# Climate change mitigation through ecosystem management

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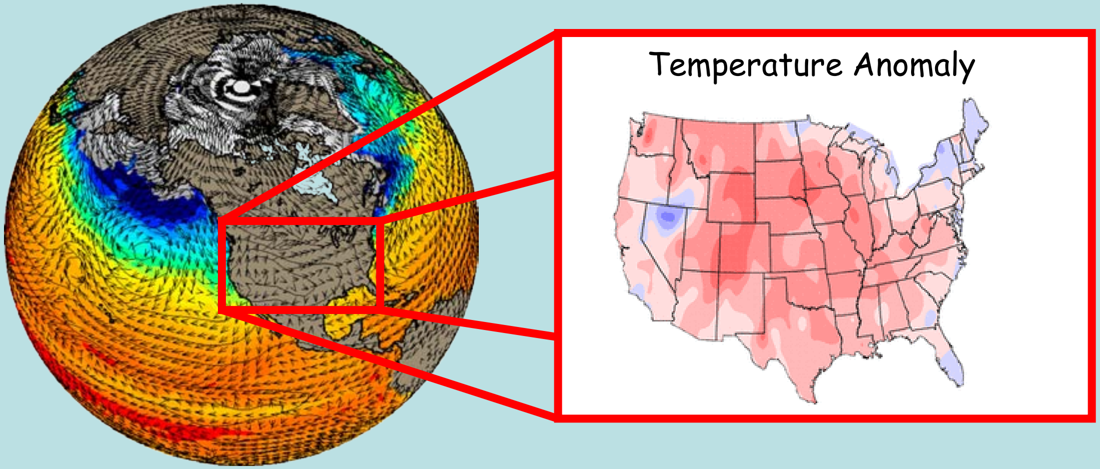

Center on Global Change
Duke University
Durham, NC
March 19, 2009

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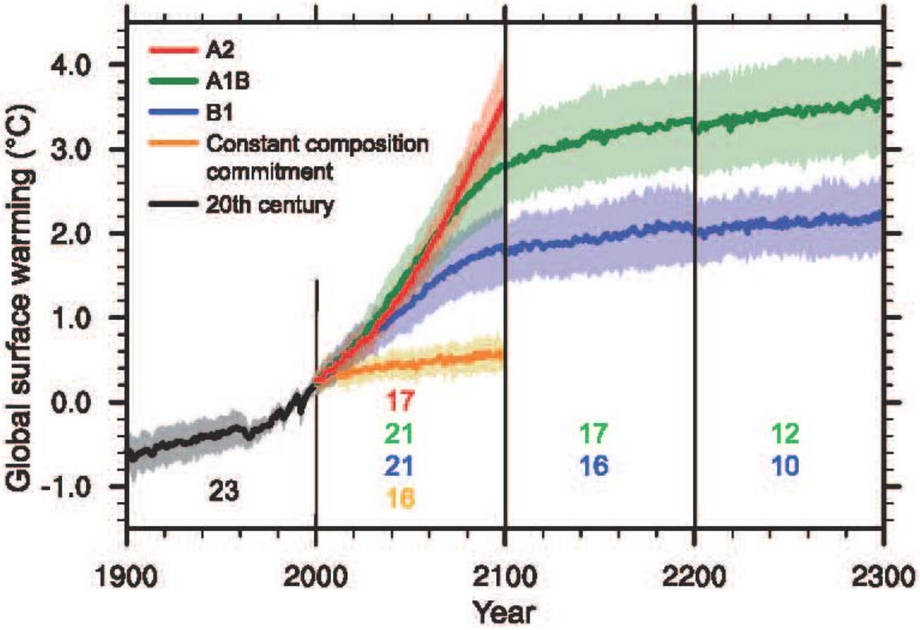
**National Center for Atmospheric Research**
**Boulder, Colorado**

# Climate of the 21st century

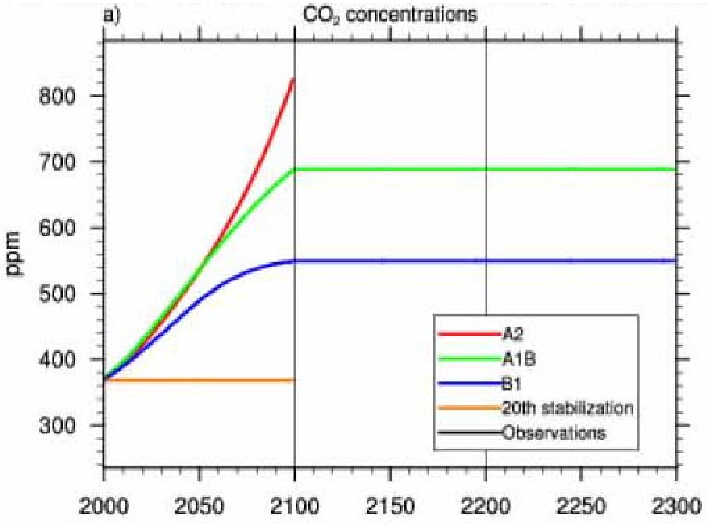
## Multi-model mean surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1



Multi-model mean warming and uncertainty for 2090 to 2099 relative to 1980 to 1999:

A2: +3.4°C (2.0°C to 5.4°C)
A1B: +2.8°C (1.7°C to 4.4°C)
B1: +1.8°C (1.1°Cto 2.9°C)

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

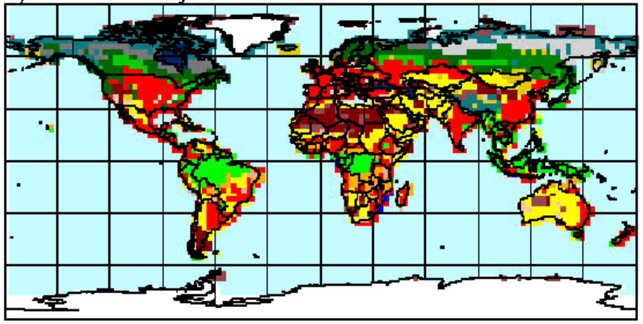


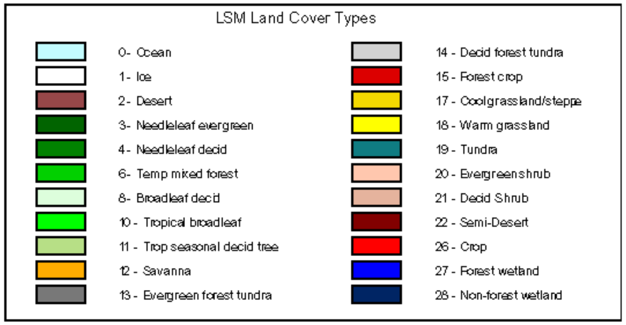
For 5th assessment report
- As land cover change and the carbon cycle are added as climate forcings and feedbacks, will uncertainty in these simulations increase?
- Can ecosystems be managed to mitigate climate change?

# Land use choices affect 21st century climate

## Future IPCC SRES land cover scenarios for NCAR LSM/PCM

a) Present day land cover

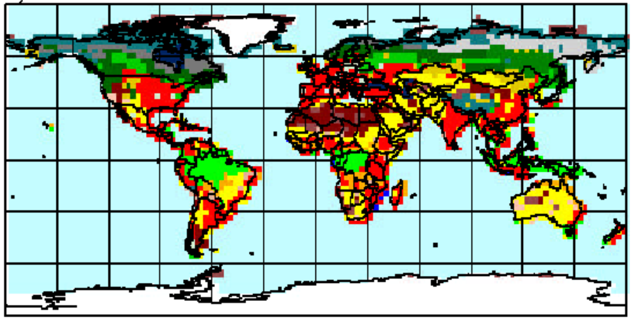




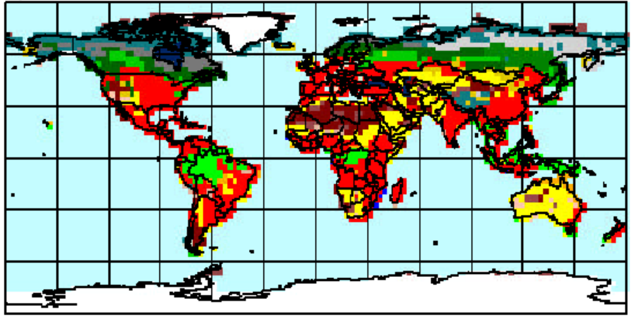
LSM Land Cover Types

| | | | |
|---|---|---|---|
| 🟦 | 0- Ocean | ⬜ | 14 - Decid forest tundra |
| ⬜ | 1- Ice | 🟥 | 15 - Forest crop |
| 🟫 | 2- Desert | 🟨 | 17 - Coolgrassland/steppe |
| 🟩 | 3- Needleleaf evergreen | 🟨 | 18 - Warm grassland |
| 🟩 | 4- Needleleaf decid | 🟦 | 19 - Tundra |
| 🟩 | 6- Temp mixed forest | 🟧 | 20 - Evergreenshrub |
| 🟩 | 8- Broadleaf decid | 🟧 | 21 - Decid Shrub |
| 🟩 | 10 - Tropical broadleaf | 🟫 | 22 - Semi-Desert |
| 🟩 | 11 - Trop seasonal decid tree | 🟥 | 26 - Crop |
| 🟧 | 12 - Savanna | 🟦 | 27 - Forest wetland |
| ⬛ | 13 - Evergreen forest tundra | 🟦 | 28 - Non-forest wetland |

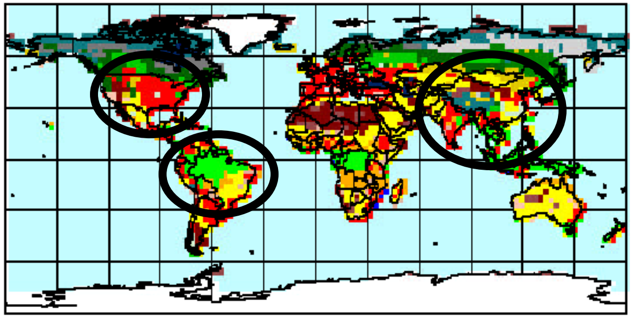
b) B1 2050 land cover



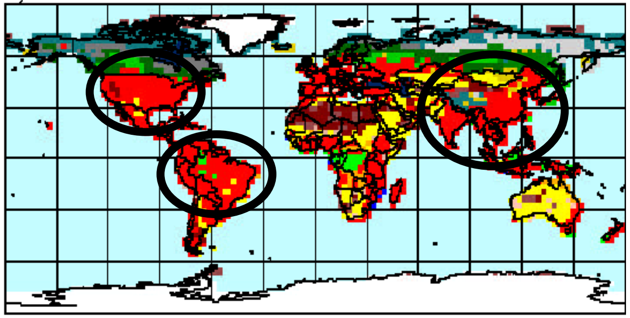
d) A2 2050 land cover



c) B1 2100 land cover



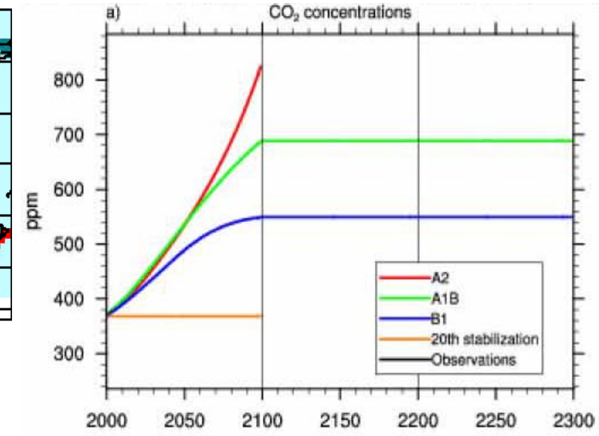
e) A2 2100 and cover



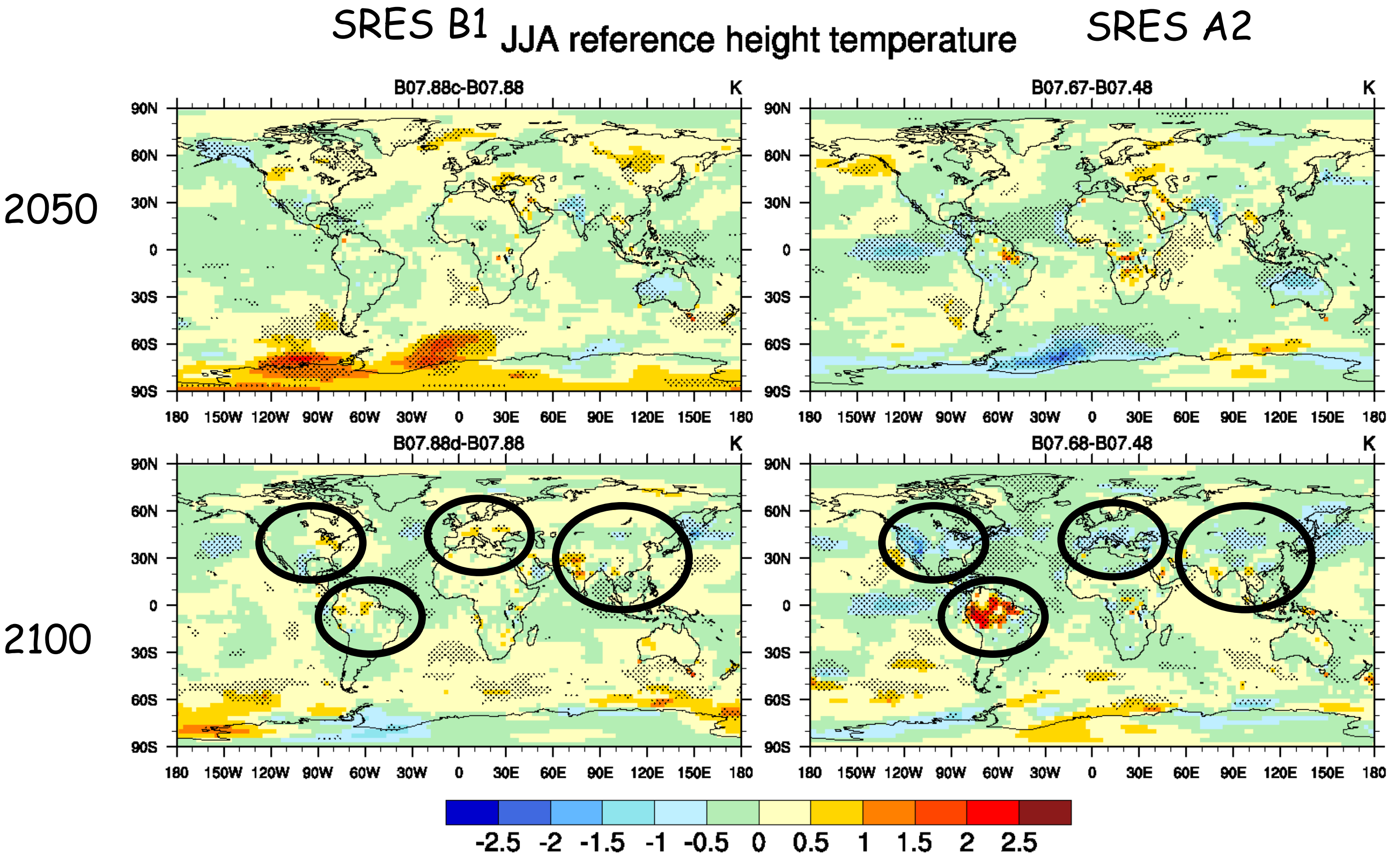
Feddema et al. (2005) Science 310:1674-1678

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



# Land use choices affect 21st century climate



Change in temperature due to land cover

**B1**
- Weak temperate warming
- Weak tropical warming

**A2**
- Temperate cooling
- Tropical warming

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

# Integrated land cover change (2100)

**Biogeophysical**

A2 – cooling with widespread cropland

B1 – warming with temperate reforestation

**Biogeochemical**

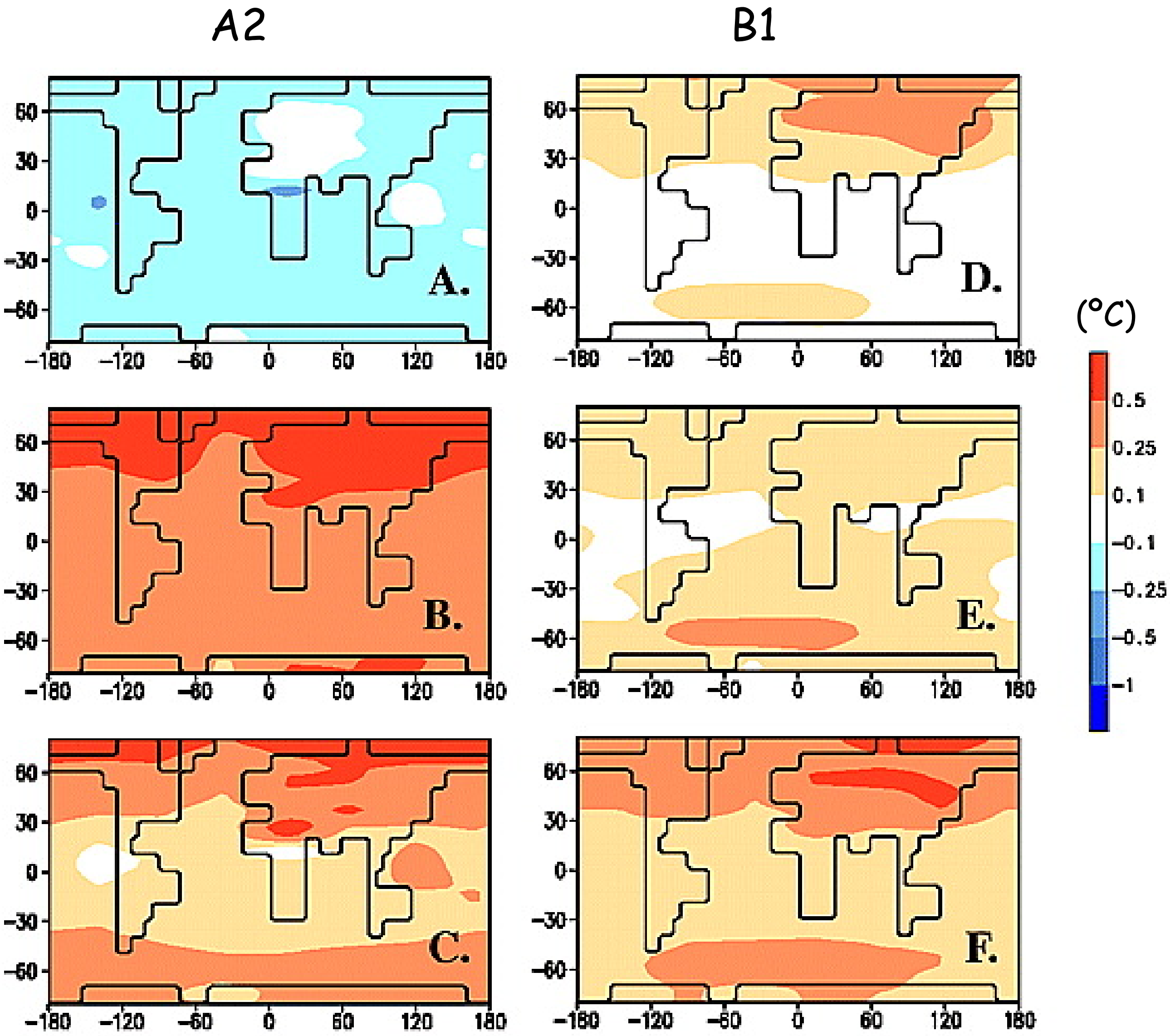
A2 – large warming with widespread deforestation

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

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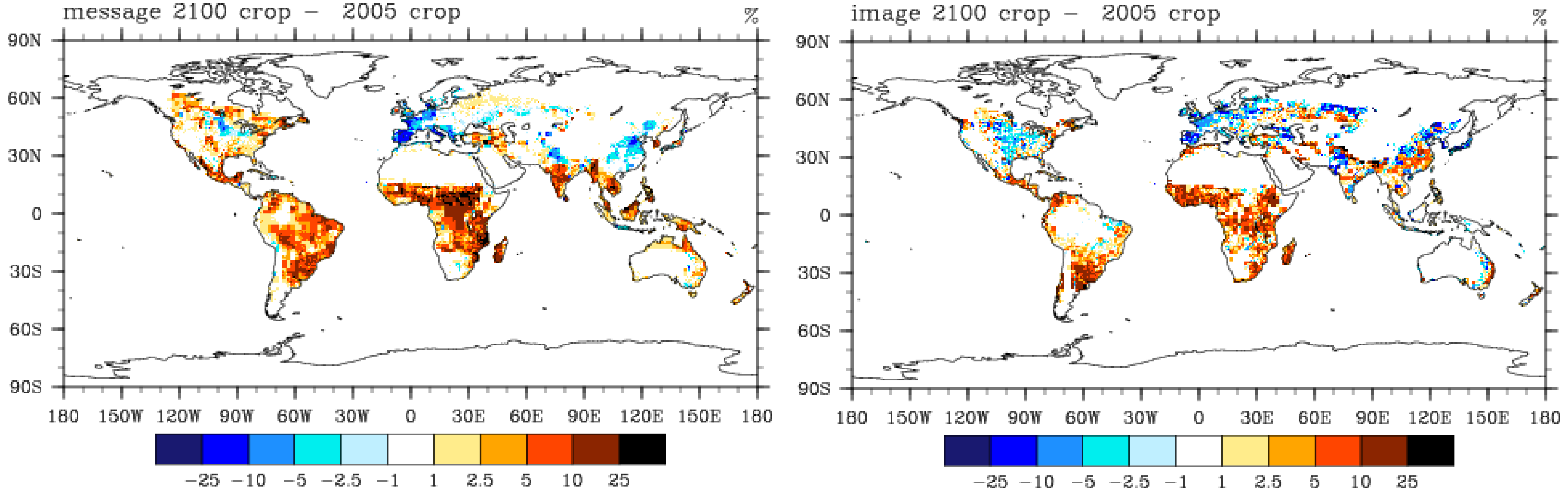
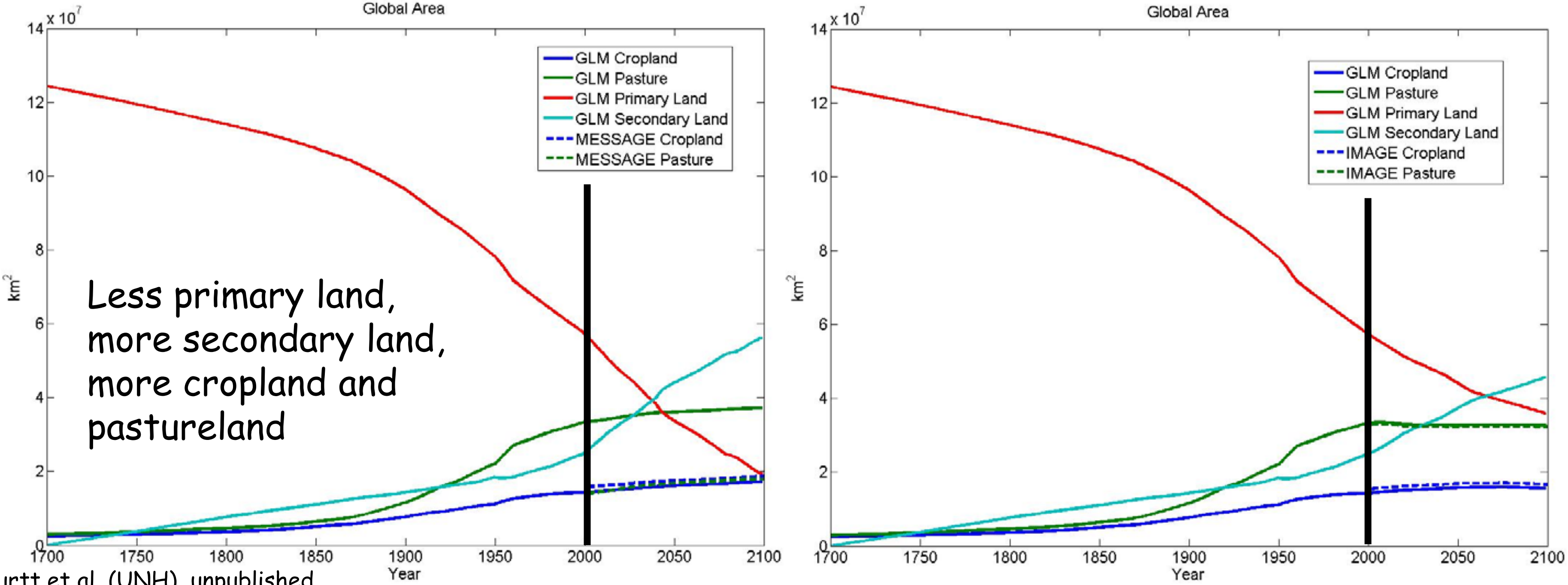
# MESSAGE (RCP 8.5) vs IMAGE (RCP 3.0)



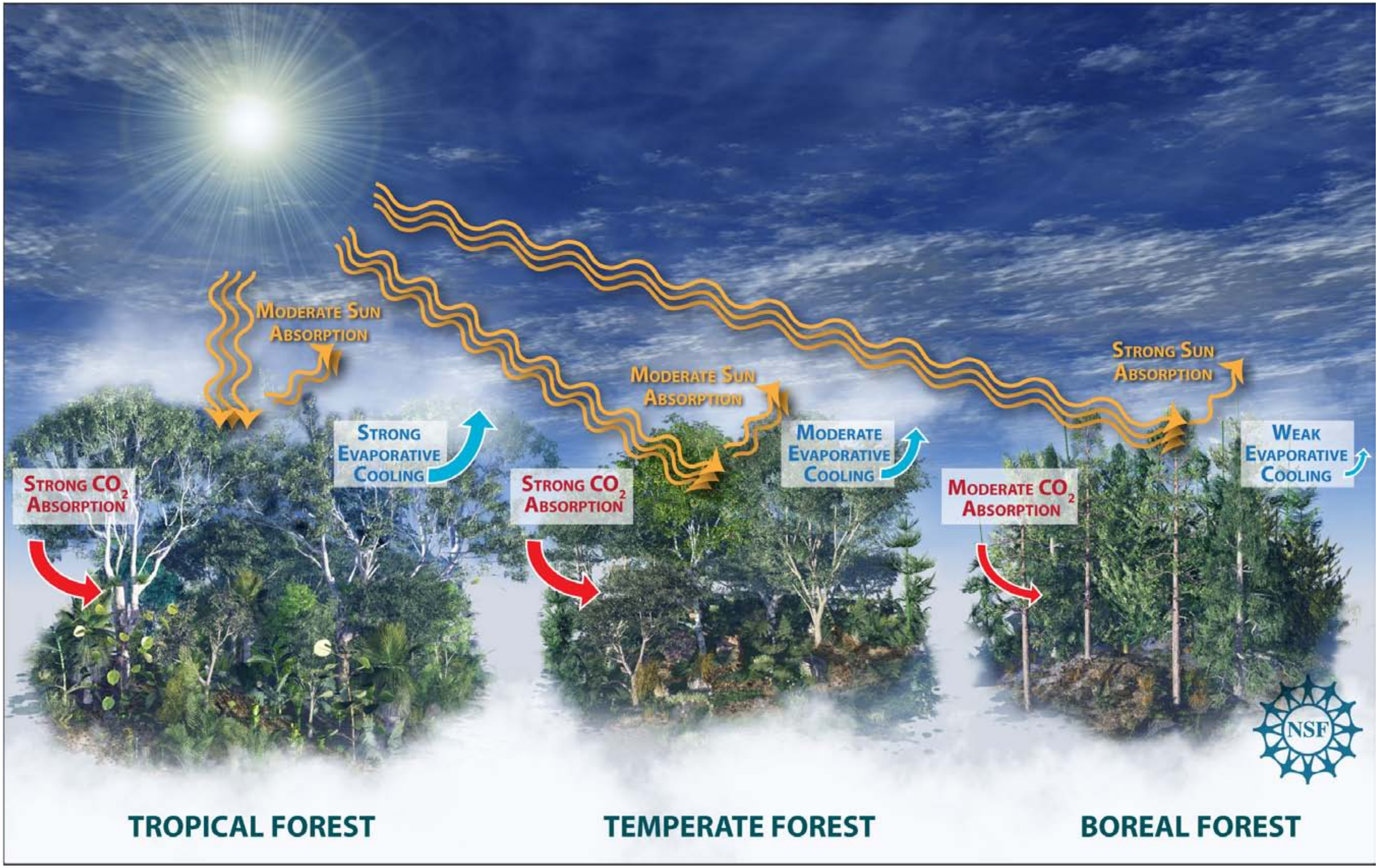


Less primary land,
more secondary land,
more cropland and
pastureland

Hurtt et al. (UNH), unpublished

# Forests and climate change

## Multiple competing influences of land cover change



Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*

# 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 $CO_2$

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# The Community Land Model

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

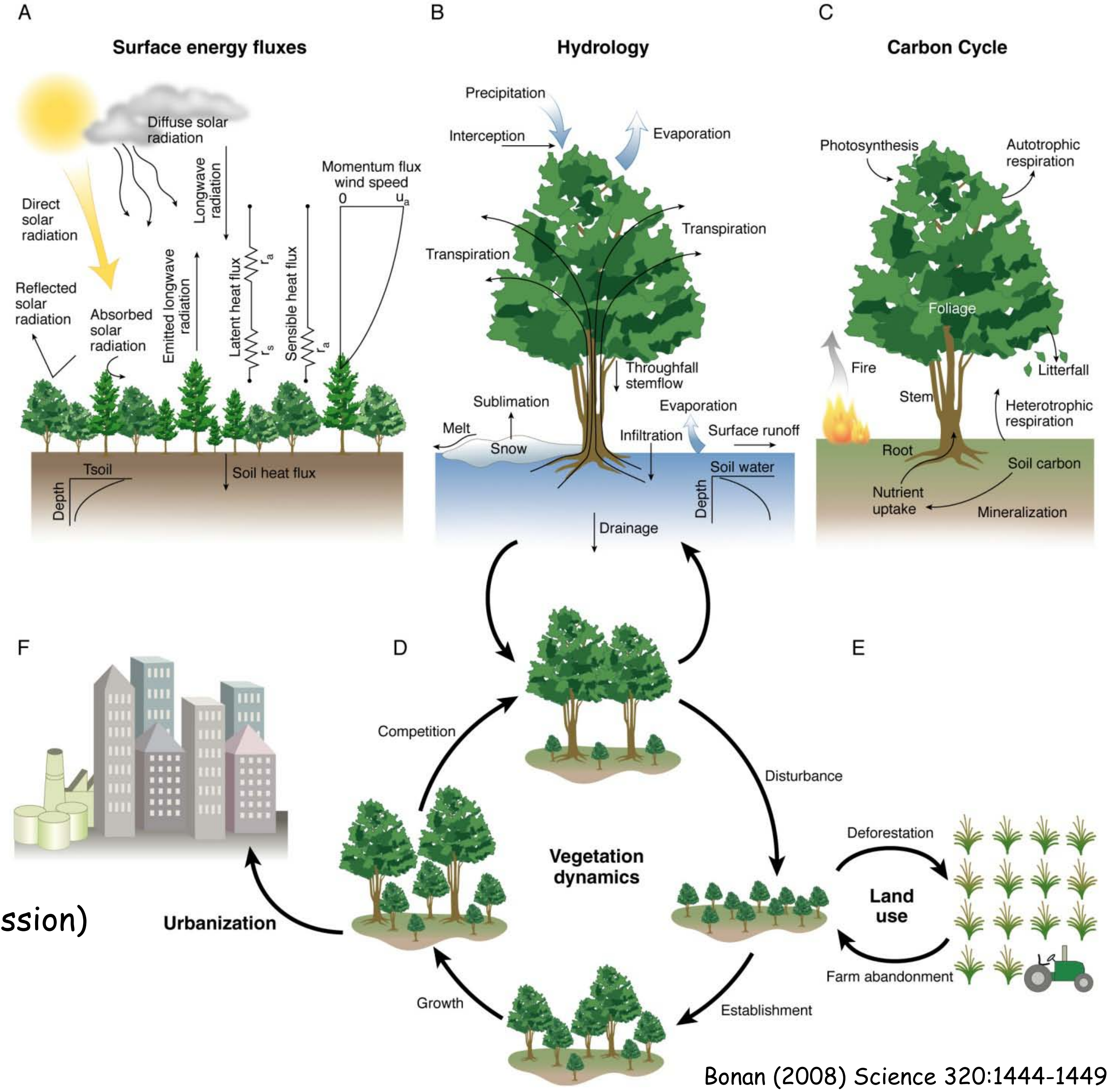
Oleson et al. (2004) NCAR/TN-461+STR

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

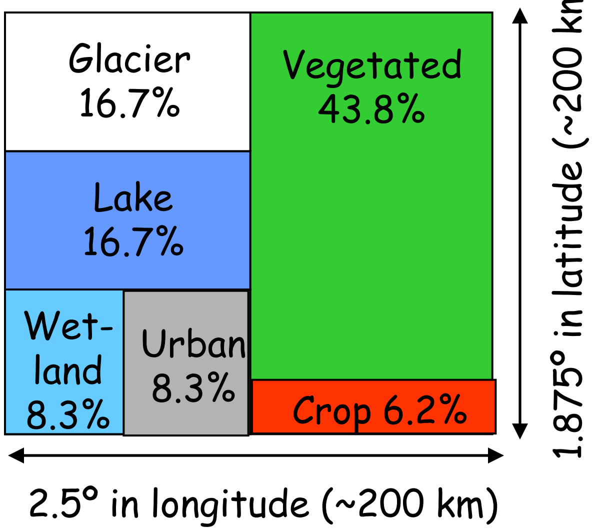
**Temporal scale**
- <30-minute coupling with atmosphere
- Seasonal-to-interannual variability (phenology)
- Decadal-to-century climate (disturbance, land use, succession)
- Paleoclimate (biogeography)



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





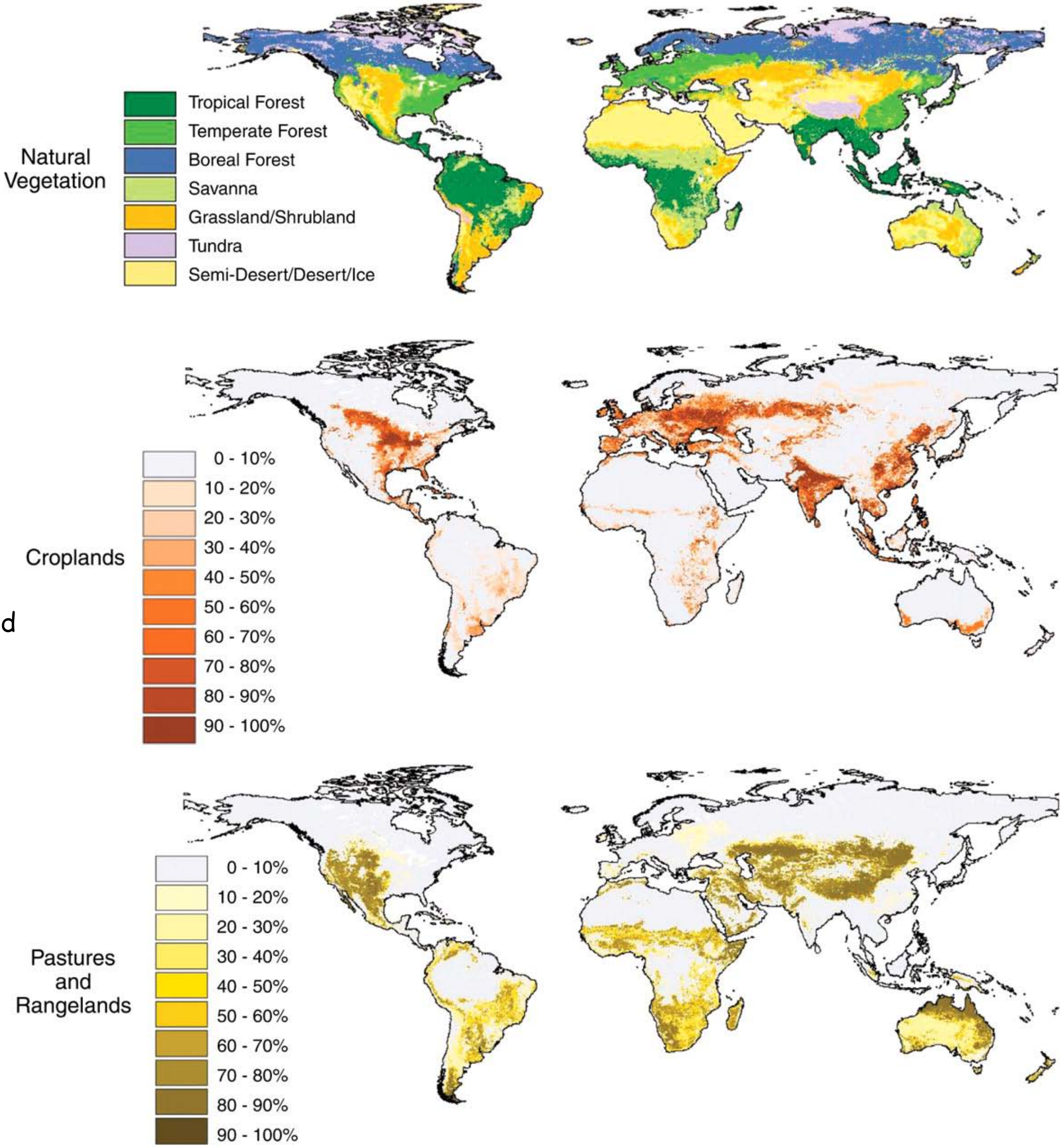
Bonan et al. (2002) GBC, 16, doi:10.1029/2000GB001360

# Global land use

Local land use is spatially heterogeneous

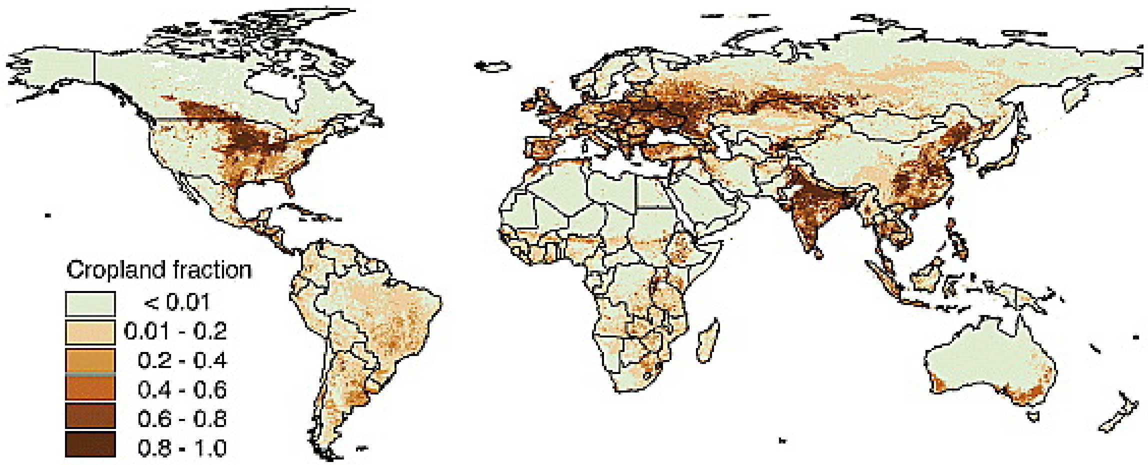
NSF/NCAR C-130 aircraft above a patchwork of agricultural land during a research flight over Colorado and northern Mexico

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



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

# Multi-model ensemble of global land use climate forcing



The LUCID inter-comparison study of the land use forcing (1992-1870)

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

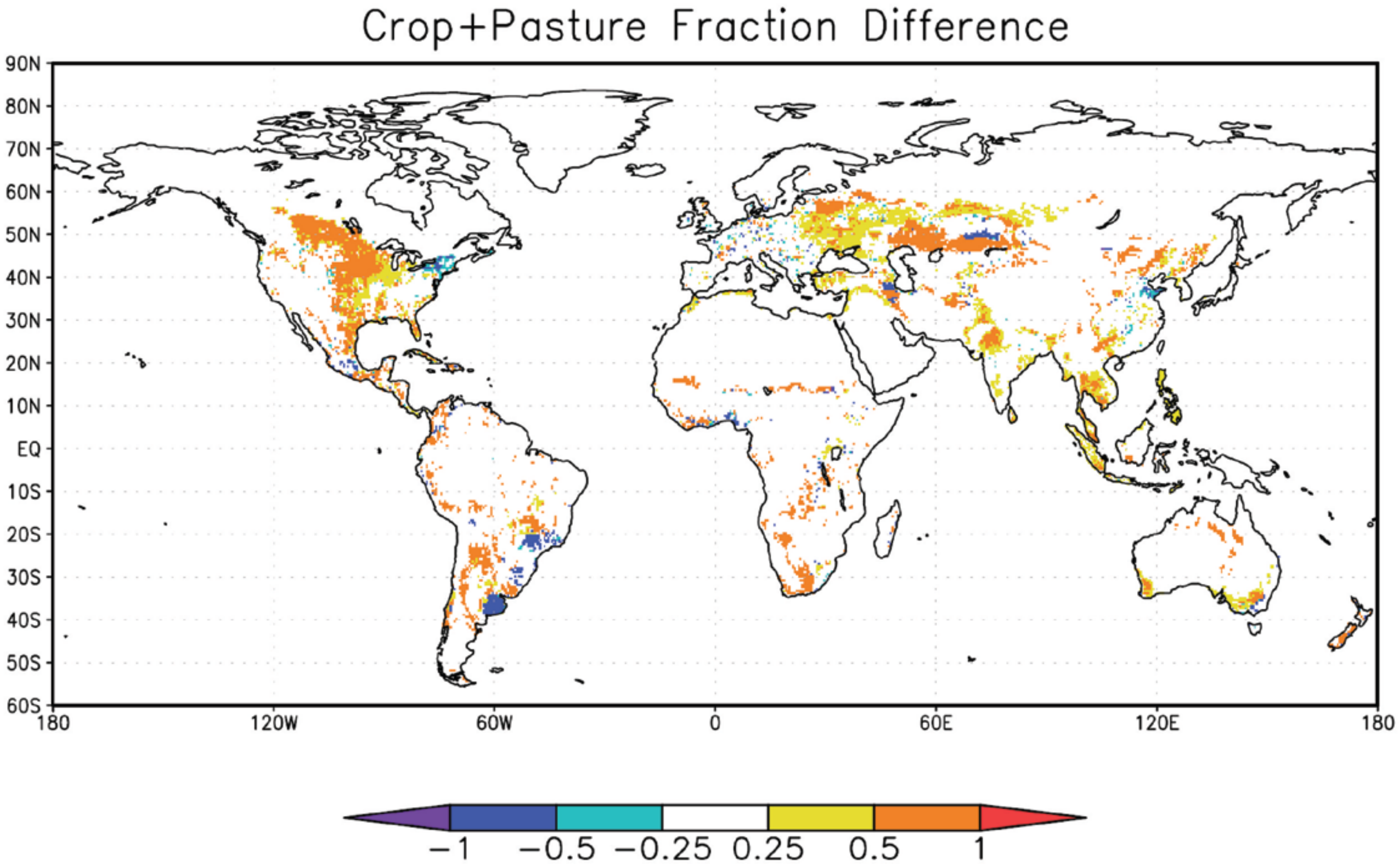
**Experiments**
30-year simulations ($CO_2$ = 375 ppm, SSTs = 1972-2001)
  PD – 1992 vegetation
  PDv - 1870 vegetation
30-year simulations ($CO_2$ = 280 ppm, SSTs = 1871-1900)
  PI – 1870 vegetation
  PIv – 1992 vegetation

**No irrigation**

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

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

# LUCID land cover change

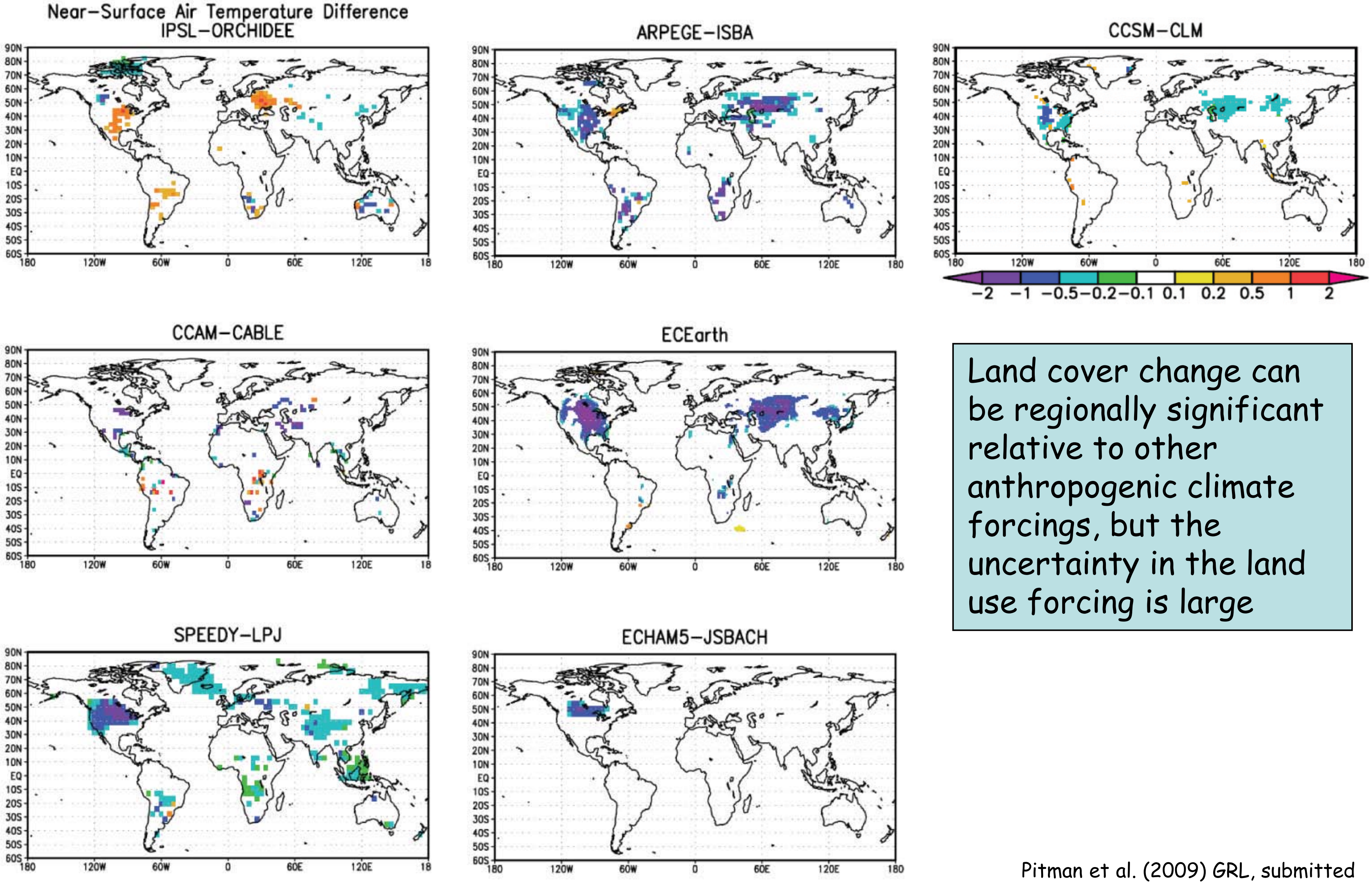


Extent of land cover change between experiments PD and PDv (PD – PDv) expressed as the difference in crop and pasture cover between the two experiments. Blue colours represent changes that decrease pasture and crop cover while yellows and browns are increases (25%-50% and 50-100% respectively).

Pitman et al. (2009) GRL, submitted

# The LUCID intercomparison study

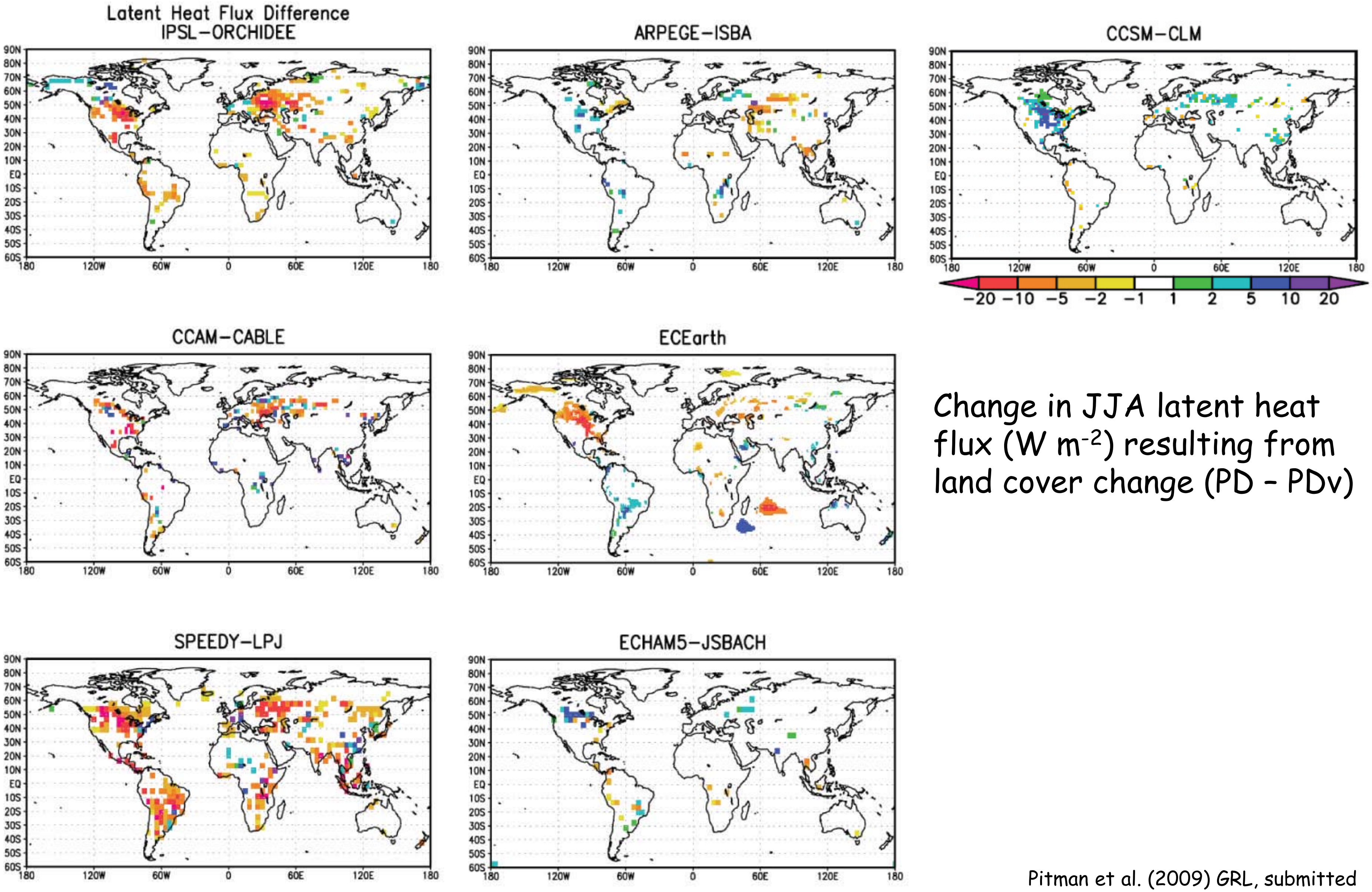
## Change in JJA near-surface air temperature (PD – PDv)



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

# The LUCID intercomparison study


Latent Heat Flux Difference
IPSL–ORCHIDEE

ARPEGE–ISBA

CCSM–CLM

CCAM–CABLE

ECEarth

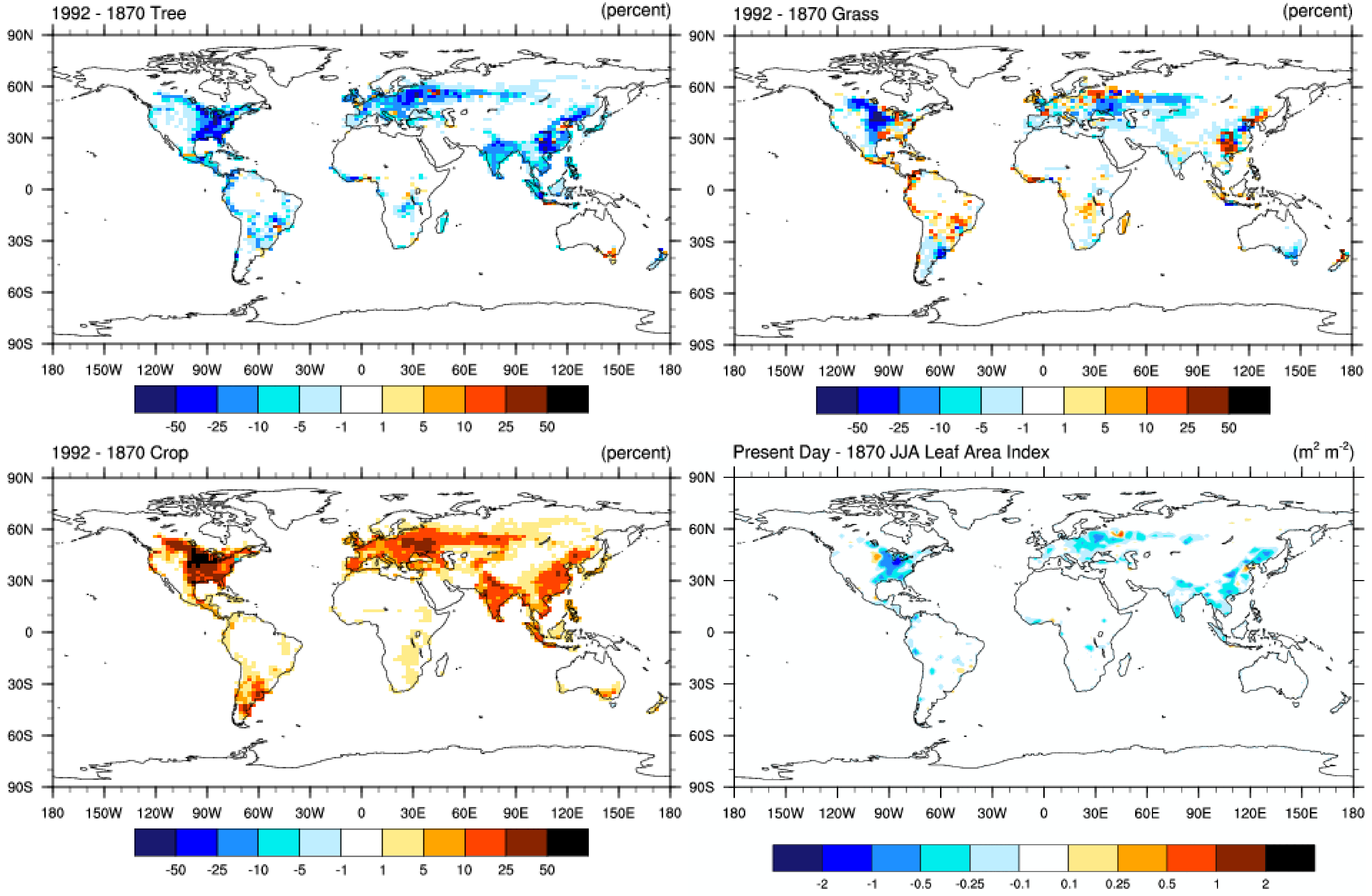
SPEEDY–LPJ

ECHAM5–JSBACH

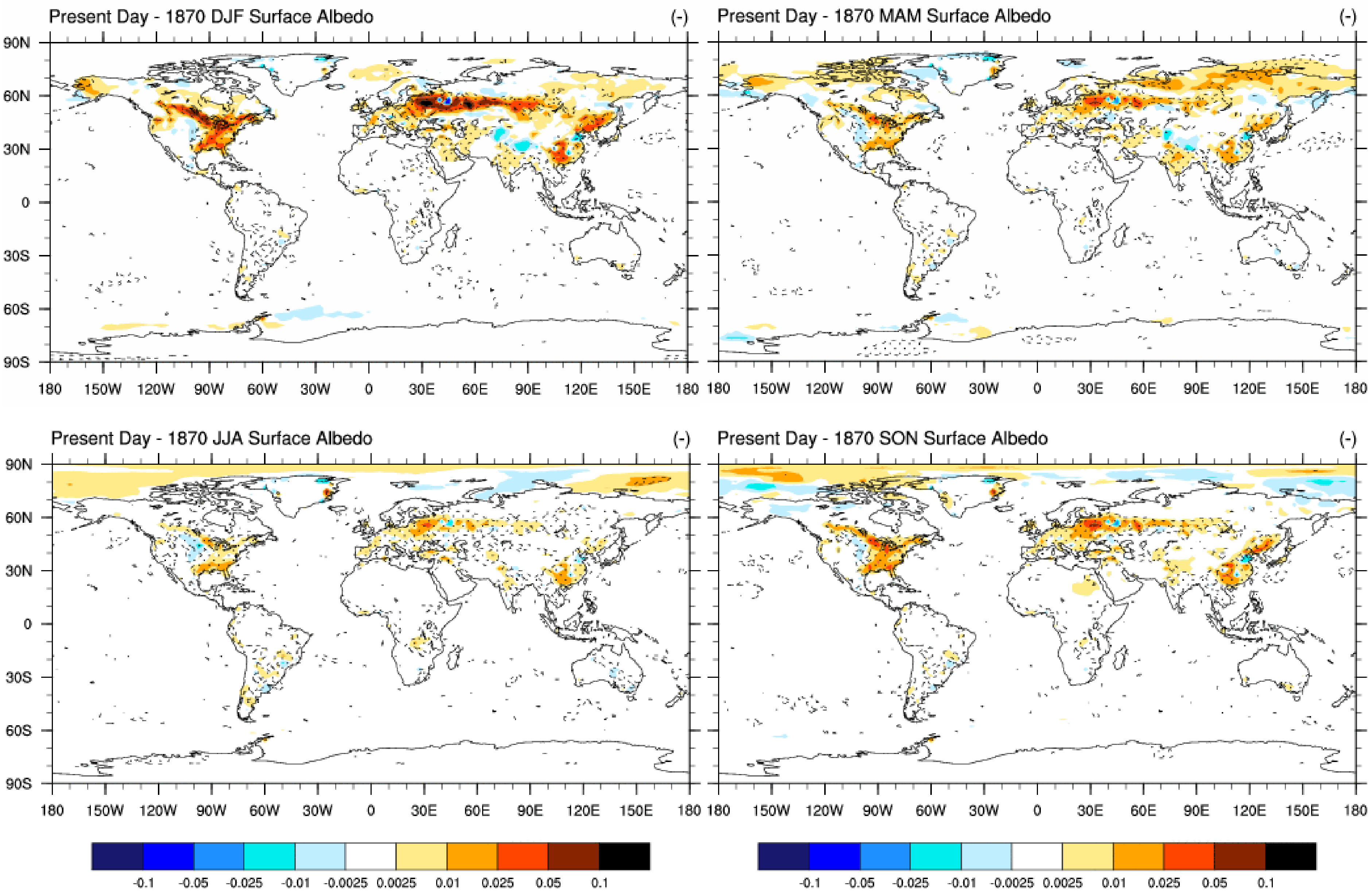
Change in JJA latent heat flux (W $m^{-2}$) resulting from land cover change (PD – PDv)

Pitman et al. (2009) GRL, submitted

# Land cover change, 1870 to 1992



# Albedo forcing, 1992-1870



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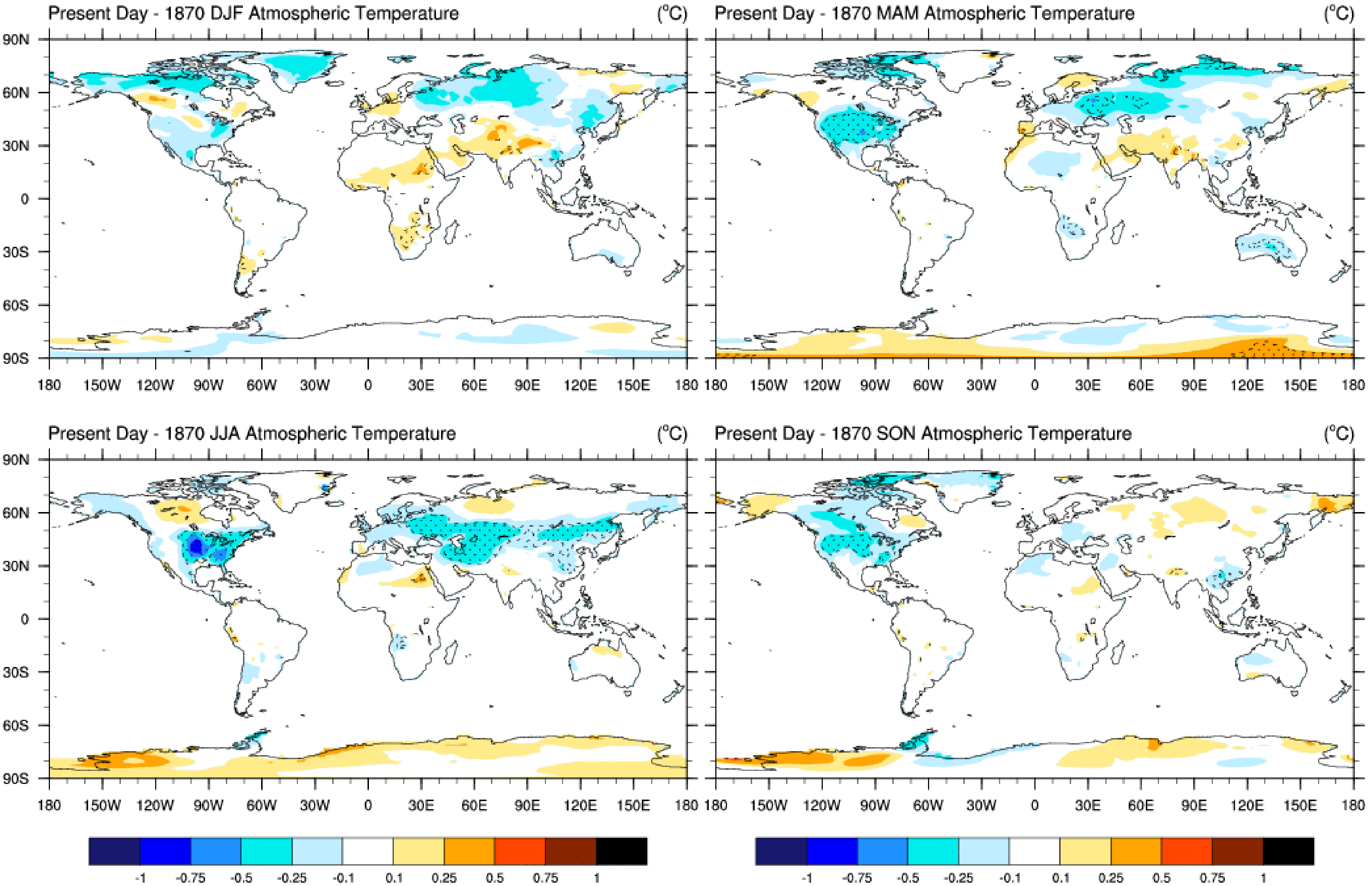
# Near-surface temperature, 1992-1870



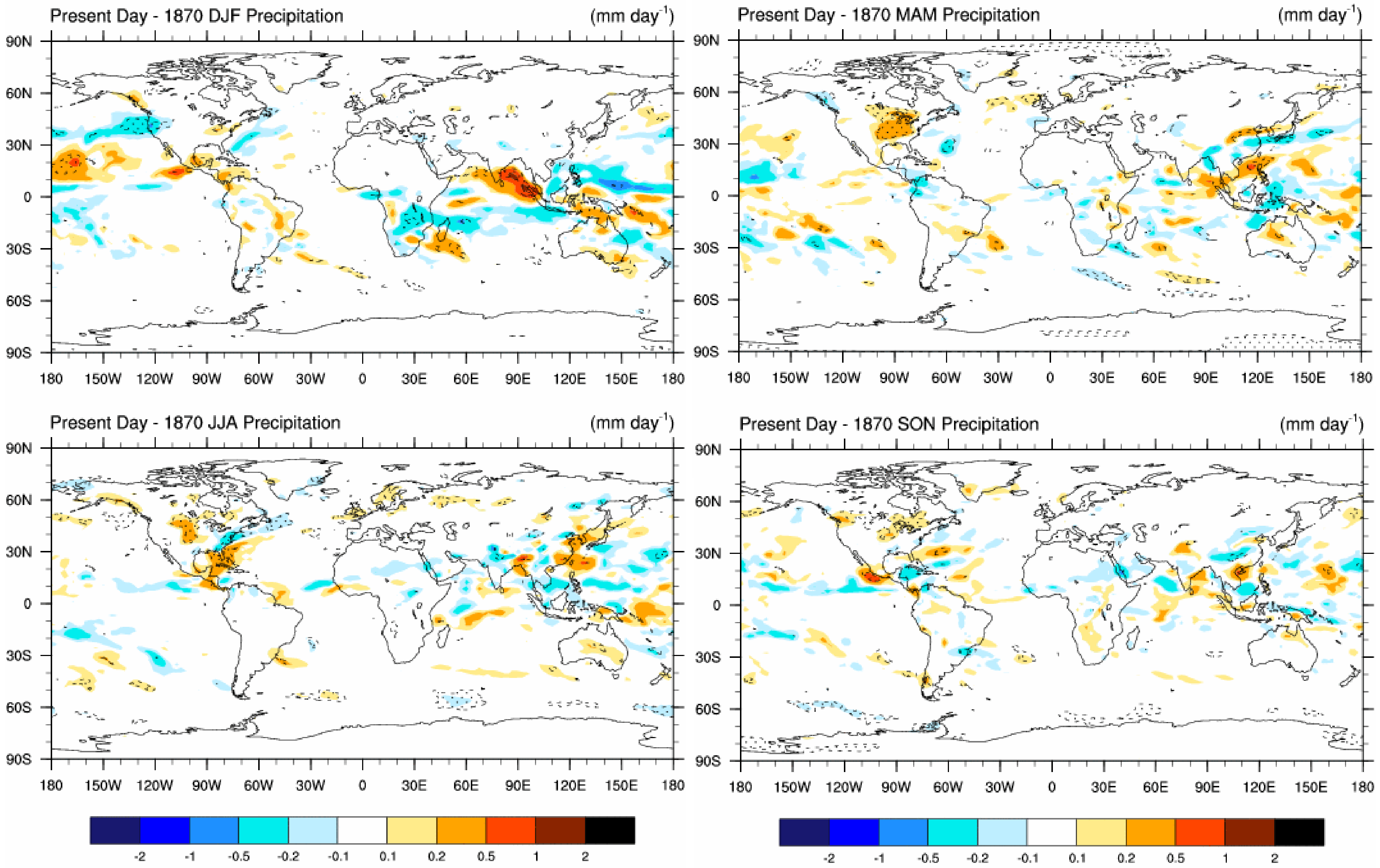
Present Day - 1870 DJF Atmospheric Temperature (°C)

Present Day - 1870 MAM Atmospheric Temperature (°C)

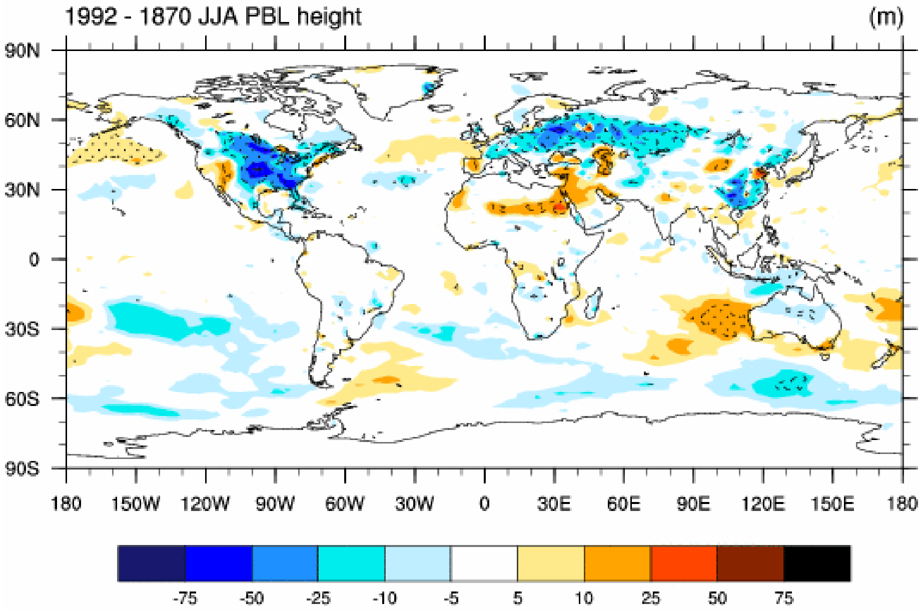
Present Day - 1870 JJA Atmospheric Temperature (°C)

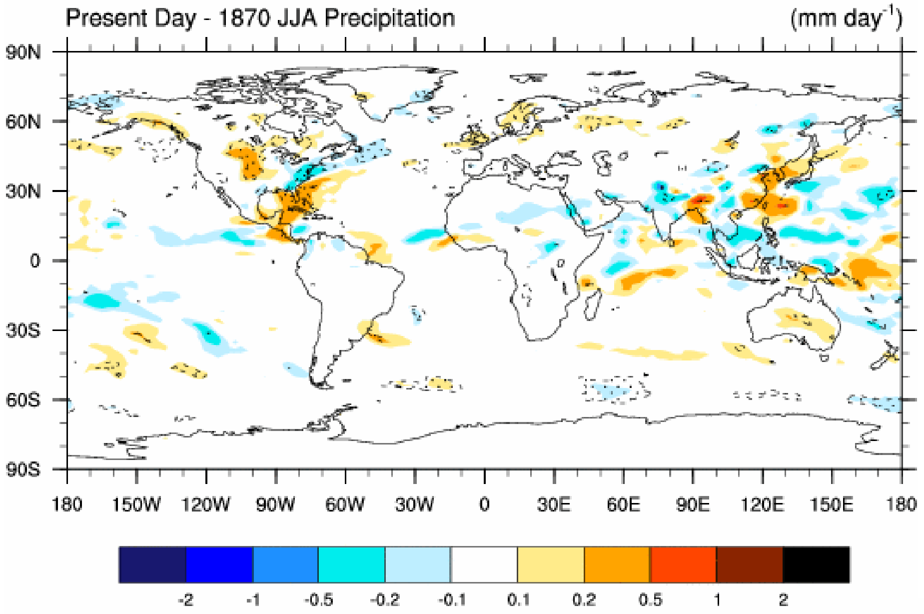
Present Day - 1870 SON Atmospheric Temperature (°C)

# Precipitation, 1992-1870



# Atmospheric feedbacks

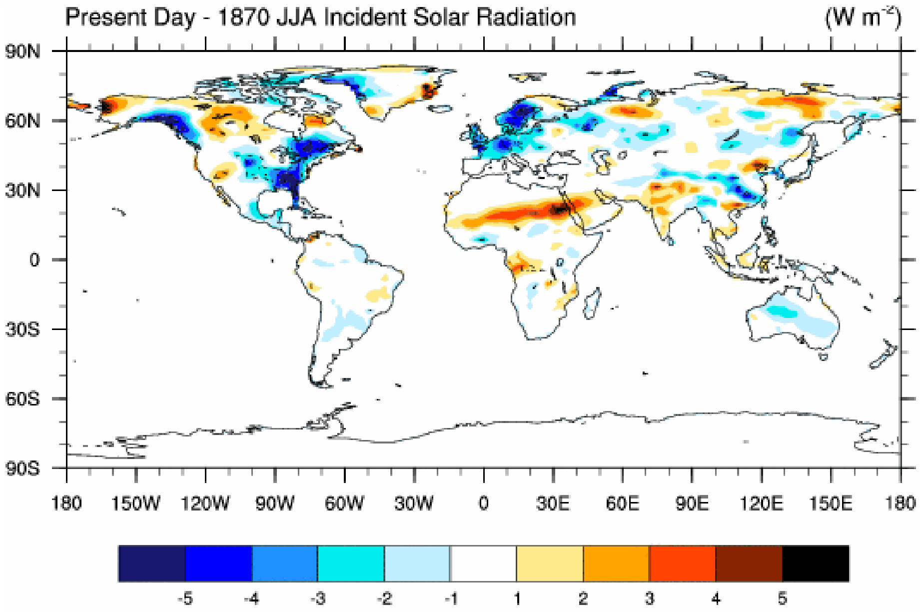

1992 - 1870 JJA PBL height (m)


Present Day - 1870 JJA Precipitation (mm day$^{-1}$)

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

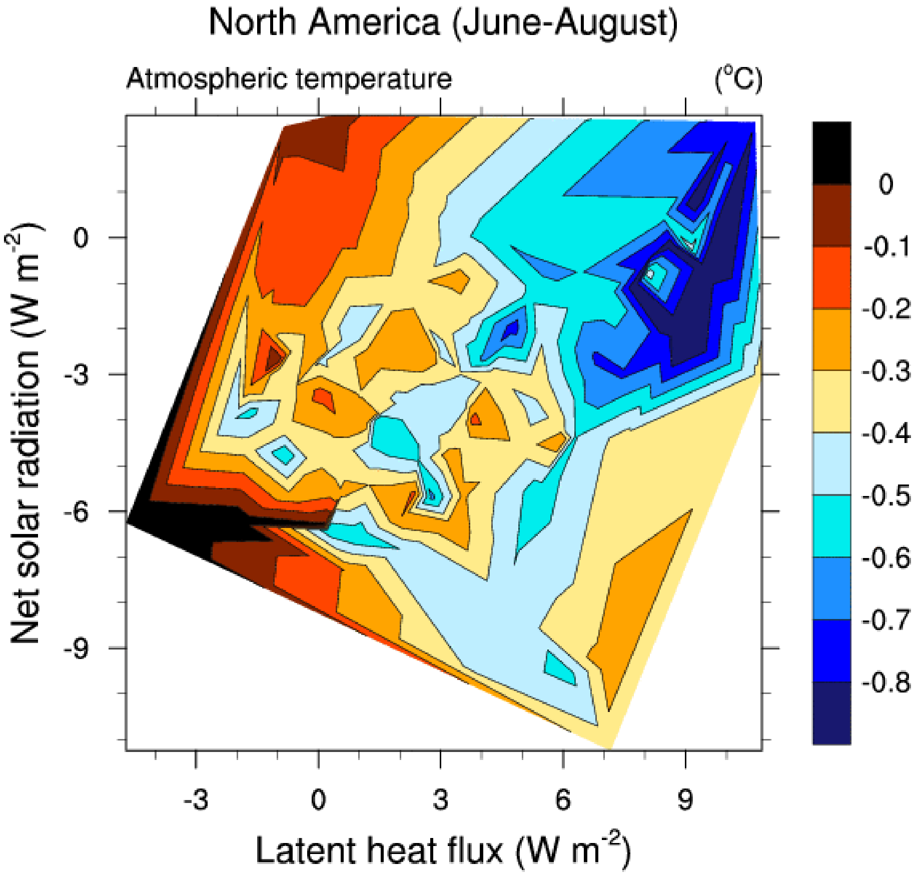
- Increased rainfall enhances latent heat flux
- Increased cloudiness reduces solar radiation
- Reduced PBL height

Flux towers measure local response


Present Day - 1870 JJA Incident Solar Radiation (W m$^{-2}$)

# Functional relationships to explain model response

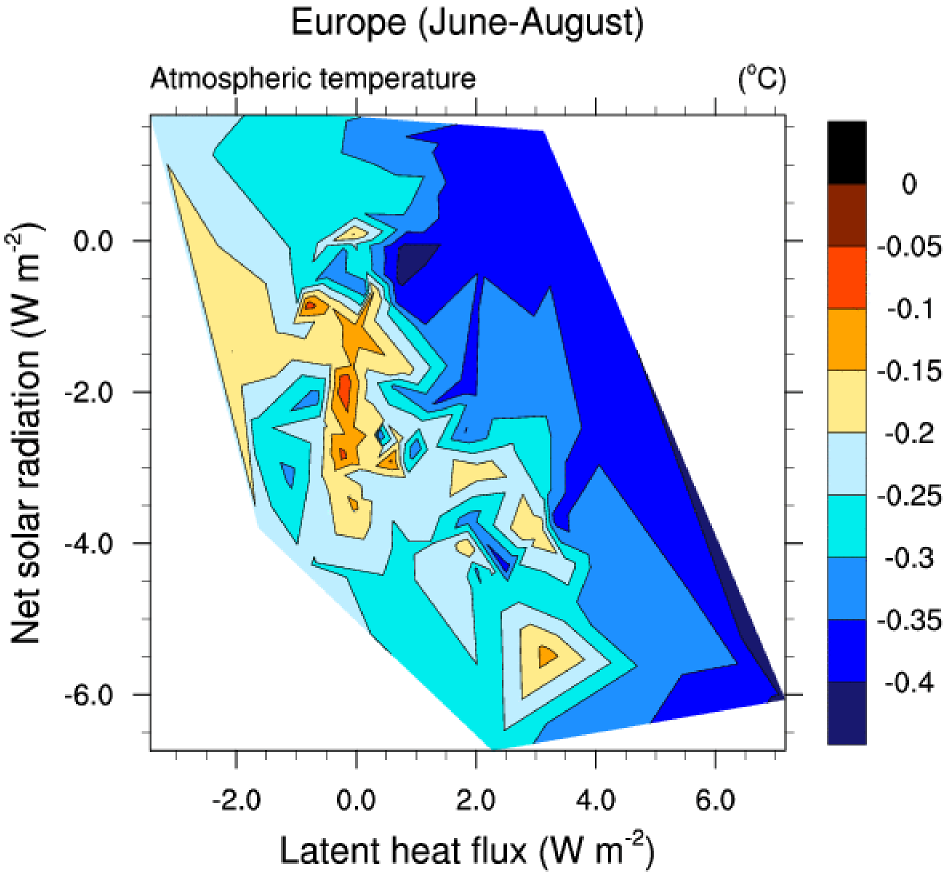
122 grid cells, 30-50 °N, east of 100 °W



$\Delta T = -0.27 - 0.04\ \Delta LH,\ r^2 = 0.48$

$\Delta T = -0.46 - 0.02\ \Delta S_{net},\ r^2 = 0.05$

119 grid cells, 45-60 °N, 15-50 °E

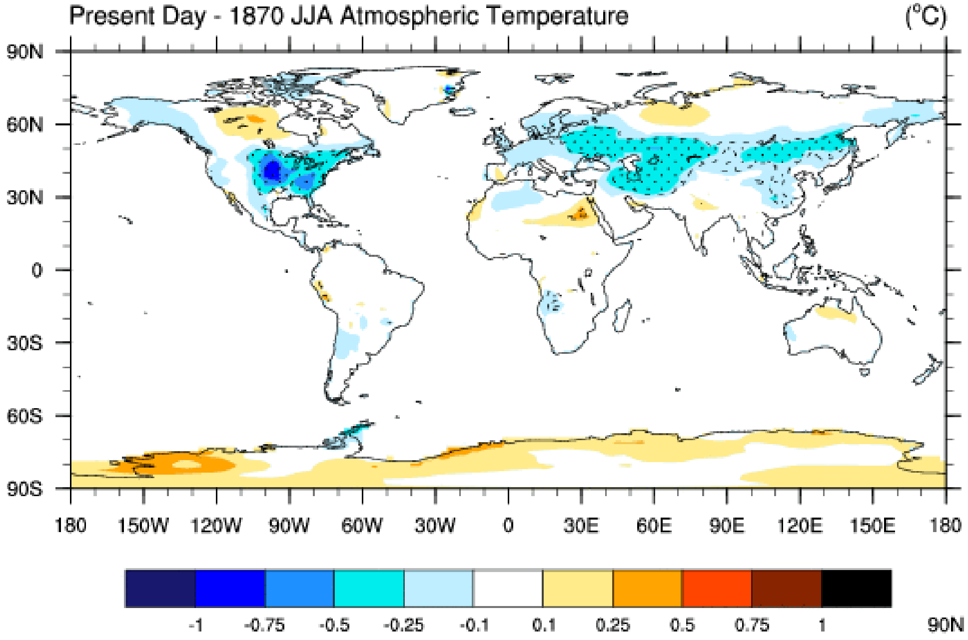


$\Delta T = -0.24 - 0.02\ \Delta LH,\ r^2 = 0.18$

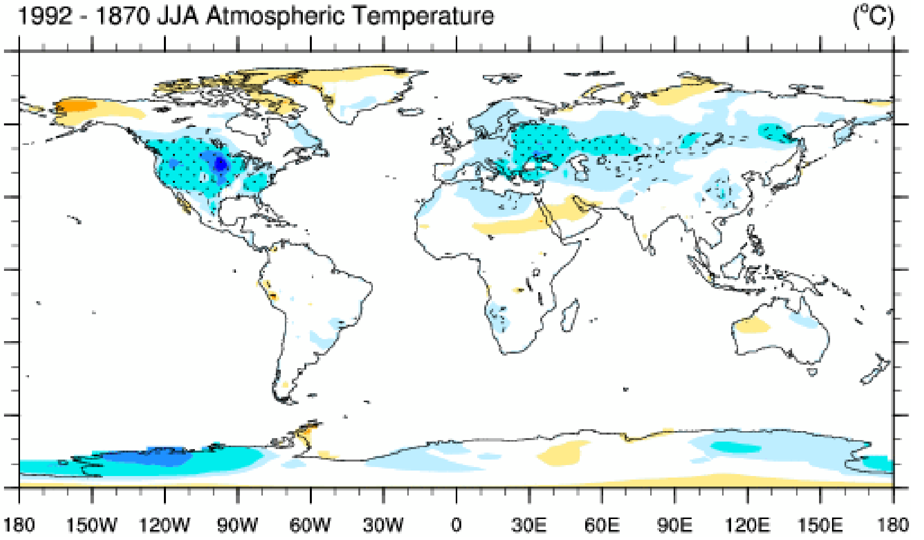
$\Delta T = -0.27 - 0.01\ \Delta S_{net},\ r^2 = 0.02$

# Land cover change offsets greenhouse gas warming

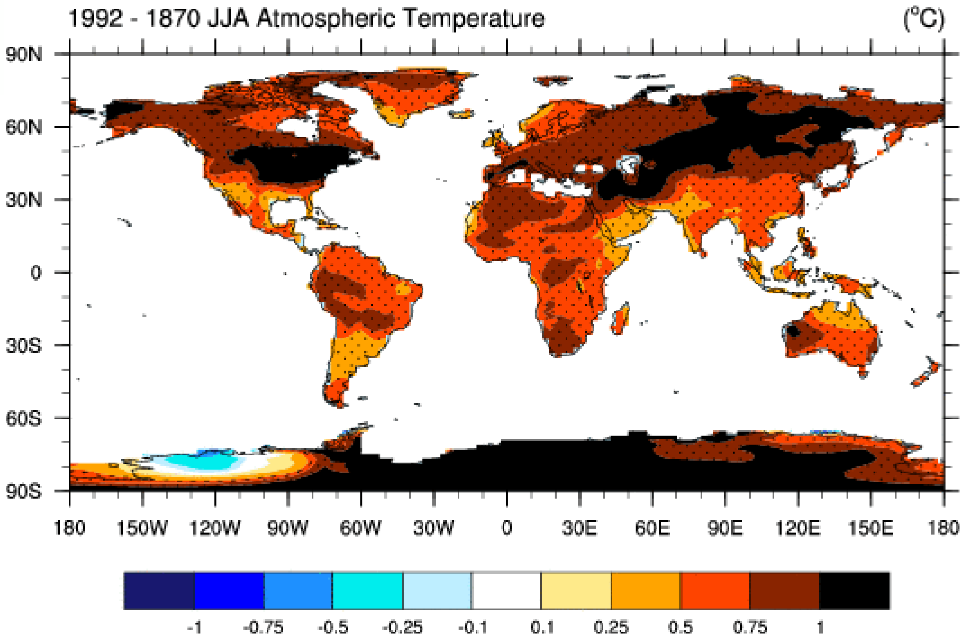
Land cover change with $CO_2$ = 375 ppm (1992)



Land cover change with $CO_2$ = 280 ppm (1870)



$CO_2$ forcing with 1870 land cover



# Surface forcing in North America

North America: 122 grid cells east of 100 °W and between 30-50 °N

| | Forest (n=69) | Grassland (n=18) | Savanna (n=35) |
|---|---|---|---|
| **1870** | | | |
| Tree (%) | 78 | 4 | 50 |
| Grass (%) | 4 | 83 | 42 |
| Crop (%) | 10 | 0 | 6 |
| **1992-1870** | | | |
| ΔTree (%) | -21 | -3 | -21 |
| ΔGrass (%) | 3 | -40 | -16 |
| ΔCrop (%) | 18 | 44 | 37 |
| ΔLAI ($m^2$ $m^{-2}$)[a] | -0.29 | 0.07 | -0.43 |
| ΔSAI ($m^2$ $m^{-2}$)[a] | -0.15 | -0.10 | -0.25 |

[a] June-August

Decrease in LAI, SAI, and roughness explain part of the surface forcing

| | z0 (cm) |
|---|---|
| | |
| NET | 94 |
| BDT | 110 |
| Grass | 6 |
| Crop | 6 |

# Plant functional types

## Leaf and stem albedo

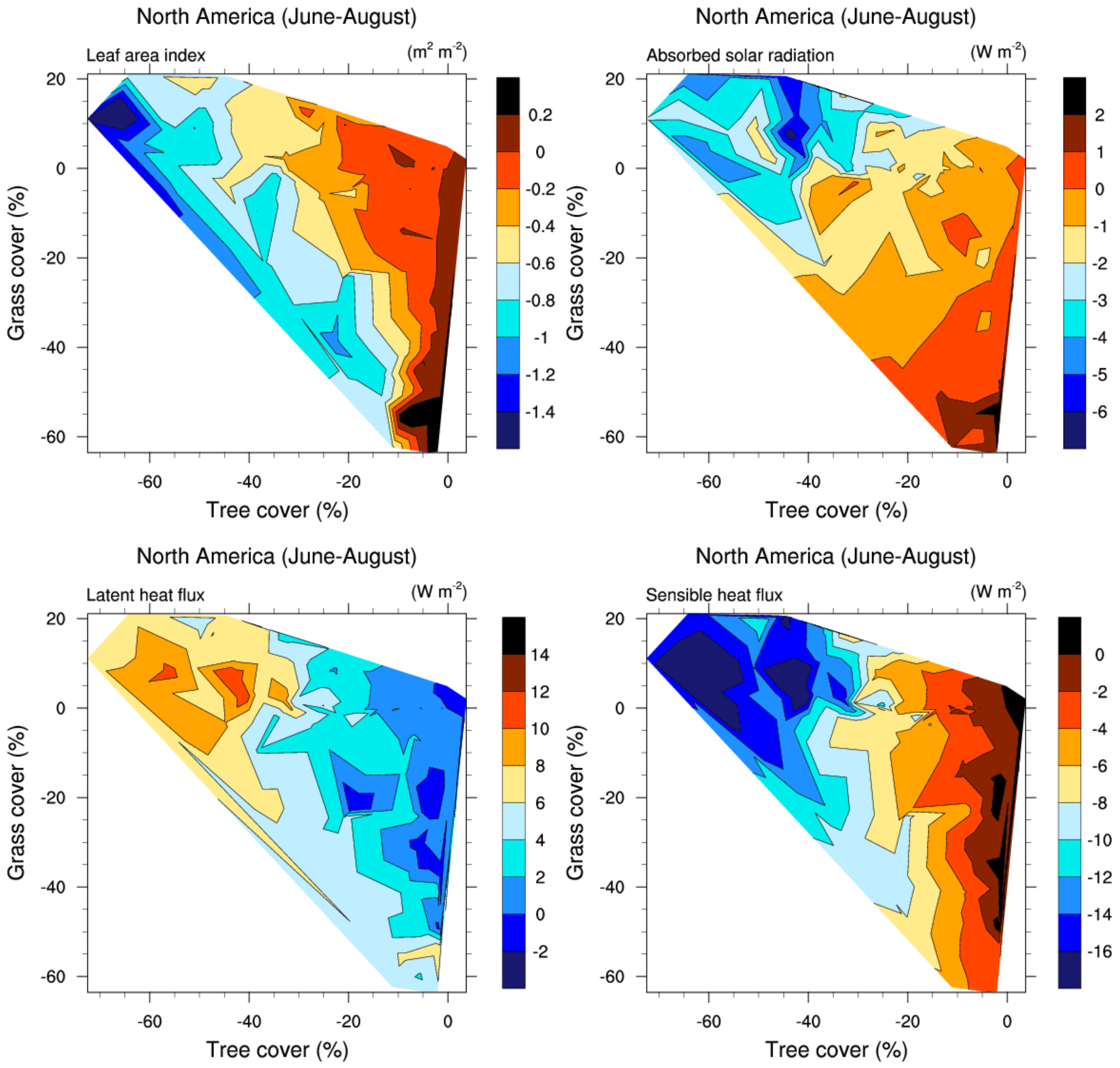
| | NET | BDT | Grass | Crop |
|---|---|---|---|---|
| **Leaf** | | | | |
| Direct | | | | |
| VIS | 0.02 | 0.03 | 0.03 | 0.03 |
| NIR | 0.11 | 0.24 | 0.20 | 0.20 |
| Diffuse | | | | |
| VIS | 0.03 | 0.04 | 0.04 | 0.04 |
| NIR | 0.16 | 0.31 | 0.28 | 0.28 |
| **Stem** | | | | |
| Direct | | | | |
| VIS | 0.03 | 0.03 | 0.09 | 0.09 |
| NIR | 0.09 | 0.10 | 0.26 | 0.26 |
| Diffuse | | | | |
| VIS | 0.05 | 0.06 | 0.14 | 0.14 |
| NIR | 0.15 | 0.16 | 0.37 | 0.37 |

Albedo depends on: leaf and stem reflectance and transmittance, leaf orientation, leaf area index, stem area index, soil color, soil water, snow, and zenith angle. Calculations are for LAI = 6 $m^2$ $m^{-2}$ or SAI = 6 $m^2$ $m^{-2}$, soil albedo of 0.1 (visible) and 0.2 (near-infrared), and zenith angle = 30°.

## Light-saturated photosynthesis and stomatal conductance under optimal conditions

| | A ($\mu$mol $CO_2$ $m^{-2}$ $s^{-1}$) | $g_s$ (mm $s^{-1}$) |
|---|---|---|
| NET | 11.5 | 4.6 |
| BDT | 9.4 | 5.6 |
| C3 grass | 10.6 | 6.3 |
| C4 grass | 31.2 | 10.5 |
| Crop | 11.8 | 7.0 |

Increase in albedo and stomatal conductance explain part of the surface forcing



Offline CLM3.5 simulations with NCEP-derived forcing (1972-2001) using 1870 and 1992 land cover

Contour plots (PD-PDv) for 122 grid cells east of 100 °W and between 30-50 °N

**Loss of tree cover**
- Decreases LAI
- Decreases $S_{net}$
- Increases LH flux
- Decreases SH flux

# Model summary

**Land cover change has cooled temperature of mid-latitudes, especially in summer**

- Increased albedo, increased latent heat flux, and decreased sensible heat flux
- Atmospheric feedbacks: clouds, precipitation, PBL height
- The climate forcing is robust with respect to atmosphere (1870 vs 1992)
- Can be regionally important relative to greenhouse gas warming

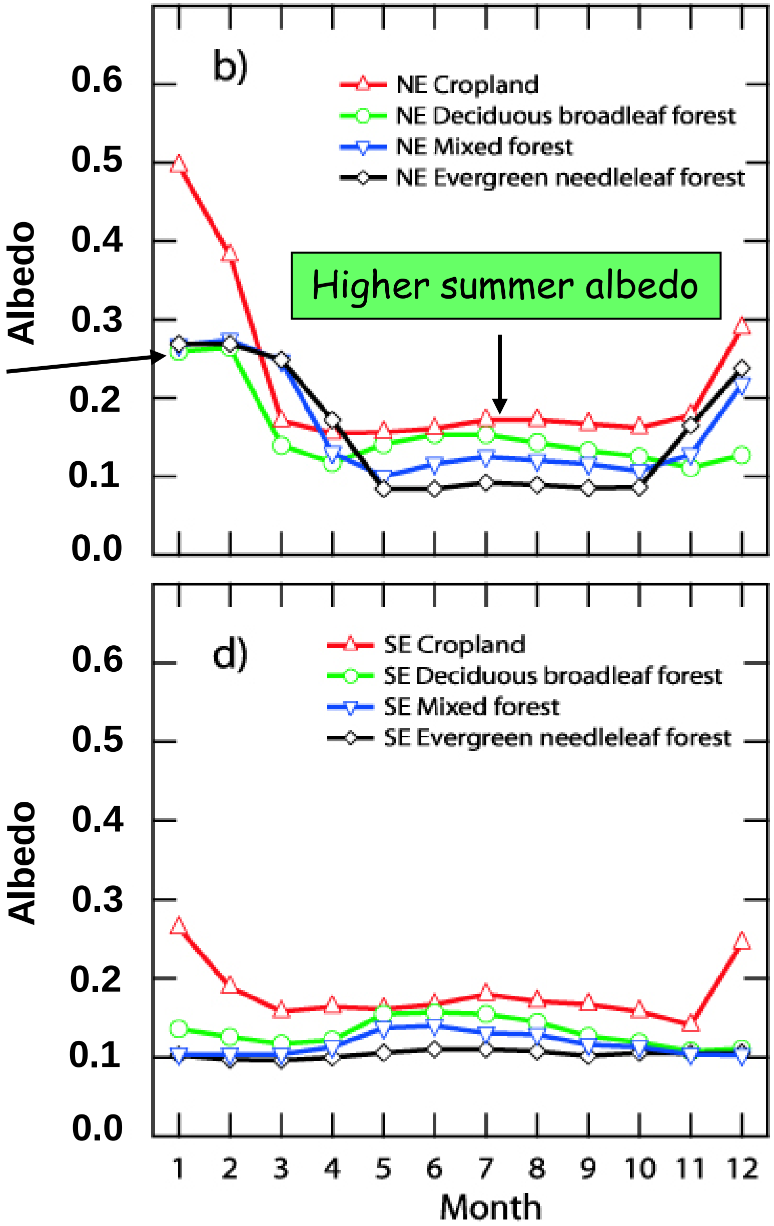
**The surface forcing**

- Relatively small: ~10 W $m^{-2}$ changes in $R_n$, LH flux, SH flux
- Related to changes in roughness, LAI, SAI
- Related to higher albedo and stomatal conductance of crops relative to trees
    - NET vs crop is particularly important
- Root profile is not important but
    - Relatively minor differences among plant functional types
    - Soils are wet
    - No deep roots or hydraulic redistribution
- Latent heat flux increases, mostly in soil evaporation

# 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



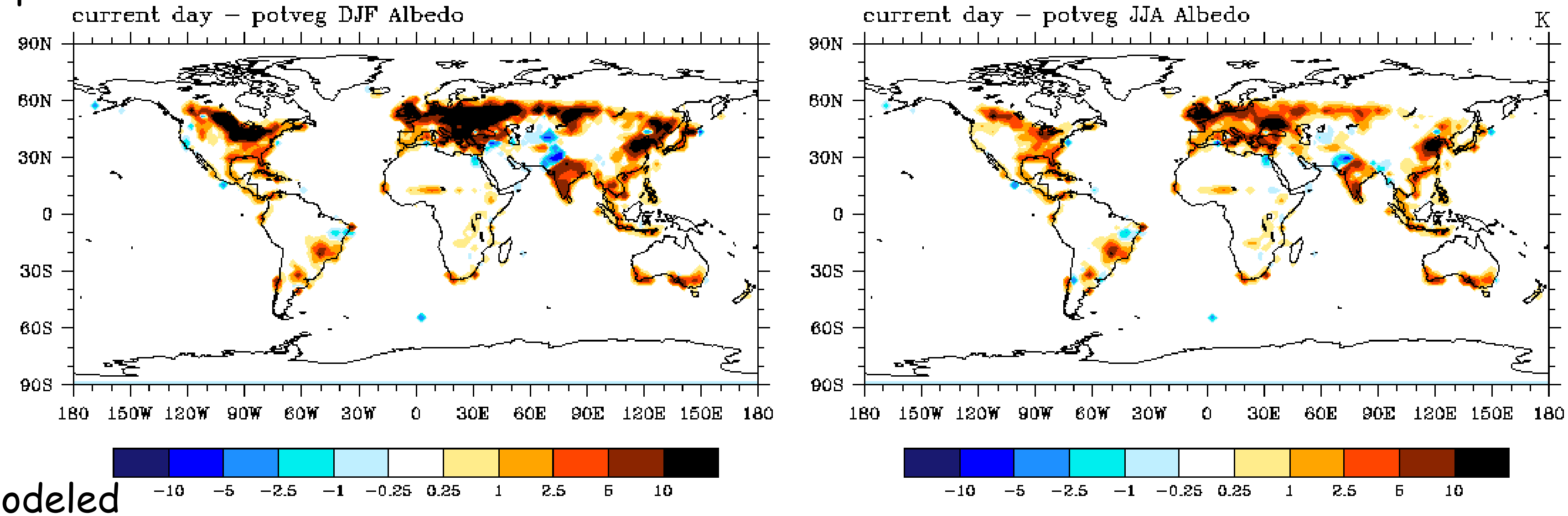
Higher summer albedo

Forest masking

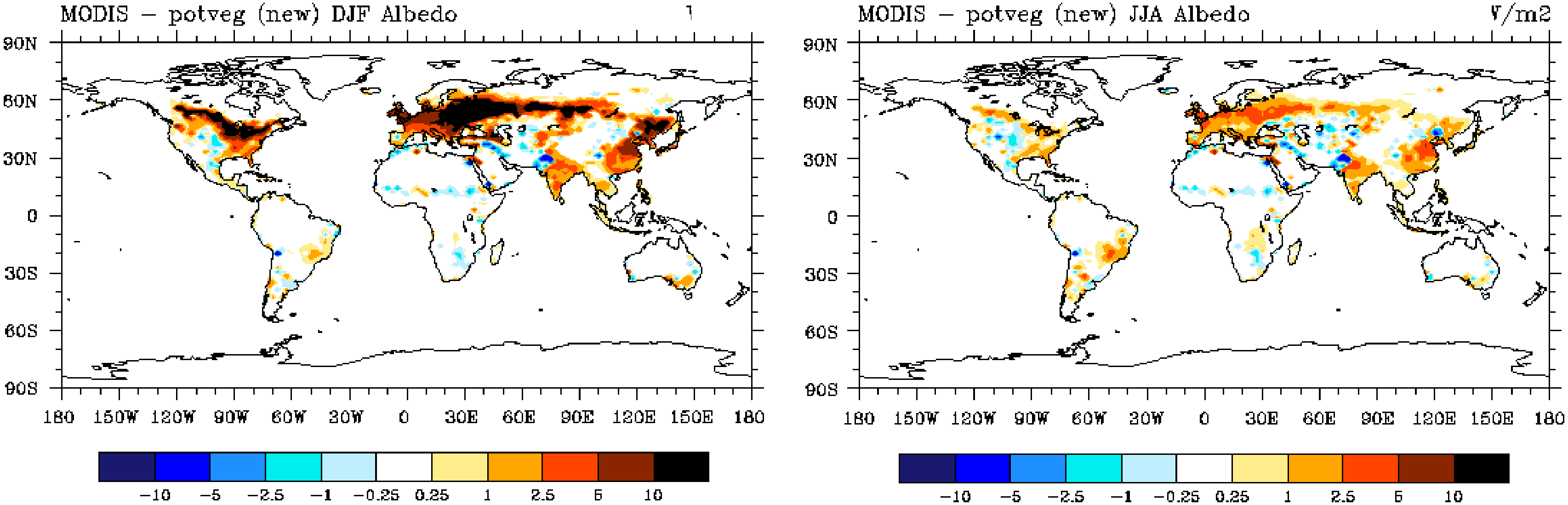
Cropland has a high winter and summer albedo compared with forest

# Albedo land use forcing

Expected



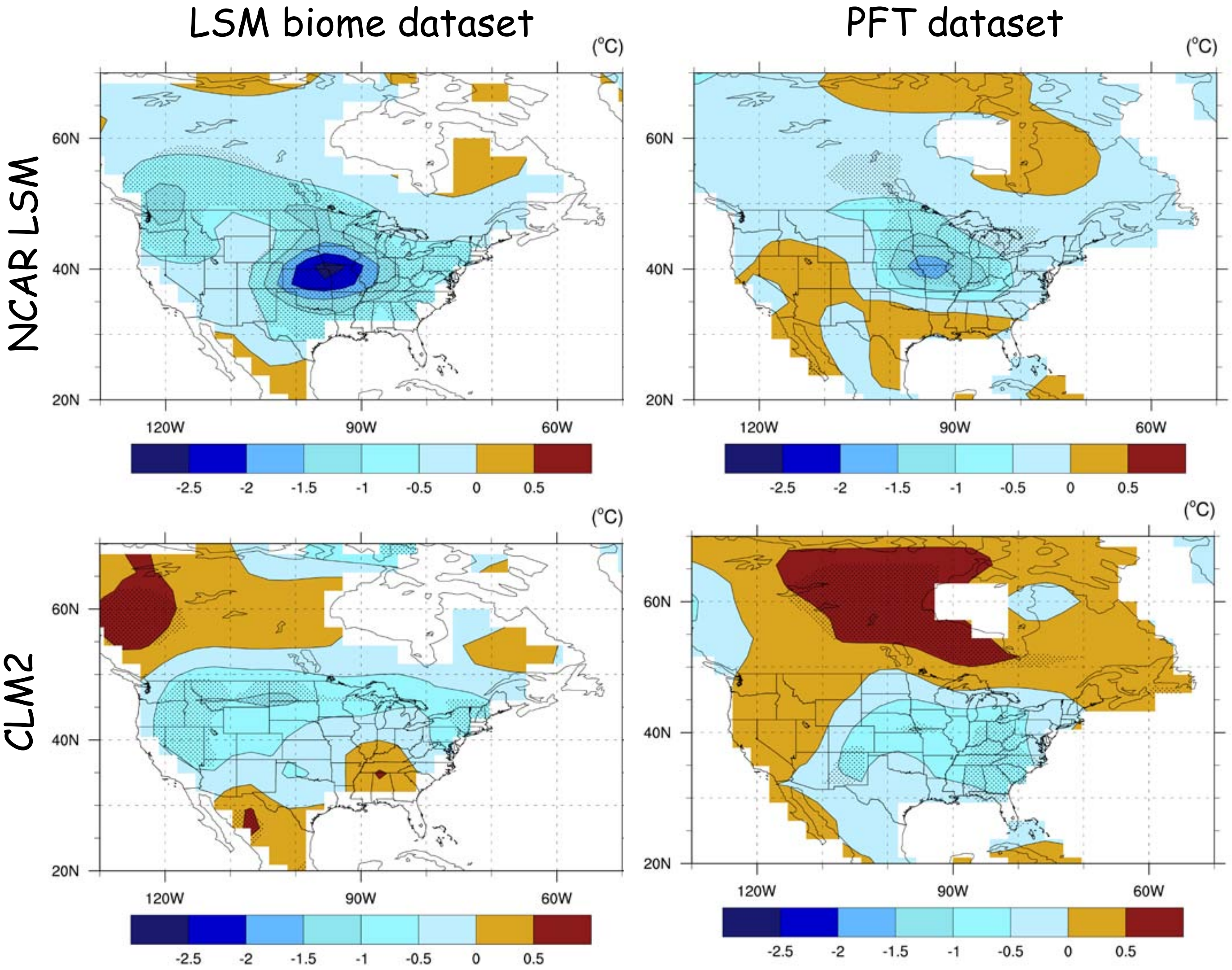
Modeled



Units are Δalbedo × 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**

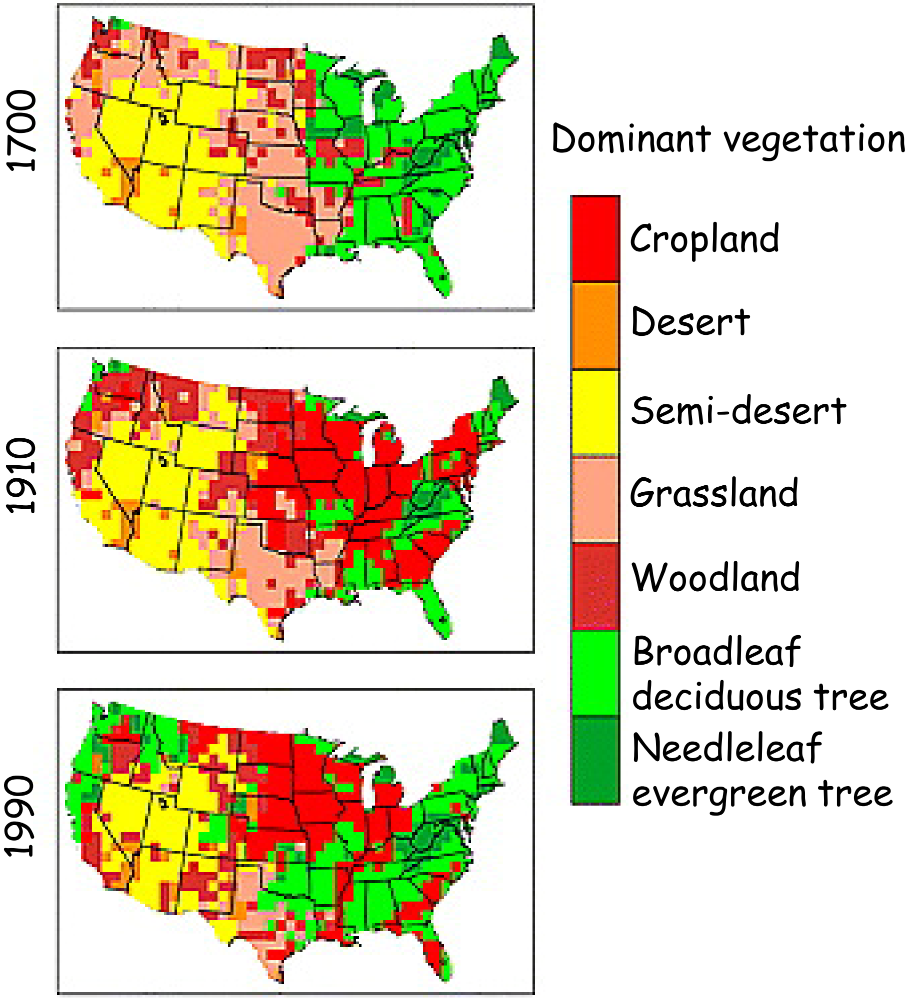
Magnitude of cooling associated with croplands is sensitive to surface datasets and model physics

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

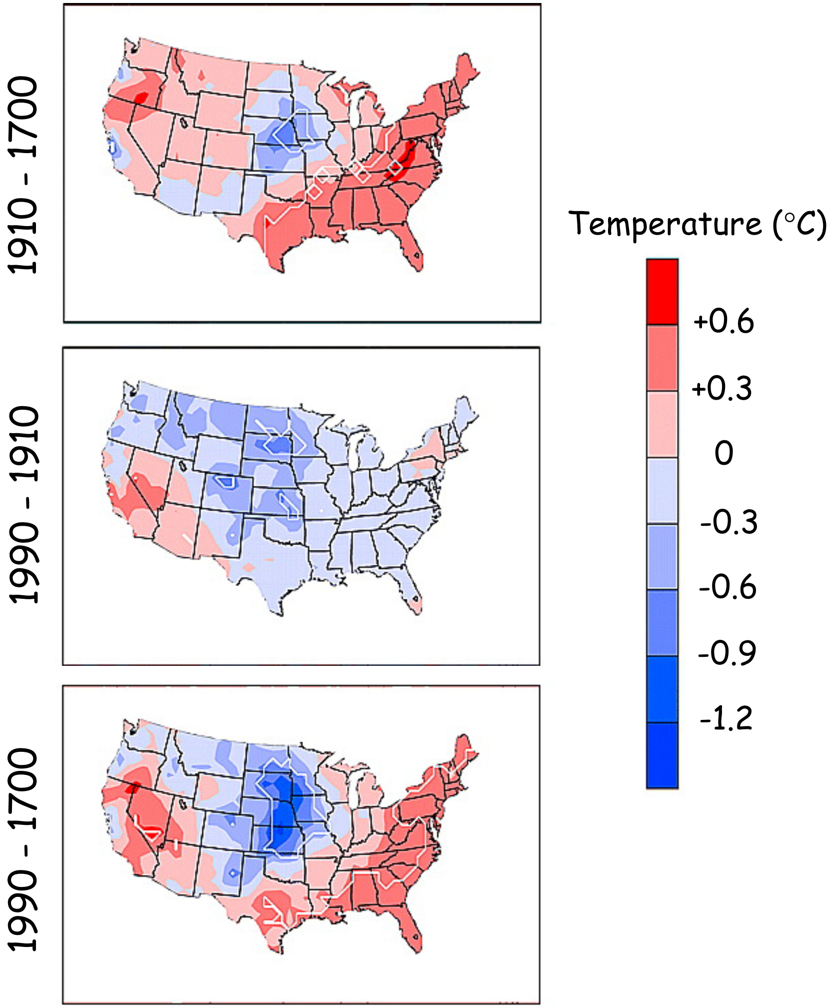
# Temperate deforestation warms climate

RAMS with LEAF-2
6-member July simulations

Land cover



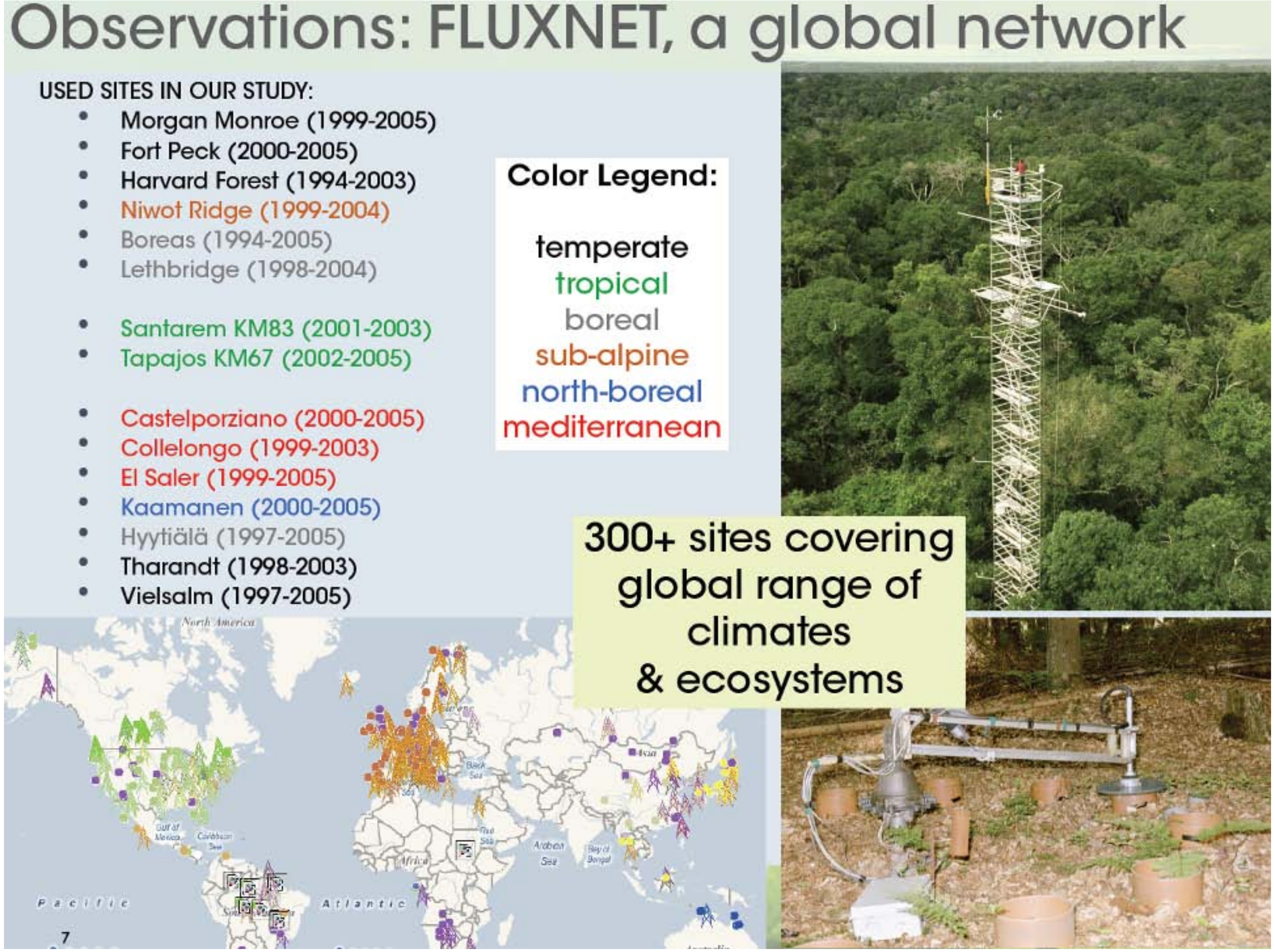
July temperature difference



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

# Use of FLUXNET in the Community Land Model development



## Observations: FLUXNET, a global network

USED SITES IN OUR STUDY:

- Morgan Monroe (1999-2005)
- Fort Peck (2000-2005)
- Harvard Forest (1994-2003)
- Niwot Ridge (1999-2004)
- Boreas (1994-2005)
- Lethbridge (1998-2004)

- Santarem KM83 (2001-2003)
- Tapajos KM67 (2002-2005)

- Castelporziano (2000-2005)
- Collelongo (1999-2003)
- El Saler (1999-2005)
- Kaamanen (2000-2005)
- Hyytiälä (1997-2005)
- Tharandt (1998-2003)
- Vielsalm (1997-2005)

**Color Legend:**

temperate
tropical
boreal
sub-alpine
north-boreal
mediterranean

300+ sites covering global range of climates & ecosystems

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

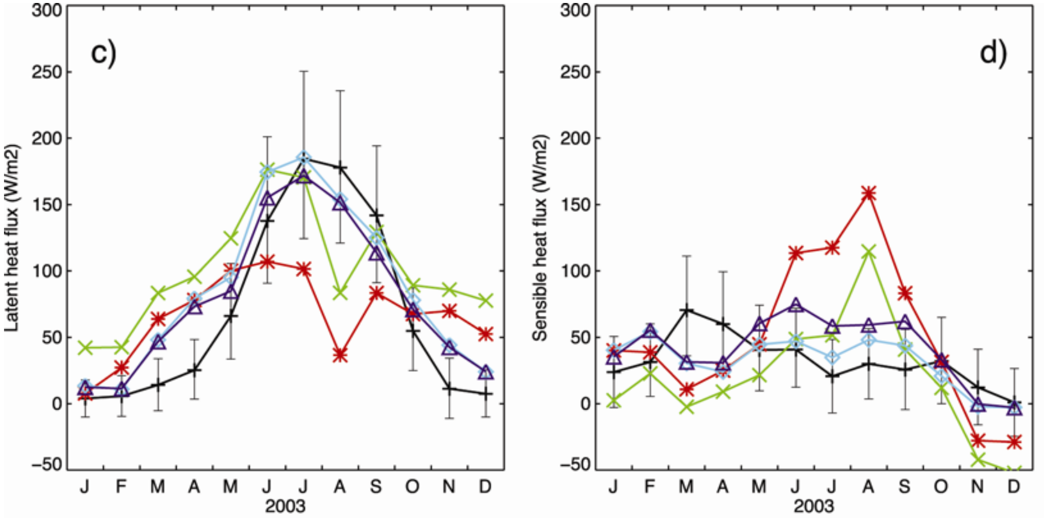
15 sites

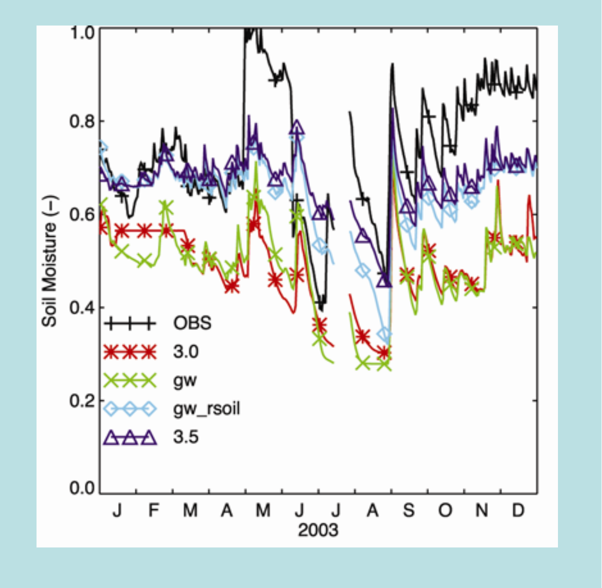
**Climate gradient**
Tundra, boreal, subalpine, temperate, Mediterranean, tropical

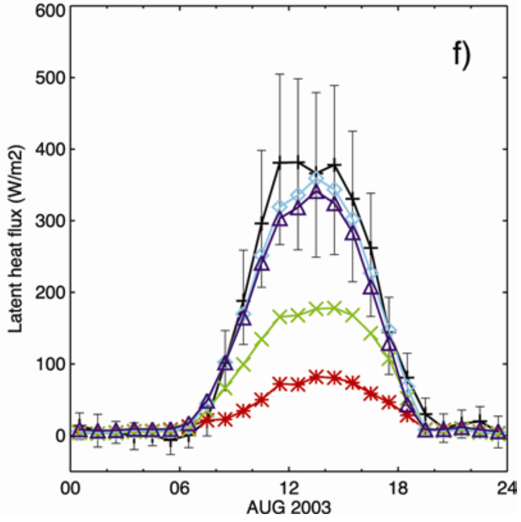
**Ecological gradient**
Evergreen broadleaf forest
Deciduous broadleaf forest
Evergreen needleleaf forest
Mixed forest
Grassland

# Flux tower measurements – temperate deciduous forest

Morgan Monroe State Forest, Indiana





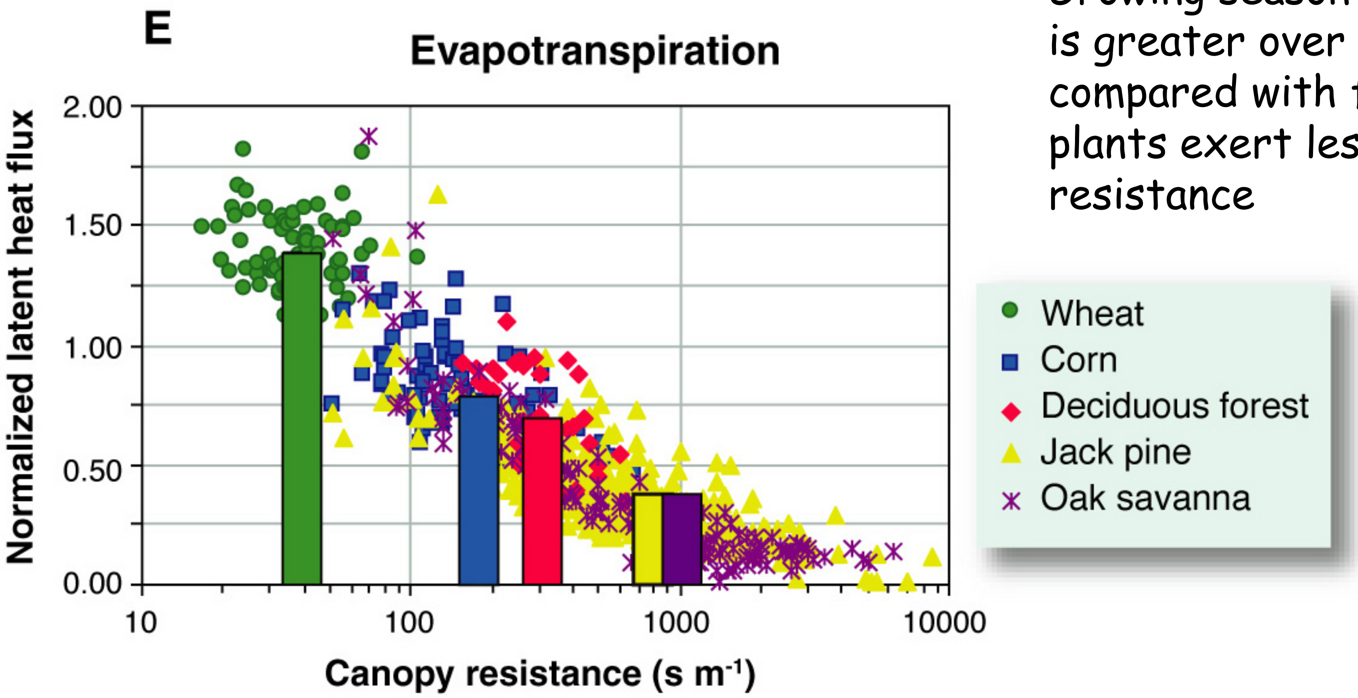


CLM3 – dry soil, low latent heat flux, high sensible heat flux
CLM3.5 – wetter soil and higher latent heat flux

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

# Crop latent heat flux

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

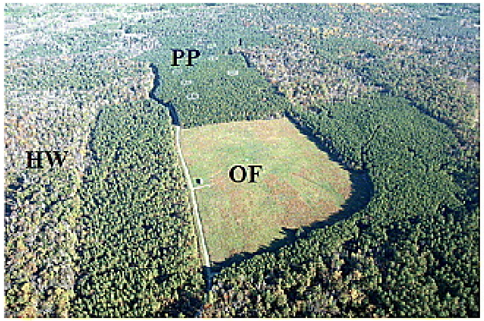


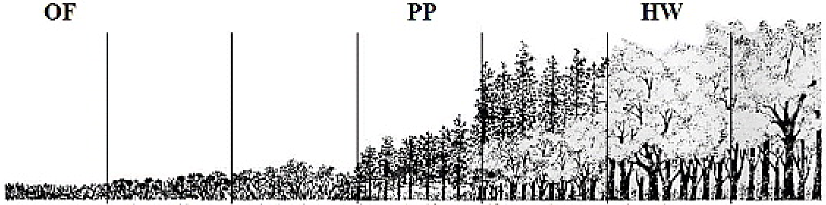
Bonan (2008) Science 320:1444-1449

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 (-)

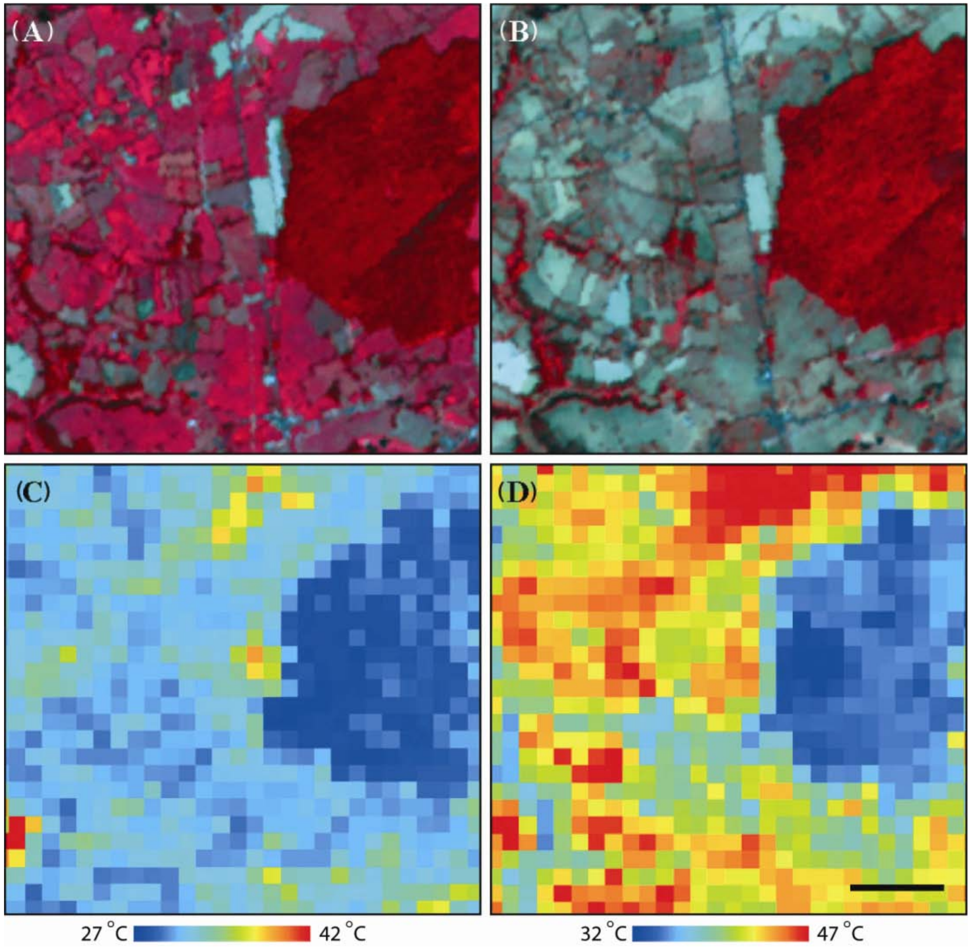
Juang et al. (2007) GRL, 34, doi:10.1029/2007GL031296

# Soil water affects the Δ(forest-crop)

Central France

1 August 2000 10 August 2003

Surface reflectance



Surface temperature

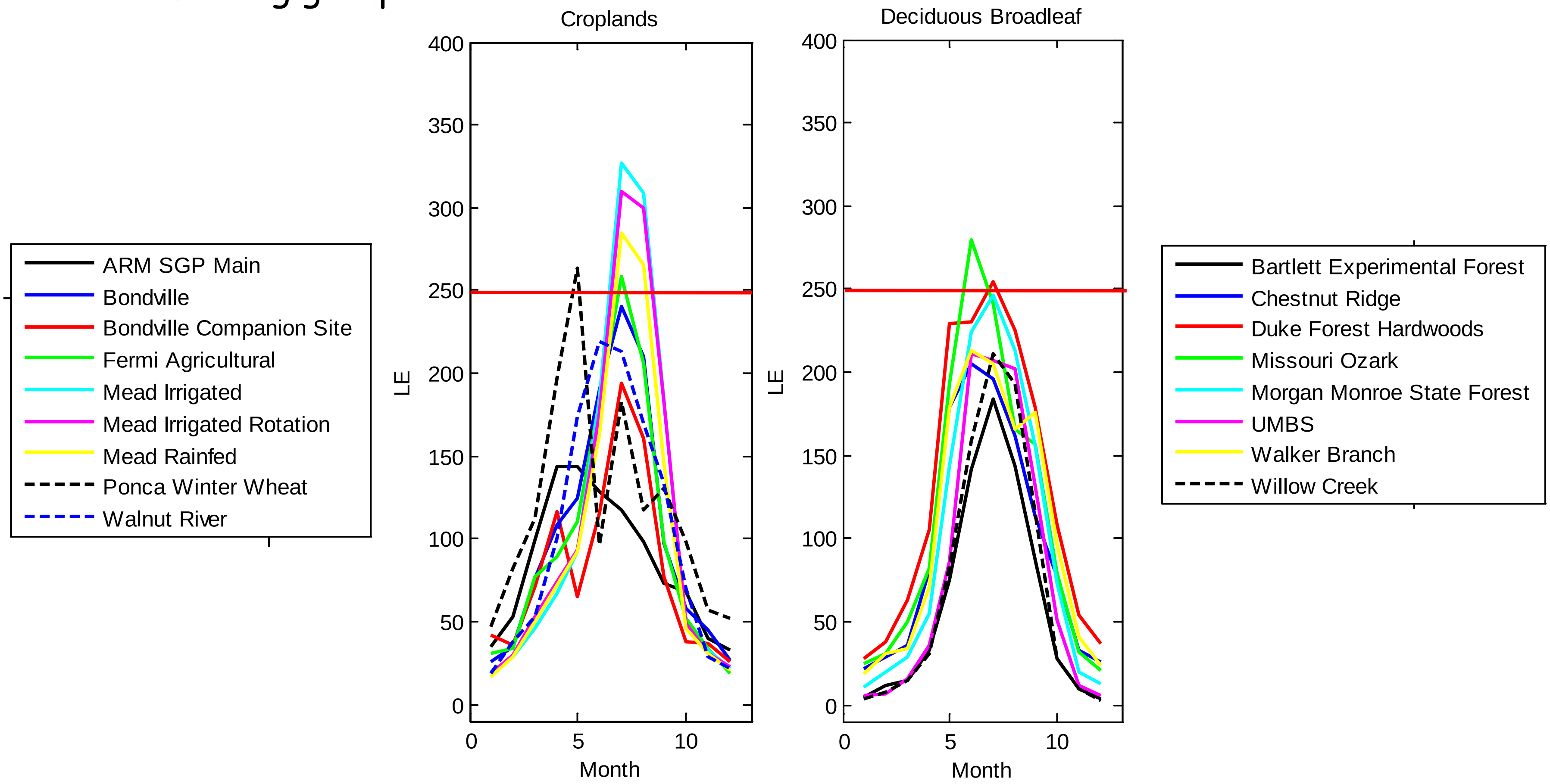
| | 2000 | 2003 | Change |
|---|---|---|---|
| *Forest* | | | |
| NDVI | 0.87 | 0.87 | 0 |
| Albedo | 0.19 | 0.17 | -0.02 |
| $T_R$ (°C) | 29 | 40 | +11 |
| *Crops* | | | |
| NDVI | 0.81 | 0.43 | -0.37 |
| Albedo | 0.22 | 0.22 | 0 |
| $T_R$ (°C) | 30 | 54 | +24 |
| *Barren* | | | |
| NDVI | 0.27 | 0.29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

# Can Ameriflux provide insights?

## NCEAS "Forest and Climate Policy" working group



**Crops**

Mead irrigated sites have highest LH

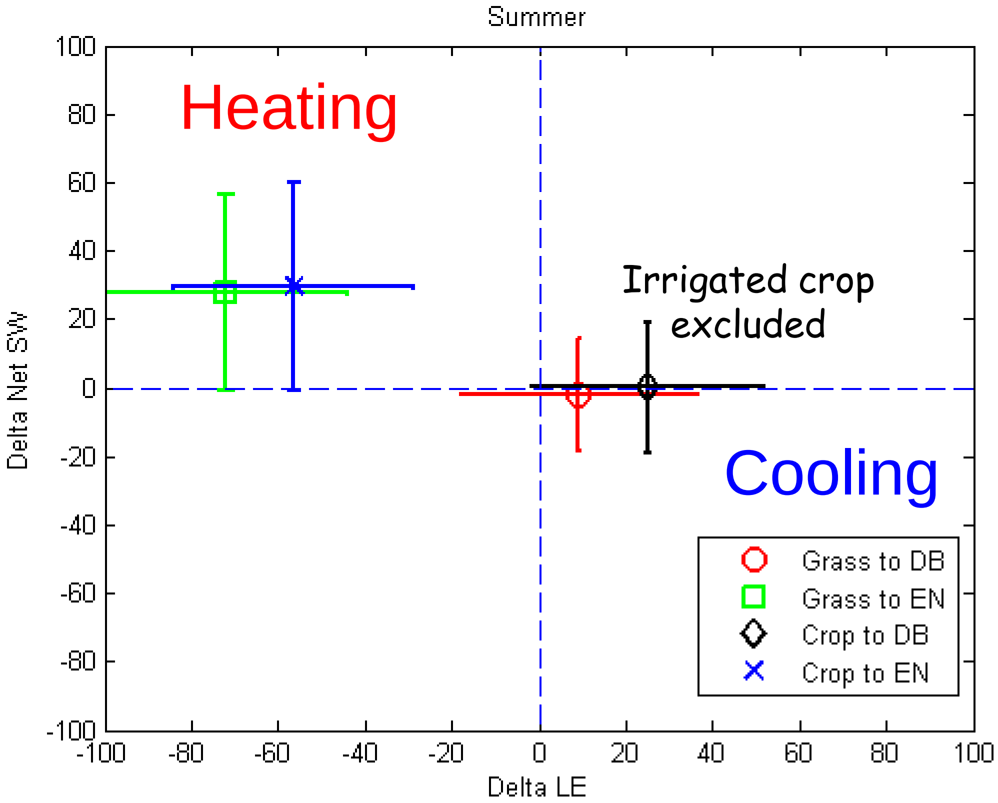
LH varies with crop rotation

LH varies with crop type (winter wheat)

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

# Shifts in surface energy balance from afforestation

NCEAS "Forest and Climate Policy" working group

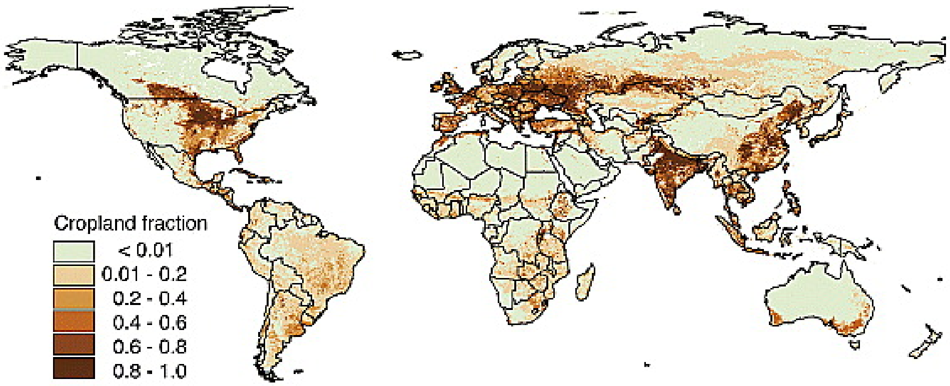


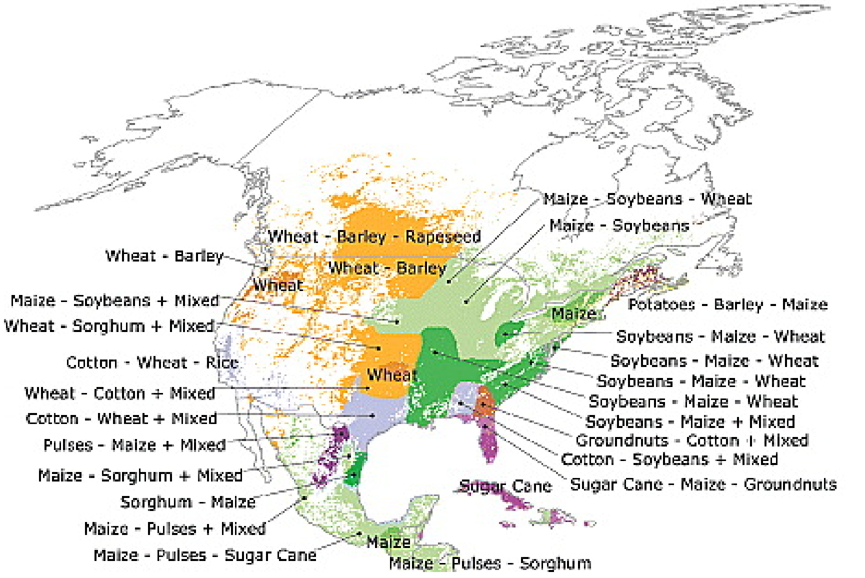
Differences in energy fluxes among forest, cropland, and grassland

Based on ~90 site-years of AmeriFlux data. *O'Halloran et al., 2009. in prep.*

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

# A broad diversity of crops worldwide

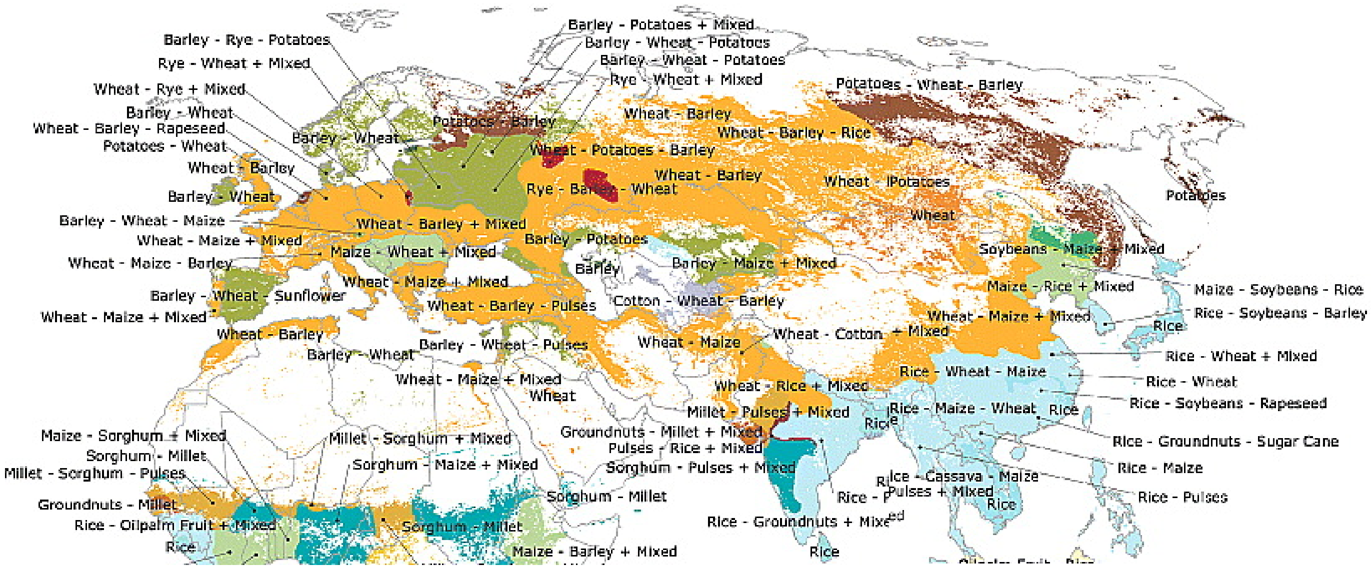




The type of land cover change matters:

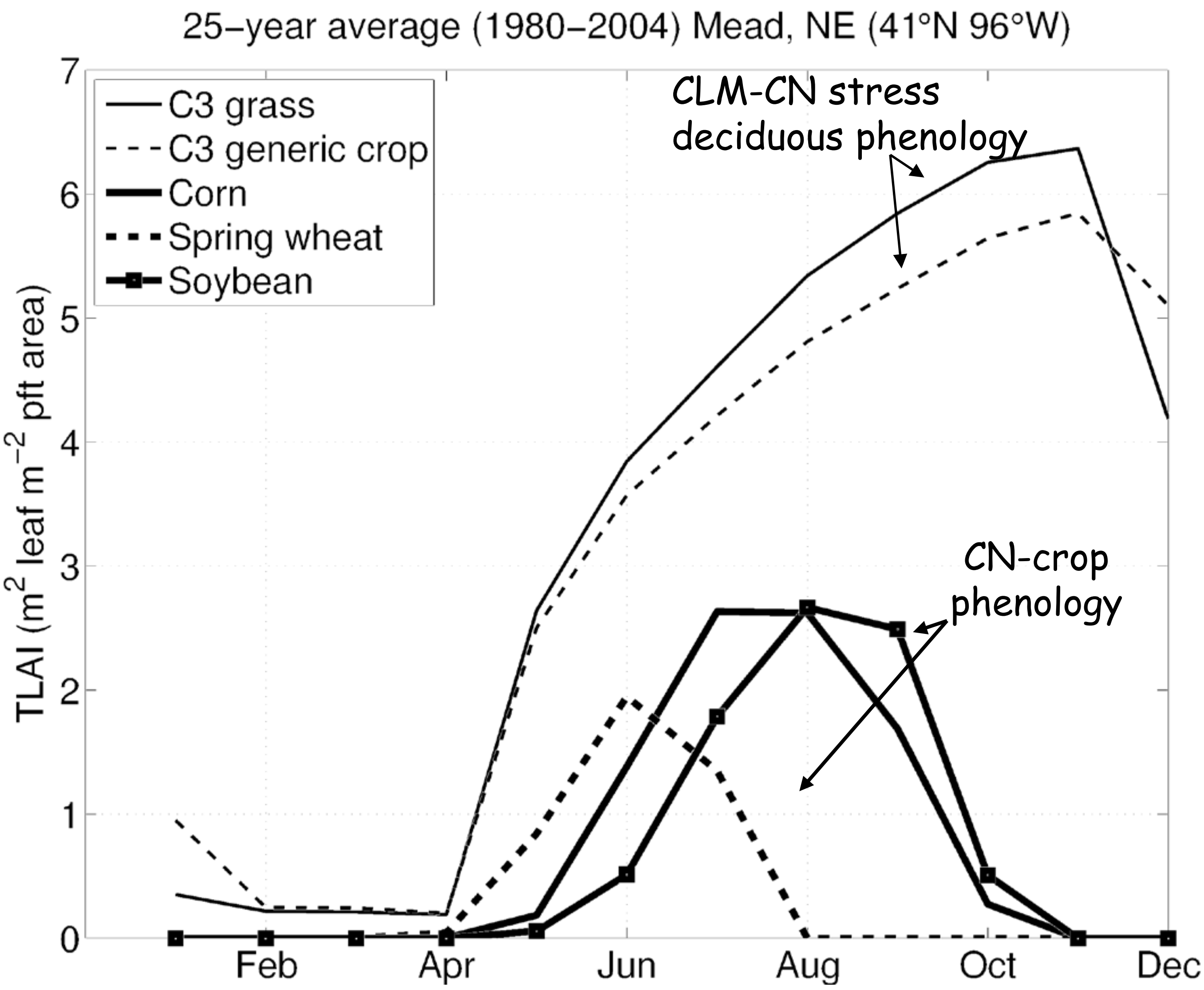
Forest → winter crop
Forest → spring crop
Forest → summer crop

Forest vs grassland



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

# Current carbon models do not represent crop phenology



CLM-CN stress deciduous phenology

CN-crop phenology

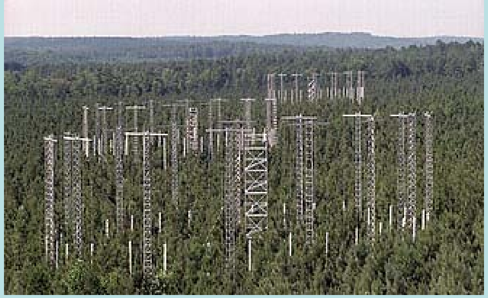
# Integrate ecological studies with earth system models

## Environmental Monitoring

Eddy covariance flux tower
(courtesy Dennis Baldocchi)

## Experimental Manipulation

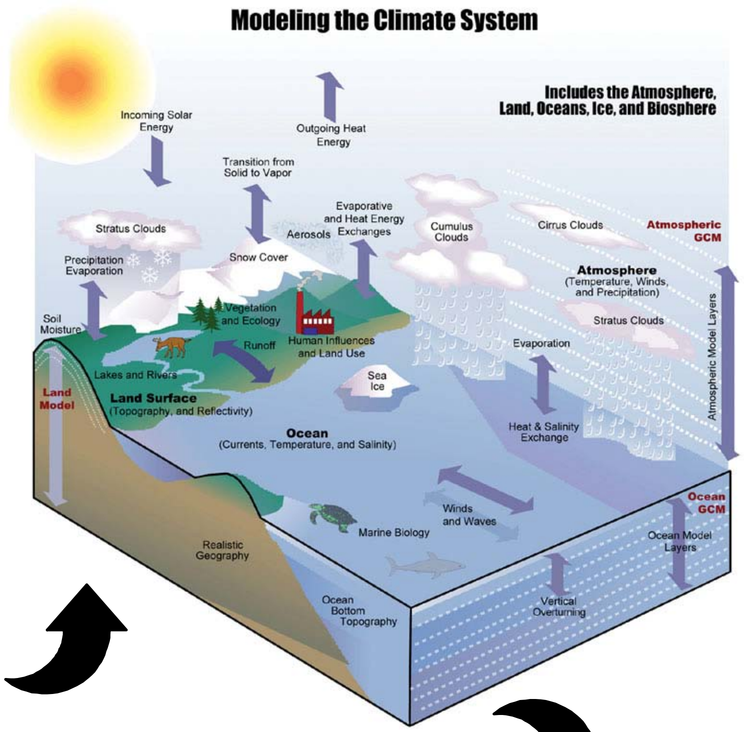
Soil warming, Harvard Forest



$CO_2$ enrichment, Duke Forest

Hubbard Brook
Ecosystem Study

Test model-generated hypotheses of earth system functioning with observations



Planetary energetics
Planetary ecology
Planetary metabolism