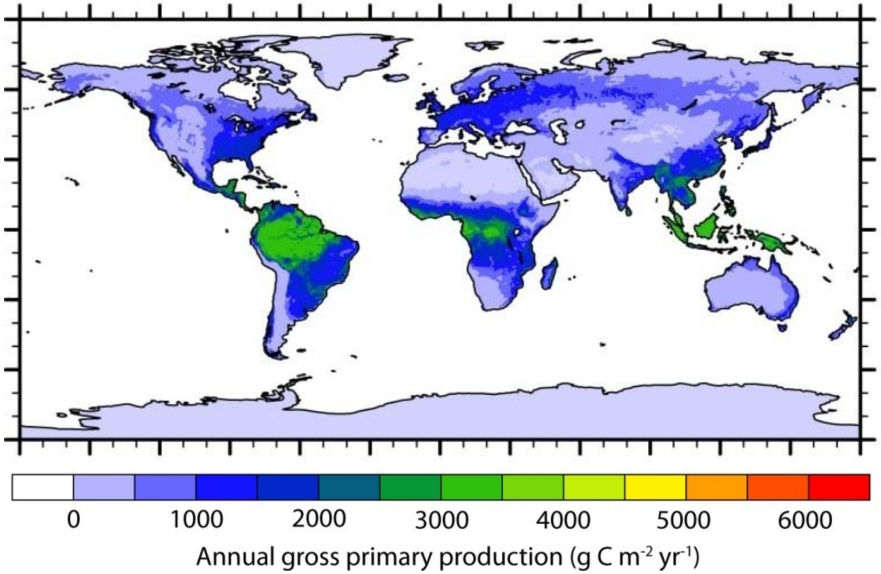
Carbon cycle



Nitrogen cycle



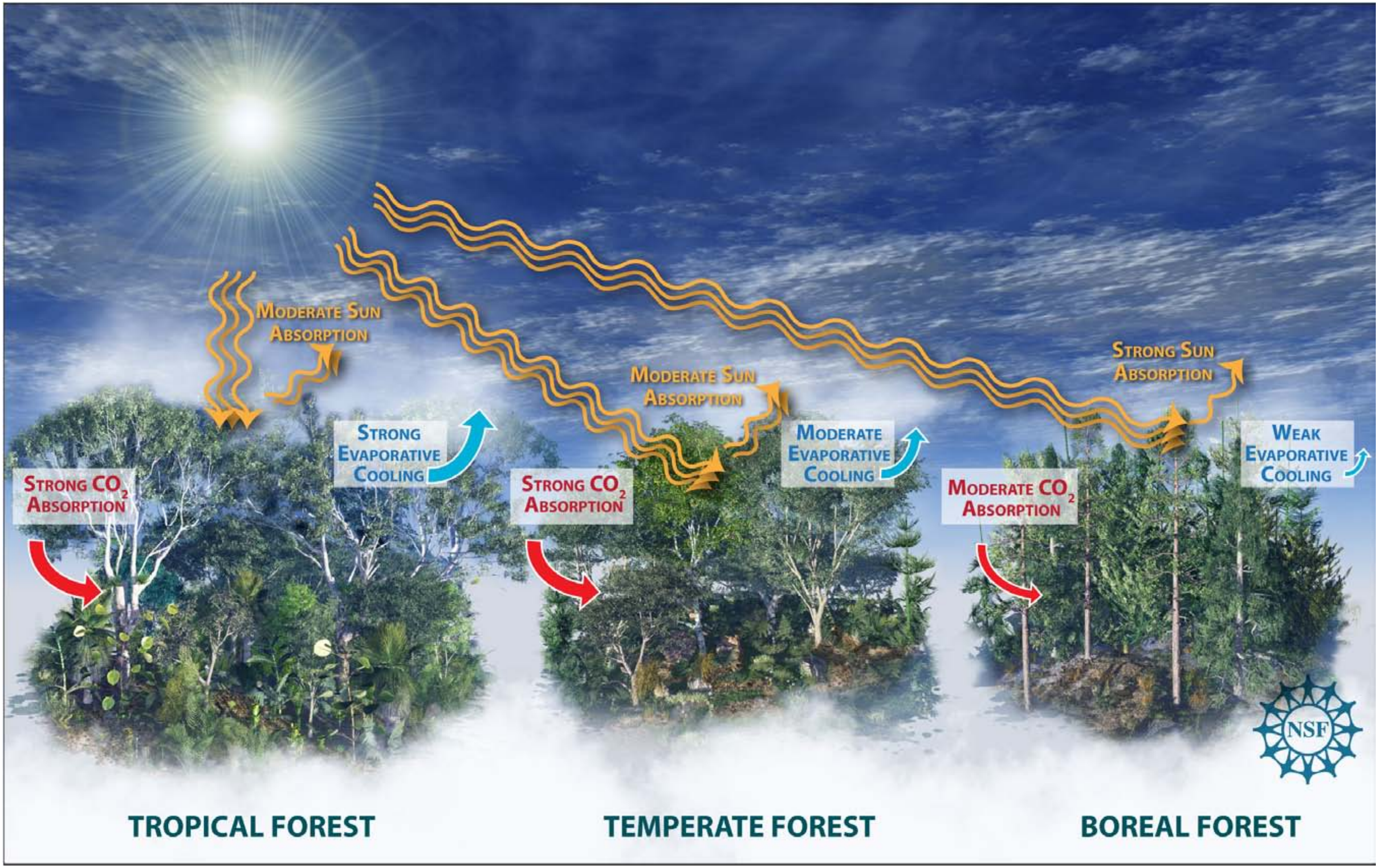
Annual gross carbon uptake



- Net carbon flux varies among vegetation
- Carbon loss with warming is a positive feedback

Forests and climate change

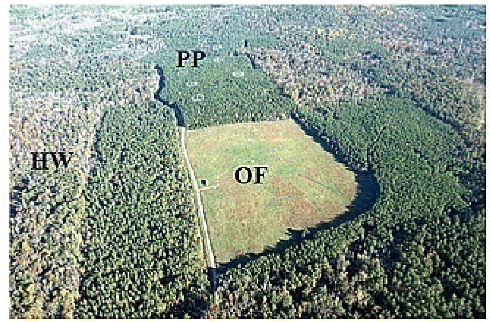
Multiple **biogeophysical** and **biogeochemical** influences of ecosystems

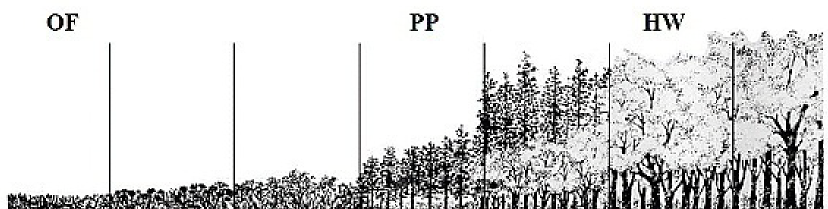


Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*

Evapotranspiration cools climate locally





(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

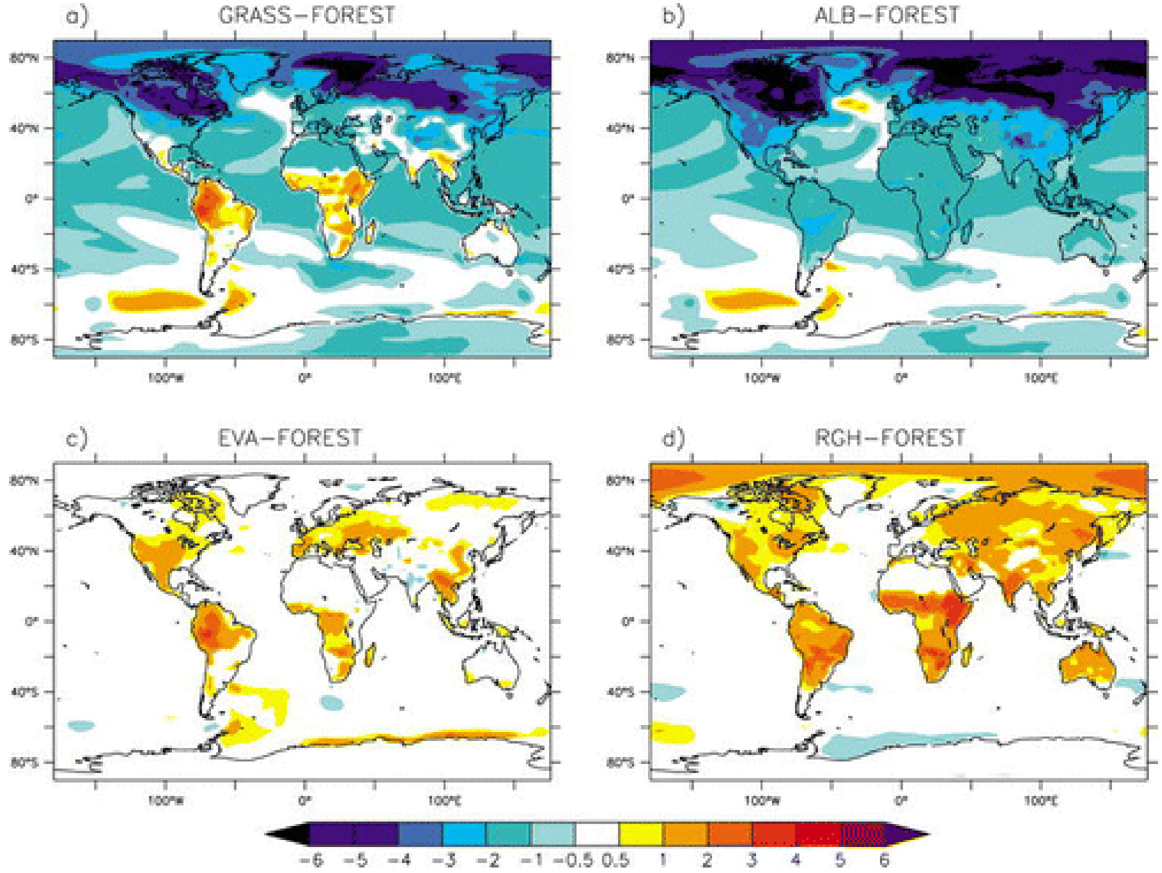
Forest
Lower albedo (+)

Greater leaf area index, aerodynamic conductance, and latent heat flux (-)

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

Forests influences on global climate

Annual mean surface temperature change (°C)

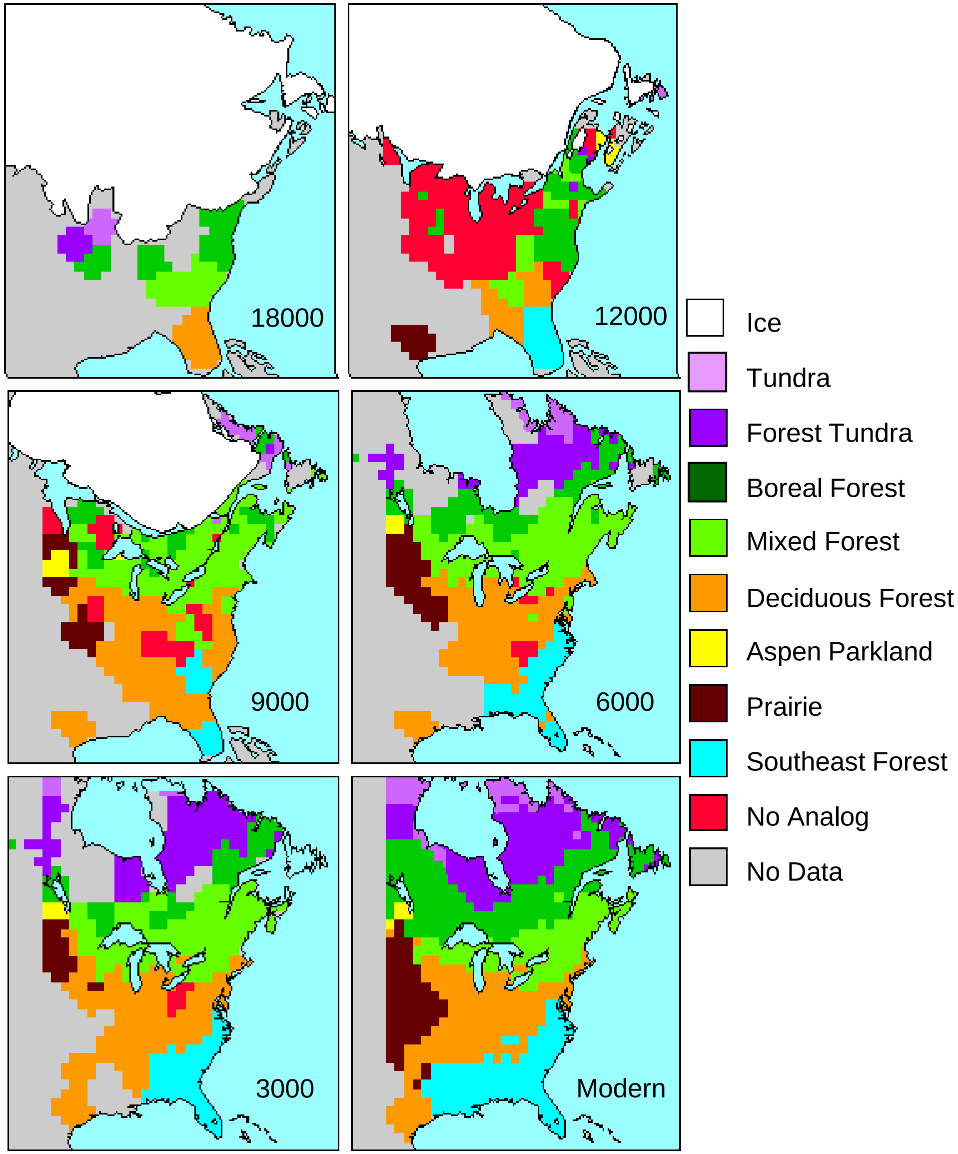


Prevailing biogeophysical paradigm
- Boreal and temperate forests warm climate
- Tropical forests cool climate

Davin & de Noblet-Ducoudré (2010) J Climate 23:97–112

Effect of boreal forests on climate

Vegetation change since Last Glacial Maximum



Climate model experiments

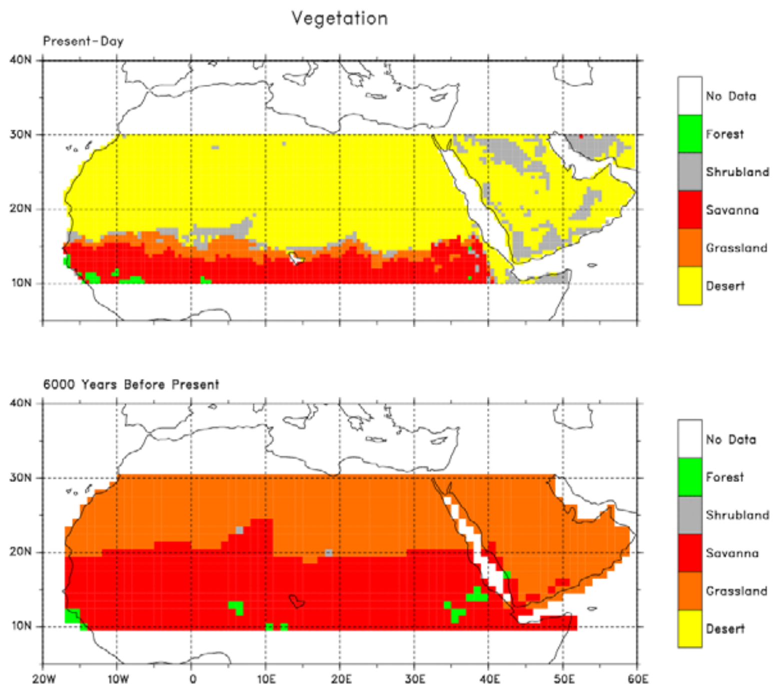
Southward retreat of boreal forest is thought to have reinforced glacial climate

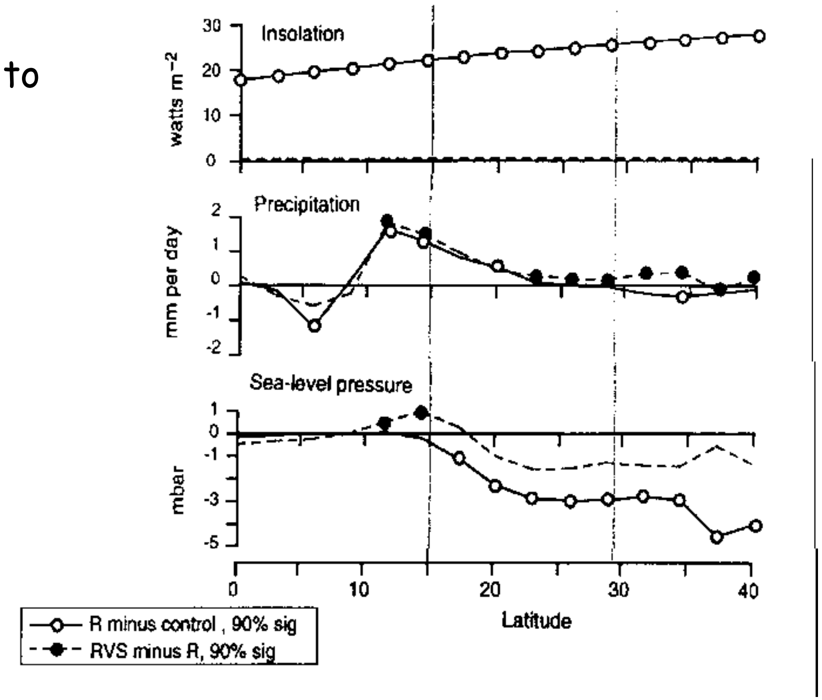
Expansion of boreal forest northward 6000 years BP is thought to have warmed climate

Greening of North Africa

Climate 6000 years BP
Increased Northern Hemisphere summer solar radiation
Strengthened African monsoon
Wetter North African climate allowed vegetation to expand

Two climate model experiments
Desert North Africa
Green North Africa





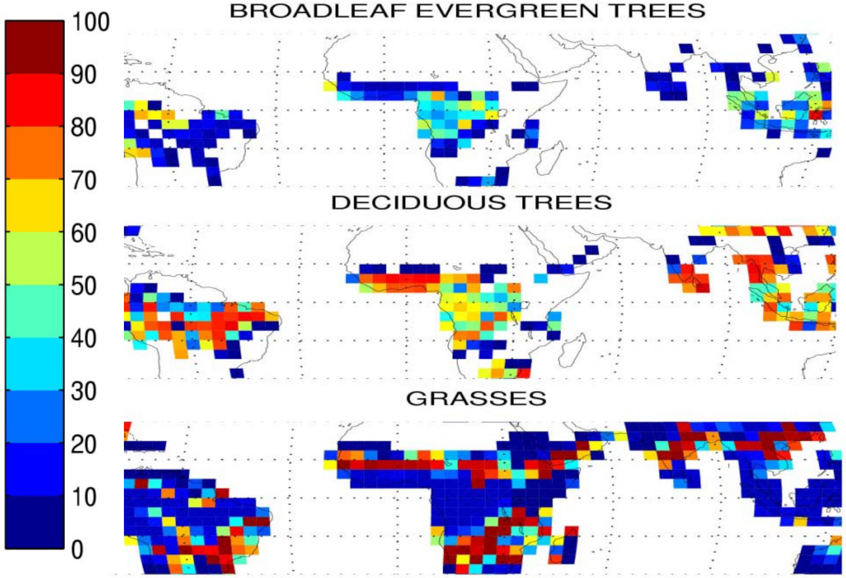
Kutzbach et al. (1996) Nature 384:623-626

Climate model experiments show:

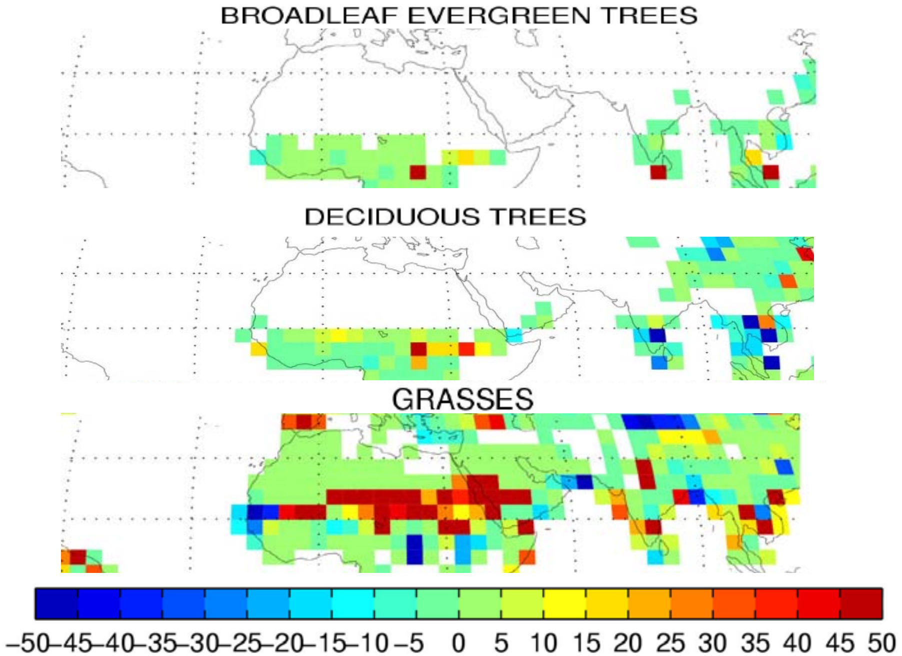
- ➢ Strengthened monsoon due to radiative forcing
- ➢ Vegetation forcing similar in magnitude to radiative forcing

Greening of North Africa

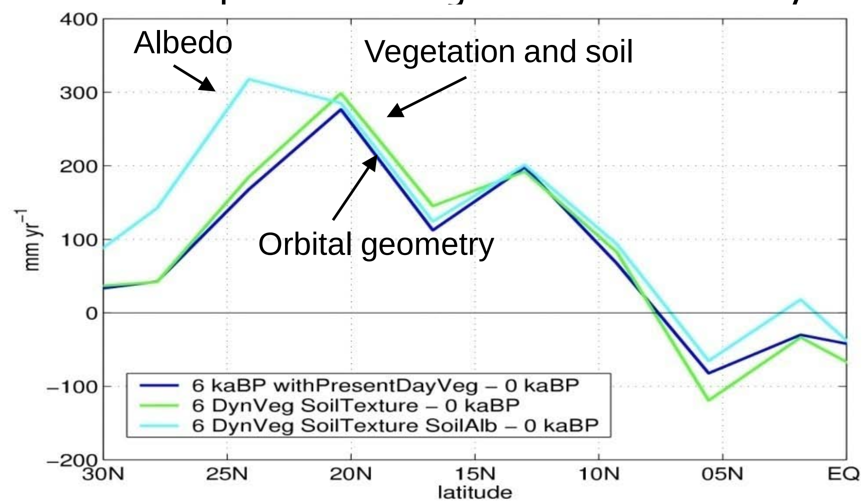
Present Day Biogeography
(percent of grid cell)



6kaBP – 0 kaBP



Precipitation Change From Present Day

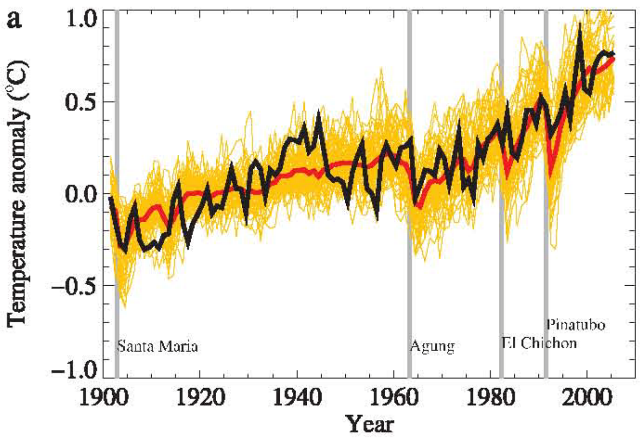


Dominant forcing
Increase in evaporation
Decrease in soil albedo

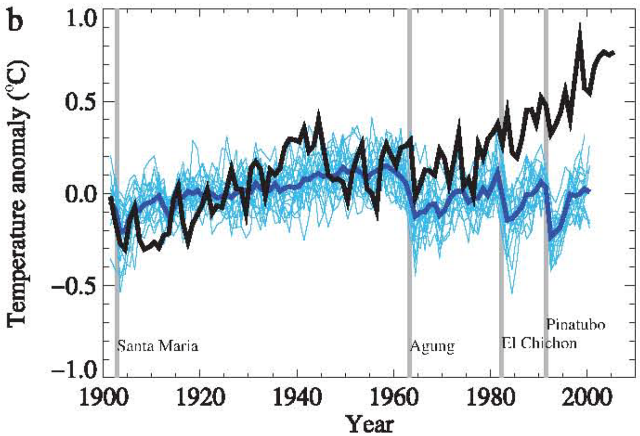
Levis et al. (2004) Climate Dynamics 23:791-802

Climate of the 20th and 21st centuries

Anthropogenic and natural forcings



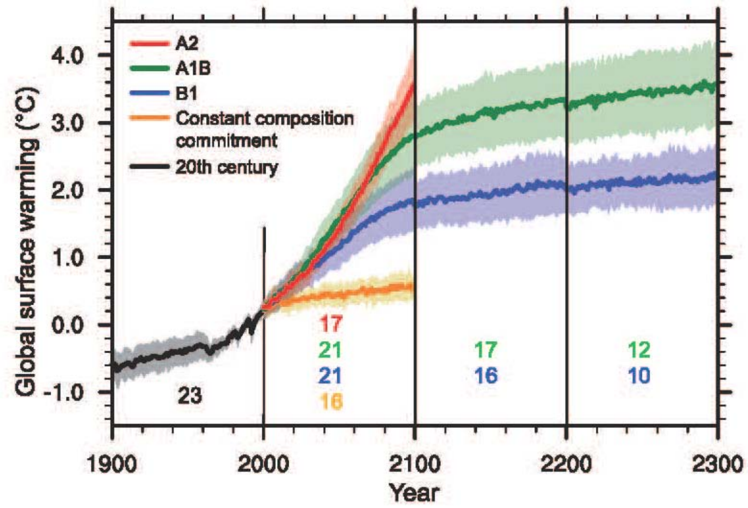
Natural forcings only

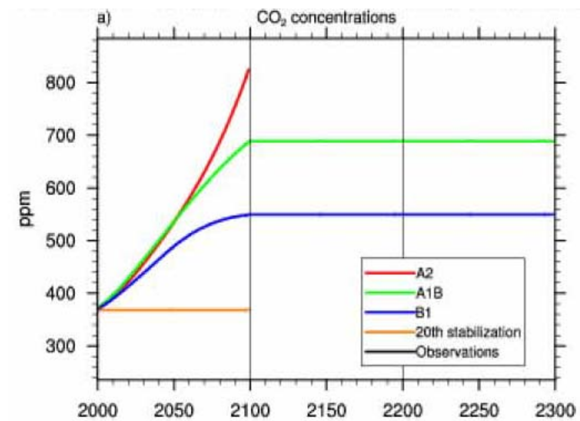


Anthropogenic forcings
Greenhouse gases
Sulfate aerosols
Black carbon aerosols
Ozone

Natural forcings
Solar variability
Volcanic aerosols

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





Meehl et al. (2007) in *Climate Change 2007: The Physical Science Basis,* Solomon et al., Eds., 747-845

- Ecosystem feedbacks with climate
- How have people altered ecosystem functions and contributed to climate change
- Can ecosystems be managed to mitigate climate change?

Ecosystems and climate policy

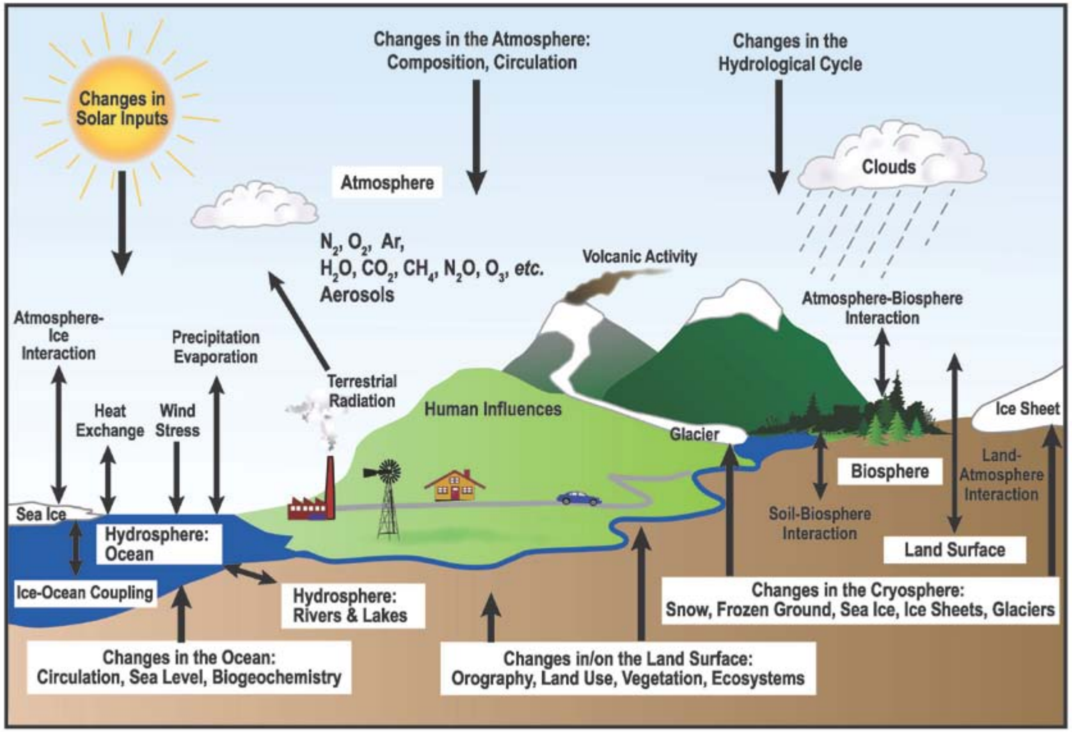
Boreal forest – menace to society – no need to promote conservation

Temperate forest – reforestation and afforestation

Tropical rainforest – planetary savior – promote avoided deforestation, reforestation, or afforestation

Biofuel plantations to lower albedo and reduce atmospheric CO_2

Earth system models



(IPCC 2007)

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**

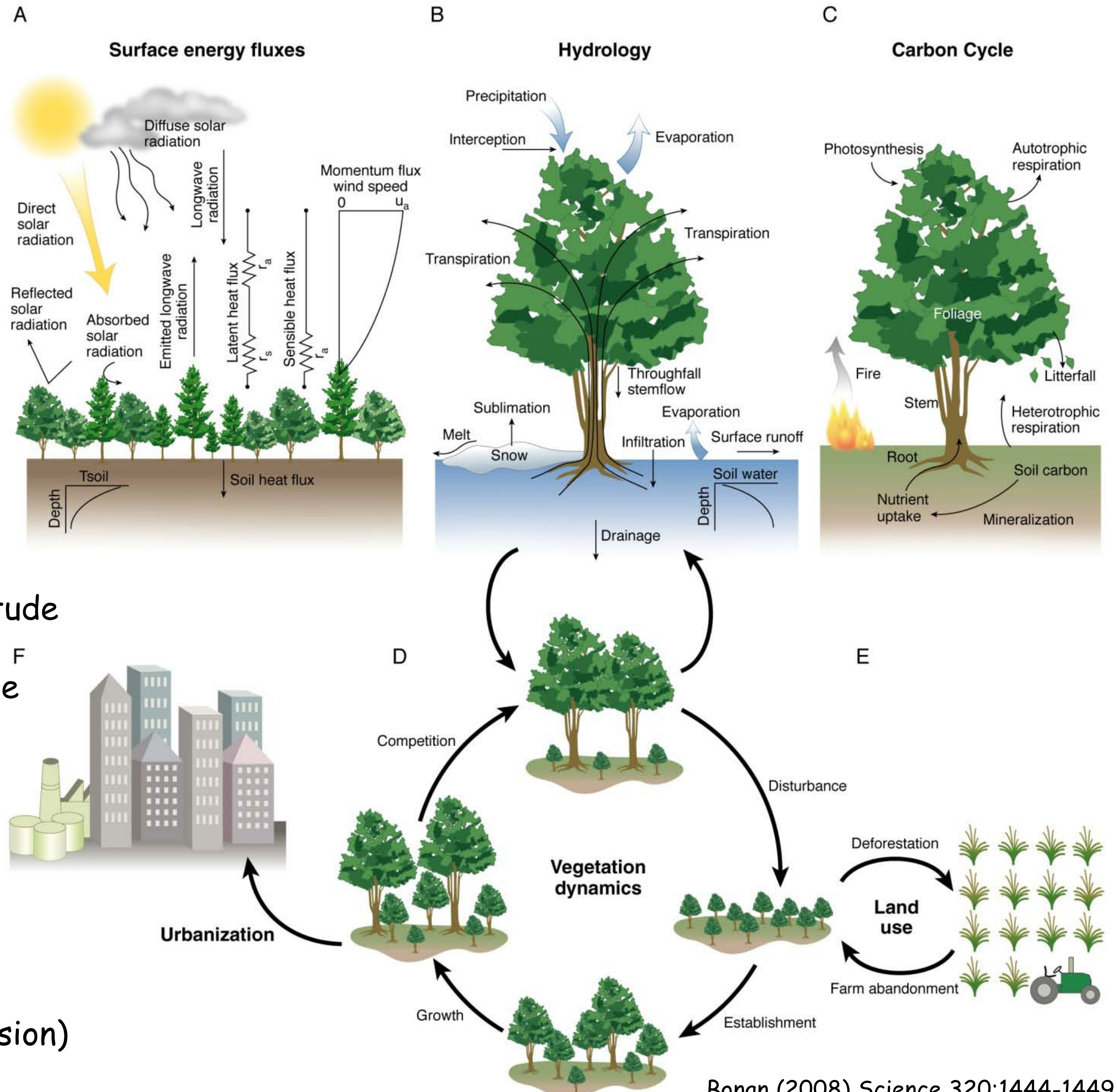
Land is represented by its ecosystems, watersheds, people, and socioeconomic drivers of environmental change

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. (2010) NCAR/TN-478+STR



Bonan (2008) Science 320:1444-1449

Spatial scale

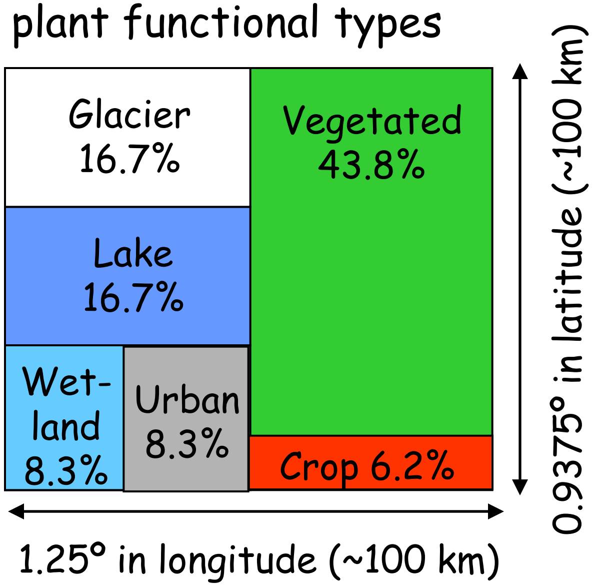
- 1.25° longitude × 0.9375° latitude (288 × 192 grid)
- 2.5° longitude × 1.875° latitude (144 × 96 grid)

Temporal scale

- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century climate (disturbance, land use, succession)
- Paleoclimate (biogeography)

Land surface heterogeneity

Subgrid land cover and plant functional types



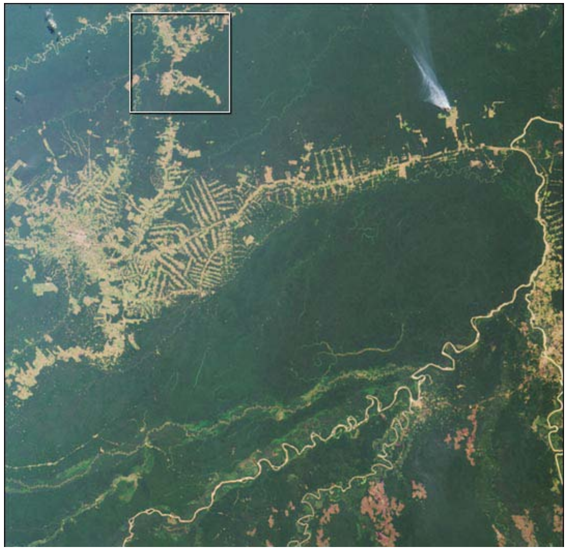
CLM represents a model grid cell as a mosaic of up to 6 primary land cover types. Vegetated land is further represented as a mosaic of plant functional types

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

Global land use

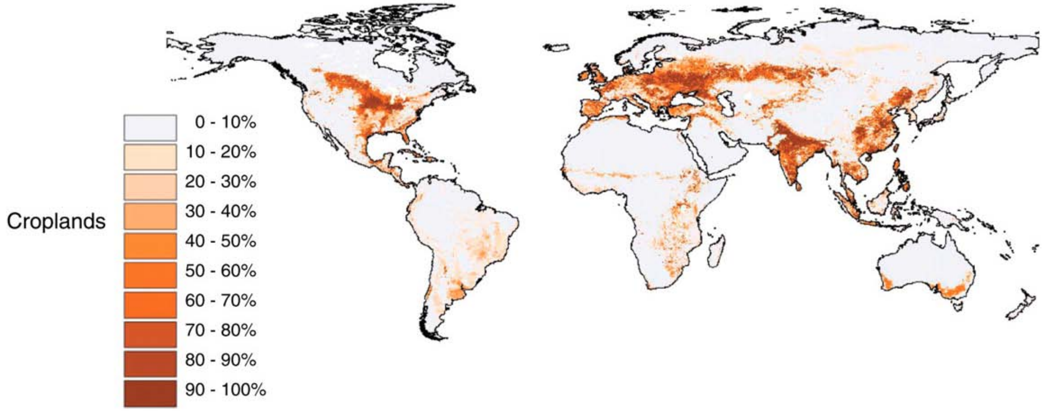
Local land use is spatially heterogeneous

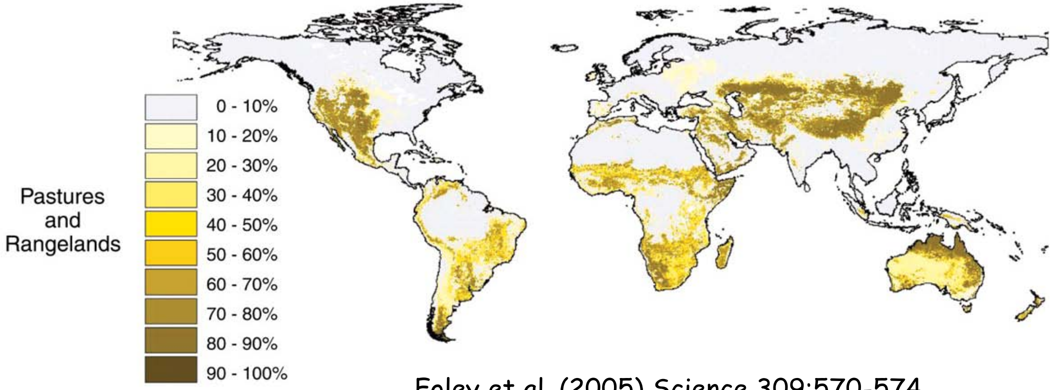
Patchwork of agricultural land, Colorado (NCAR)



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 (NASA/GSFC/LaRC/JPL)

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

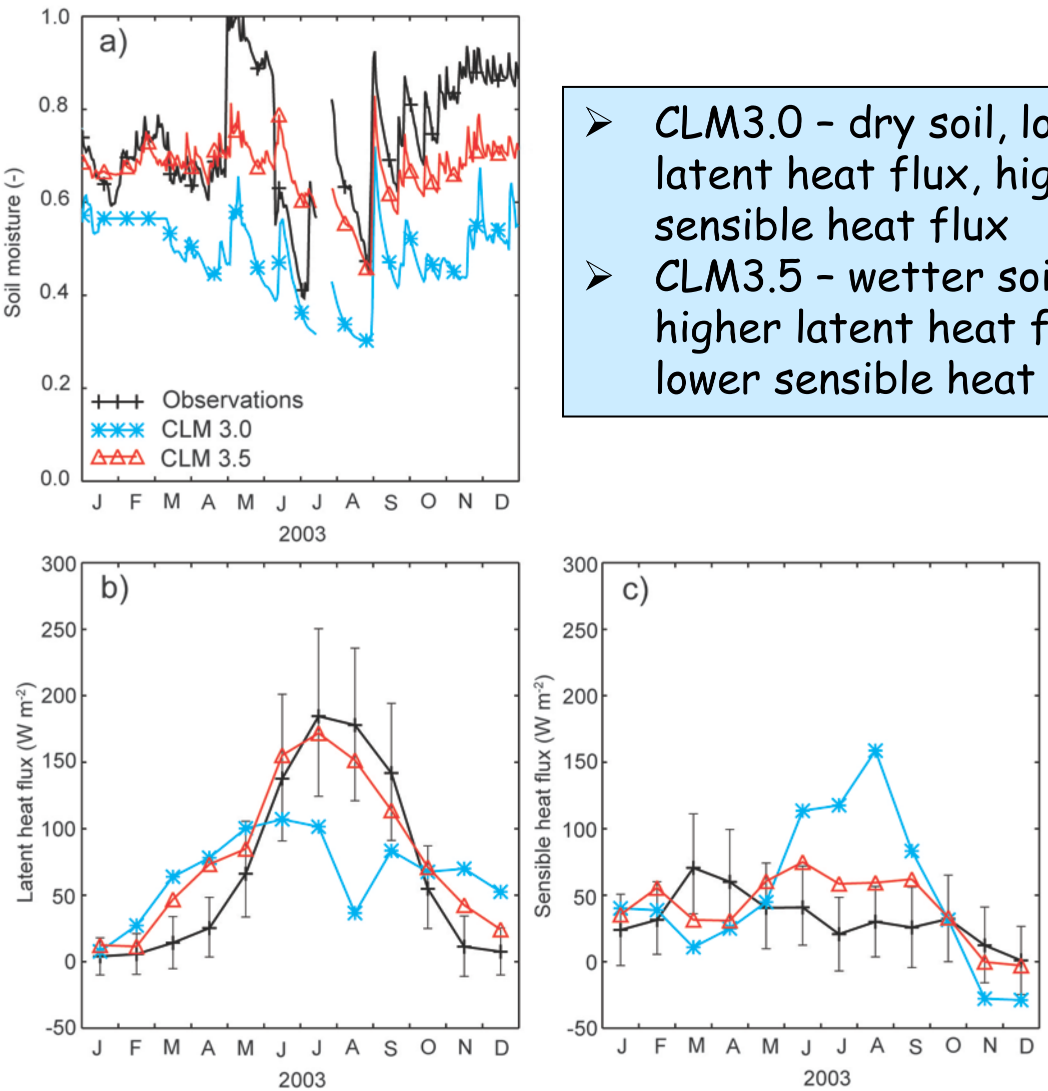




Foley et al. (2005) Science 309:570-574

Flux tower measurements – temperate deciduous forest

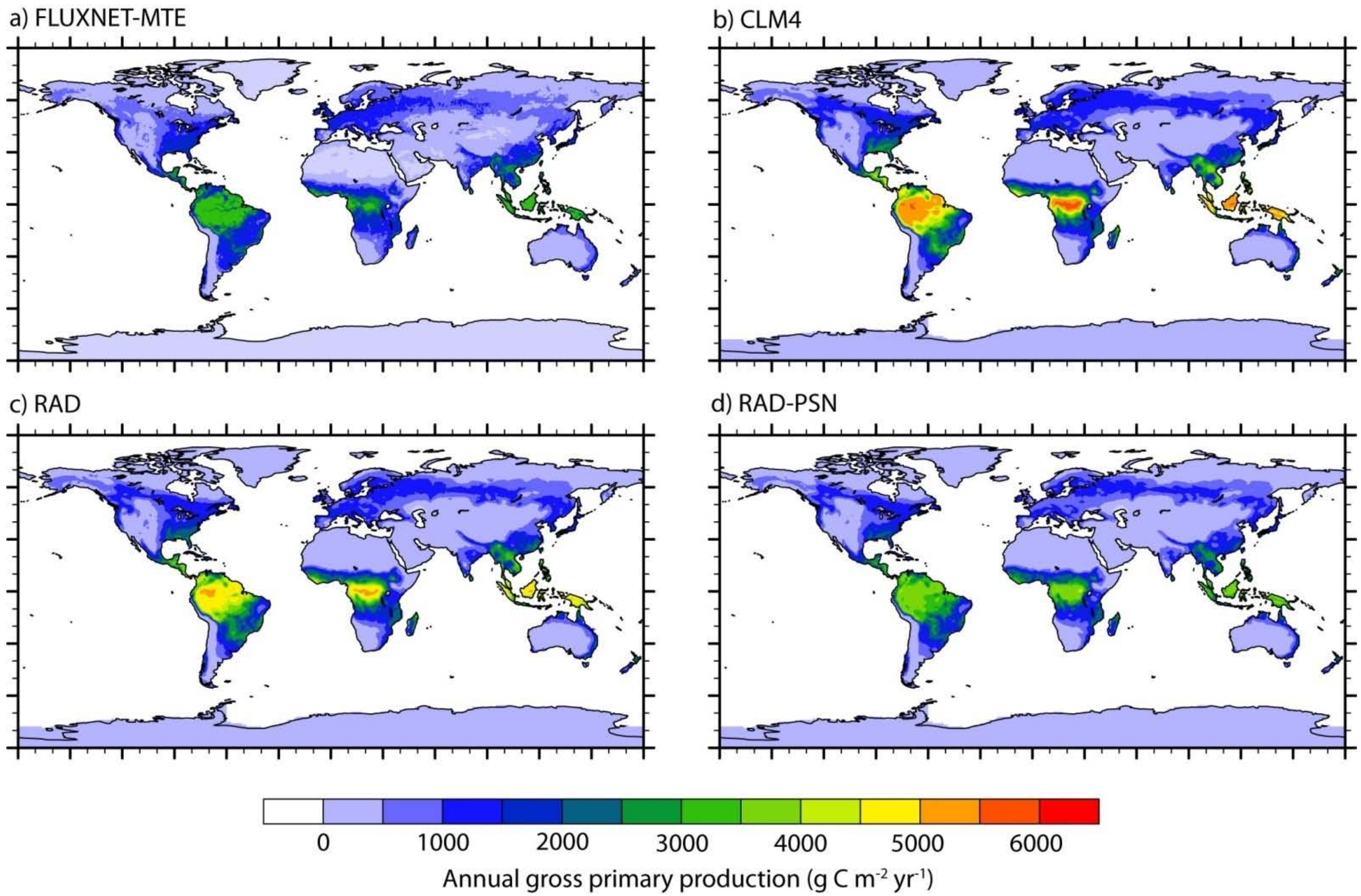
Morgan Monroe State Forest, Indiana



- CLM3.0 – dry soil, low latent heat flux, high sensible heat flux
- CLM3.5 – wetter soil, higher latent heat flux, lower sensible heat flux

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

Annual gross primary production



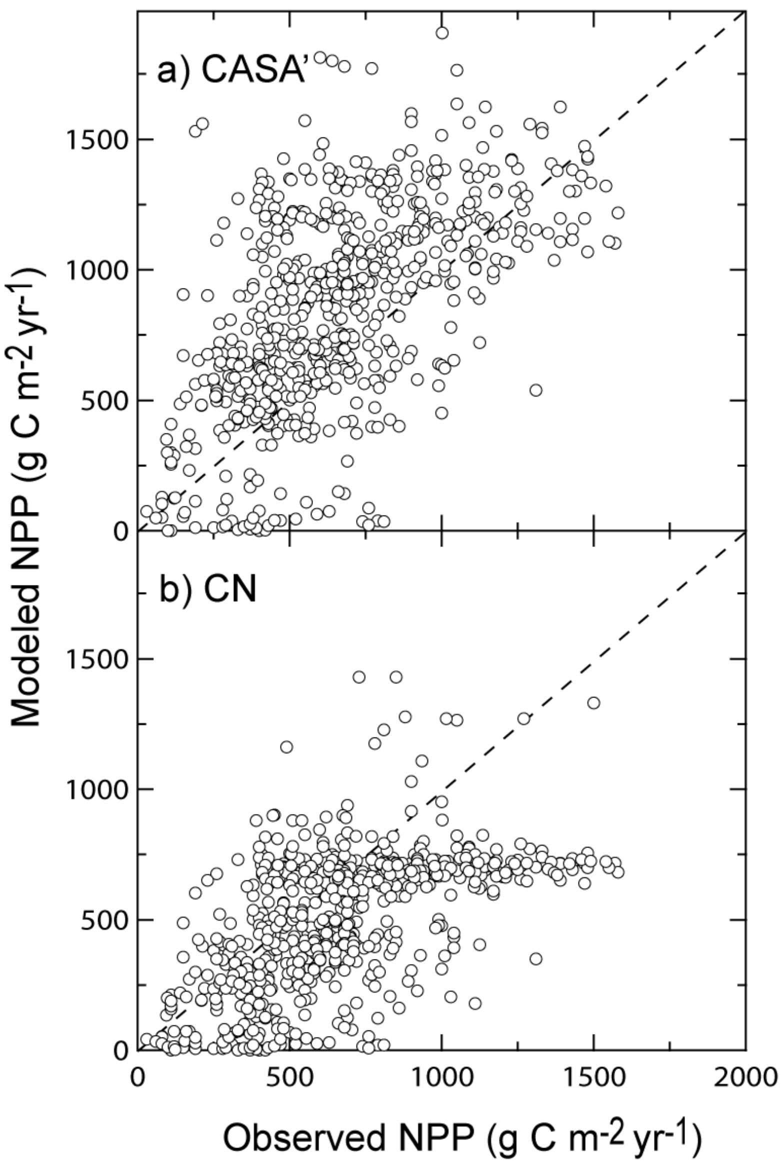
Bonan et al. (2010) in preparation

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

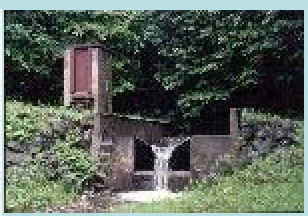


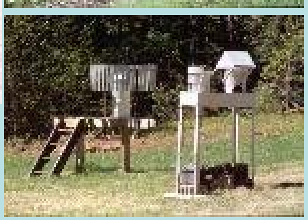
Randerson et al. (2009) *GCB* 15:2462-2484

Integrate ecological studies with earth system models

Environmental Monitoring

Eddy covariance flux tower
(courtesy Dennis Baldocchi)





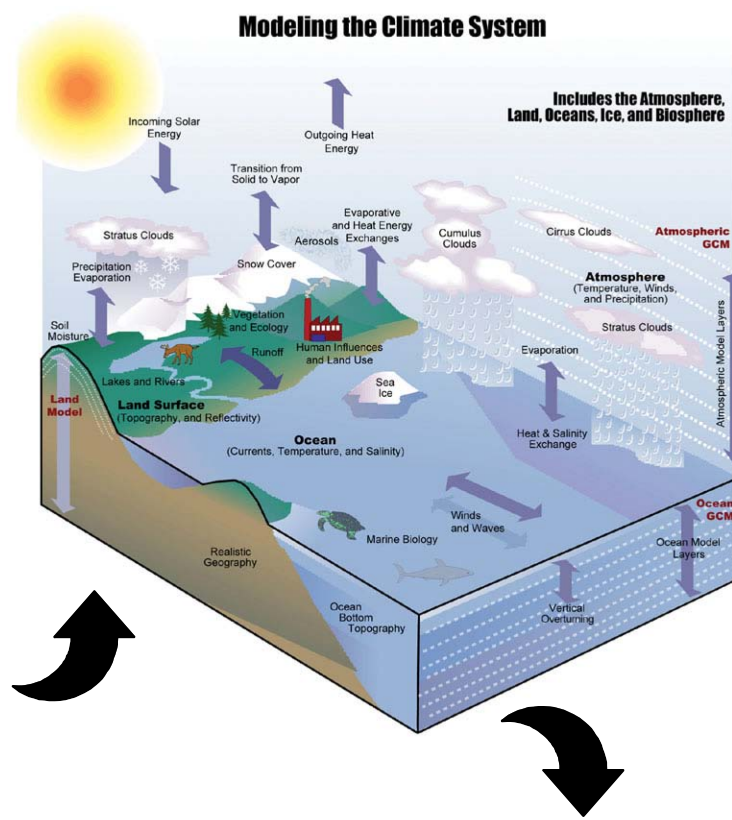
Hubbard Brook
Ecosystem Study

Experimental Manipulation

Soil warming, Harvard Forest

CO_2 enrichment, Duke Forest

CO_2 × N
enrichment,
Cedar Creek

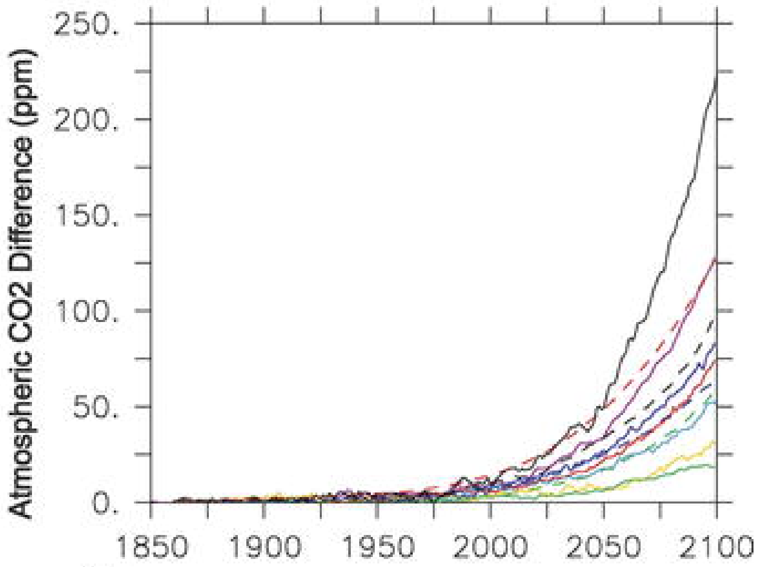


Planetary energetics
Planetary ecology
Planetary metabolism

Test model-generated hypotheses of earth system functioning with observations

C4MIP – Climate and carbon cycle

Effect of climate change on carbon cycle



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

Climate-carbon cycle feedback

11 carbon cycle-climate models of varying complexity

All models have a positive climate-carbon cycle feedback (20 ppm to >200 ppm)

Atmospheric carbon increases compared with no climate-carbon cycle feedback, while land carbon storage decreases

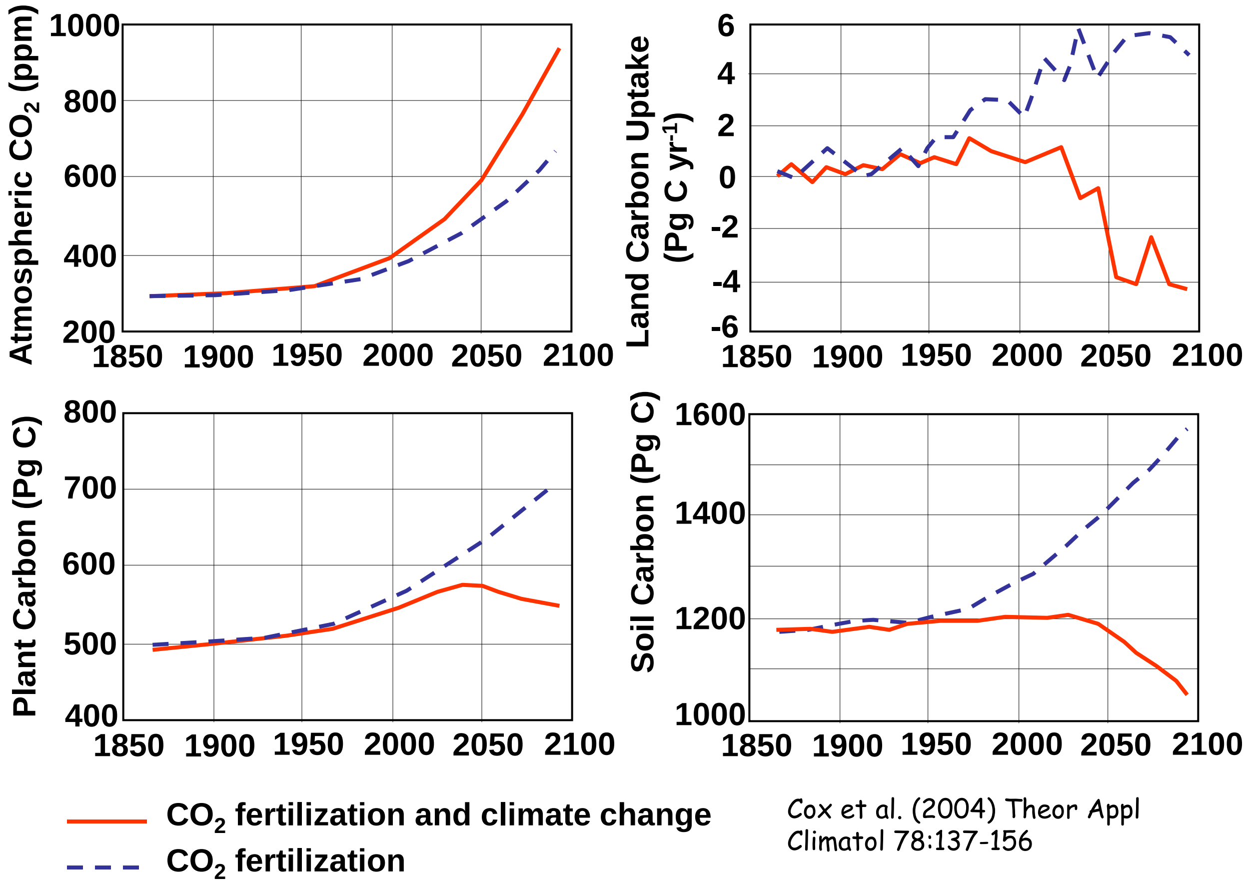
Prevailing model paradigm

CO_2 fertilization enhances carbon uptake, diminished by decreased productivity and increased soil carbon loss with warming

But what about the nitrogen cycle and land use?

Prevailing modeling paradigm

CO_2 fertilization enhances carbon uptake, diminished by decreased productivity and increased soil carbon loss with warming



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

$\Delta C_L = \beta_L \Delta C_A$ — $\beta_L > 0$: concentration-carbon feedback (Pg C ppm^{-1})

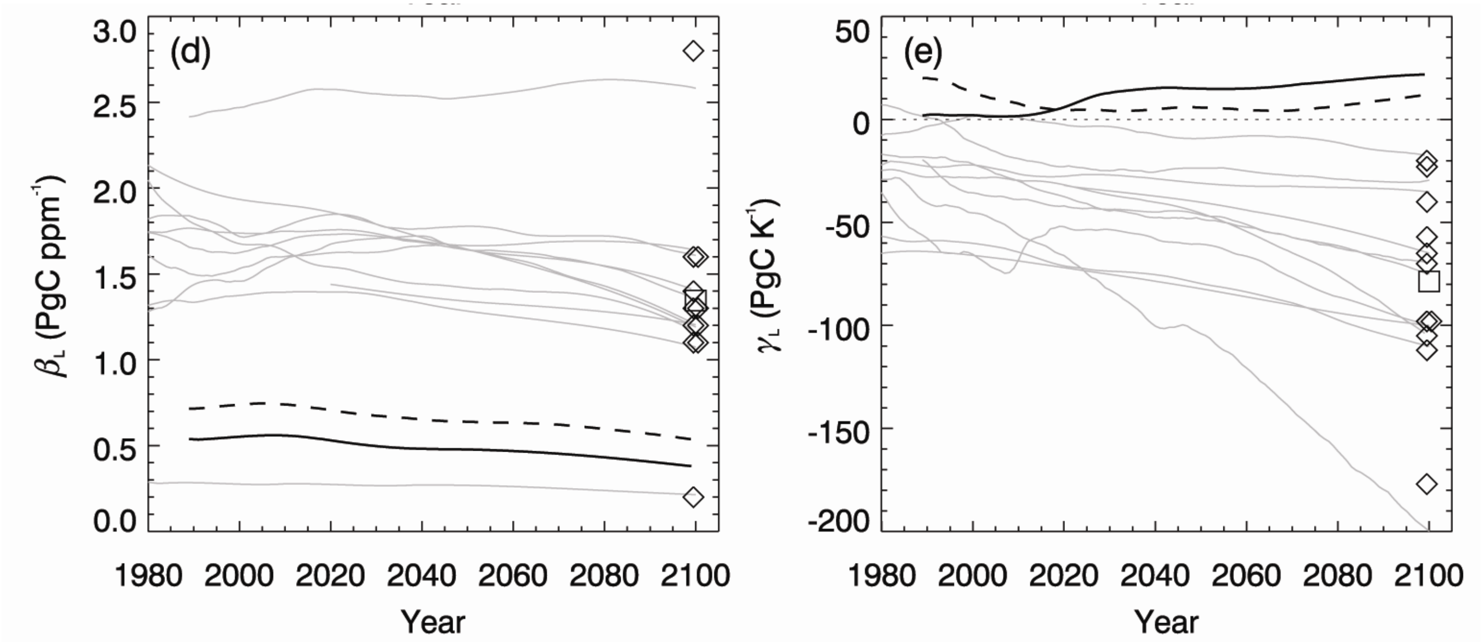
$\Delta C_L = \beta_L \Delta C_A + \gamma_L \Delta T$ — $\gamma_L < 0$: climate-carbon feedback (Pg C K^{-1})

Carbon-nitrogen interactions

Reduces concentration-carbon feedback (β_L)
- Nitrogen limitation reduces the CO_2 fertilization gain in productivity

Changes sign of climate-carbon feedback (γ_L)
- Greater N mineralization with warming stimulates plant growth

Sokolov et al. (2008) J Climate 21:3776-3796
Thornton et al. (2009) Biogeosci 6:2099-2120



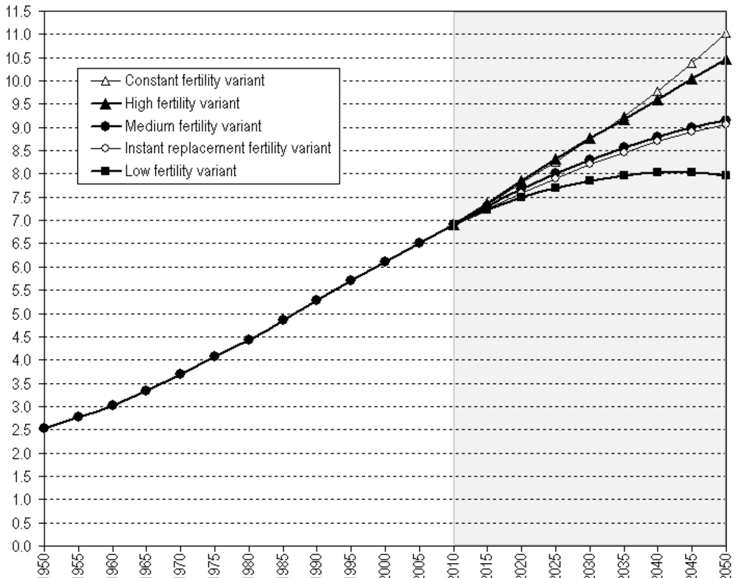
Land biosphere response to CO_2 — Land biosphere response to temperature

Thick solid line is with preindustrial nitrogen deposition
Thick dashed line is with anthropogenic nitrogen deposition
Thin gray lines are C4MIP models

Thornton et al. (2009) Biogeosci 6:2099-2120

The Anthropocene

Population of the world, 1950-2050, according to different projection variants (in billion)



Source: United Nations, Department of Economic and Social Affairs, Population Division (2009): World Population Prospects: The 2008 Revision. New York

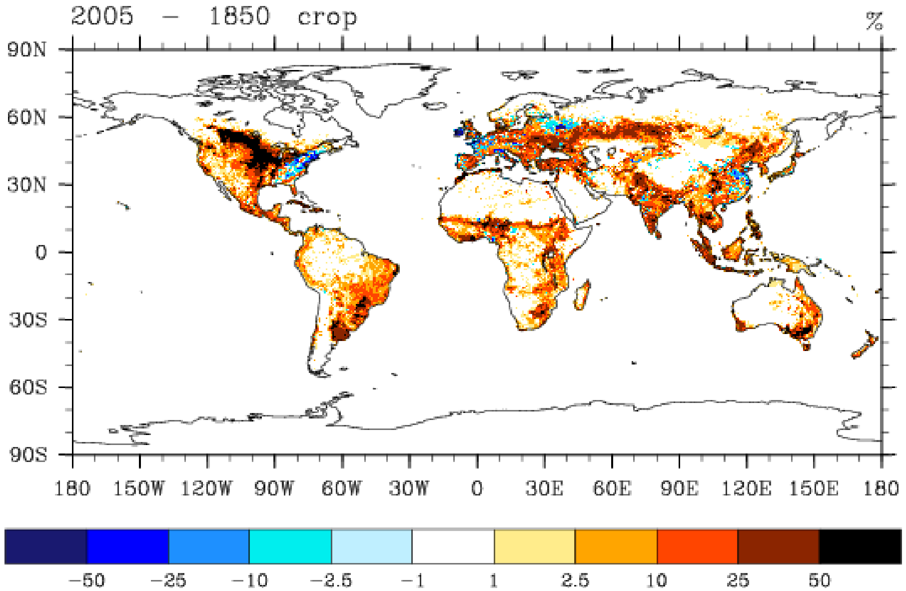




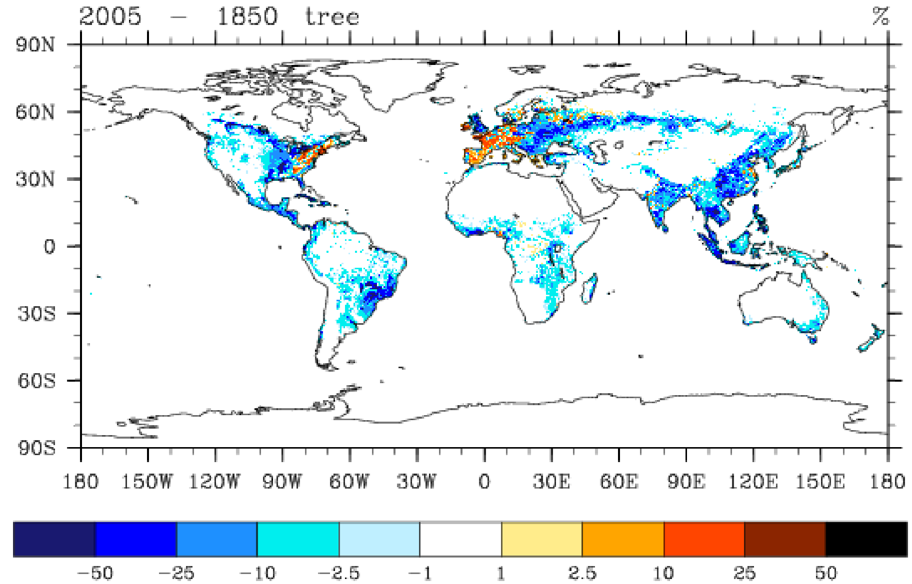



Historical land cover change, 1850 to 2005

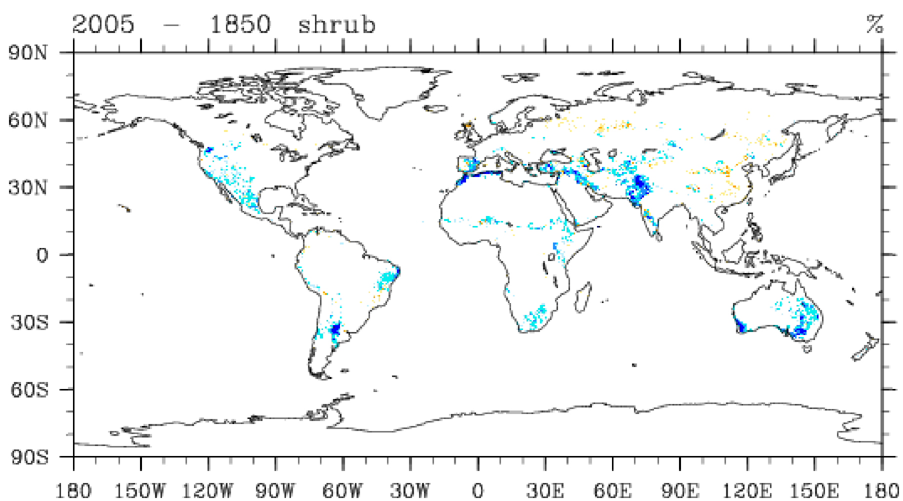
Crop PFT



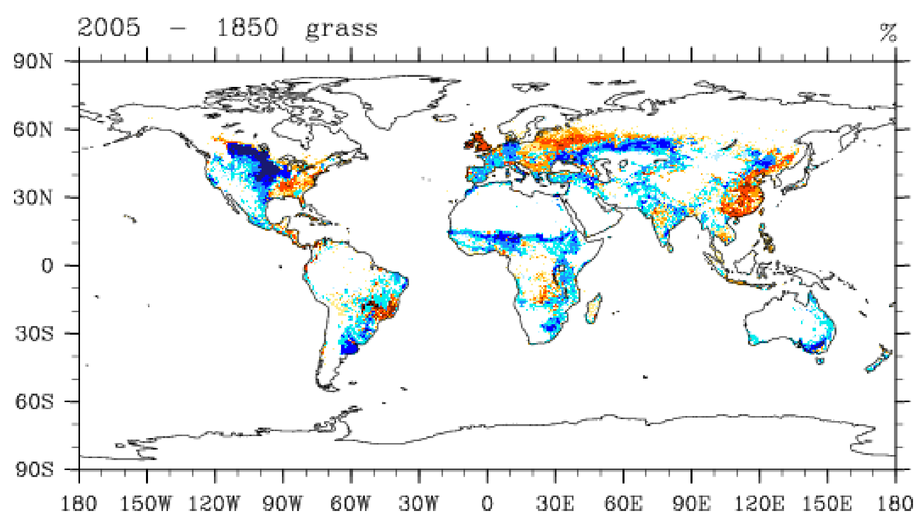
Tree PFTs



Shrub PFTs



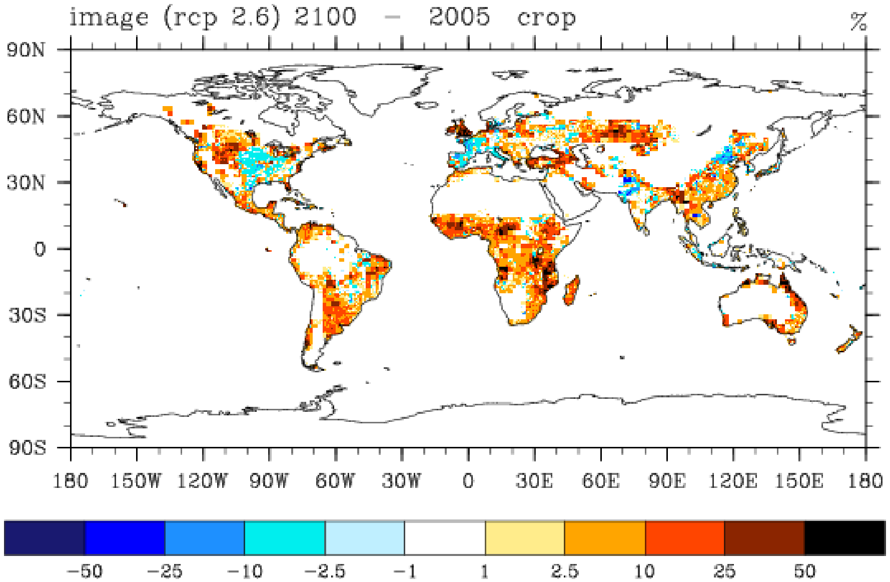
Grass PFTs



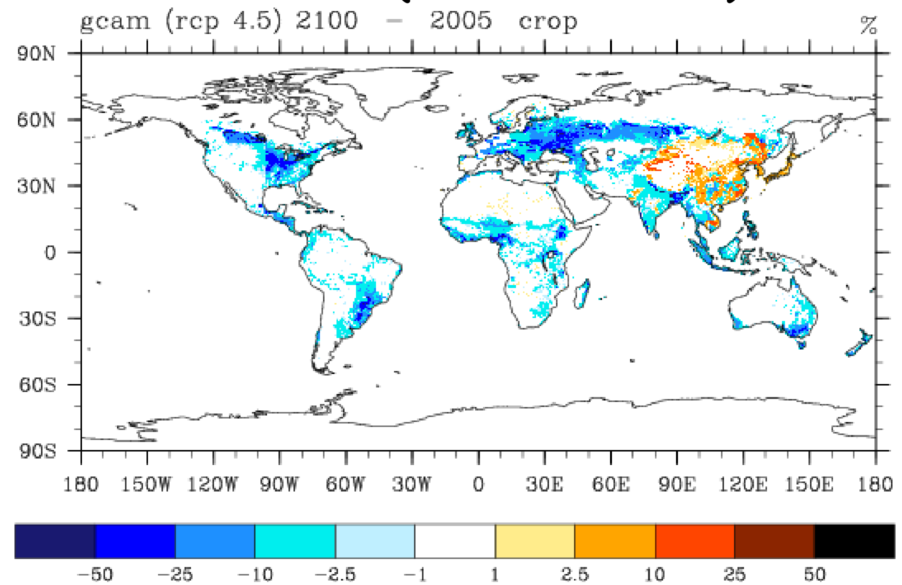
(datasets by Lawrence & Feddema)

Future land cover change, 2005 to 2100

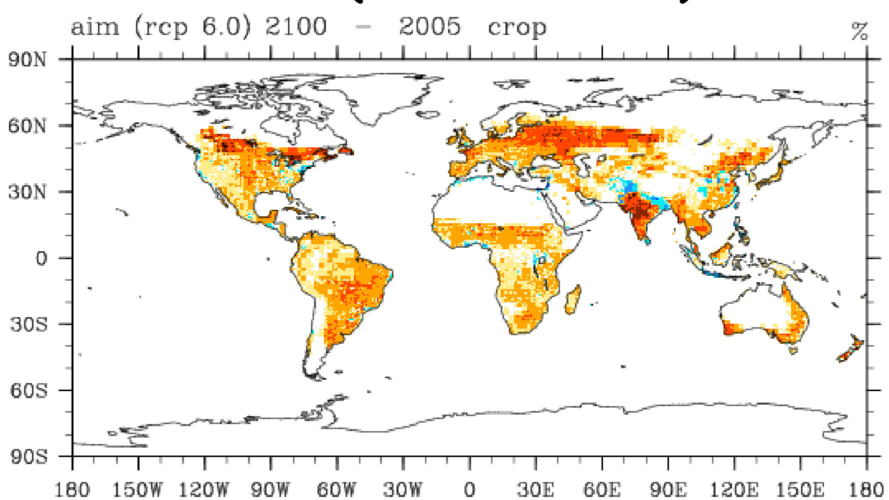
IMAGE (RCP 2.6 W m^{-2})



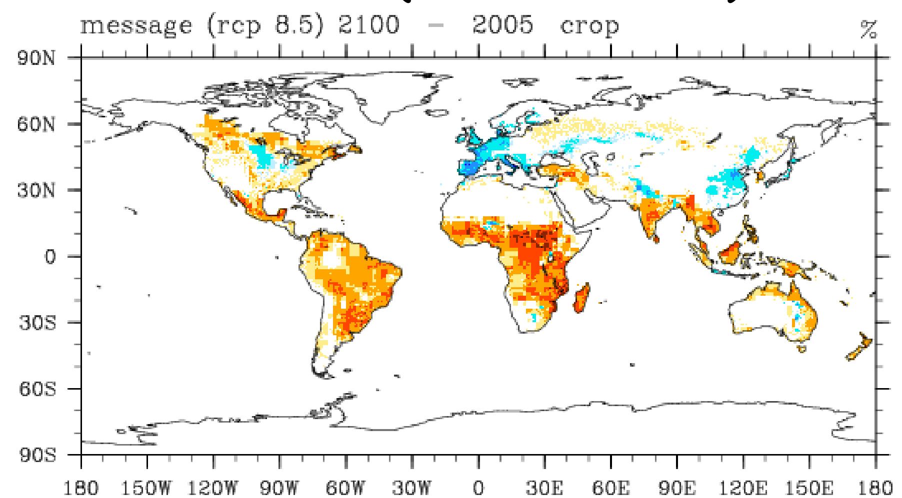
MINICAM (RCP 4.5 W m^{-2})



AIM (RCP 6.0 W m^{-2})



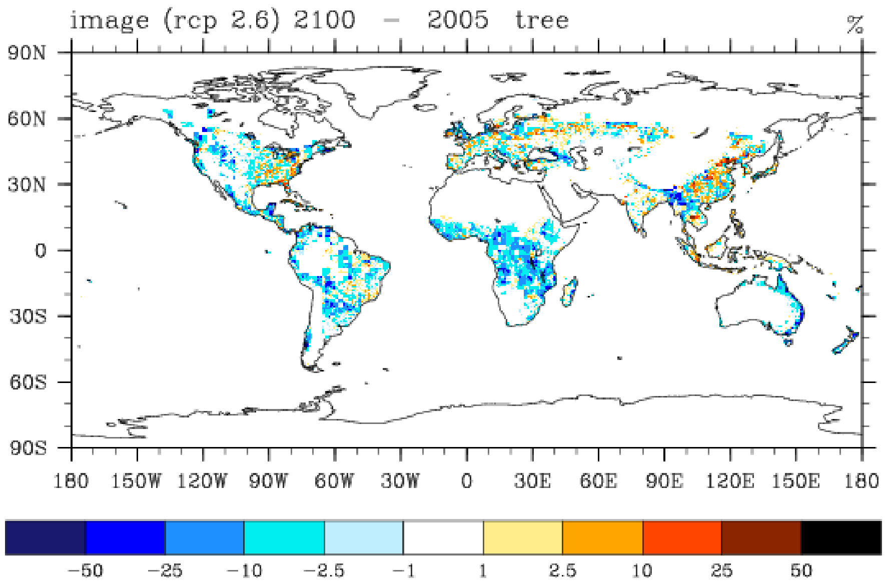
MESSAGE (RCP 8.5 W m^{-2})



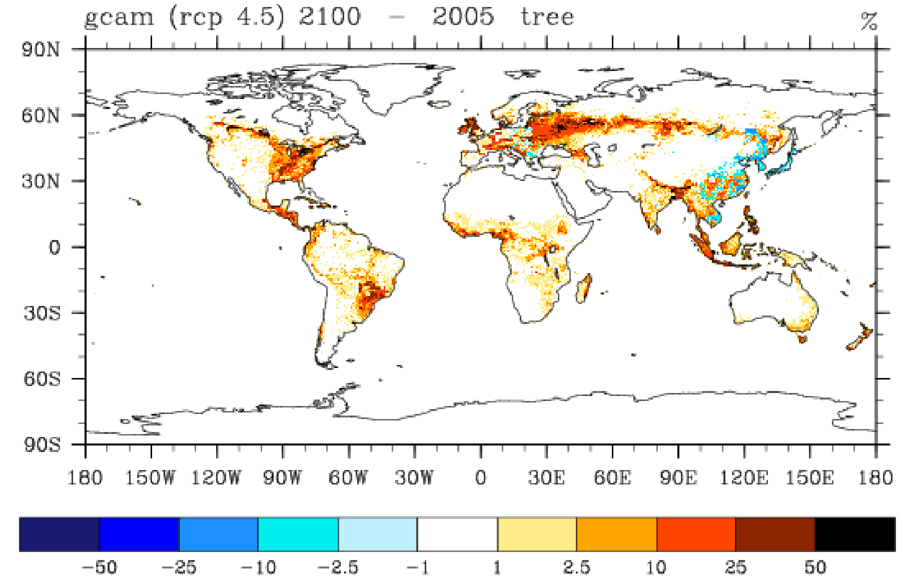
(datasets by Lawrence & Feddema)

Future land cover change, 2005 to 2100

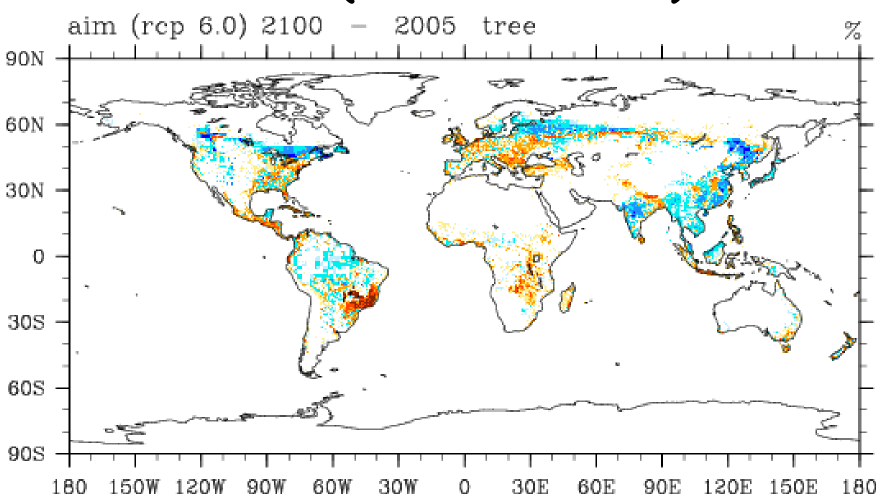
IMAGE (RCP 2.6 W m^{-2})



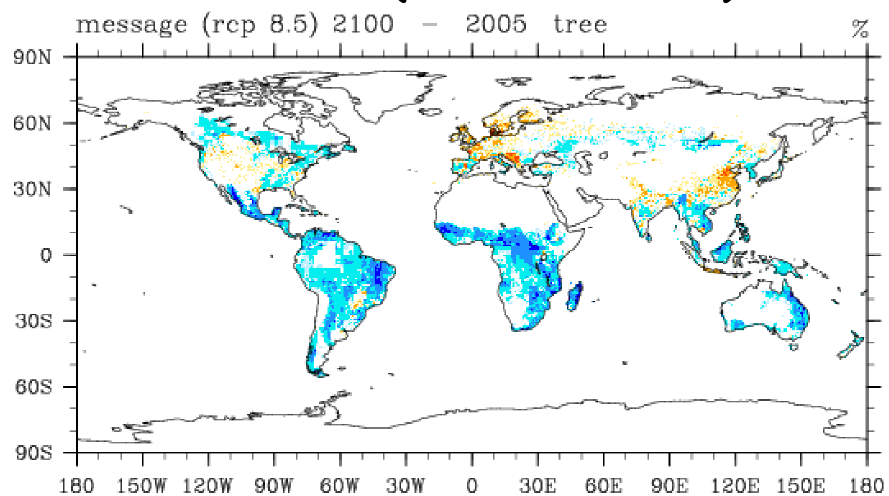
MINICAM (RCP 4.5 W m^{-2})



AIM (RCP 6.0 W m^{-2})

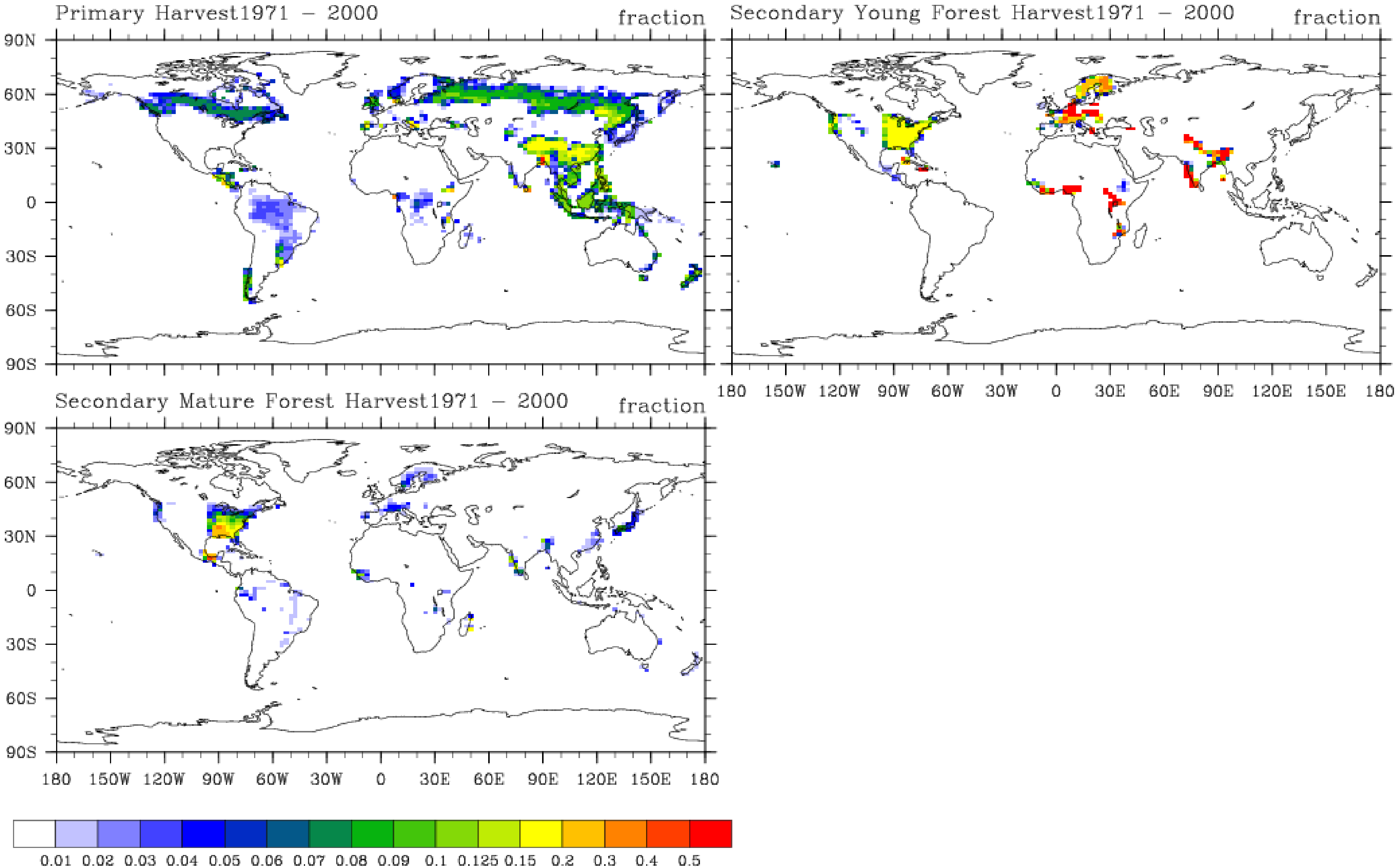


MESSAGE (RCP 8.5 W m^{-2})



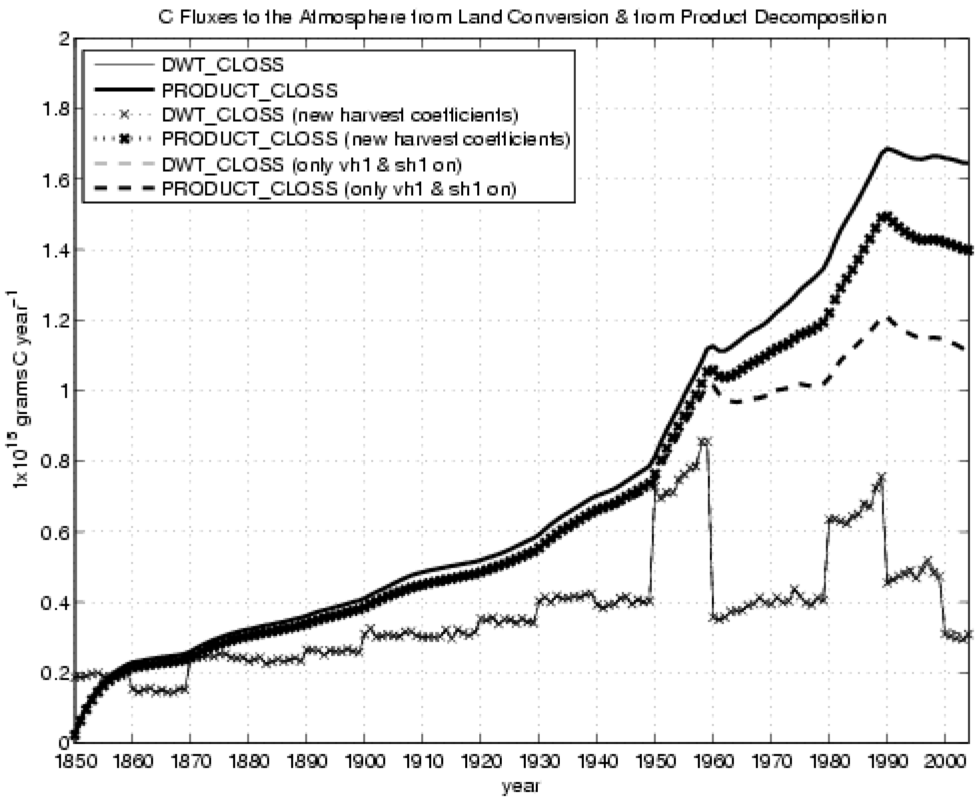
(datasets by Lawrence & Feddema)

Land use – wood harvest



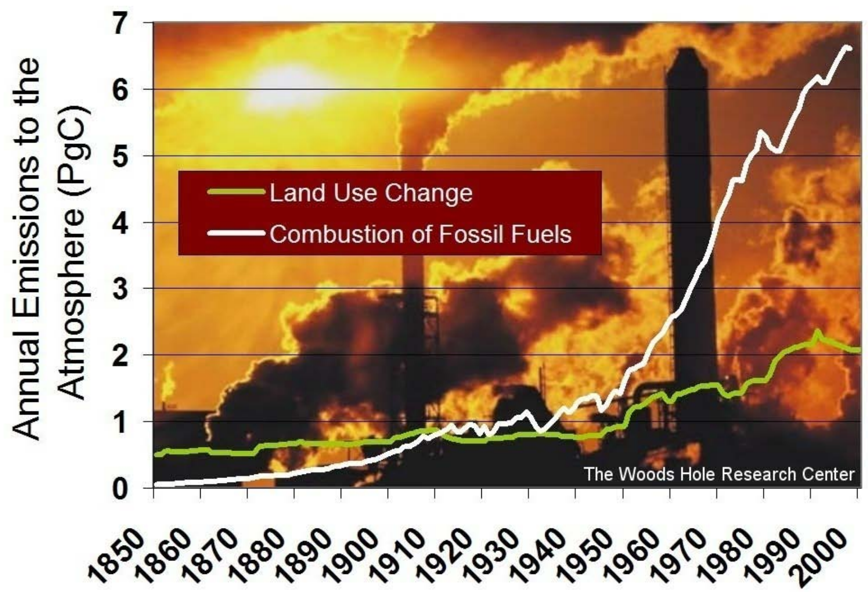
(datasets by Lawrence & Feddema)

Land use carbon flux



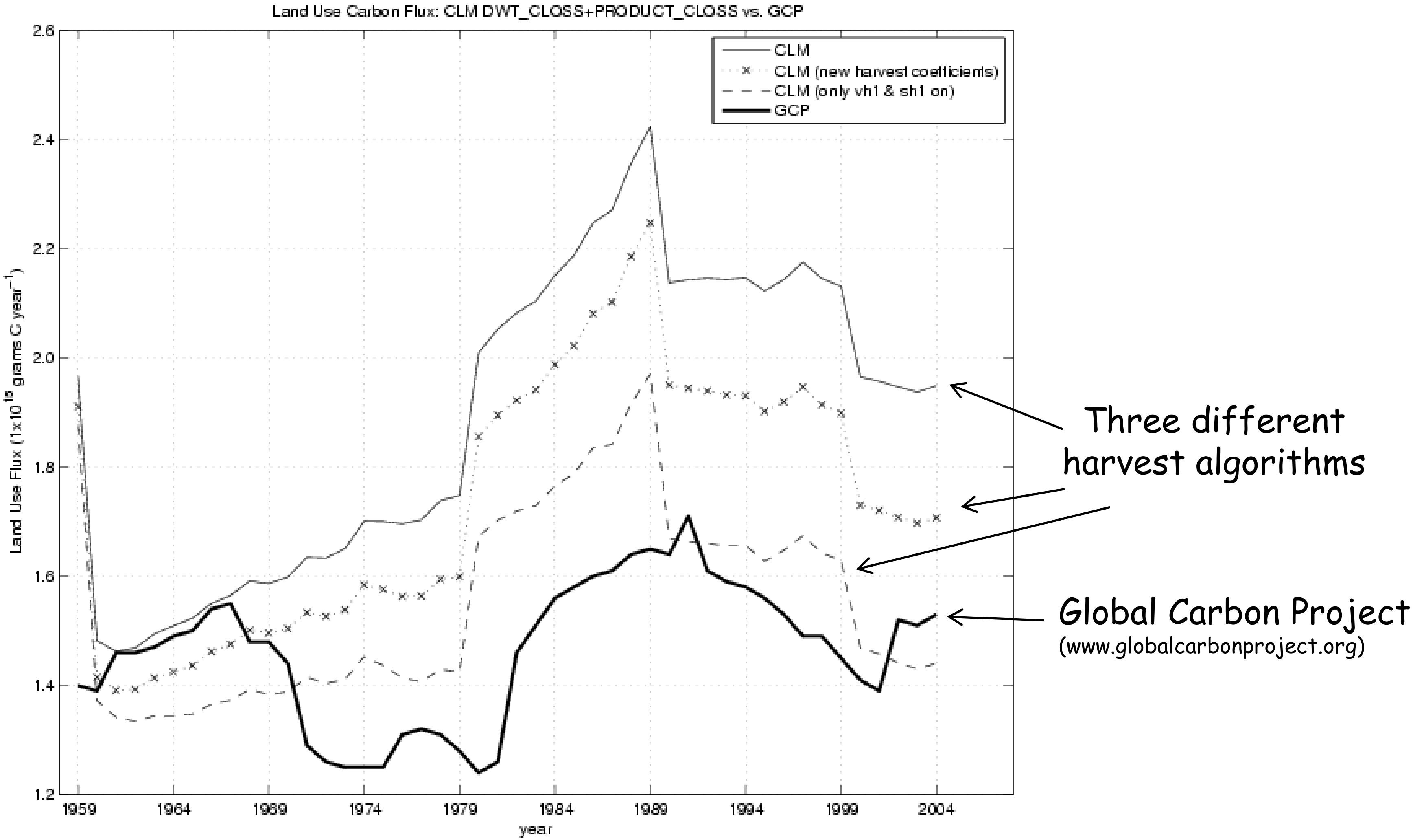
Wood harvesting

Land cover change (e.g., deforestation)



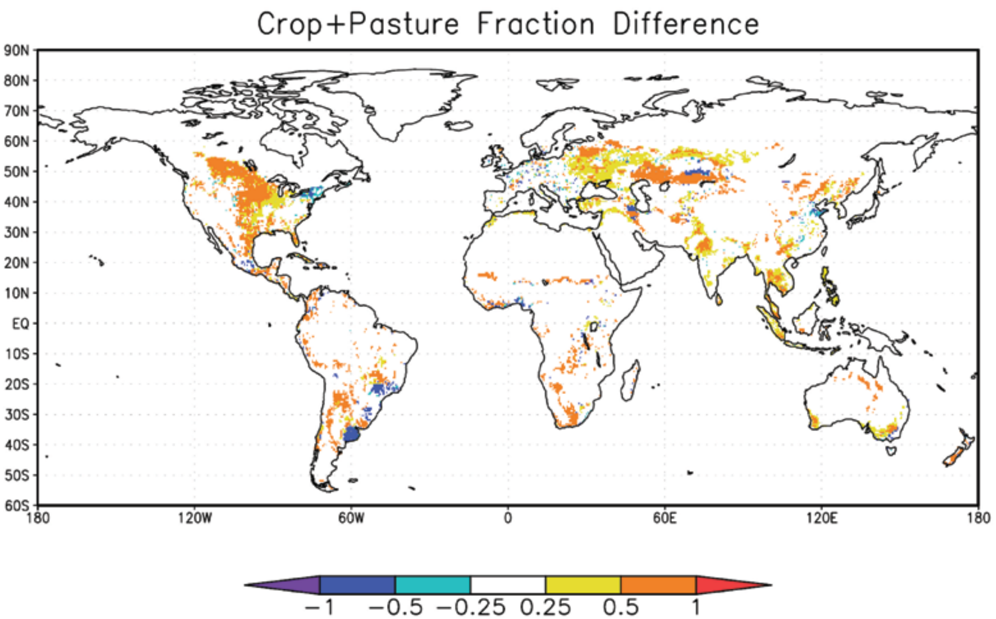
(simulations by Sam Levis)

Land use carbon flux



(simulations by Sam Levis)

The LUCID intercomparison study



Multi-model ensemble of global land use climate forcing (1992-1870)

Seven climate models of varying complexity with imposed land cover change (1992-1870)

Pitman, de Noblet-Ducoudré, et al. (2009) GRL, 36, doi:10.1029/2009GL039076

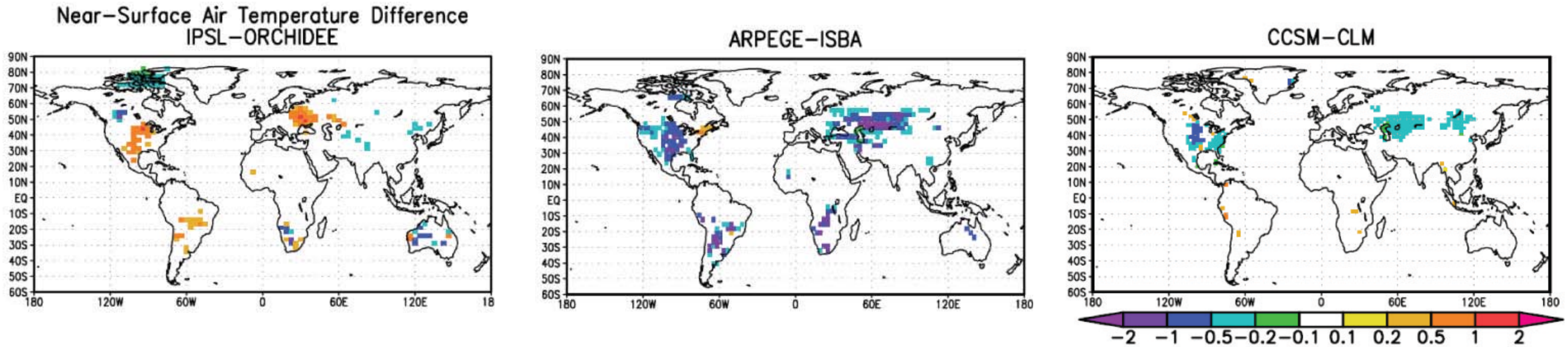
Models
Atmosphere - CAM3.5
Land - CLM3.5 + new datasets for present-day vegetation + grass optical properties
Ocean - Prescribed SSTs and sea ice

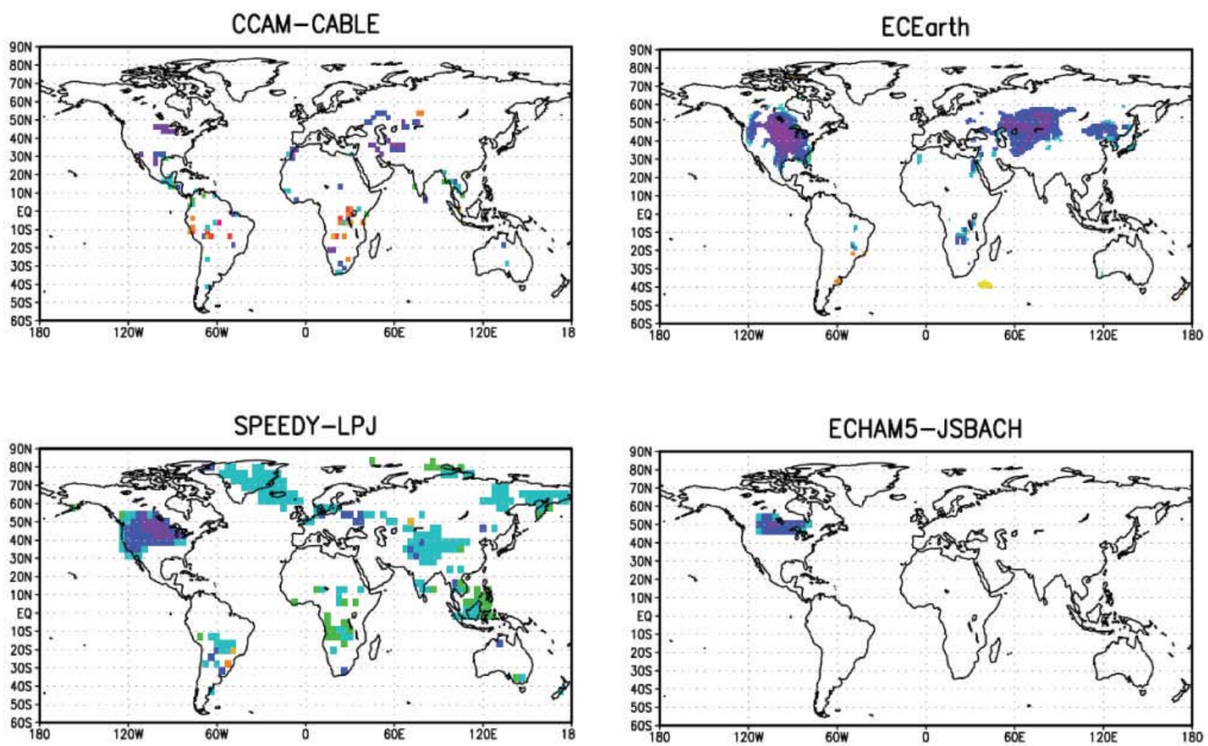
Experiments
30-year simulations (CO_2 = 375 ppm, SSTs = 1972-2001)
PD – 1992 vegetation
PDv - 1870 vegetation
30-year simulations (CO_2 = 280 ppm, SSTs = 1871-1900)
PI – 1870 vegetation
PIv – 1992 vegetation

No irrigation

5-member ensembles each
Total of 20 simulations and 600 model years

The LUCID intercomparison study

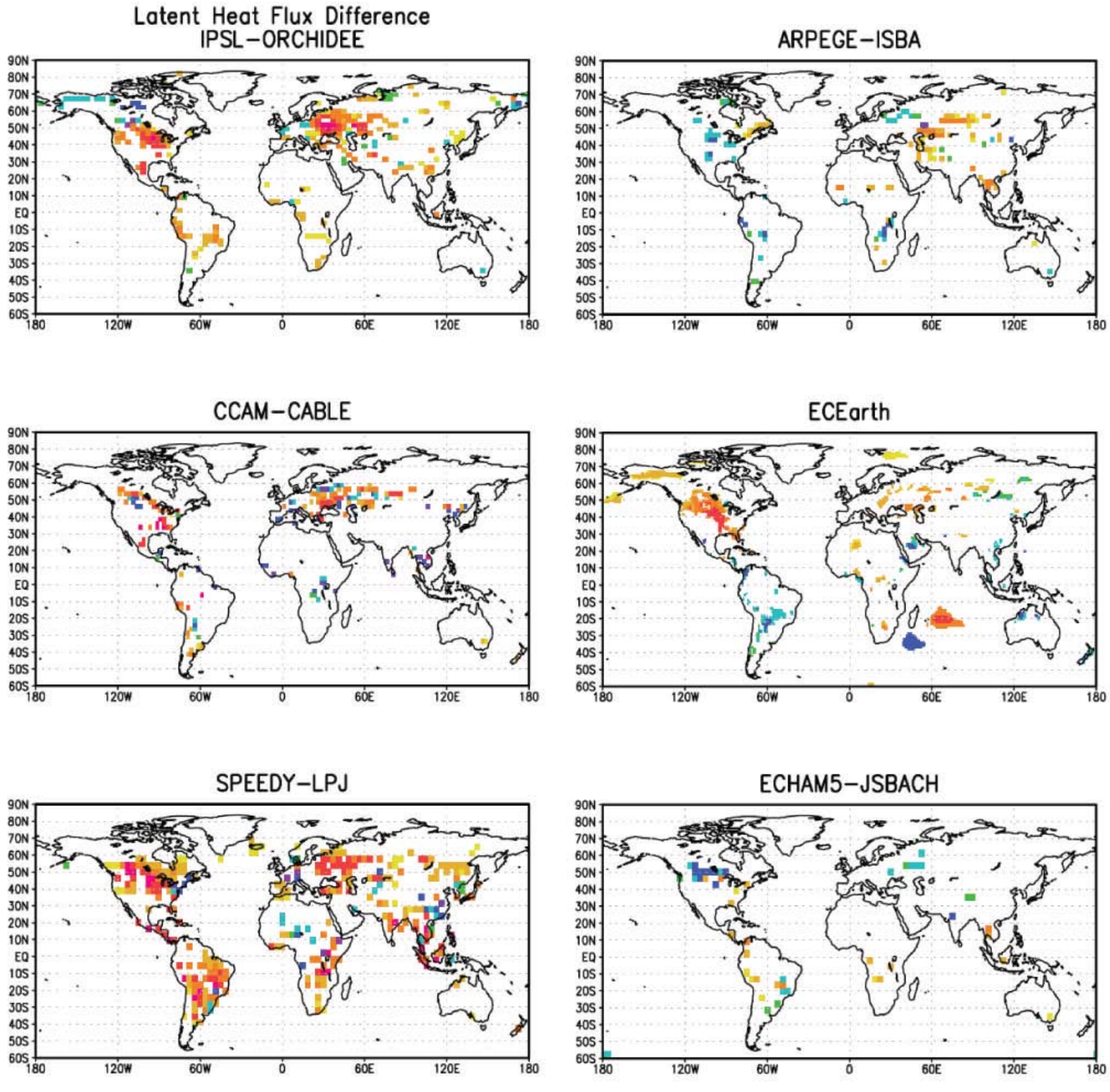




Change in JJA near-surface air temperature (°C) resulting from land cover change (PD – PDv)

Pitman, de Noblet-Ducoudré, et al. (2009) GRL, 36, doi:10.1029/2009GL039076

The LUCID intercomparison study



Change in JJA latent heat flux (W m^{-2}) resulting from land cover change (PD – PDv)

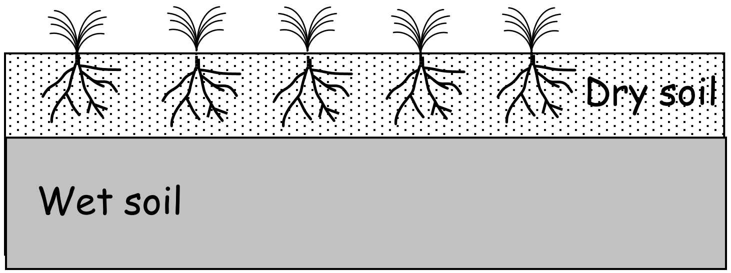
Pitman, de Noblet-Ducoudré, et al. (2009) GRL, 36, doi:10.1029/2009GL039076

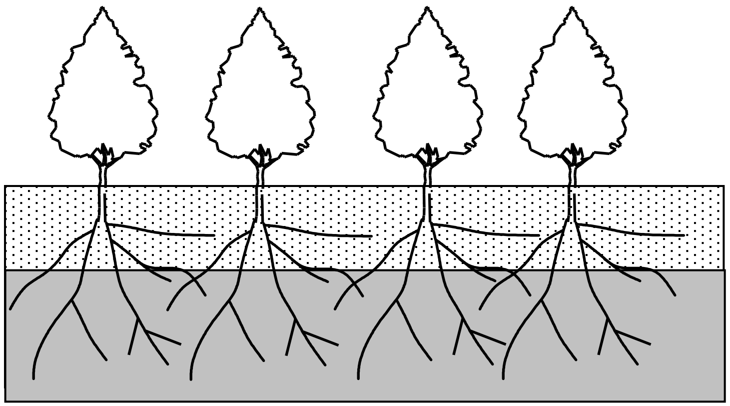
Land cover change and evapotranspiration

Prevailing model paradigm

Crops
Low latent heat flux because of:
- Low roughness
- Shallow roots decrease soil water availability

Trees
High latent heat flux because of:
- High roughness
- Deep roots allow increased soil water availability



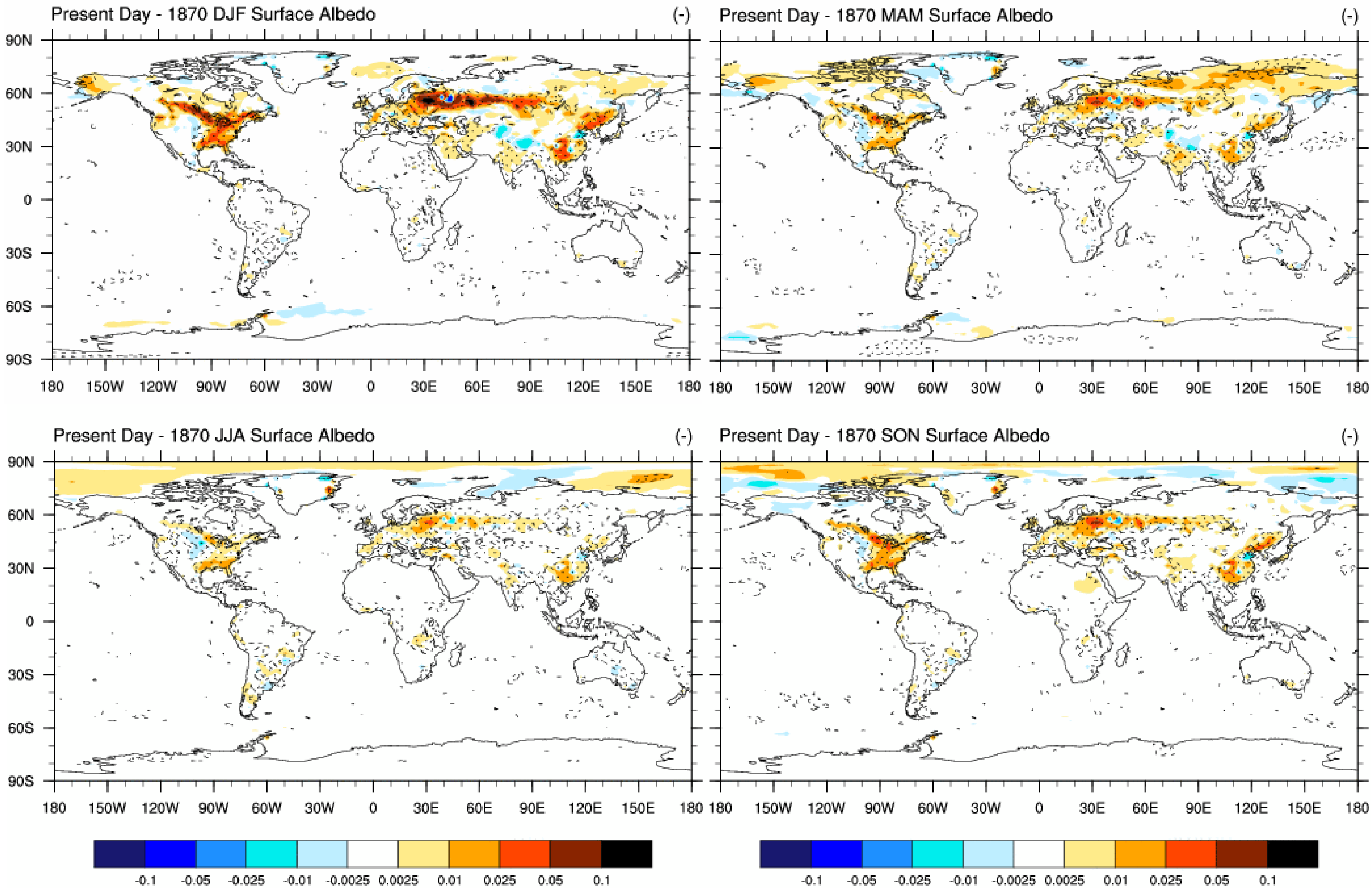


Tropical forest – cooling from higher surface albedo of cropland and pastureland is offset by warming associated with reduced evapotranspiration

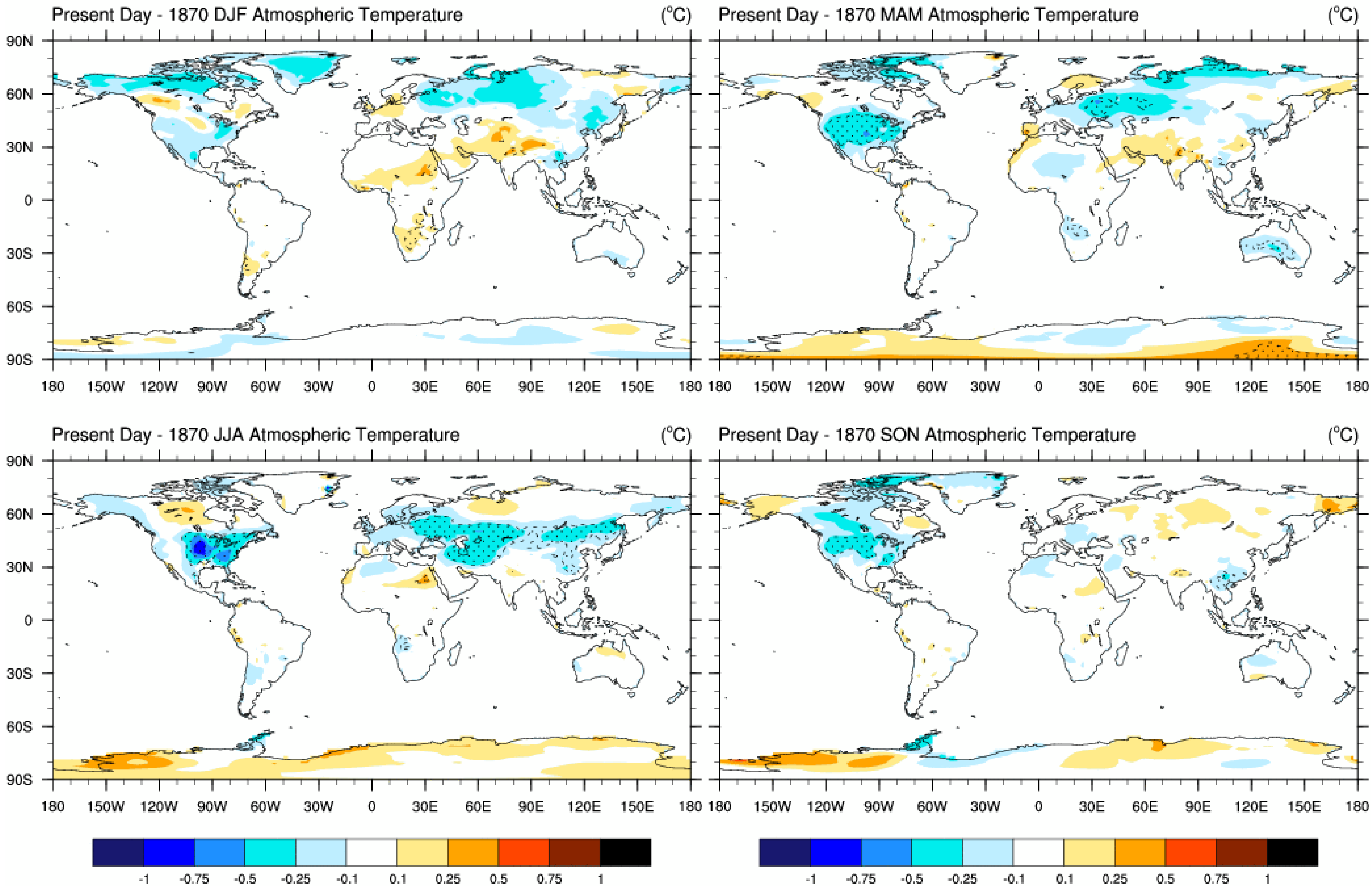
Temperate forest - higher albedo leads to cooling, but changes in evapotranspiration can either enhance or mitigate this cooling

Bonan (2008) Science 320:1444-1449

Albedo forcing, 1992-1870



Near-surface temperature, 1992-1870



Conclusions

The ecology of climate models

- Detailed representation of ecosystems
- Allows exploration of ecological feedbacks and mitigation options, principally related to albedo, evapotranspiration, and carbon

Carbon cycle

- CO_2 fertilization enhances carbon gain, diminished by carbon loss with warming
- N cycle reduces the concentration–carbon gain and decreases climate–carbon loss
- The CO_2 fertilization effect is larger than the climate feedback effect

Human influences on the biosphere - land use and land cover change

Biogeochemistry
- Land use flux is important, especially the wood harvest flux
- Uncertainty in land use flux may be greater than the N-cycle feedback

Biogeophysics
- Higher albedo of croplands cools climate
- Less certainty about role of evapotranspiration
- Implementation of land cover change (spatial extent, crop parameterization) matters

Climate benefits of 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.

Ecology or climatology

Climatic Interpretation

Lamb (1977) Climate: Present, Past and Future. Volume 2, Climatic History and the Future

Lamb (1995) Climate, History and the Modern World

- Painted in the winter of 1565
- Records Bruegel's impression of severe winter
- Start of a long interest in Dutch winter landscapes that coincided with an extended period of colder than usual winters

Ecological Interpretation

Forman & Godron (1986) Landscape Ecology

Defines ecological concept of a landscape
- heterogeneity of landscape elements
- spatial scale
- movement across the landscape

Pieter Bruegel the Elder's 'Hunters in the Snow'

Bonan (2008) Ecological Climatology. 2nd ed (Cambridge Univ. Press)