Land cover and land use change as climate forcing: from historical conjecture to modern theories

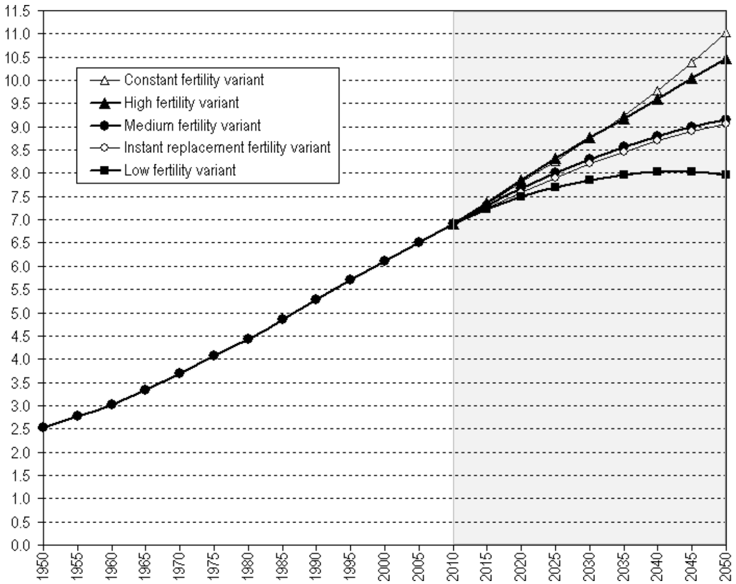
Gordon Bonan
National Center for Atmospheric Research
Boulder, Colorado, USA

World Climate Research Programme
Open Science Conference
Denver, Colorado
27 October 2011

NCAR is sponsored by the
National Science Foundation

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

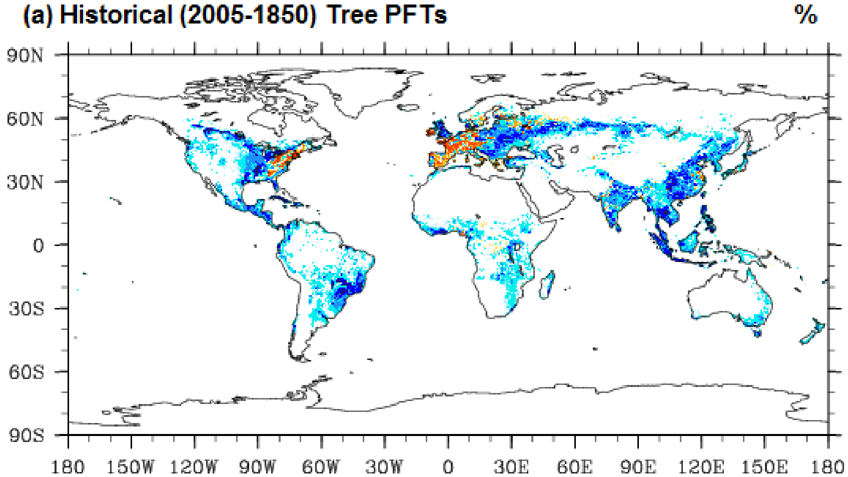
Human activities (agriculture, deforestation, urbanization) and their effects on climate, water resources, and biogeochemical cycles

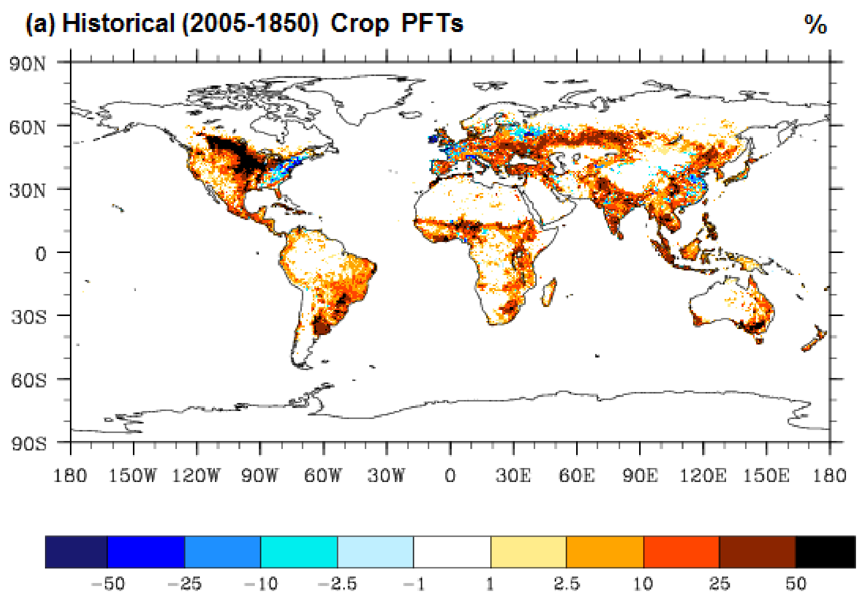
What is our collective future?

Can we manage the Earth system, especially its ecosystems, to create a sustainable future?

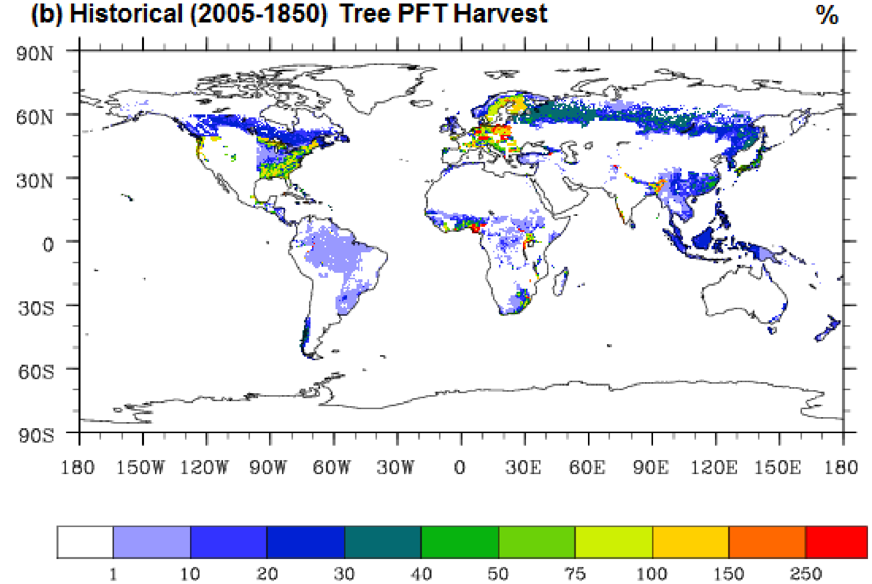
Historical land use and land cover change, 1850 to 2005

Change in tree and crop cover (percent of grid cell)





Cumulative percent of grid cell harvested



Historical LULCC in CLM4

- ❑ Loss of tree cover and increase in cropland
- ❑ Farm abandonment and reforestation in eastern U.S. and Europe
- ❑ Extensive wood harvest

Peter Lawrence et al. (2012) J. Clim., in press

A long-standing interest

An Early Settler Clears a Homestead 1740 A.D. (Fisher Museum Harvard Forest, Harvard University)

Height of Forest Clearing and Agriculture 1830 A.D. (Fisher Museum Harvard Forest, Harvard University)

The European tradition

Theophrastus (*circa* 300 BC)

Pliny the Elder (*circa* 1st century AD)

The American tradition

- Christopher Columbus, 1494
- Constantin-François Volney, 1803 : "very perceptible partial changes in the climate…as the land was cleared"
- Alexander von Humboldt, 1807: "The statements so frequently advanced…are now generally discredited"
- Samuel Aughey, 1880: cultivation of the Great Plains increases rainfall, "rain follows the plow"
- U.S. Congress, 1873: legislation to promote afforestation to increase rainfall

CSU Libraries, Archives & Special Collections Agricultural Archive, Historical Photograph Collection

Ecosystems and climate policy

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

Temperate forest – reforestation and afforestation

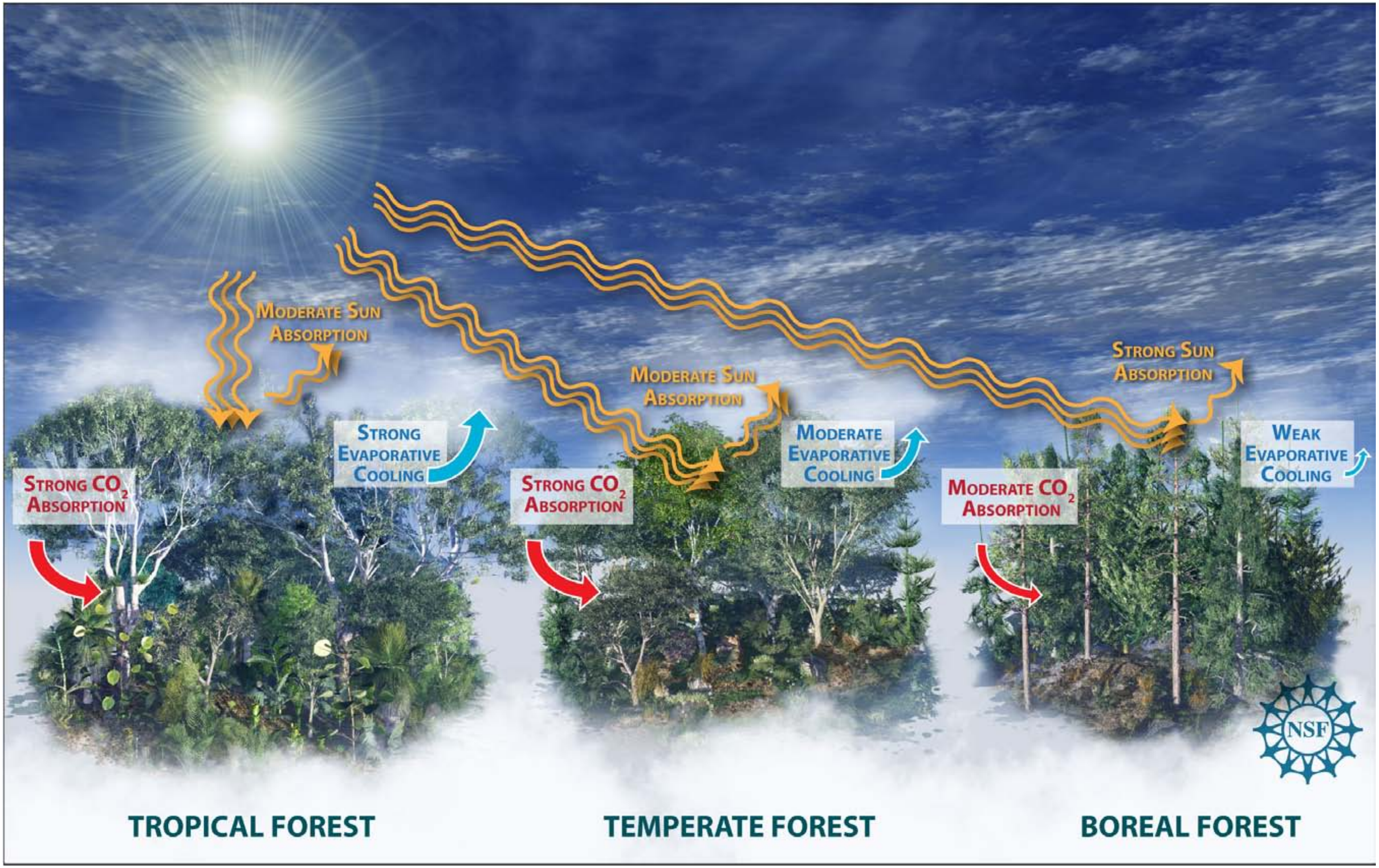
Tropical rainforest – planetary savior – promote avoided deforestation, reforestation, or afforestation

Biofuel plantations to lower albedo and reduce atmospheric CO_2

These comments are tongue-in-cheek and do not advocate a particular position

Forests and climate change

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



Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*

20th century LULCC forcing

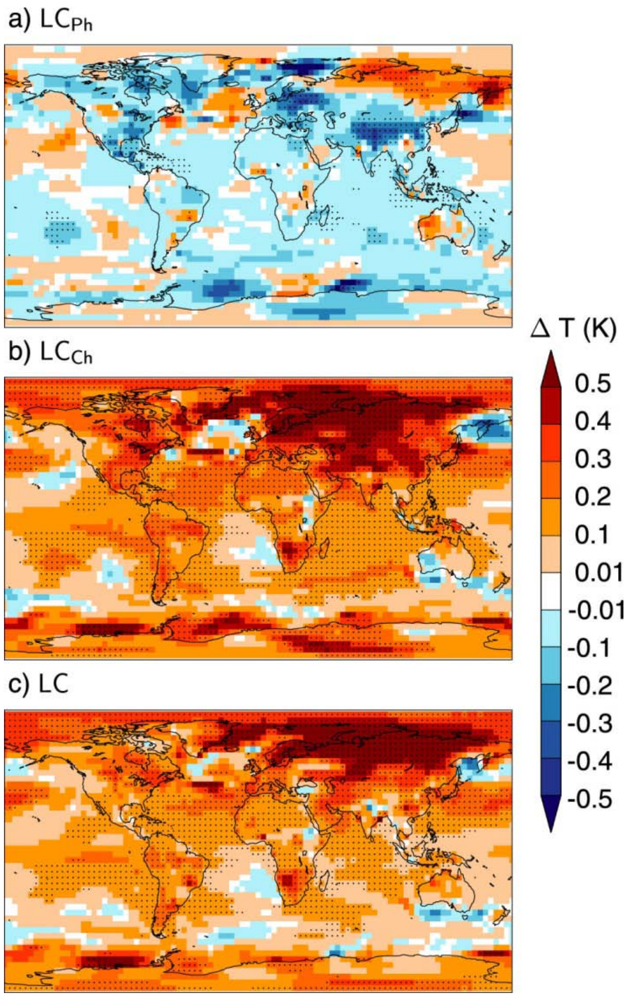
Prevailing paradigm
The dominant competing signals from historical deforestation are an increase in surface albedo countered by carbon emission to the atmosphere

Change in annual surface temperature from anthropogenic LULCC over the 20th century

Biogeophysical
Weak global cooling (–0.03 °C)

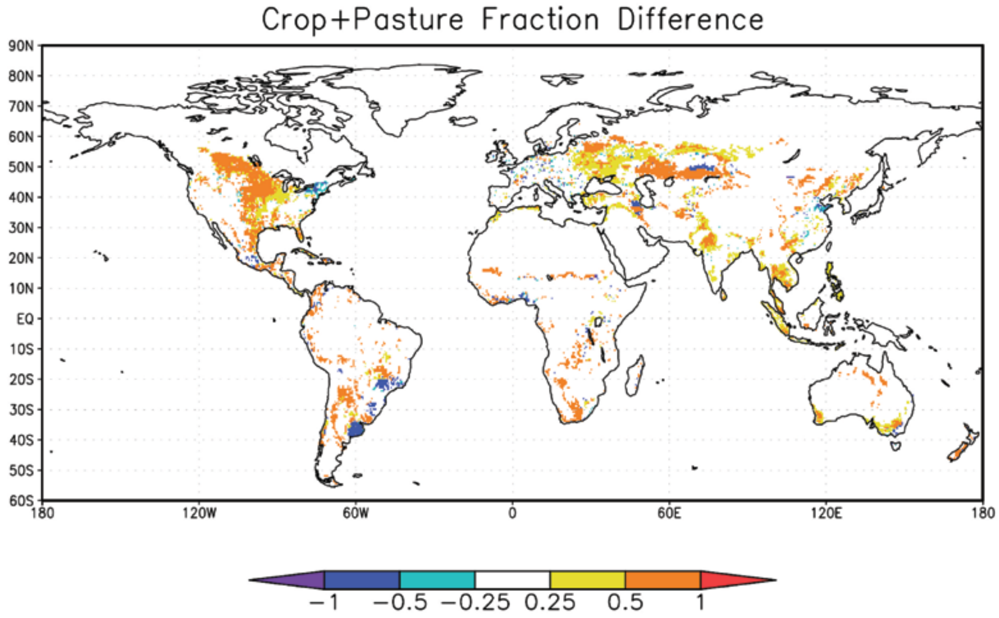
Biogeochemical
Strong warming (0.16–0.18 °C)

Net
Warming (0.13-0.15 °C)



Pongratz et al. (2010) GRL,37, doi:10.1029/2010GL043010

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)

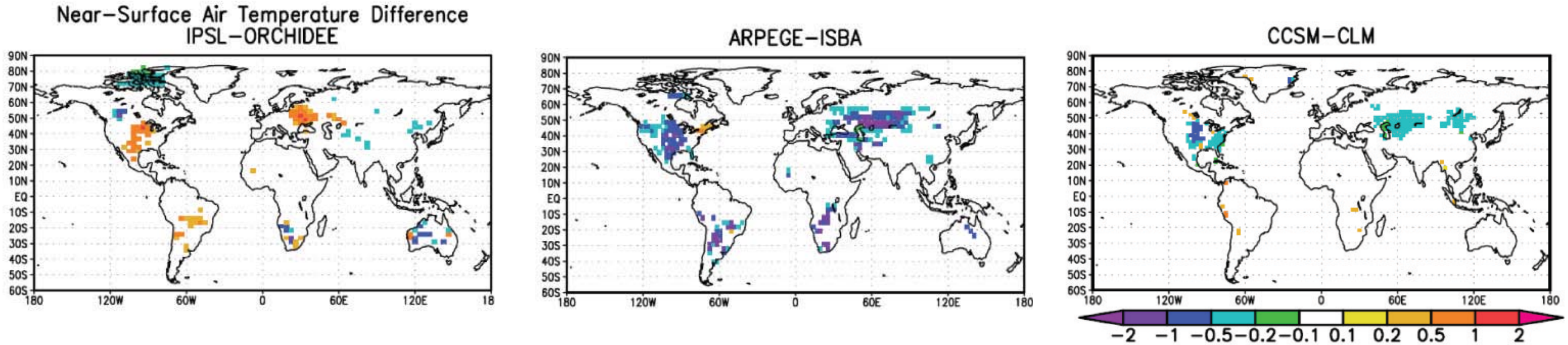
Pitman, de Noblet-Ducoudré, et al. (2009) GRL, 36, doi:10.1029/2009GL039076

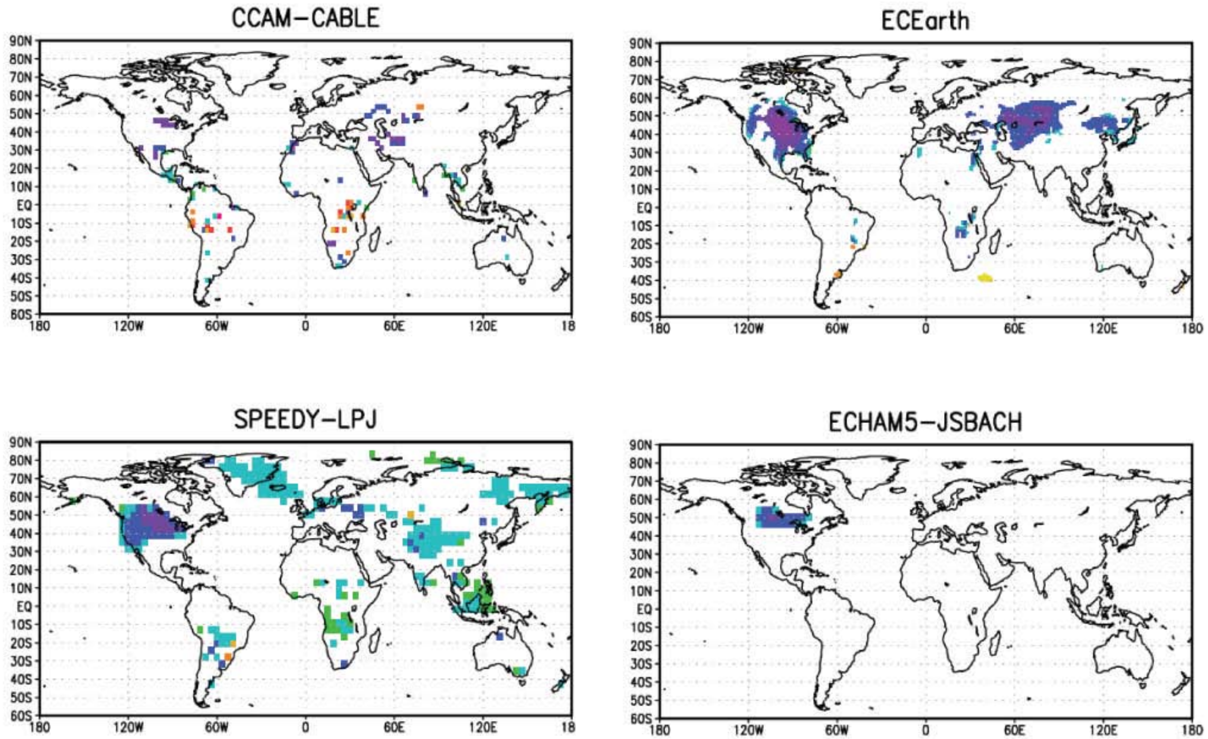
Experiments

- 4 experiments, 5-member ensembles each
- 30-year simulations
- Total of 20 simulations and 600 model years

Case	Land cover	CO_2	SST & SIC
PD	1992	375 ppm	1972-2001
PDv	1870	375 ppm	1972-2001
PI	1870	280 ppm	1871-1900
PIv	1992	280 ppm	1871-1900

Boreal summer temperature





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

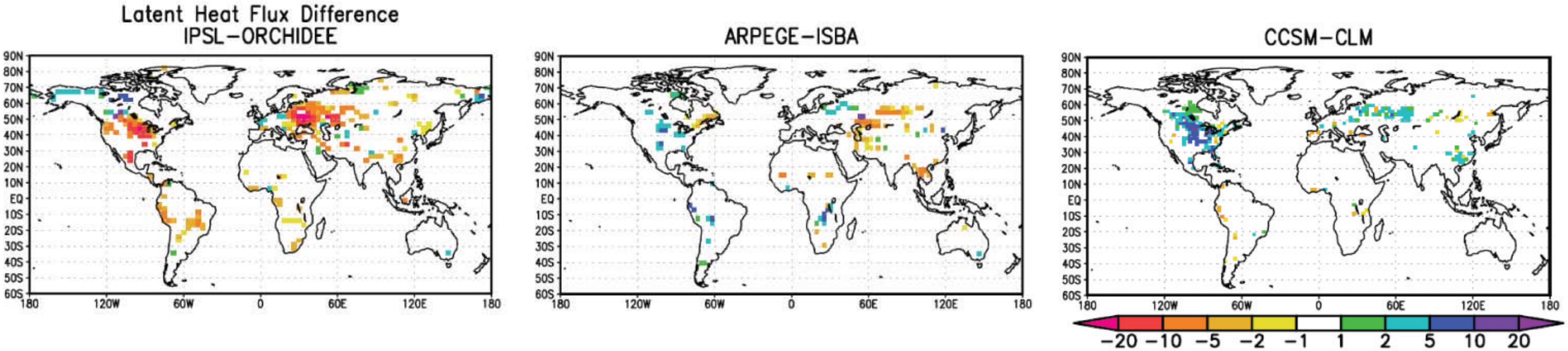
Key points:

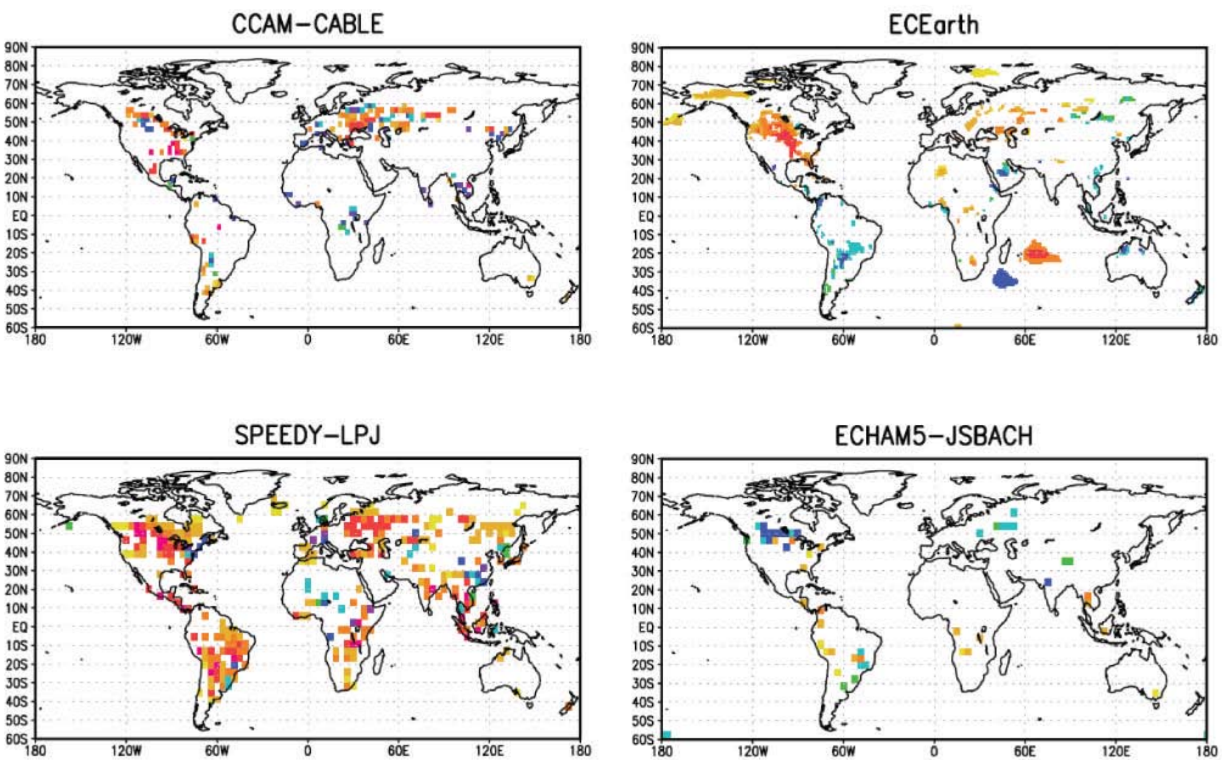
The LULCC forcing is regional

Differences among models matter

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

Latent heat flux





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

Key points:

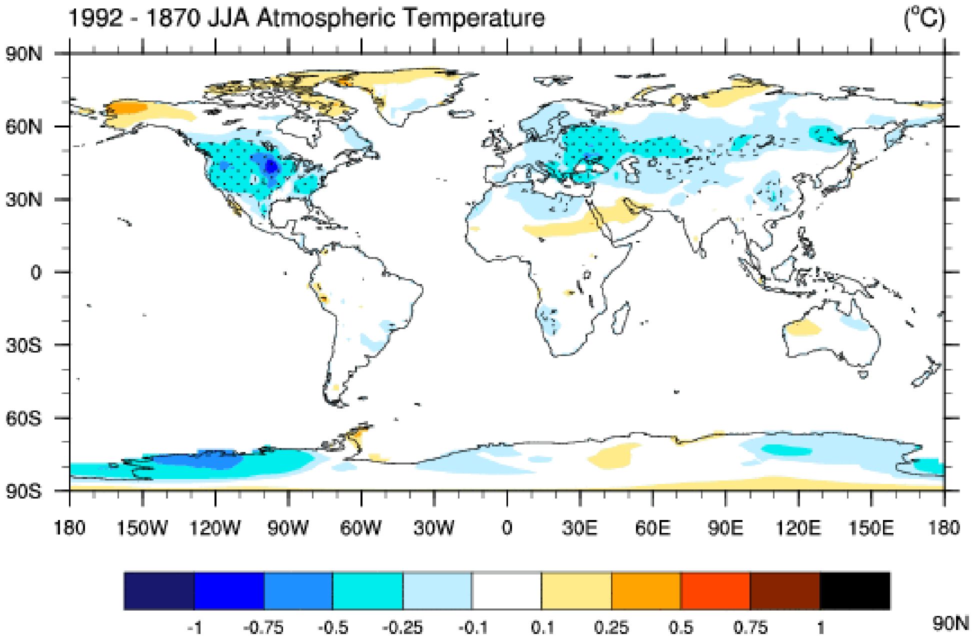
The LULCC forcing is regional

Differences among models matter

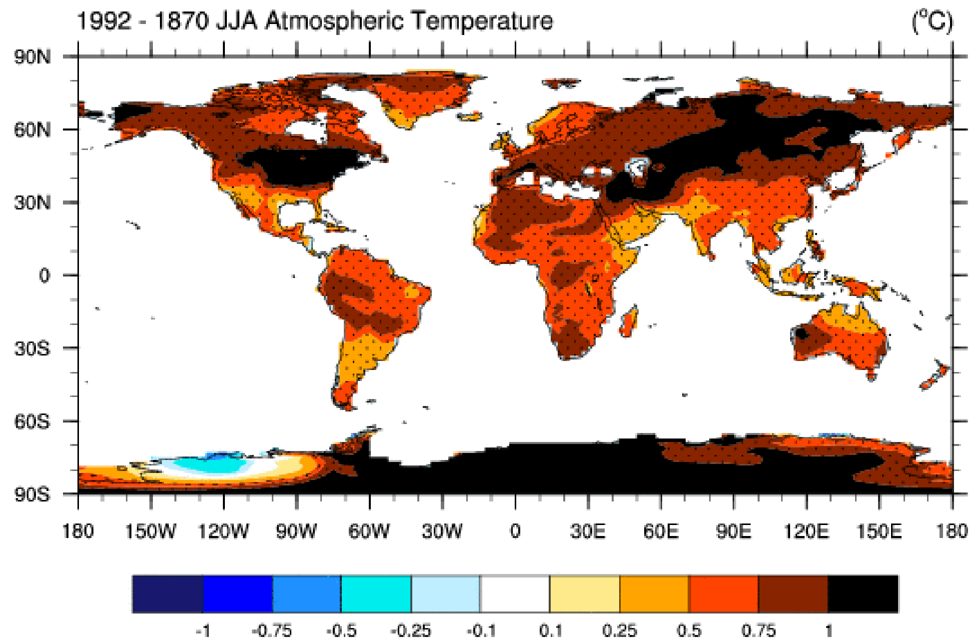
Pitman, de Noblet-Ducoudré, et al. (2009) GRL, 36, doi:10.1029/2009GL039076

Land cover change offsets greenhouse gas warming

Land cover change (PIv – PI)



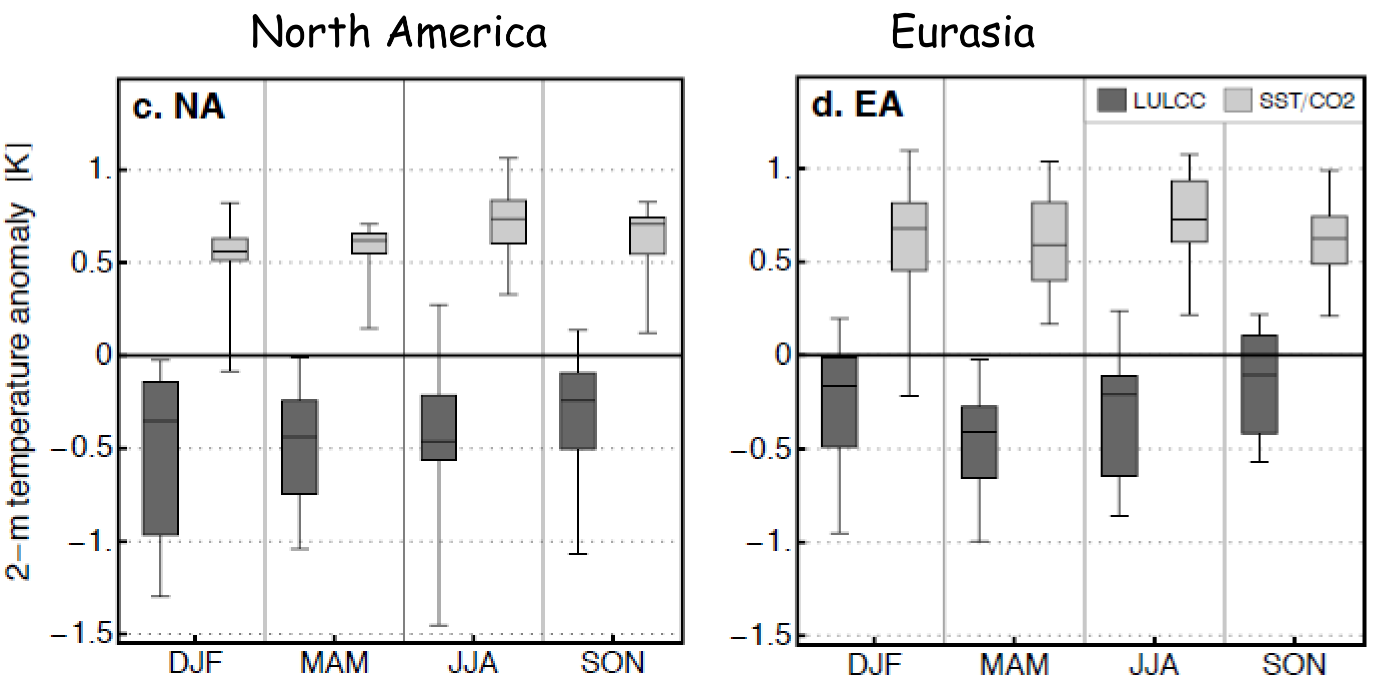
CO_2 + SST + SIC
(PDv – PI)



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

Climate change attribution

Multi-model ensemble of the simulated changes between the pre-industrial time period and present-day



CO_2 + SST + SIC forcing leads to warming

LULCC leads to cooling

de Noblet-Ducoudré, Boiser, Pitman, et al. (2012) J. Clim., in press

Key points:

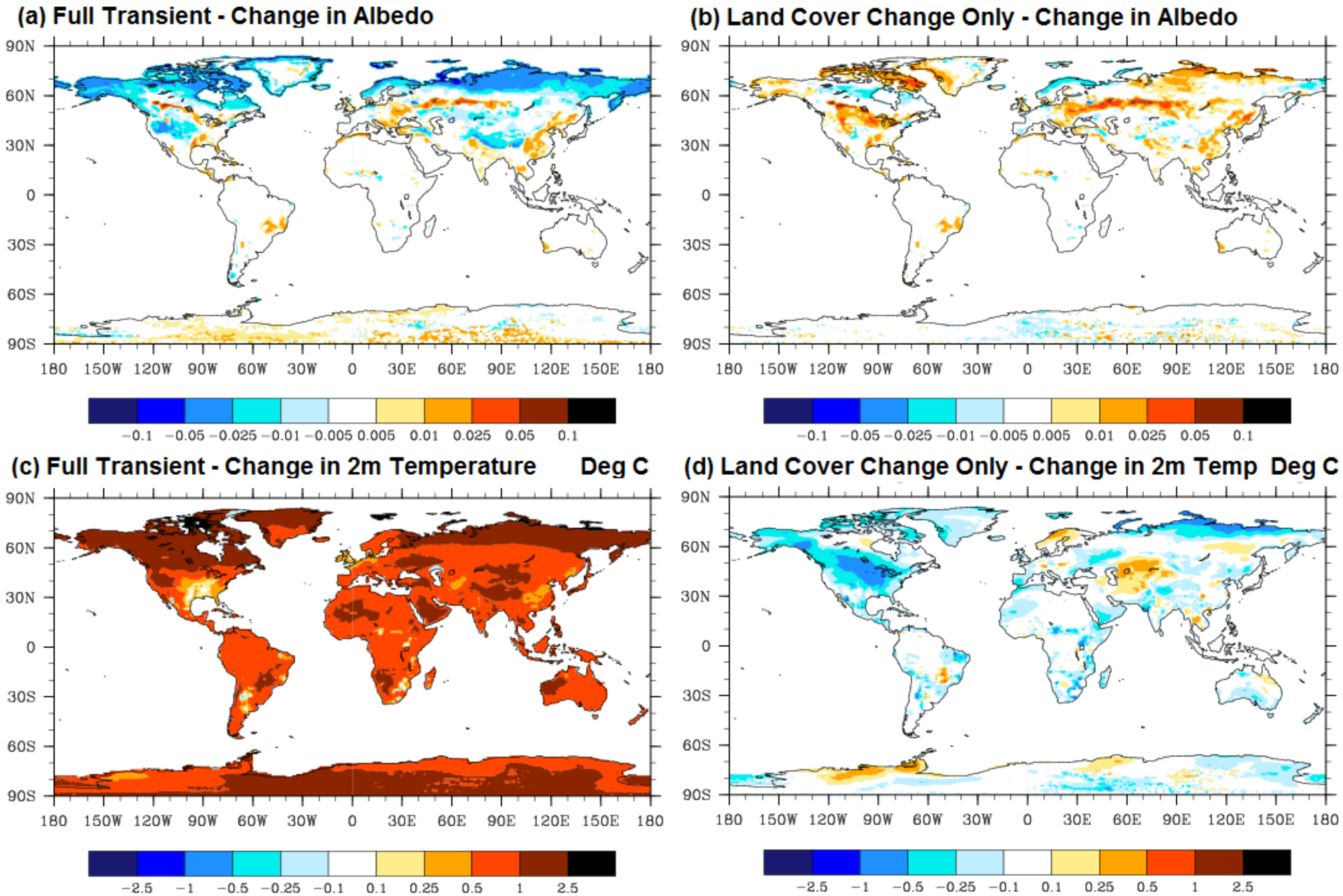
The LULCC forcing is counter to greenhouse warming

The LULCC forcing has large inter-model spread, especially JJA

The bottom and top of the box are the 25th and 75th percentile, and the horizontal line within each box is the 50th percentile (the median). The whiskers (straight lines) indicate the ensemble maximum and minimum values.

Community Earth System Model CMIP5 simulations

Full transient (all forcings) Land cover change only



Historical changes in annual surface albedo and temperature (1850 to 2005)

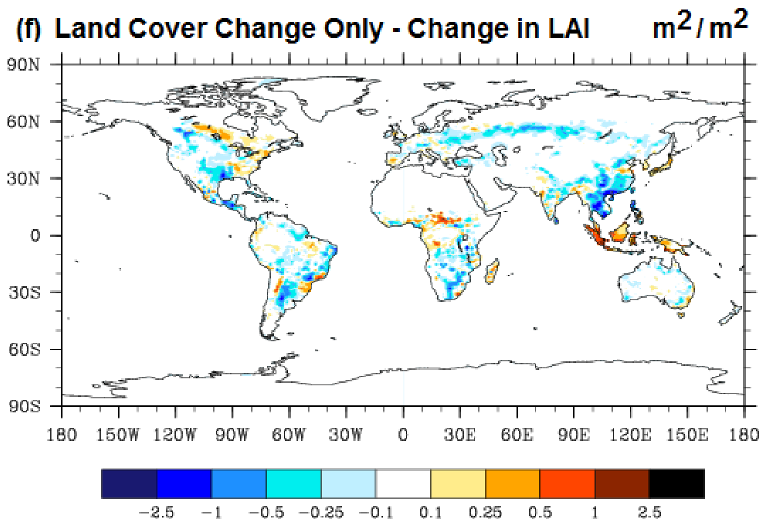
<u>Key points:</u>

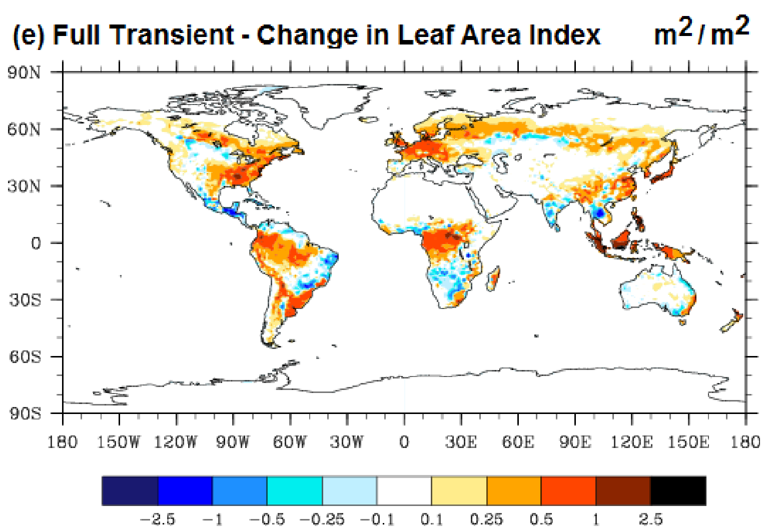
LULCC forcing is counter to all forcing

LULCC forcing is regional, all forcing is global

Peter Lawrence et al. (2012) J. Clim., in press

Opposing trends in vegetation





Historical changes in annual leaf area index (1850 to 2005)

Single forcing simulation
Land cover change only

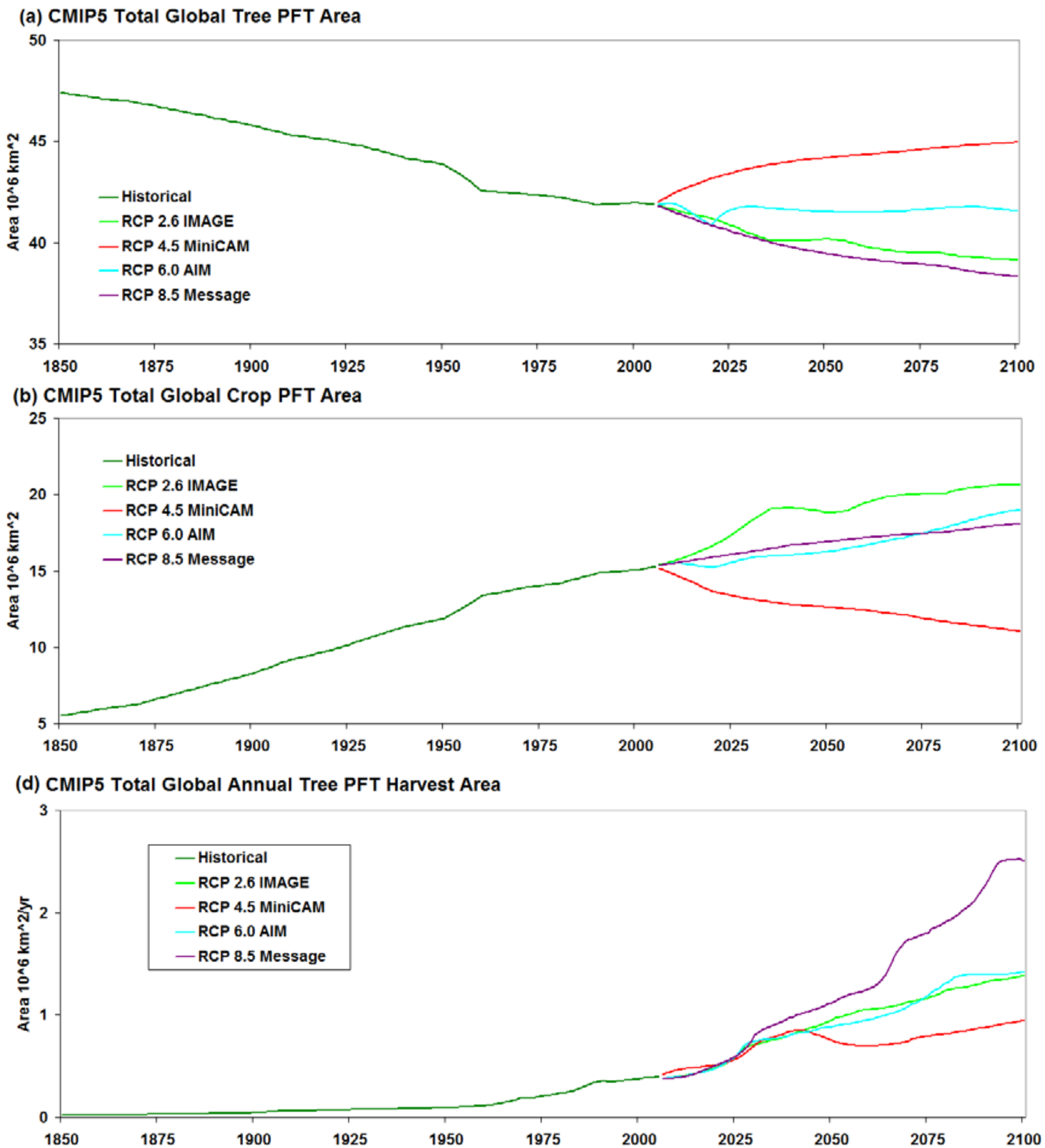
Loss of leaf area, except where reforestation

All forcing simulation
CO_2
Climate
Nitrogen deposition
Land cover change

Increase in leaf area, except where agricultural expansion

Peter Lawrence et al. (2012) J. Clim., in press

21st century land use & land cover change



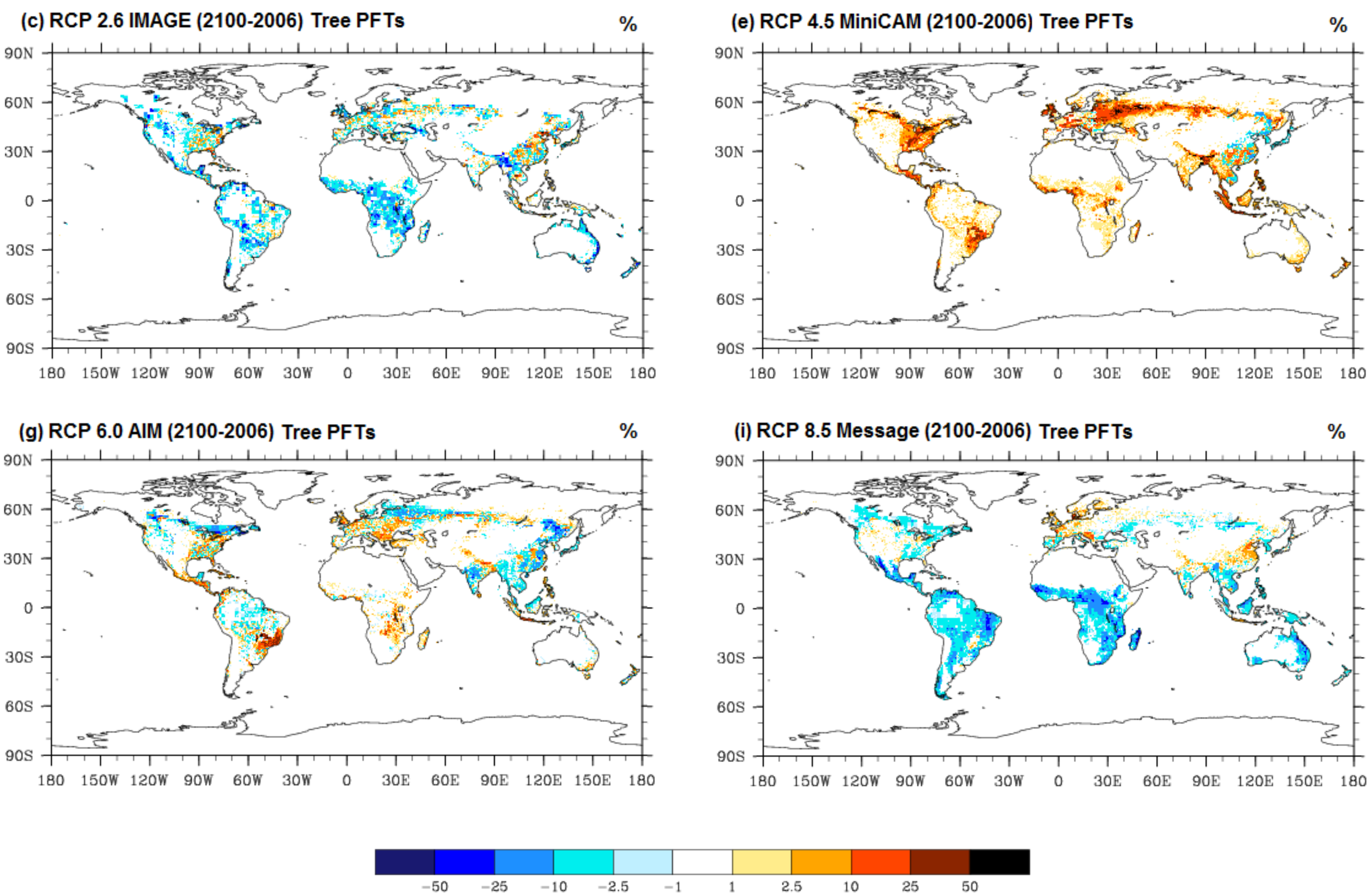
Description

- RCP 2.6 - Largest increase in crops. Forest area declines.
- ***RCP 4.5*** - Largest decrease in crop. Expansion of forest areas for carbon storage.
- RCP 6.0 - Medium cropland increase. Forest area remains constant.
- ***RCP 8.5*** - Medium increases in cropland. Largest decline in forest area. Biofuels included in wood harvest.

Peter Lawrence et al. (2012) J. Clim., in press

21st century forests

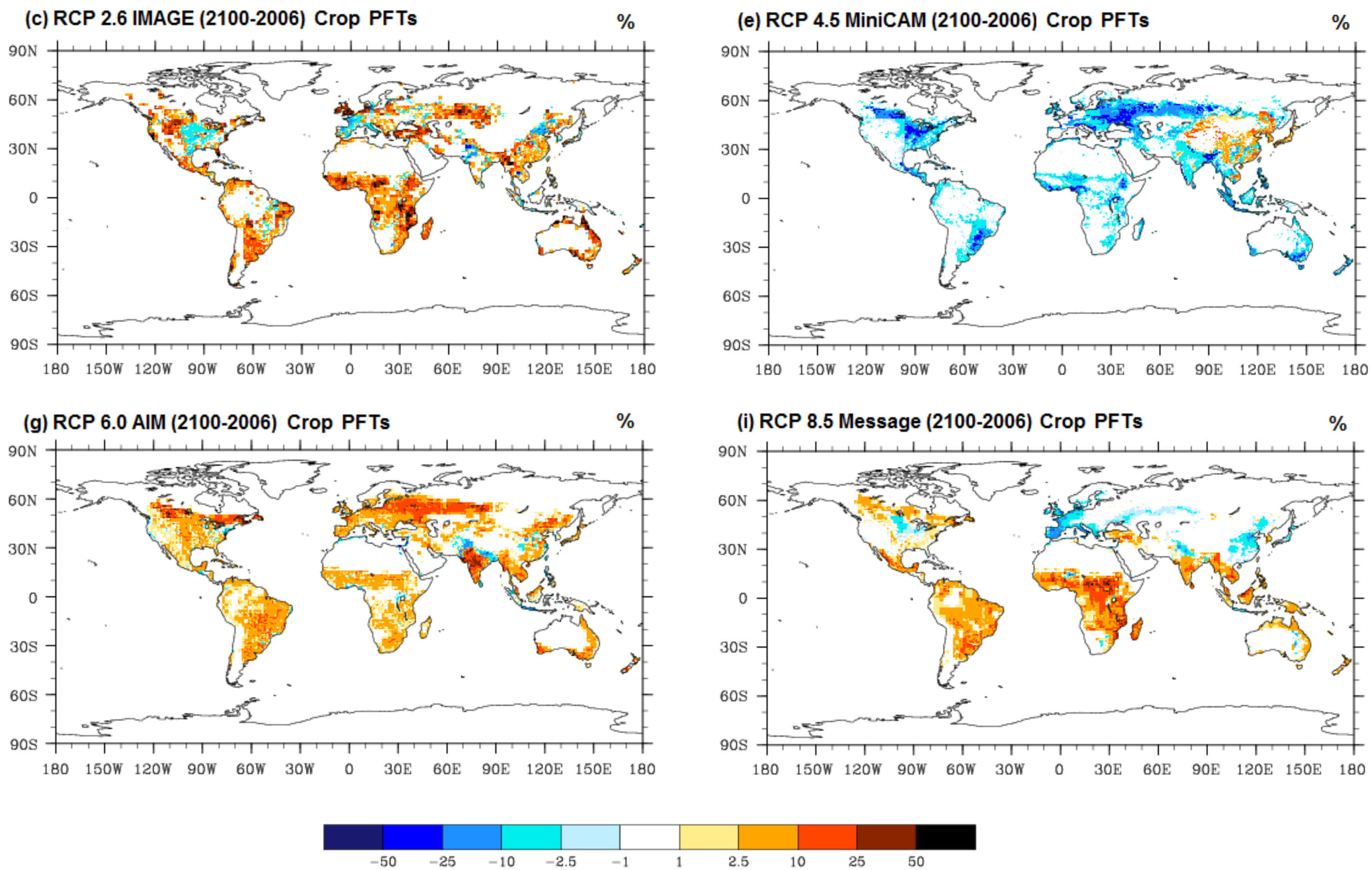
Change in tree cover (percent of grid cell) over the 21st century



Peter Lawrence et al. (2012) J. Clim., in press

21st century cropland

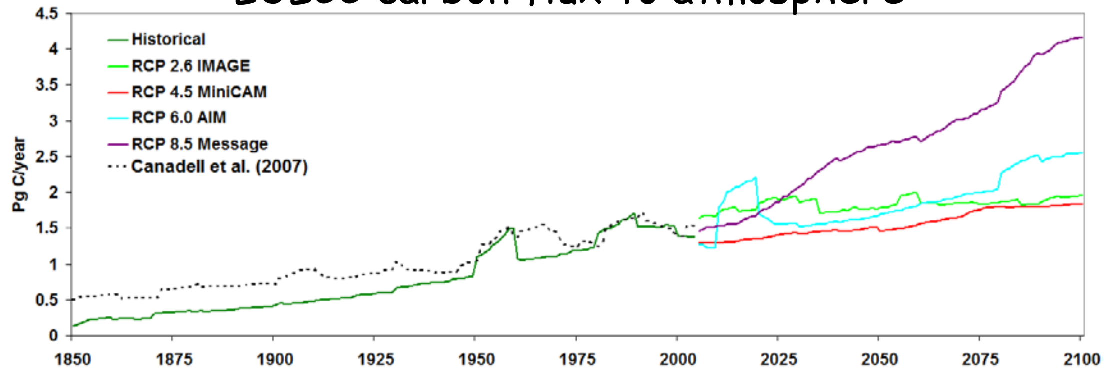
Change in crop cover (percent of grid cell) over the 21st century



Peter Lawrence et al. (2012) J. Clim., in press

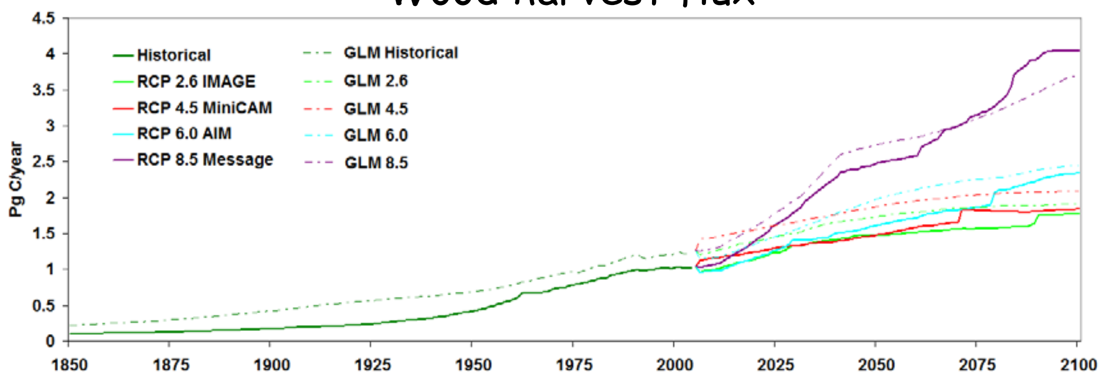
Carbon cycle

LULCC carbon flux to atmosphere



Simulations with CLM/CESM are consistent with the estimated land use flux over the historical period

Wood harvest flux

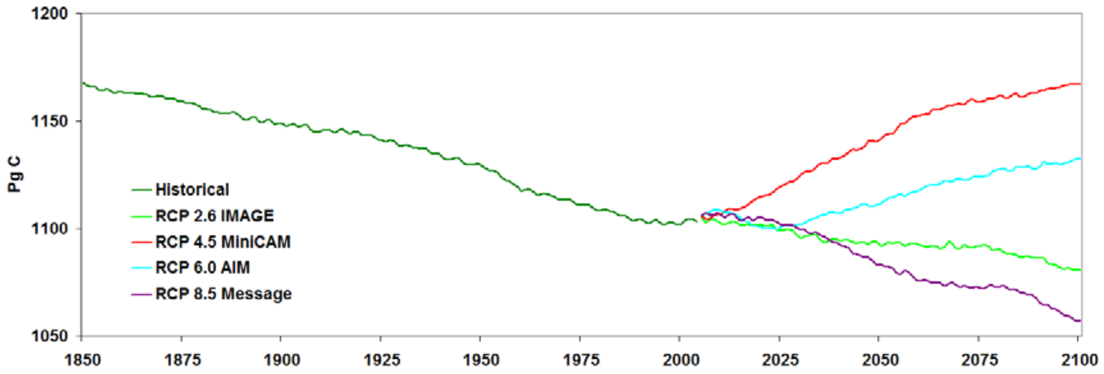


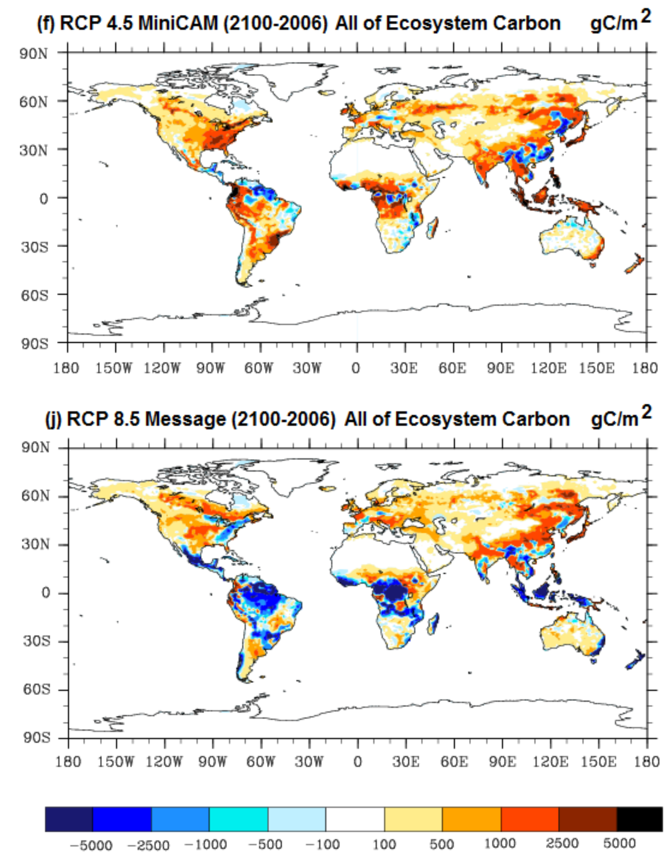
Simulations with CLM/CESM are consistent with the estimated wood harvest flux over the historical period and the RCPs

Peter Lawrence et al. (2012) J. Clim., in press

Land use choices matter

Ecosystem carbon (excluding product pools)





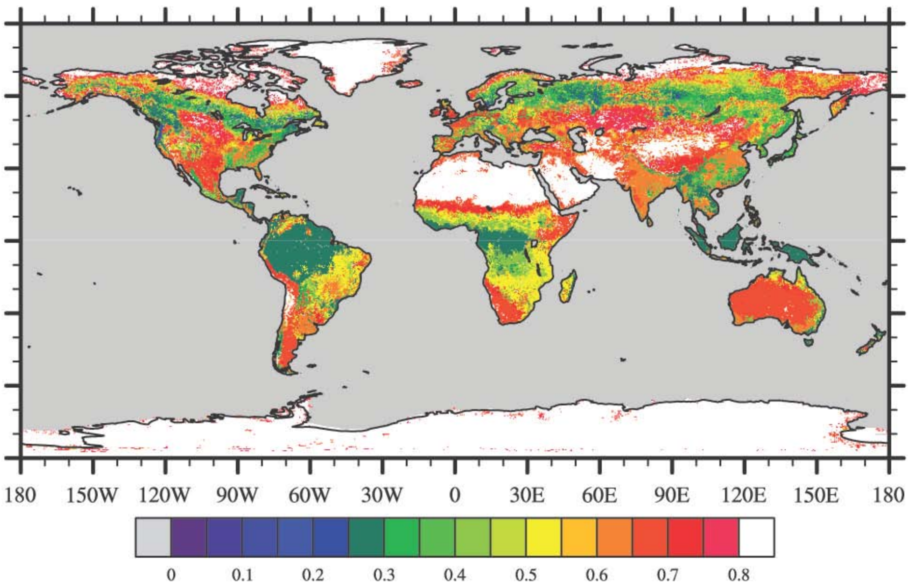
RCP 4.5: reforestation drives carbon gain

RCP 8.5: deforestation and wood harvest drive carbon loss

Peter Lawrence et al. (2012) J. Clim., in press

Surface albedo

Maximum snow-covered albedo



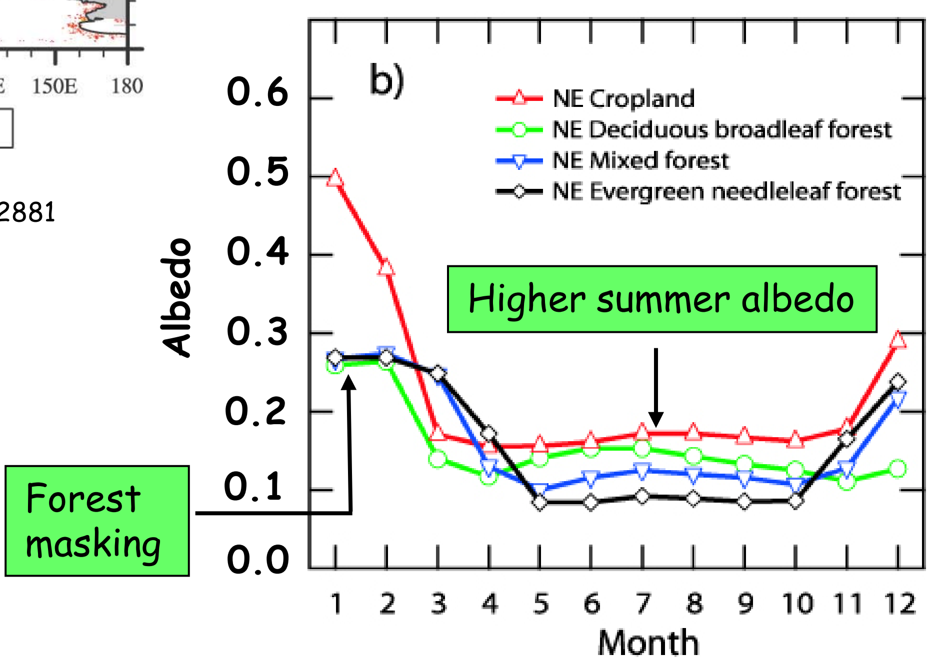
Barlage et al. (2005) GRL, 32, doi:10.1029/2005GL022881

LULCC effects

- Vegetation masking of snow
- High albedo of crops

Colorado Rocky Mountains

Monthly surface albedo (MODIS) by land cover type in NE US



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

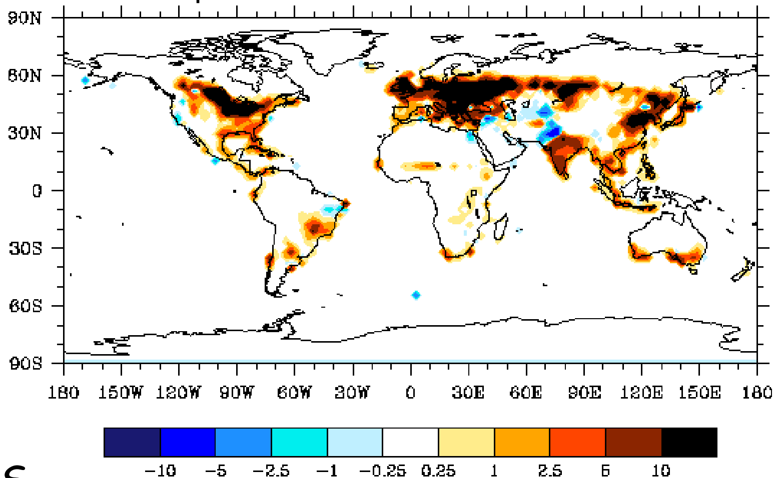
Surface albedo: present day – potential vegetation

DJF

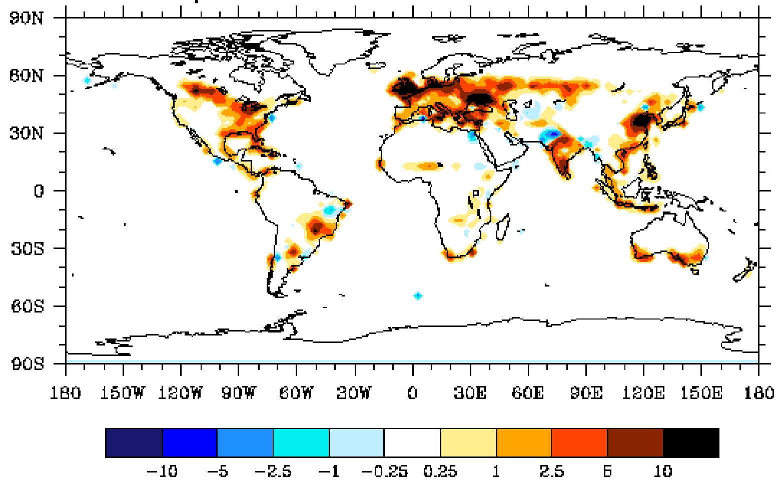
JJA

CLM3.5

current - potential

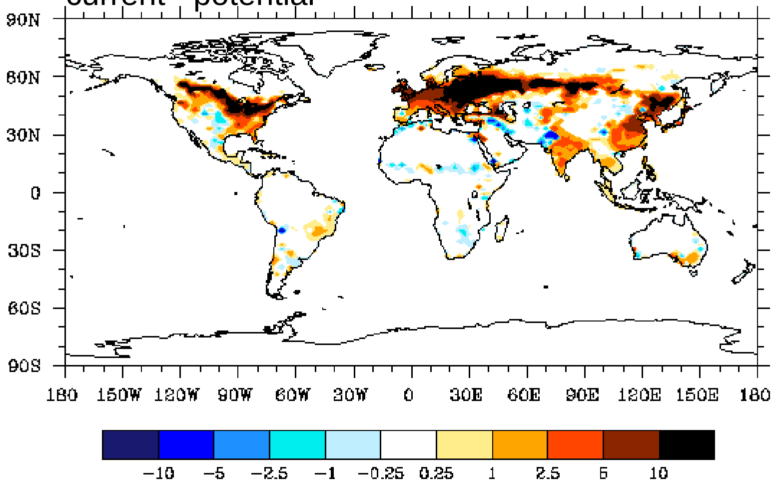


current - potential

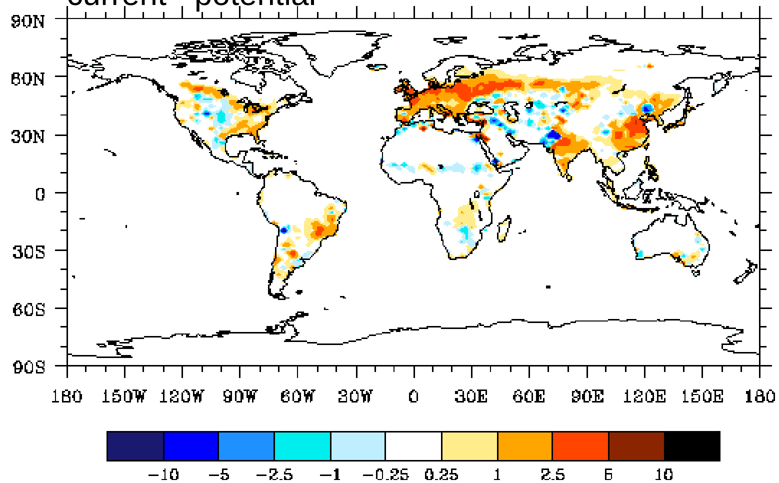


MODIS

current - potential



current - potential



Units are Δalbedo × 100

Peter Lawrence, unpublished

Land cover change and evapotranspiration

Prevailing model paradigm

Crops & grasses

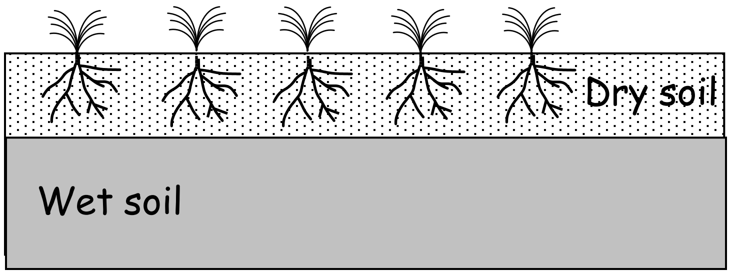
Low latent heat flux because of:

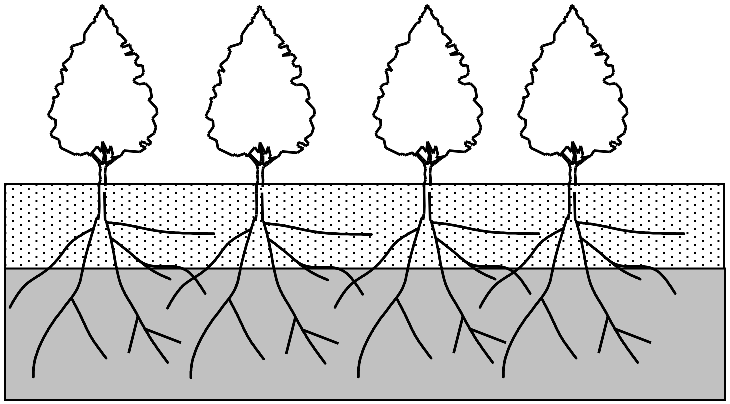
- Low roughness
- Shallow roots decrease soil water availability

Trees

High latent heat flux because of:

- High roughness
- Deep roots allow increased soil water availability



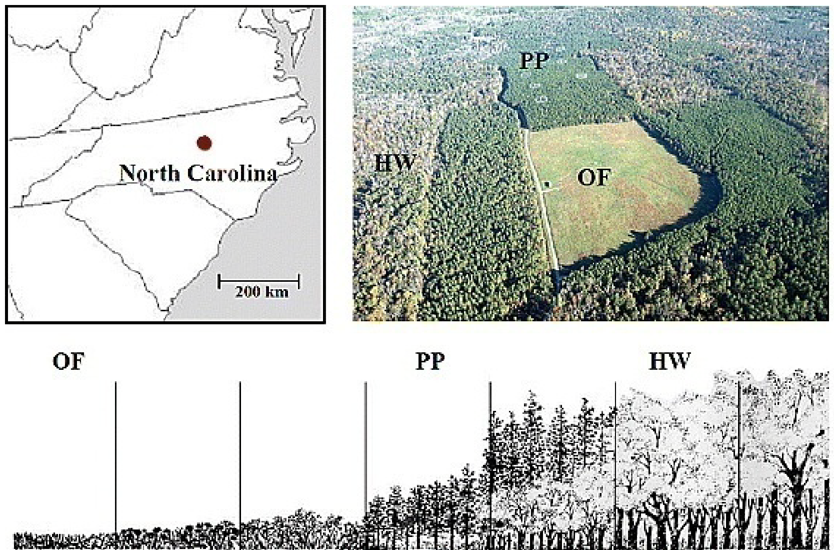


Tropical forest – cooling from higher surface albedo of cropland and pastureland is offset by warming associated with reduced evapotranspiration

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

Bonan (2008) Science 320:1444-1449

Forest evapotranspiration cools climate locally



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

Annual mean temperature change

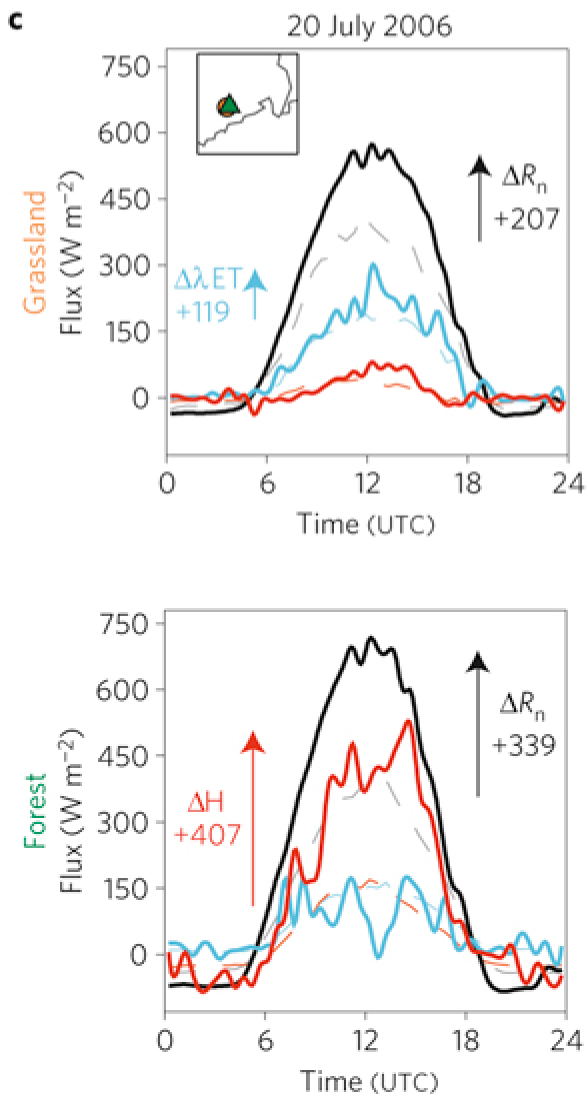
	OF to PP	OF to HW
Albedo	+0.9°C	+0.7°C
Ecophysiology and aerodynamics	-2.9°C	-2.1°C

Forest
Lower albedo (+)

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

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

Response to heatwave and drought



Energy exchanges at the peak of the July 2006 heatwave for neighboring flux towers over forest and grassland. **c**, Grillenburg and Tharandt (distance 4 km). The solid lines indicate HWD values; the dashed lines indicate the baseline conditions in a normal year. Black: net radiation (R_n), blue: latent heat flux (λET), red: sensible heat flux (H).

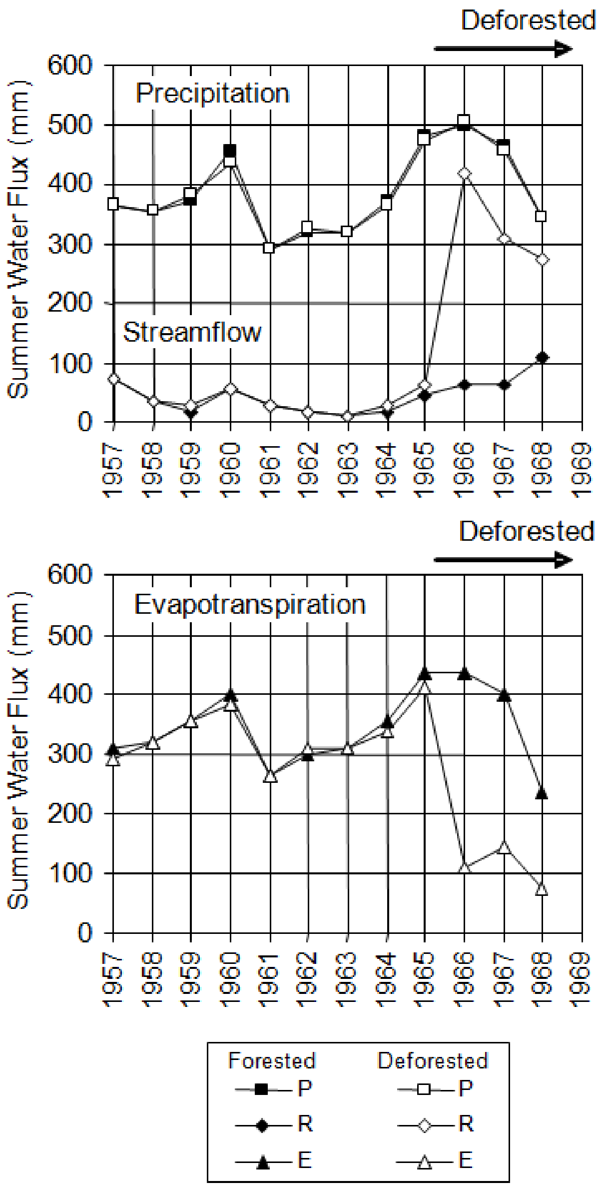
Teuling et al. (2010) Nature Geosci 3:722-727

Watershed deforestation studies

Hubbard Brook
Experimental Forest

P – E = R

Deforestation decreases evapotranspiration (E) and increases runoff (R)



Conclusions

Broad conclusions

- LULCC matters at the regional scale and so must be included in detection & attribution studies
- The choices we make in LULCC will likely influence future climate
- Differences among models matter and so we must devise appropriate model tests

Biogeochemistry

- Land use flux is important, especially the wood harvest flux

Biogeophysics

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

Climate biases matter

- Vegetation masking of snow albedo is less important when snow cover is biased low
- Evapotranspiration feedbacks depend on the precipitation biases
- The regionality of LULCC challenges models in their climate simulation