Climate change mitigation through ecosystem management – fact, fantasy, and possibility

Gordon Bonan
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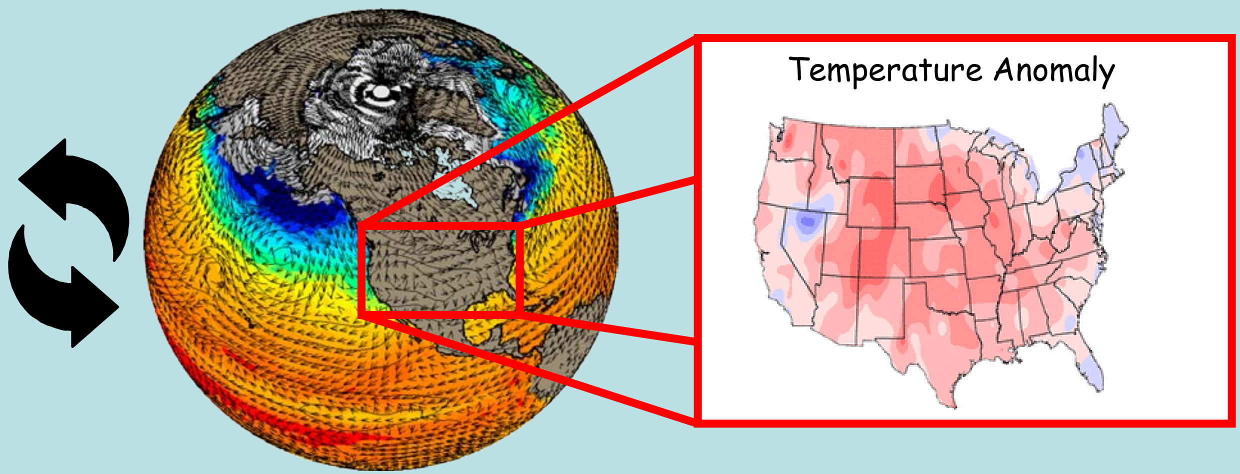

Department of Atmospheric Sciences
University of Illinois
Urbana, IL
February 25, 2009

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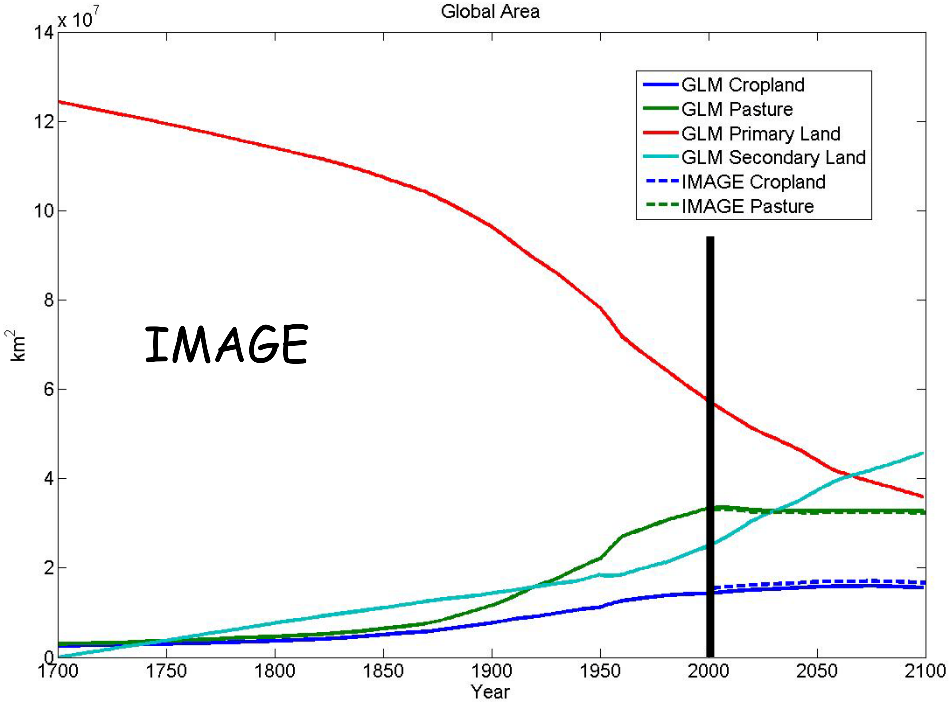
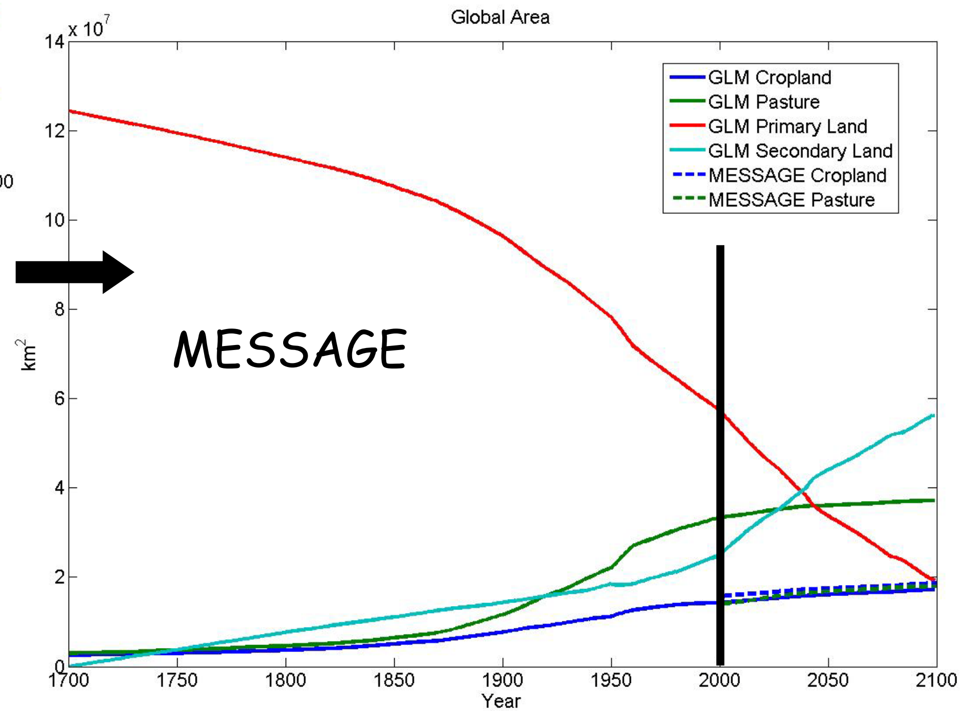
Global land cover change



Land use alters:

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

Less primary land, more secondary land, more cropland and pastureland



For 5th assessment report

- o What is the land use climate forcing?
- o Can ecosystems be managed to mitigate climate change?

George Hurtt et al. (UNH), unpublished

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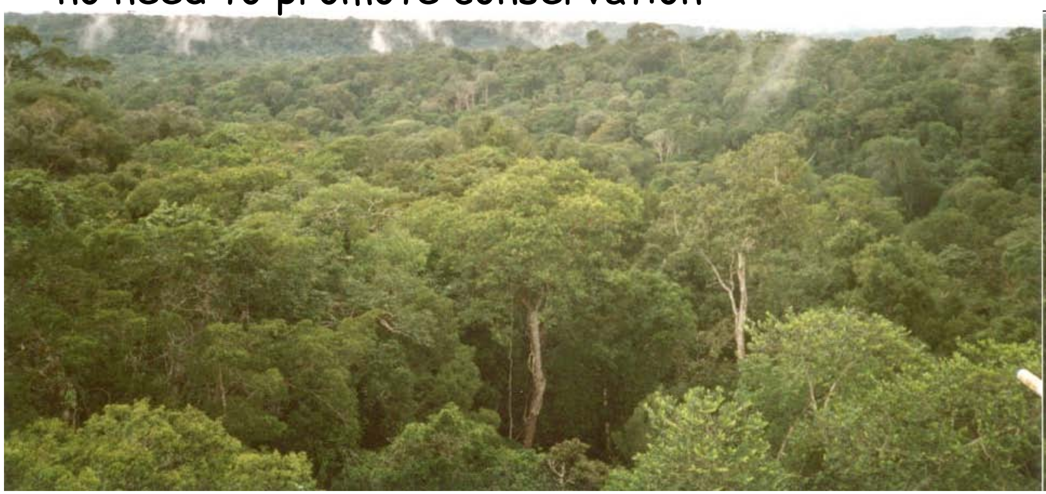
Ecosystems and climate policy

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

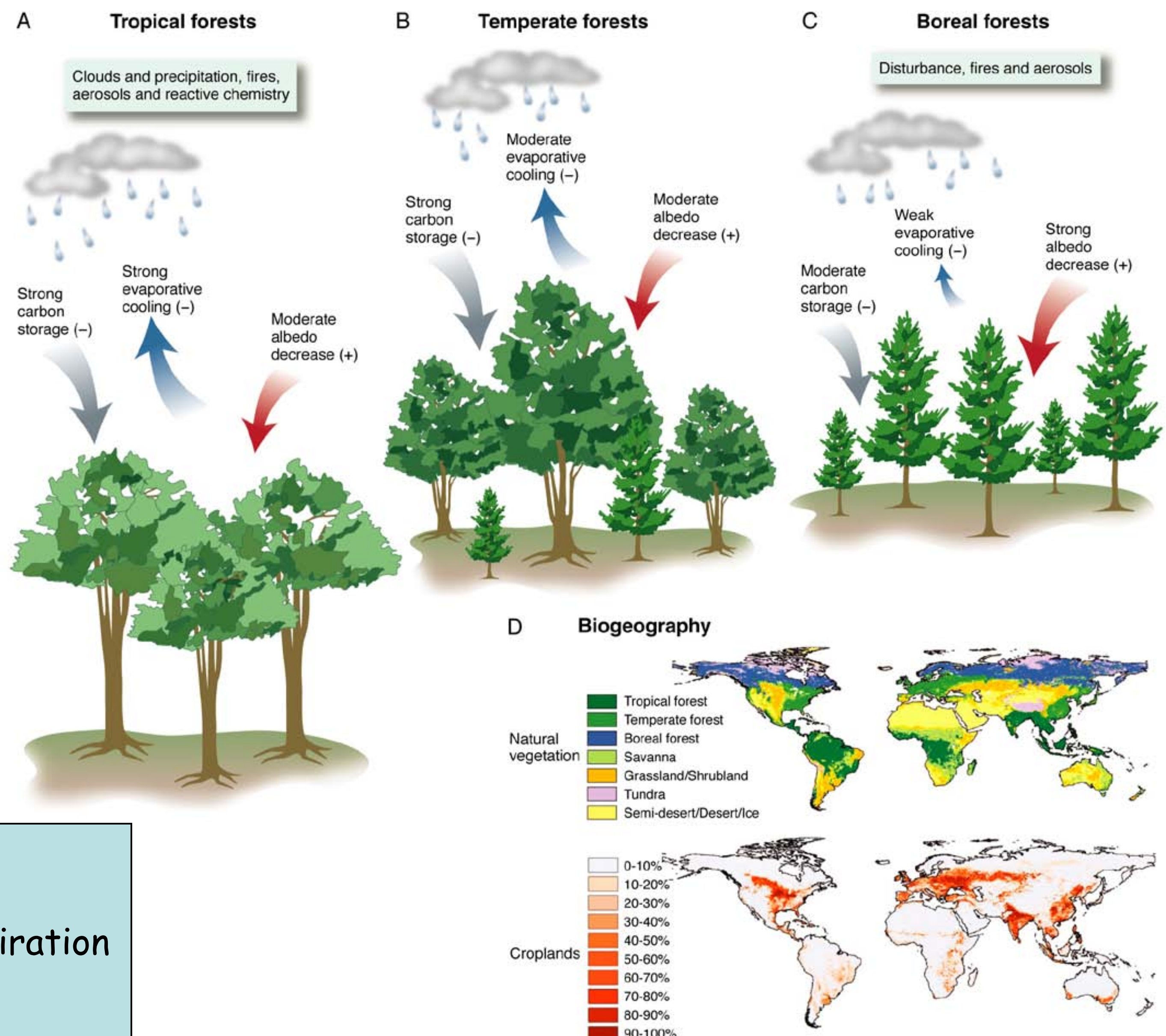
Temperate forest – reforestation and afforestation?



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

Biofuel plantations to lower albedo and reduce atmospheric CO_2

Forests and climate change

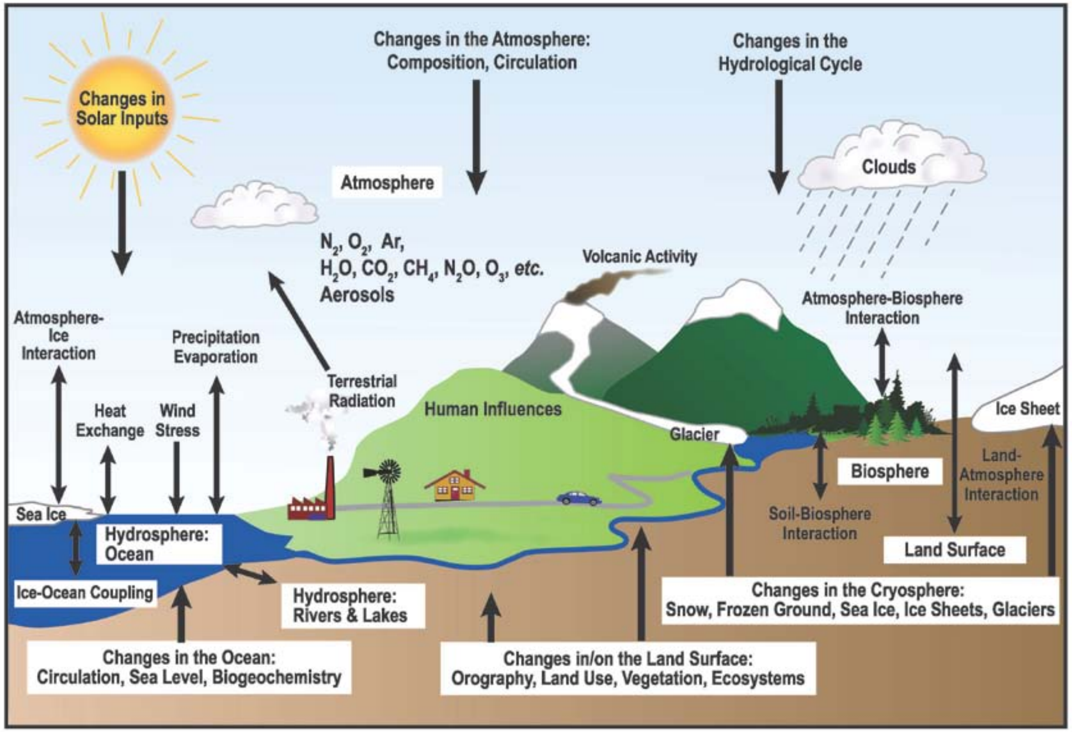


Biogeophysical
- Albedo
- Evapotranspiration

Biogeochemical
- Carbon

Bonan (2008) Science 320:1444-1449

The Earth system



(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

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The Community Land Model

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

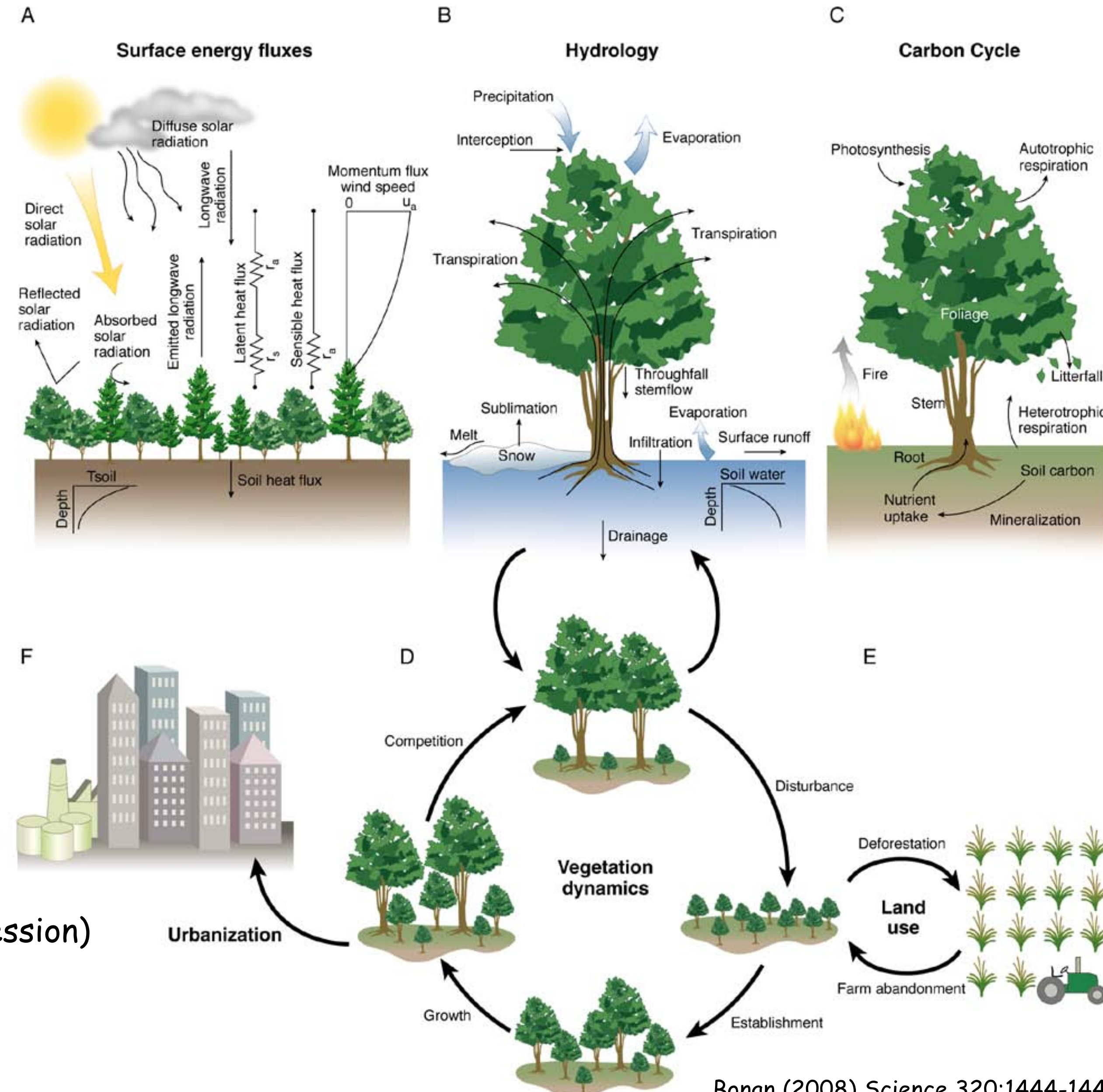
Oleson et al. (2004) NCAR/TN-461+STR

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

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

Spatial scale
2.5° longitude × 1.875° latitude

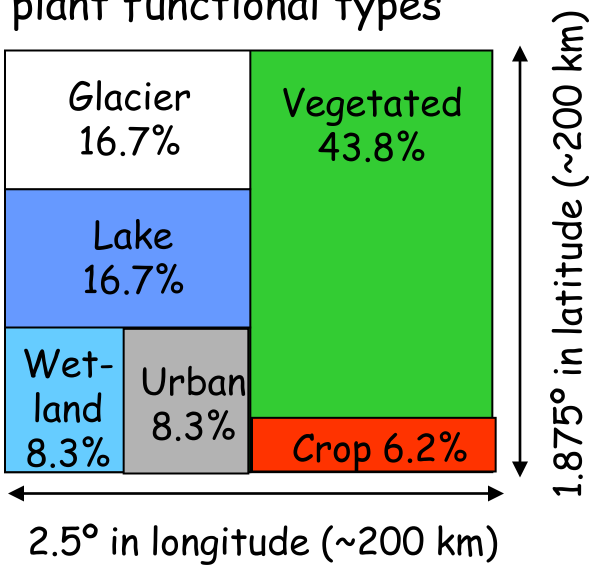
Temporal scale
- <30-minute coupling with atmosphere
- Seasonal-to-interannual variability (phenology)
- Decadal-to-century climate (disturbance, land use, succession)
- Paleoclimate (biogeography)



Bonan (2008) Science 320:1444-1449

Land surface heterogeneity

Subgrid land cover and plant functional types



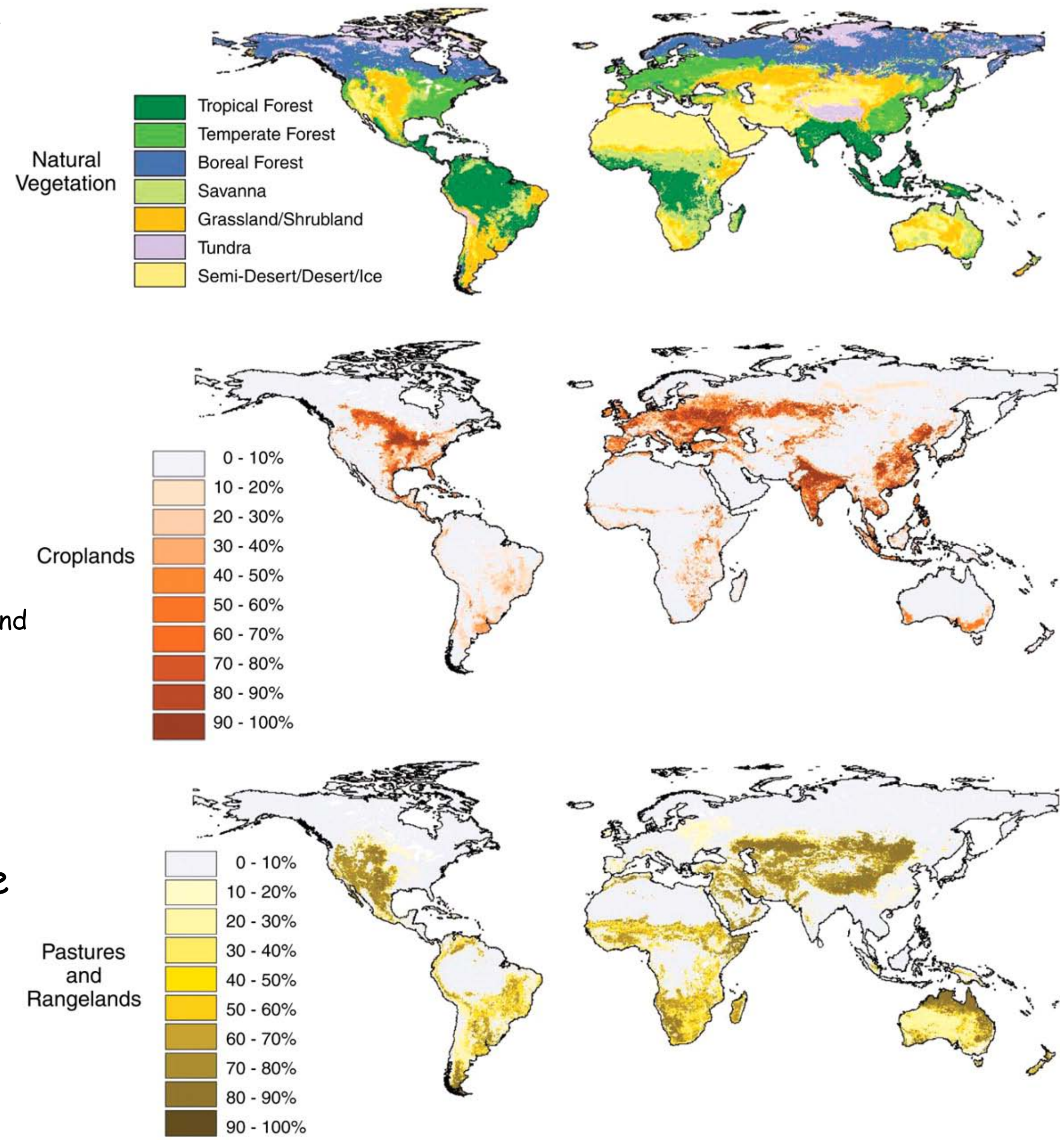
CLM represents a model grid cell as a mosaic of up to 6 primary land cover types. Vegetated land is further represented as a mosaic of several plant functional types

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

Global land use

Local land use is spatially heterogeneous

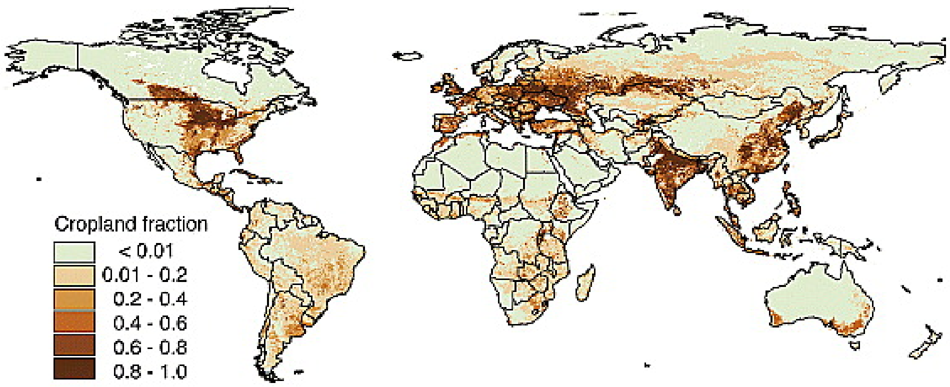
NSF/NCAR C-130 aircraft above a patchwork of agricultural land during a research flight over Colorado and northern Mexico



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

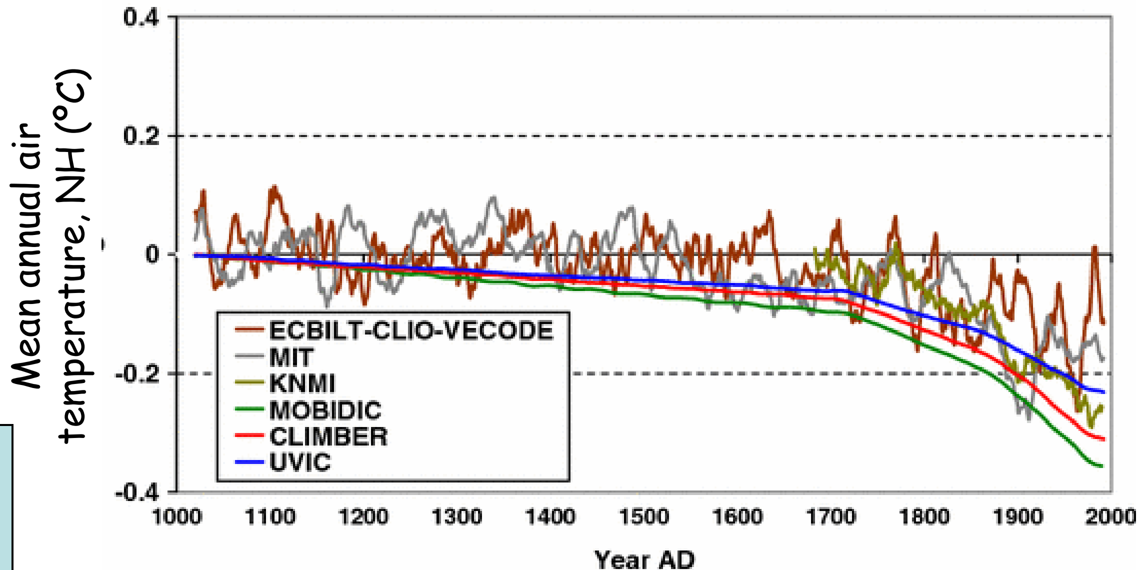
Global land use is abstracted to the fractional area of crops and pasture

Historical 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)

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

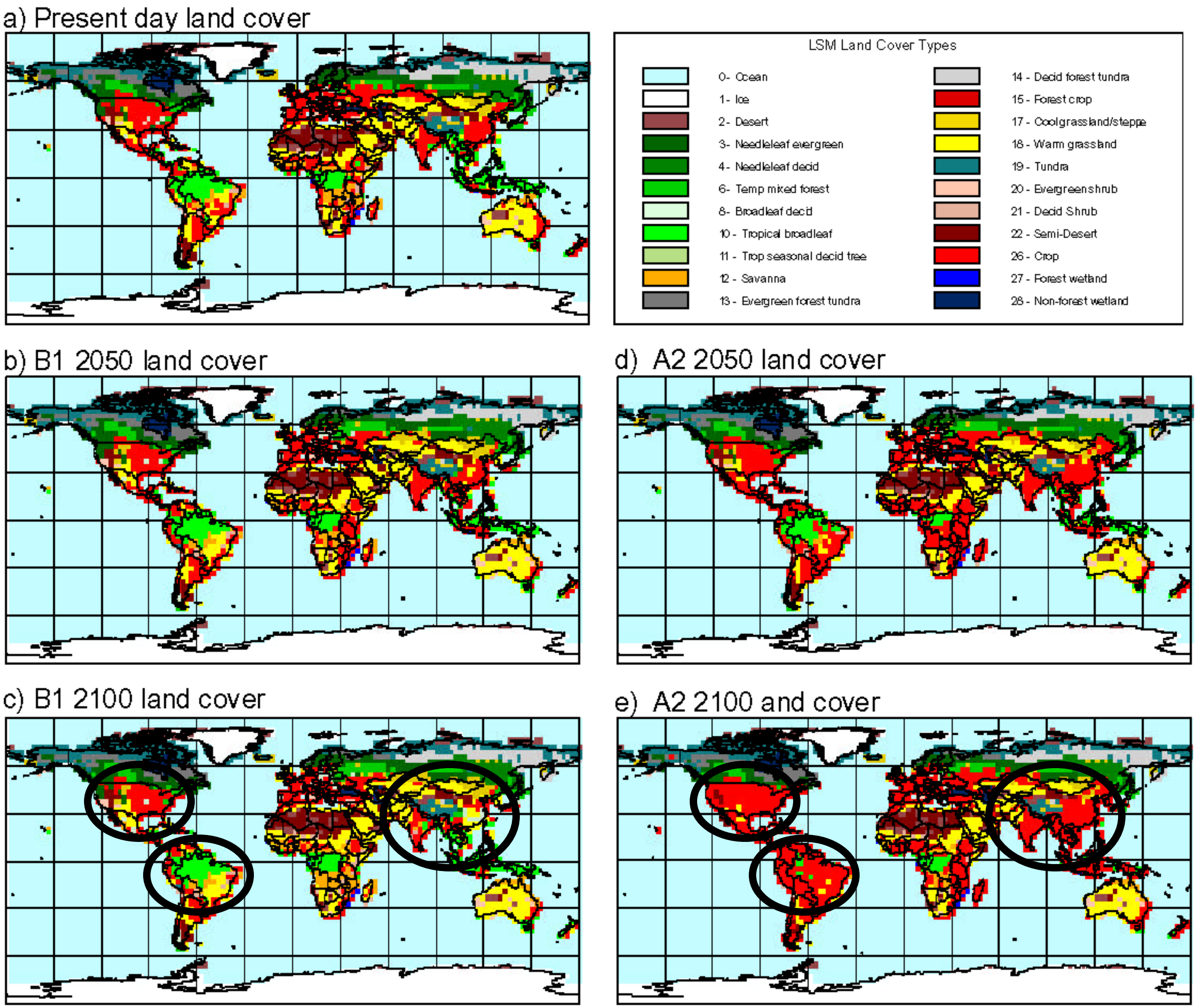


Brovkin et al. (2006) Climate Dynamics 26:587-600

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

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

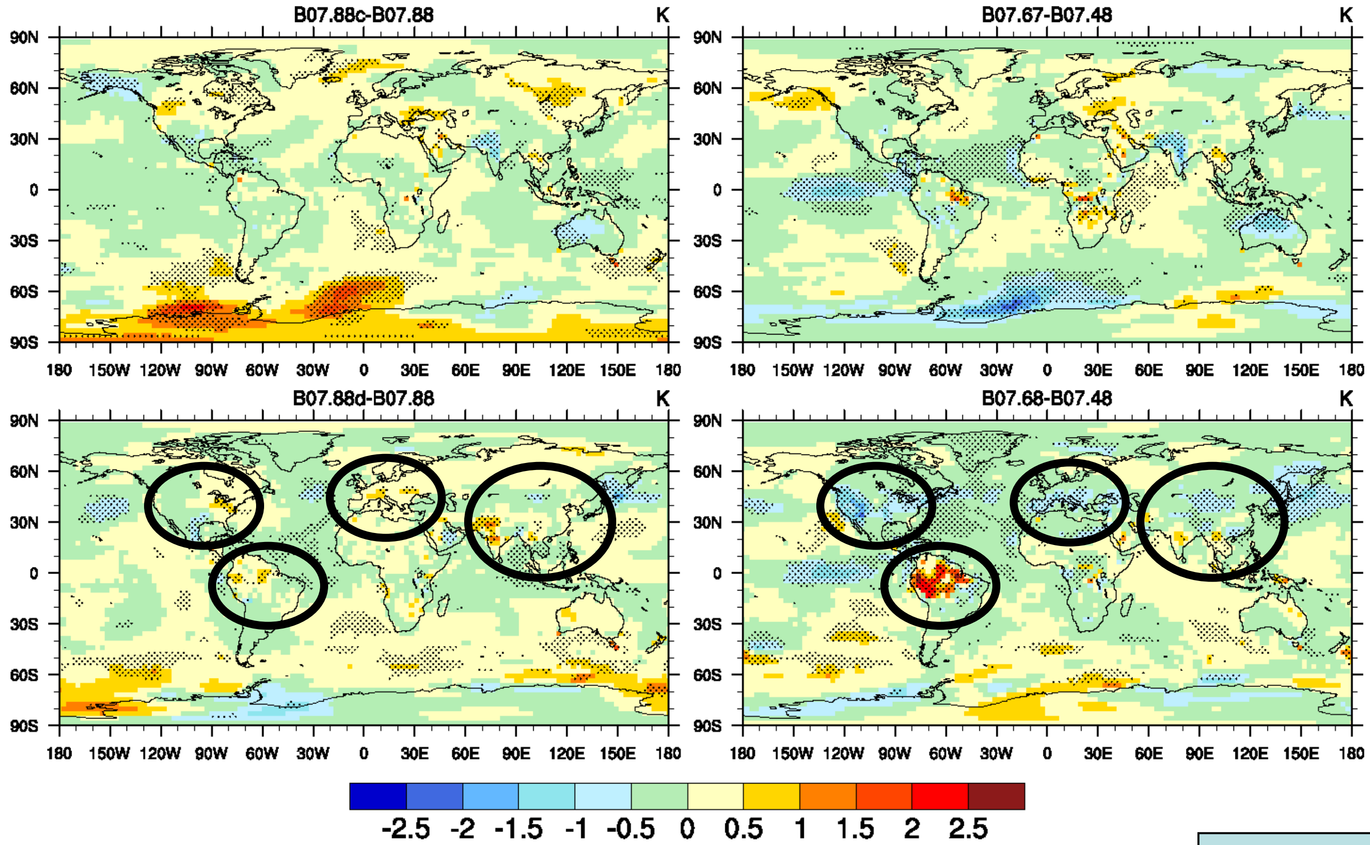
Future land cover change

Change in temperature due to land cover

SRES B1 JJA reference height temperature SRES A2

2050

2100



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

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

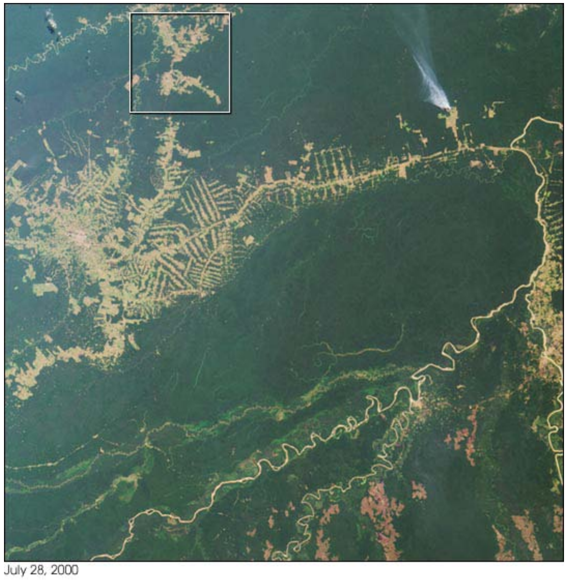
Land use choices affect climate

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

Land use and carbon

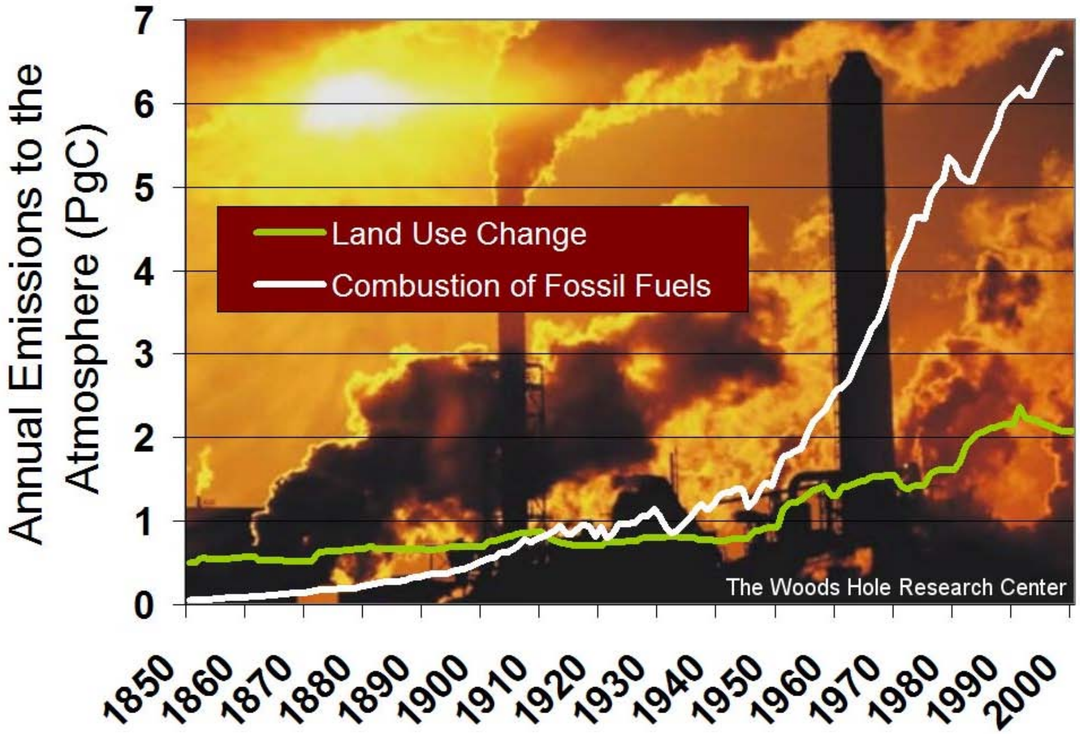
There is a net flux of carbon to the atmosphere from changes in land use

- 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.



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Integrated land cover change (2100)

Biogeophysical

A2 – cooling with widespread cropland

B1 – warming with temperate reforestation

Biogeochemical

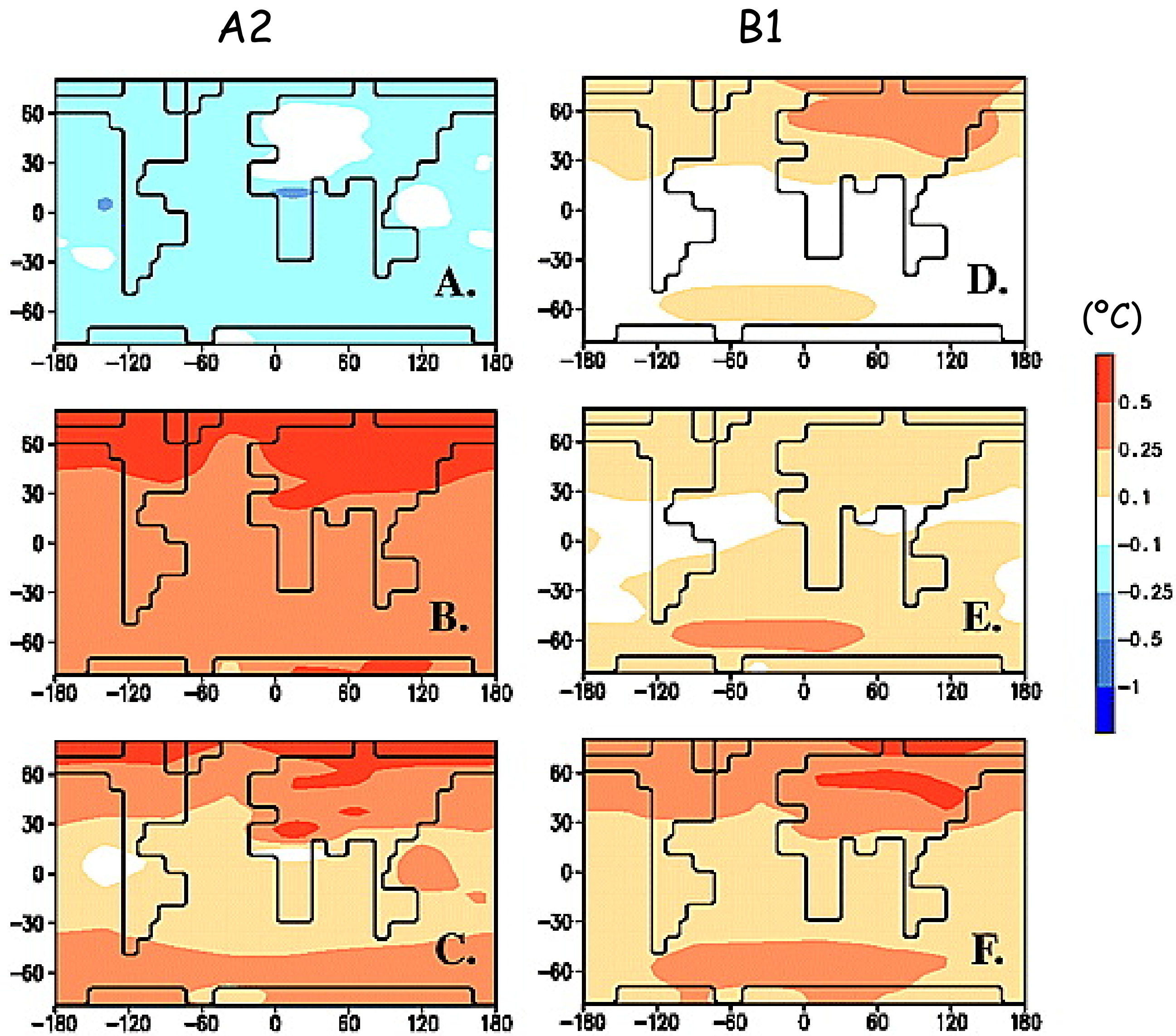
A2 – large warming with widespread deforestation

B1 – weak warming; less tropical deforestation; temperate reforestation

Net effect

A2 – BGC warming offsets BGP cooling

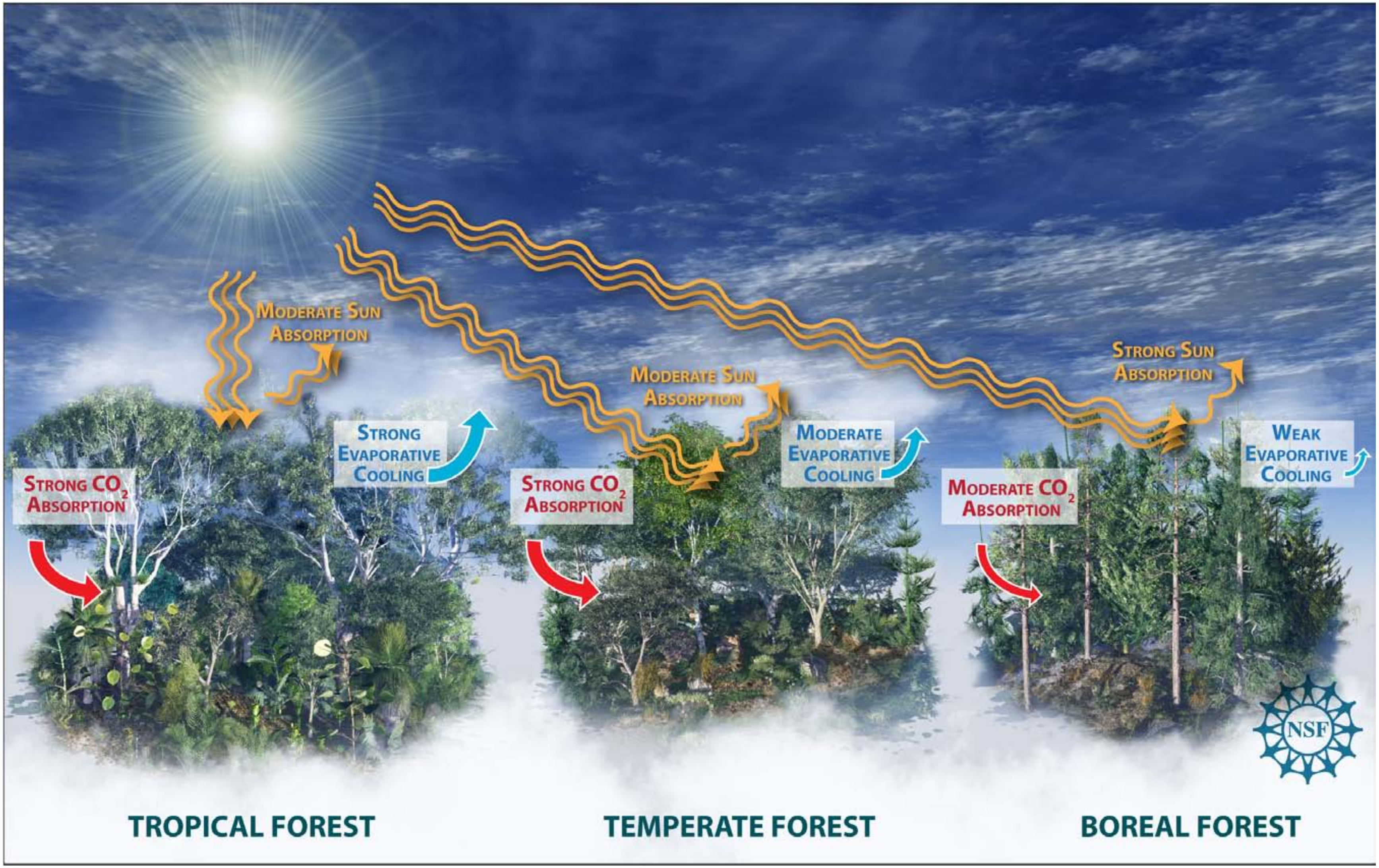
B1 – moderate BGP warming augments weak BGC warming



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

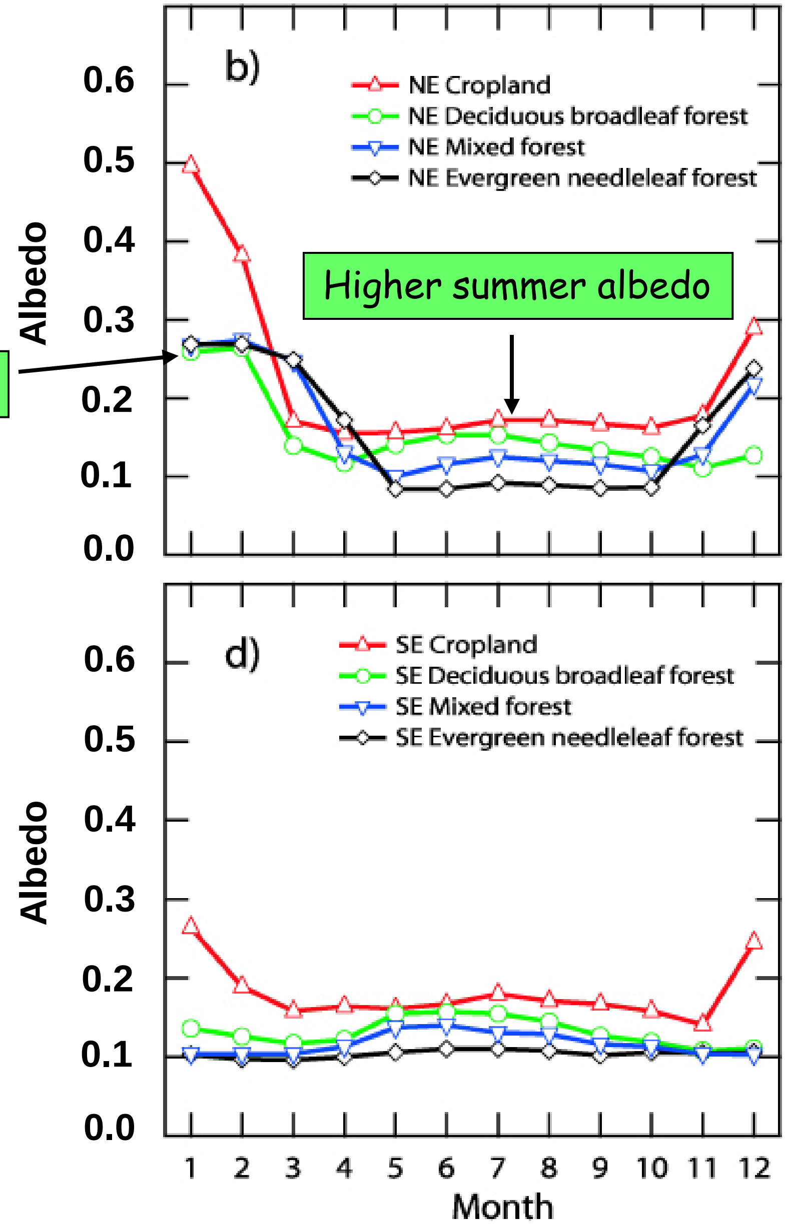
Credit: *Nicolle Rager Fuller, National Science Foundation*

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



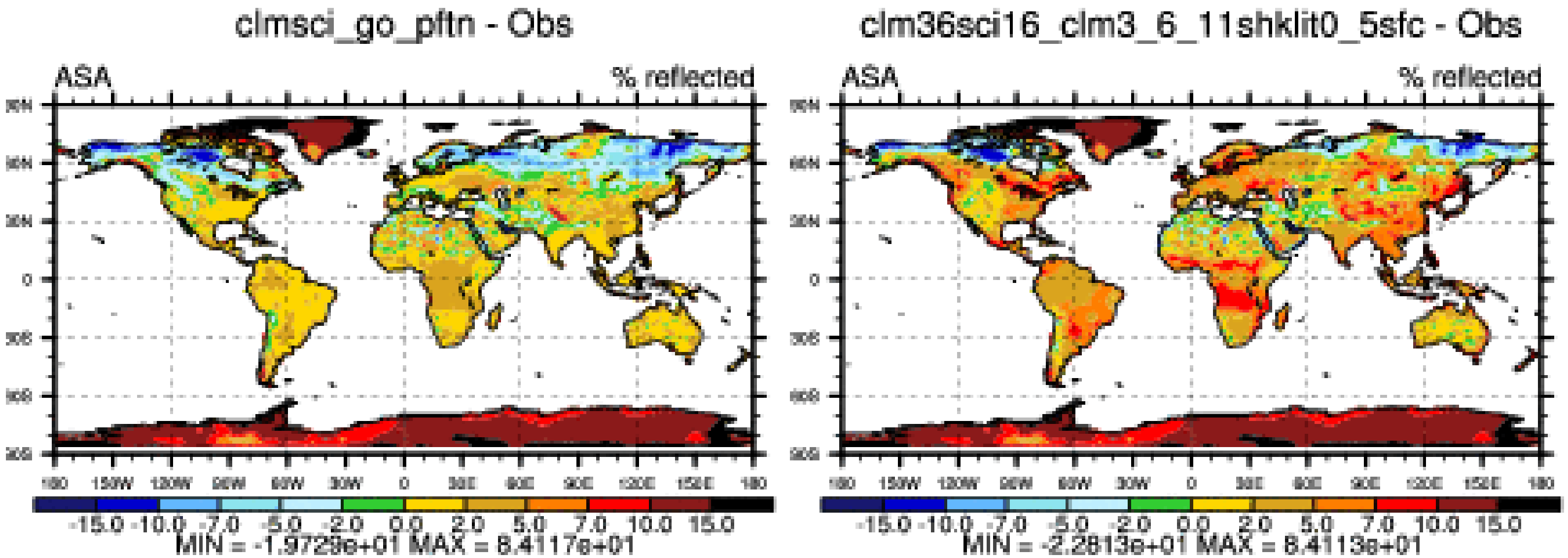
Cropland has a high winter and summer albedo compared with forest

Surface albedo

- Reinterpret MODIS VCF herbaceous fraction in forests
- Optical properties of grasses are much less reflective in both the visible and near infrared (Asner et al. 1998. Remote Sens. Environ. 63:200-215)

Annual all-sky albedo

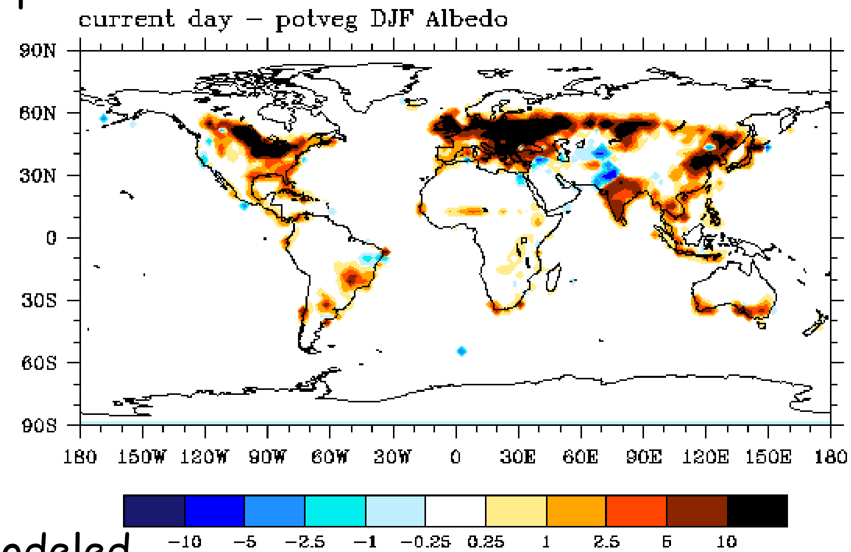
CLM4 | CLM3.5

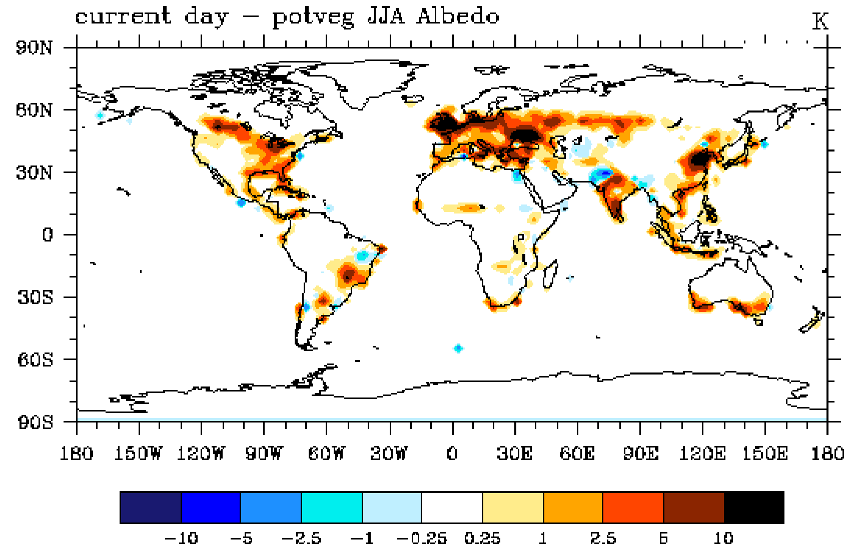


Units are Δalbedo $\times$ 100

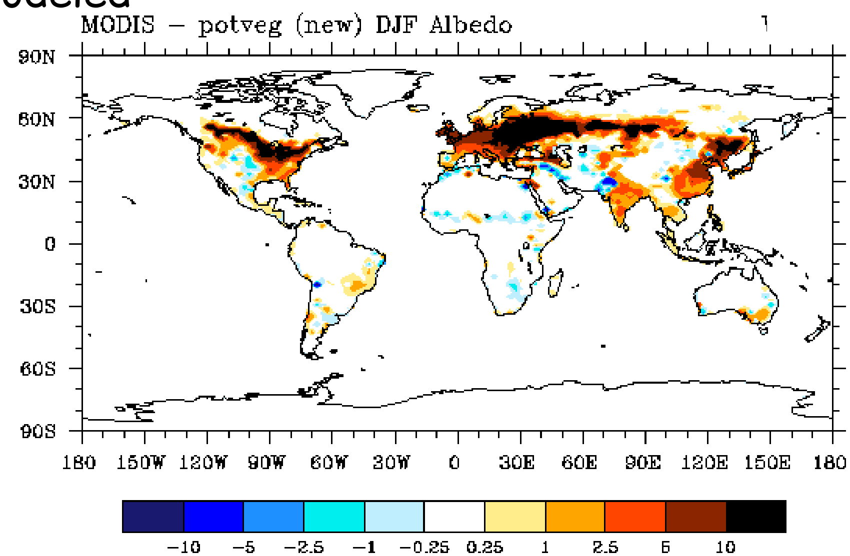
Albedo land use forcing

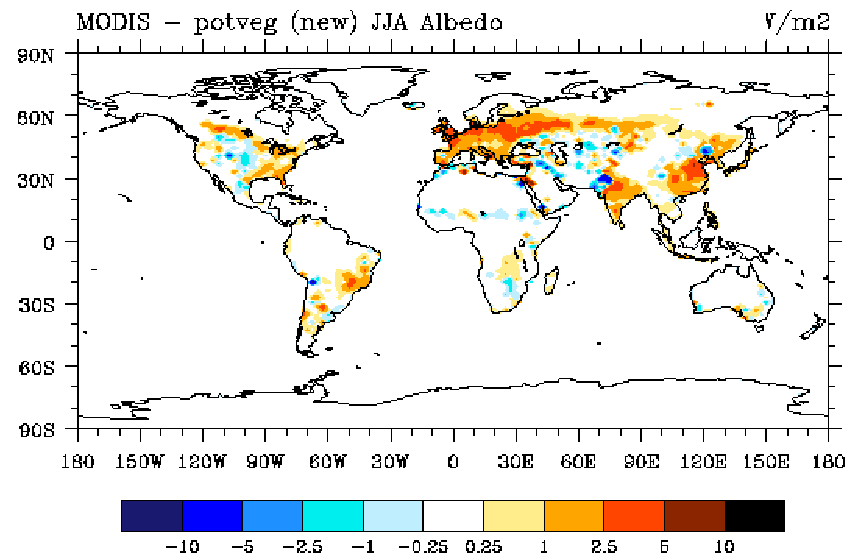
Expected





Modeled

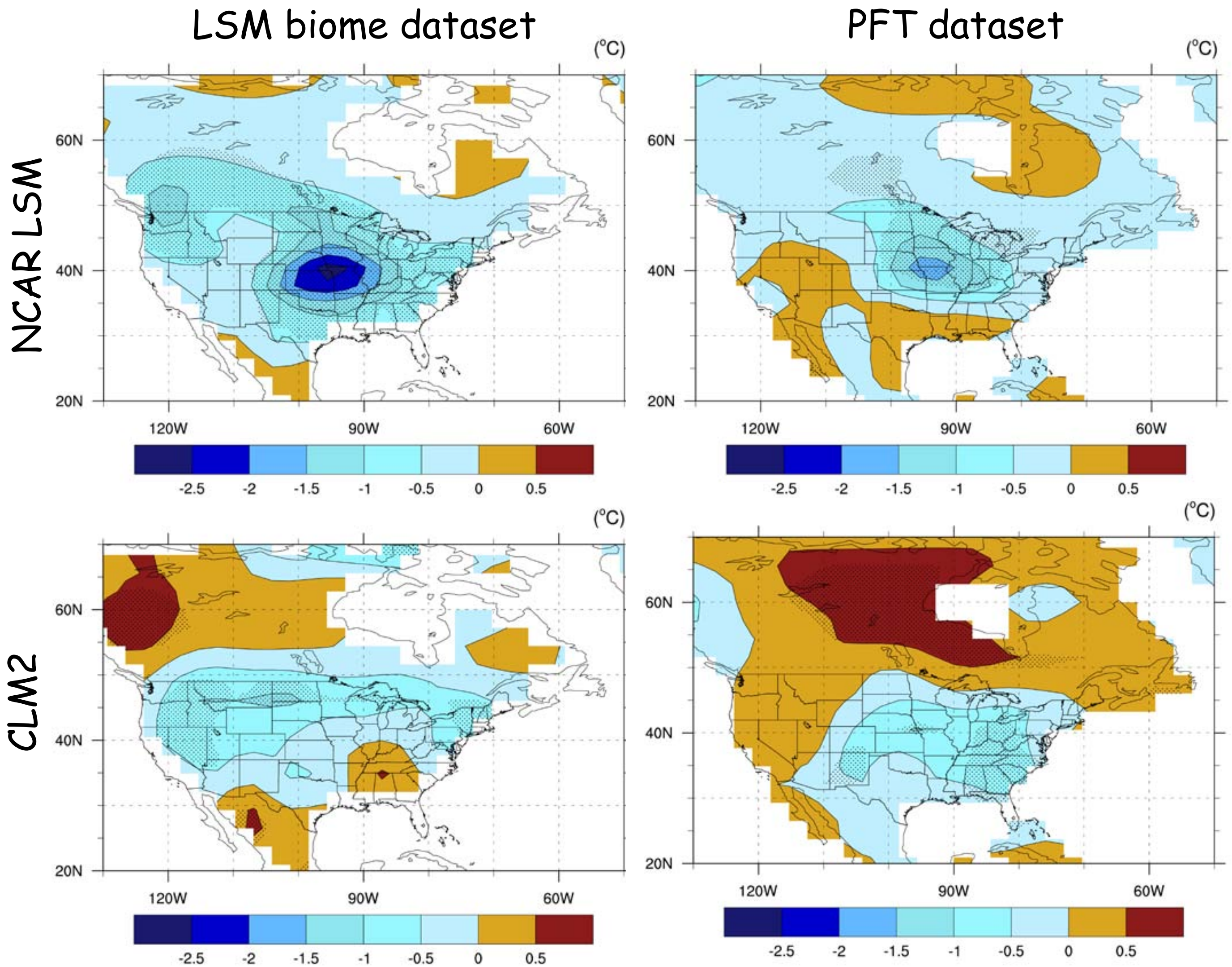




Units are Δalbedo $\times$ 100

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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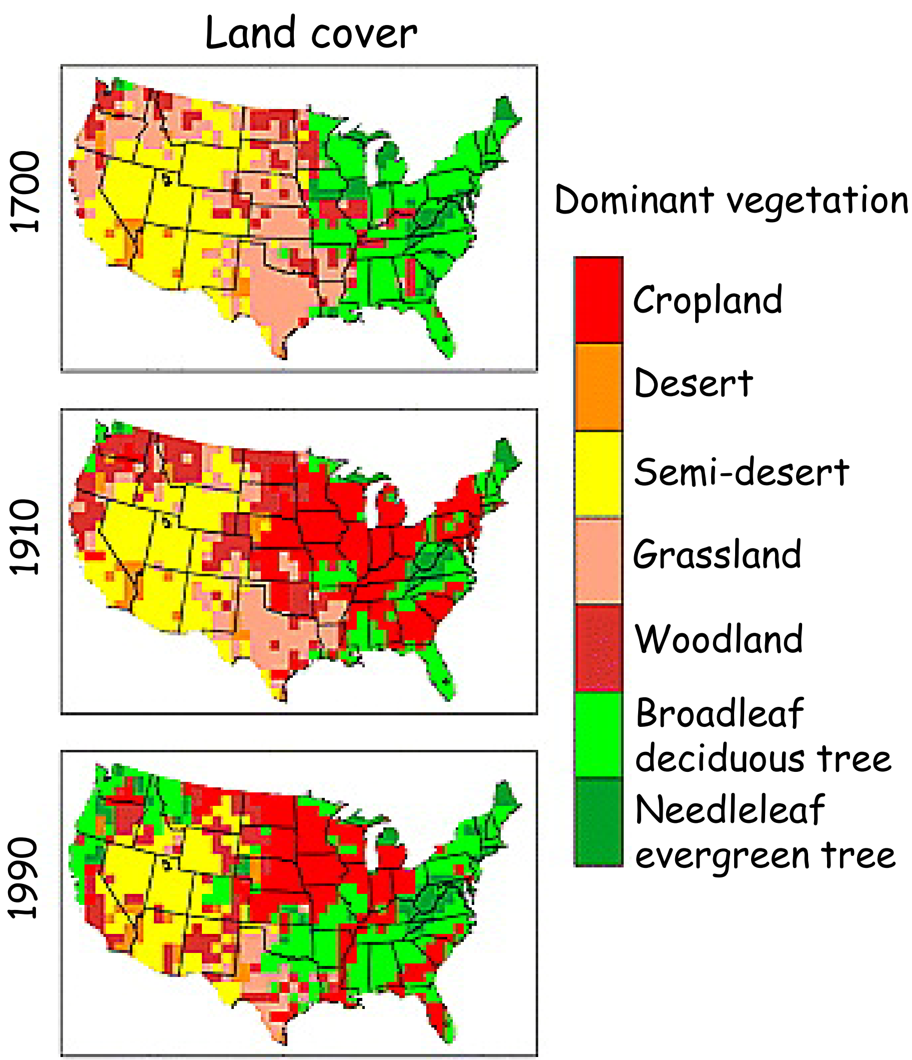
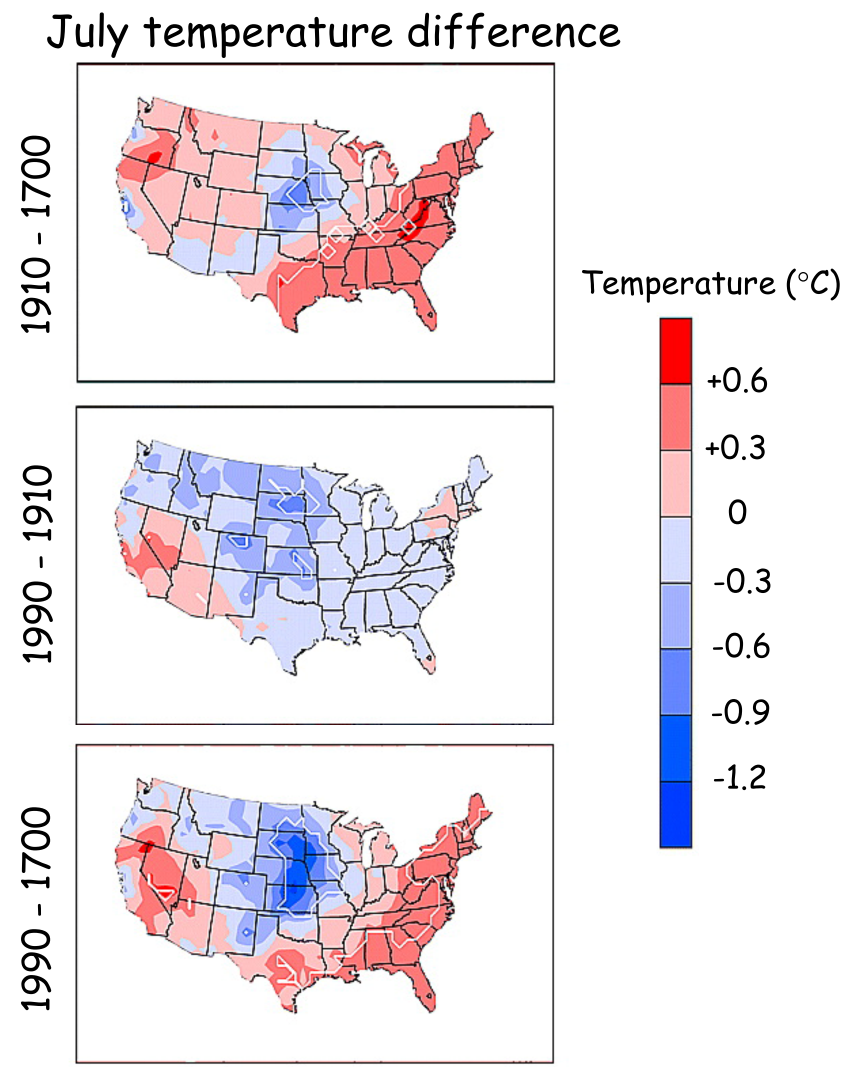
Temperate deforestation warms climate

RAMS with LEAF-2
6-member July simulations





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

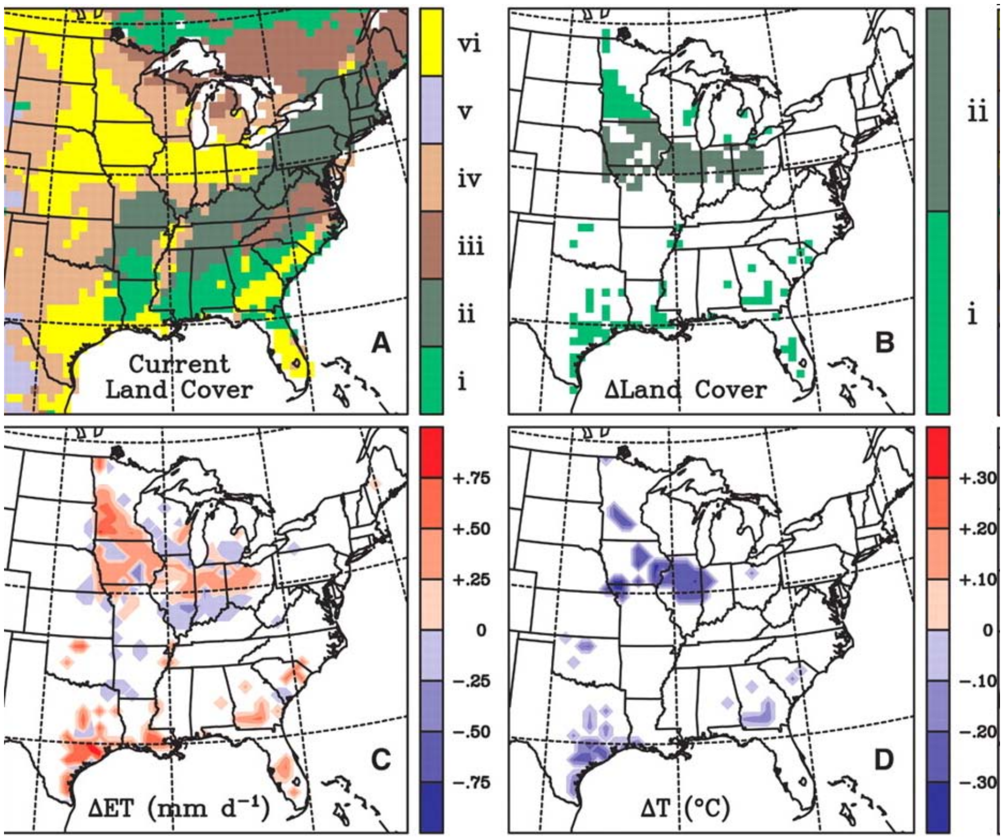
Reforestation cools climate

Regional climate model
RAMS with LEAF-2

(**A**) Dominant land-cover type: (i) evergreen needleleaf forest, (ii) deciduous broadleaf forest, (iii) other forest, (iv) grass/shrubland, (v) desert/semi-desert, and (vi) farmland.

(**B**) Model grid cells where crops and pasture were replaced by softwood (i) and hardwood (ii) plantations

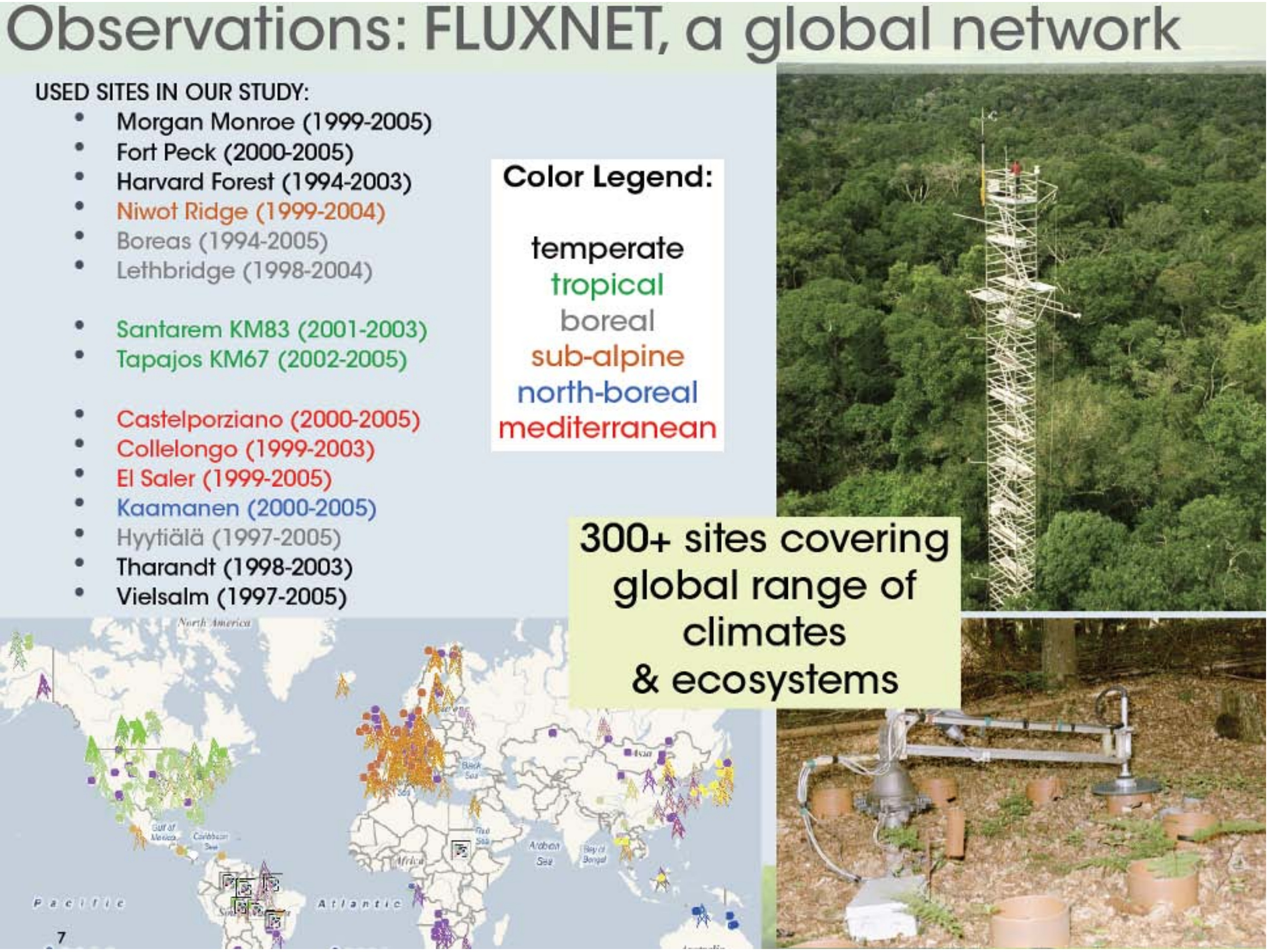
11-member July simulations



Plantations increase summer evapotranspiration and decrease summer surface air temperature

Jackson et al. (2005) Science 310:1944-1947

Use of FLUXNET in the Community Land Model development



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

15 sites

Climate gradient
Tundra, boreal, subalpine, temperate, Mediterranean, tropical

Ecological gradient
Evergreen broadleaf forest
Deciduous broadleaf forest
Evergreen needleleaf forest
Mixed forest
Grassland

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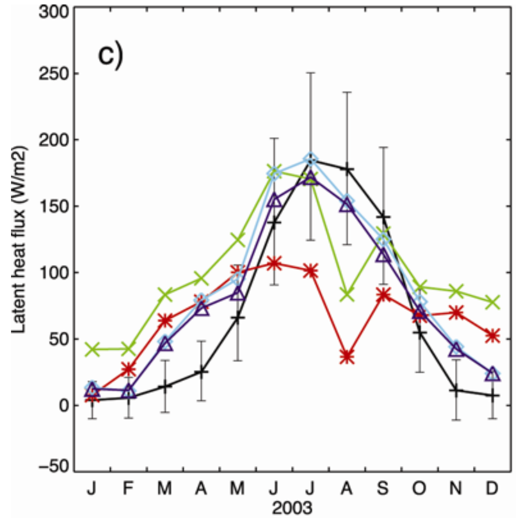
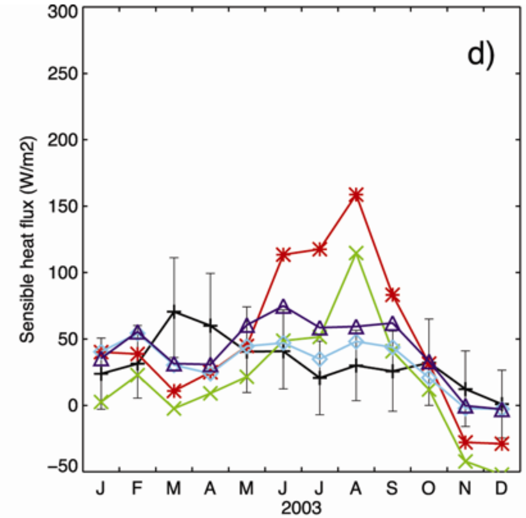
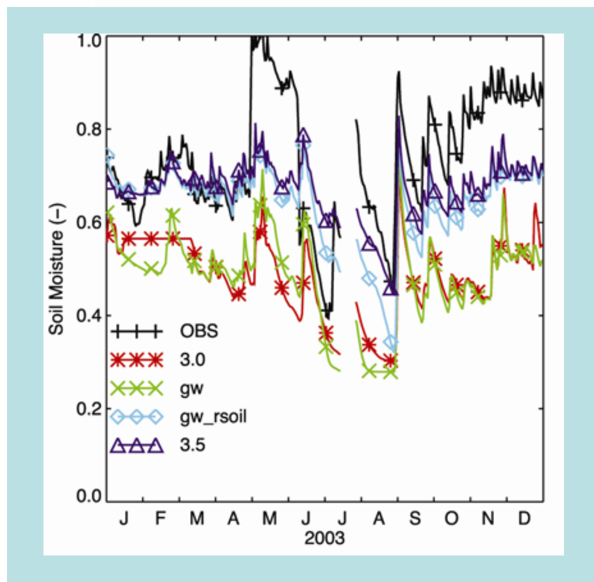
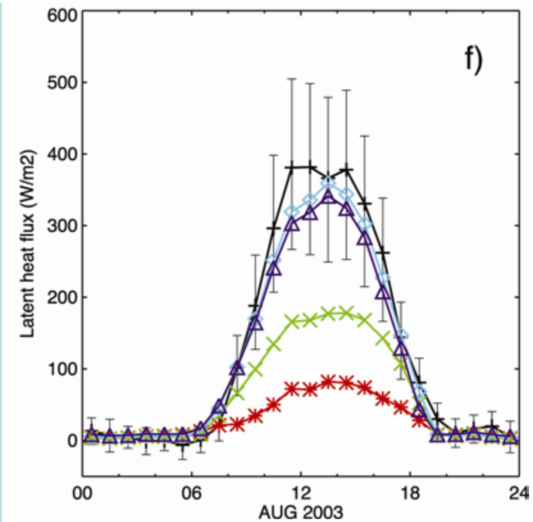
Flux tower measurements

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

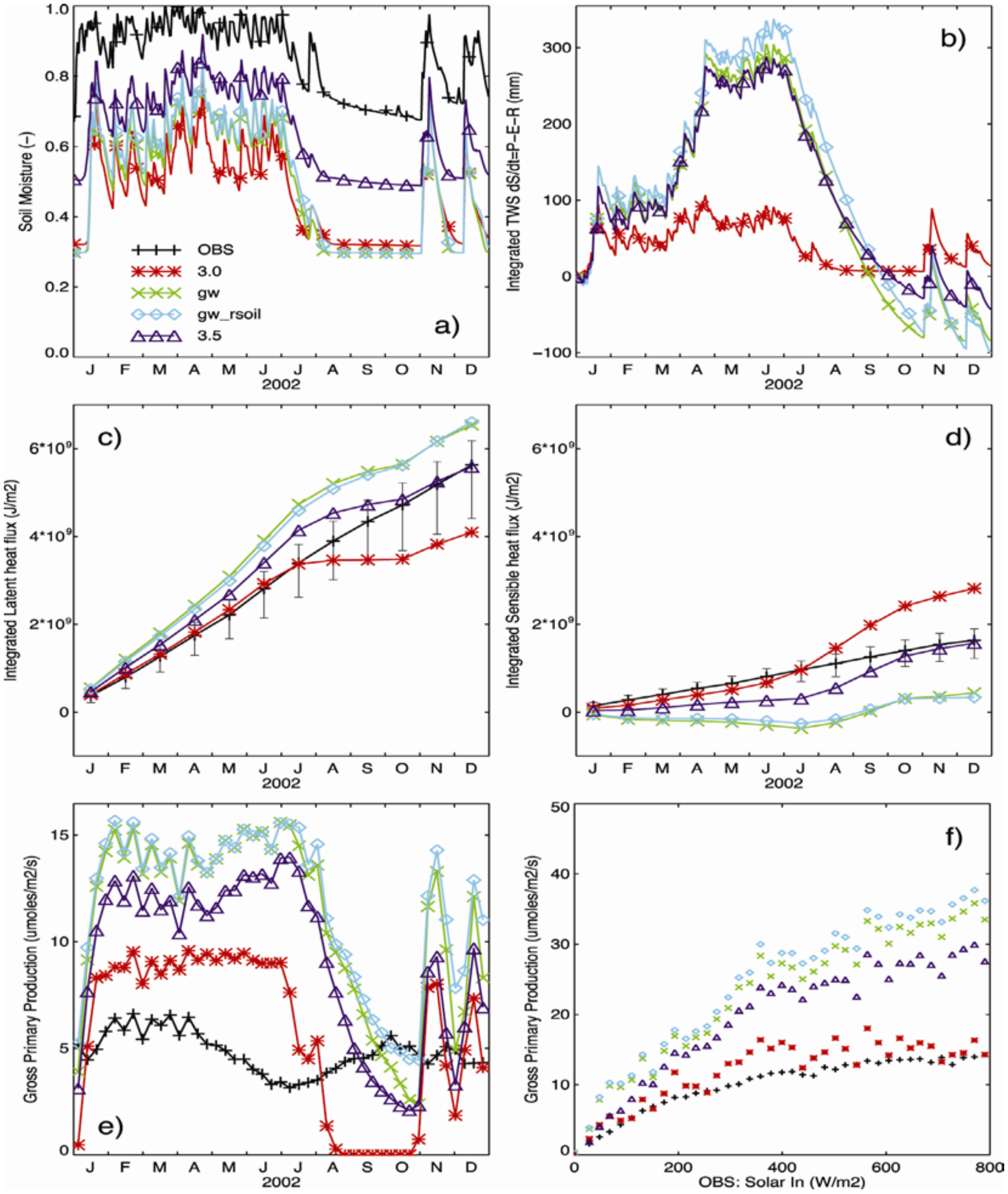
Stöckli et al. (2008) JGR, 113, doi:10.1029/2007JG000562

Flux tower measurements – tropical evergreen forest

Tropical evergreen forest
(Santarem KM83, Brazil)

CLM3 – dry soil, low dry season latent heat flux, high dry season sensible heat flux

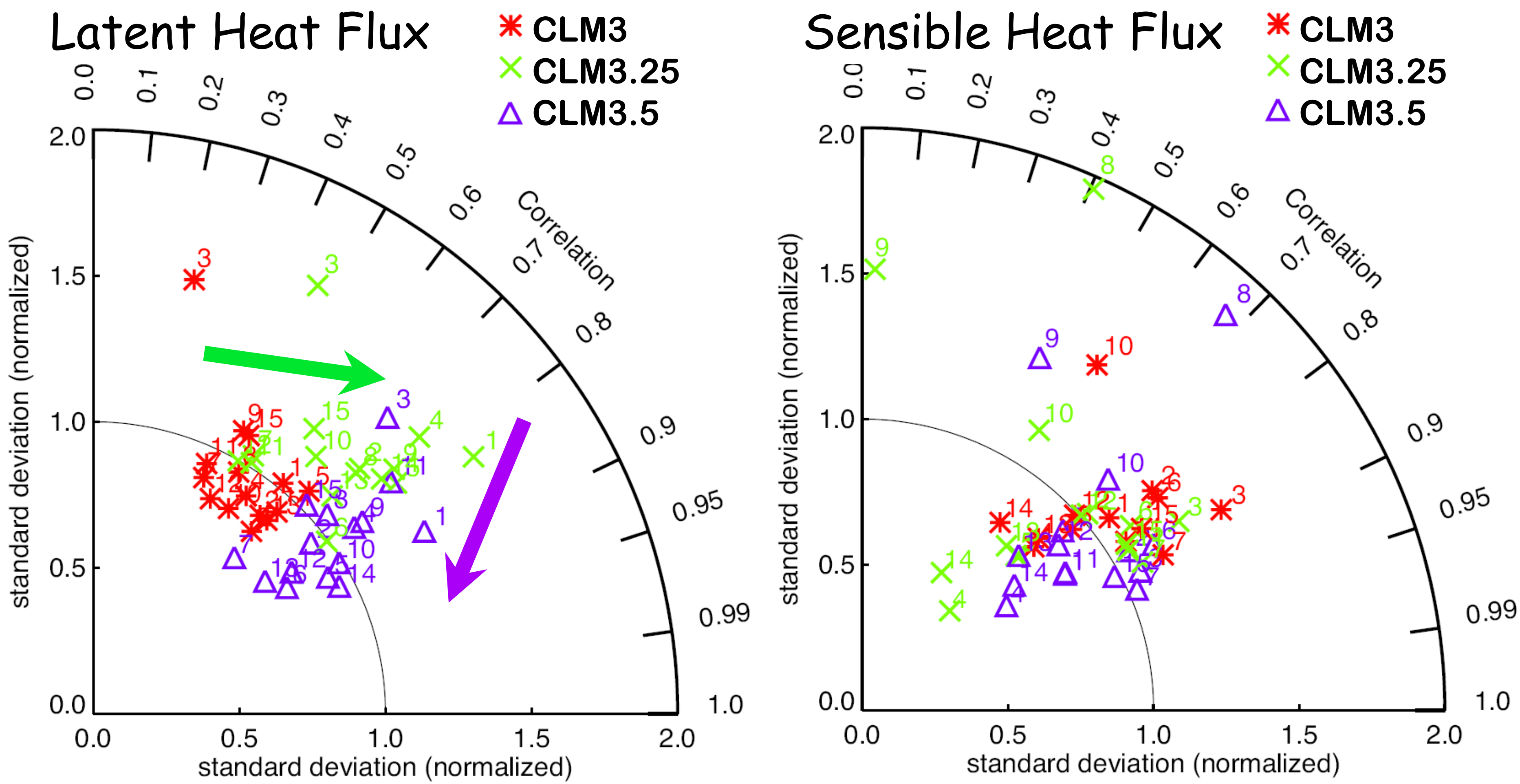
CLM3.5 – wetter soil and higher latent heat flux during dry season



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

Flux tower measurements – all sites

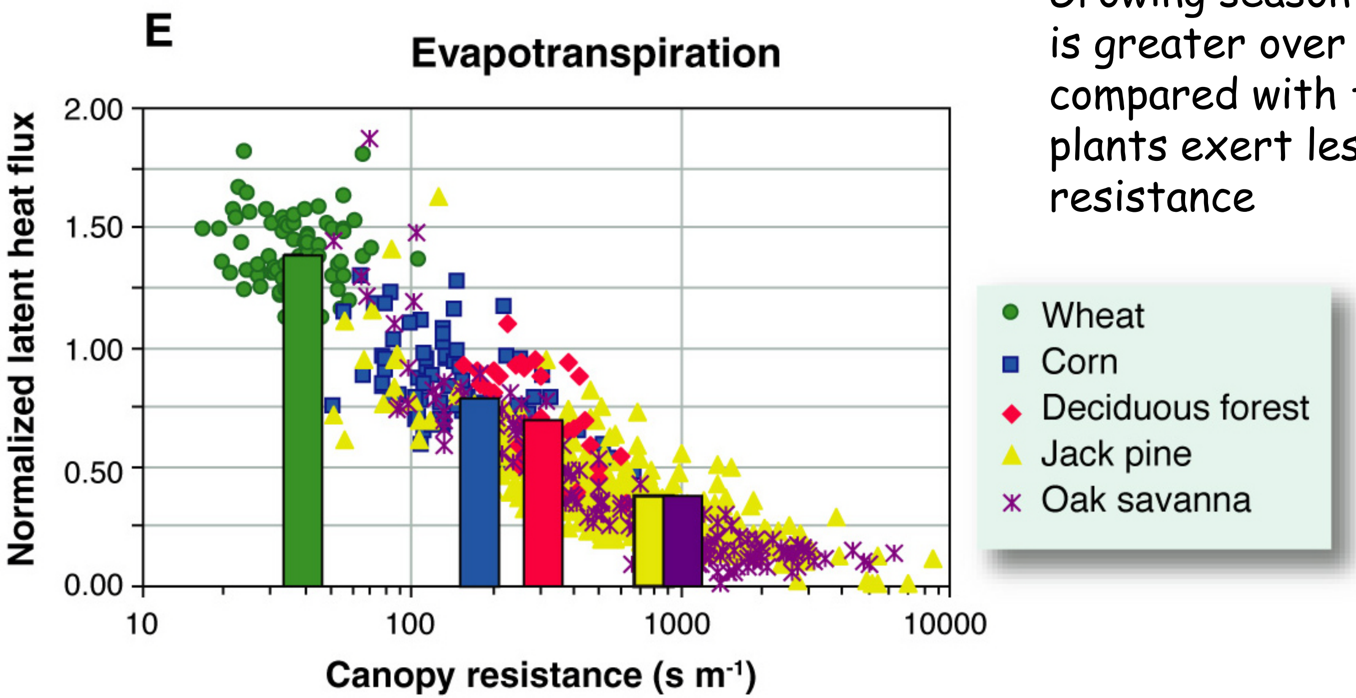
Multi-site, multi-year synthesis



CLM3.25 – increases correlation with observations
CLM3.5 – reduces variance compared with observations

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

Crop latent heat flux



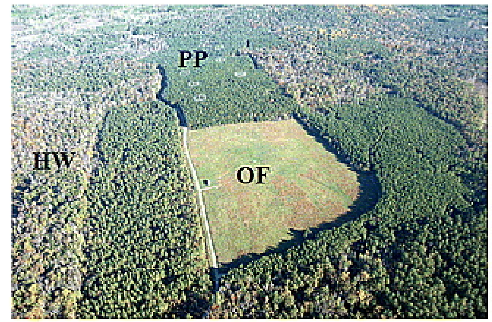
Bonan (2008) Science 320:1444-1449

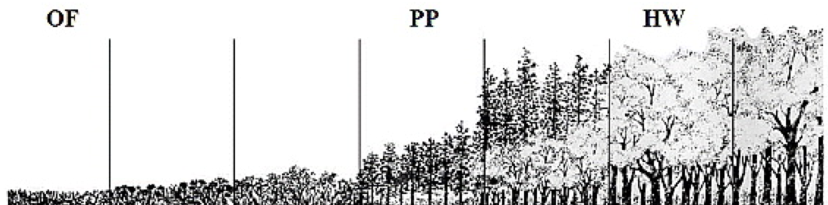
Growing season evaporative cooling is greater over watered crops compared with forests and these plants exert less evaporative resistance

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 (-)

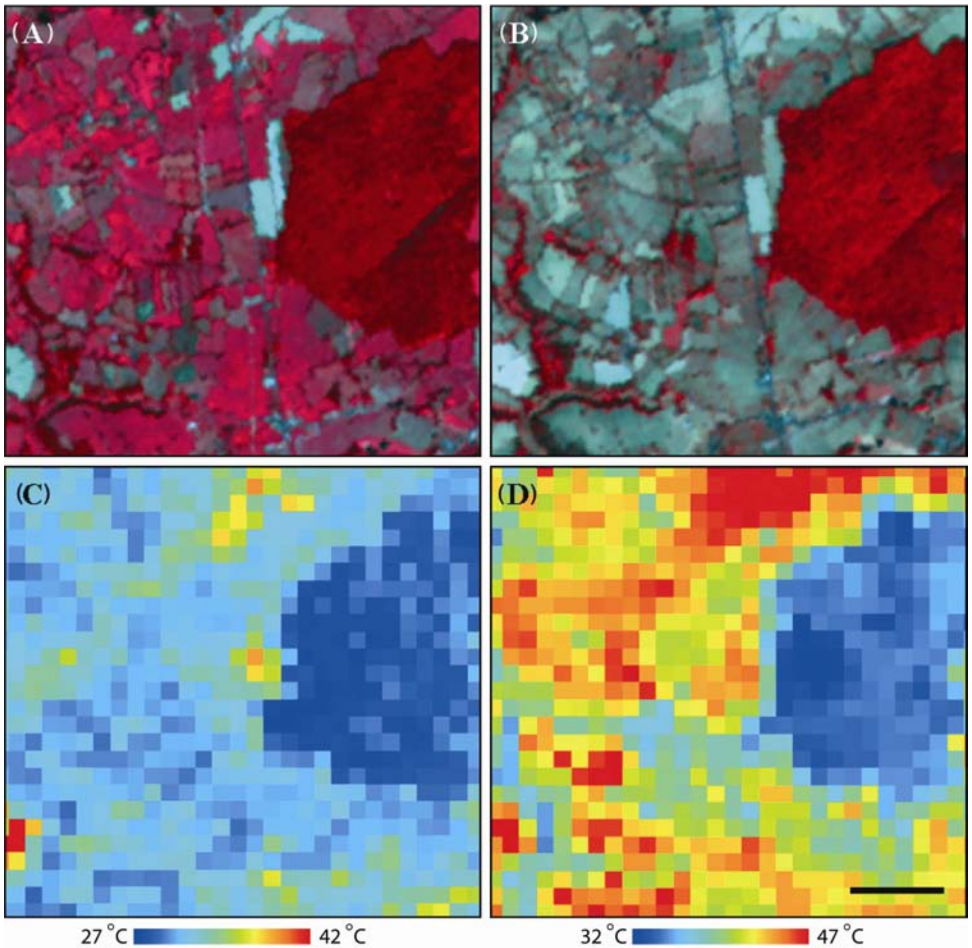
Juang et al. (2007) GRL, 34, doi:10.1029/2007GL031296

Soil water affects the Δ(forest–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

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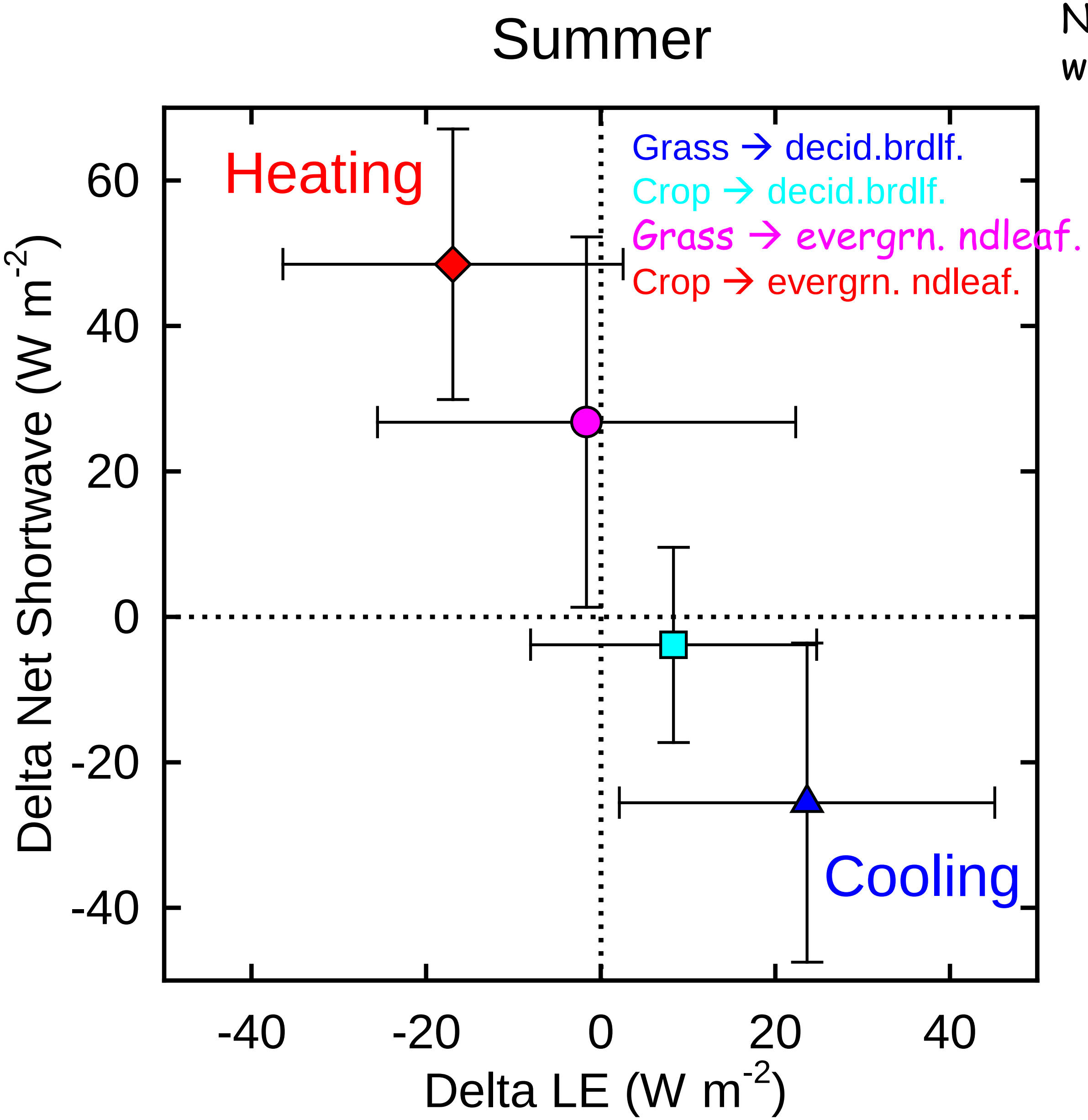
Shifts in surface energy balance from afforestation



NCEAS "Forest and Climate Policy" working group

Differences in energy fluxes among forest, cropland, and grassland

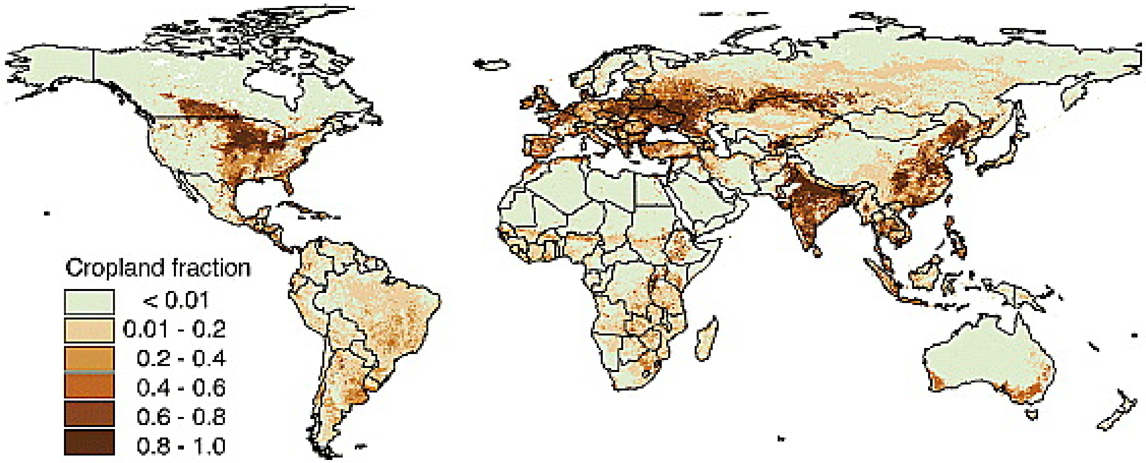
Based on ~100 site-years of AmeriFlux data. *O'Halloran et al., 2009. in prep.*

Δ affected by:
Proximity of towers
Leaf area index
Soil water status

Thomas O'Halloran
Oregon State University
Department of Forest Ecosystems & Society

NCAR
National Center for Atmospheric Research
Boulder, Colorado

Multi-model ensemble of global land use climate forcing



The LUCID inter-comparison study

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

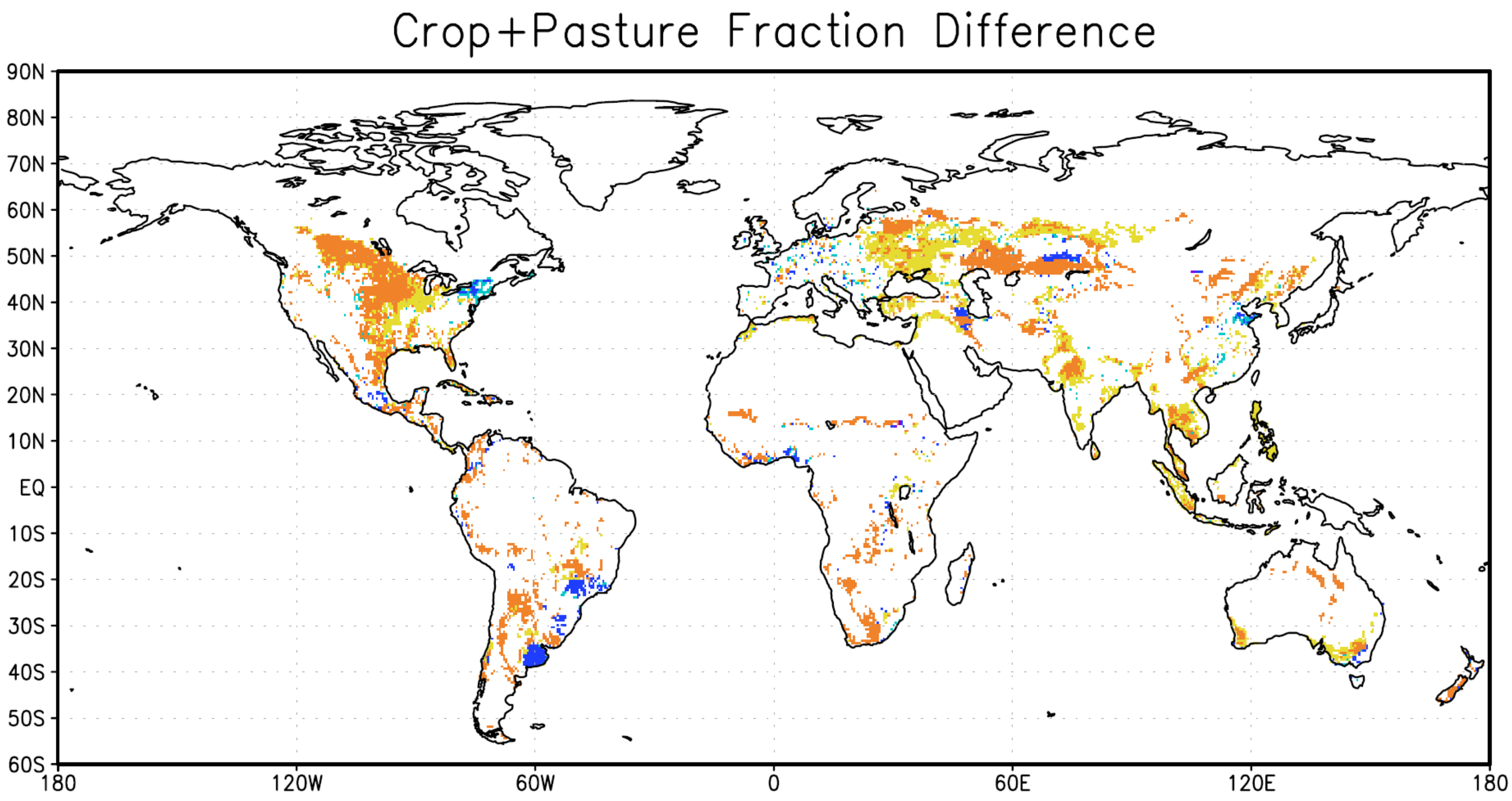
Experiments
30-year simulations (CO_2 = 375 ppm, SSTs = 1972-2001)
- PD – 1992 vegetation
- PDv - 1870 vegetation

30-year simulations (CO_2 = 280 ppm, SSTs = 1871-1900)
- PI – 1870 vegetation
- PIv – 1992 vegetation

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

Pitman et al. (2009) Land use and climate via the LUCID intercomparison study: Implications for experimental design in AR5. Geophysical Research Letters, submitted.

The LUCID intercomparison study

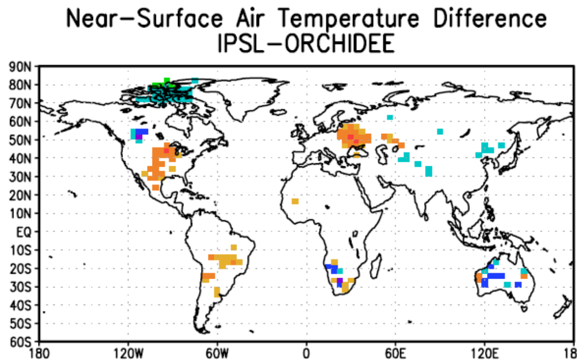


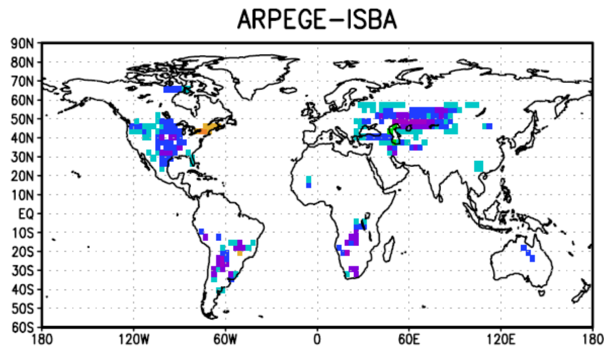
Extent of land cover change between experiments PD and PDv (PD – PDv) expressed as the difference in crop and pasture cover between the two experiments. Blue colours represent changes that decrease pasture and crop cover while yellows and browns are increases (25%-50% and 50-100% respectively).

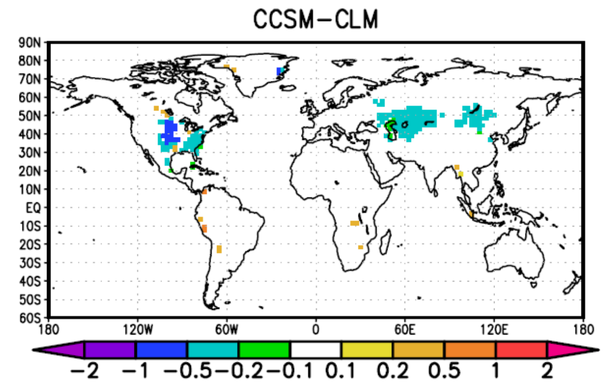
Pitman et al. (2009) GRL, submitted

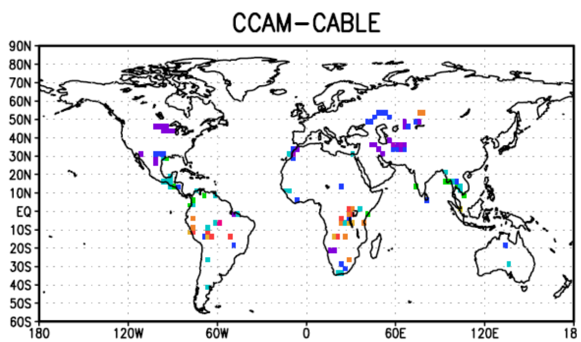
The LUCID intercomparison study

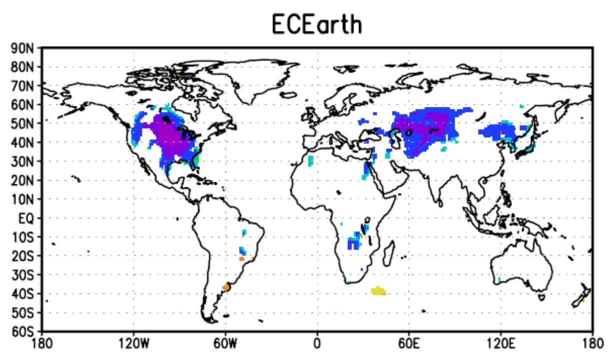
Change in JJA near-surface air temperature (K) resulting from land cover change (PD – PDv)



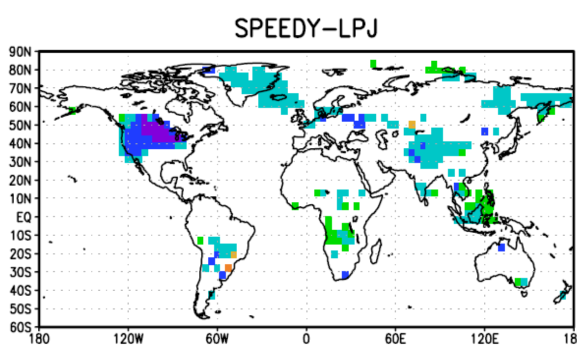


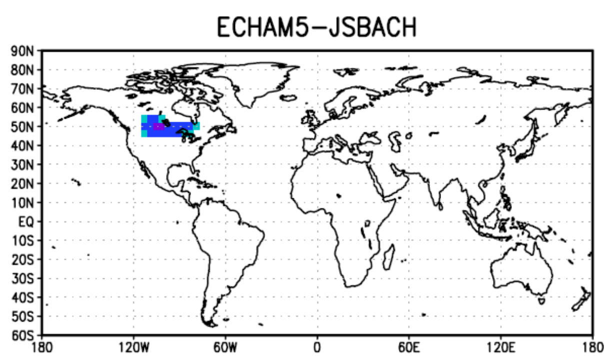






Land cover change can be regionally significant relative to other anthropogenic climate forcings, but the uncertainty in the land use forcing is large





Pitman et al. (2009) GRL, submitted

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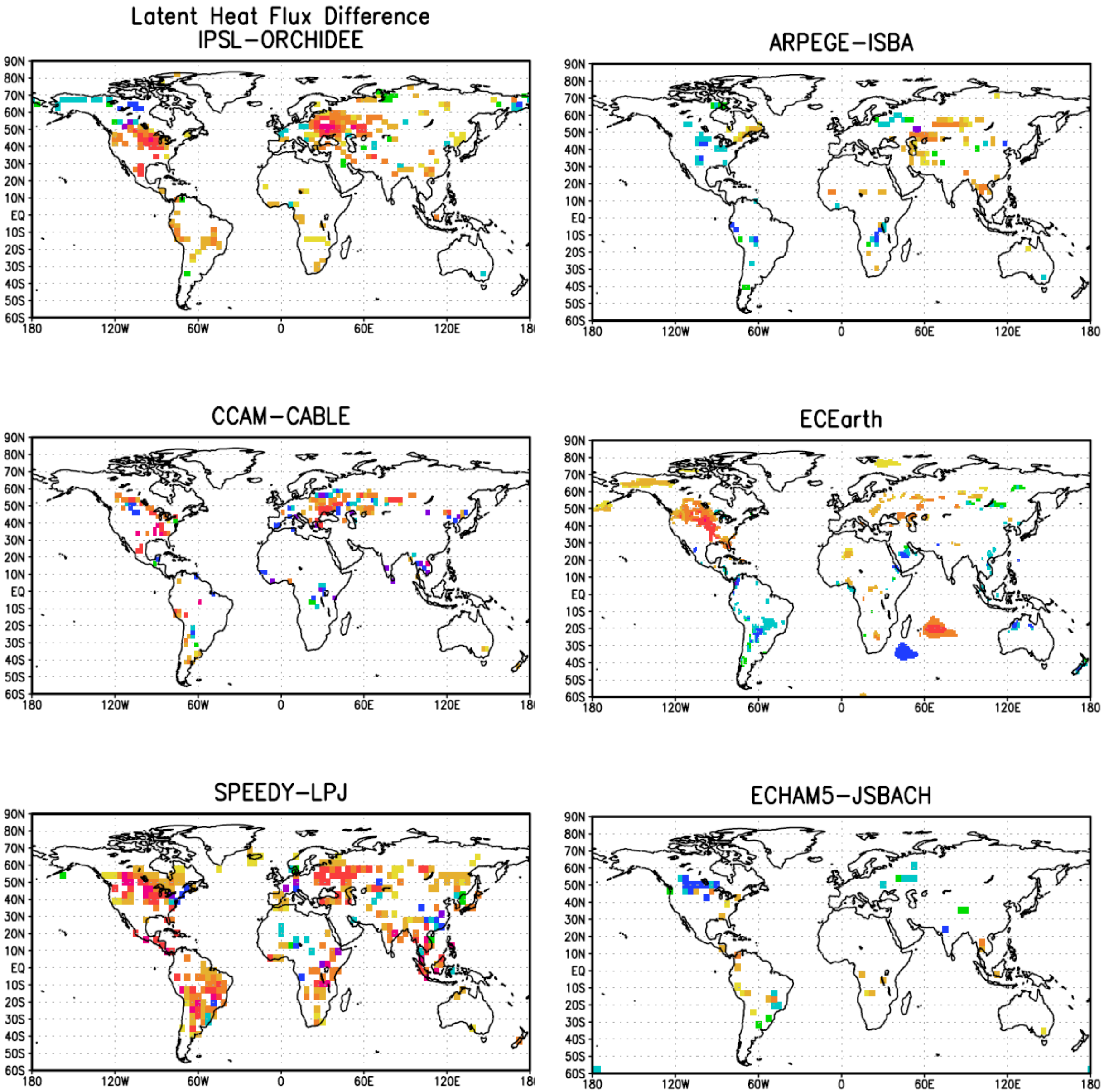
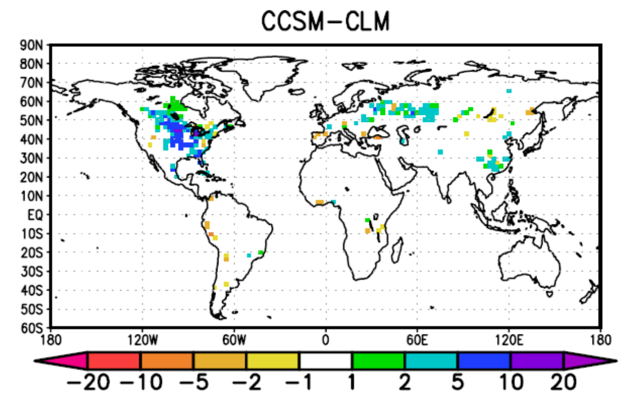
The LUCID intercomparison study





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

Pitman et al. (2009) GRL, submitted

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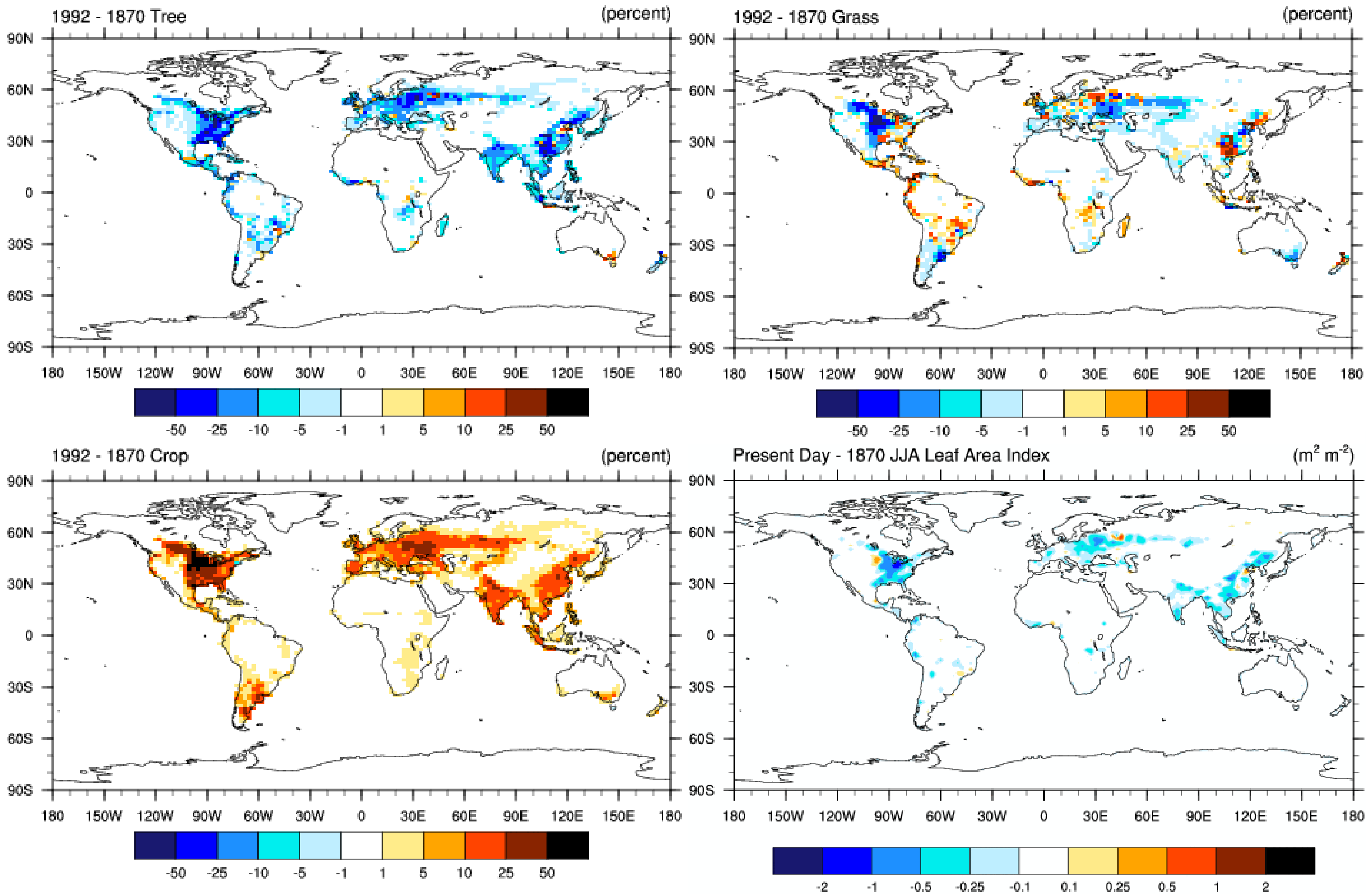
Land cover change, 1870 to 1992



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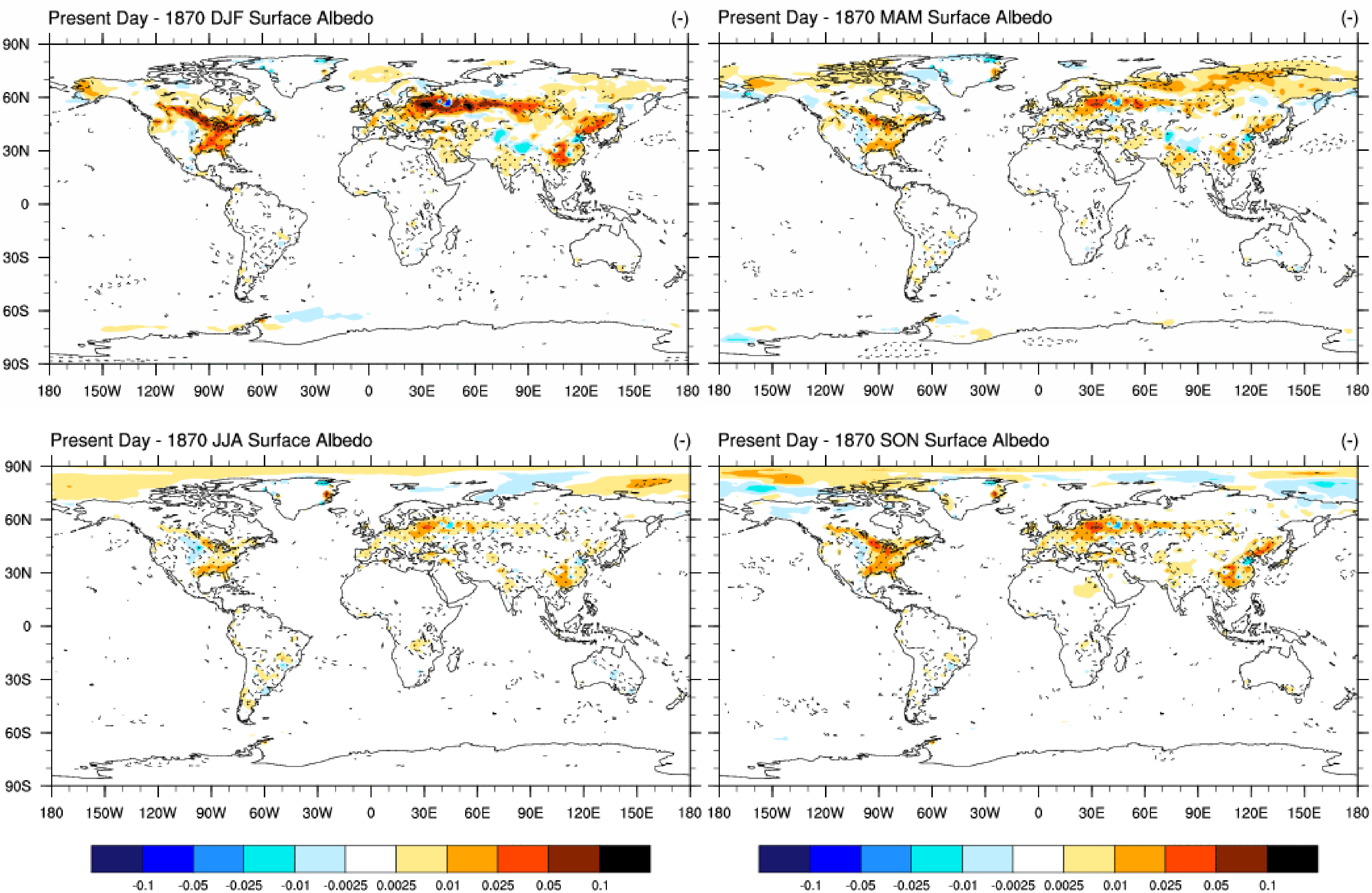
Albedo forcing, 1992-1870



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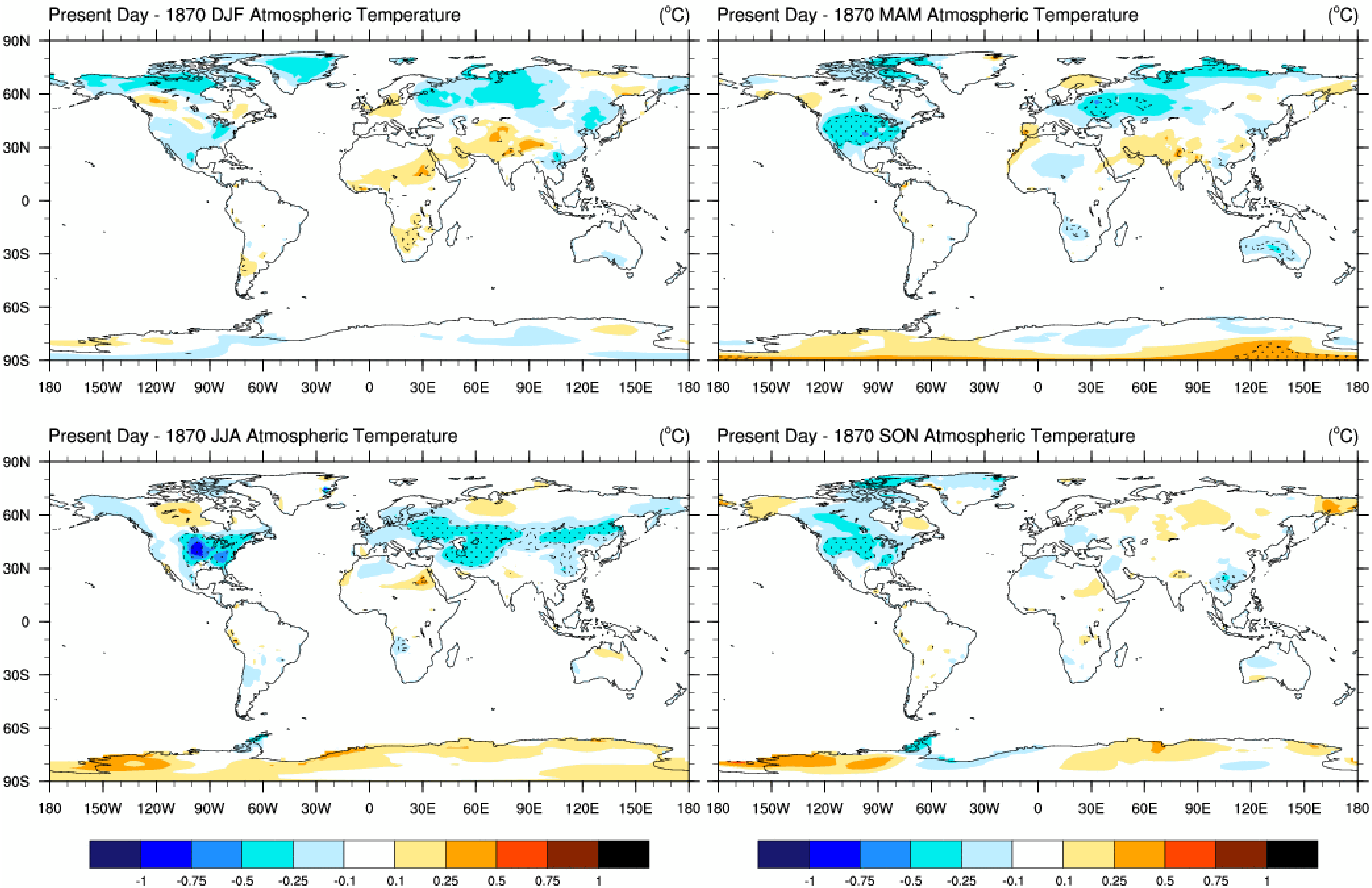
Near-surface temperature, 1992-1870



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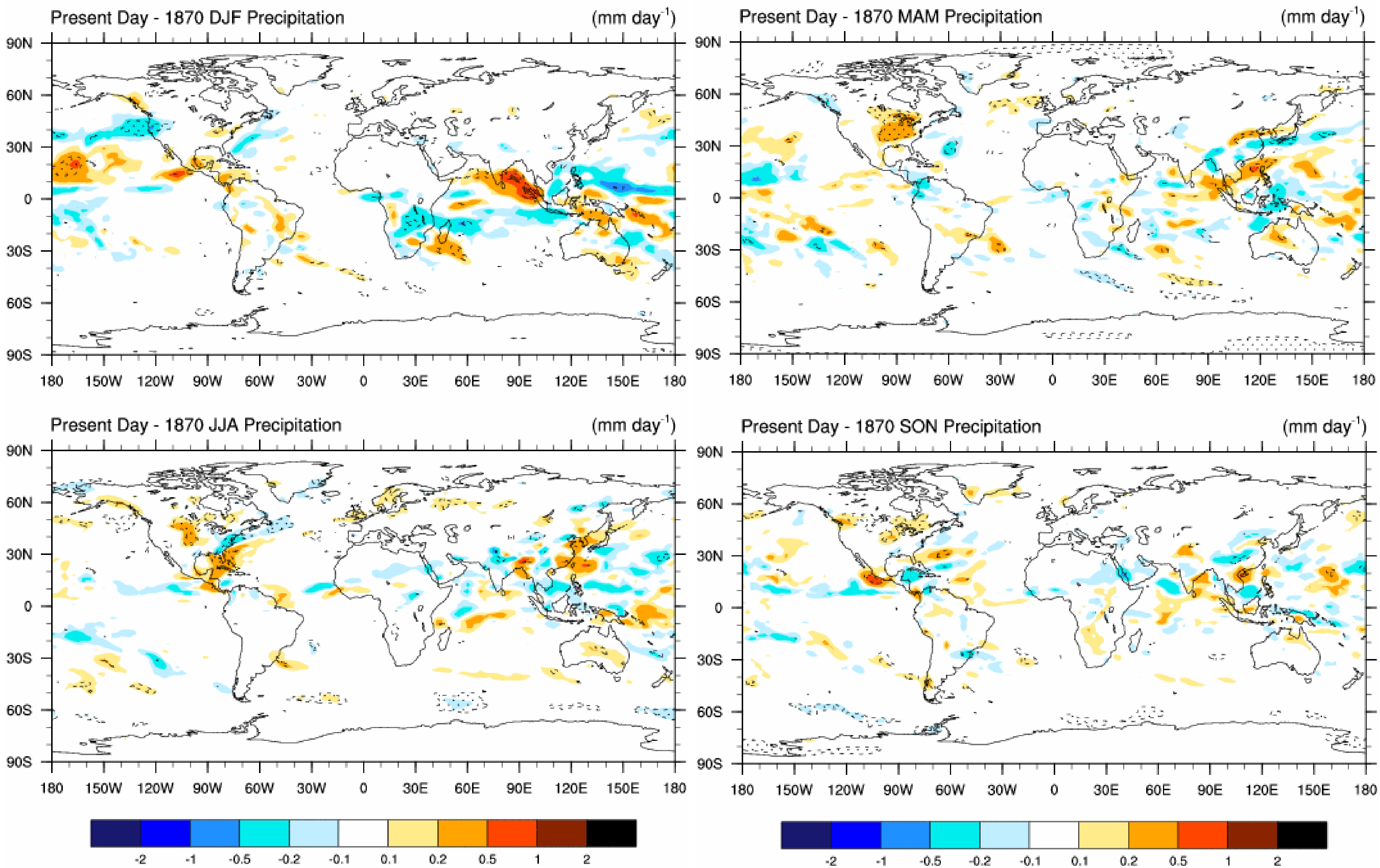
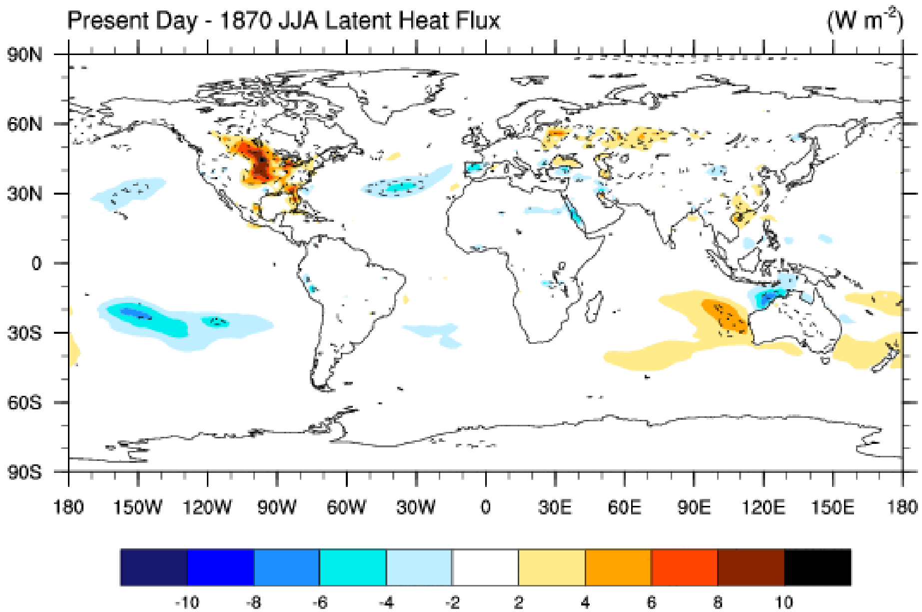
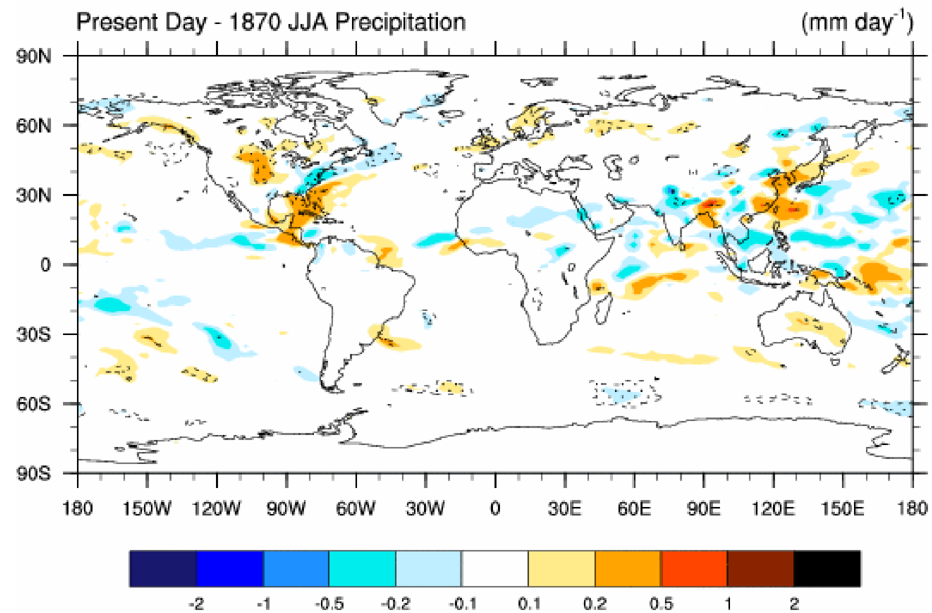
Precipitation, 1992-1870



Atmospheric feedbacks

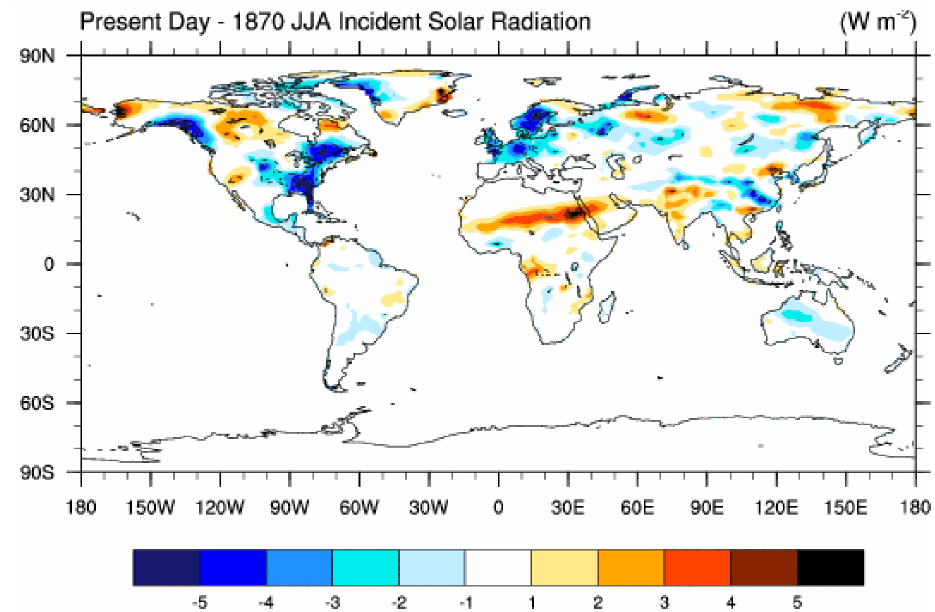




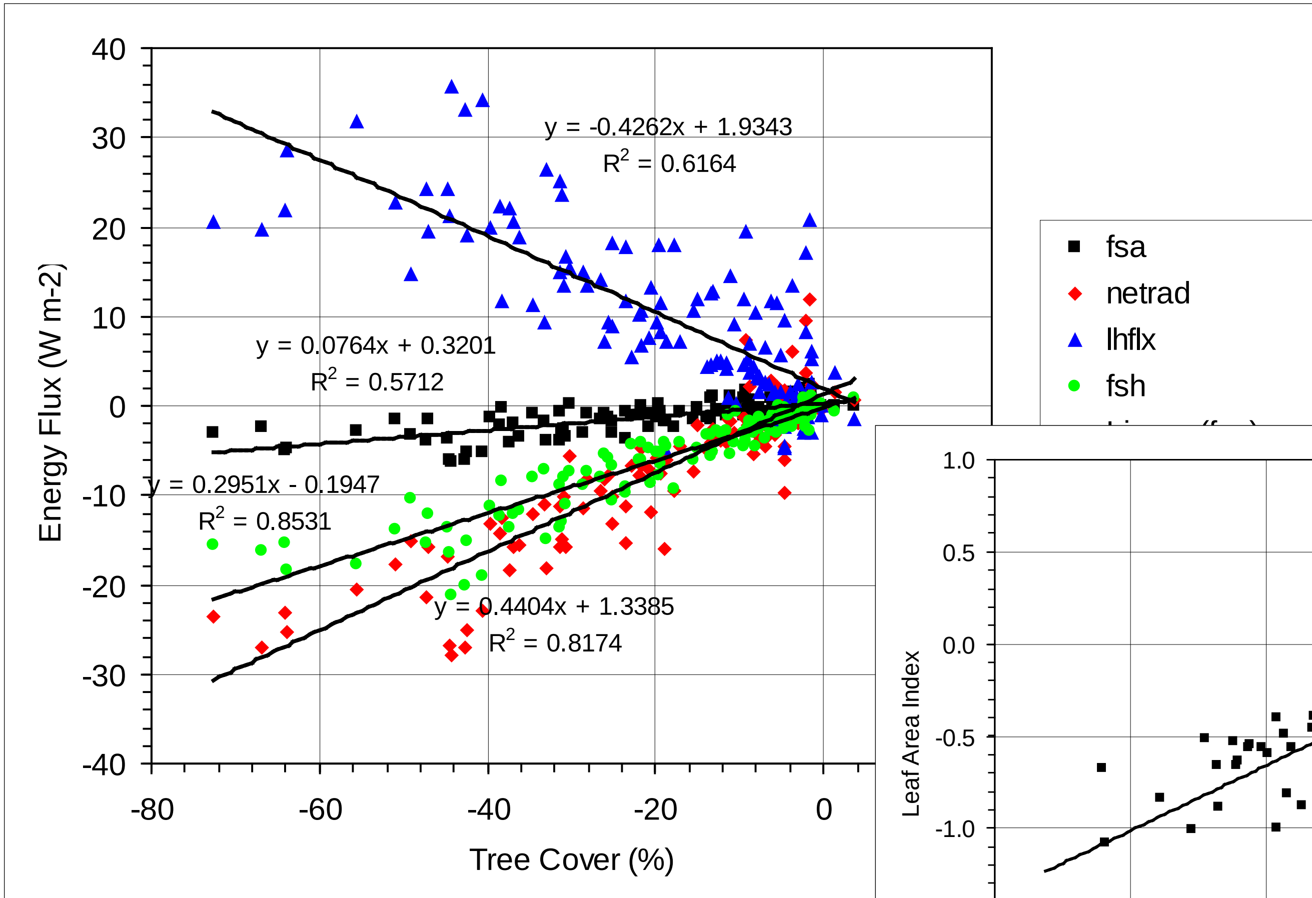
Climate models simulate the large-scale response and include feedbacks with the atmosphere:

- Increased rainfall enhances latent heat flux
- Increased cloudiness reduces solar radiation

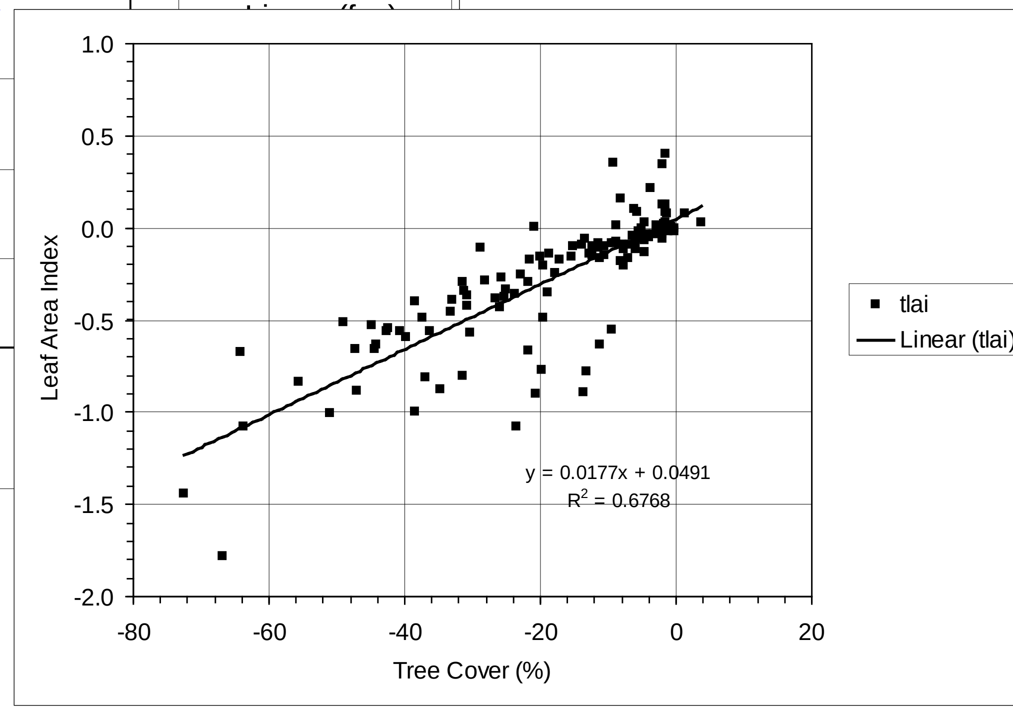
Flux towers measure local response



Functional relationships for surface forcing



Offline CLM3.5 simulations with NCEP-derived forcing, 1972-2001



Eastern North America

Summer season (June-August)

(PD – PDv)

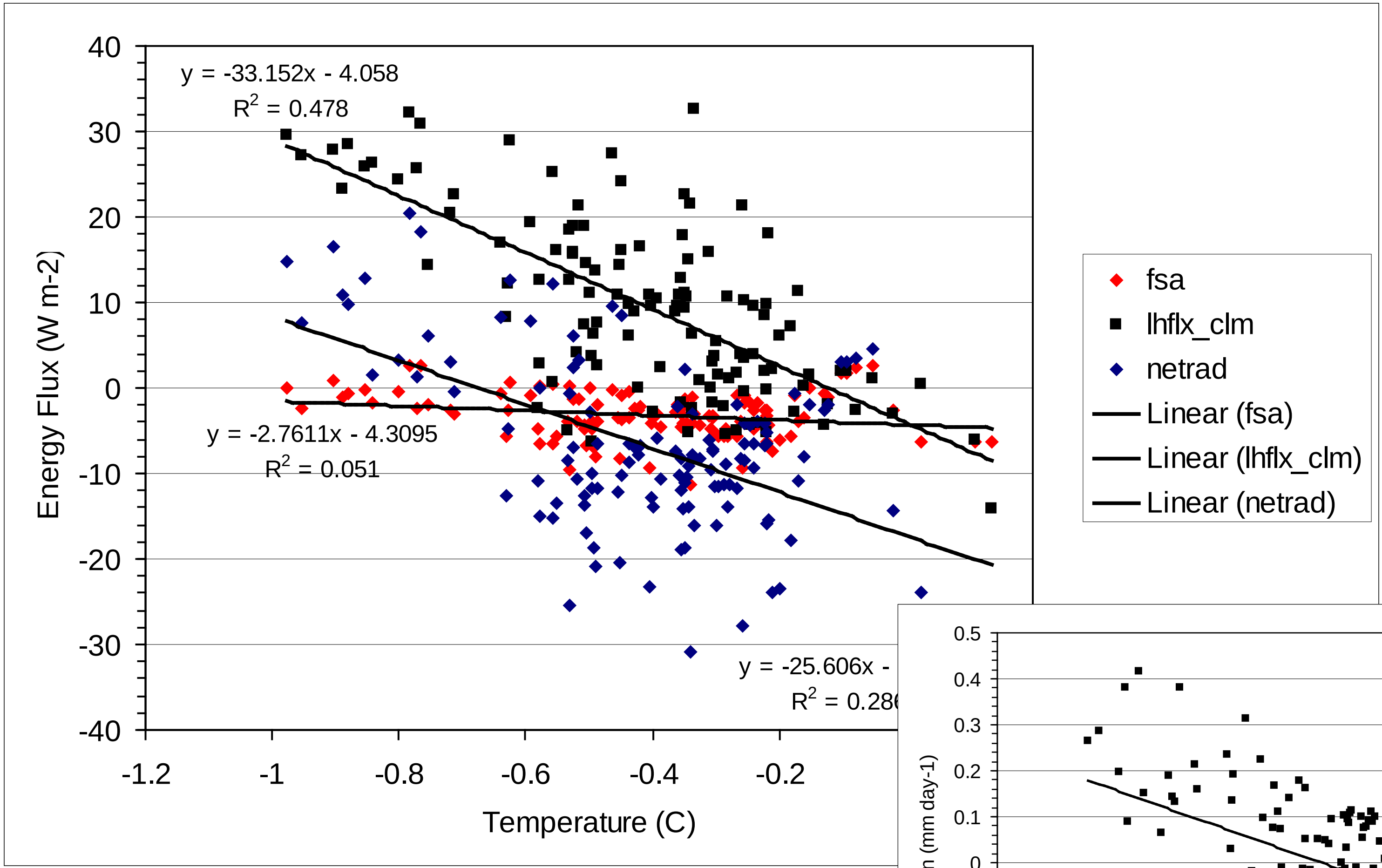
LHFLX – latent heat flux

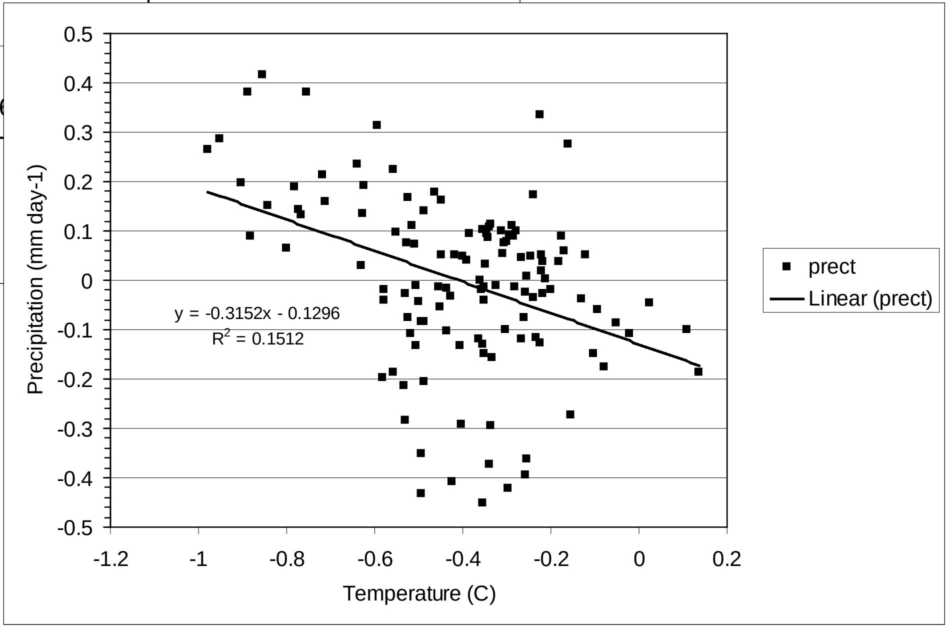
FSA – absorbed solar radiation

FSH – sensible heat flux

NETRAD – net radiation

Functional relationships for CAM/CLM



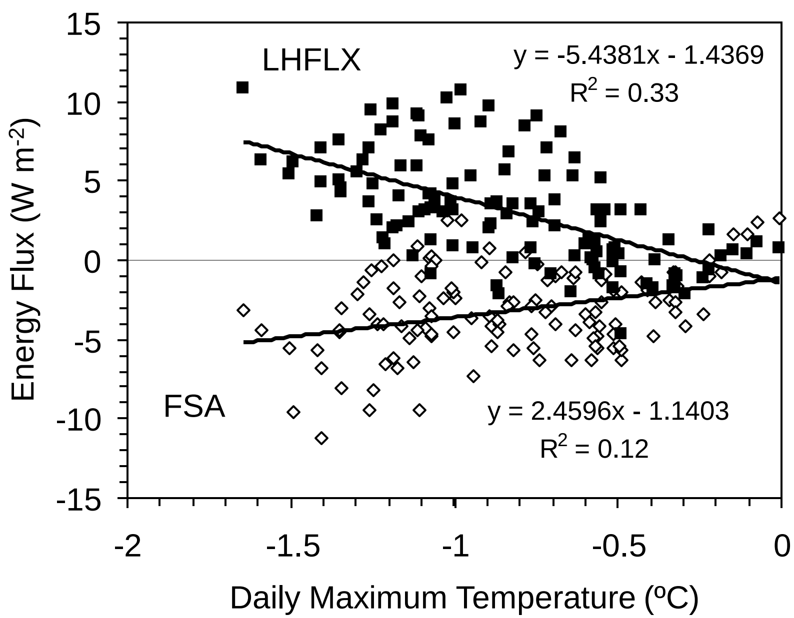


Eastern North America

Summer season (June-August)

(PD – PDv)

Functional relationships to explain model response



Eastern North America

Summer season (June-August)

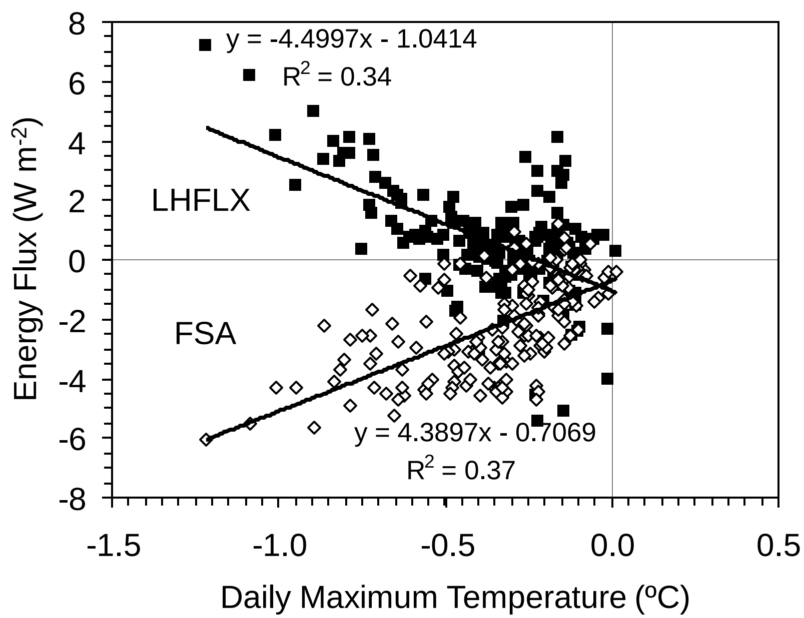
(PD – PDv)

CAM/CLM simulations

Europe

Summer season (June-August)

(PD – PDv)



LHFLX – latent heat flux
FSA – absorbed solar radiation

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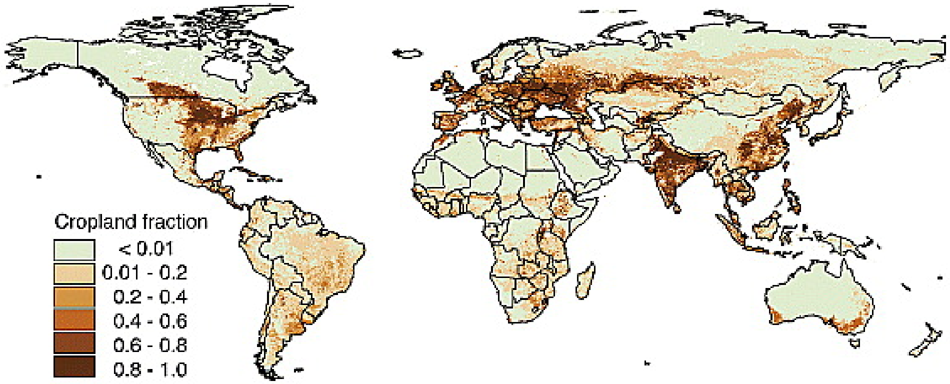
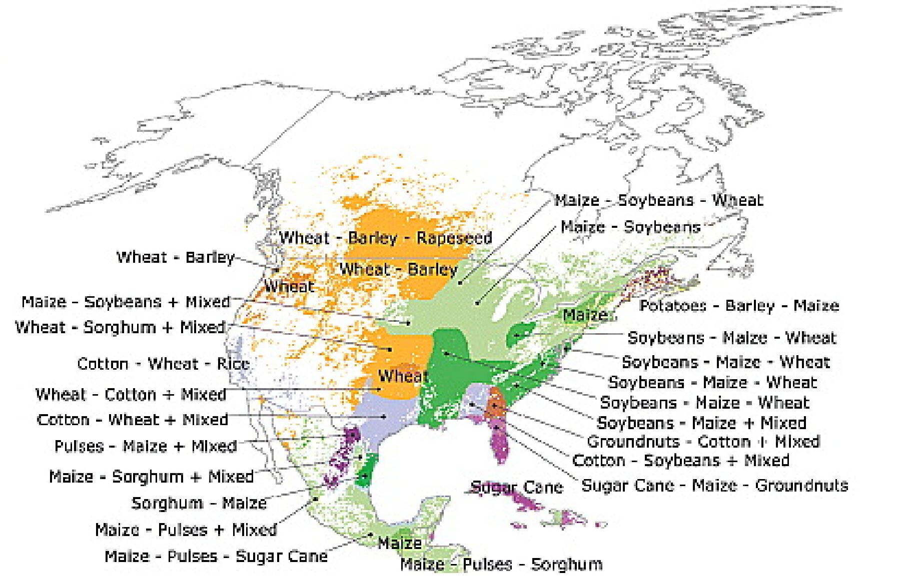
A broad diversity of crops worldwide

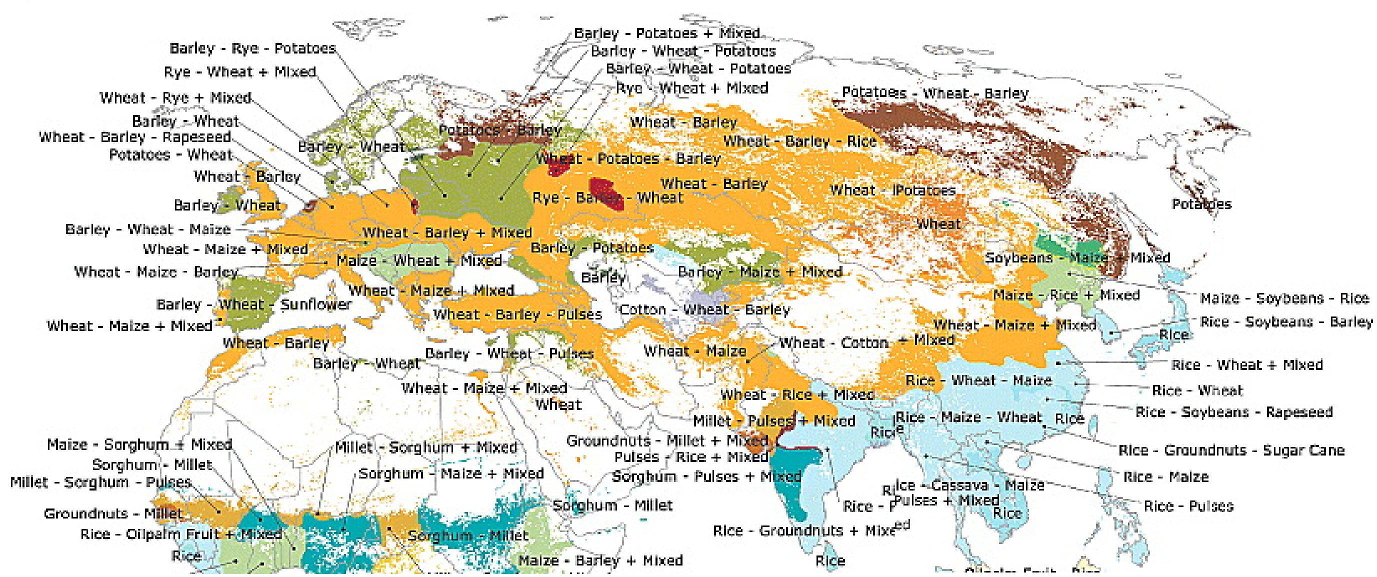




The type of land cover change matters:

Forest → winter crop
Forest → spring crop
Forest → summer crop

Forest vs grassland



Leff et al. (2004) GBC, 18, doi:10.1029/2003GB002108

Integrate ecological studies with earth system models

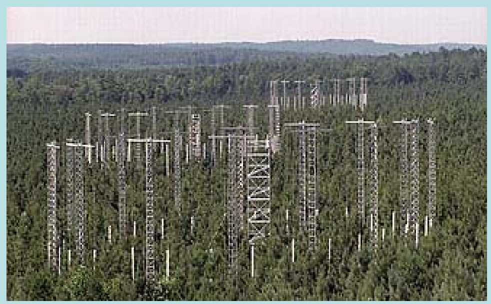
Environmental Monitoring

Eddy covariance flux tower
(courtesy Dennis Baldocchi)

Hubbard Brook
Ecosystem Study

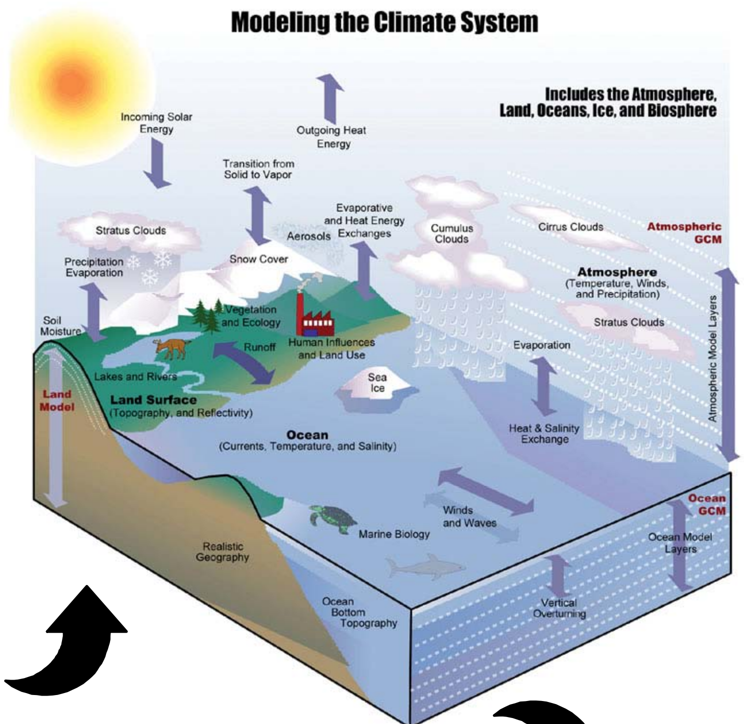
Experimental Manipulation

Soil warming, Harvard Forest



CO_2 enrichment, Duke Forest

Test model-generated hypotheses of earth system functioning with observations



Planetary energetics
Planetary ecology
Planetary metabolism