Climate Forcing and Feedback from the Terrestrial Carbon Cycle and Land Cover Change

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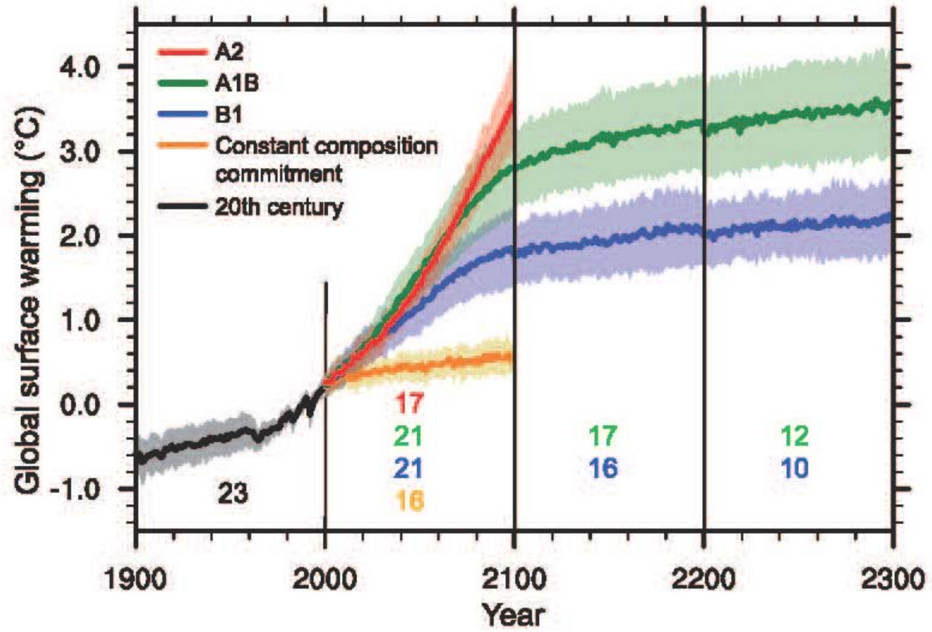
Biogeochemistry and Environmental Biocomplexity
Cornell University
Ithaca, New York

Climate of the 21st century

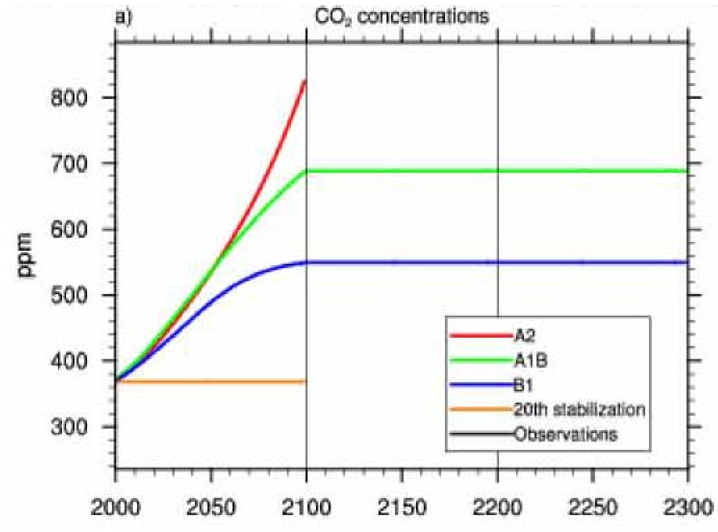
Multi-model mean surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1



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



Previous simulations

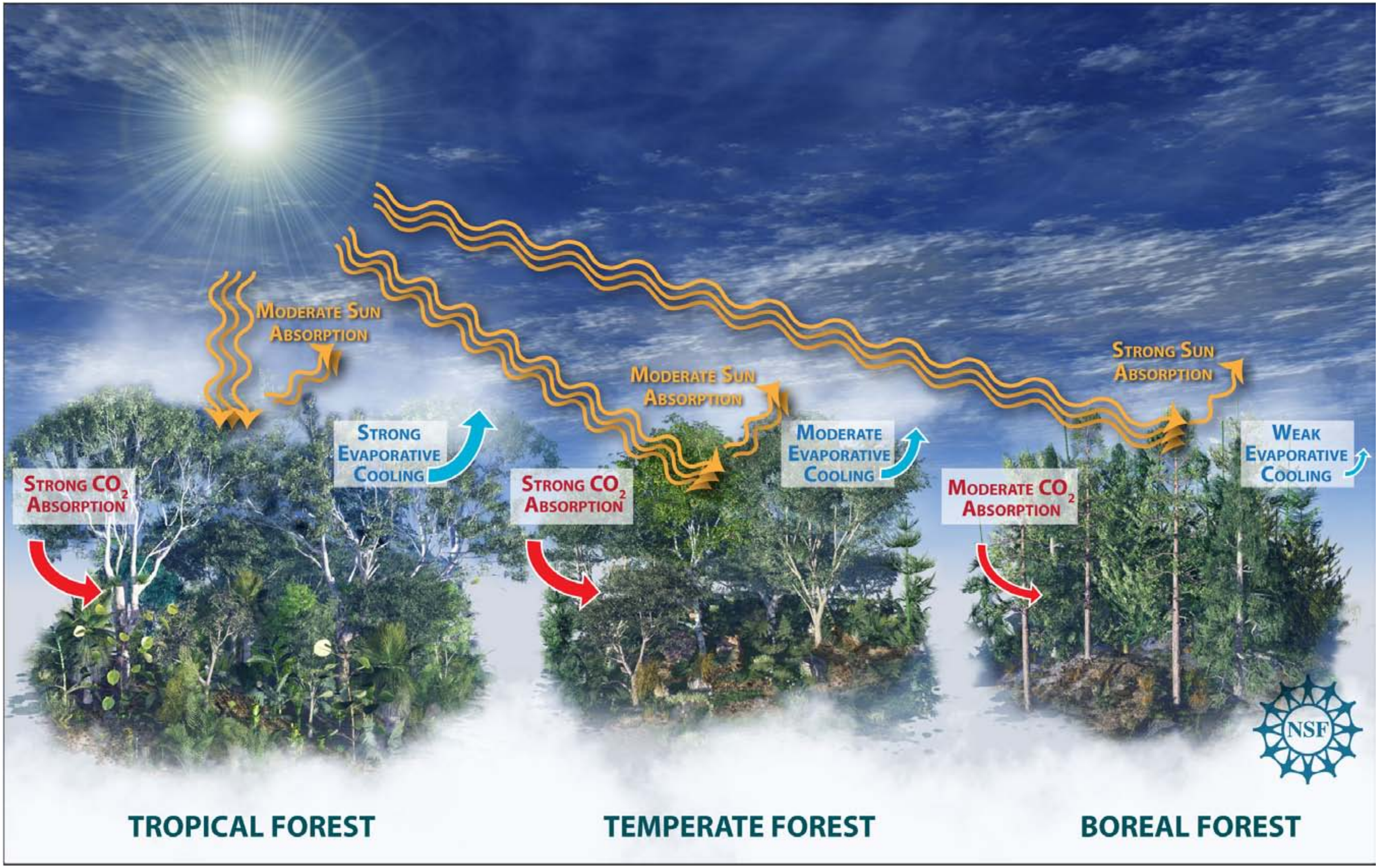
- Natural forcings (solar variability, volcanoes)
- Anthropogenic forcings (GHG, ozone, aerosols)

Current simulations

- Land cover change and the carbon cycle

Forests and climate change

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



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

Outline of talk

1. Introduction

2. Representing ecosystems in climate models

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

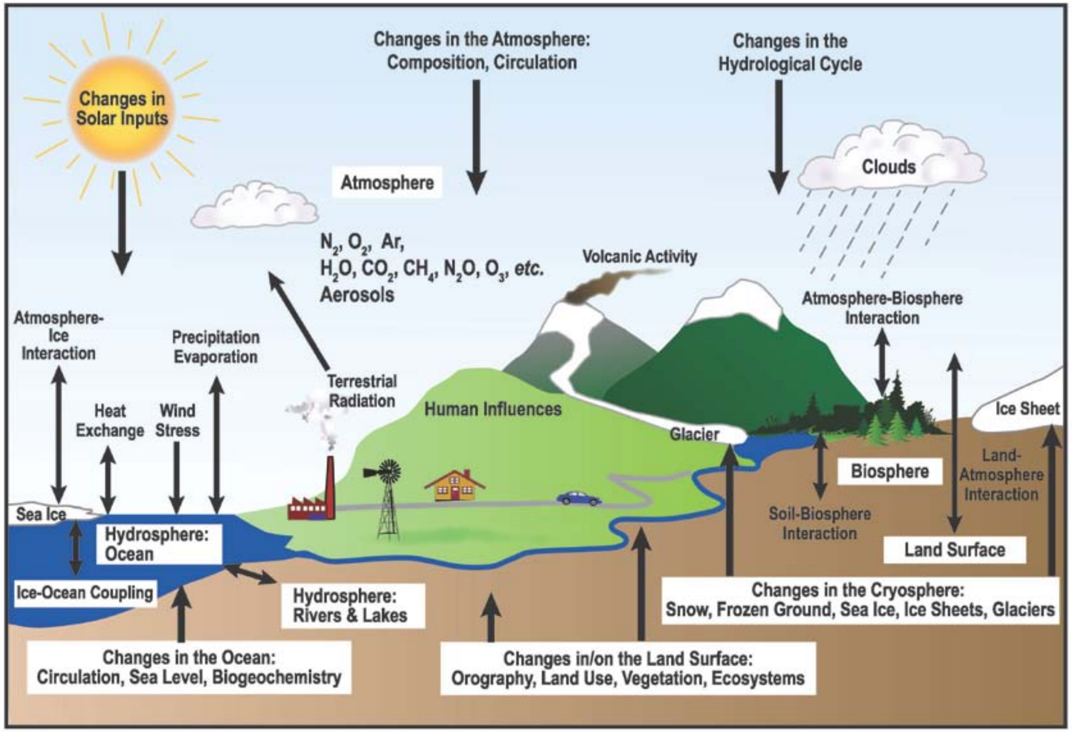
4. Land use and land cover change

4a. Biogeochemical
Land use carbon flux

4b. Biogeophysical
Albedo and evapotranspiration

5. Climate change mitigation

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

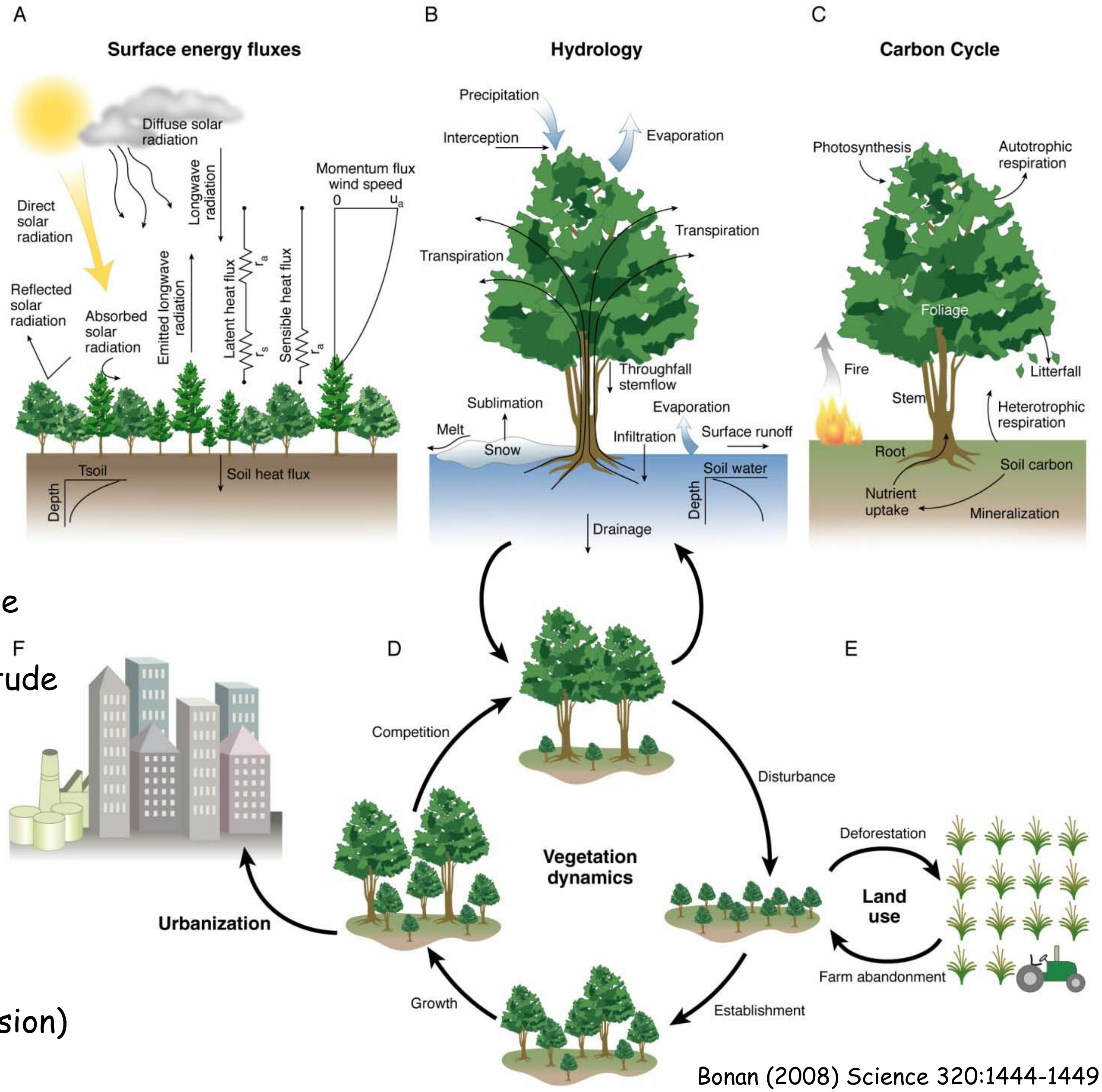
The Community Land Model

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

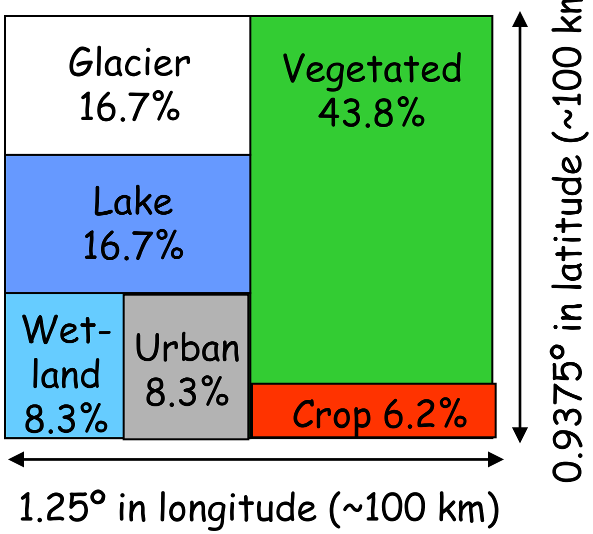
Temporal scale

- 30-minute coupling with atmosphere
- Seasonal-to-interannual (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



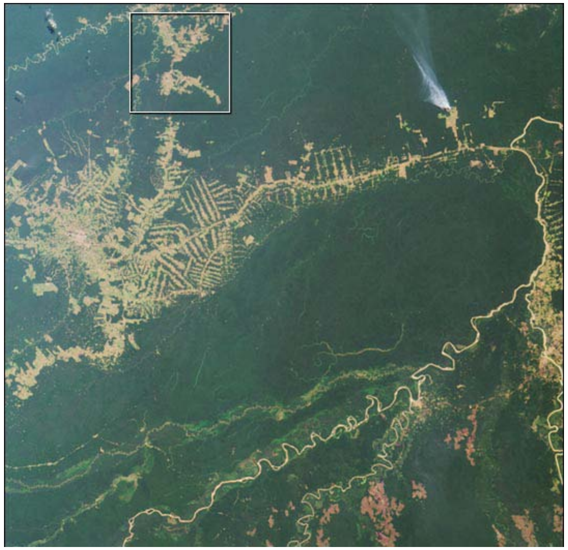
CLM represents a model grid cell as a mosaic of up to 6 primary land cover types. Vegetated land is further represented as a mosaic of plant functional types

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

Global land use

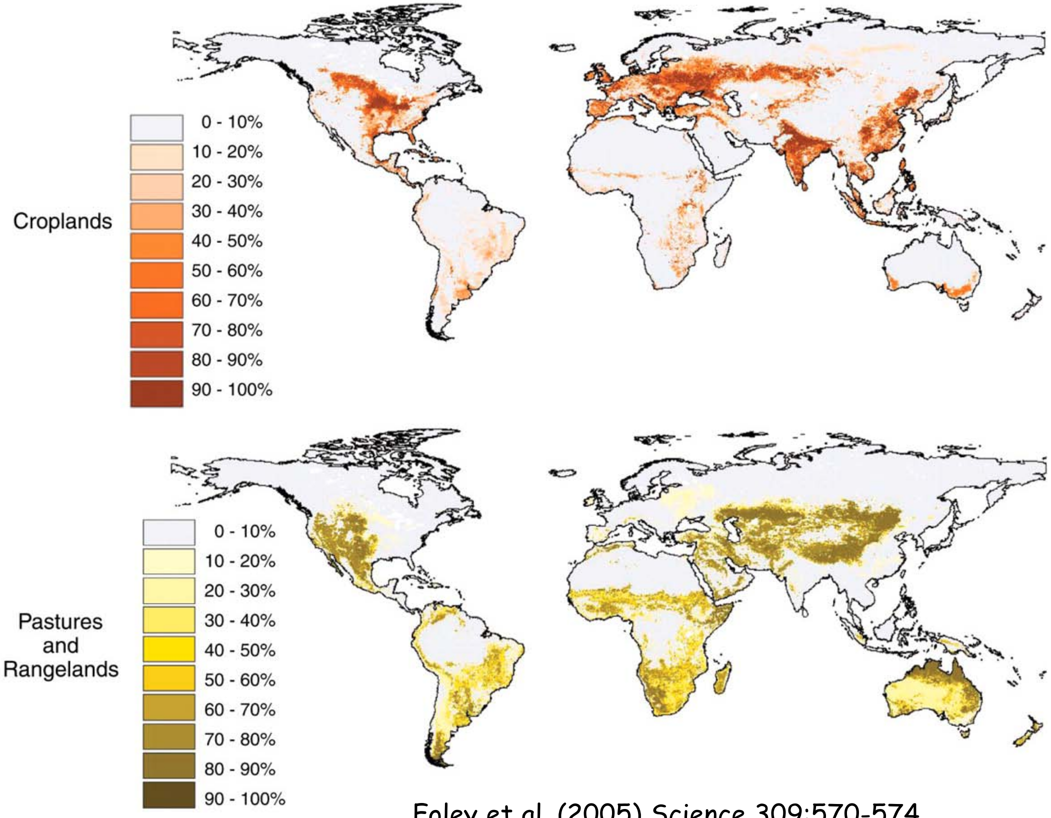
Local land use is spatially heterogeneous

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)

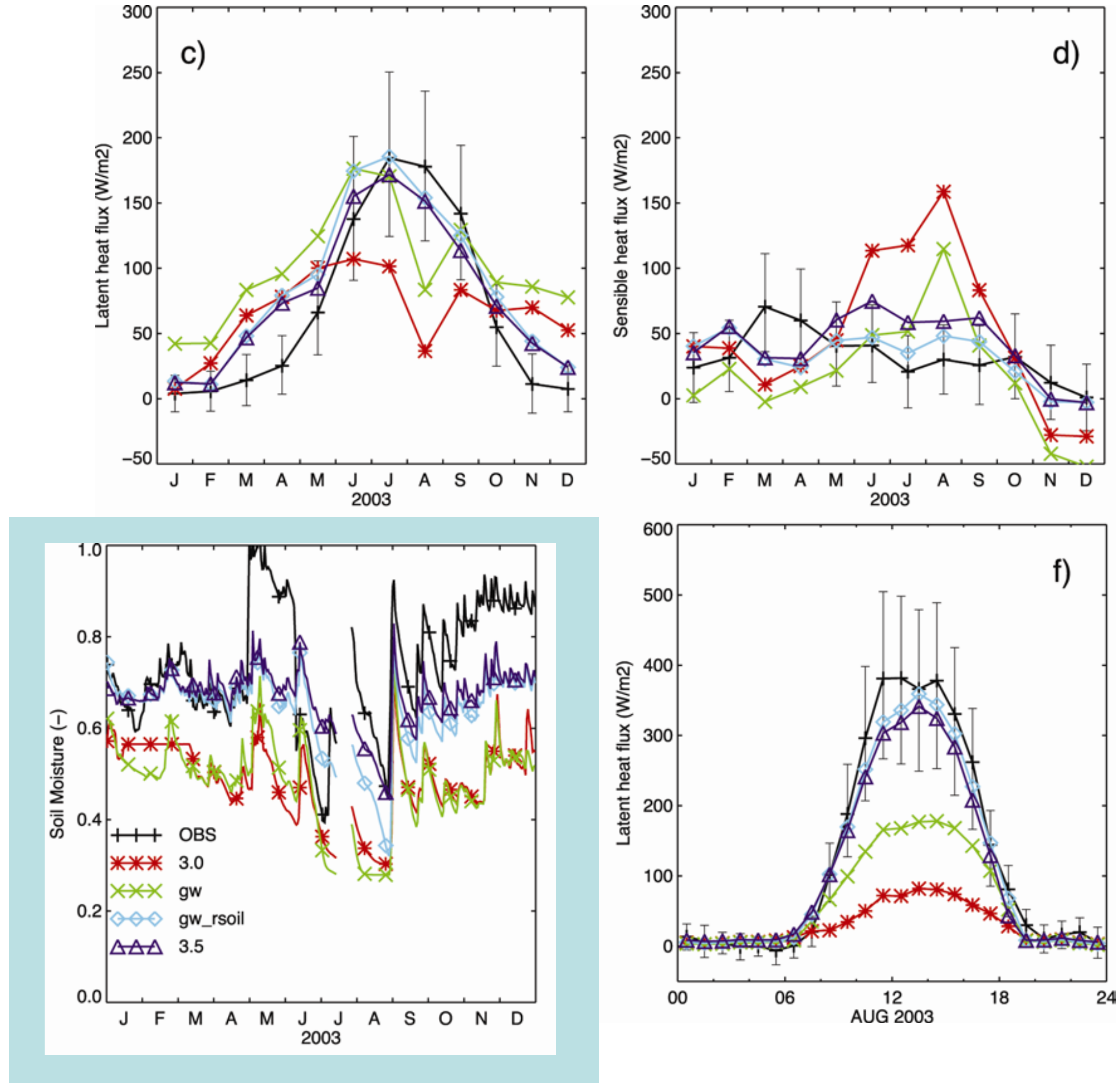
Global land use is abstracted to the fractional area of crops and pasture



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 and higher latent heat flux

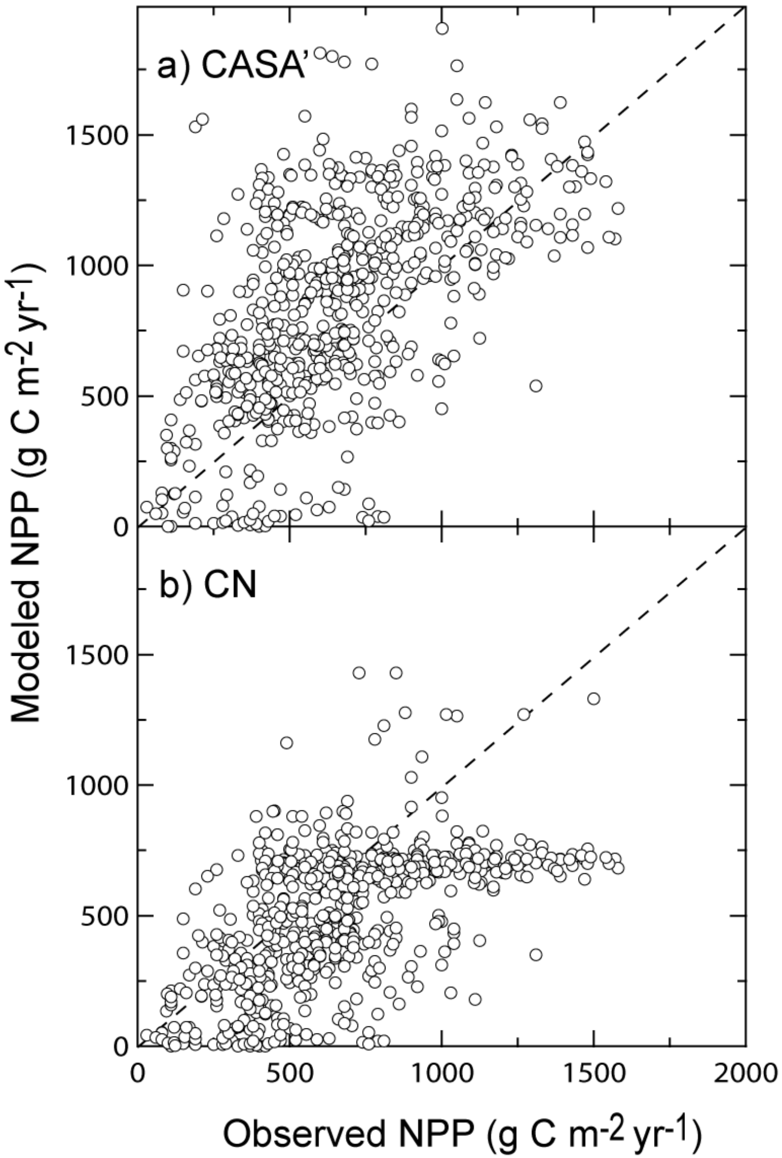
Stöckli et al. (2008) JGR, 113, doi:10.1029/2007JG000562

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

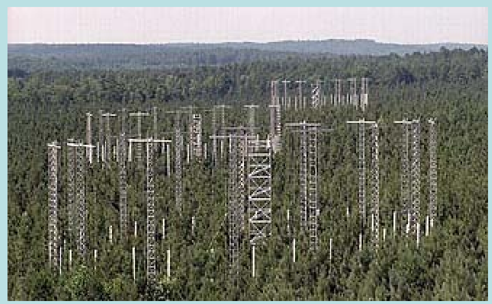
Environmental Monitoring

Eddy covariance flux tower
(courtesy Dennis Baldocchi)

Hubbard Brook
Ecosystem Study

Experimental Manipulation

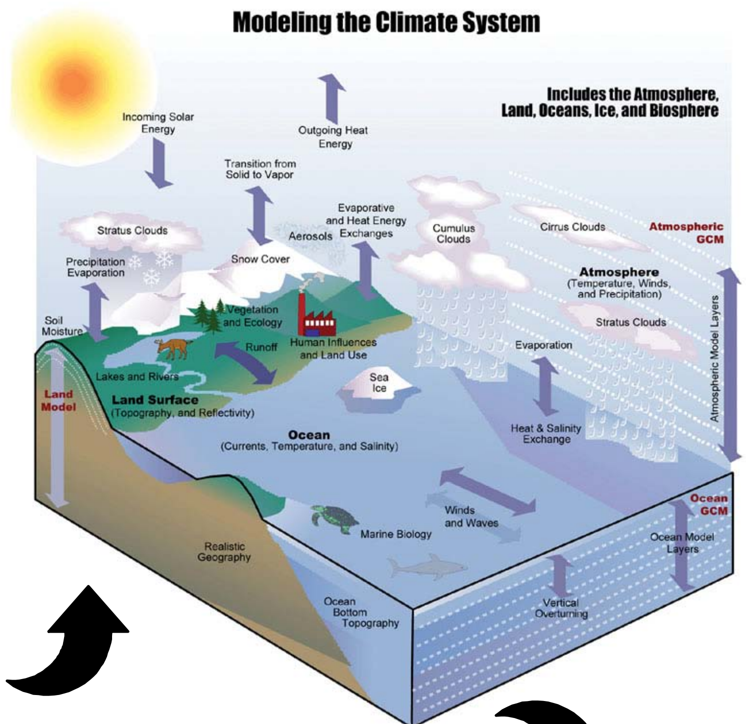
Soil warming, Harvard Forest



CO_2 enrichment, Duke Forest

$CO_2 \times N$
enrichment,
Cedar Creek

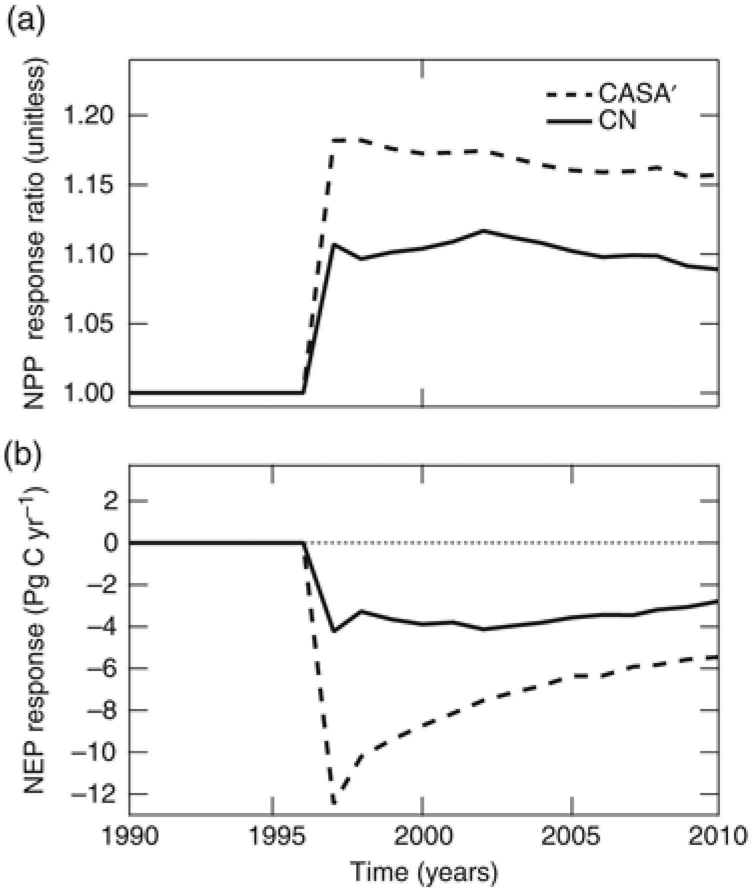
Test model-generated hypotheses of earth system functioning with observations



Planetary energetics
Planetary ecology
Planetary metabolism

Comparison with FACE experiments

Global response to a step change in atmospheric CO_2 from 362 ppm to 550 ppm



Site-level response for 4 FACE sites

	Observed	CASA'	CN
NPP (%)	27 ± 2%	17 ± 2%	7 ± 3%
β_{fert}	0.67	0.43 ± 0.04	0.18 ± 0.09

Norby et al. (2005) PNAS
102:18052–18056

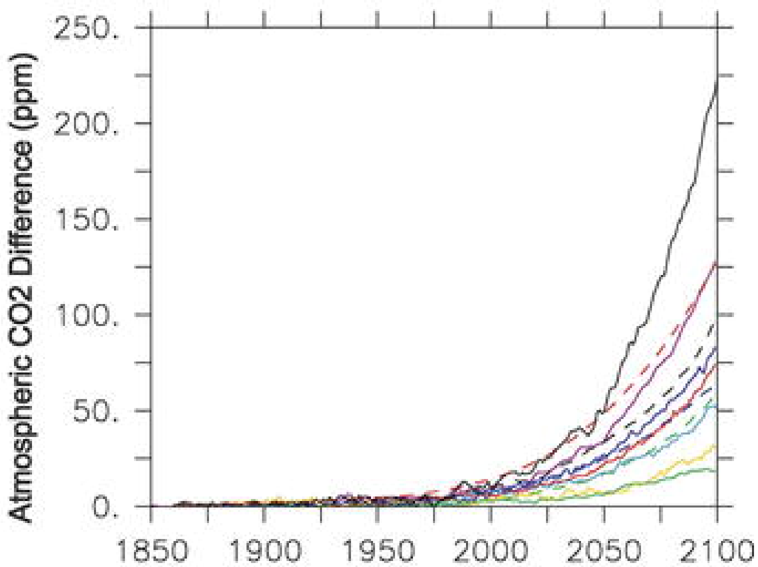
DukeFACE (NC)
AspenFACE (WI)
ORNL-FACE (TN)
POP-EuroFACE (Italy)

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

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

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

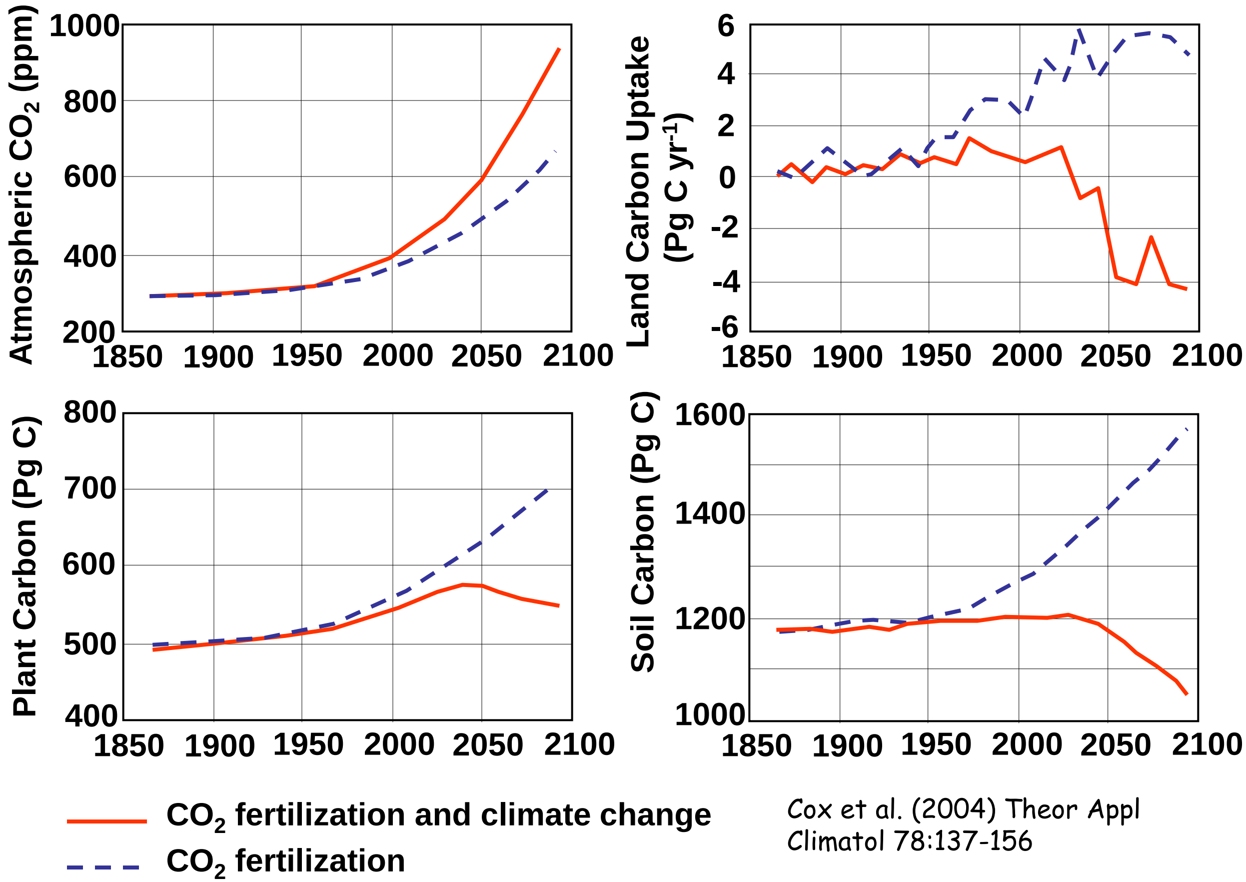
Prevailing model paradigm

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

$\Delta C_L = \beta_L \, \Delta C_A$

$\Delta C_L = \beta_L \, \Delta C_A + \gamma_L \, \Delta T$

$\beta_L > 0$: concentration–carbon feedback (Pg C ppm^{-1})

$\gamma_L < 0$: climate–carbon feedback (Pg C K^{-1})

Carbon-nitrogen interactions

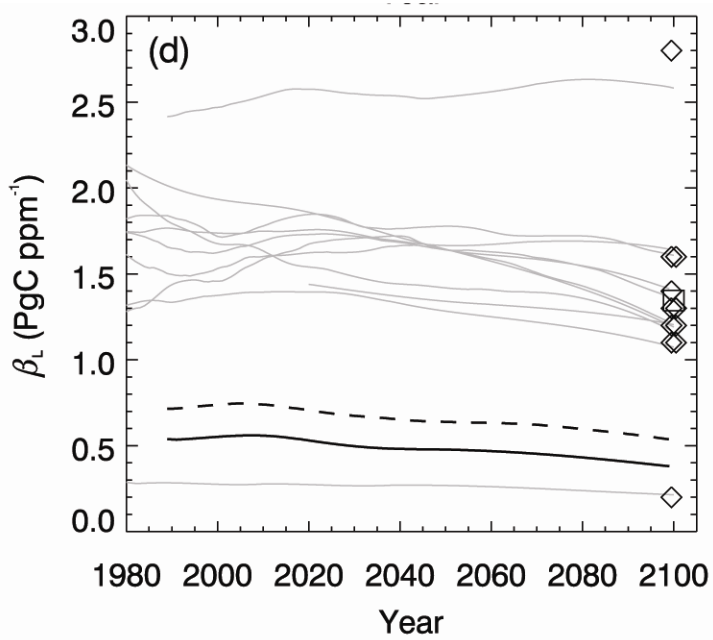
Reduces concentration-carbon feedback (β_L)

- Nitrogen limitation reduces the CO_2 fertilization gain in productivity

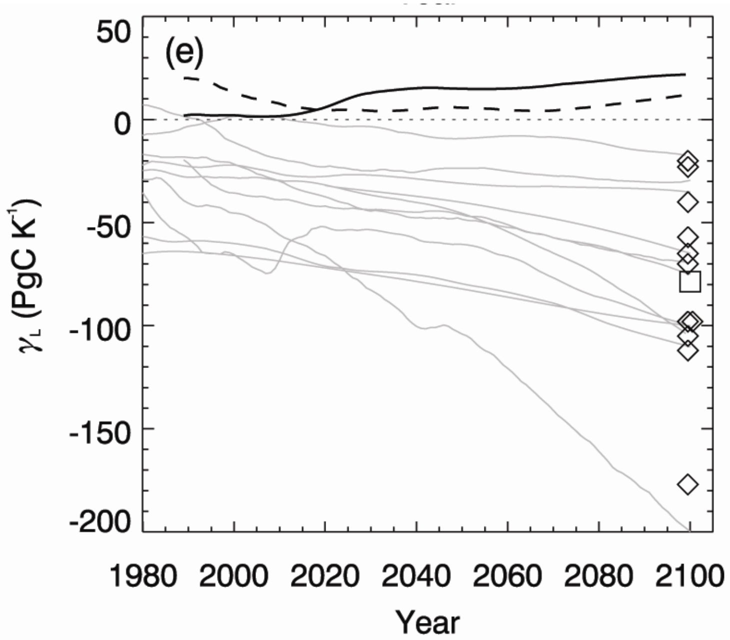
Changes sign of climate-carbon feedback (γ_L)

- 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

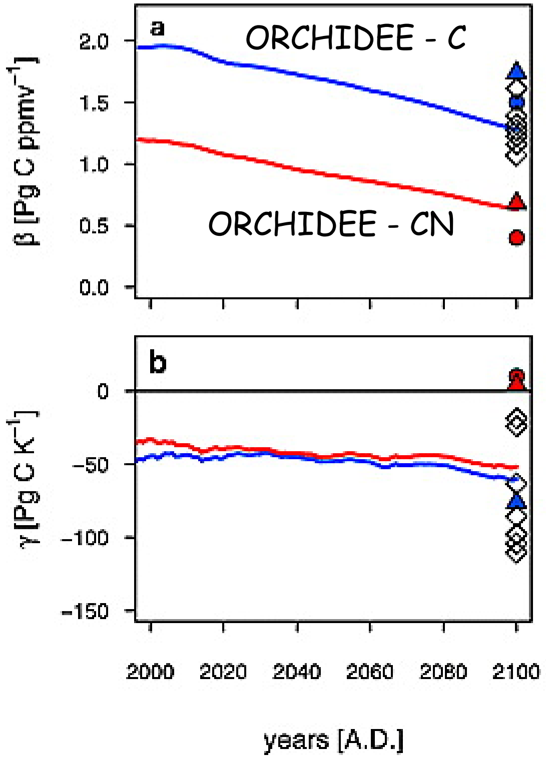


Land biosphere response to temperature

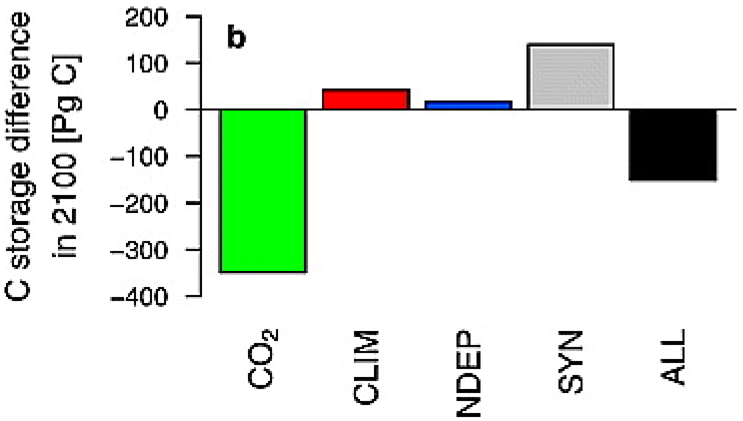
Thick solid line is with preindustrial nitrogen deposition
Thick dashed line is with anthropogenic nitrogen deposition
Thin gray lines are C4MIP models

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

Carbon-nitrogen interactions



Effect of nitrogen on carbon storage, 1860-2100



- Nitrogen reduces β_L by 50%
- Nitrogen reduces carbon loss with climate change, but γ_L remains negative

The effect of nitrogen to reduce CO_2 fertilization is 7 times greater than the effect of nitrogen on the carbon-climate feedback

Zaehle et al. (2010) GRL, 37, doi:10.1029/2009GL041345

Quantifying carbon-nitrogen feedbacks in CLM4

Annual Mean Forcings (Land Only) for Control and Experiment Simulations

				Land Use	
Simulations	Atmos. CO_2 [ppm]	Temperature [K]	N deposition [Tg N yr^{-1}]	Cropland [10^6 km^2]	Wood harvest [10^6 km^2 yr^{-1}]
Control	328.6	280.8	48.5	14.0	0
Experiments					
1973-77	331.0	280.9	51.2	14.1	0.14
2000-04	372.8	281.8	63.9	15.2	0.22
Change	41.8	0.9	12.7	1.1	0.08

Forcings are constant for control simulations and vary with time for experiment simulations. Shown are the 1973-1977 and 2000-2004 means and the temporal change.

Bonan & Levis (2010) GRL, in press

Quantifying carbon-nitrogen feedbacks in CLM4

Carbon fluxes 1973 – 2004

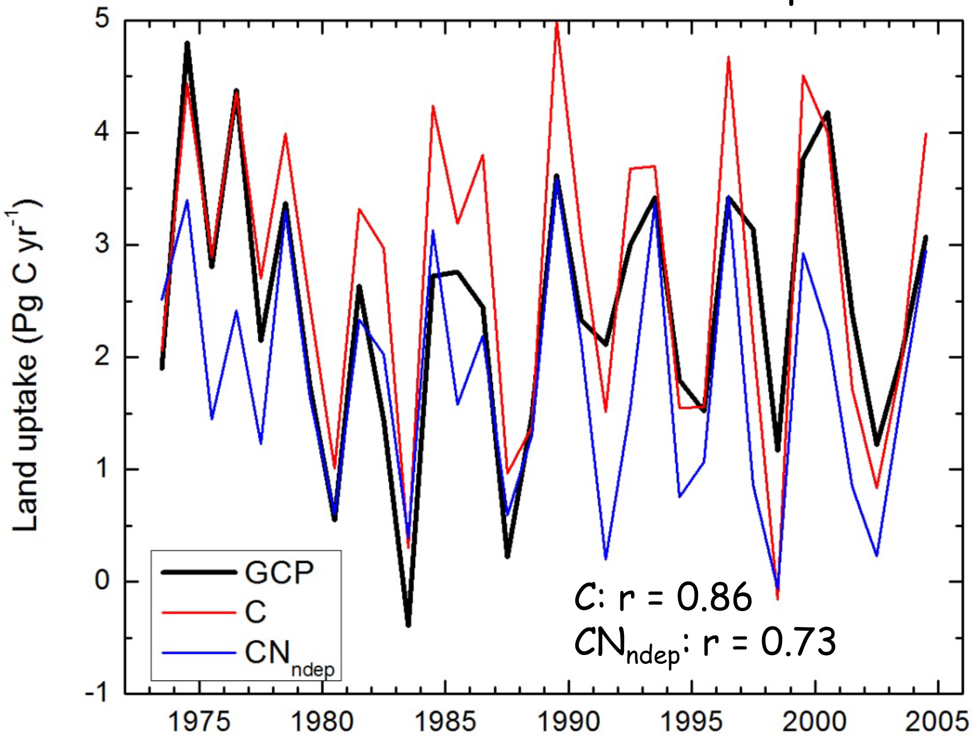
	C	CN_{ndep}	GCP
Land use ($Pg\ C\ yr^{-1}$)	1.8	1.8	1.5
Land sink ($Pg\ C\ yr^{-1}$)	2.5	1.8	2.0 – 2.4

2.4 is C-only estimate with 0.4 residual
2.0 has zero residual

Global Carbon Project (www.globalcarbonproject.org)

Le Quéré et al. (2009) Nature Geosci 2:831-836

Time series of annual land uptake



Bonan & Levis (2010) GRL, in press

Quantifying carbon-nitrogen feedbacks in CLM4

β_L and γ_L Calculated for Carbon-Only and Carbon-Nitrogen Simulations

	Without HLCC		With HLCC
β_L (Pg C ppm^{-1})	Constant Climate	Climate Change	Climate Change
C	0.94	0.94	0.92
CN	0.24	0.25	0.24
CN_{ndep} (+ $\Delta\Delta C_L^{NDEP}$)	0.37	0.38	0.37
γ_L (Pg C K^{-1})	Constant CO_2	Increasing CO_2	Increasing CO_2
C	-11.7	-11.7	-11.0
CN	-0.7	-0.1	0.3
CN_{ndep} (+ $\Delta\Delta C_L^{NDEP}$)	4.8	5.9	6.0

C mean β_L is 3.7 times greater than CN mean (i.e., 73% reduction in β_L)
- 19% [*Jain et al.*, 2010], 50% [*Zaehle et al.*, 2010], 58% [*Sokolov et al.*, 2008]

Additional carbon from N deposition increases β_L by 50%

CN reduces carbon loss with climate change, i.e., γ_L increases

Bonan & Levis (2010) GRL, in press

Quantifying carbon-nitrogen feedbacks in CLM4

Carbon budget analysis (Pg C yr^{-1})

$$\Delta C_L' = \Delta C_L^{HIST} + \Delta\Delta C_L^{CONC} + \Delta\Delta C_L^{CLIM} + \Delta\Delta C_L^{NDEP} + \Delta\Delta C_L^{HLCC}$$

					$\Delta\Delta C_L$			
Simulation	ΔC_L	$\Delta C_L'$	ΔC_L^{HIST}		CONC	CLIM	NDEP	HLCC
C	**0.62**	**0.62**	1.54		**1.43**	**-0.37**	0.00	-1.97
CN_{ndep}	**-0.13**	**-0.11**	1.22		0.38	0.01	0.19	**-1.92**
CN_{ndep} – C	-0.75	-0.73	-0.32		**-1.04**	**0.38**	**0.19**	0.05

C: CONC feedback is four times greater than CLIM feedback
- Similar to *Gregory et al.* [2009]

CN_{ndep}: decrease in CONC uptake is three times greater than reduction in CLIM loss

The influence of nitrogen on the concentration-carbon feedback is of greater importance for near-term climate change simulations than its effect on the climate-carbon feedback

The land use carbon flux greatly exceeds these carbon-nitrogen biogeochemical feedbacks

Bonan & Levis (2010) GRL, in press

Representing land use and land cover change

1. For IPCC AR5 land use and land cover change are to be described consistently with Representative Concentration Pathways (RCP) scenarios

2. All pathways share the same historical trajectory to 2005. After 2005 they diverge following own representative pathway.

3. For the historical period and for each RCP, land use that results in land cover change is described through annual changes in four basic land units:

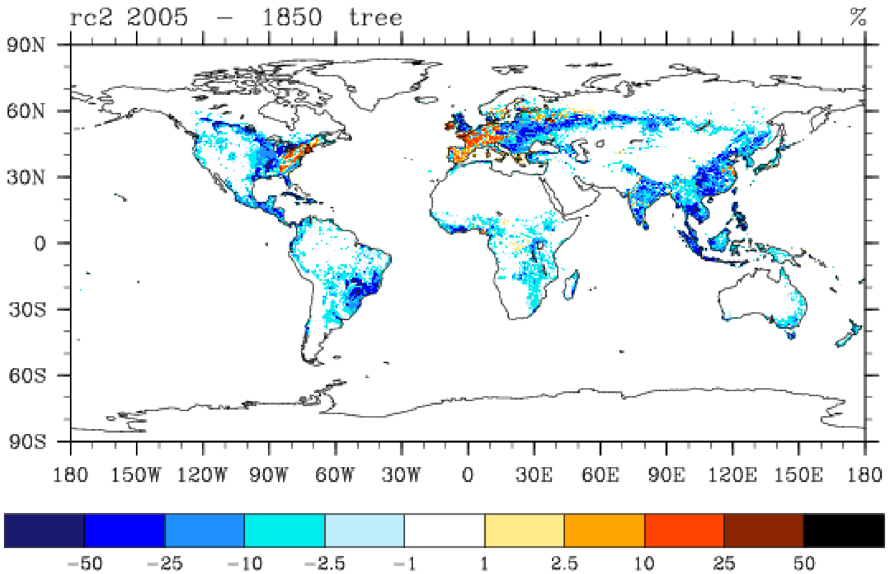
   - Primary Vegetation (V)
   - Secondary Vegetation (S)
   - Cropping (C)
   - Pasture (P)

4. Harvesting of biomass is also prescribed for both primary and secondary vegetation land units

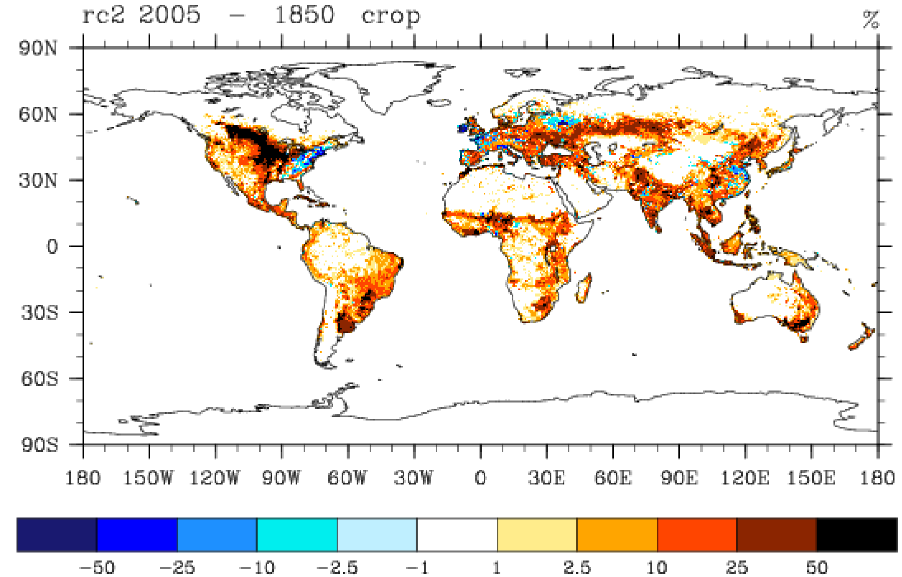
5. George Hurtt and colleagues at University of New Hampshire are harmonizing the historical and RCP data (luh.unh.edu)

Historical land cover change, 1850 to 2005

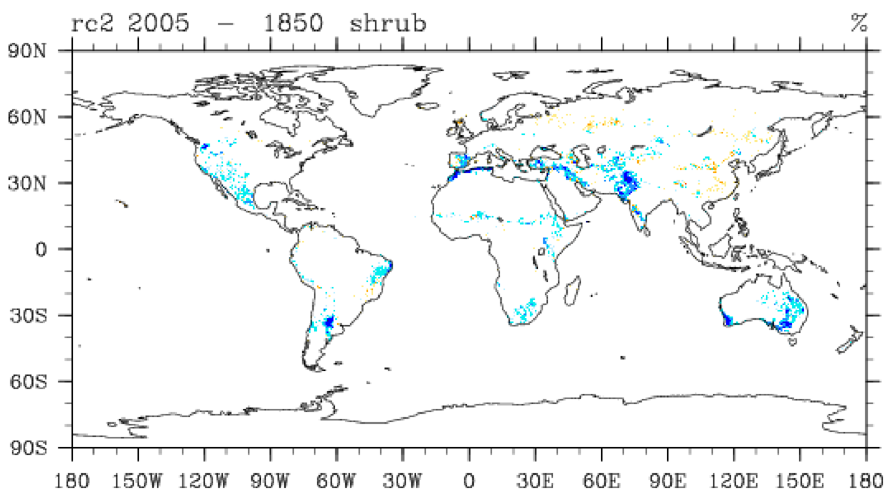
Tree PFTs



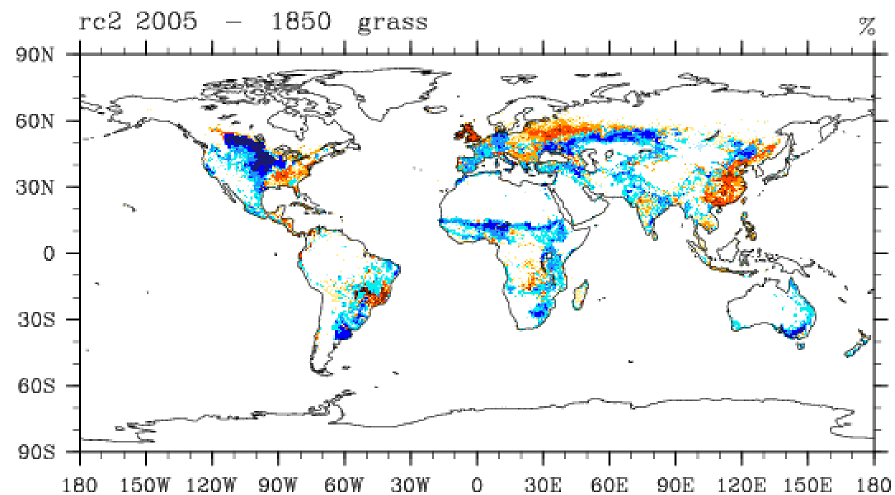
Crop PFT



Shrub PFTs



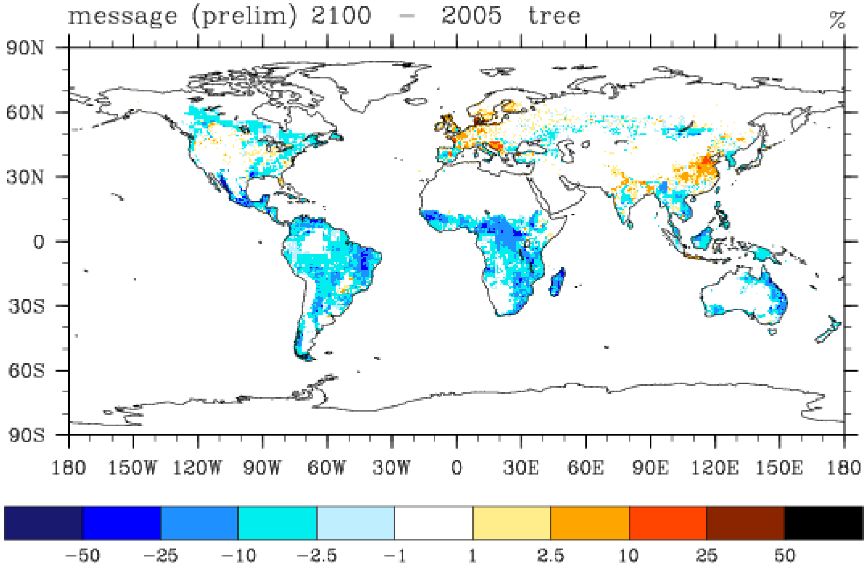
Grass PFTs



(datasets by Lawrence & Feddema)

Future land cover change, 2005 to 2100

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



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

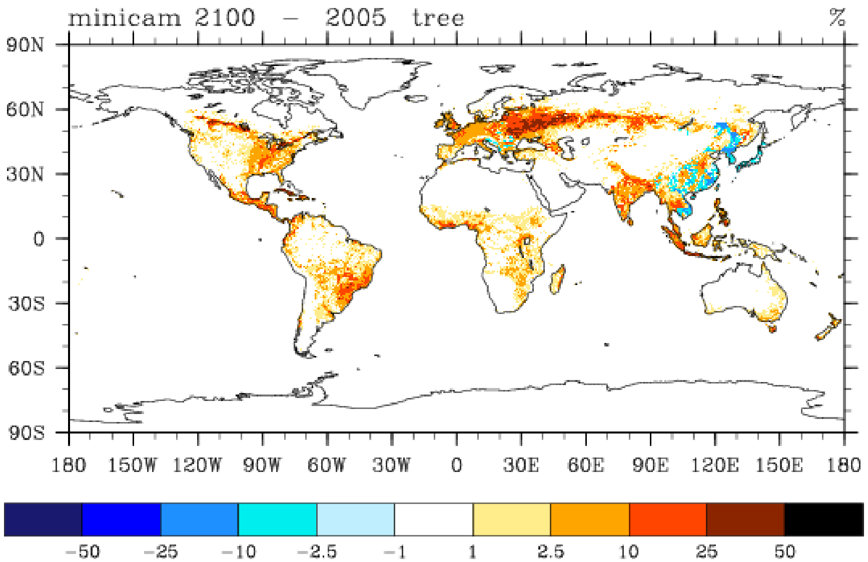
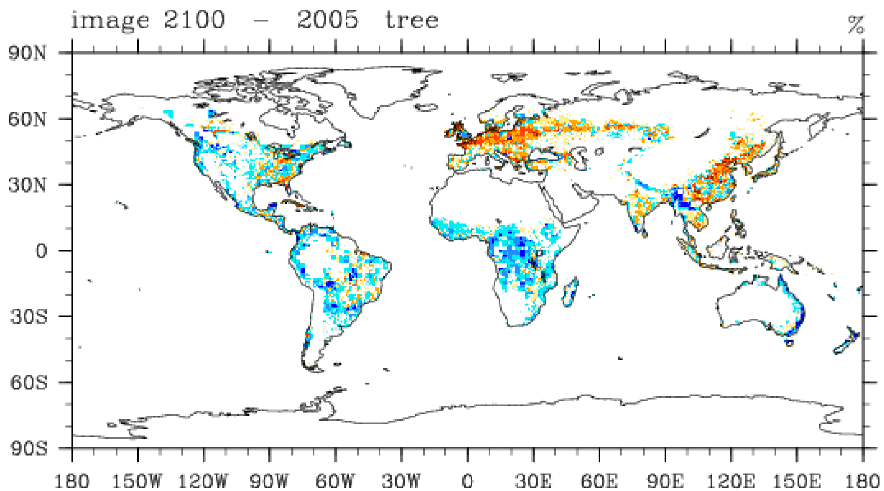


IMAGE (RCP 2.6 W m^{-2})



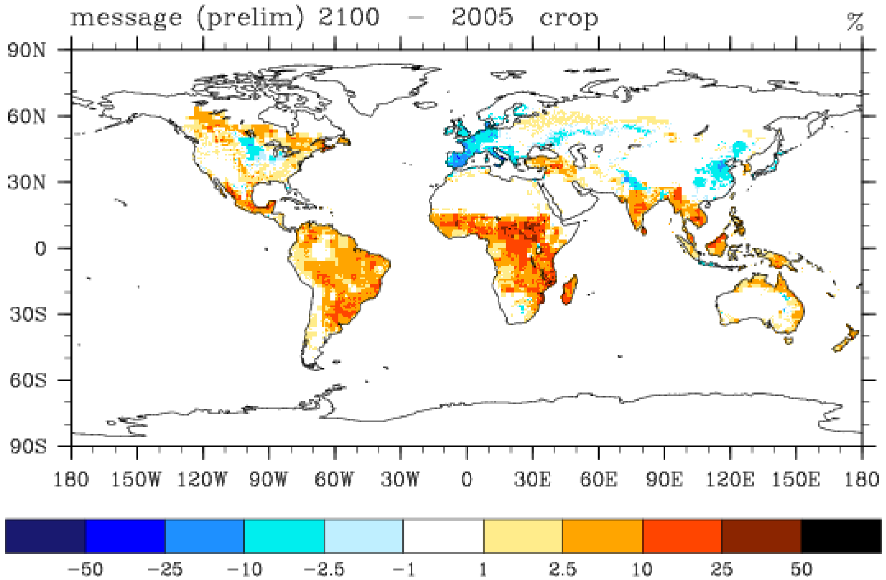
AIM (RCP 6.0 W m^{-2})

(In development)

(datasets by Lawrence & Feddema)

Future land cover change, 2005 to 2100

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



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

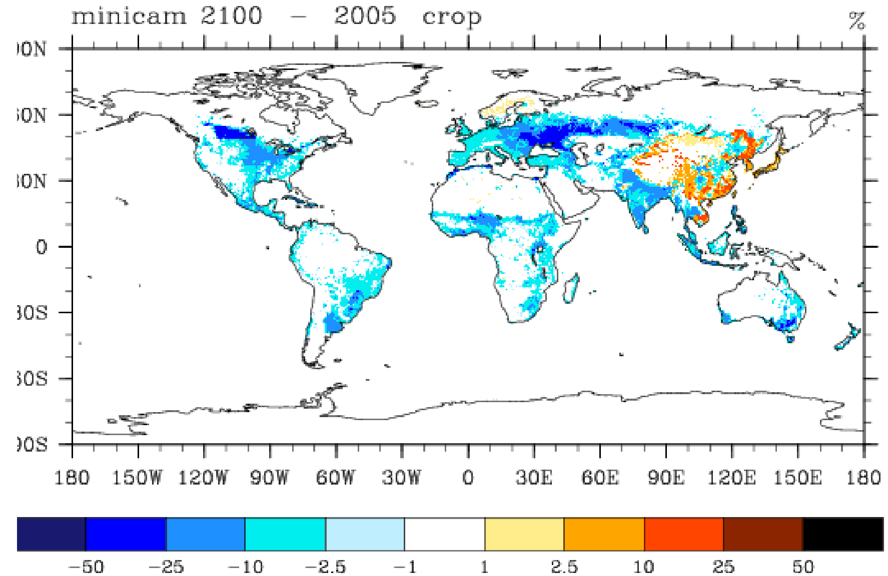
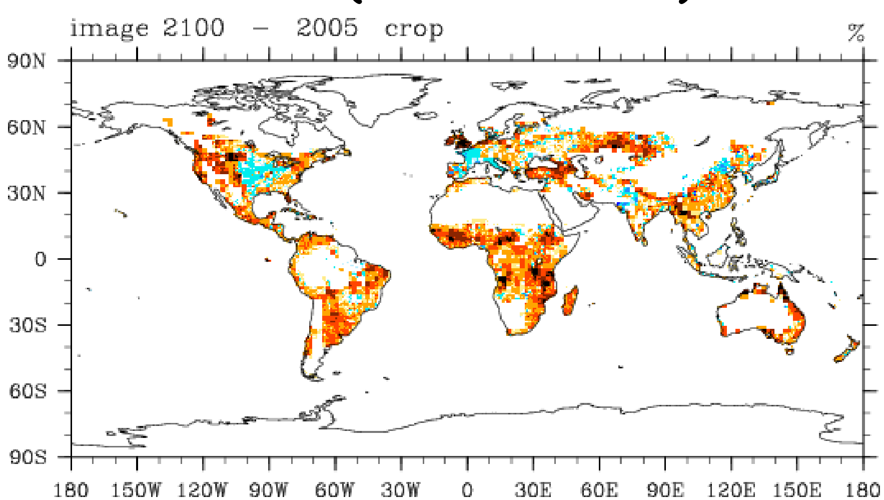


IMAGE (RCP 2.6 W m^{-2})

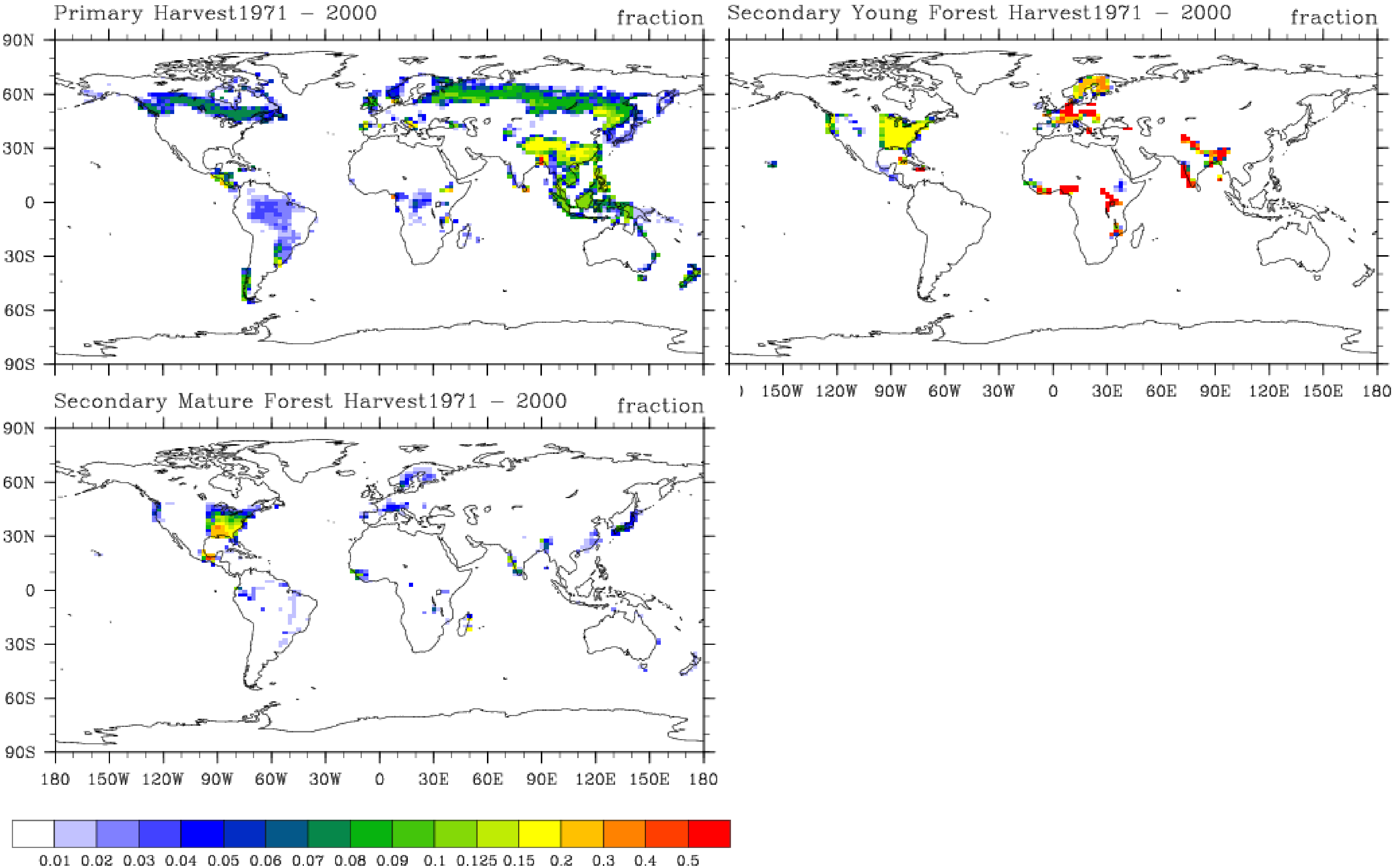


AIM (RCP 6.0 W m^{-2})

(In development)

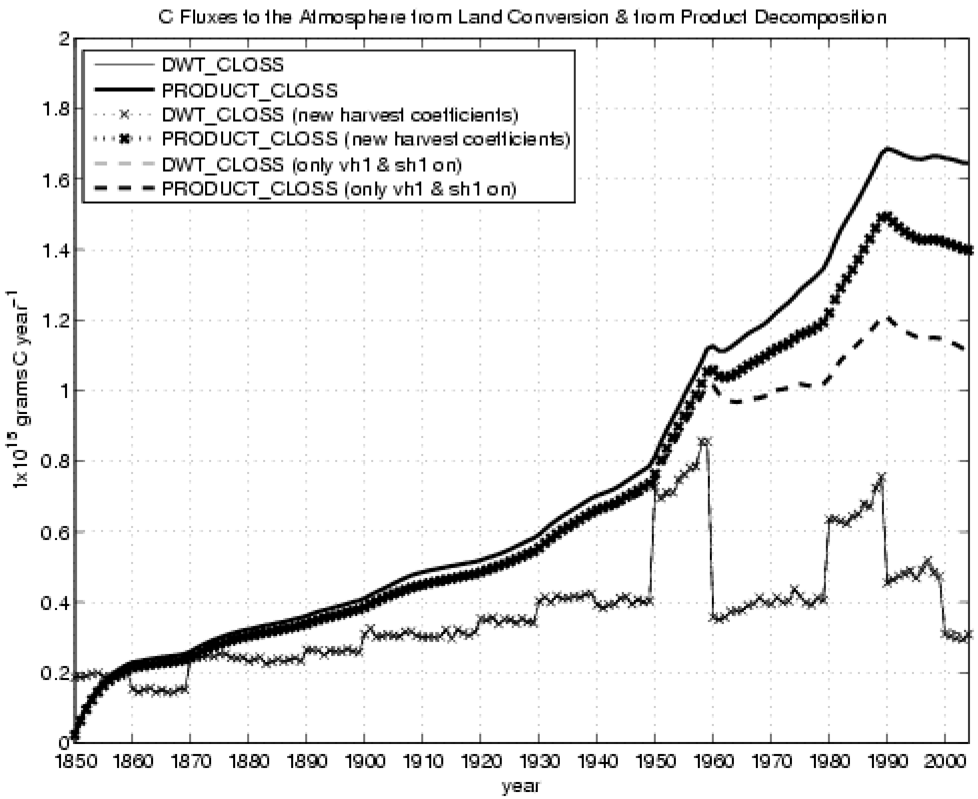
(datasets by Lawrence & Feddema)

Land use – wood harvest



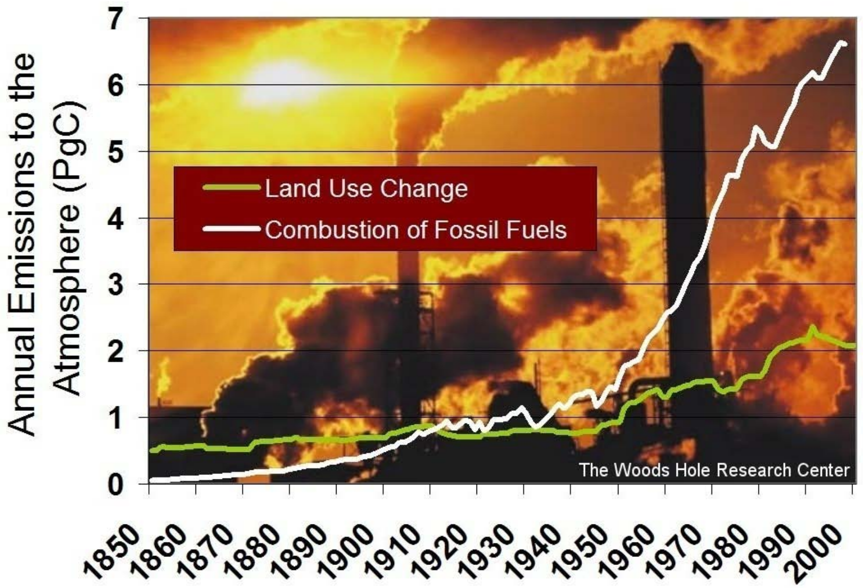
(datasets by Lawrence & Feddema)

Land use carbon flux



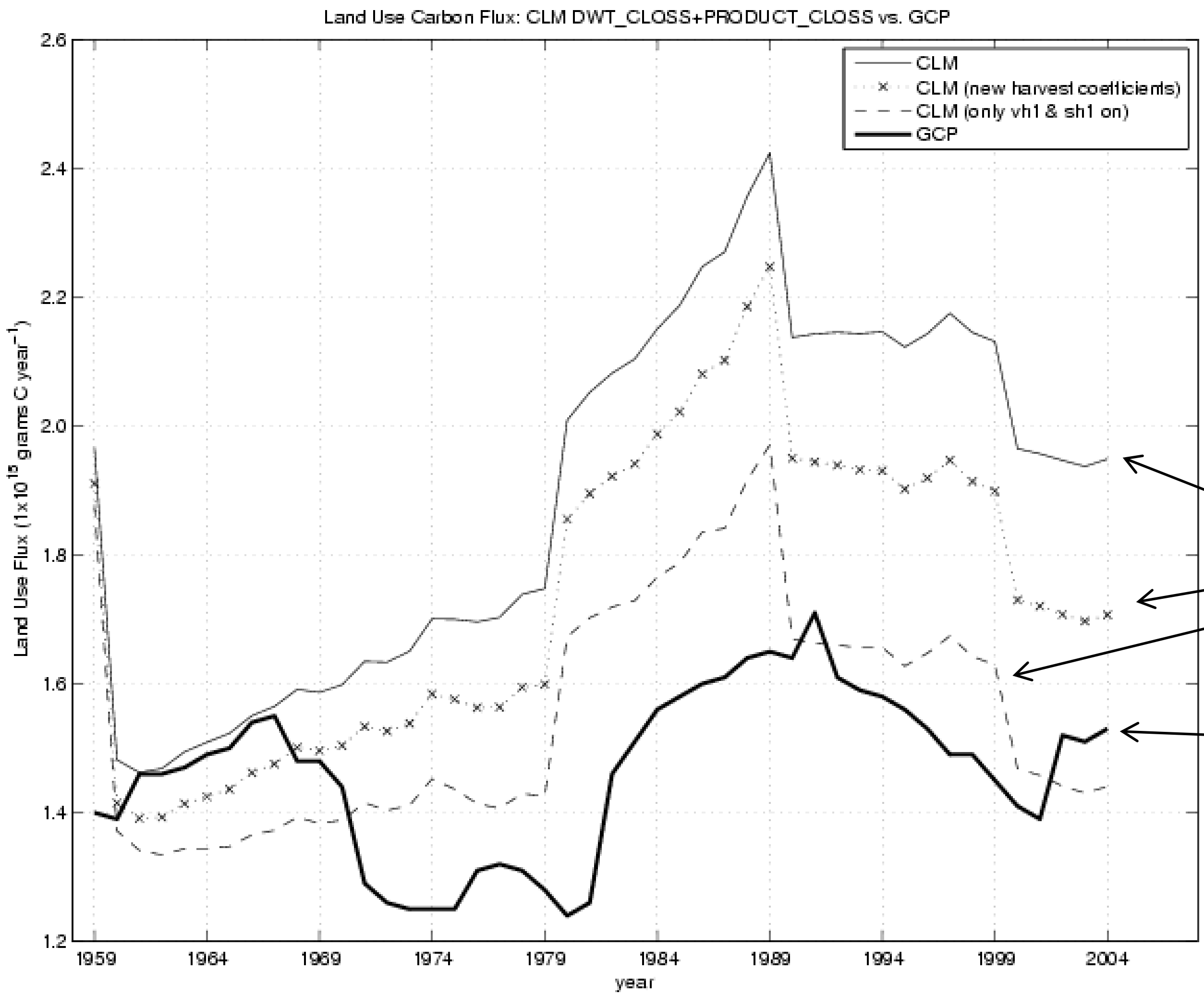
Wood harvesting

Land cover change
(e.g., deforestation)



(simulations by Sam Levis)

Land use carbon flux

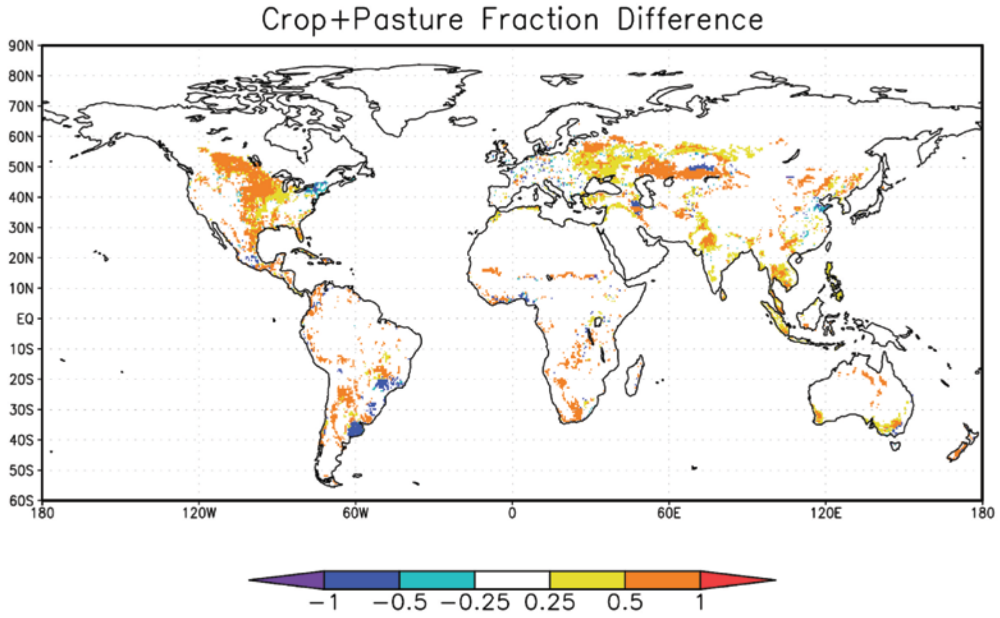


Three different harvest algorithms

Global Carbon Project
(www.globalcarbonproject.org)

(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

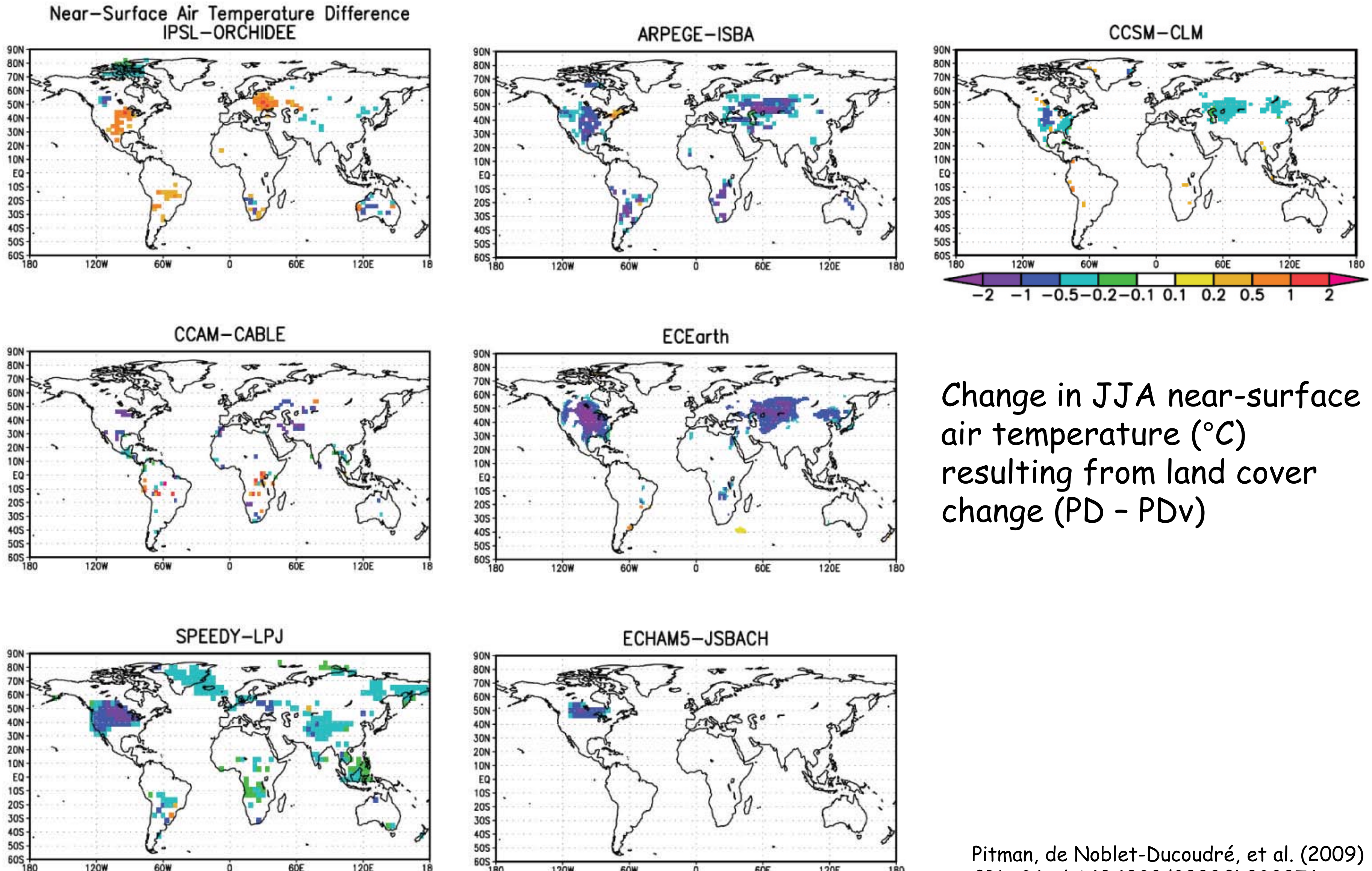
Models
Atmosphere - CAM3.5
Land - CLM3.5 + new datasets for present-day vegetation + grass optical properties
Ocean - Prescribed SSTs and sea ice

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

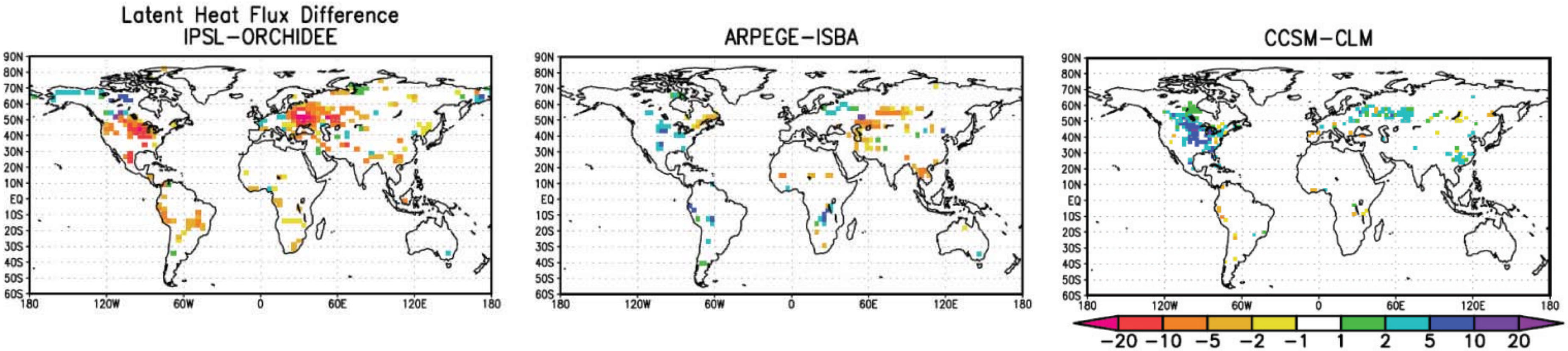
The LUCID intercomparison study

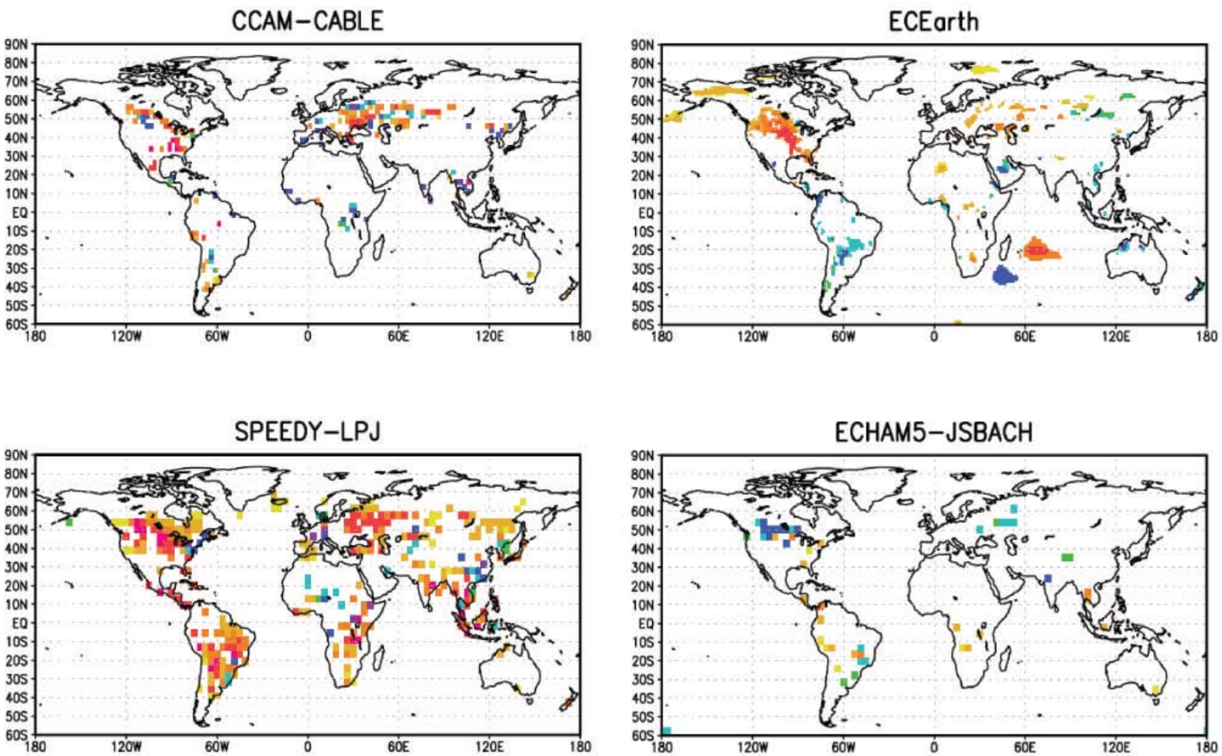


Change in JJA near-surface air temperature (°C) resulting from land cover change (PD – PDv)

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

The LUCID intercomparison study

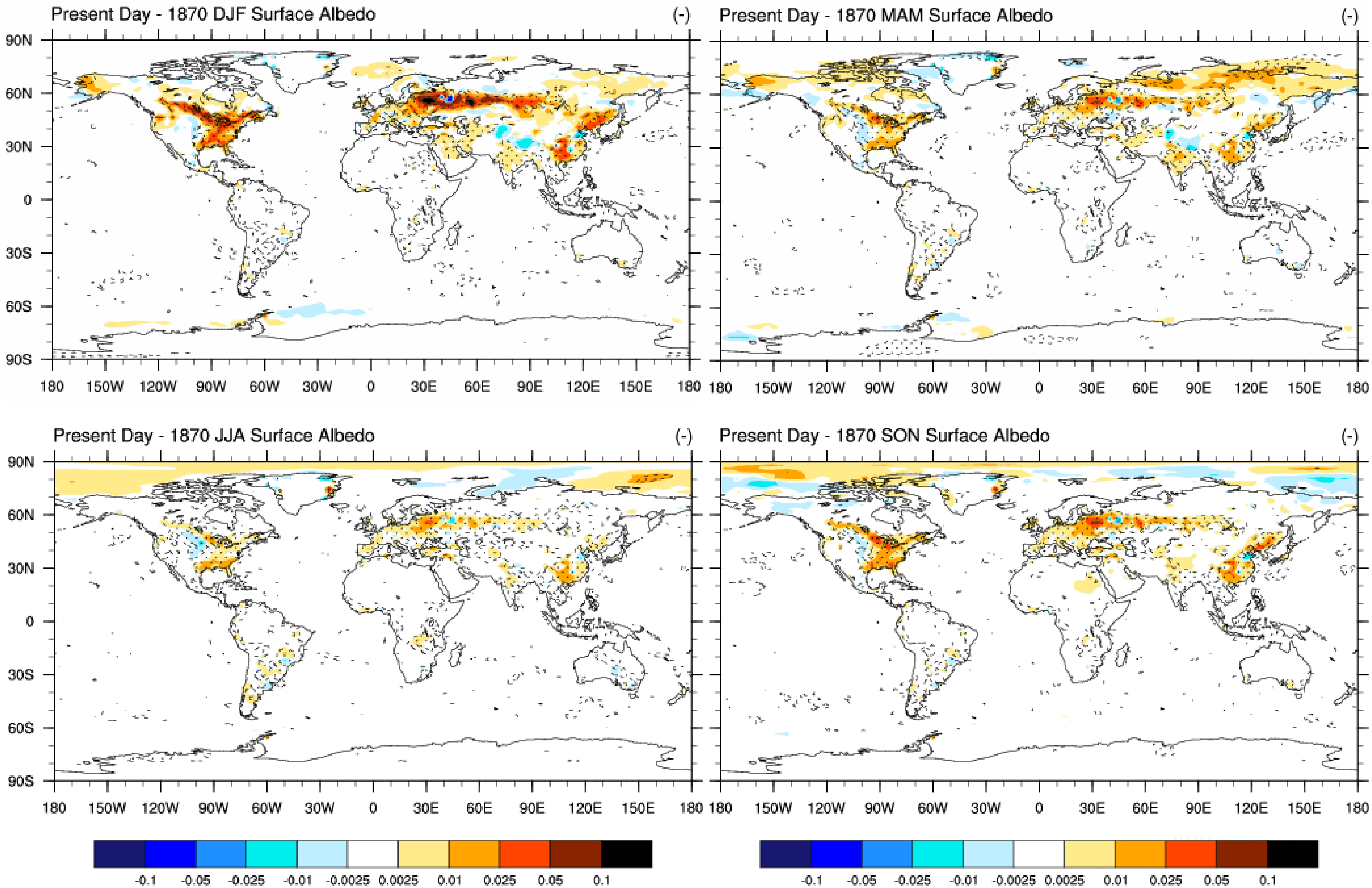




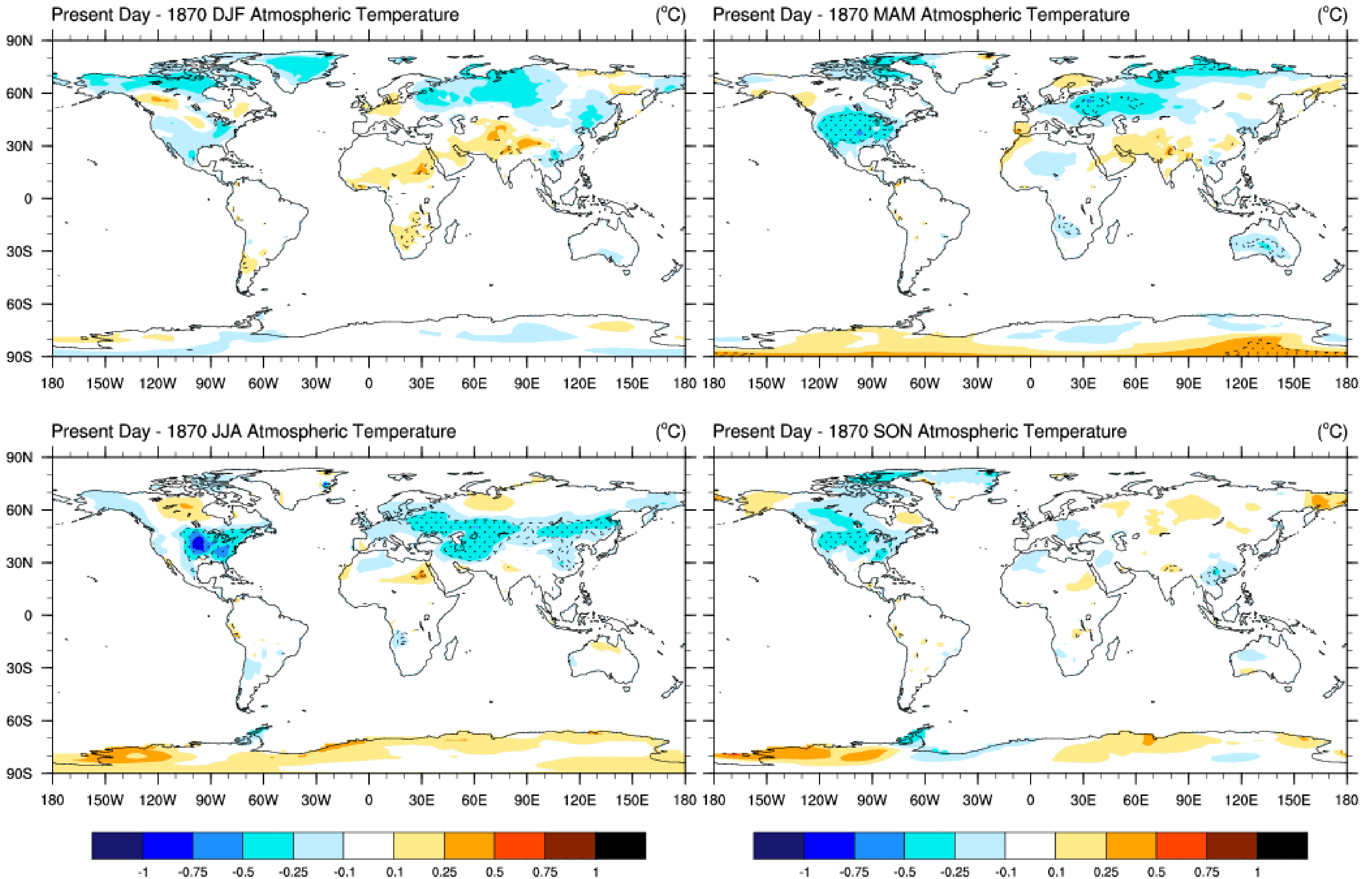
Change in JJA latent heat flux (W m^{-2}) resulting from land cover change (PD – PDv)

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

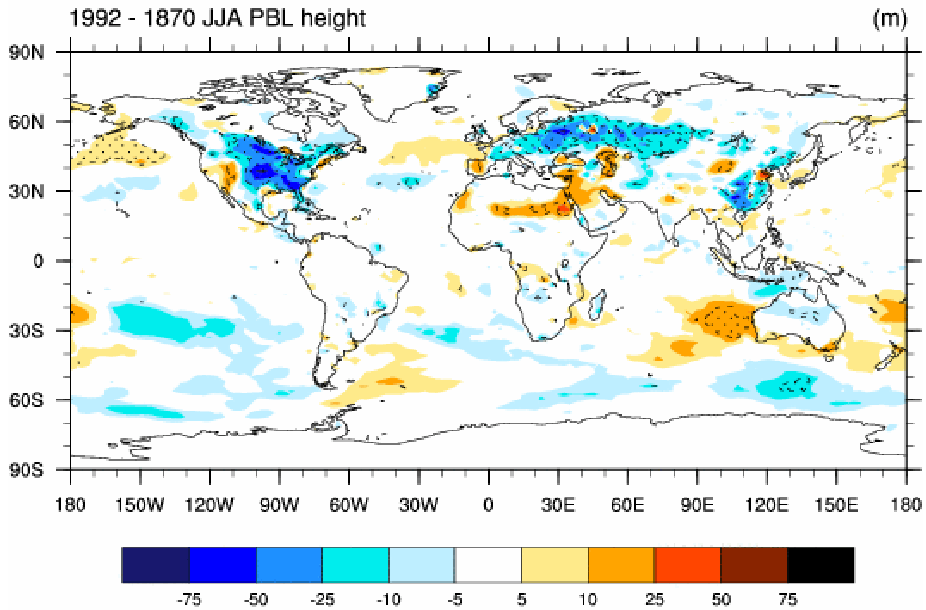
Albedo forcing, 1992-1870

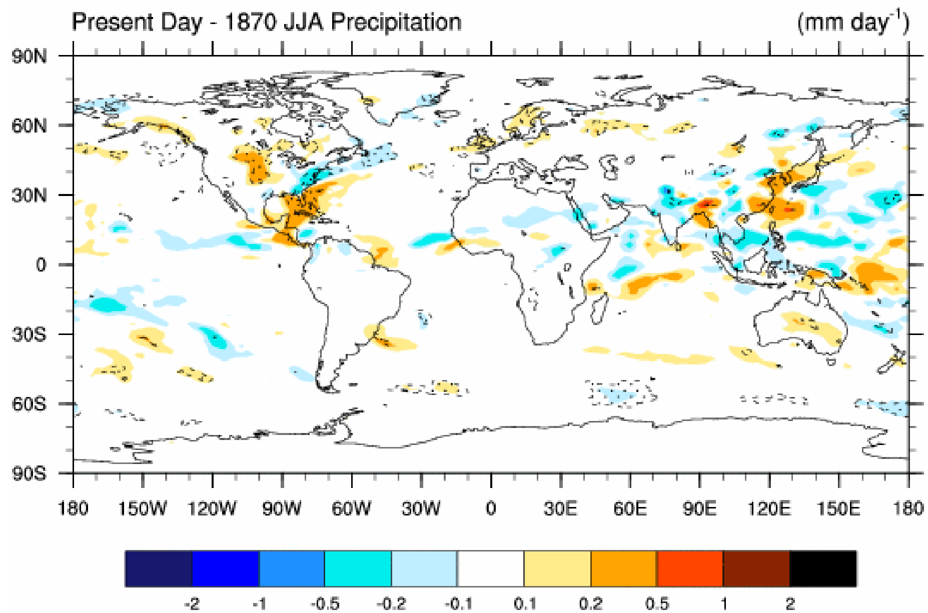


Near-surface temperature, 1992-1870



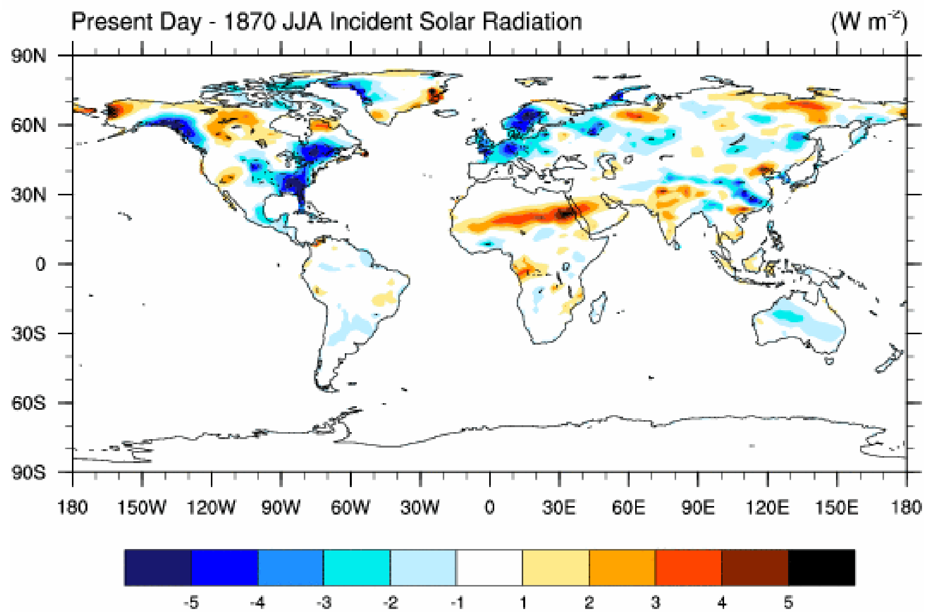
Atmospheric feedbacks





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

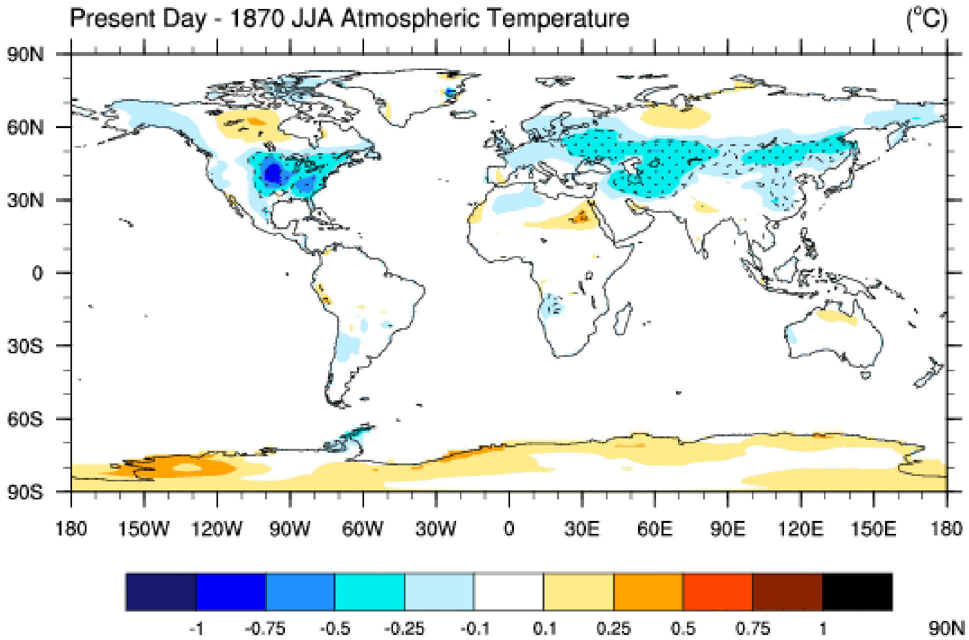
- Increased rainfall enhances latent heat flux
- Increased cloudiness reduces solar radiation
- Reduced PBL height



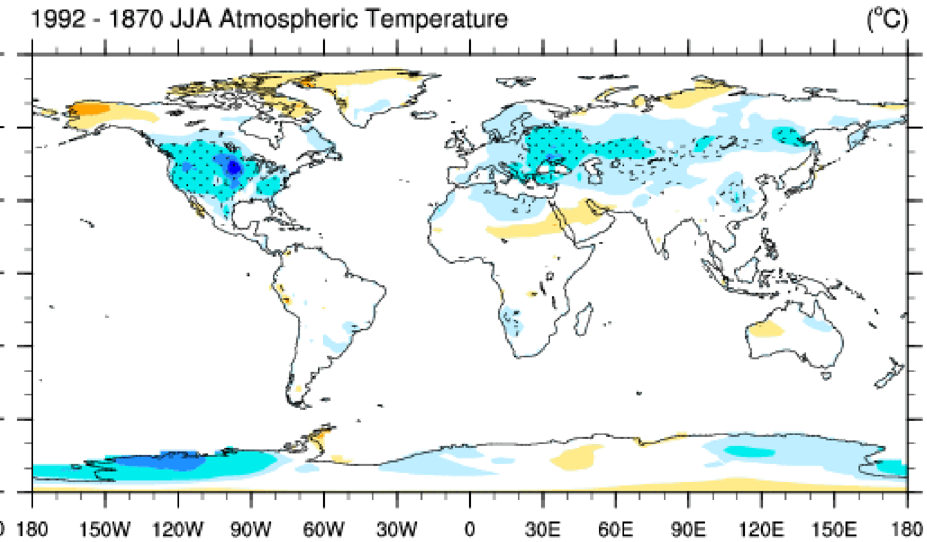
Flux towers measure local response

Land cover change offsets greenhouse gas warming

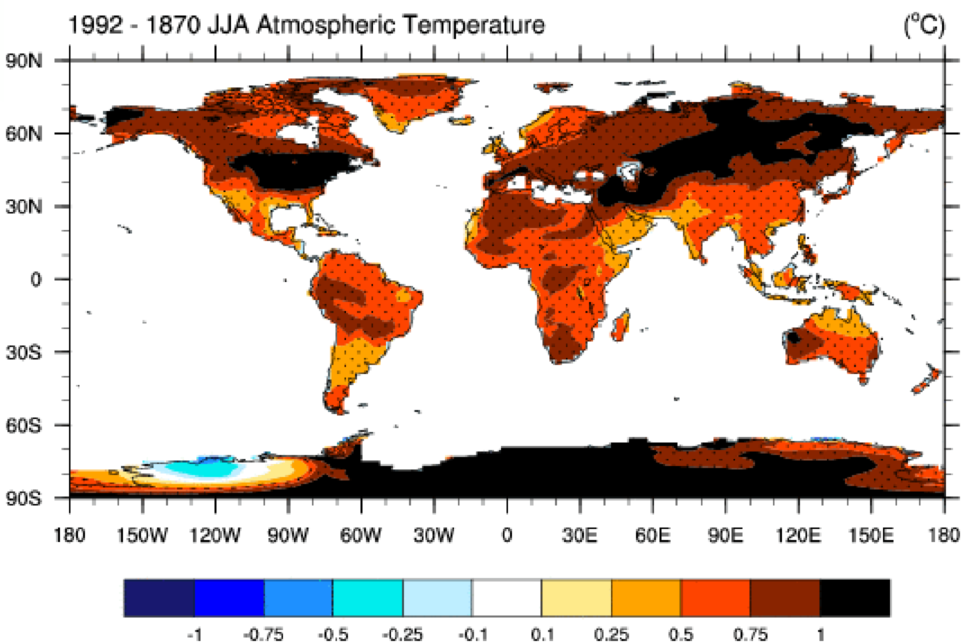
Land cover change with CO_2 = 375 ppm (1992)



Land cover change with CO_2 = 280 ppm (1870)



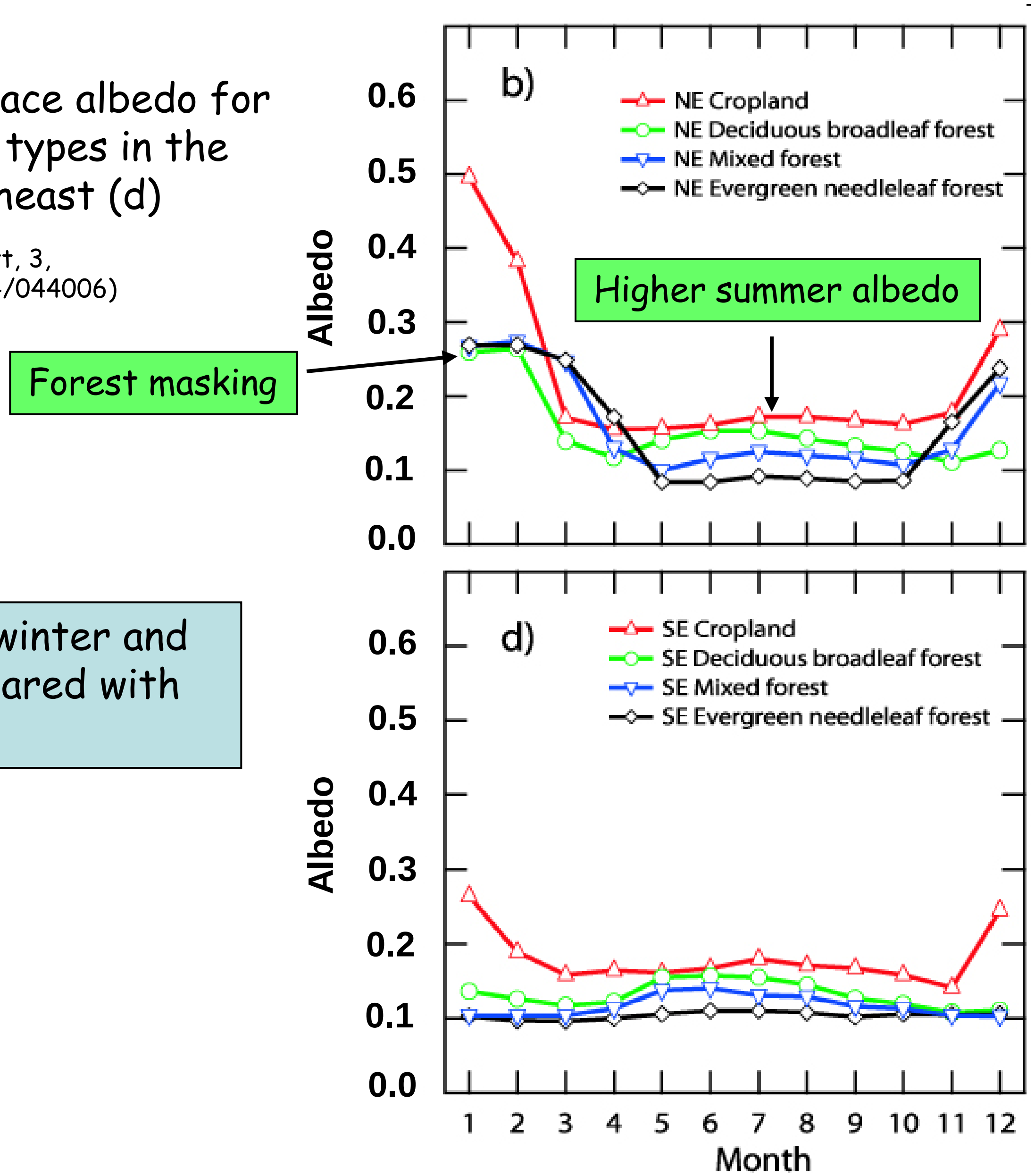
CO_2 forcing with 1870 land cover



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, 3, 044006 (doi:10.1088/1748-9326/3/4/044006)



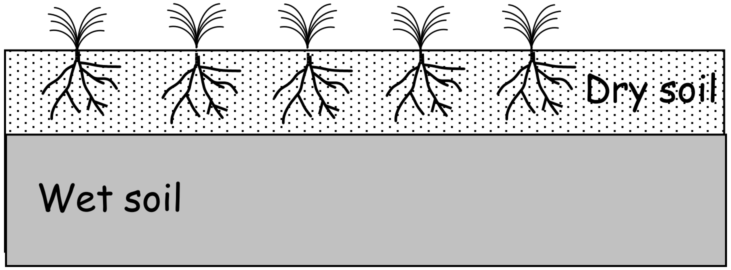
Cropland has a high winter and summer albedo compared with forest

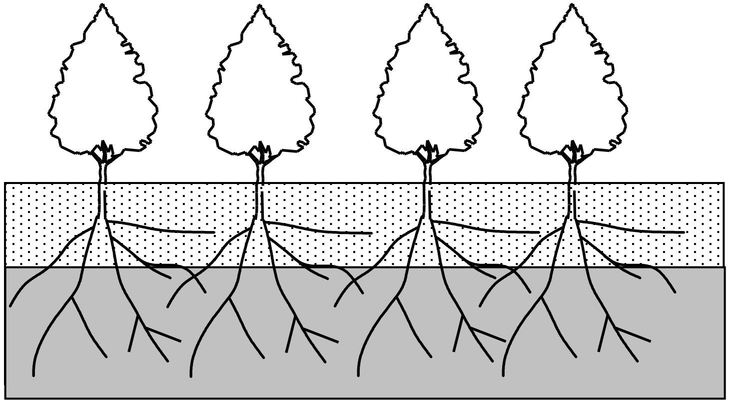
Land cover change and evapotranspiration

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



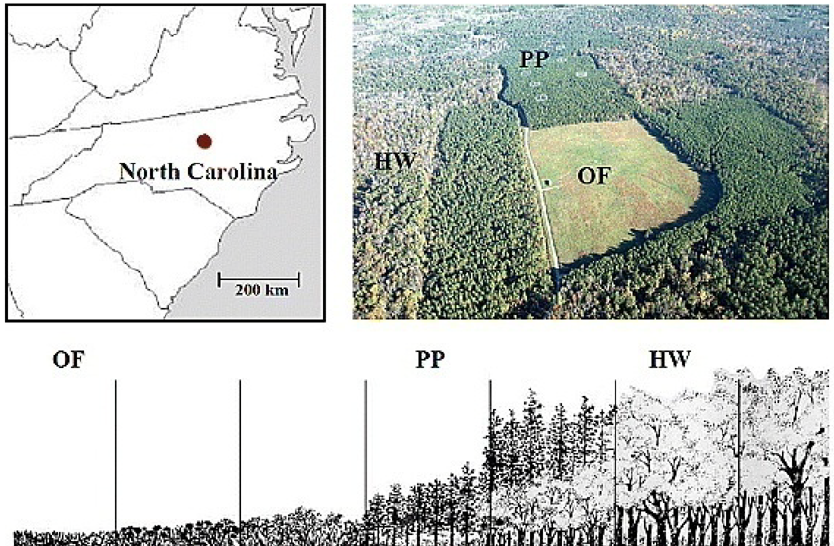


Tropical forest – cooling from higher surface albedo of cropland and pastureland is offset by warming associated with reduced evapotranspiration

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

Bonan (2008) Science 320:1444-1449

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

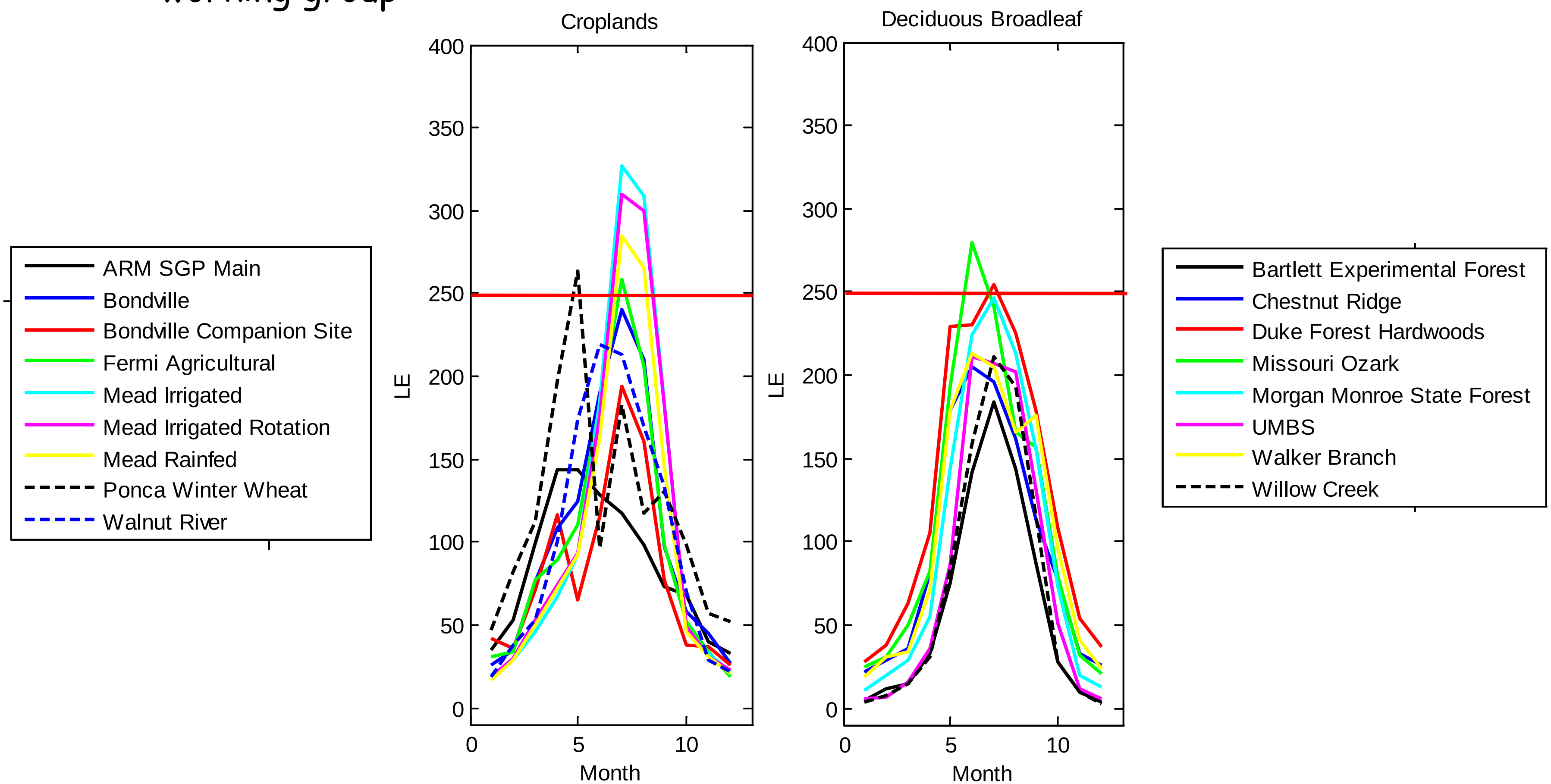
Forest
Lower albedo (+)

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

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

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

Climate change mitigation

Ecosystems

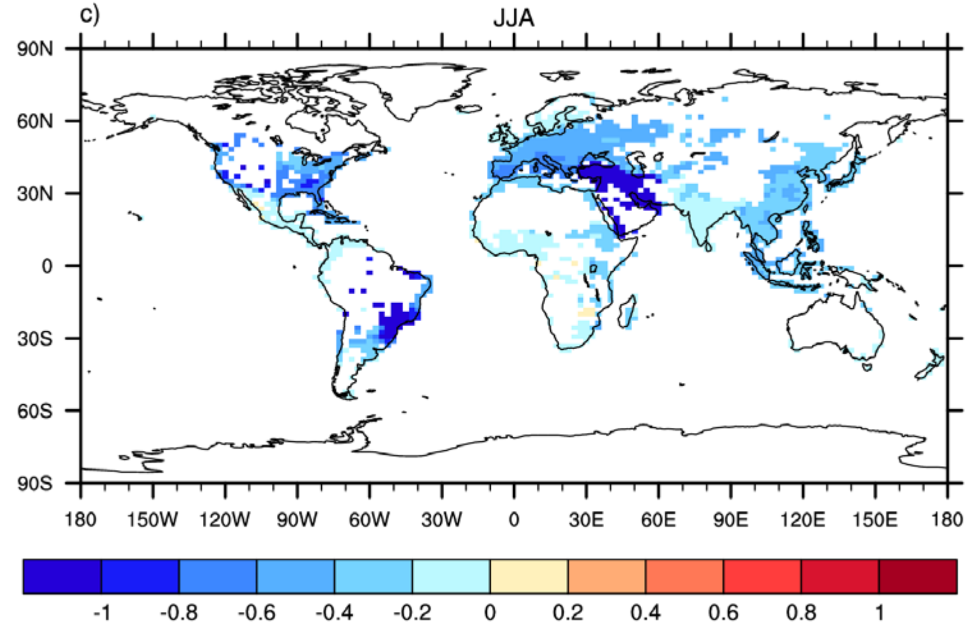
Management strategies
- Reforestation, afforestation, avoided deforestation
- Biofuels

Consequences
Biogeophysics and biogeochemistry (albedo, ET, carbon)

Urban planning and design

- White roofs
- Greenspaces

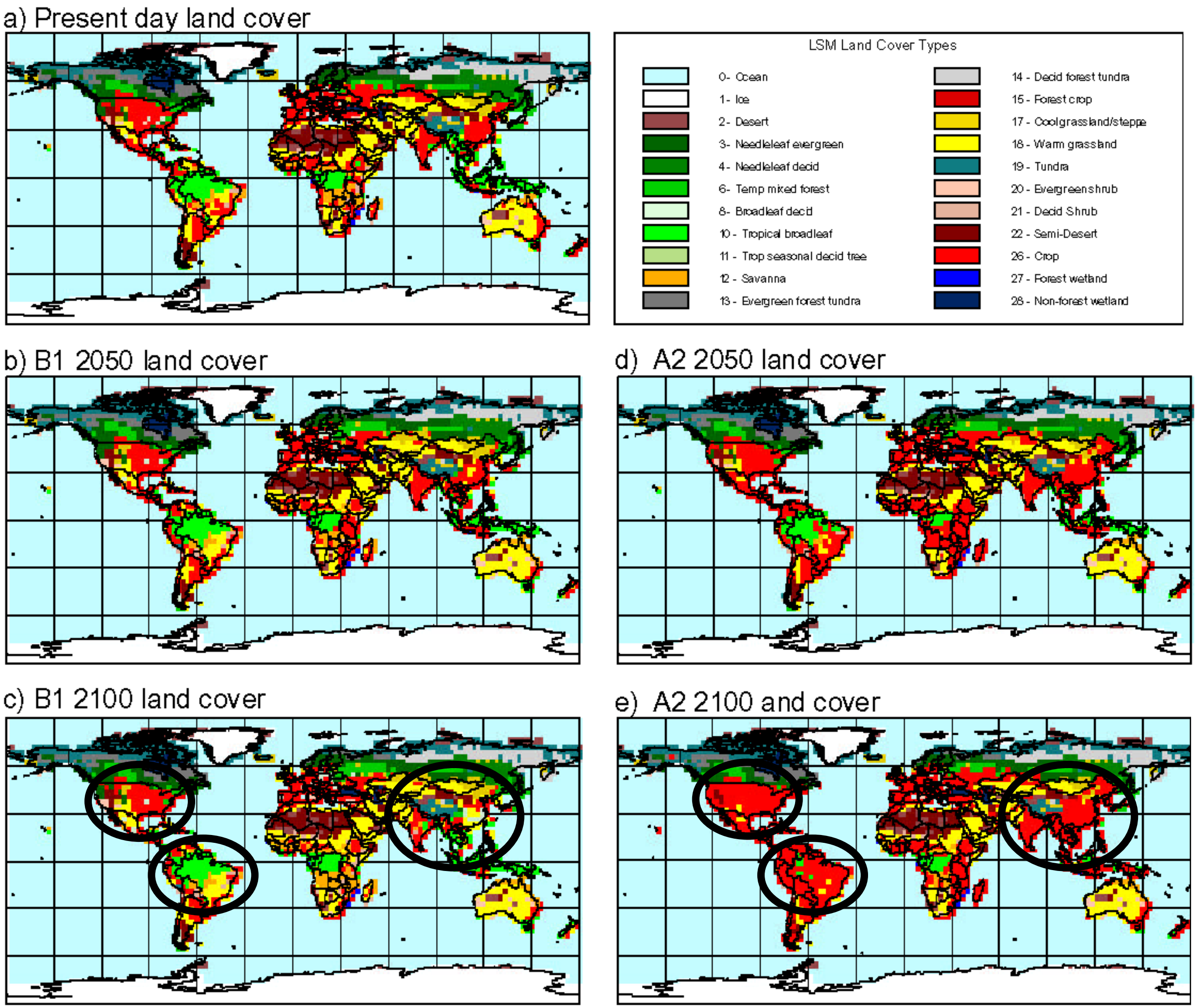
Average summer difference in the urban minus rural air temperature with roof albedos maximized



Oleson et al. (2010) GRL, 37, doi:10.1029/2009GL042194

Land use choices affect 21st century climate

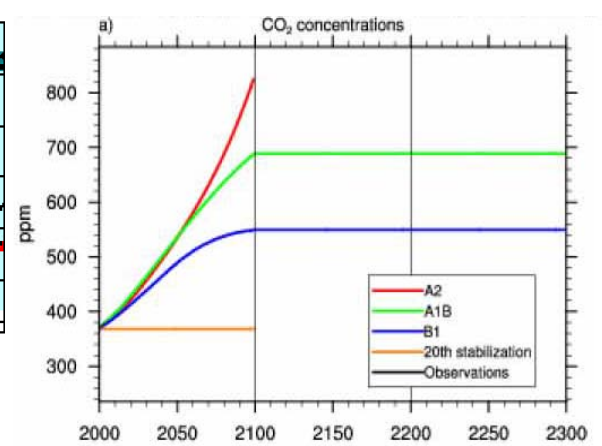
Future IPCC SRES land cover scenarios for NCAR LSM/PCM



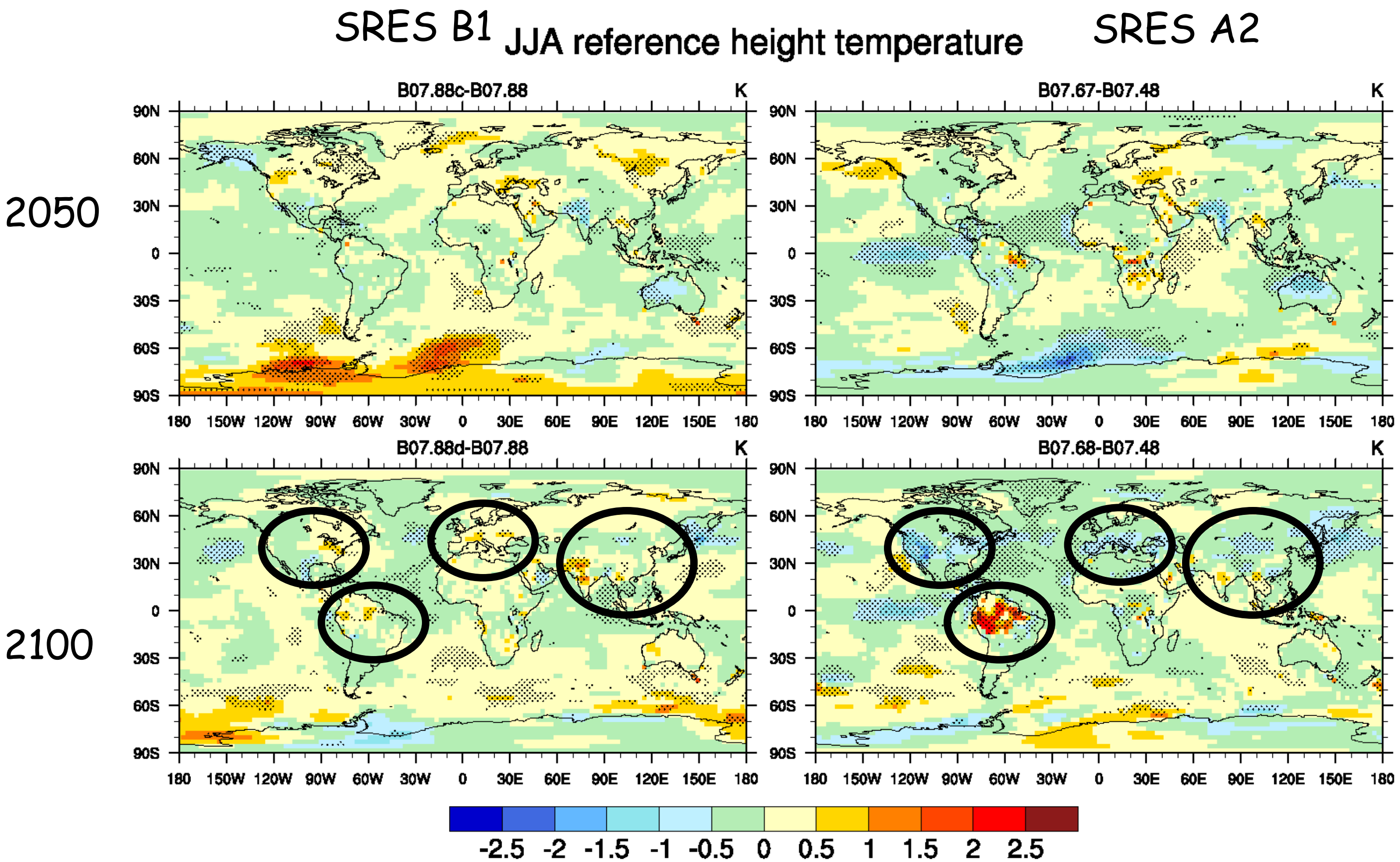
Feddema et al. (2005) Science 310:1674-1678

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

Conclusions

The ecology of climate models

- Detailed representation of ecosystems
- Allows exploration of ecological feedbacks and mitigation options

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

Land use and land cover change

Biogeochemistry
- Wood harvest flux is important
- 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 latent heat flux
- Implementation of land cover change (spatial extent, crop parameterization) matters