The Terrestrial Carbon Cycle and Land Cover Change in the Community Climate System Model

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National Center for Atmospheric Research
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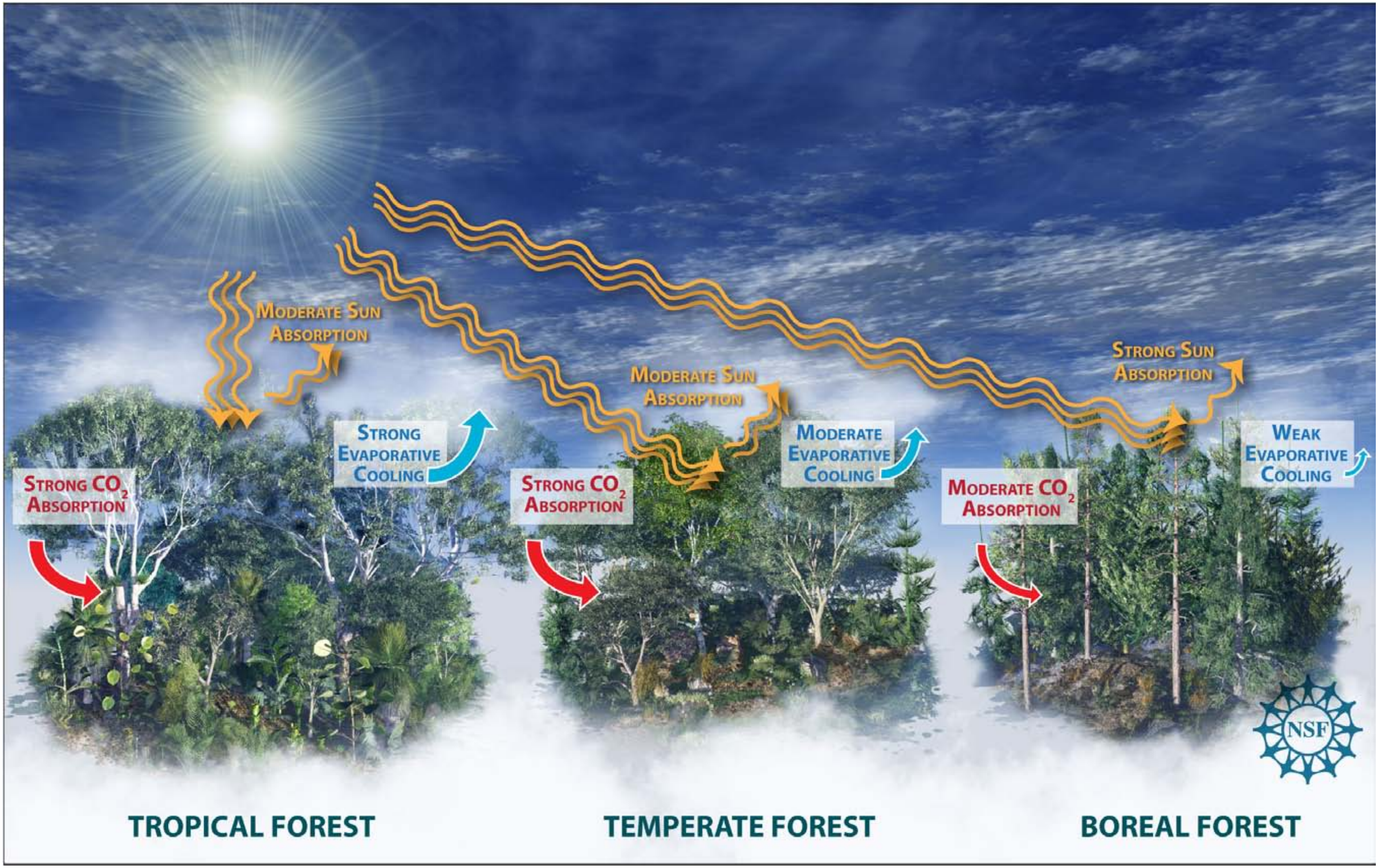
21 August 2009
CSIRO Marine and Atmospheric Research
Aspendale, Victoria, Australia

Forests and climate change

Multiple competing 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

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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

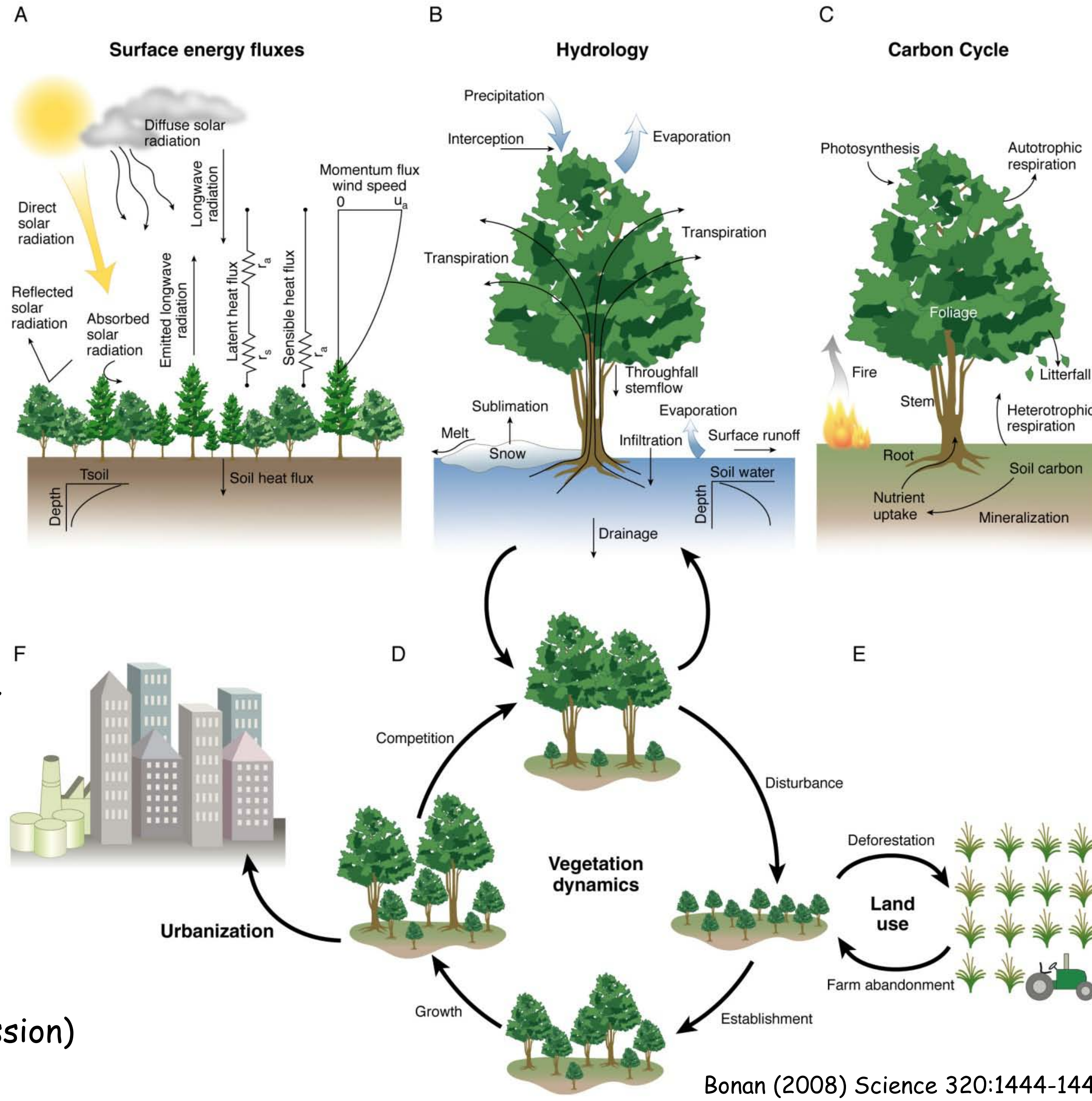
Stöckli et al. (2008) JGR, 113, doi:10.1029/2007JG000562

Spatial scale

2.5° longitude × 1.875° latitude
(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

Outline of talk

1. Carbon cycle – climate feedback
   Nitrogen cycle and model evaluation

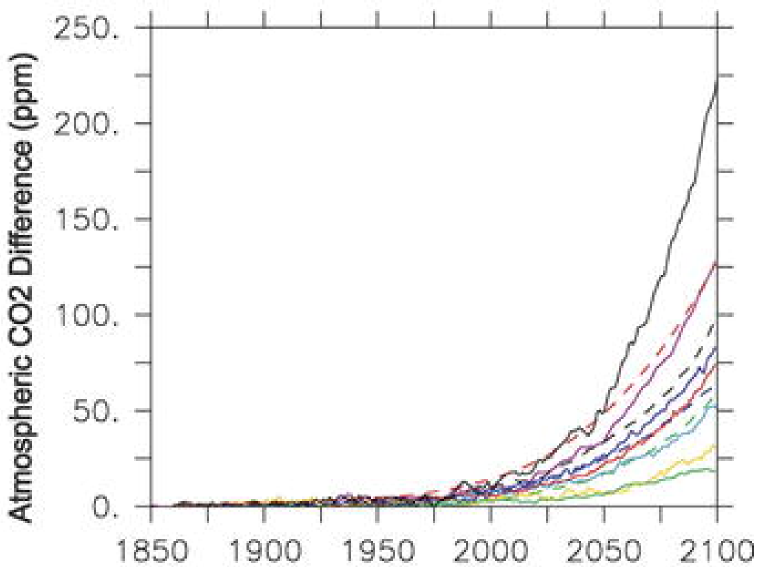
2. Land use and land cover change

2a. Biogeochemical
Wood harvesting
Land use carbon flux

2b. Biogeophysical
Albedo and evapotranspiration

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 plant productivity, offset by decreased productivity and increased soil carbon loss with warming …

But what about the nitrogen cycle and land use?

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Carbon-nitrogen interactions

Inclusion of N cycle reduces CO_2 fertilization (β_L) and changes carbon cycle-temperature feedback (γ_L) from positive to negative

Sokolov et al. (2008) J Climate 21:3776-3796

Carbon cycle–climate feedback in response to increasing atmospheric CO_2 and warming, with and without nitrogen

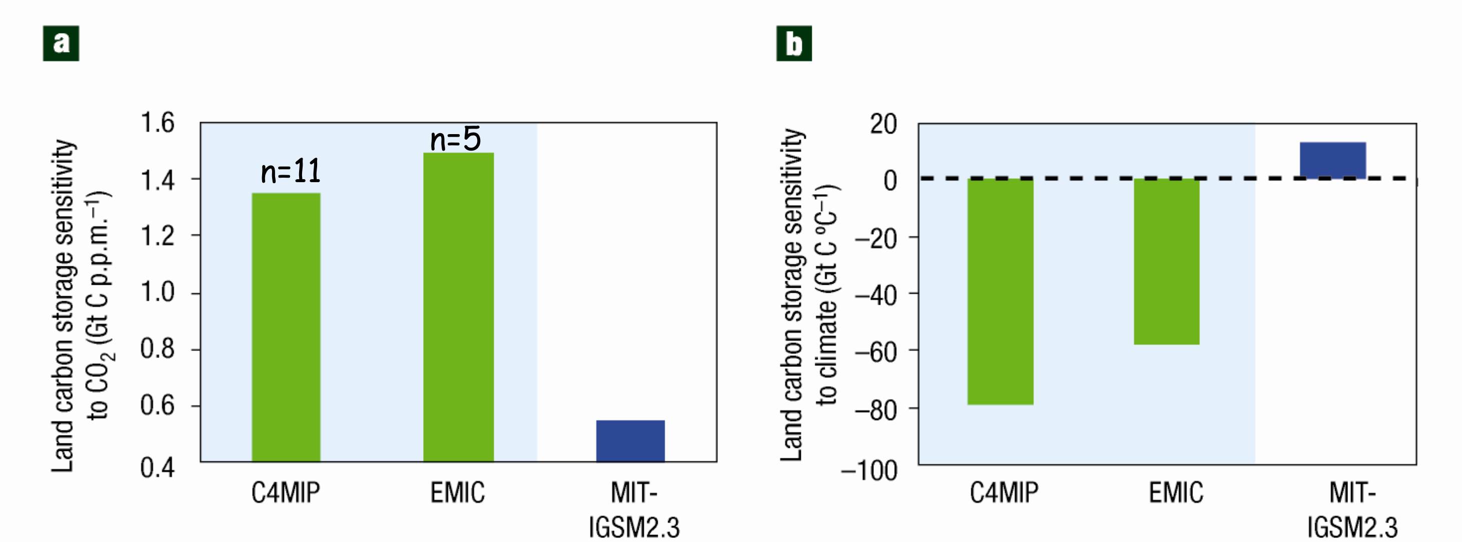

Figure from Bonan (2008) Nature Geoscience 1:645-646

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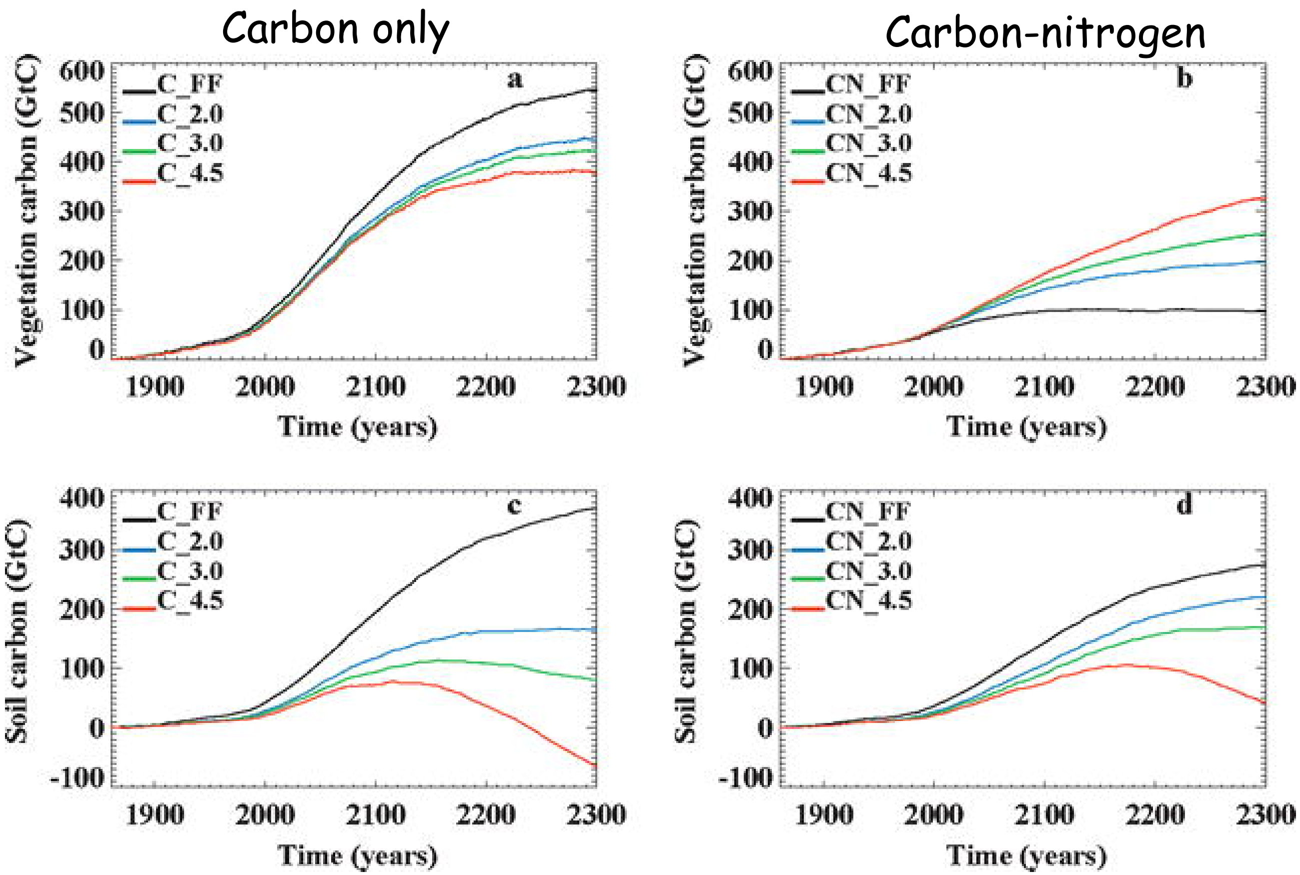
Carbon-nitrogen interactions

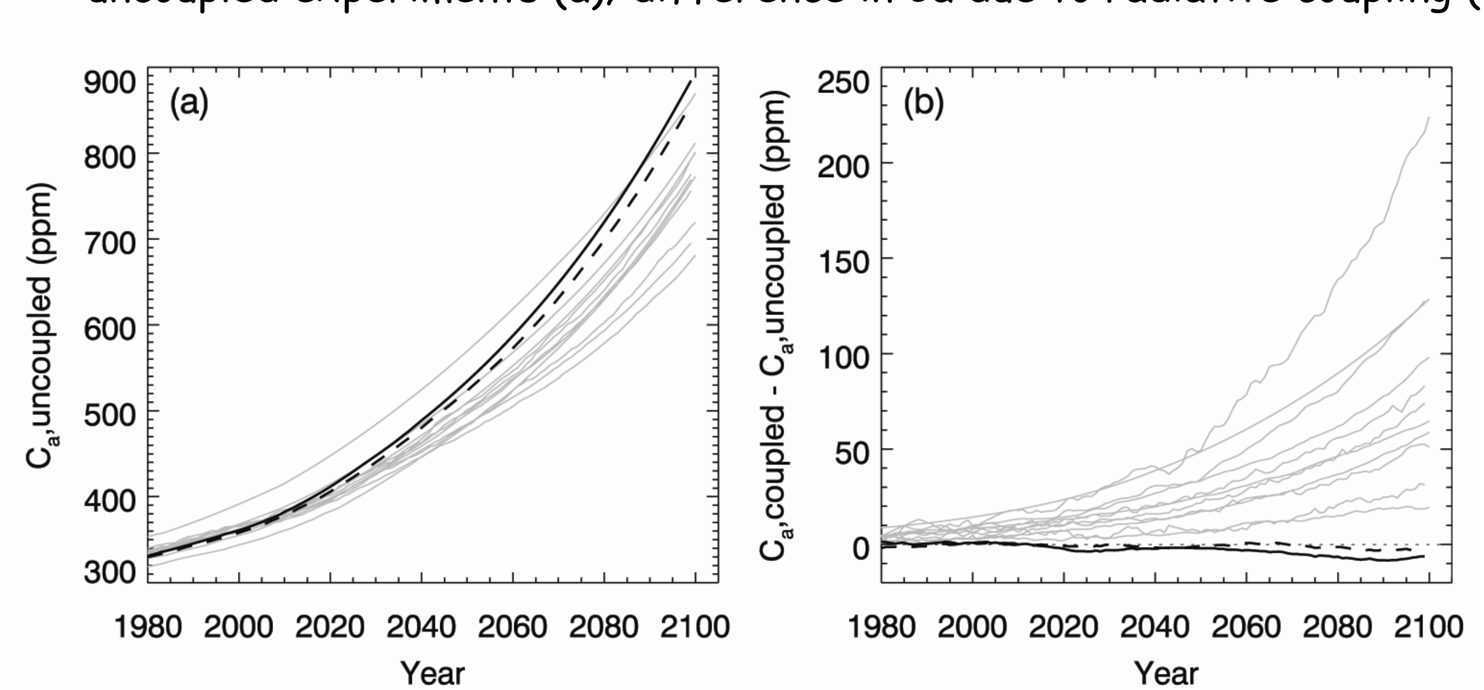


- Nitrogen limitation reduces the CO_2 fertilization effect
- Greater N mineralization with warming stimulates plant growth
- Overall, terrestrial carbon sequestration is reduced, but climate warming increases carbon sequestration in a negative, rather than a positive feedback

Sokolov et al. (2008) J Climate 21:3776-3796

CCSM3.1 carbon cycle-climate feedback

Simulated atmospheric CO_2 and climate-carbon cycle feedback: Ca from uncoupled experiments (a); difference in Ca due to radiative coupling (b)

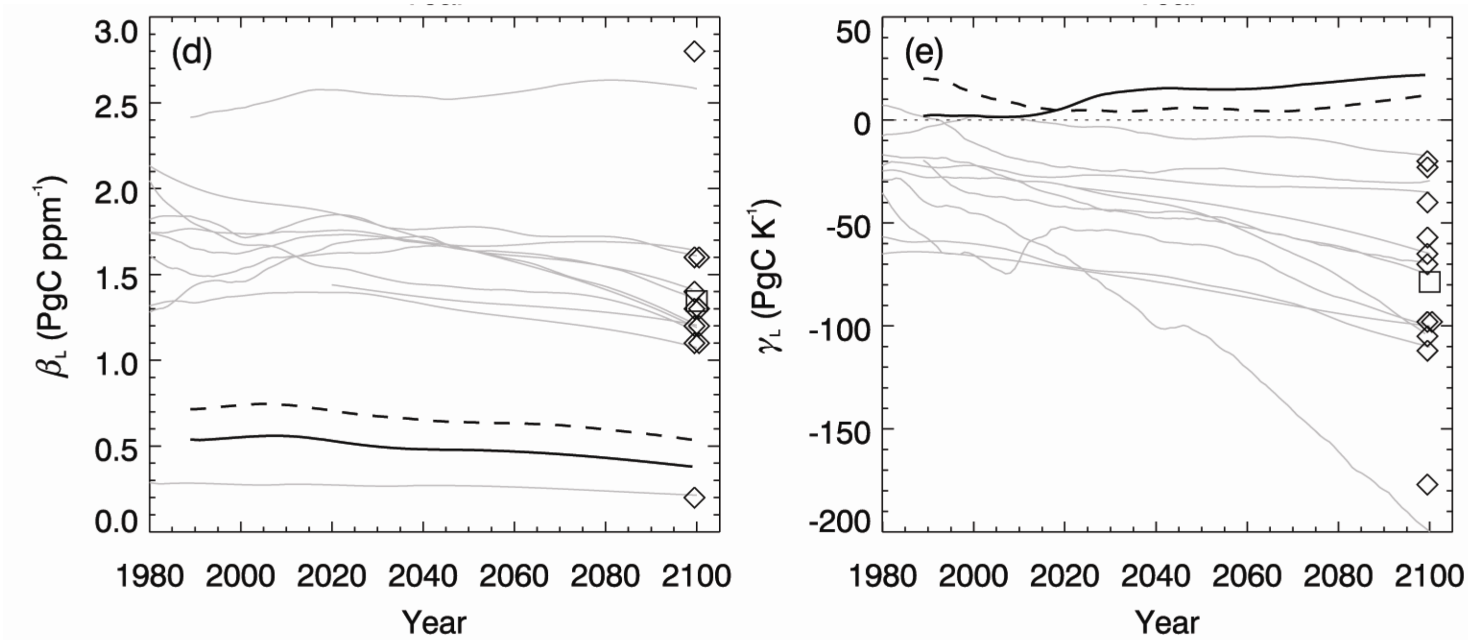


Thick solid line is with preindustrial nitrogen deposition
Thick dashed line is with anthropogenic nitrogen deposition
Thin gray lines are C4MIP models (Friedlingstein et al. 2006)

Inclusion of N cycle leads to high atmospheric CO_2 and introduces a negative carbon cycle-climate feedback

Thornton et al. (2009) Biogeosciences Discuss., 6, 3303-3354

CCSM3.1 carbon cycle-climate feedback



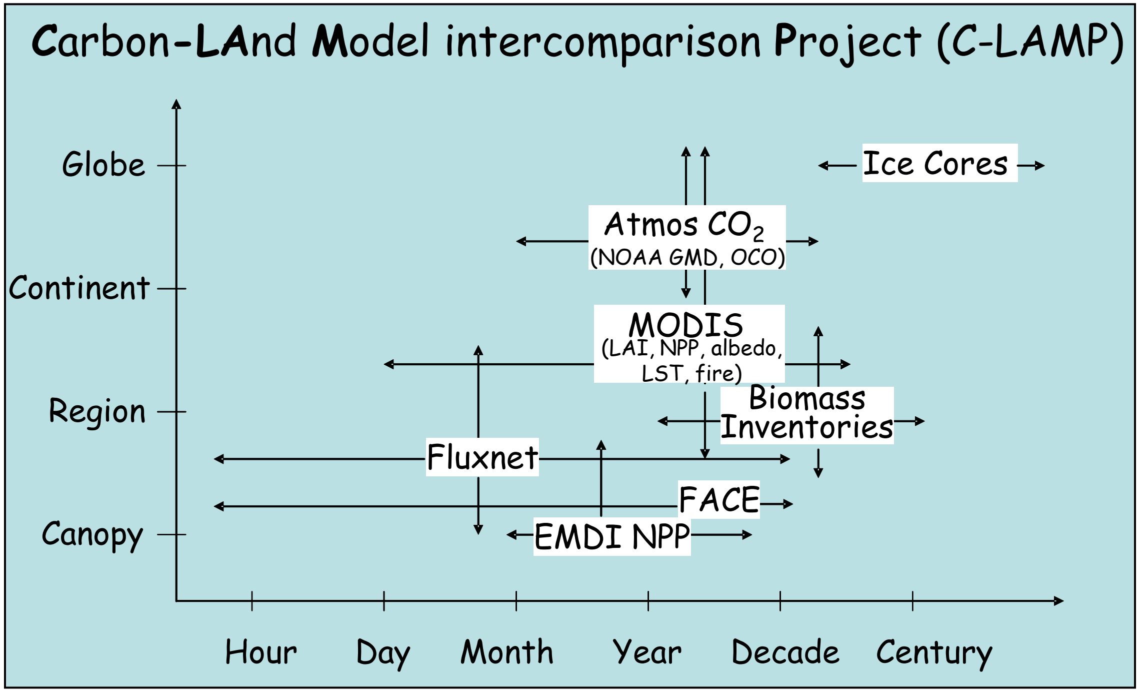
Land biosphere response to CO_2 Land biosphere response to temperature

Thick solid line is with preindustrial nitrogen deposition
Thick dashed line is with anthropogenic nitrogen deposition
Thin gray lines are C4MIP models (Friedlingstein et al. 2006)

Inclusion of N cycle reduces CO_2 fertilzation (β_L) and changes carbon cycle-temperature feedback (γ_L) negative

Thornton et al. (2009) Biogeosciences Discuss., 6, 3303-3354

Multi-scale carbon cycle evaluation



"Systematic assessment of terrestrial biogeochemistry in coupled climate-carbon models"

James T. Randerson, Forrest M. Hoffman, Peter E. Thornton, Natalie M. Mahowald, Keith Lindsay, Yen-Hui Lee, Cynthia D. Nevison, Scott C. Doney, Gordon Bonan, Reto Stocki, Steven W. Running, and Inez Fung

Global Change Biology, in press, 2009

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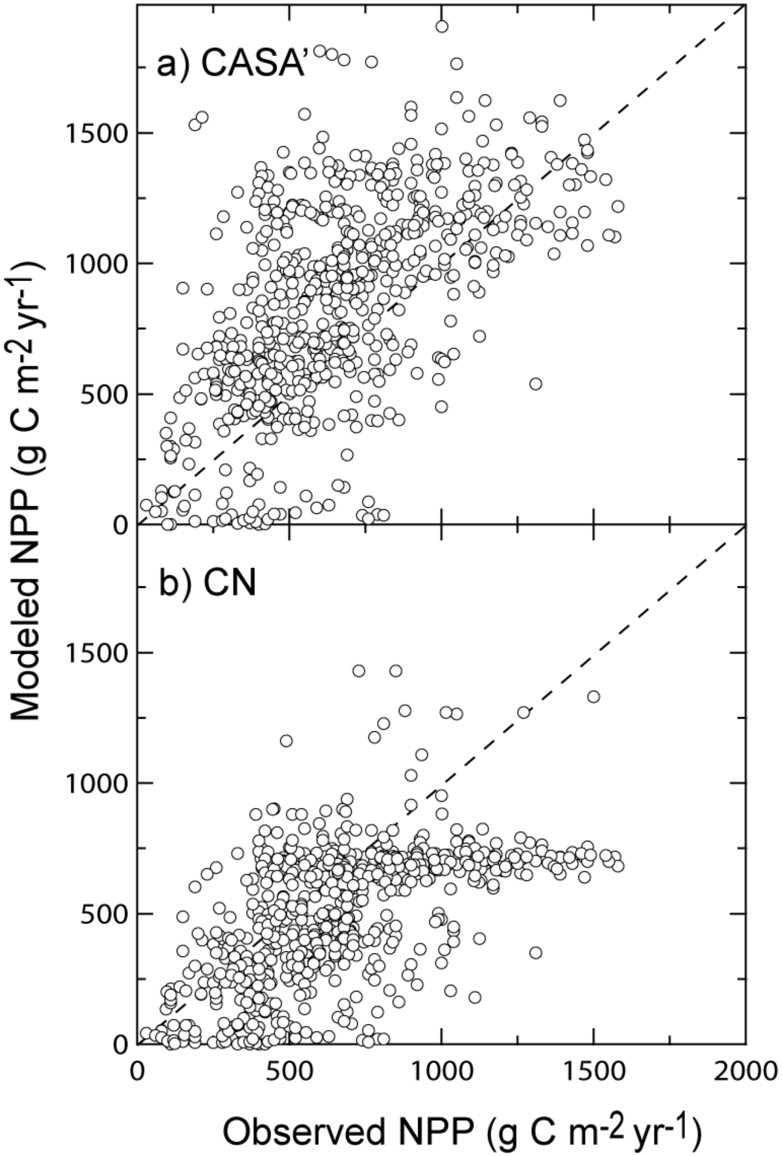
Annual net primary production

Ecosystem Model-Data Intercomparison (EMDI) compilation of observations

- Class A (81 sites)
- Class B (933 sites)

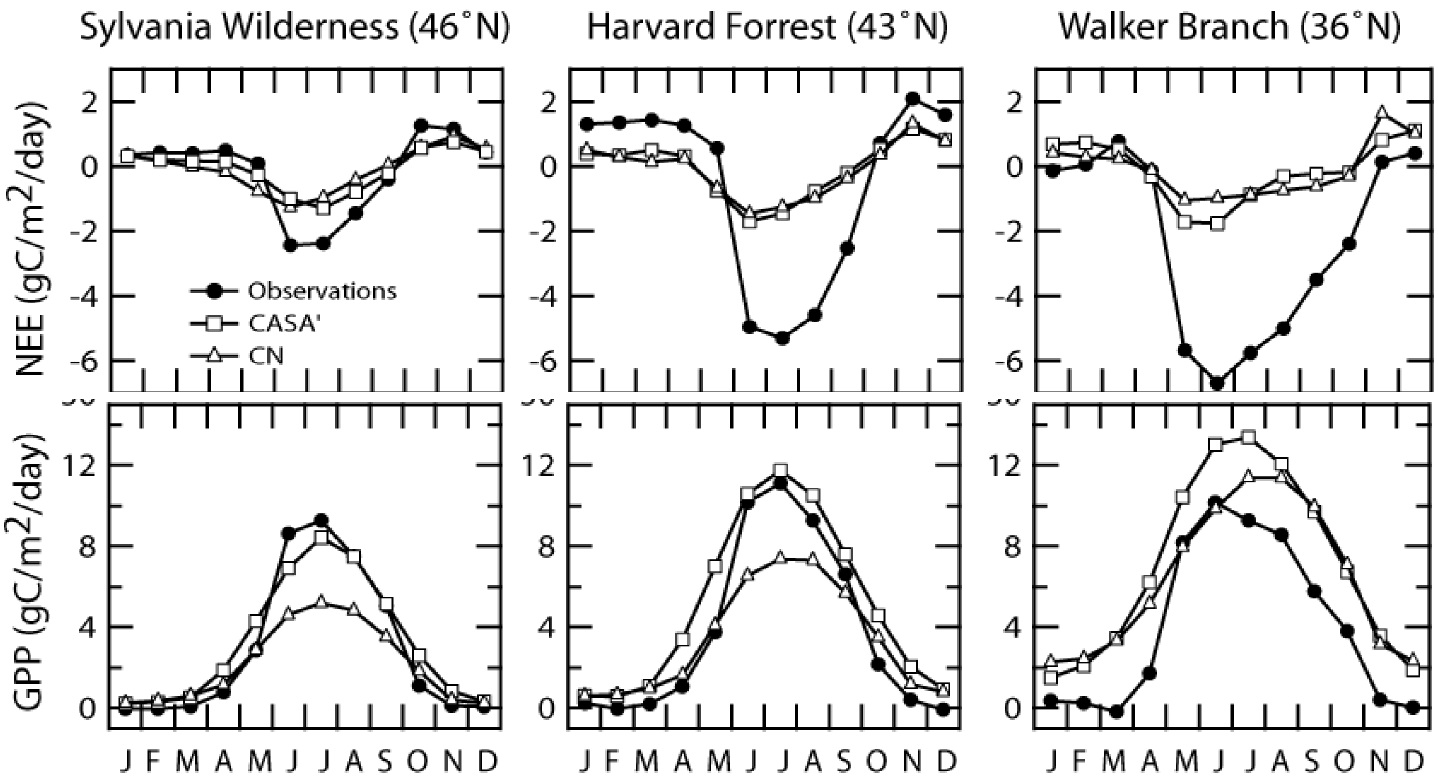
NPP extracted for each model grid cell corresponding to a measurement location



Randerson et al. (2009) GCB, in press

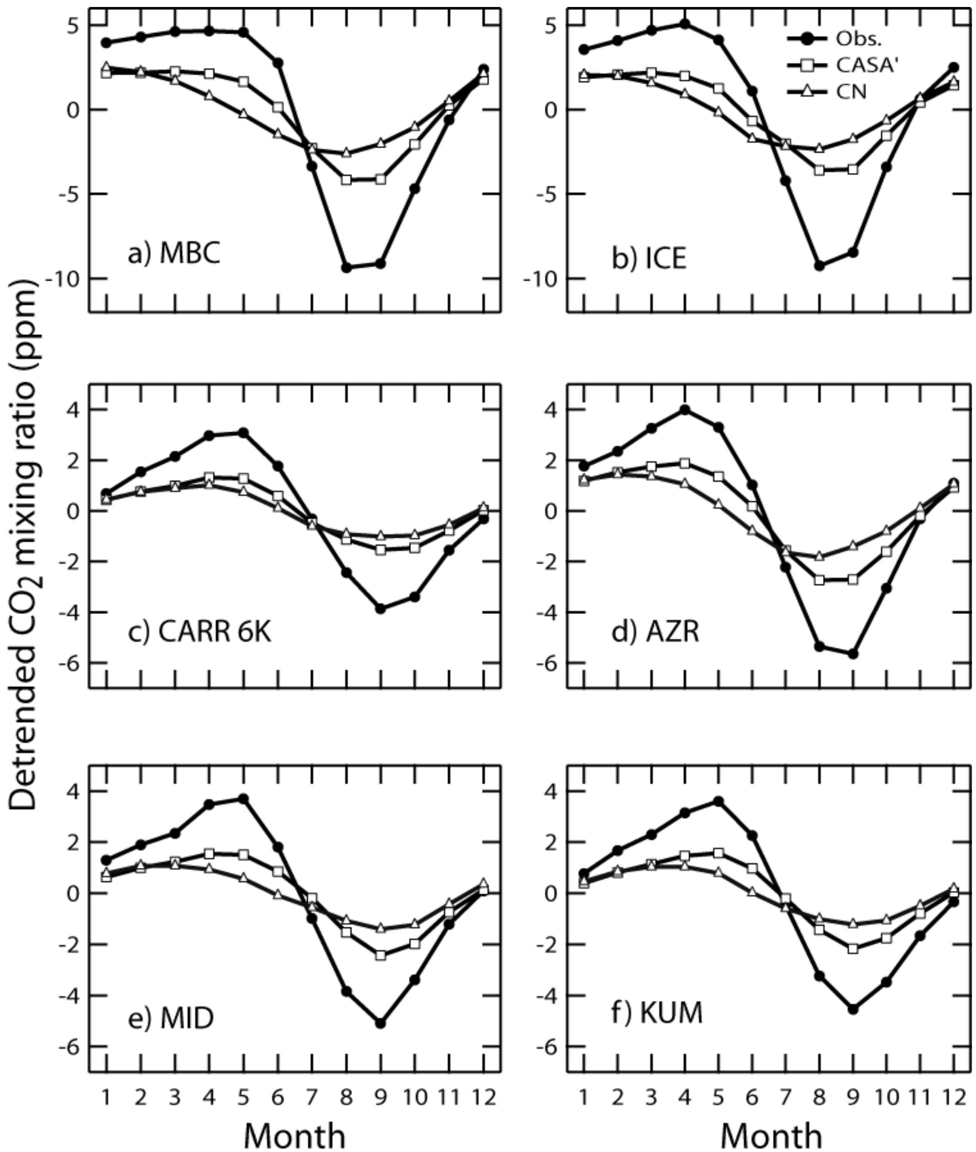
Annual cycle CO_2 fluxes

Ameriflux eddy covariance measurements



Randerson et al. (2009) GCB, in press

Annual cycle atmospheric CO_2



The annual cycle of atmospheric carbon dioxide at a) Mould Bay, Canada (76°N), b) Storhofdi, Iceland (63°N), c) Carr, Colorado (aircraft samples from 6 km masl; 41°N), d) Azores Islands (39°N), e) Sand Island, Midway (28°N), and Kumakahi, Hawaii (20°N)

Randerson et al. (2009) GCB, in press

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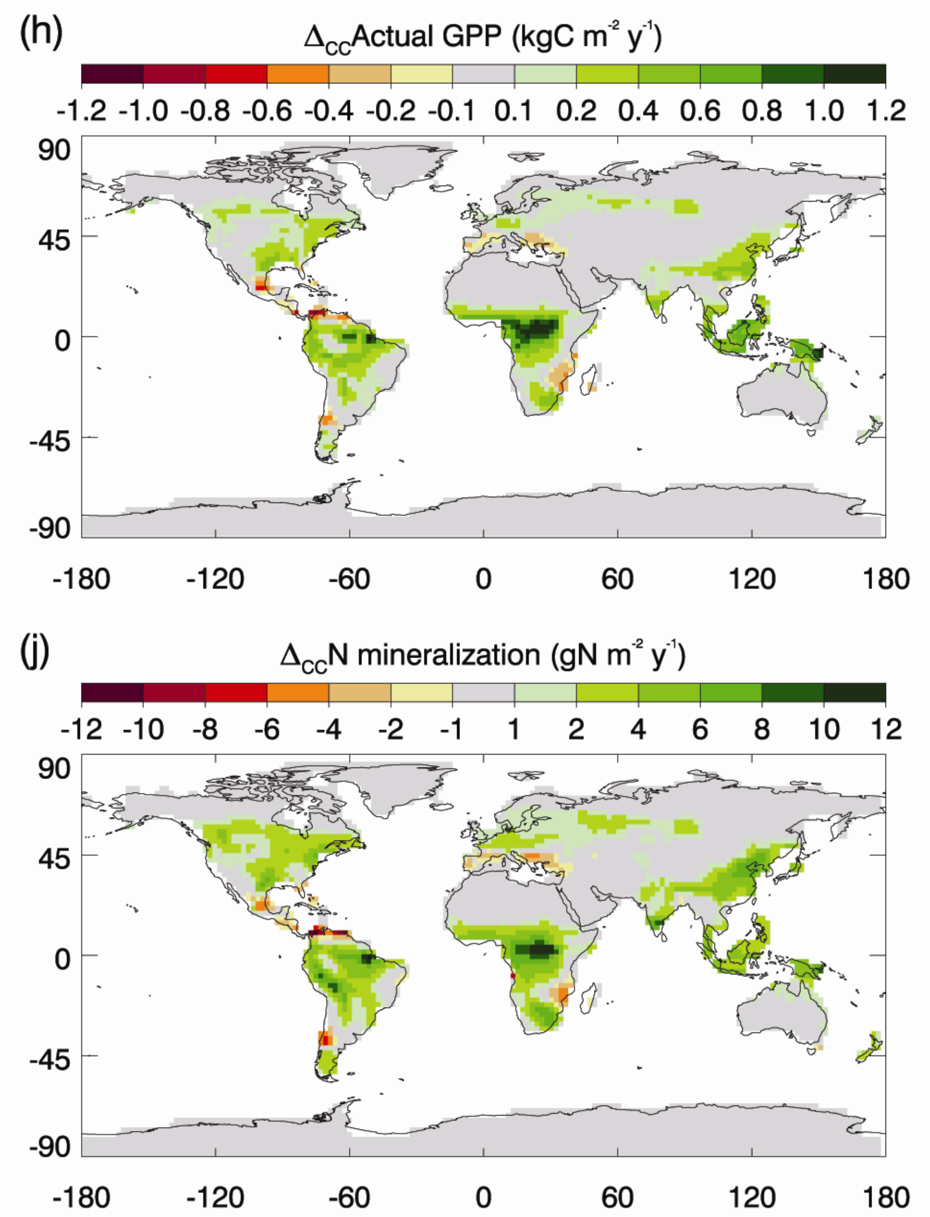
CCSM3.1 carbon cycle-climate feedback



GPP response is highly correlated with gross N mineralization

Climate-driven increase in tropical C stocks

Thornton et al. (2009) Biogeosciences Discuss., 6, 3303-3354

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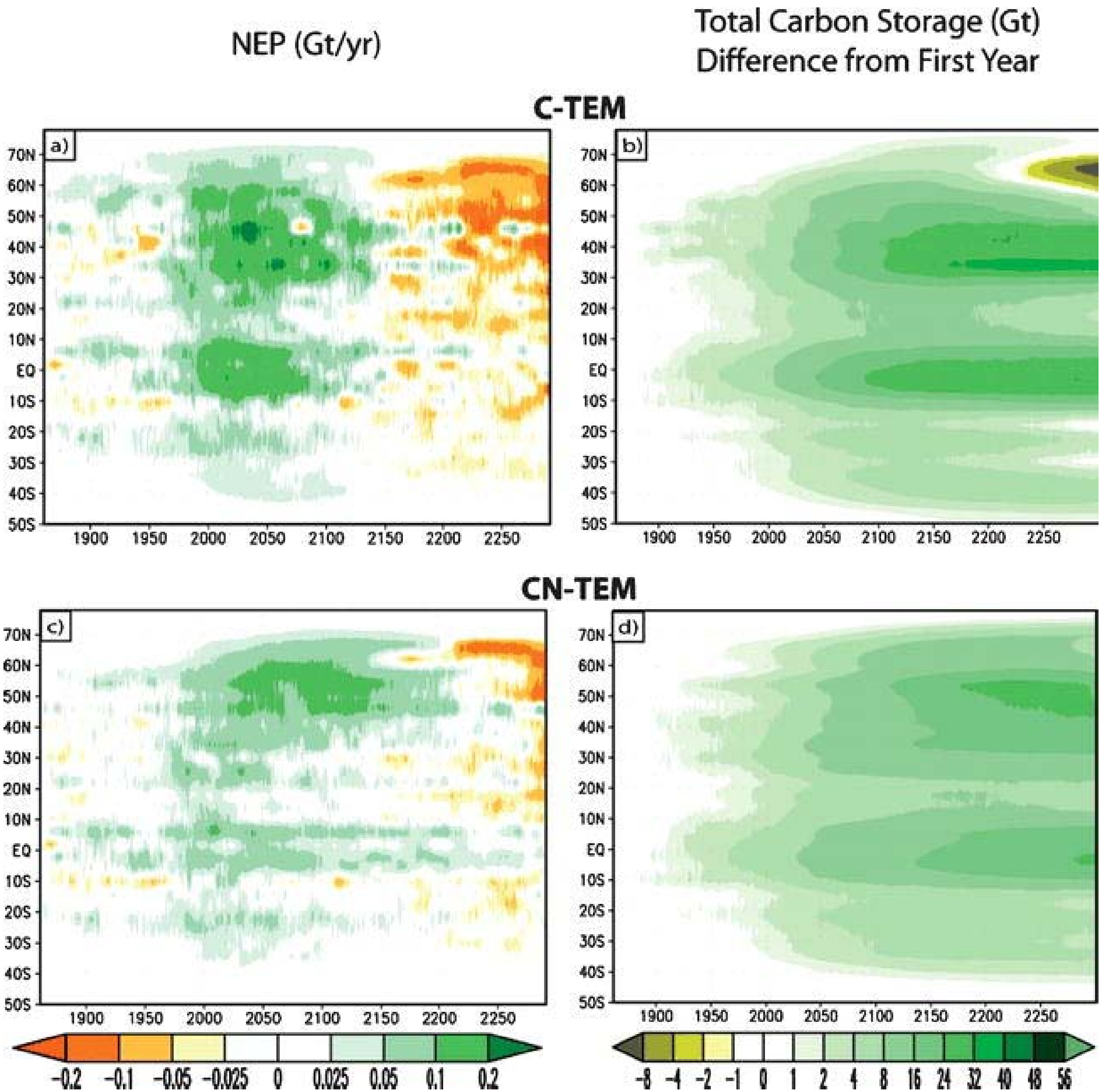
C-N interactions influence location of carbon sinks



C-TEM has larger sinks in the tropics and warmer temperate regions

CN-TEM has larger sinks in boreal and cooler temperate regions

Sokolov et al. (2008) J Climate 21:3776-3796

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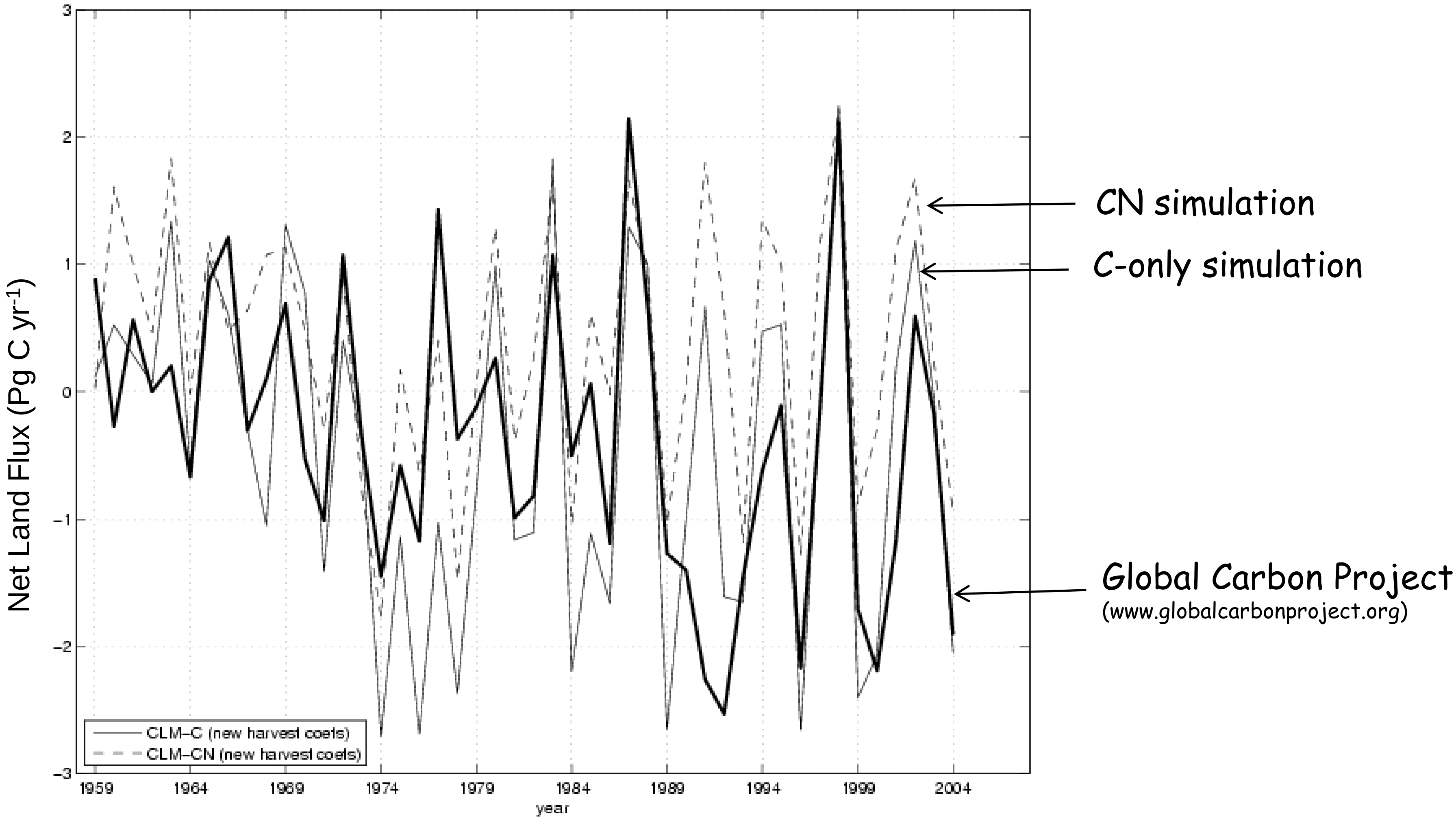
Carbon-only vs. C-N simulations



Carbon-only simulation of late-20th century is indistinguishable from C-N simulation, as compared with Global Carbon Project estimates of land carbon uptake

Net land flux = -Residual flux + Land use

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

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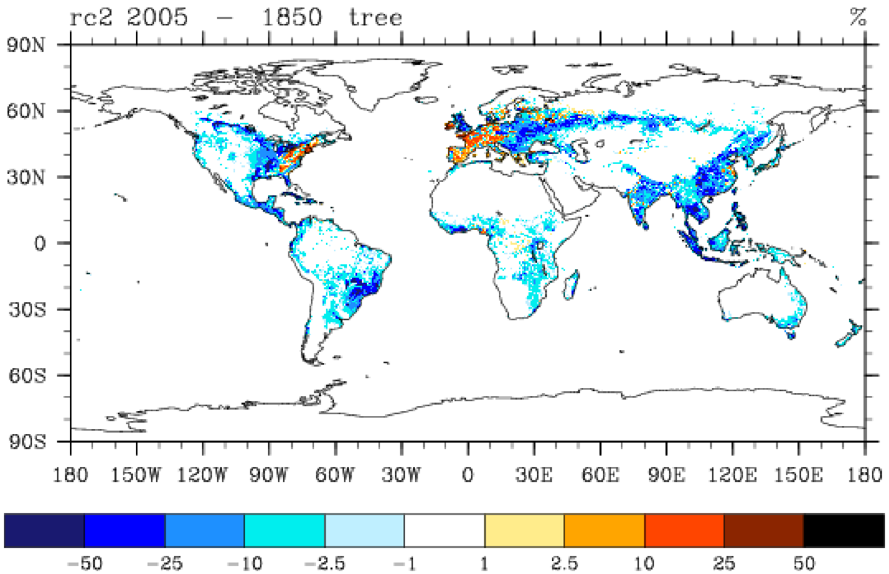
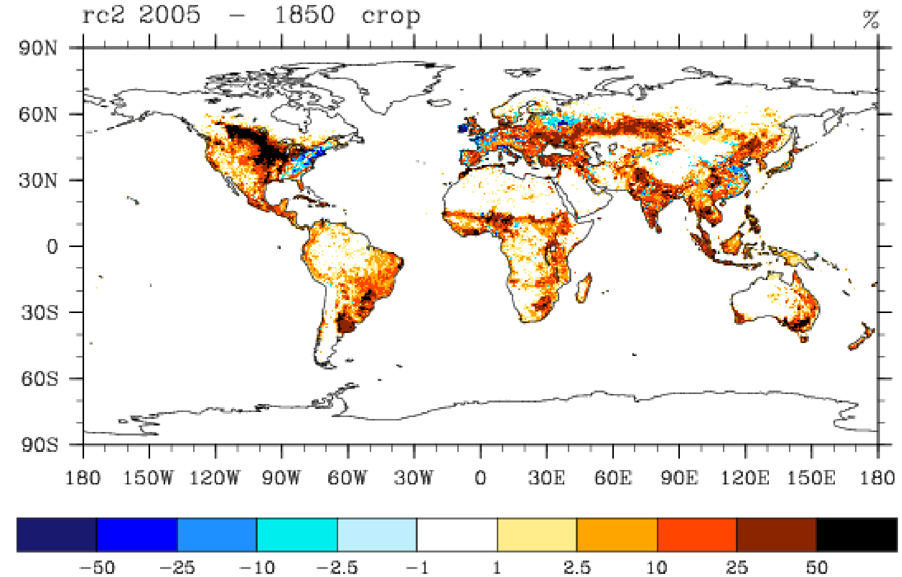
Historical land cover change, 1850 to 2005

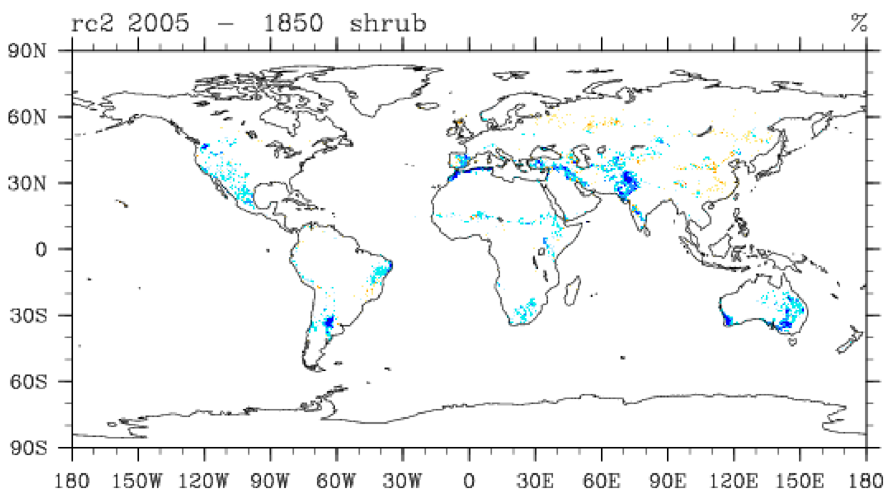
Tree PFTs



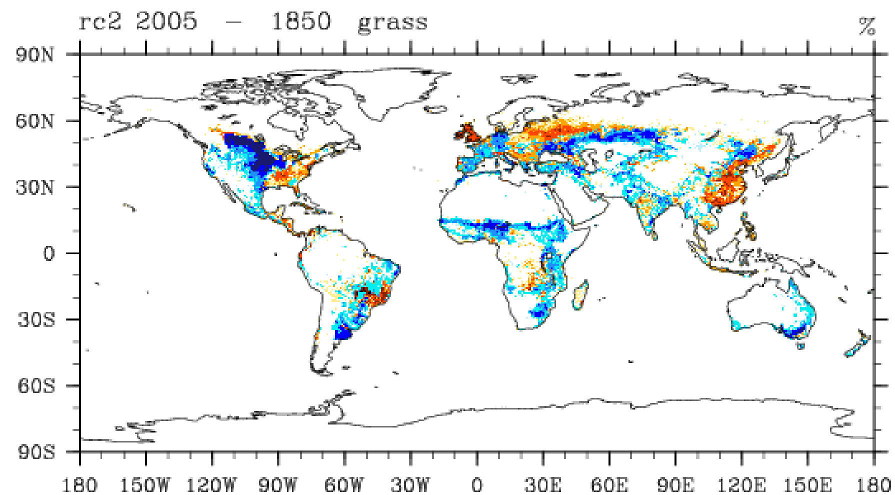
Crop PFT



Shrub PFTs



Grass PFTs



Feddema, Lawerence et al., unpublished

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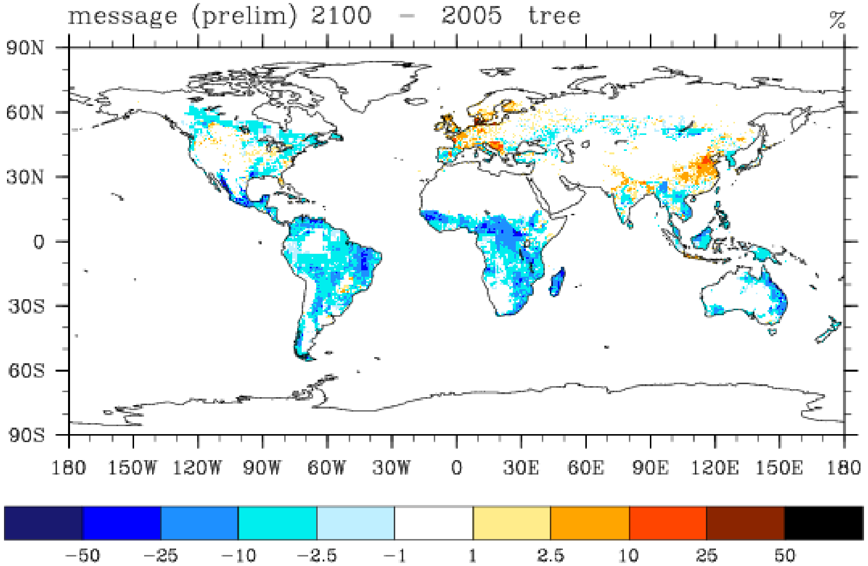
Future land cover change, 2005 to 2100

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



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

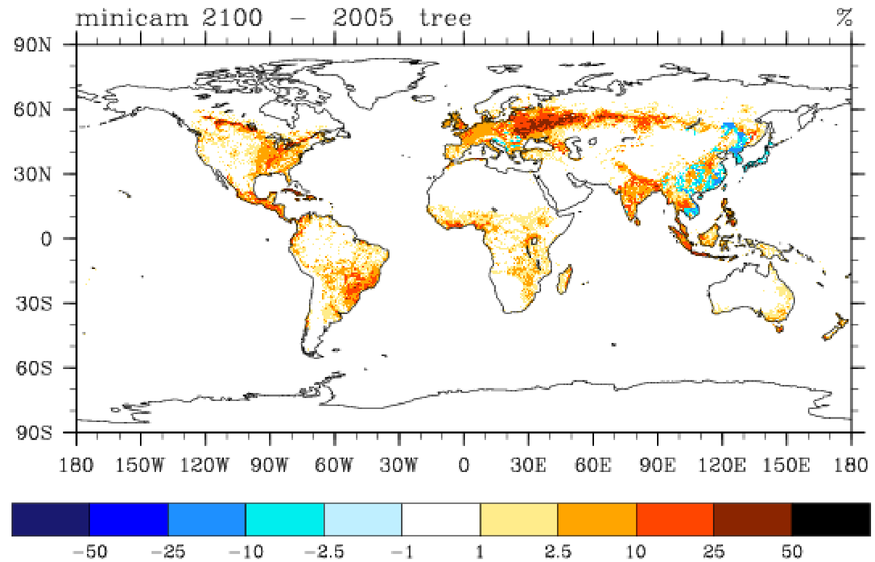
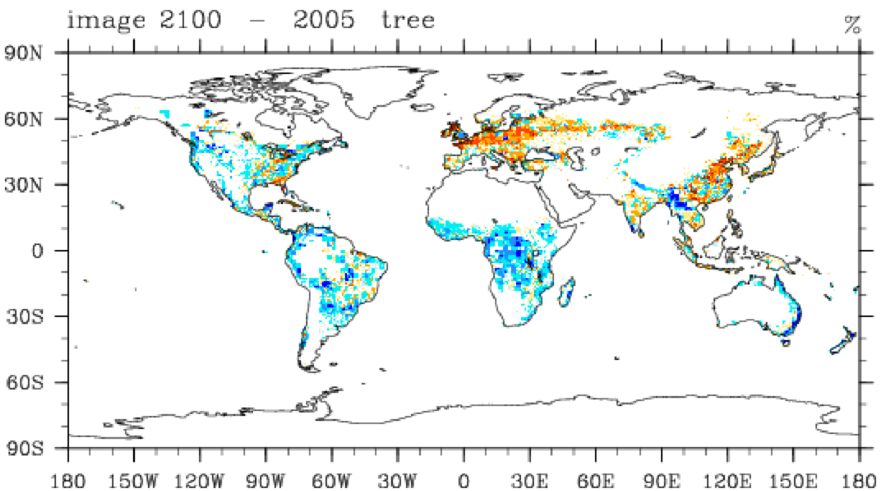


IMAGE (RCP 2.6 W m^{-2})



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

(In development)

Feddema, Lawerence et al., unpublished

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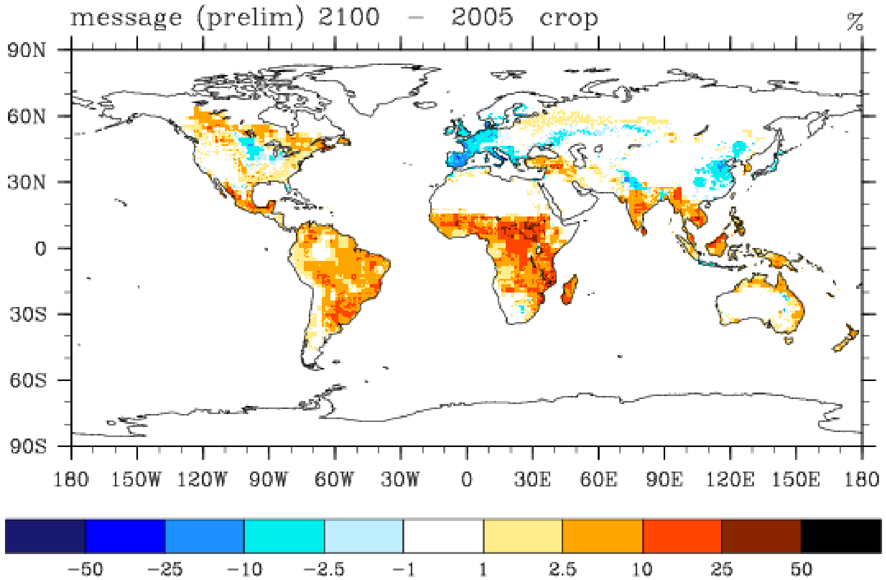
Future land cover change, 2005 to 2100 (RCPs)

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



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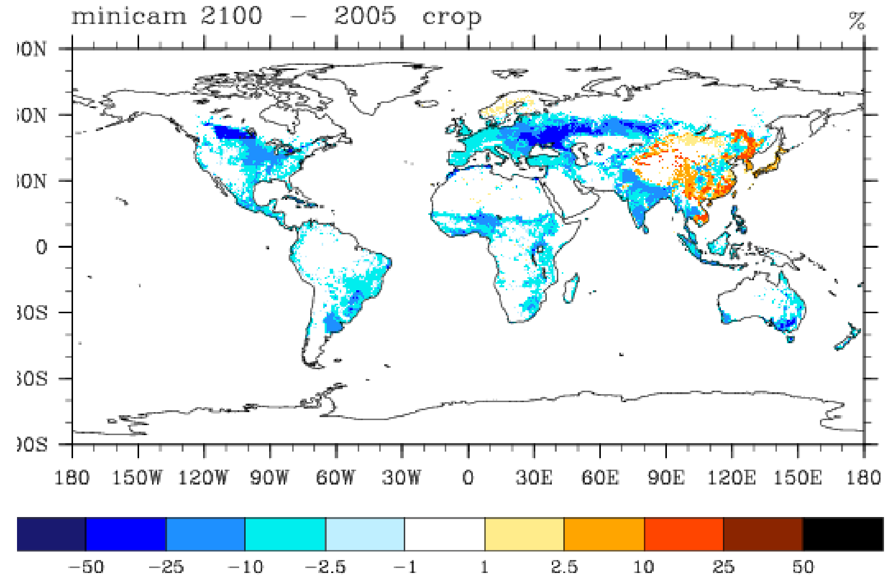
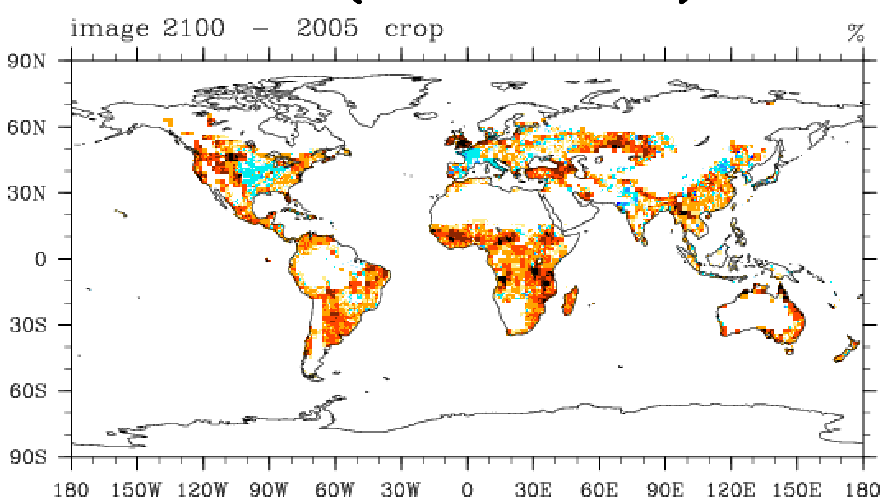


IMAGE (RCP 2.6 W m^{-2})



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

(In development)

Feddema, Lawerence et al., unpublished

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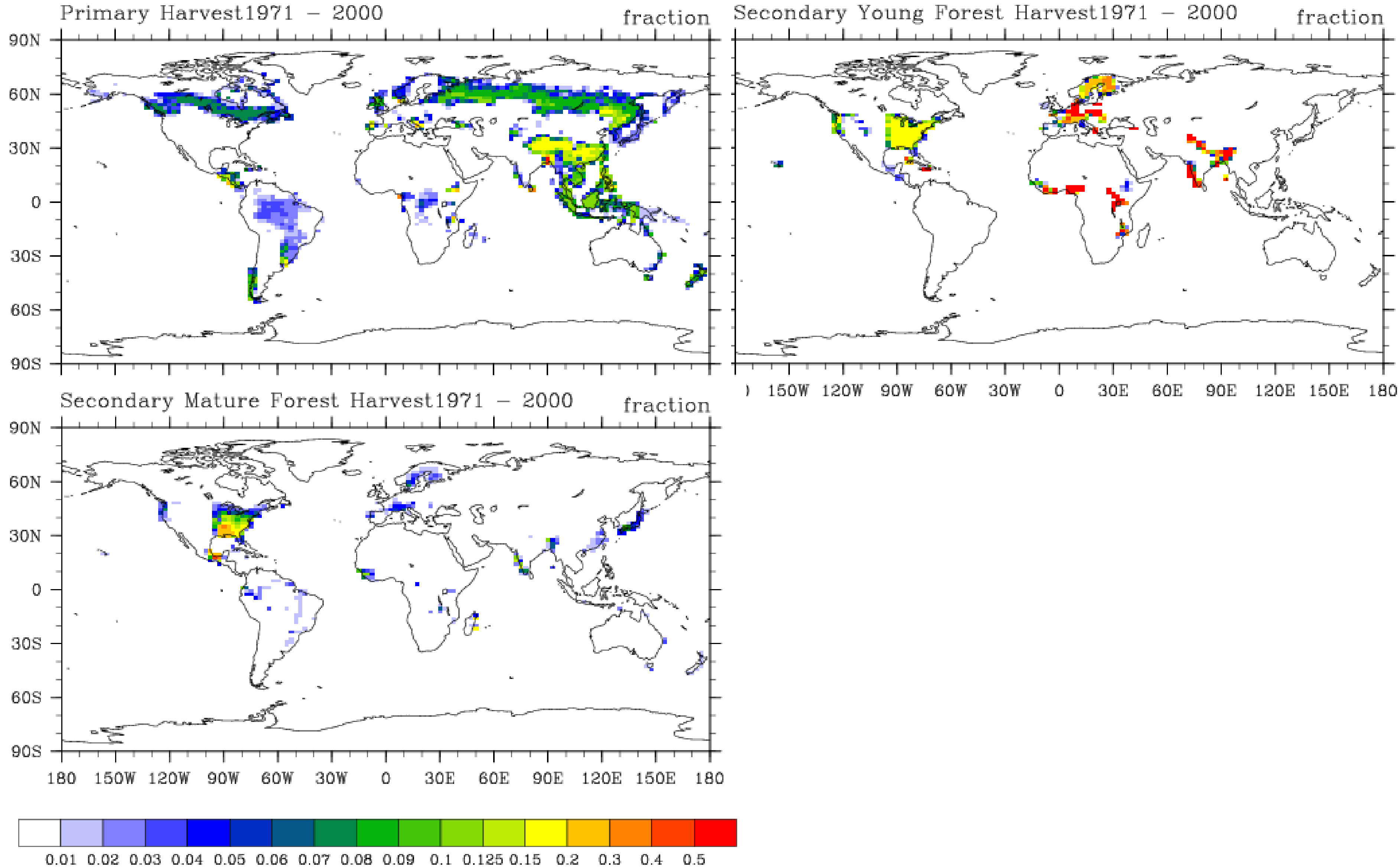
Land use – wood harvest



Feddema, Lawerence et al., unpublished

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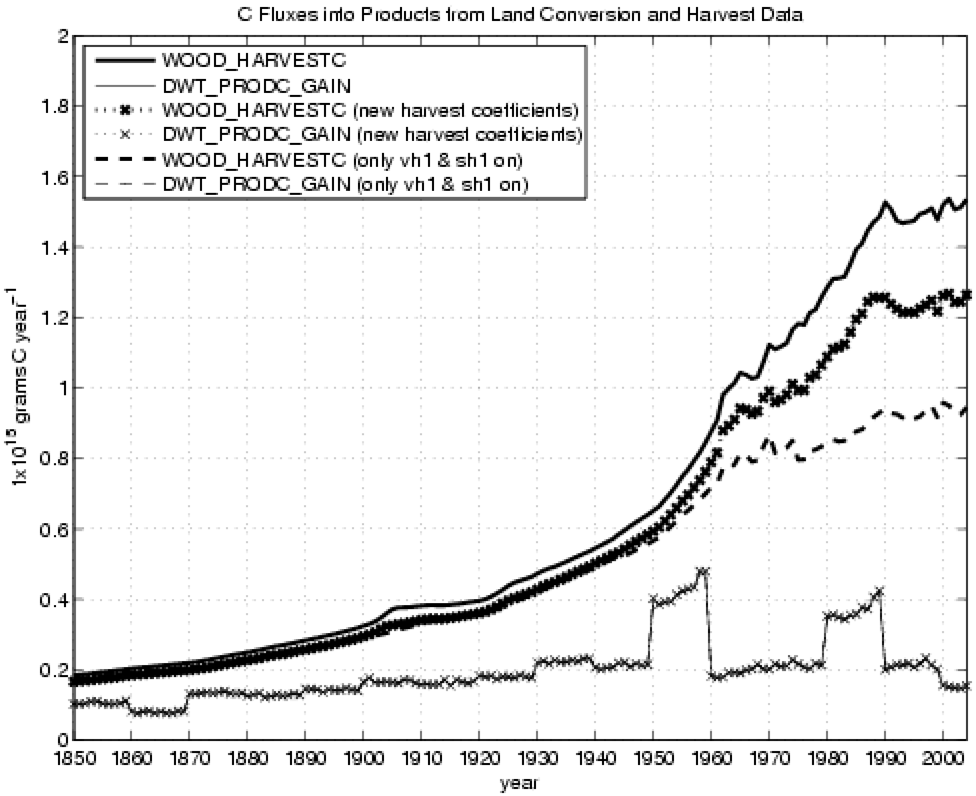
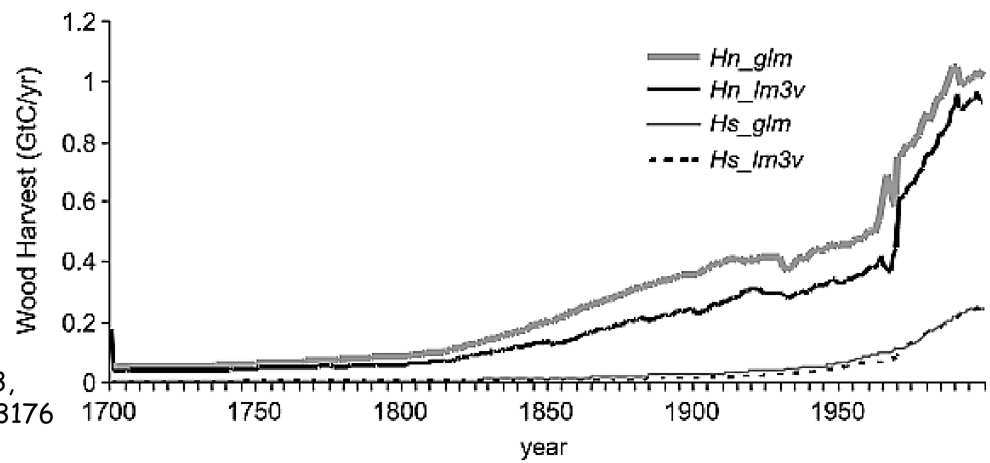
Carbon flux to wood products



Wood harvesting

Land cover change
(e.g., deforestation)

(simulations by Sam Levis)



Shevliakova et al. (2009) GBC, 23,
GB2022, doi:10.1029/2007GB003176

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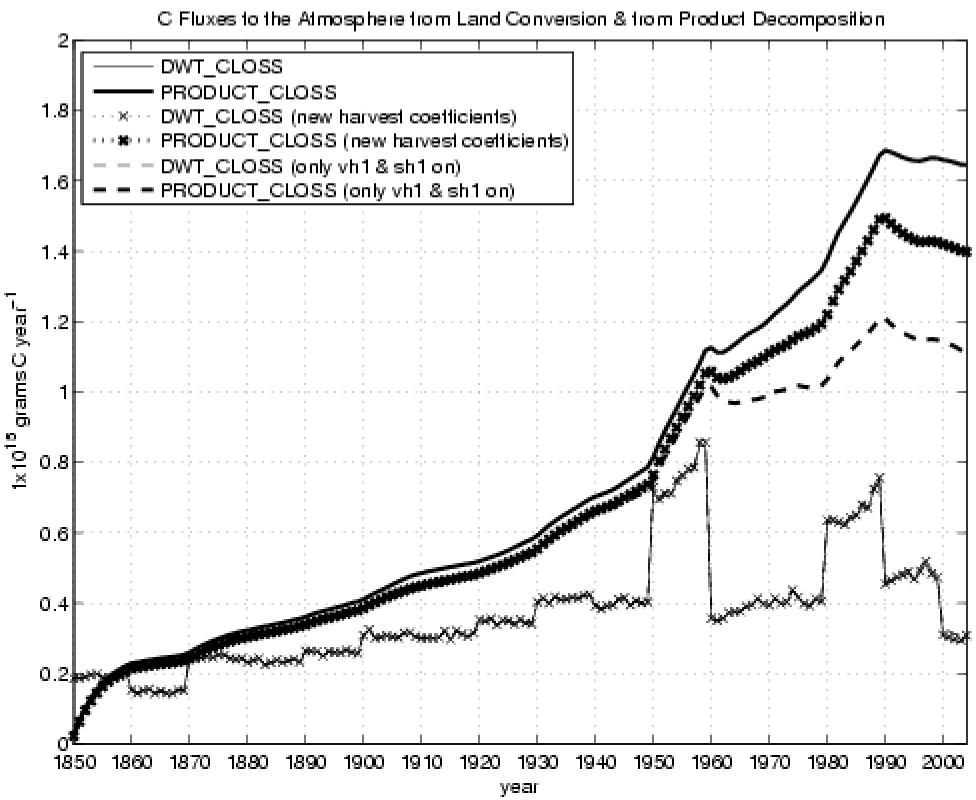
Land use carbon flux to atmosphere



Wood harvesting

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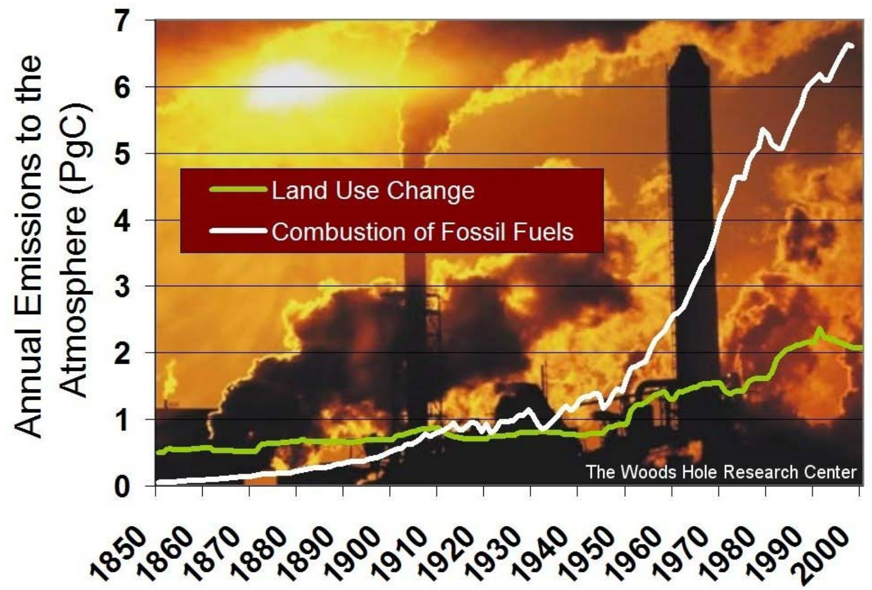
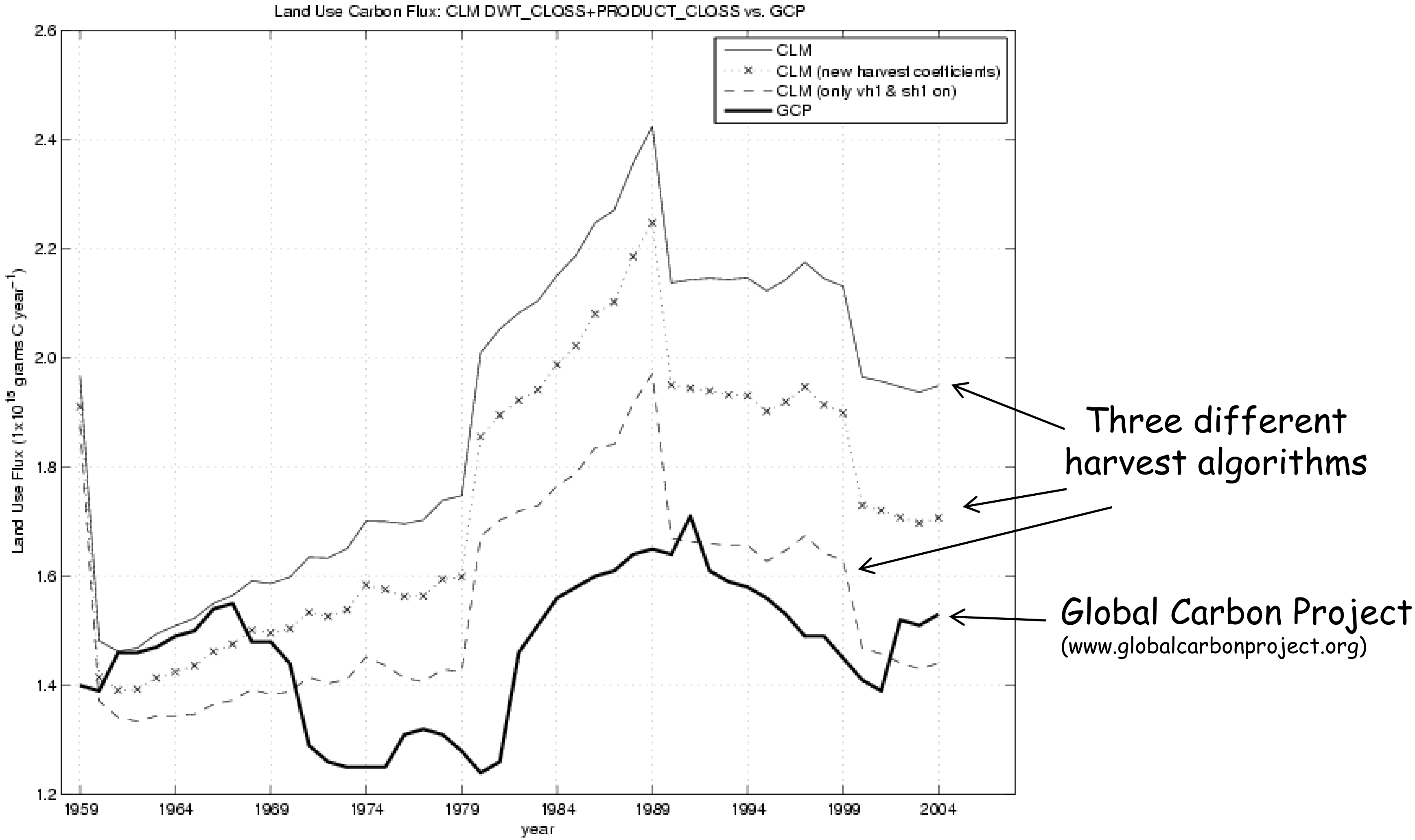


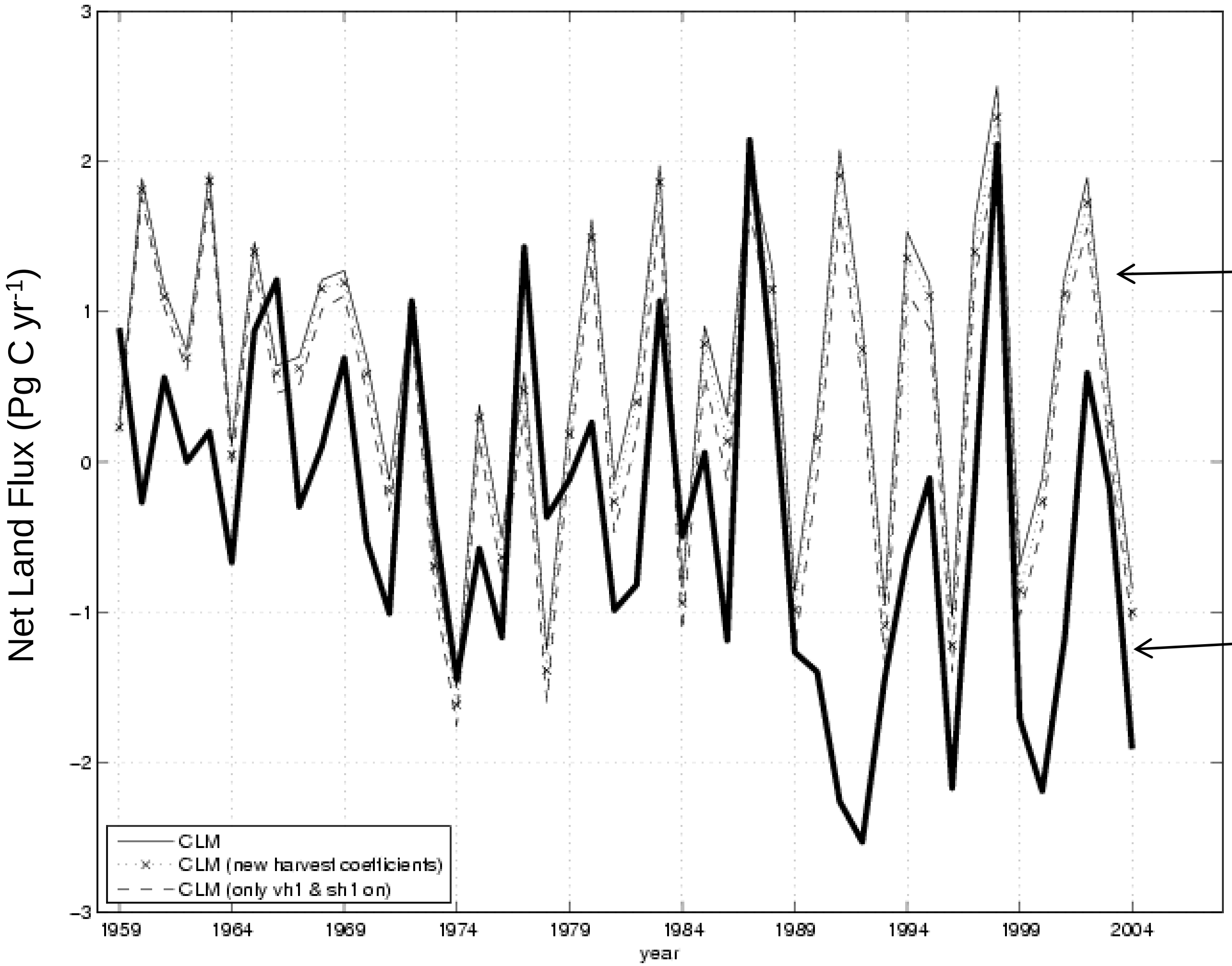
(simulations by Sam Levis)

Land use carbon flux to atmosphere



(simulations by Sam Levis)

Net land carbon flux to atmosphere



Three different harvest algorithms. Increased GPP compensates for increased land use flux

Global Carbon Project
(www.globalcarbonproject.org)

(simulations by Sam Levis)

Net land flux = -Residual flux + Land use

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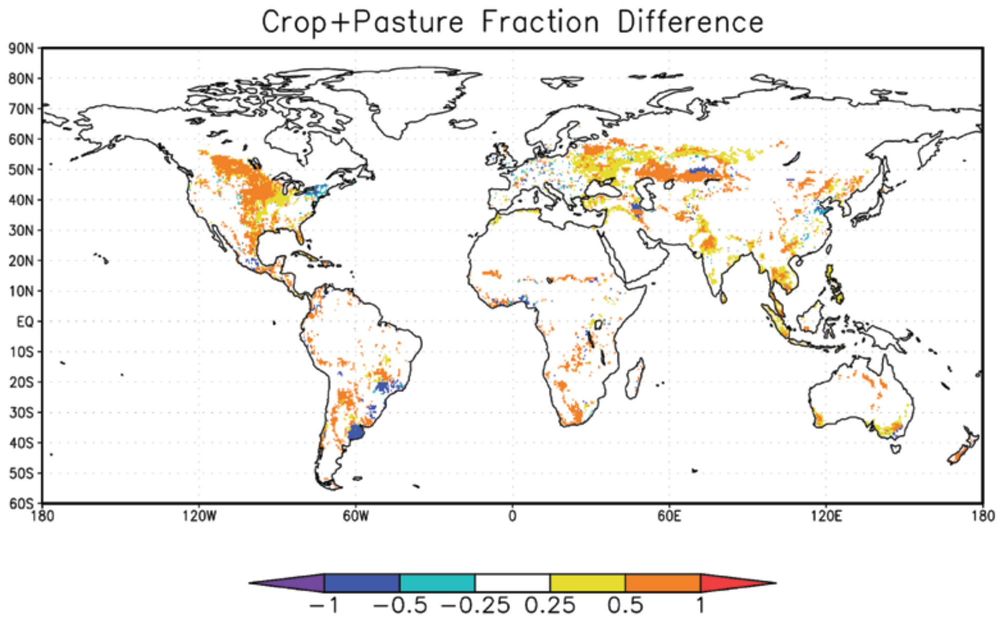
The LUCID intercomparison study



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 et al. (2009) GRL, 36, L14814, 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

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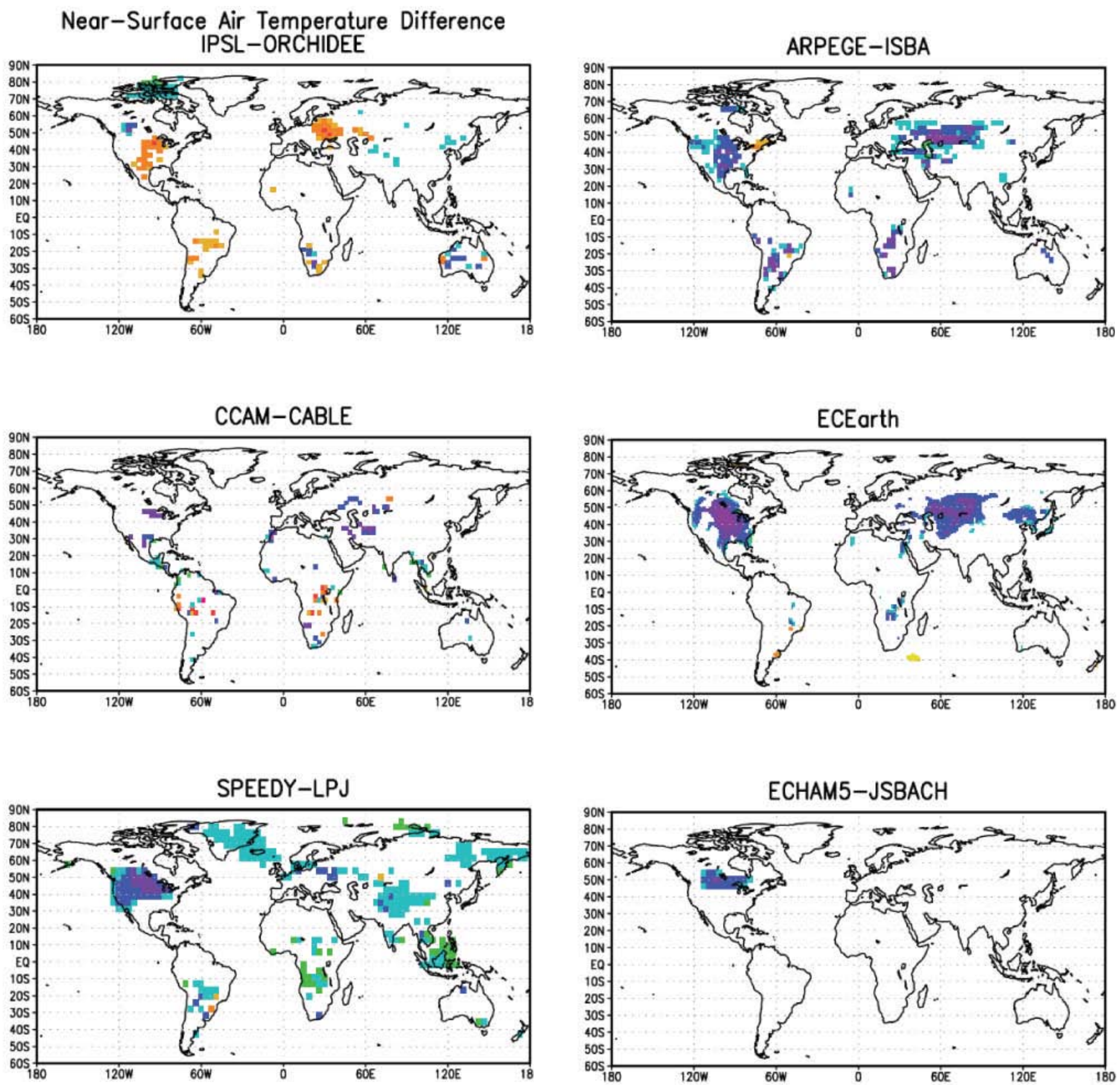
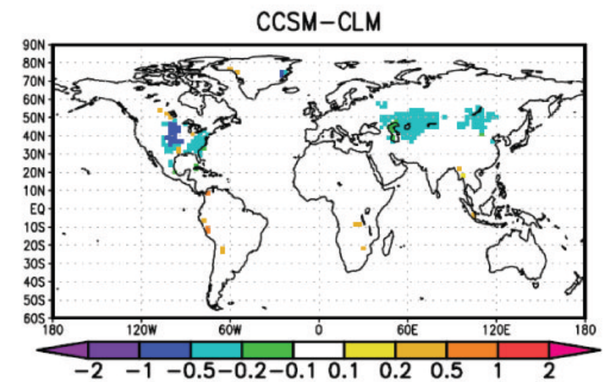
The LUCID intercomparison study





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

Pitman et al. (2009) GRL, 36, L14814, doi:10.1029/2009GL039076

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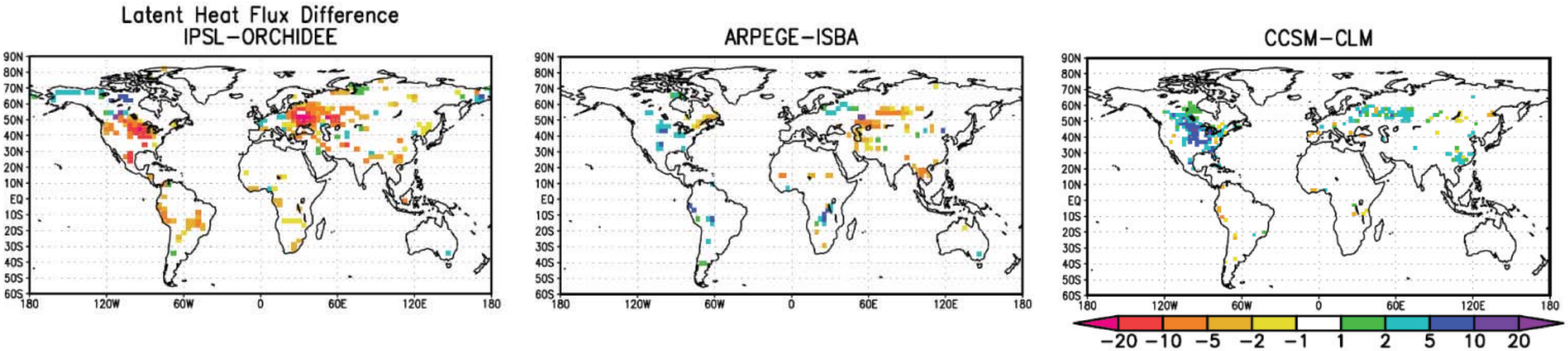
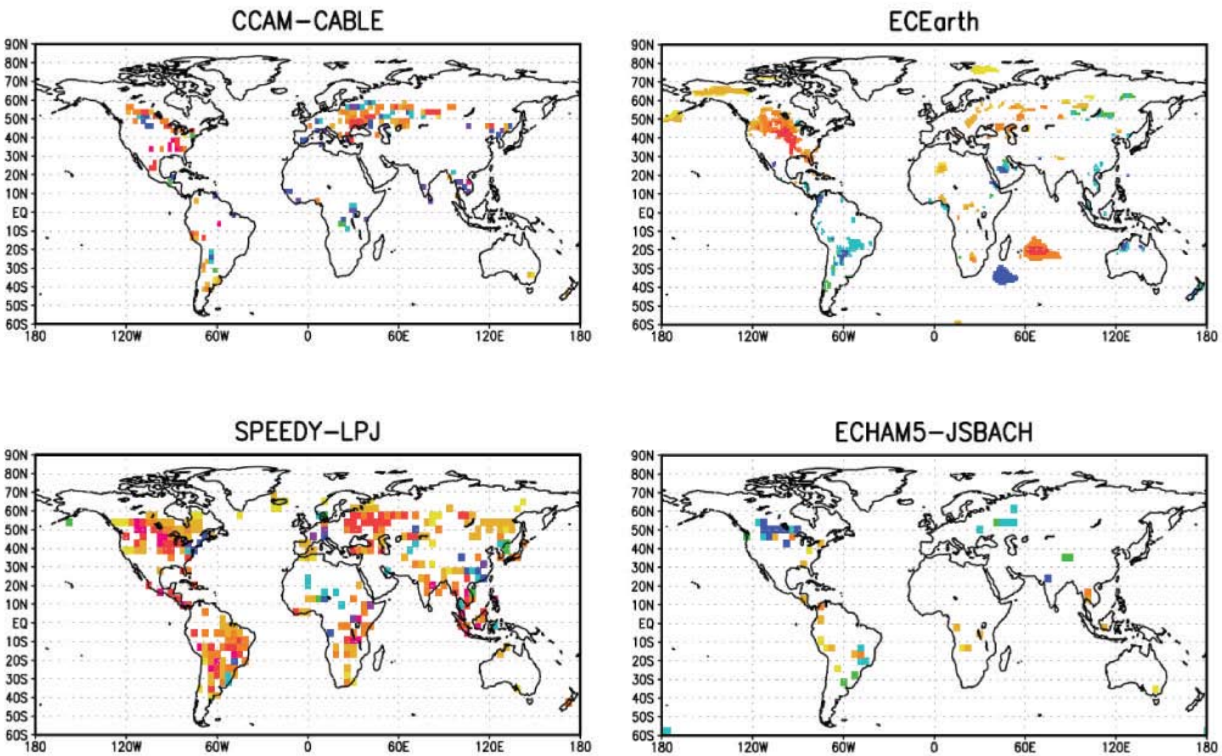
The LUCID intercomparison study





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

Pitman et al. (2009) GRL, 36, L14814, doi:10.1029/2009GL039076

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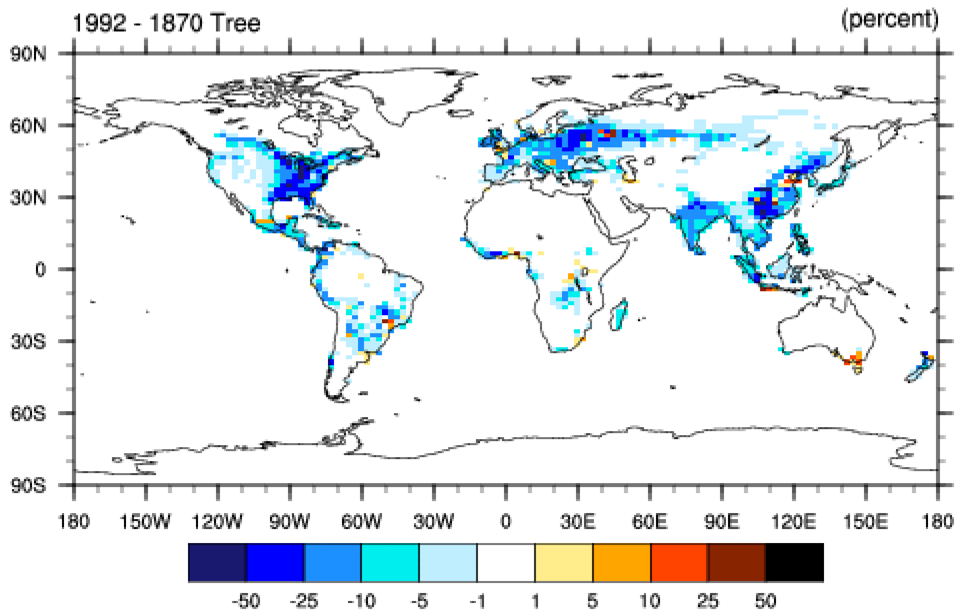
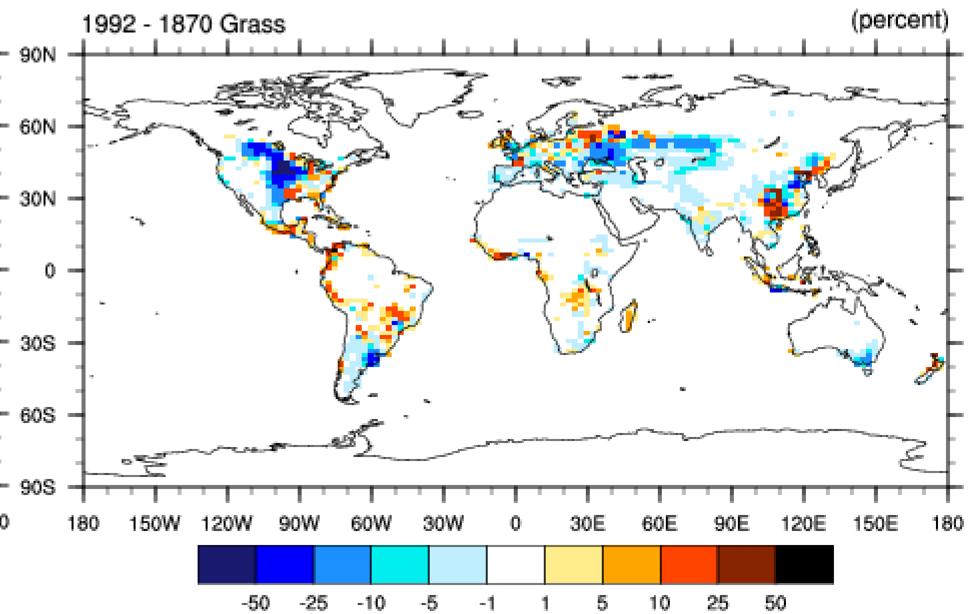
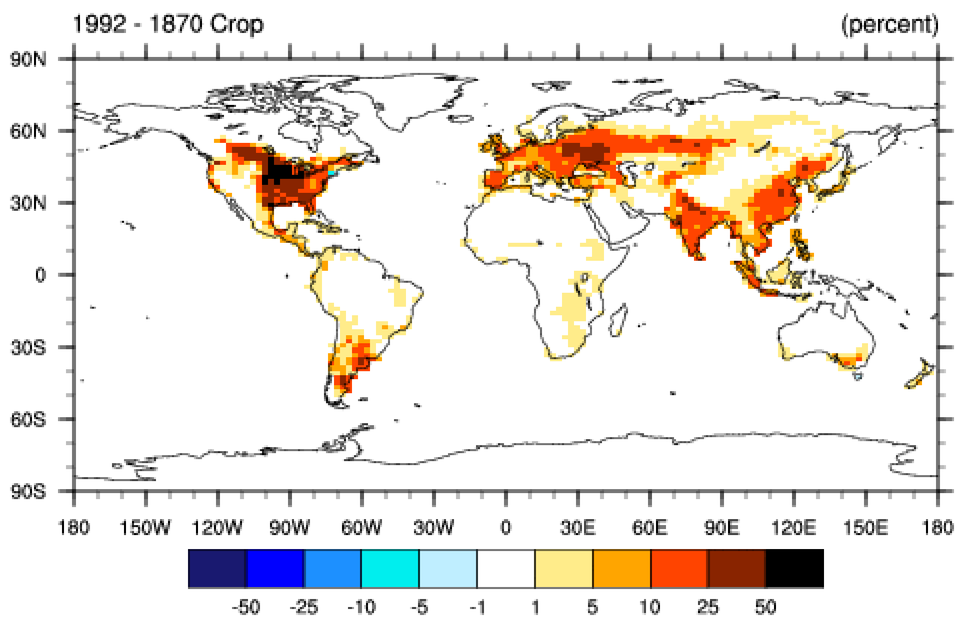
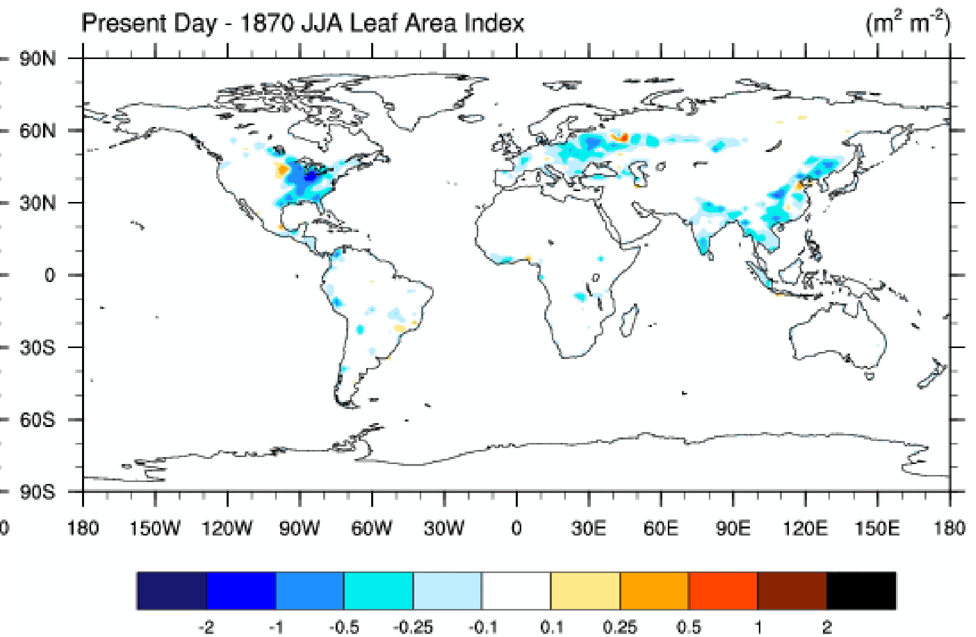
Land cover change, 1870 to 1992









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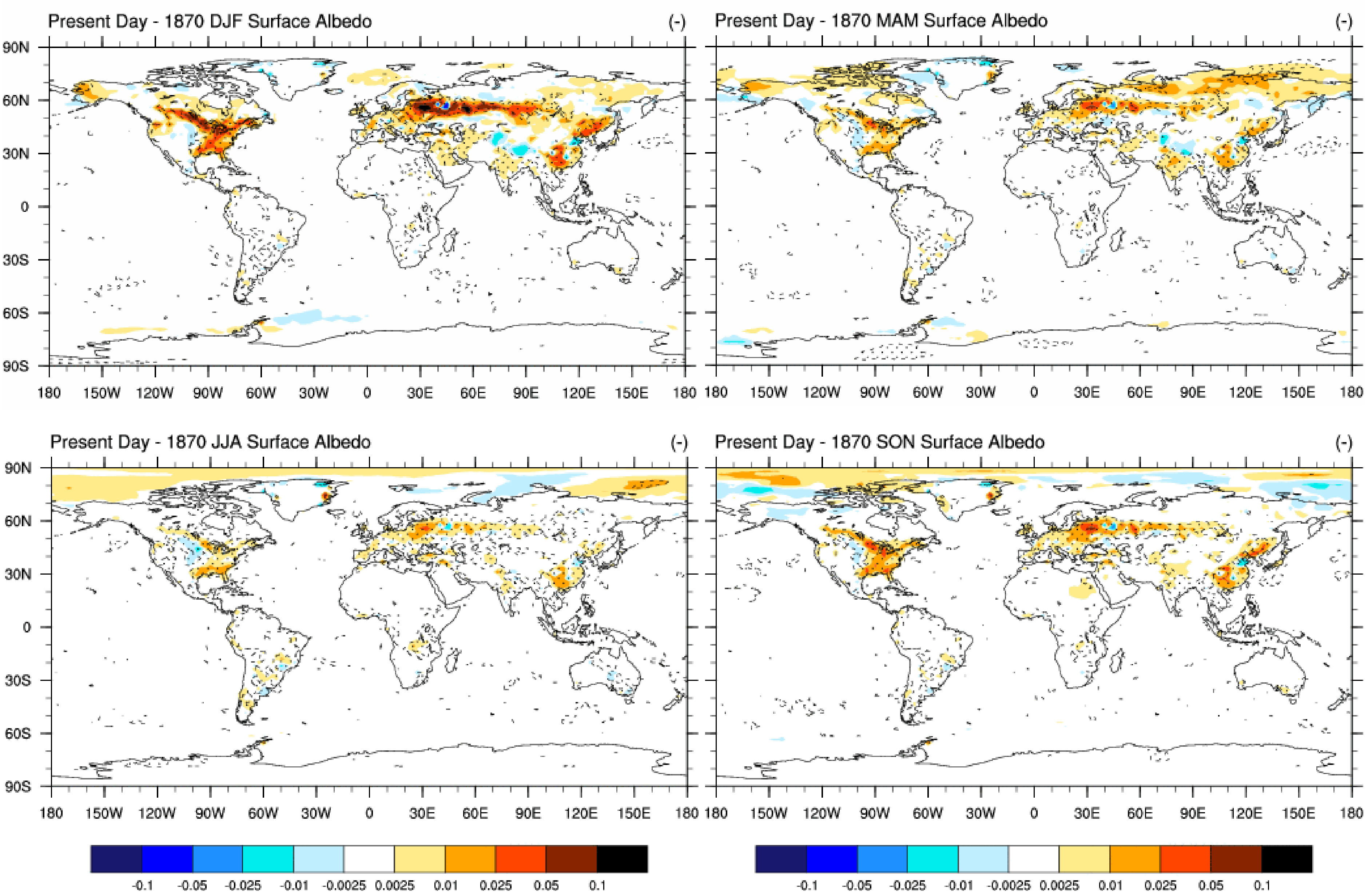
Albedo forcing, 1992-1870



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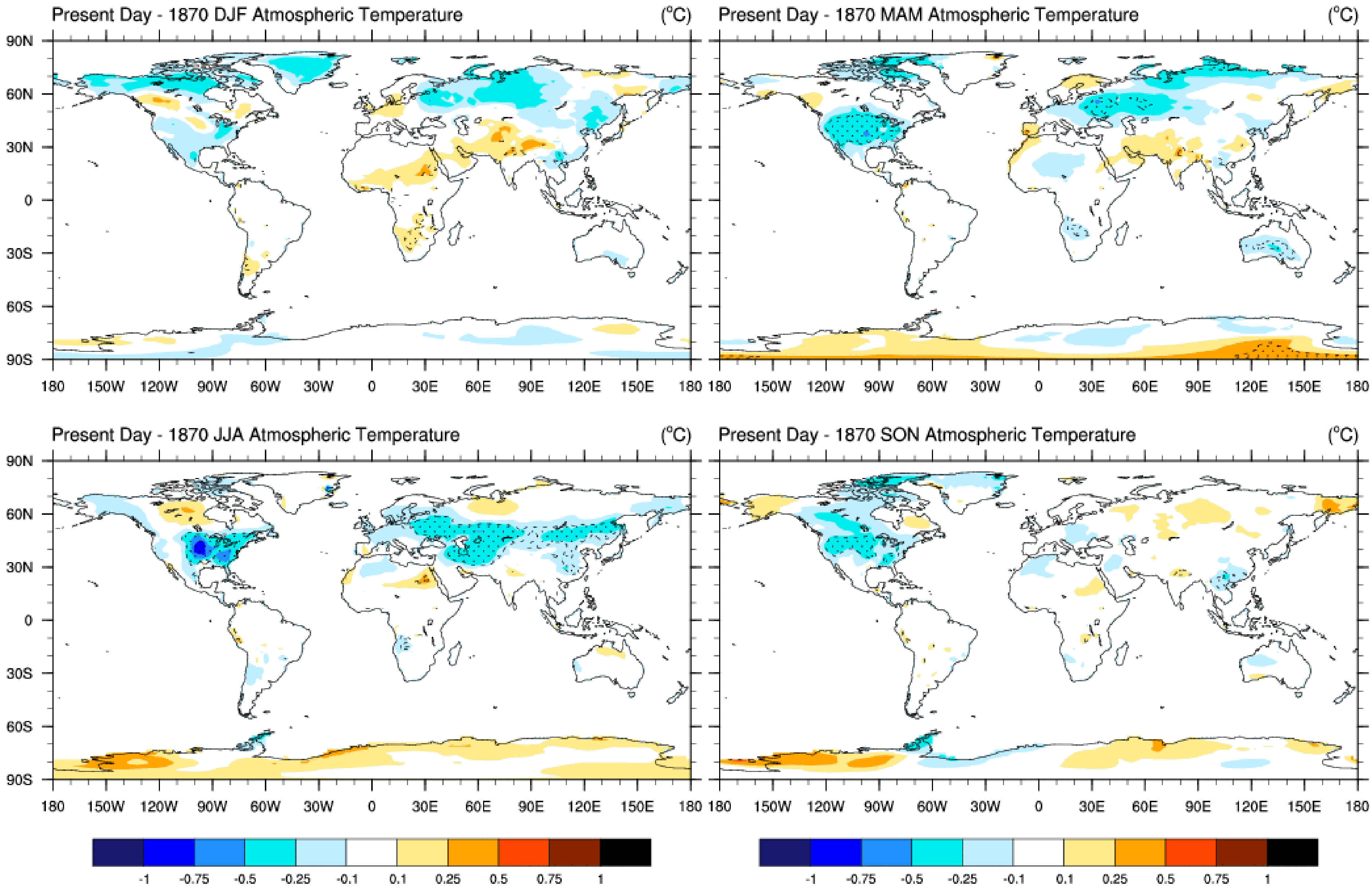
Near-surface temperature, 1992-1870



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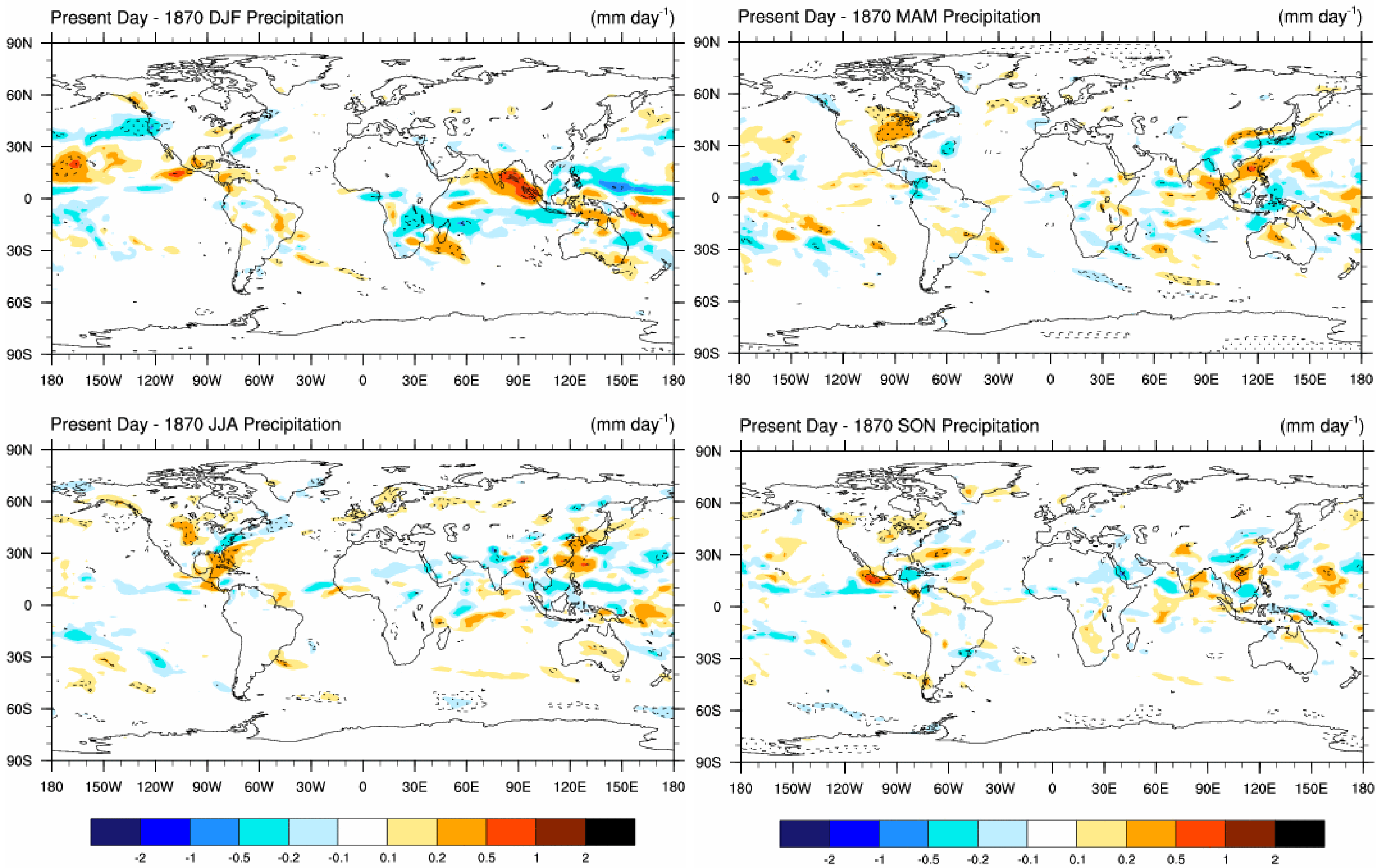
Precipitation, 1992-1870



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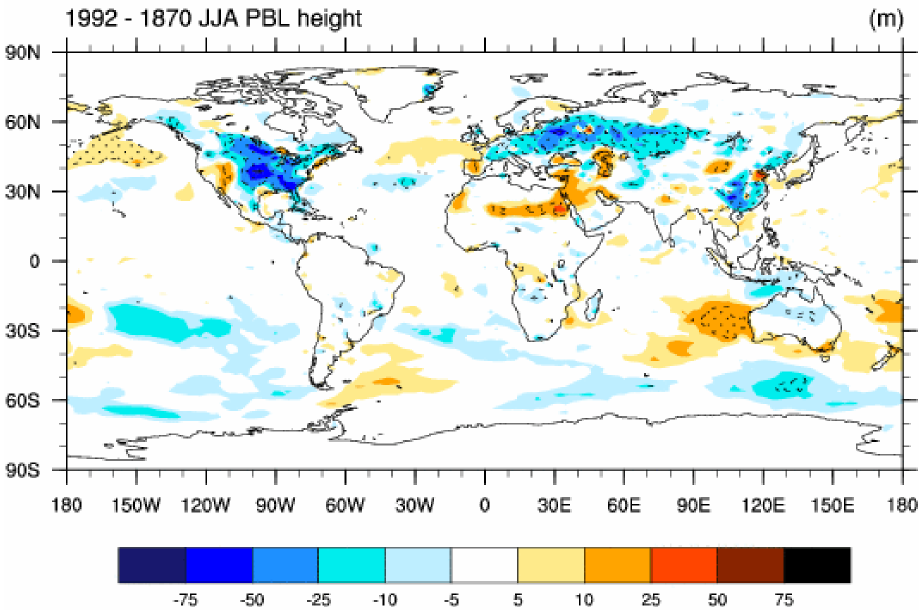
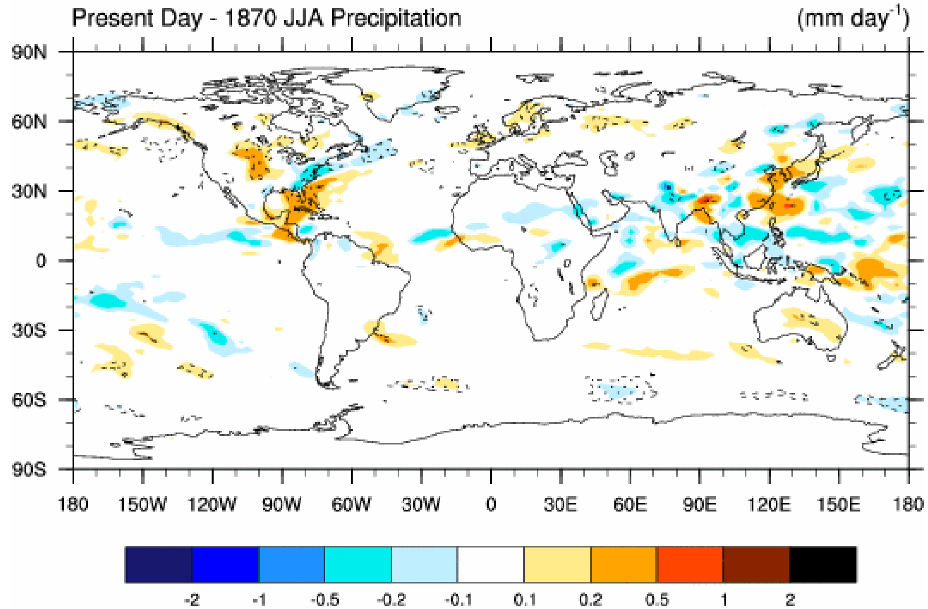
Atmospheric feedbacks

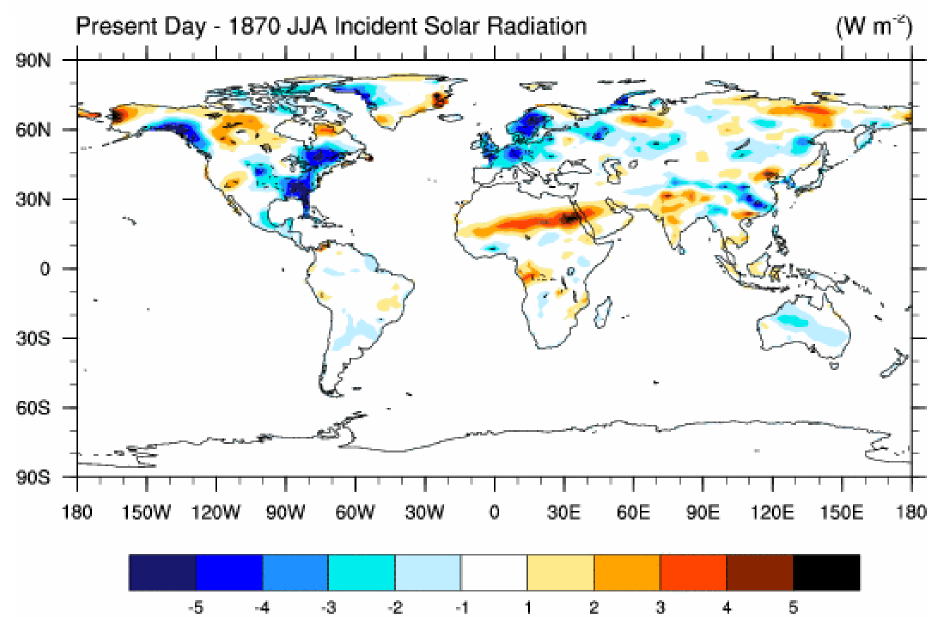




Climate models simulate the large-scale response and include feedbacks with the atmosphere:

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

Flux towers measure local response



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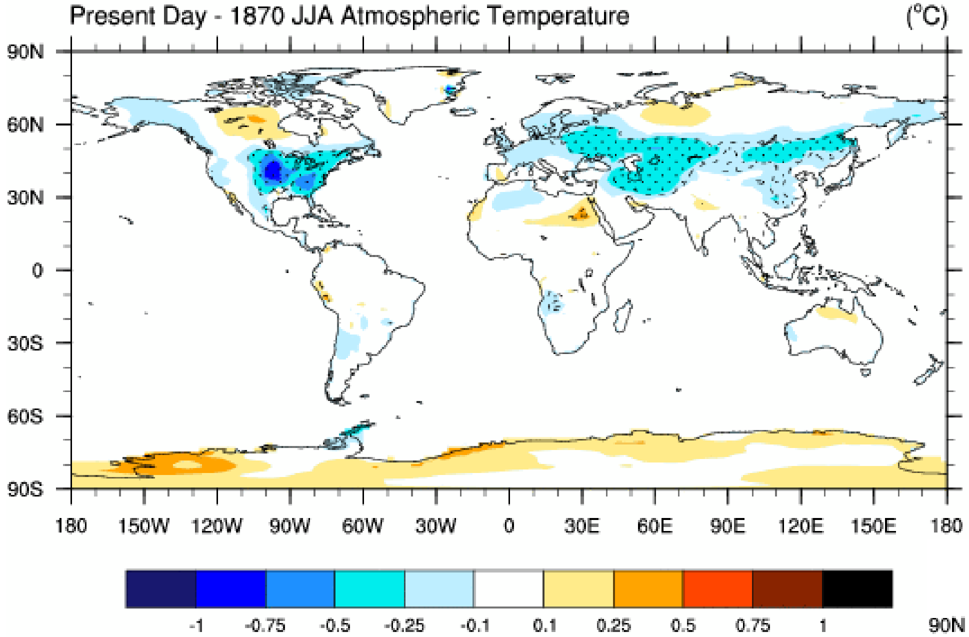
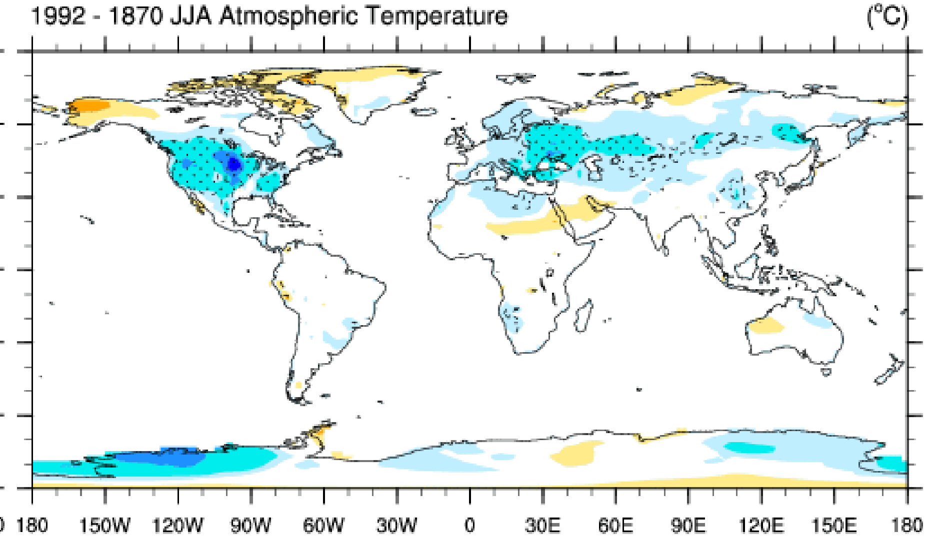
Land cover change offsets greenhouse gas warming

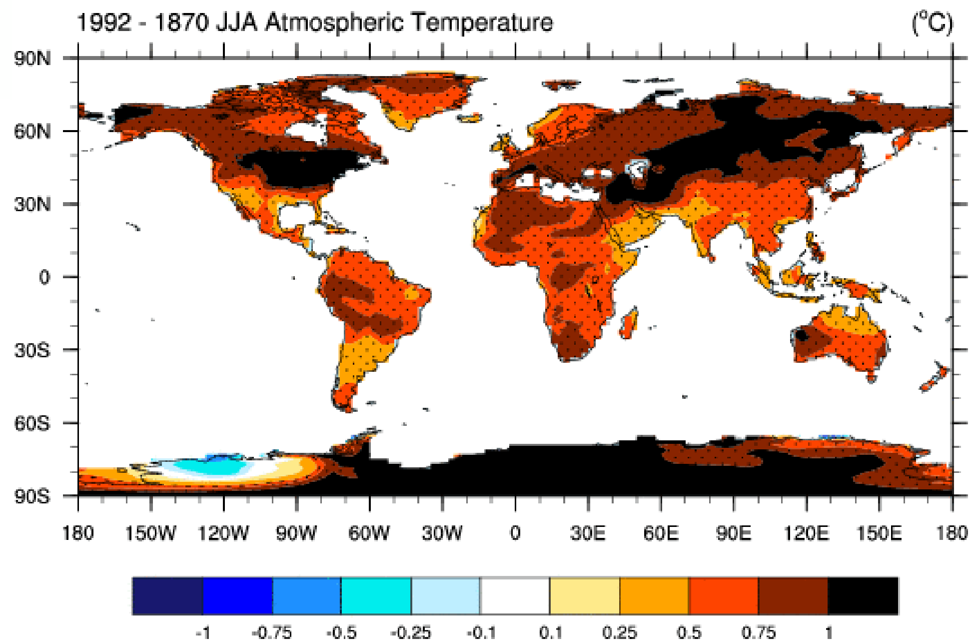
Land cover change with CO_2 = 375 ppm (1992)



Land cover change with CO_2 = 280 ppm (1870)



CO_2 forcing with 1870 land cover



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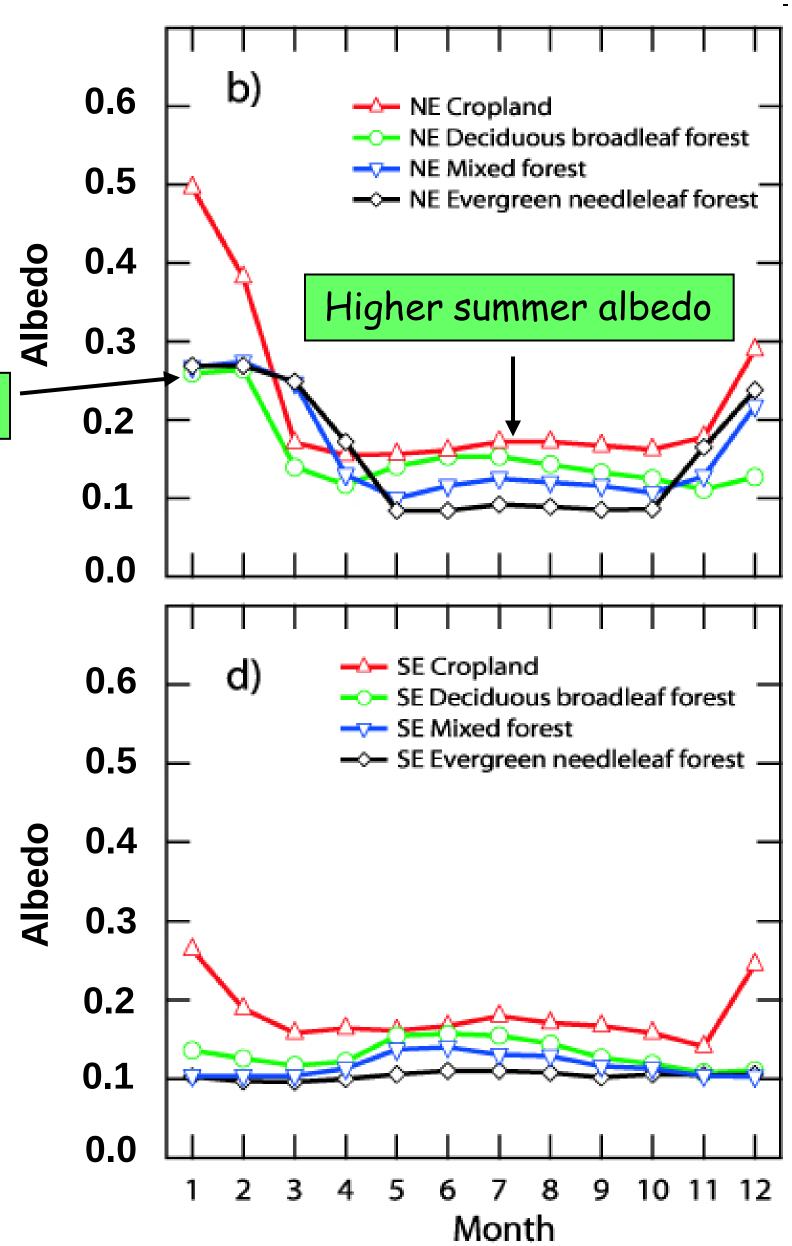
Cropland increases surface albedo

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)

Forest masking



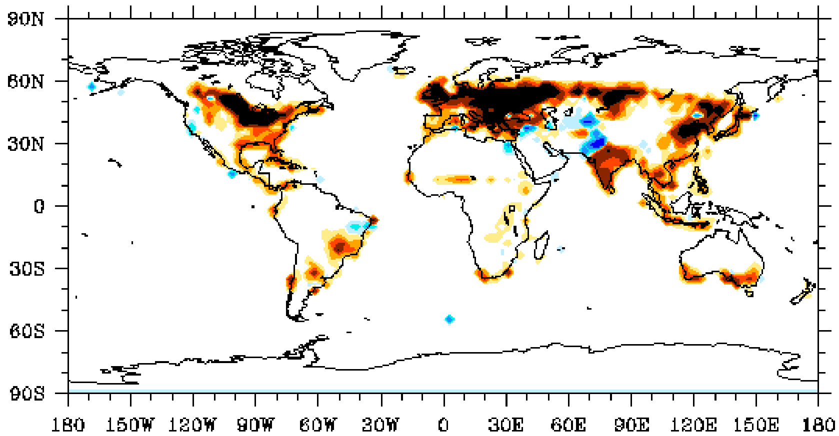
Cropland has a high winter and summer albedo compared with forest

National Center for
Atmospheric Research
Boulder, Colorado

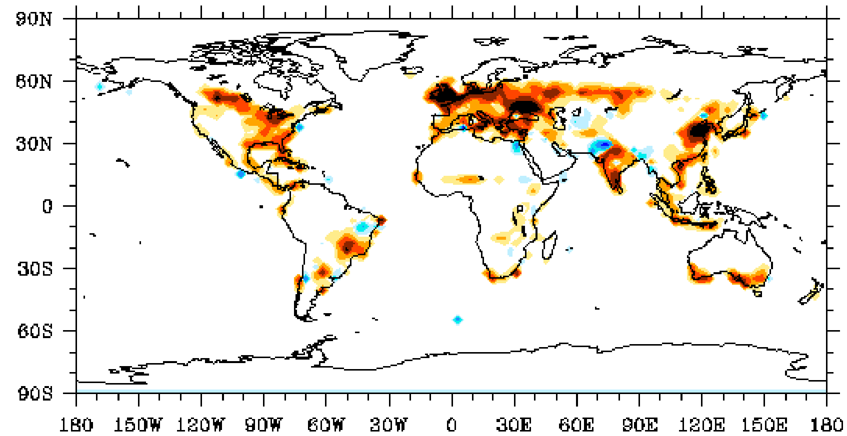
CLM albedo land use forcing (present-day minus potential vegetation)

Expected (MODIS)

DJF

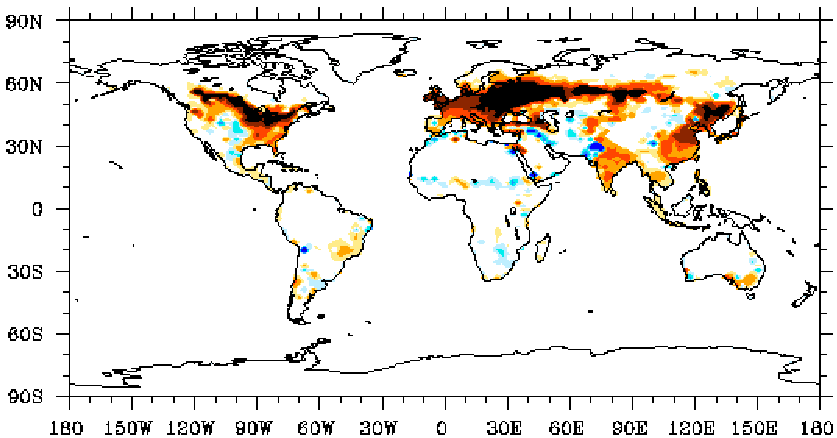


JJA



Modeled (CLM)

DJF



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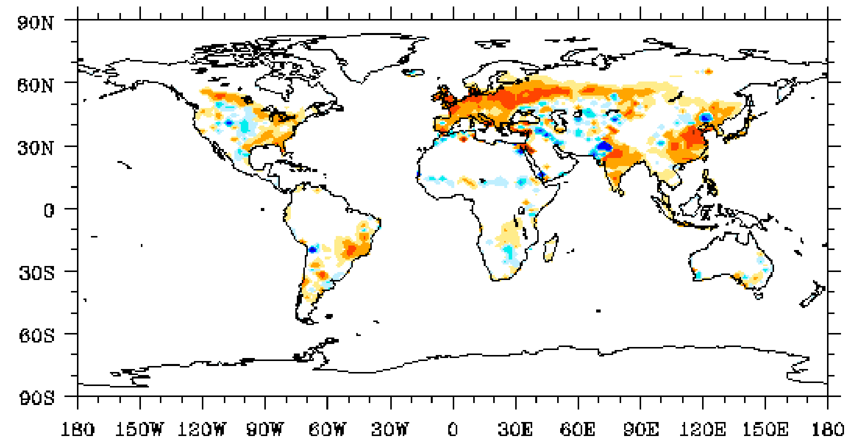
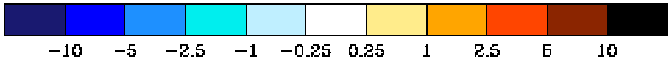
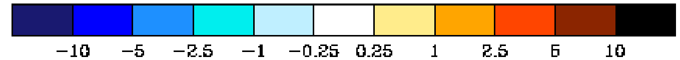






(Present-day vegetation – Potential vegetation)

Units are Δalbedo × 100

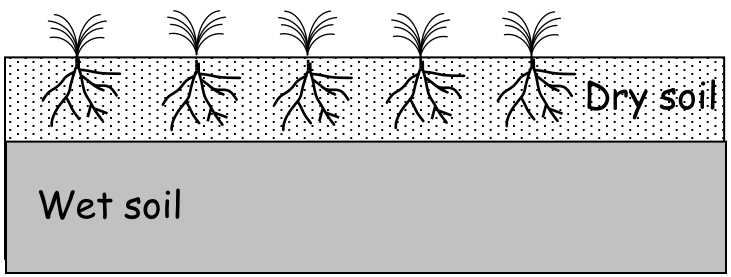
Lawrence & Chase (2009) Int J Climatol, submitted

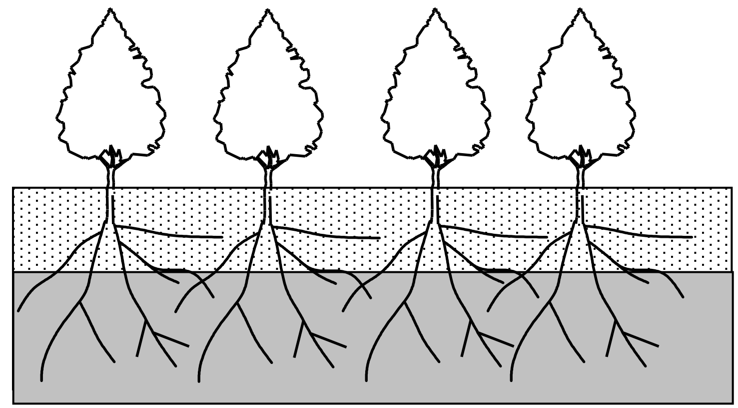
Land cover change and evapotranspiration

Prevailing model paradigm

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

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





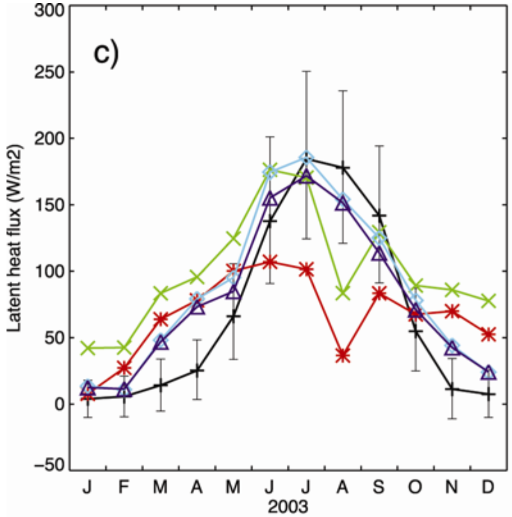
Tropical forest – cooling from higher surface albedo of cropland and pastureland is offset by warming associated with reduced evapotranspiration

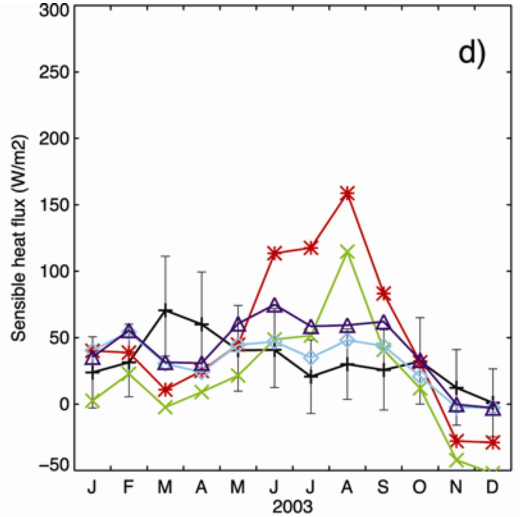
Temperate forest - higher albedo leads to cooling, but changes in evapotranspiration can either enhance or mitigate this cooling.

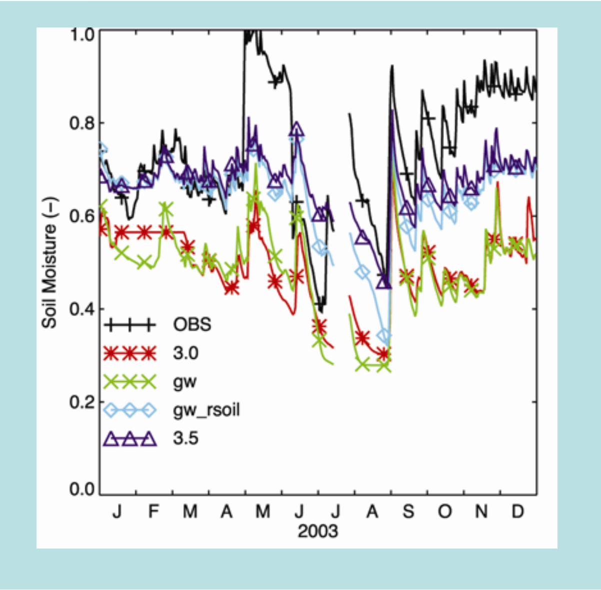
Bonan (2008) Science 320:1444-1449

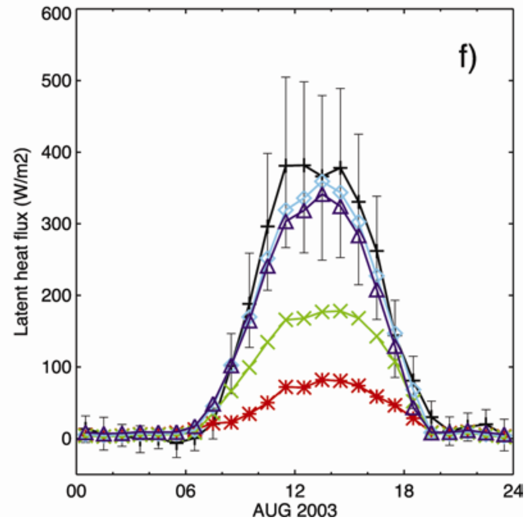
Flux tower measurements – temperate deciduous forest

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

National Center for Atmospheric Research
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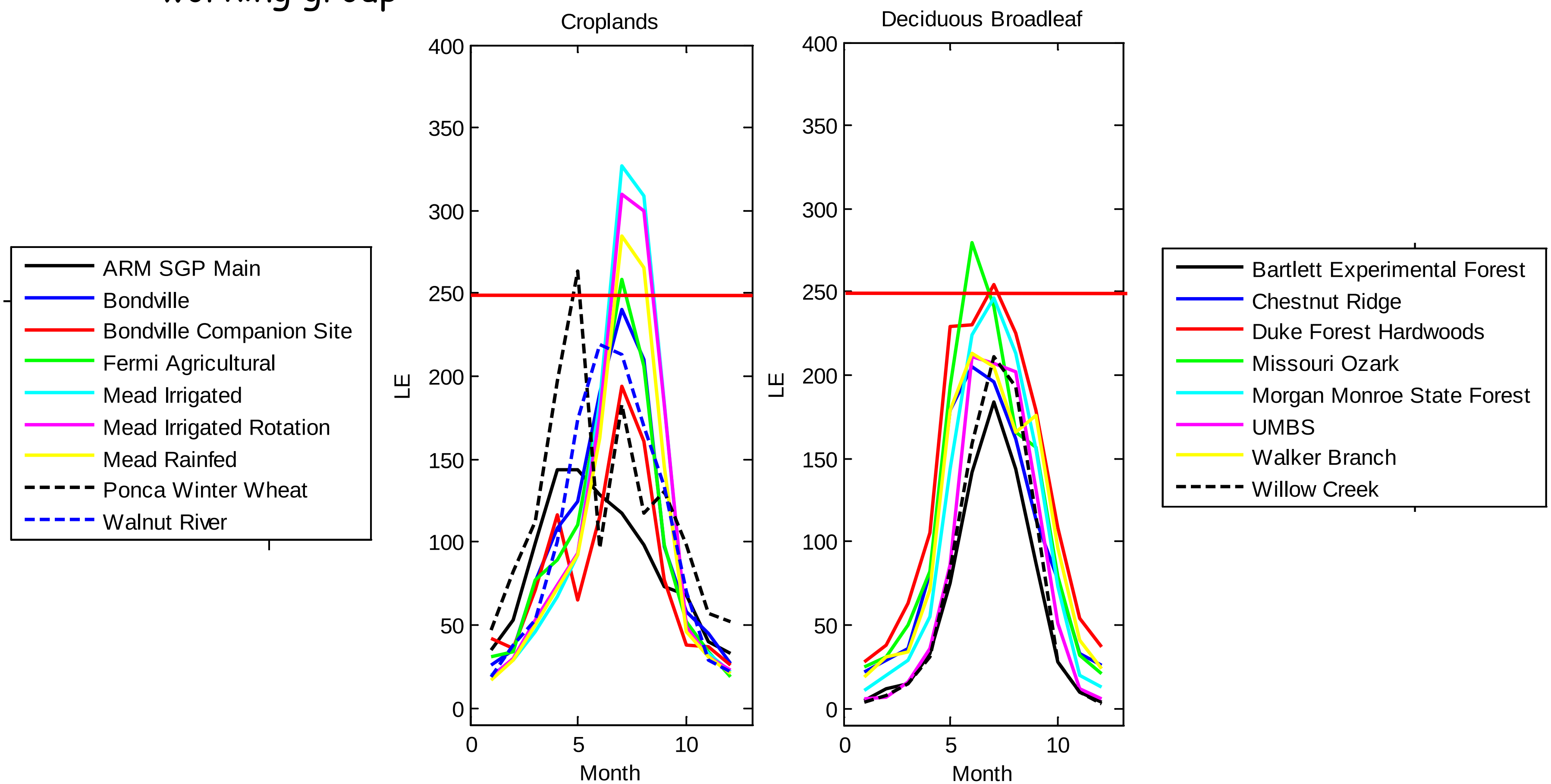
Can Ameriflux provide insights?

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

Conclusions

Carbon cycle

- CO_2 fertilization enhances plant productivity, offset by decreased productivity and increased soil carbon loss with warming
- N cycle reduces the capacity of the terrestrial biosphere to store carbon (CO_2 fertilization) and changes sign of carbon cycle-climate feedback from positive to negative. The CO_2 fertilization effect is larger than the climate feedback effect

Land use and land cover change

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

Biogeochemistry
- Wood harvest flux is important
- Uncertainty in harvest flux may be greater than the N-cycle feedback