Modeling terrestrial ecosystems: biosphere–atmosphere interactions

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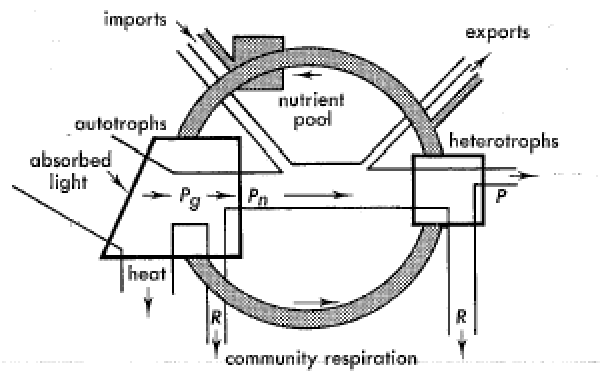
Ecosystems and biogeochemistry

An ecological perspective

boxes and flows among boxes

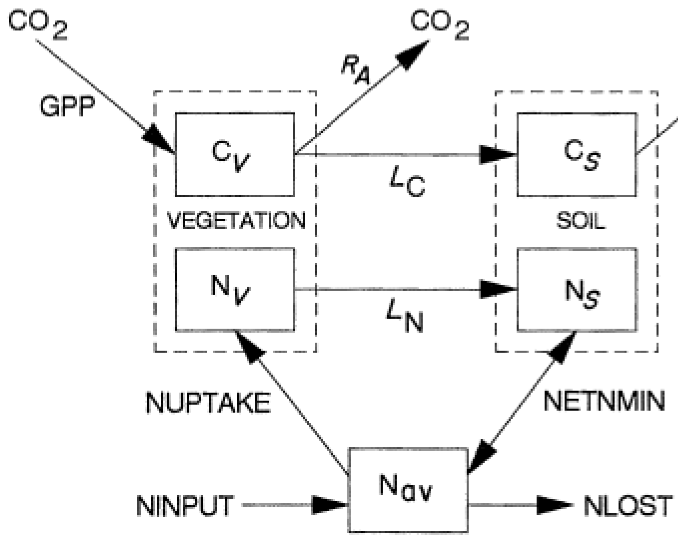
PRINCIPLES AND CONCEPTS PERTAINING TO BIOGEOCHEMICAL CYCLES 87

Figure 4–1. A biogeochemical cycle (stippled circle) superimposed upon a simplified energy-flow diagram, contrasting the cycling of material with the one-way flow of energy. P_g = gross production; P_n = net primary production, which may be consumed within the system by heterotrophs or exported from the system; P = secondary production; R = respiration. (After E. P. Odum, 1963.)



Odum, E. P. (1971). *Fundamentals of Ecology*, 3rd edn. Philadelphia: Saunders

Ecosystems and biogeochemistry



Terrestrial Ecosystem Model (TEM)

Raich et al (1991) Ecol. Appl. 1:399-429
McGuire et al (1992) GBC 6:101-124

CASA

Potter et al (1993) GBC 7:811-841

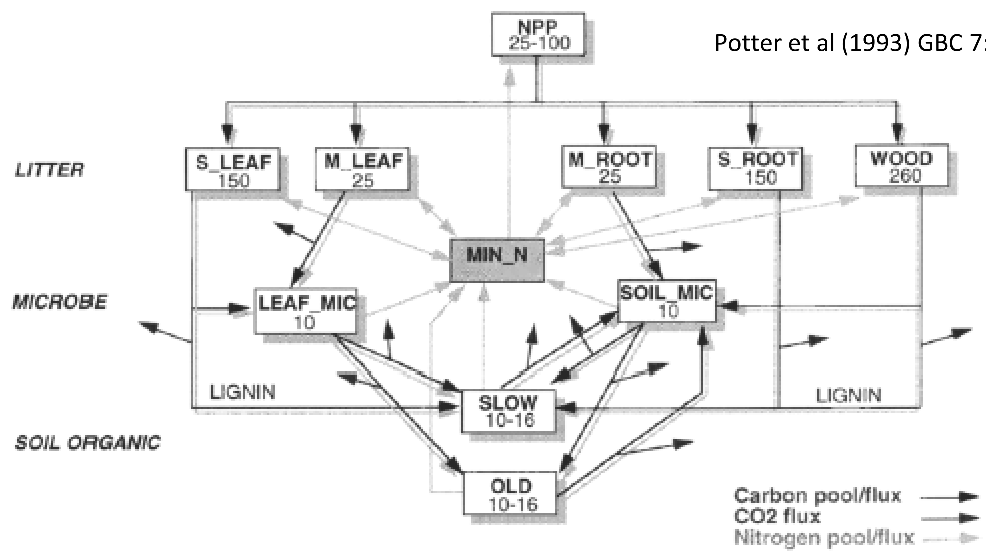
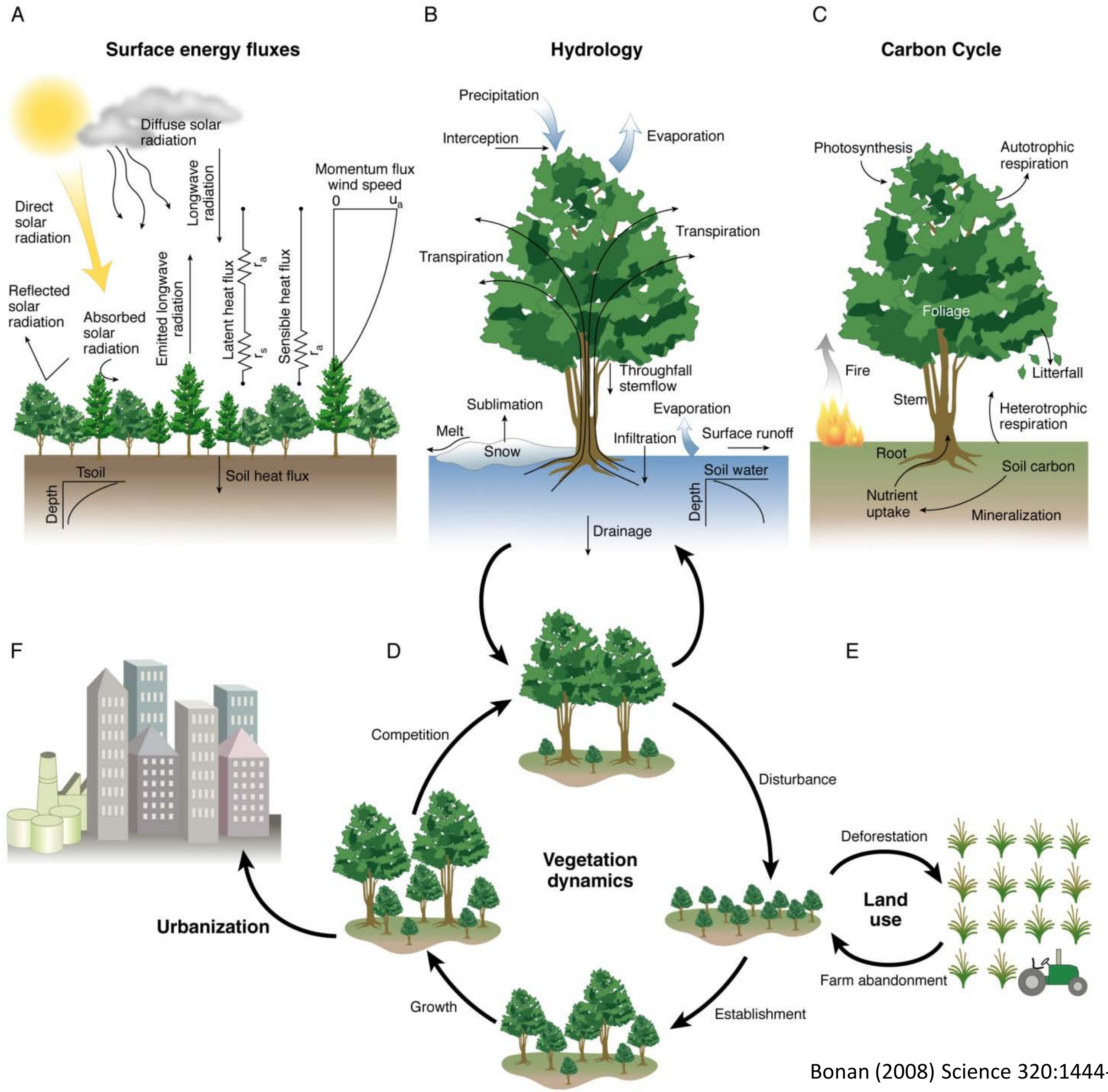


Fig. 5. Ecosystem carbon-nitrogen model. Carbon pools are outlined in black and labeled with C-to-N ratios, C fluxes in solid arrows, CO_2 production in stippled arrows; Nitrogen pools in gray, N fluxes in gray arrows. Levels of litter, microbe (MIC), and soil organic (SLOW and OLD) pools are shown. Structural (S) and metabolic (M) pools are shown for leaf and root litter.

Ecosystems and climate

Near-instantaneous (30-min) coupling with atmosphere (energy, water, chemical constituents)

Long-term dynamical processes that control these fluxes in a changing environment (disturbance, land use, succession)



Bonan (2008) Science 320:1444-1449

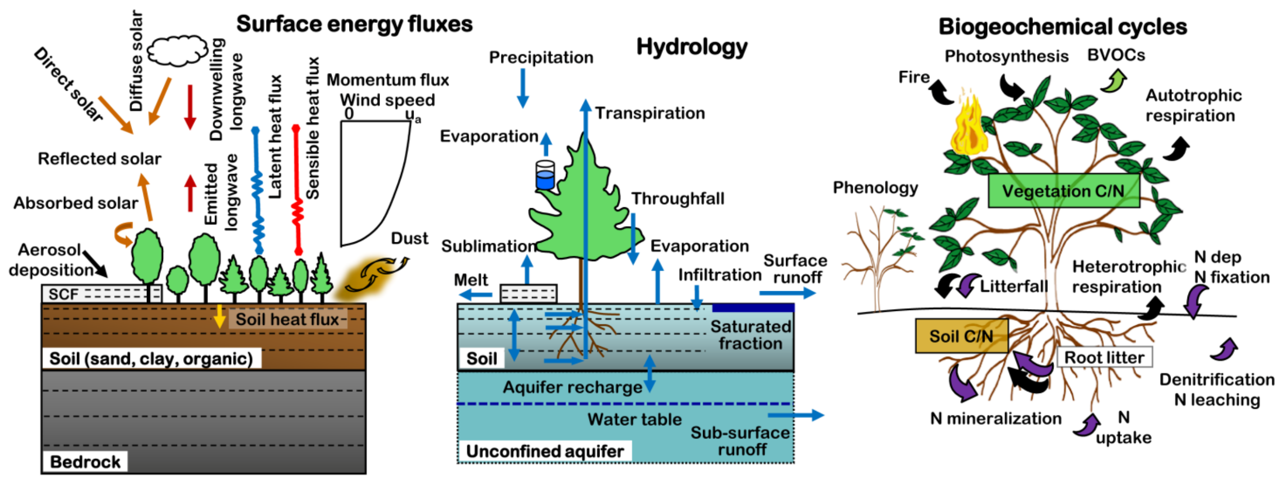
The Community Land Model (CLM4.5)

Fluxes of energy, water, carbon, and nitrogen and the dynamical processes that control these fluxes in a changing environment

Oleson et al. (2013) NCAR/TN-503+STR

D. Lawrence et al. (2011) JAMES, 3, doi: 10.1029/2011MS000045

D. Lawrence et al. (2012) J Climate 25:2240-2260

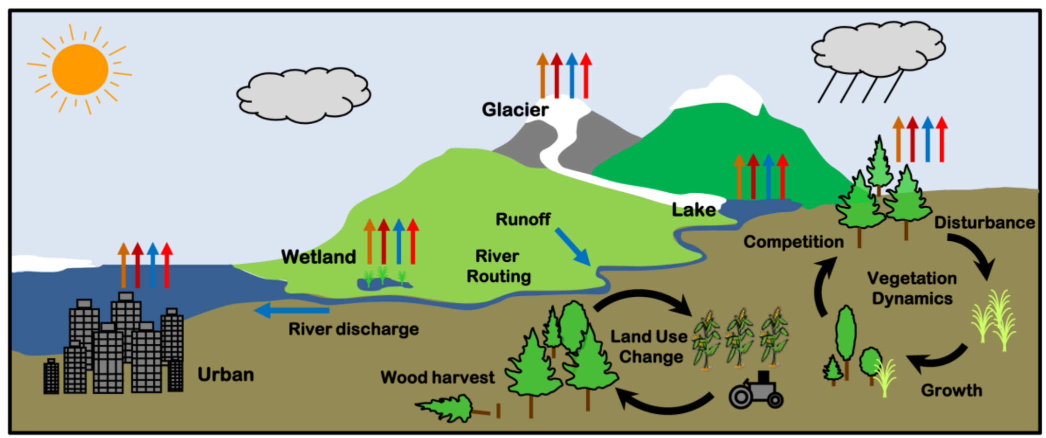


Spatial scale

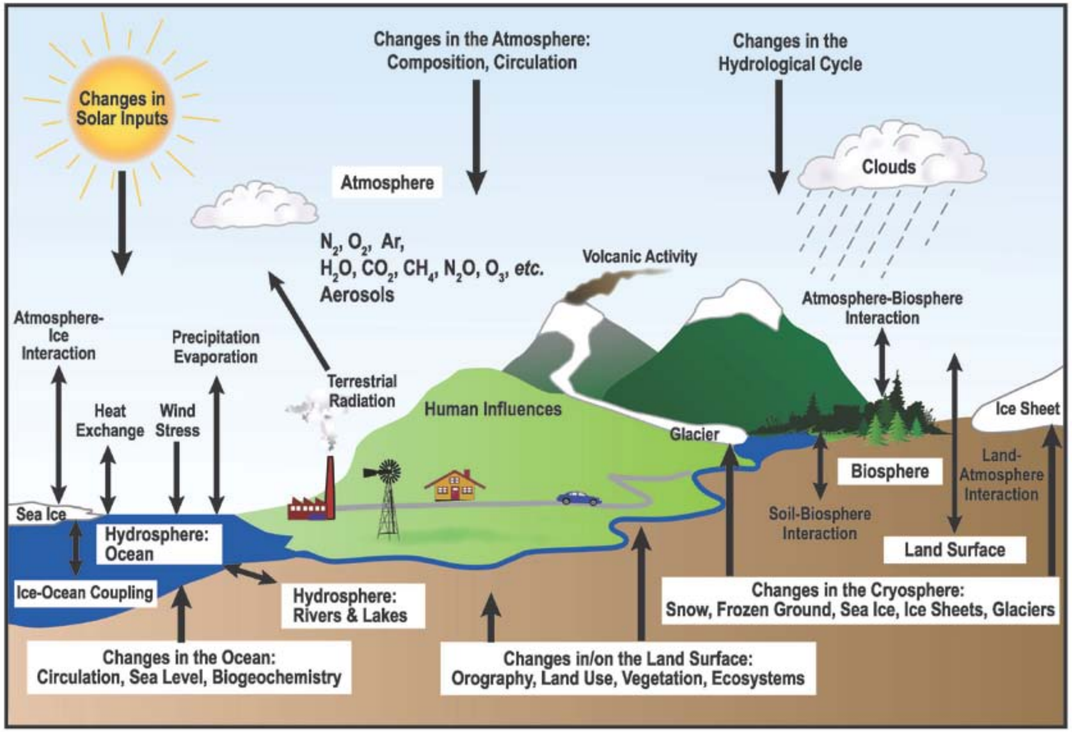
- 1.25° longitude × 0.9375° latitude (288 × 192 grid)

Temporal scale

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



Earth system models



(IPCC 2007)

Prominent terrestrial feedbacks

- Snow cover and climate
- Soil moisture-evapotranspiration-precipitation
- Land use and land cover change
- Carbon cycle
- Reactive nitrogen

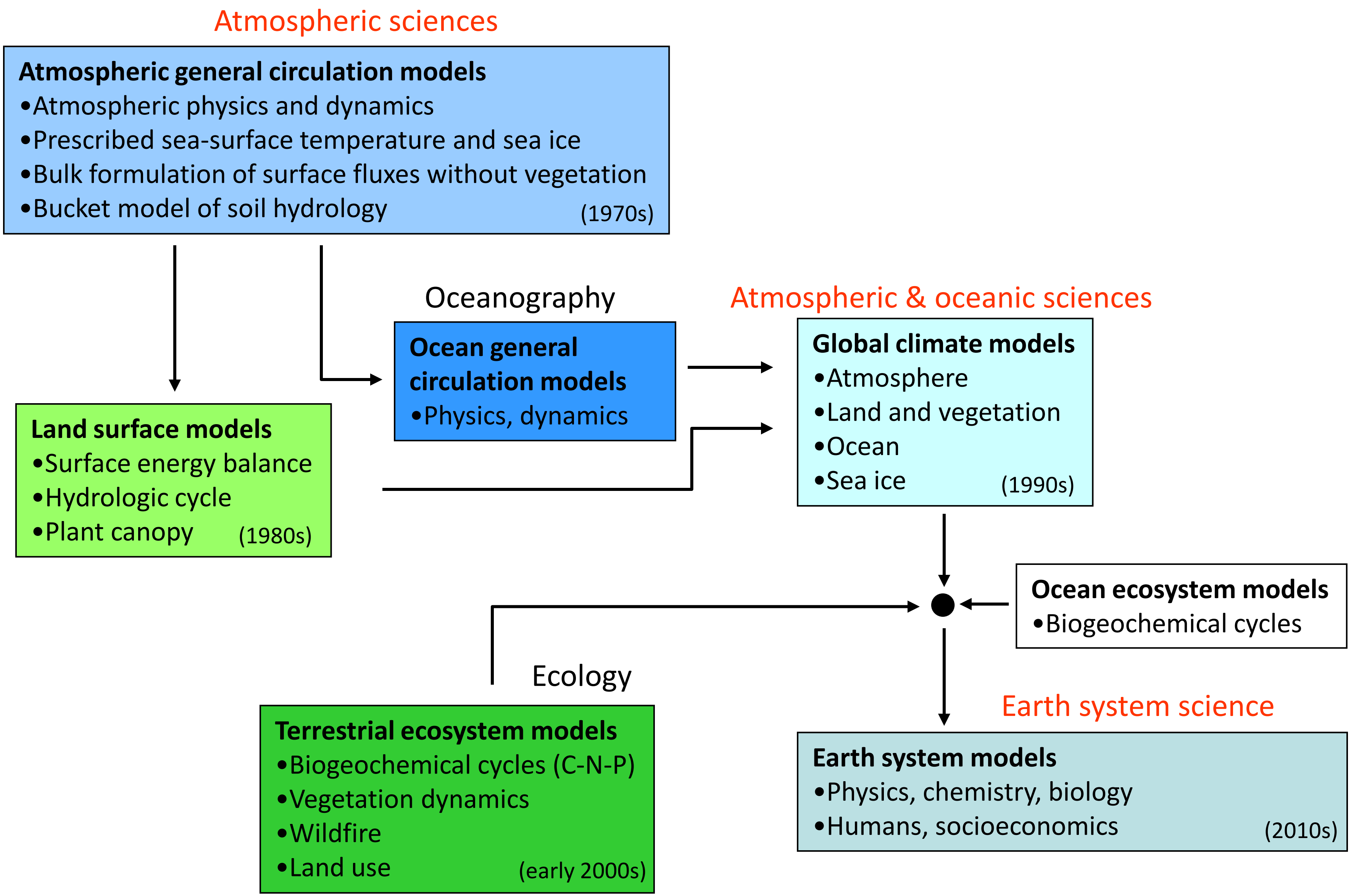
Earth system models use mathematical formulas to simulate the **physical**, **chemical**, and **biological** processes that drive Earth's atmosphere, hydrosphere, biosphere, and geosphere

A typical Earth system 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

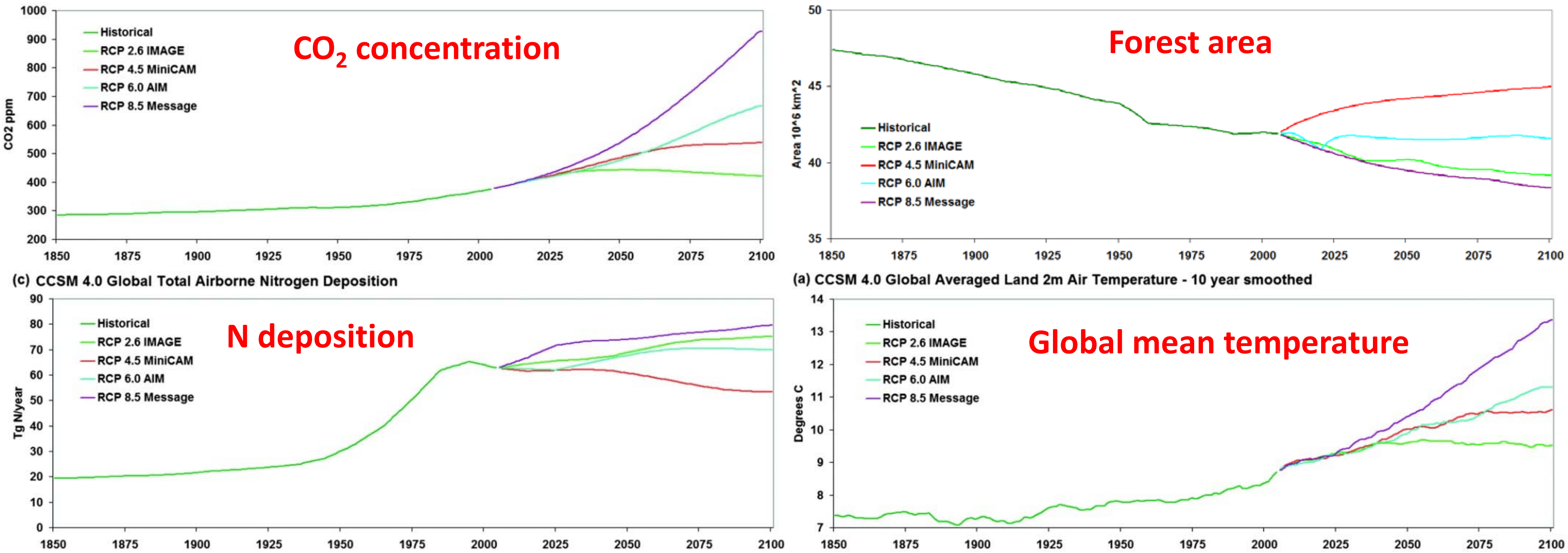
The model provides a comprehensive understanding of the processes by which people and ecosystems **feed back**, **adapt to**, and **mitigate** global environmental change

Evolution of climate science



Planetary stressors

It is not just greenhouse gases anymore …



P. Lawrence et al. (2012) J Climate 25:3071-3095

Forcings

Solar variability & volcanic aerosols

CO_2 , N_2O, CH_4, aerosols, stratospheric ozone

N deposition

Land use (land cover change, wood harvest)

Aerosol deposition on snow (black carbon)

Tropospheric ozone

Fertilizer & manure

P. Lawrence et al. (2012) J Climate 25:3071-3095

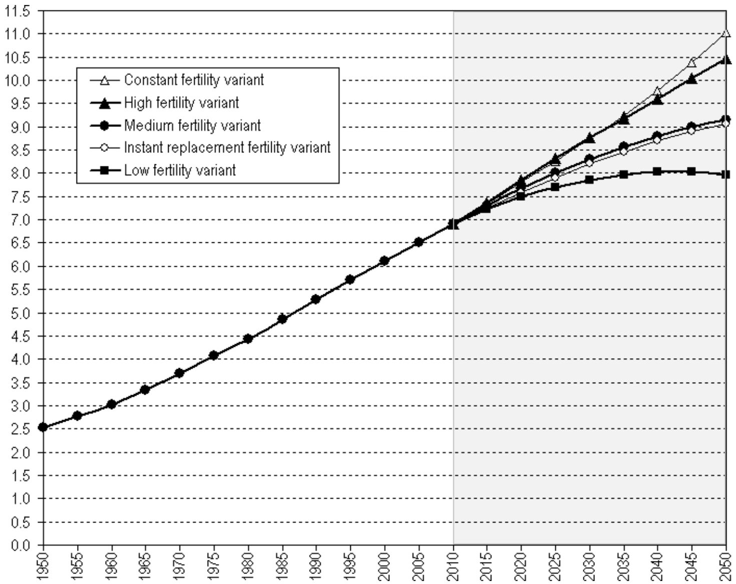
Planetary distress

2012 drought, Waterloo, NE (Nati Harnik, AP)
Sea ice retreat (Jonathan Hayward/CP file photo, www.thestar.com)
Habitat loss, NM (UCAR)
Pine beetle, CO (RJ Sangosti/Denver Post)
High Park fire, CO (RJ Sangosti/Denver Post)
Coastal flooding, NC (U.S. Coast Guard)
Texas drought (http://farmprogress.com)
Calving face of the Ilulissat Isfjord, Greenland, 7 June 2007 (www.extremeicesurvey.org)
Midway-Sunset oil field, CA (Jim Wilson/The New York Times)

It is not just atmospheric physics and dynamics …

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 (energy use, agriculture, deforestation, urbanization) and their effects on climate, water resources, and biogeochemical cycles

What is our collective future?

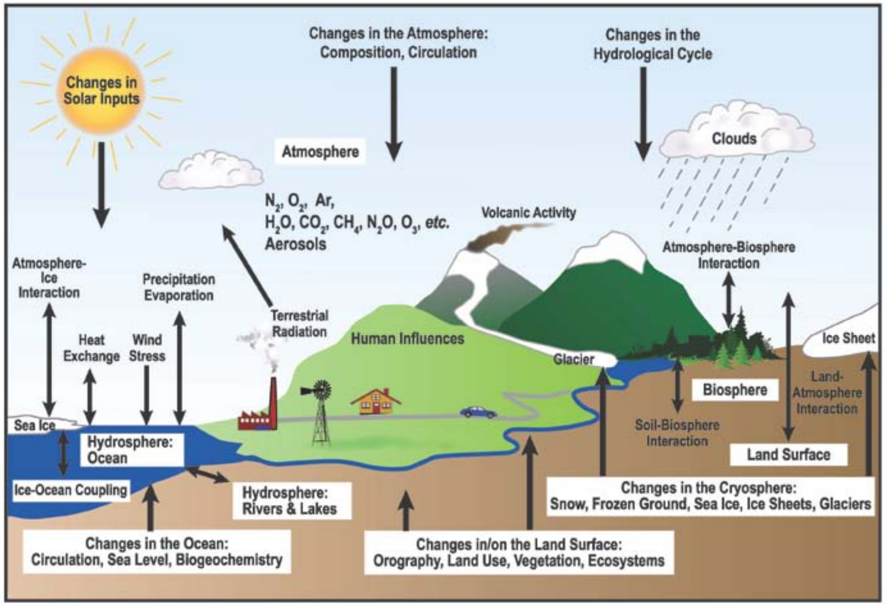
Can we manage the Earth system, especially its ecosystems, to create a sustainable future?

Terrestrial ecosystems and global environmental change

Land as the critical interface through which people affect, adapt to, and mitigate global environmental change

- **Expanded capability to simulate ecological, hydrological, biogeochemical, and socioeconomic forcings and feedbacks in the Earth system**
- **Increased emphasis on impacts, adaptation, and mitigation**
- **Requires an integrated assessment modeling framework**
  - Human systems (land use, urbanization, energy use)
  - Biogeochemical systems (C-N-P, trace gas emissions, isotopes)
  - Water systems (resource management, freshwater availability, water quality)
  - Ecosystems (disturbance, vulnerability, goods and services)

(IPCC 2007)



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

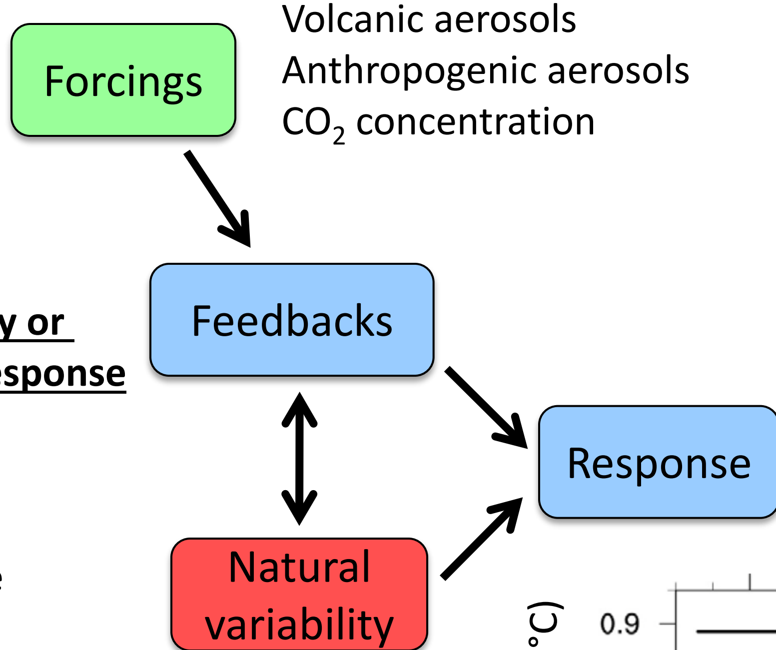
Biofuel plantations to increase albedo and reduce atmospheric CO_2

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

Understanding Earth's climate system

<u>Forcings: drivers of system change</u>

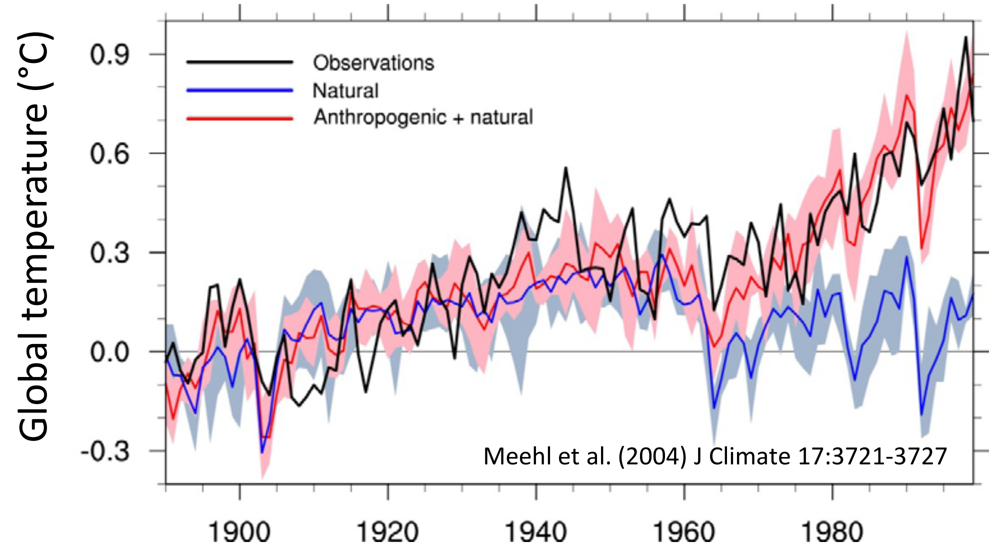
Solar irradiance
Volcanic aerosols
Anthropogenic aerosols
CO_2 concentration



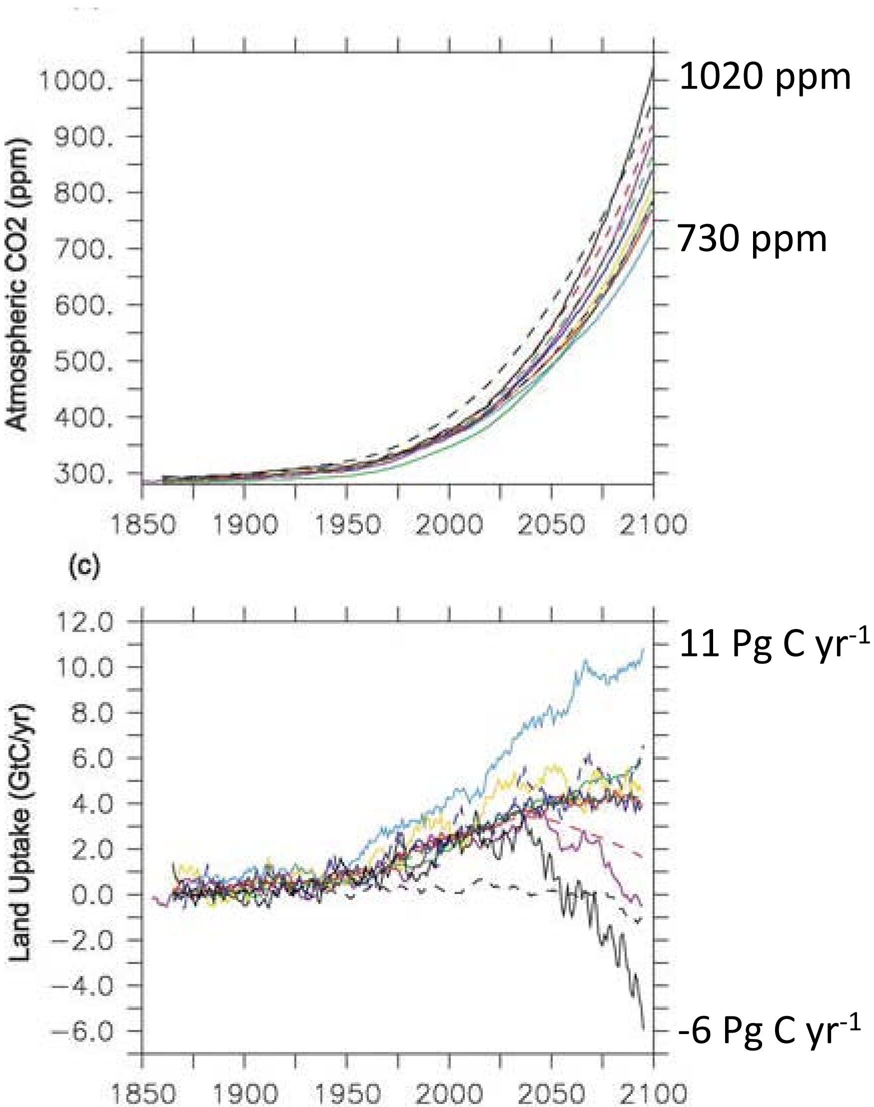
<u>Feedbacks: amplify or dampen system response</u>

Water vapor
Clouds
Snow-ice albedo
Ocean heat uptake

ENSO, NAO
PDO



C4MIP – Climate and carbon cycle



Carbon cycle-climate feedback

11 carbon cycle-climate models of varying complexity

CO_2 fertilization enhances carbon uptake, diminished by decreased productivity and increased soil carbon loss with warming

Large uncertainty:

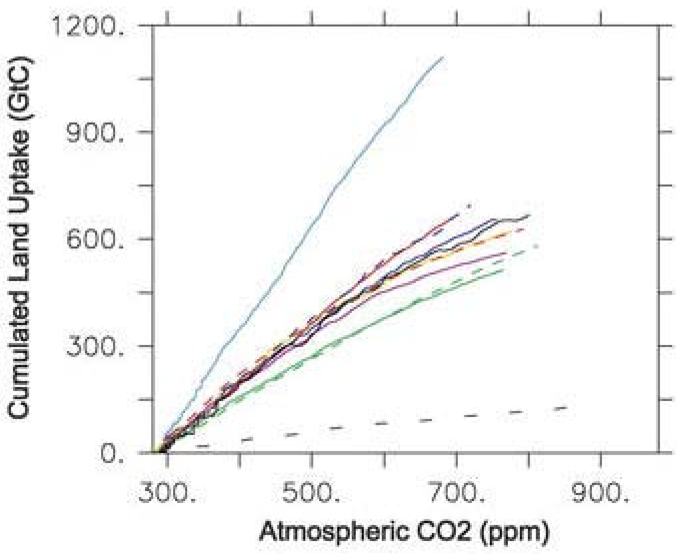
- 290 ppm difference in atmospheric CO_2 at 2100
- 17 Pg C yr^{-1} difference in land uptake at 2100

Friedlingstein et al. (2006) J Climate 19:3337-3353

Uncertainty in feedback is large

$\Delta C_L = \beta_L \Delta C_A + \gamma_L \Delta T$	$\beta_L > 0$: concentration-carbon feedback (Pg C ppm^{-1}) $\gamma_L < 0$: climate-carbon feedback (Pg C K^{-1})

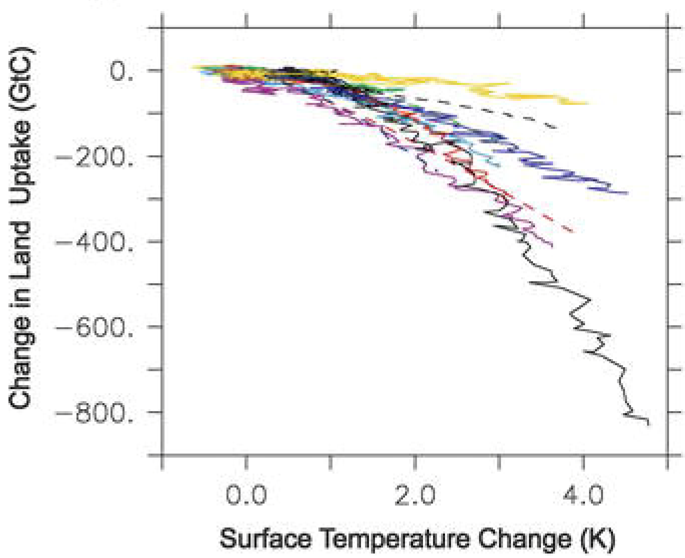
Concentration-carbon feedback



β_L=1.4 Pg C ppm^{-1} [0.2-2.8]

CO$_2$ fertilization enhances carbon uptake

Climate-carbon feedback



γ_L=-79 Pg C K^{-1} [-20 to -177]

Carbon loss with warming

Friedlingstein et al. (2006) J Climate 19:3337-3353

CMIP5 – Climate and carbon cycle

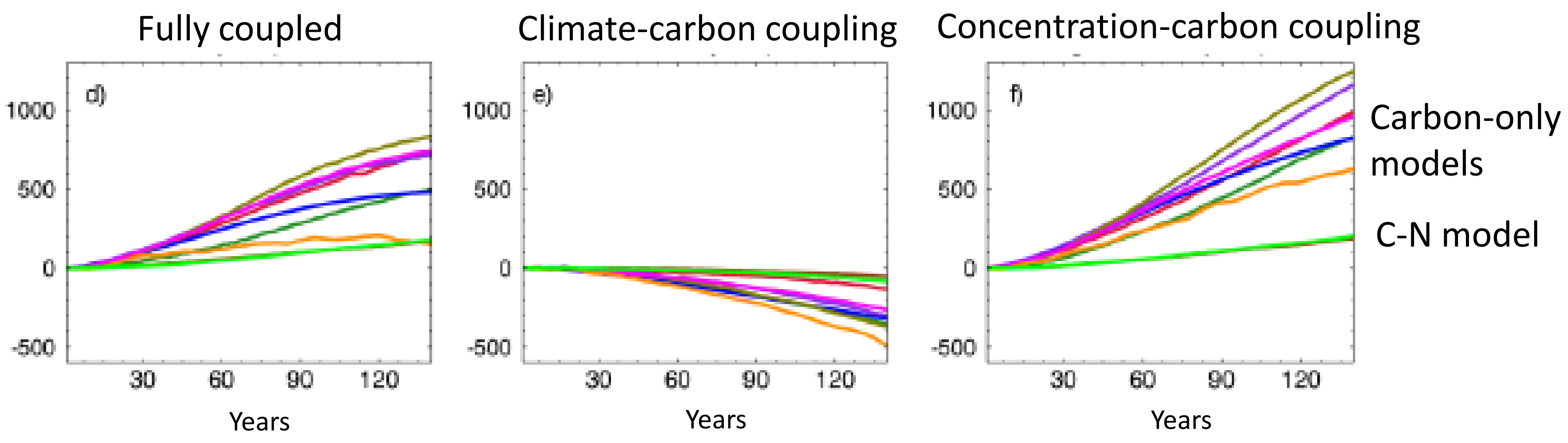
Carbon cycle-climate feedback

9 Earth system models of varying complexity

140-year simulations during which atmospheric CO_2 increases 1% per year from ~280 ppm to ~1120 ppm

Arora et al. (2013) J Climate 26:5289-5314

Cumulative land-atmosphere CO_2 flux (Pg C)

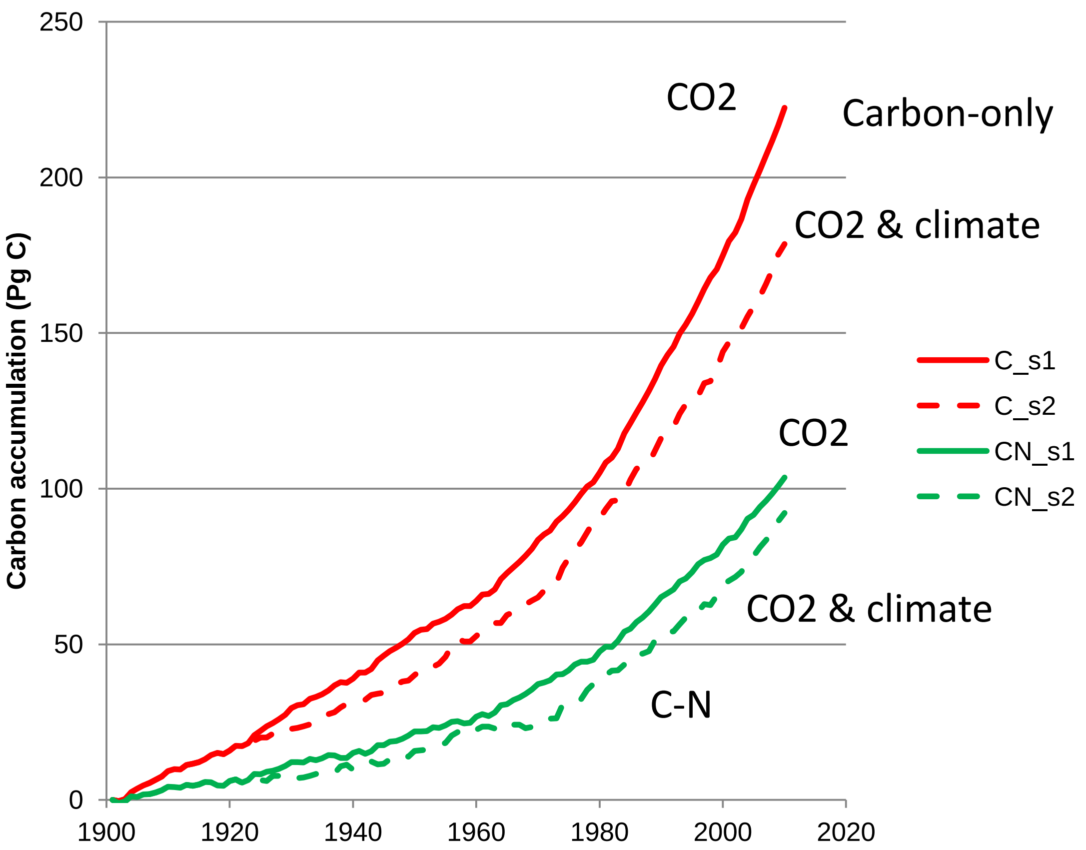


CMIP5: γ_L=-58 Pg C K^{-1} [-16 to -89] β_L=0.9 Pg C ppm^{-1} [0.2-1.5]

C4MIP: γ_L=-79 Pg C K^{-1} [-20 to -177] β_L=1.4 Pg C ppm^{-1} [0.2-2.8]

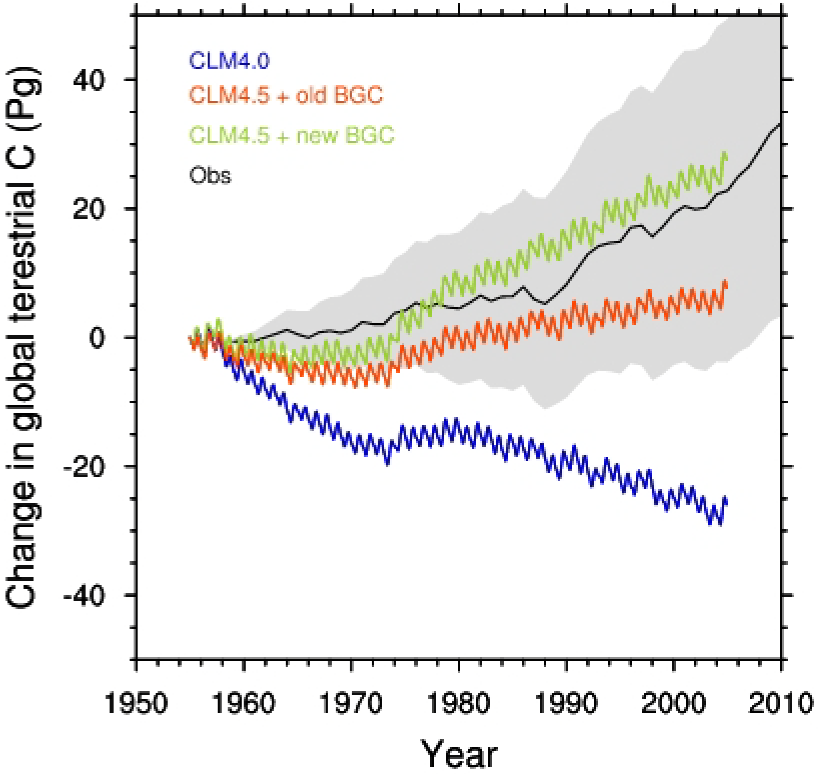
CLM4 carbon cycle

Cumulative land-atmosphere CO_2 flux (Pg C)



CLM4.5 carbon cycle

Cumulative land-atmosphere CO_2 flux (Pg C)



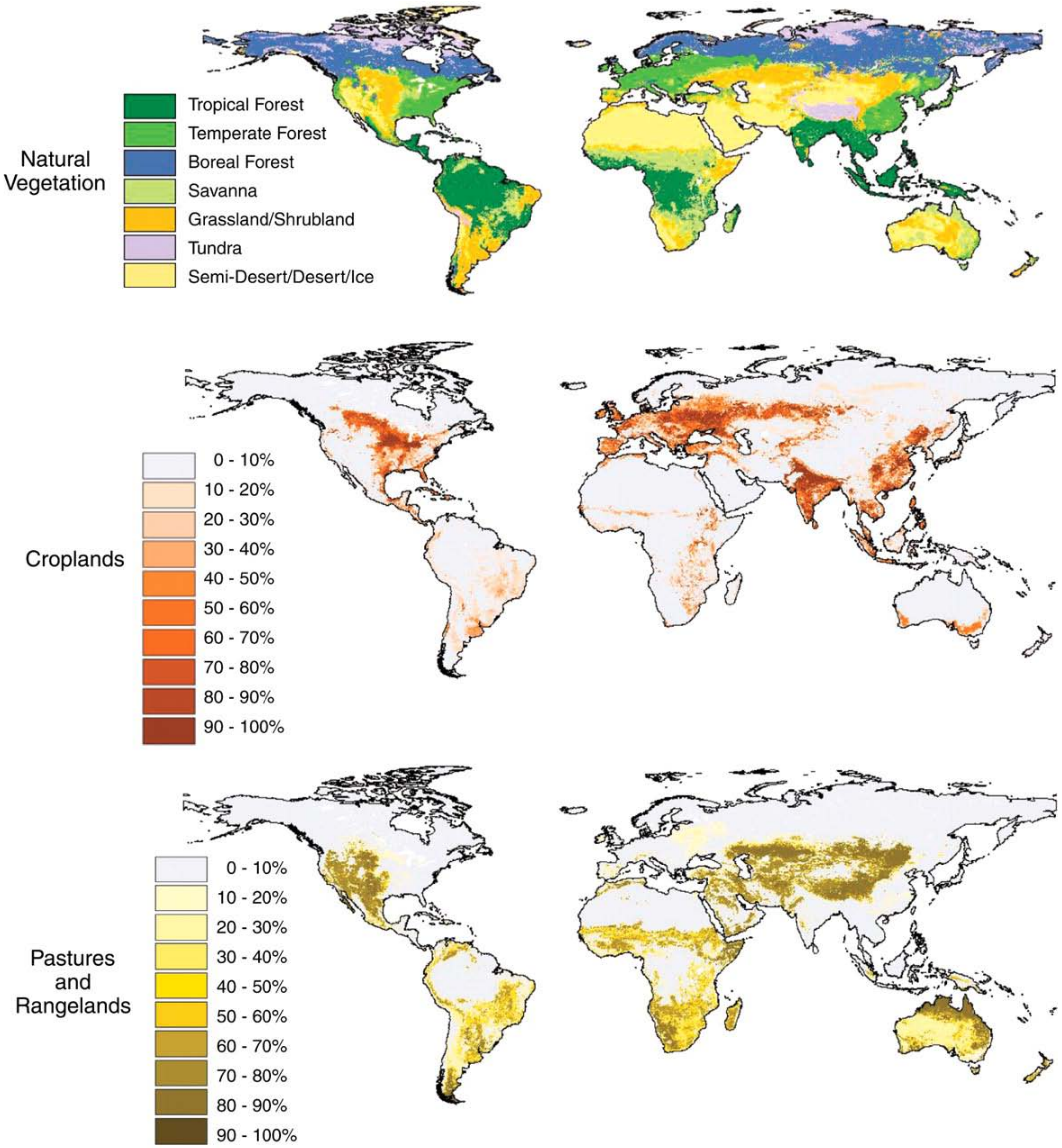
Koven et al. (2013) Biogeosciences 10:7109-7131

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

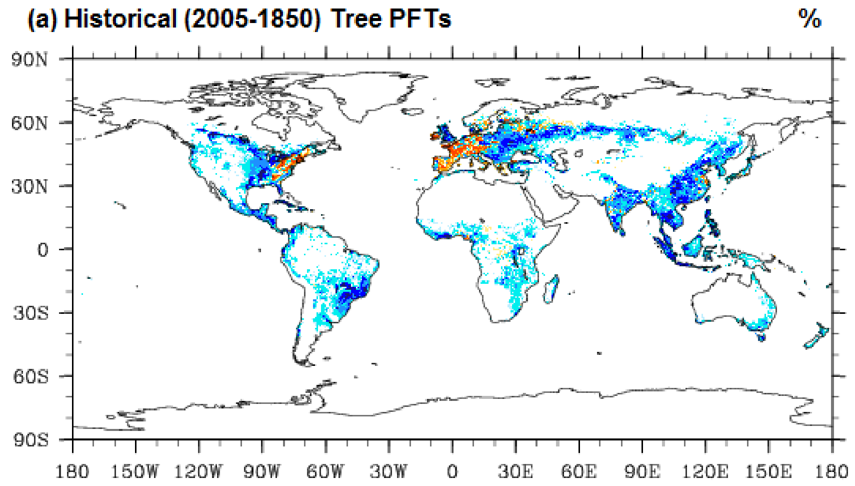
Global land use is abstracted to the fractional area of crops and pasture

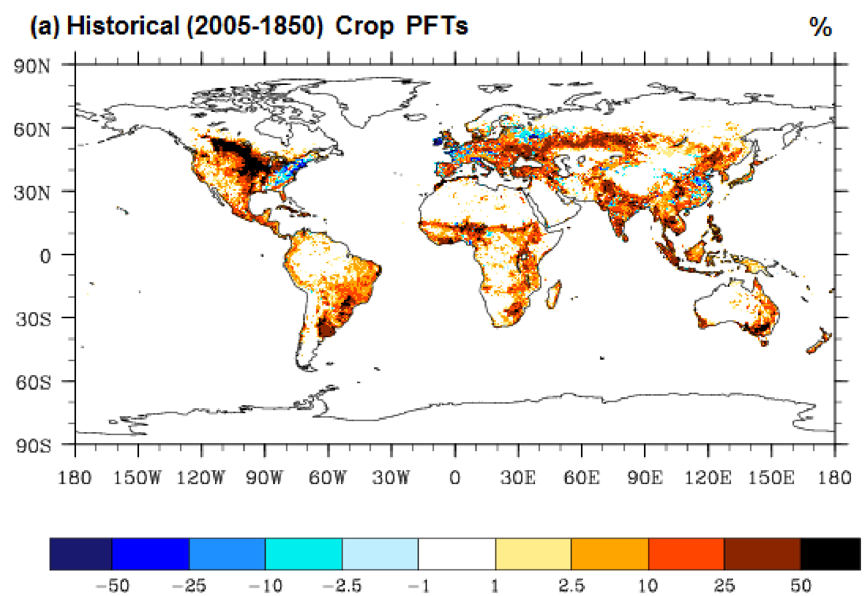


Foley et al. (2005) Science 309:570-574

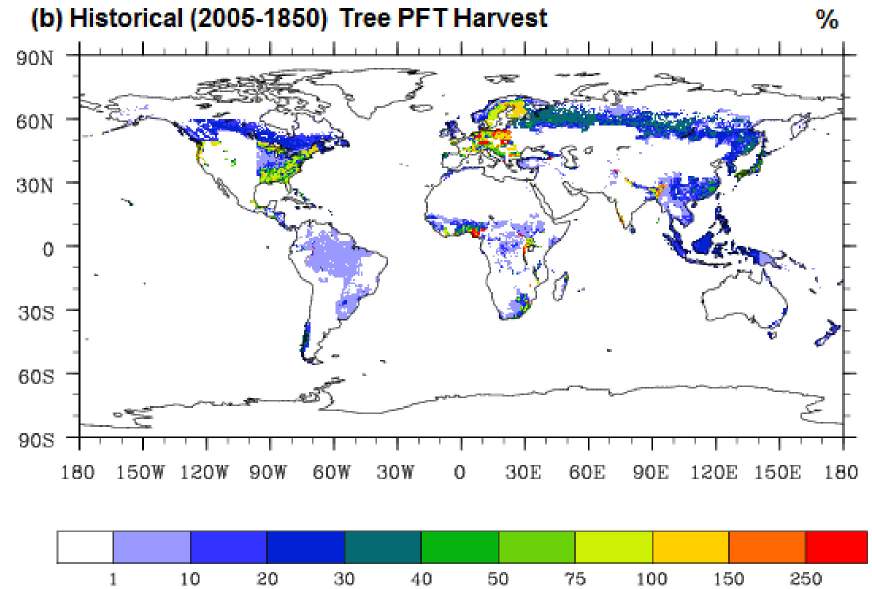
Historical land use & land cover change, 1850-2005

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





Cumulative percent of grid cell harvested



<u>Historical LULCC in CLM4</u>

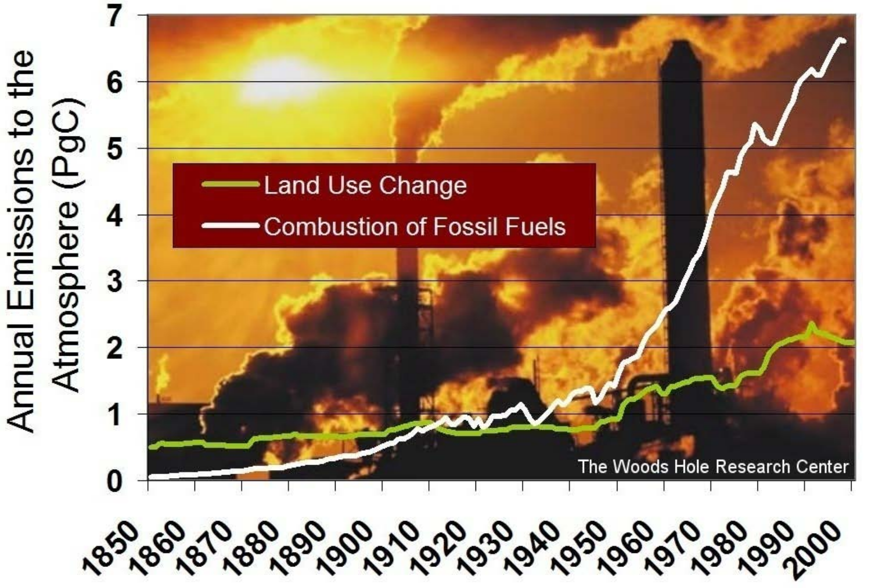
- ❑ Loss of tree cover and increase in cropland
- ❑ Farm abandonment and reforestation in eastern U.S. and Europe
- ❑ Extensive wood harvest

P. Lawrence et al. (2012) J Climate 25:3071-3095

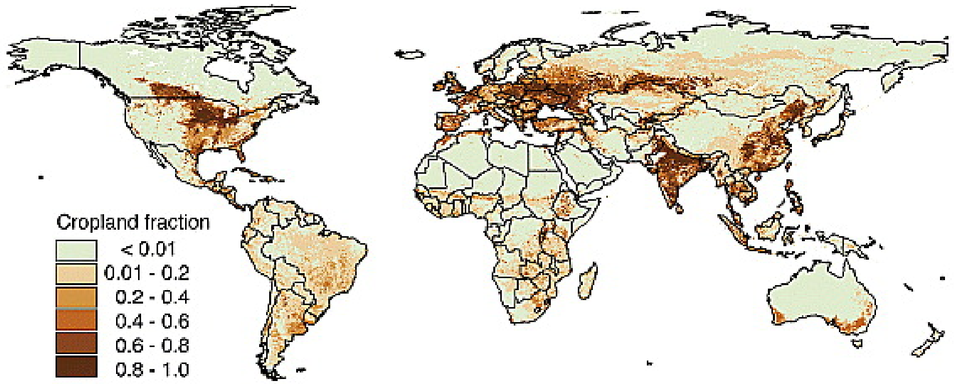
Land use carbon flux

Carbon perspective …

Land use is a source of carbon to the atmosphere



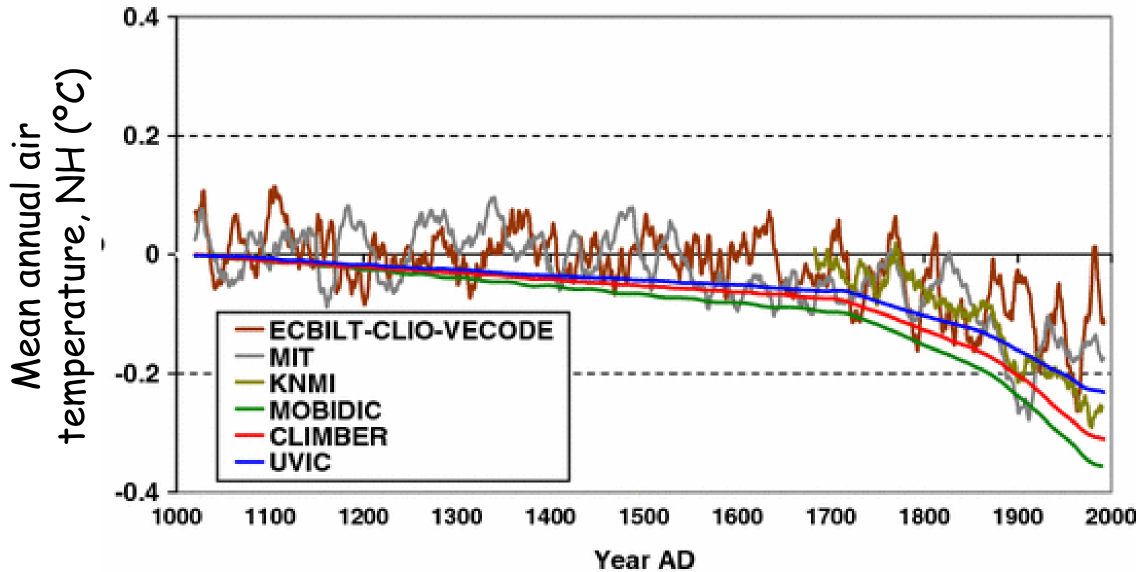
Land use forcing of climate



The emerging consensus is that land cover change in middle latitudes has cooled the Northern Hemisphere (primarily because of higher surface albedo in spring)

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

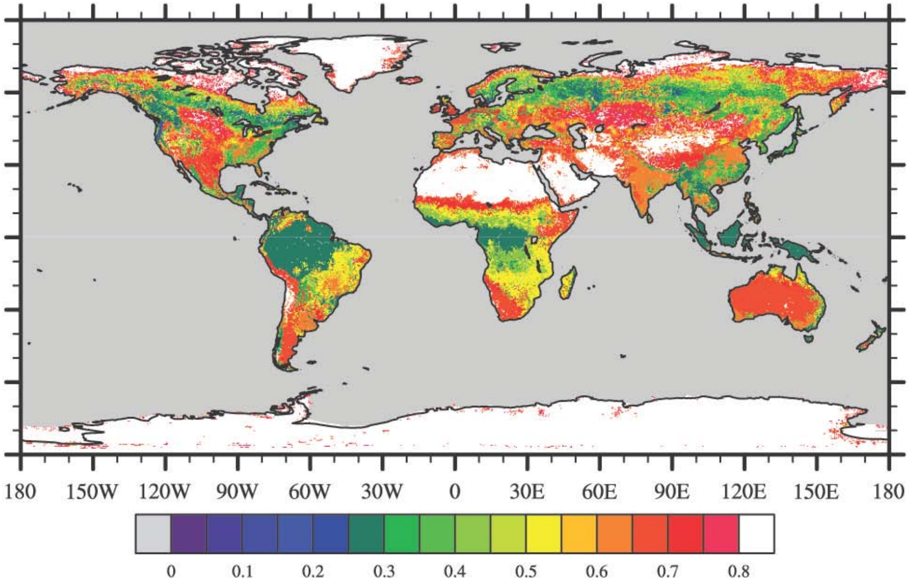
Comparison of 6 EMICs forced with historical land cover change, 1000-1992



Brovkin et al. (2006) Clim Dyn 26:587-600

Surface albedo

Maximum snow-covered albedo

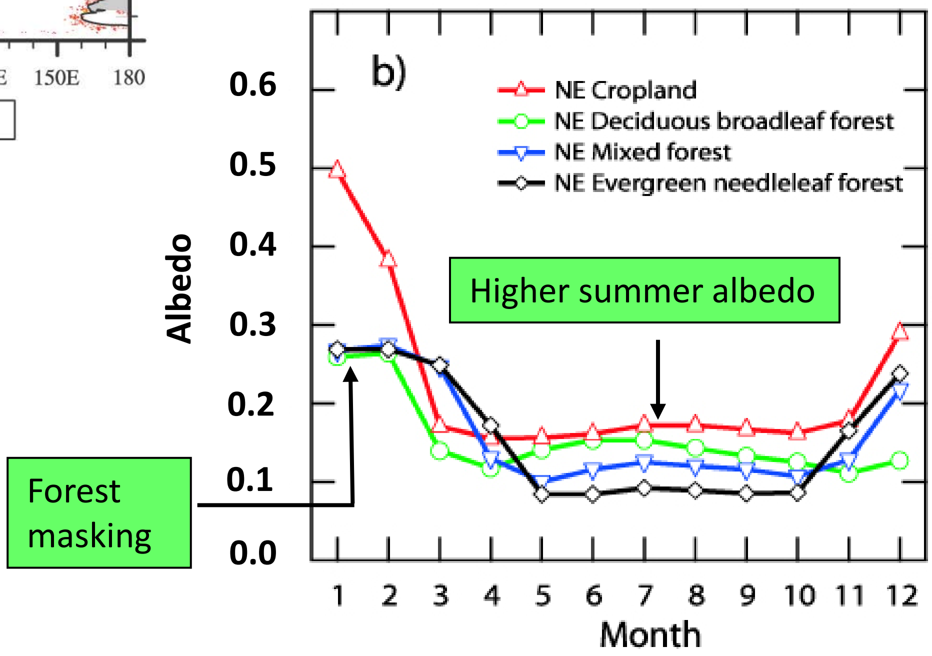


Barlage et al. (2005) GRL, 32, doi:10.1029/2005GL022881

LULCC effects

- Vegetation masking of snow
- High albedo of crops

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)

Colorado Rocky Mountains

Land cover change and evapotranspiration

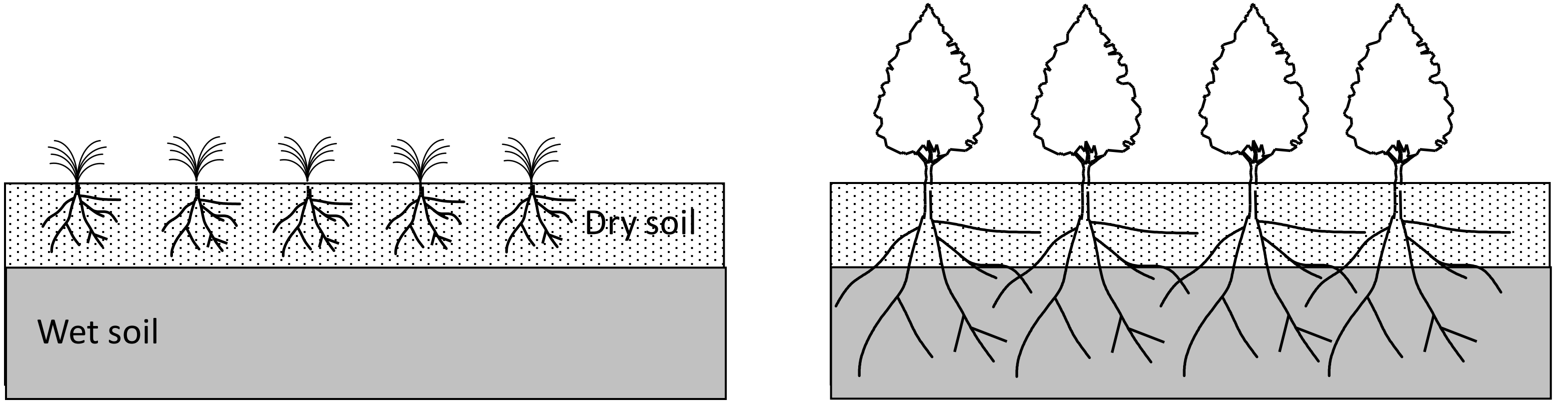
Prevailing model paradigm

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



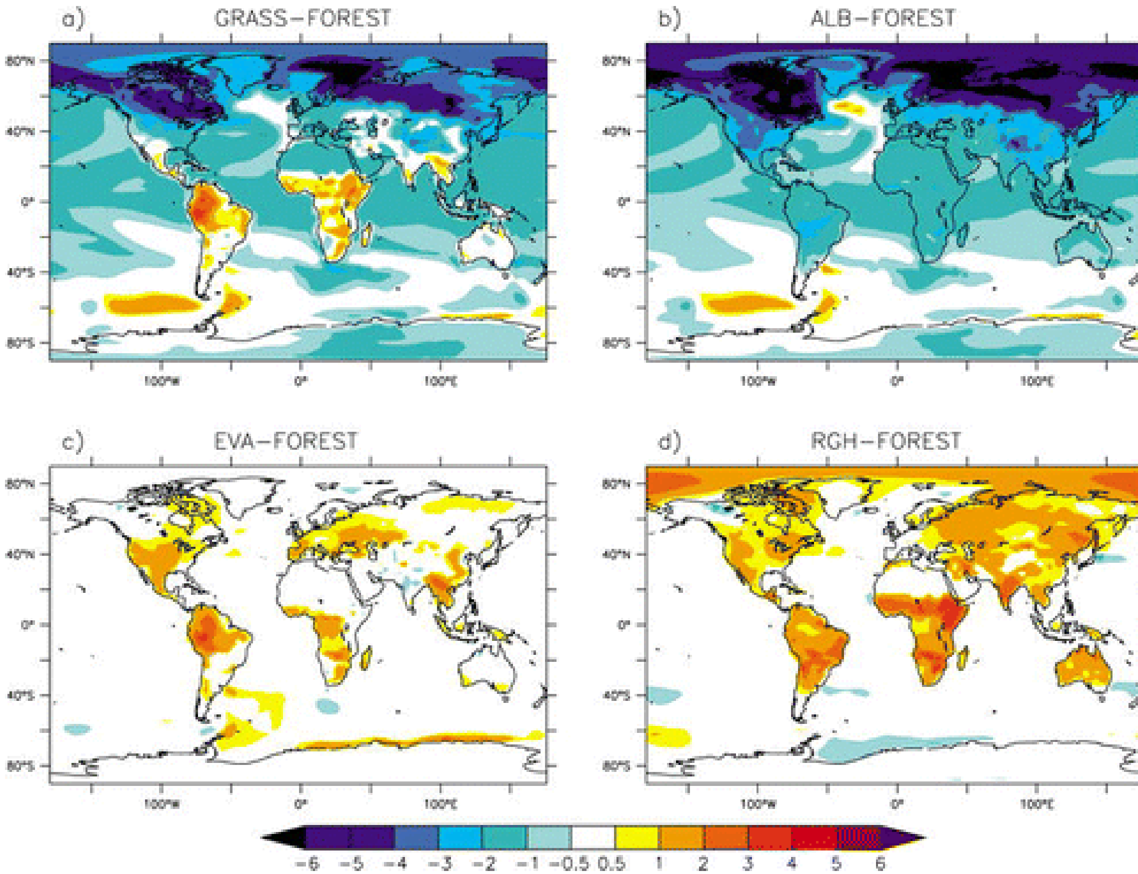
Tropical forest – cooling from higher surface albedo of cropland and pastureland is offset by warming associated with reduced evapotranspiration

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

Bonan (2008) Science 320:1444-1449

Forests influences on global climate

Annual mean surface temperature change (°C)



Prevailing biogeophysical paradigm

- ➢Boreal and temperate forests warm climate
- ➢Tropical forests cool climate

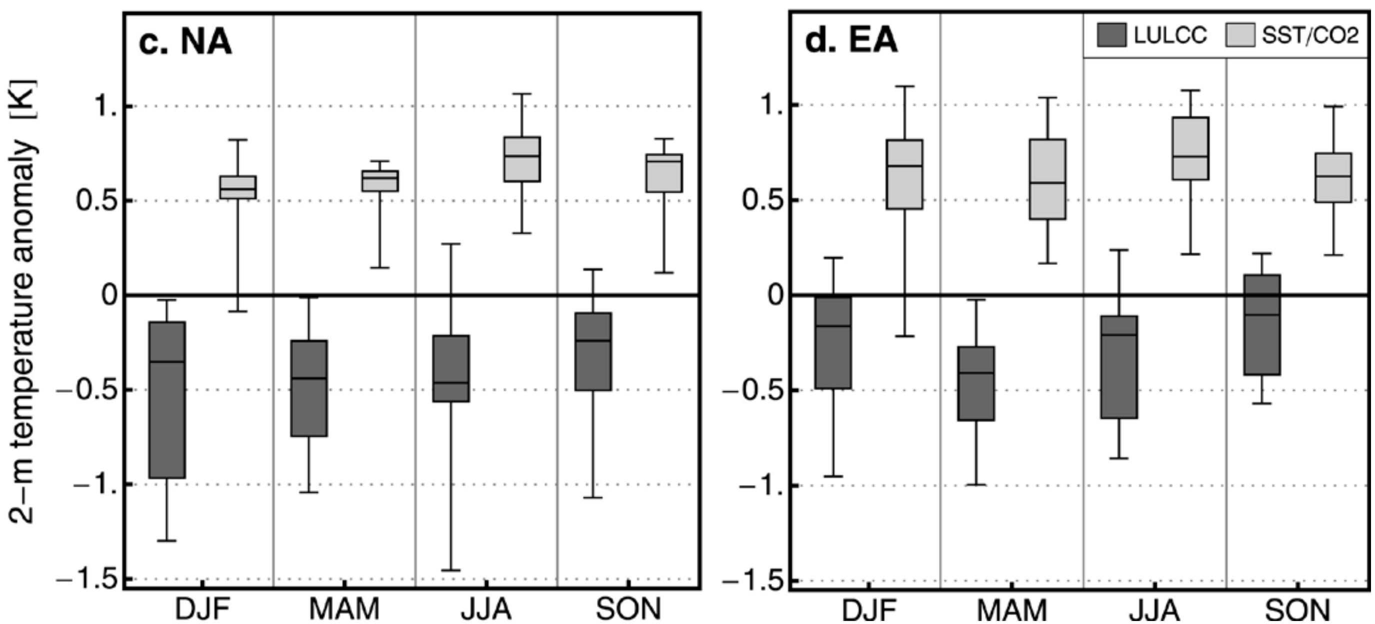
Davin & de Noblet-Ducoudré (2010) J Climate 23:97–112

LULCC relative to greenhouse warming

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

North America

Eurasia



de Noblet-Ducoudré, Boiser, Pitman, et al. (2012) J Climate 25:3261-3281

CO_2 + SST + SIC forcing leads to warming

LULCC leads to cooling

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.

Key points:

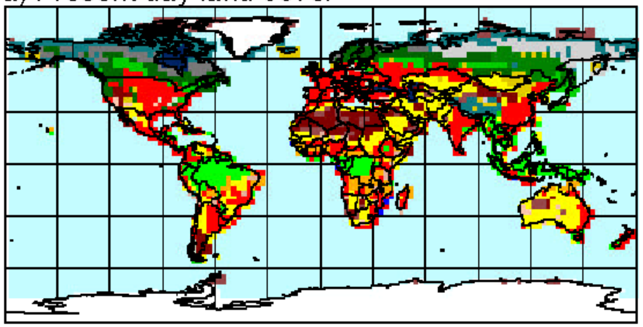
The LULCC forcing is counter to greenhouse warming

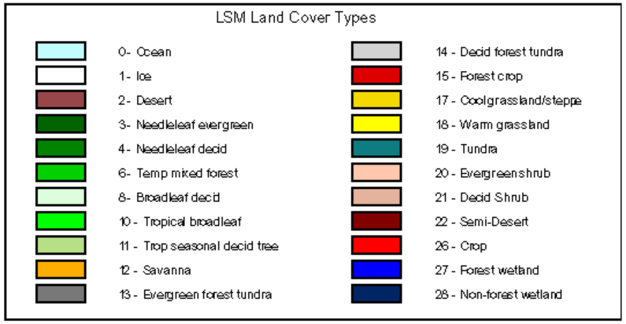
The LULCC forcing has large inter-model spread, especially JJA

Land use choices affect 21st century climate

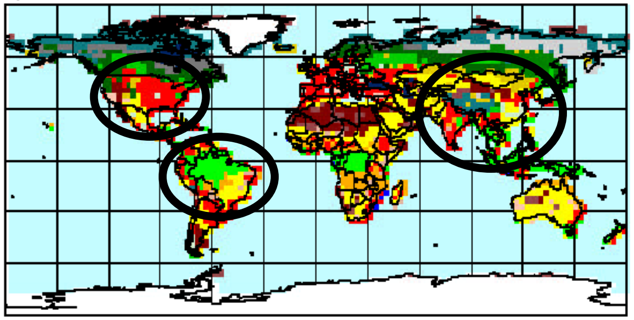
Future IPCC SRES land cover scenarios for NCAR LSM/PCM

a) Present day land cover

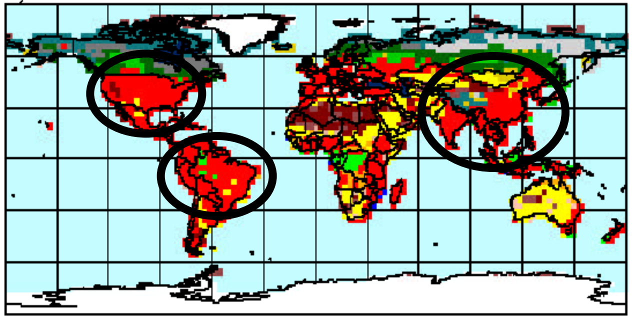




c) B1 2100 land cover

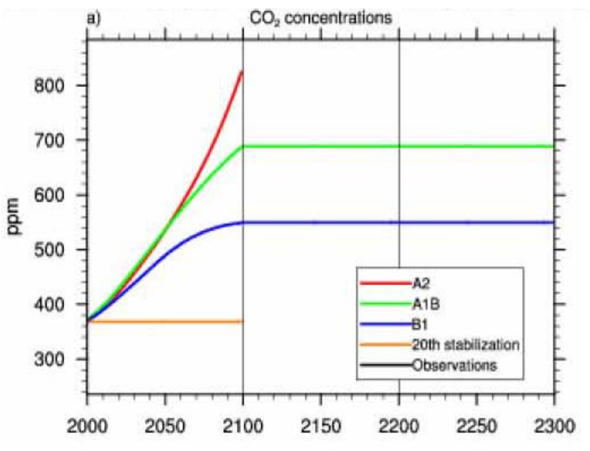


e) A2 2100 and cover



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

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

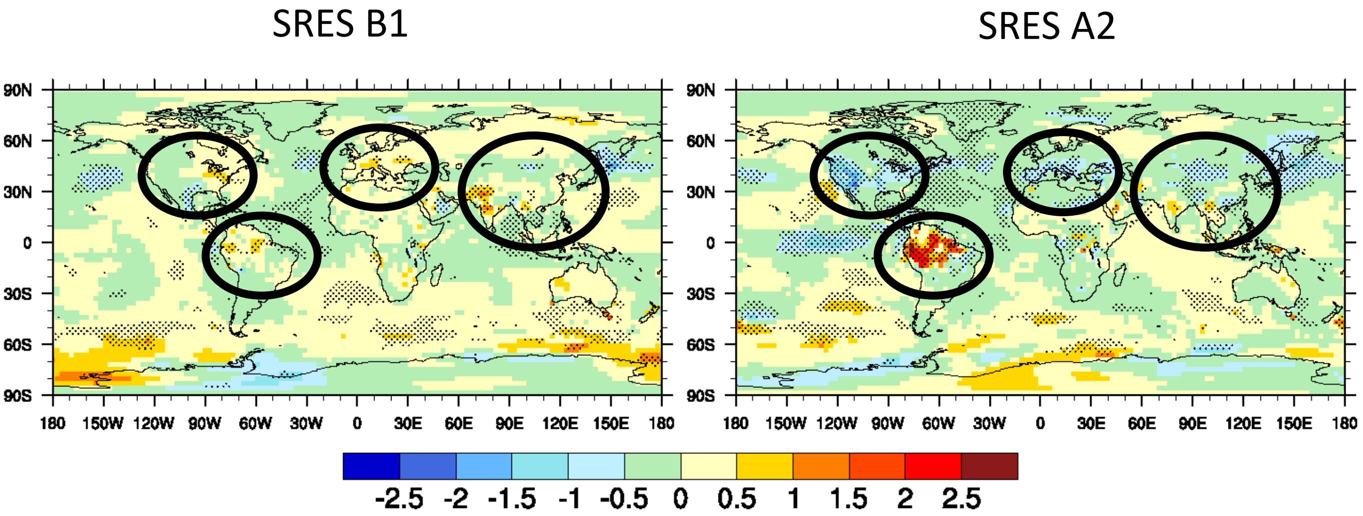


Feddema et al. (2005) Science 310:1674-1678

Climate outcome of land use choices

Change in temperature (JJA) due to land cover

2100



B1
- Weak temperate warming
- Weak tropical warming

A2
- Temperate cooling
- Tropical warming

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

Biogeophysical vs. biogeochemical interactions

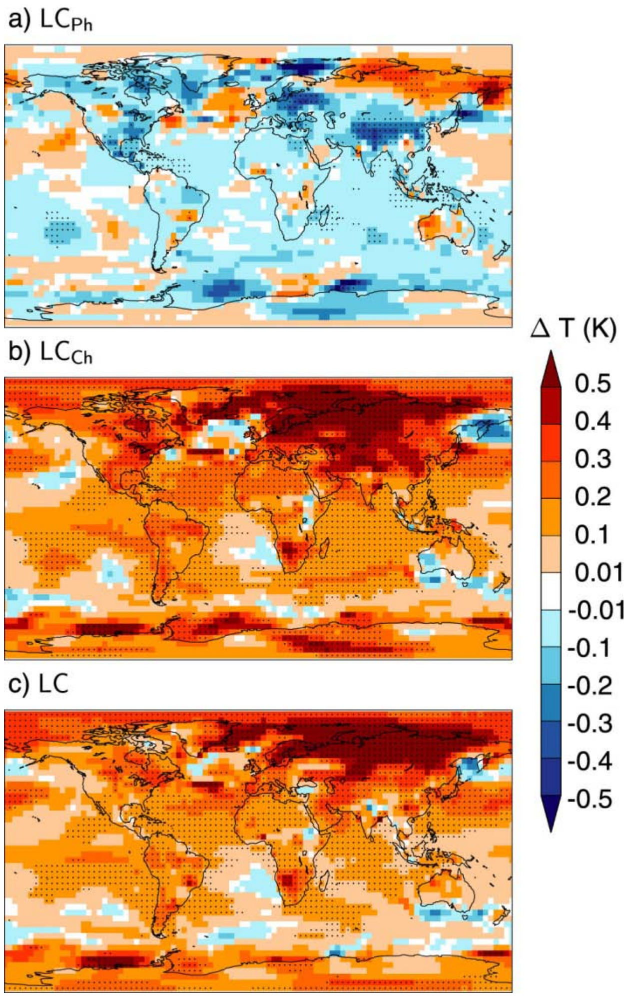
Prevailing paradigm
The dominant competing signals from historical deforestation are an increase in surface albedo countered by carbon emission to the atmosphere

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)



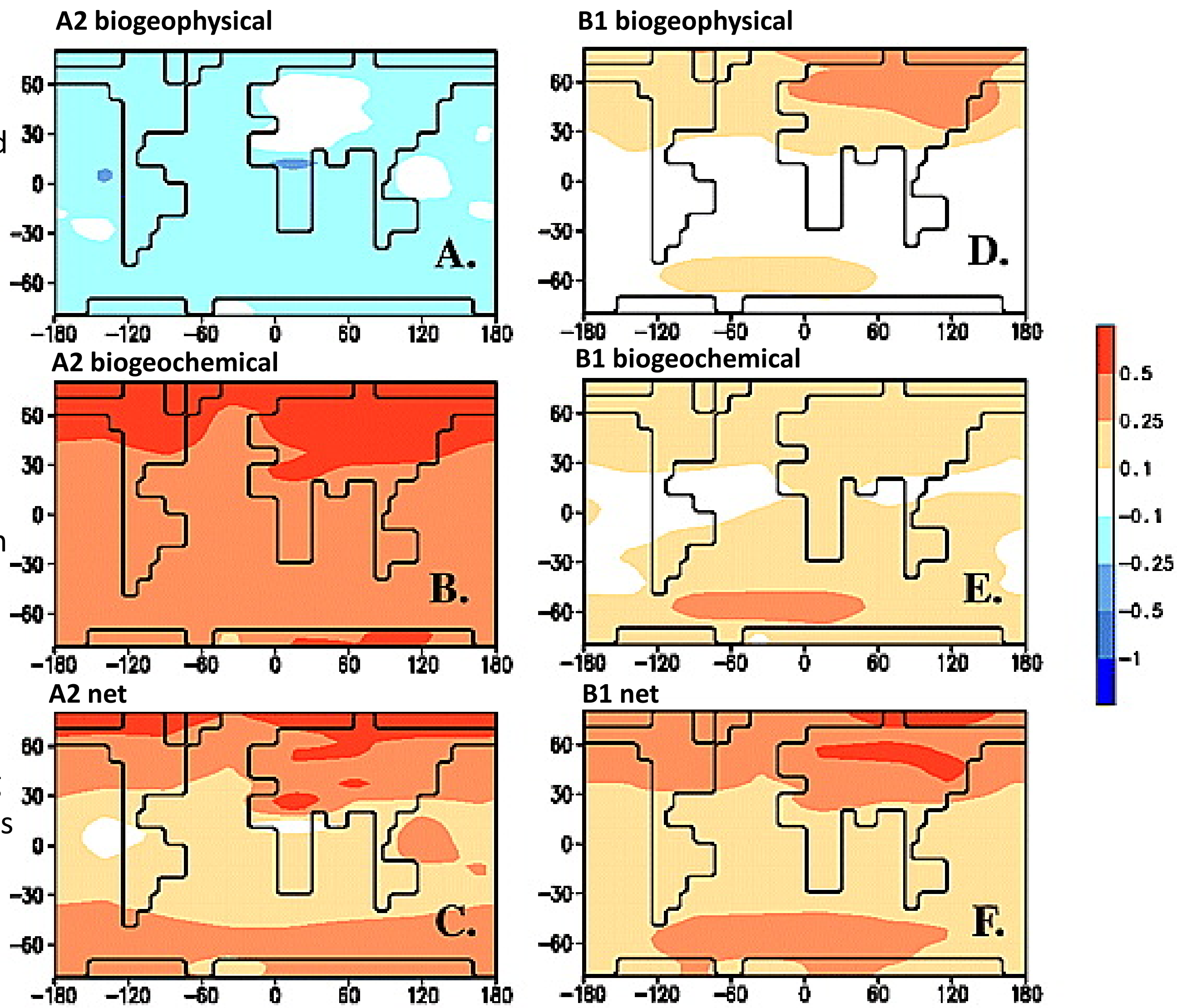
Pongratz et al. (2010) GRL,37, doi:10.1029/2010GL043010

Future land cover change

Biogeophysical
A2 – cooling with widespread cropland
B1 – warming with temperate reforestation

Biogeochemical
A2 – large warming; widespread deforestation
B1 – weak warming; less tropical deforestation, temperate reforestation

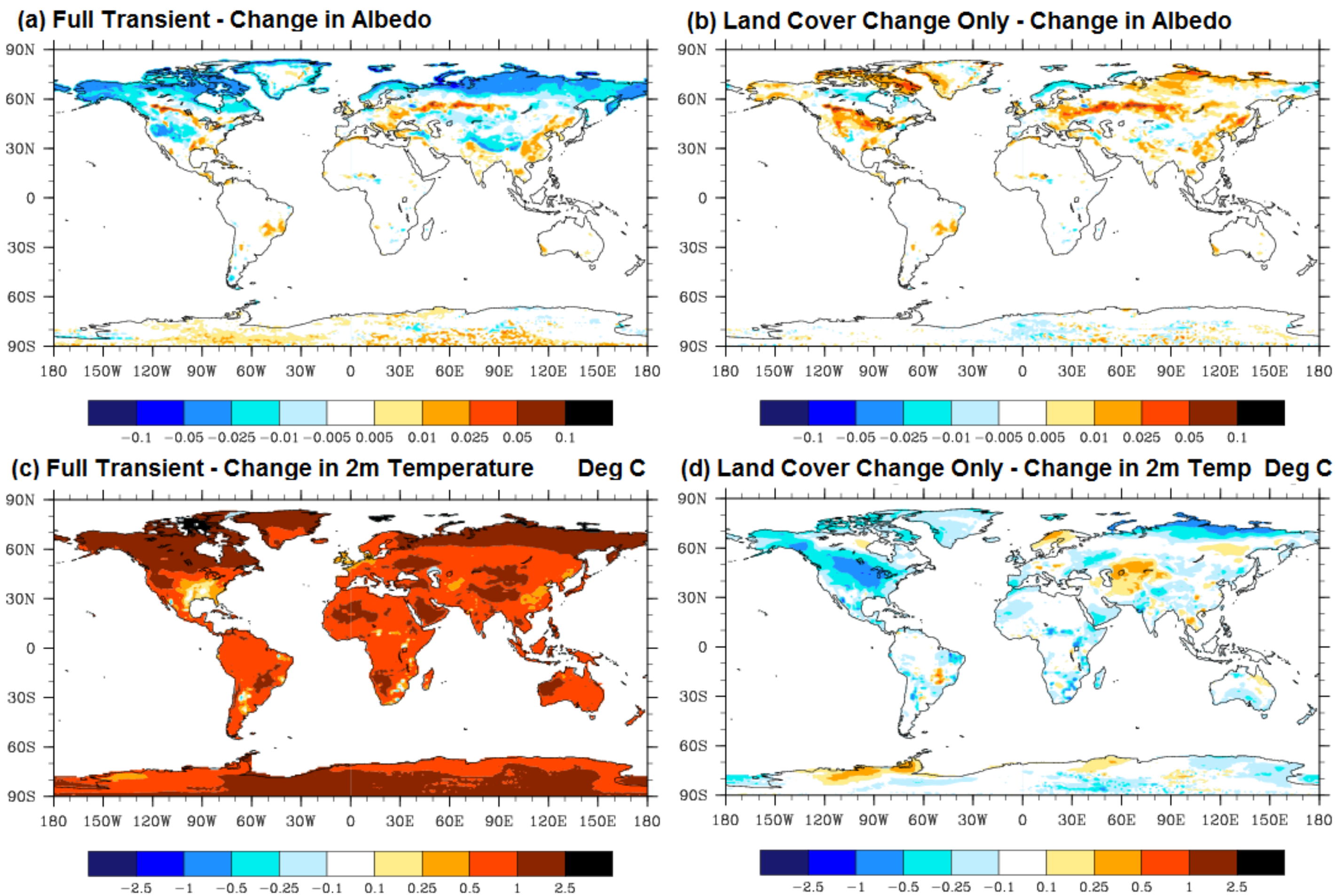
Net effect similar
A2 – BGC warming offsets BGP cooling
B1 – moderate BGP warming augments weak BGC warming



Sitch et al. (2005) GBC, 19, GB2013, doi:10.1029/2004GB002311

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)

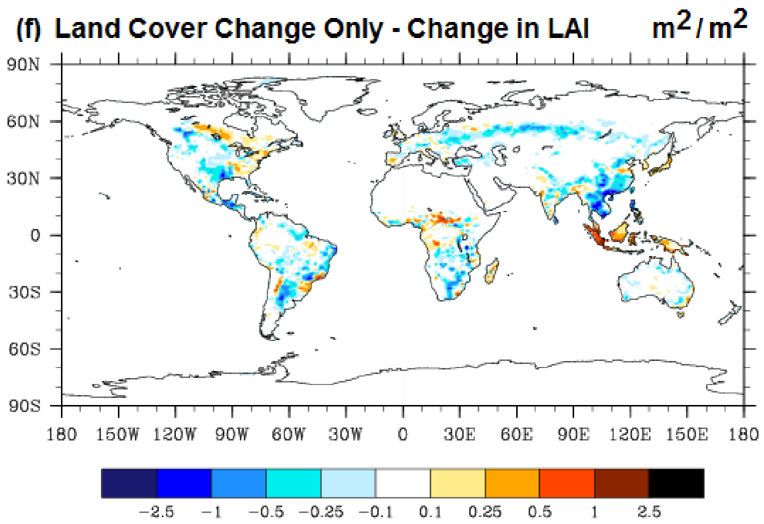
Key points:

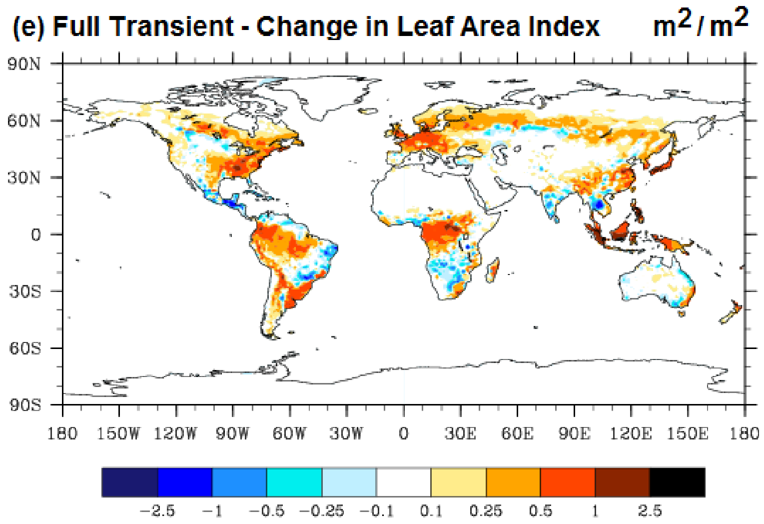
LULCC forcing is counter to all forcing

LULCC forcing is regional, all forcing is global

P. Lawrence et al. (2012) J Climate 25:3071-3095

Opposing trends in vegetation





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

Single forcing simulation
Land cover change only

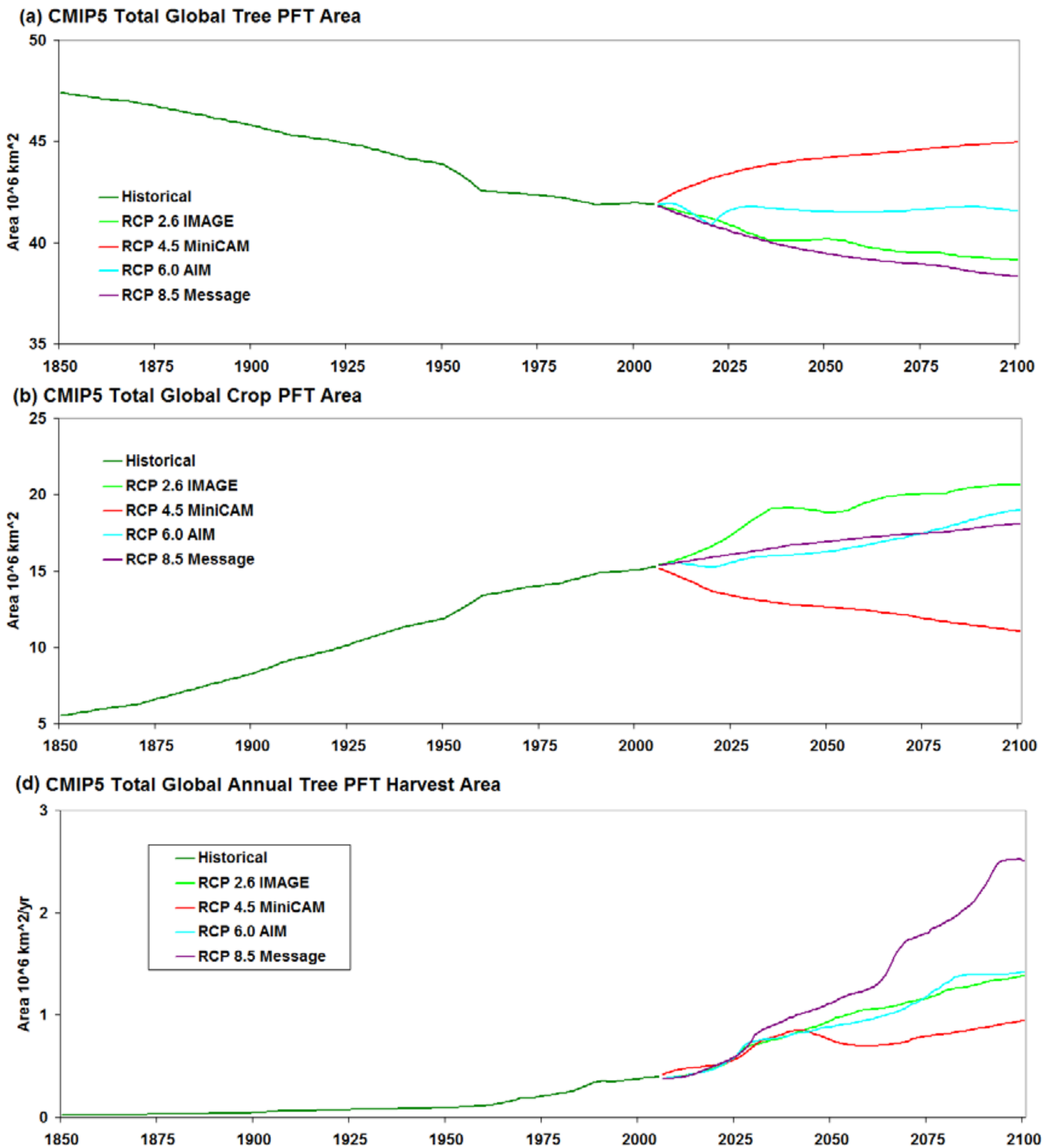
Loss of leaf area, except where reforestation

All forcing simulation
CO_2
Climate
Nitrogen deposition
Land cover change

Increase in leaf area, except where agricultural expansion

P. Lawrence et al. (2012) J Climate 25:3071-3095

21st century land use & land cover change



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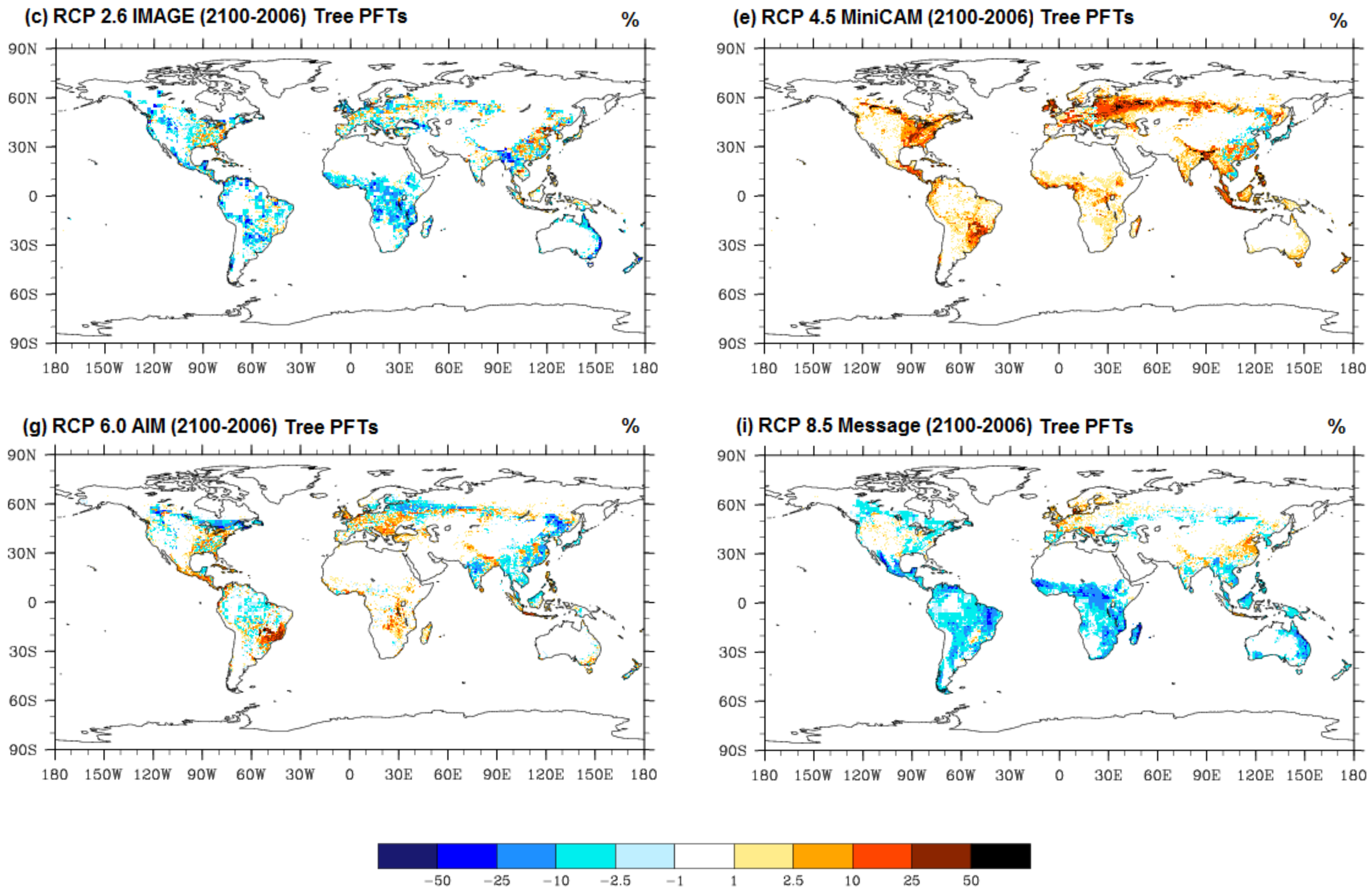
Description

- **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.

Twenty-first century forests

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



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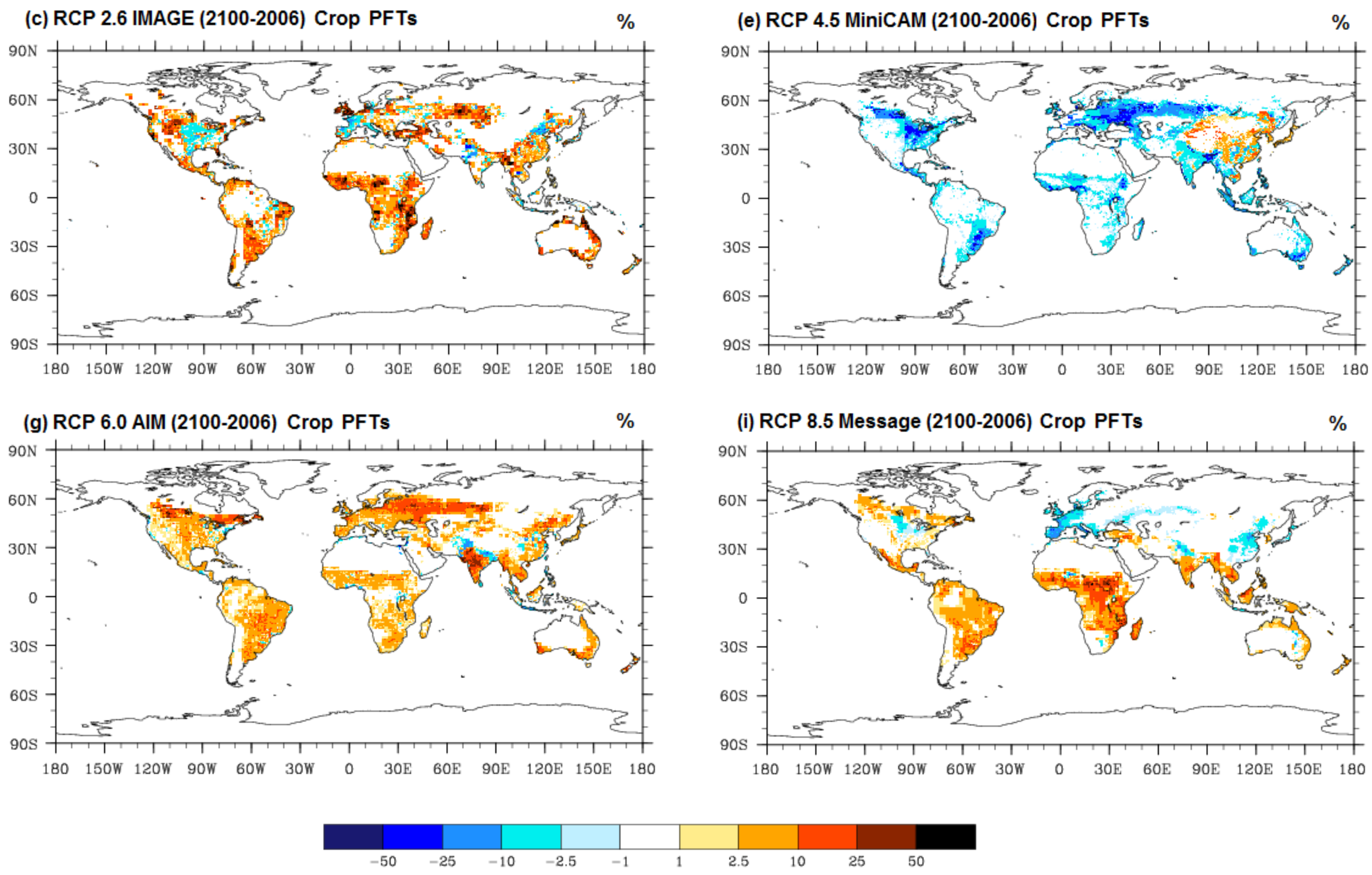
Twenty-first century cropland

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



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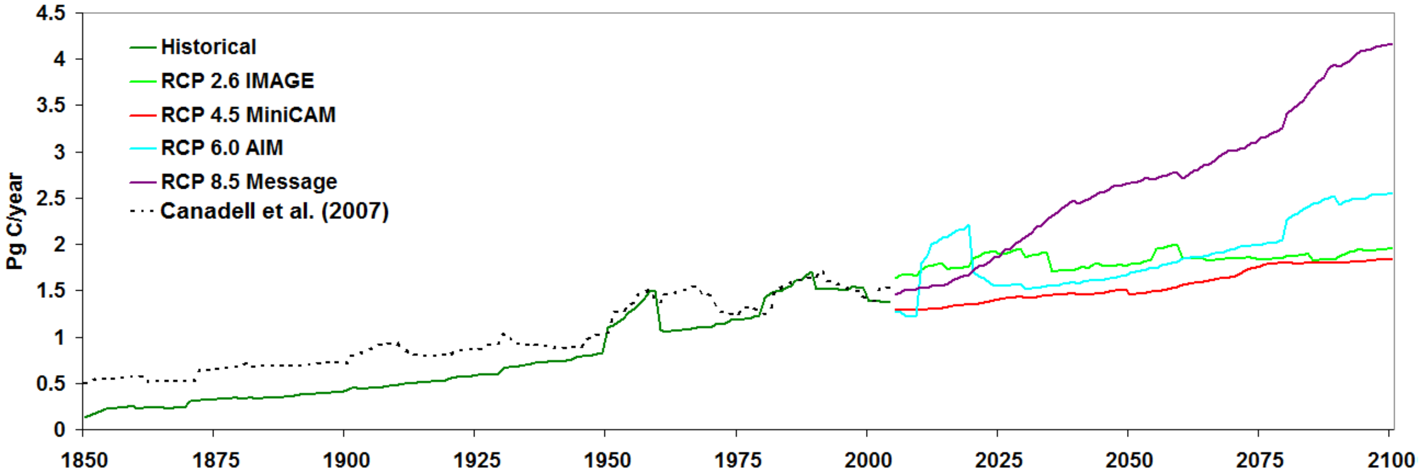
Carbon cycle

LULCC carbon flux to atmosphere



Land use choice matters

RCP 4.5 : reforestation drives carbon gain

RCP 8.5 : deforestation and wood harvest drive carbon loss

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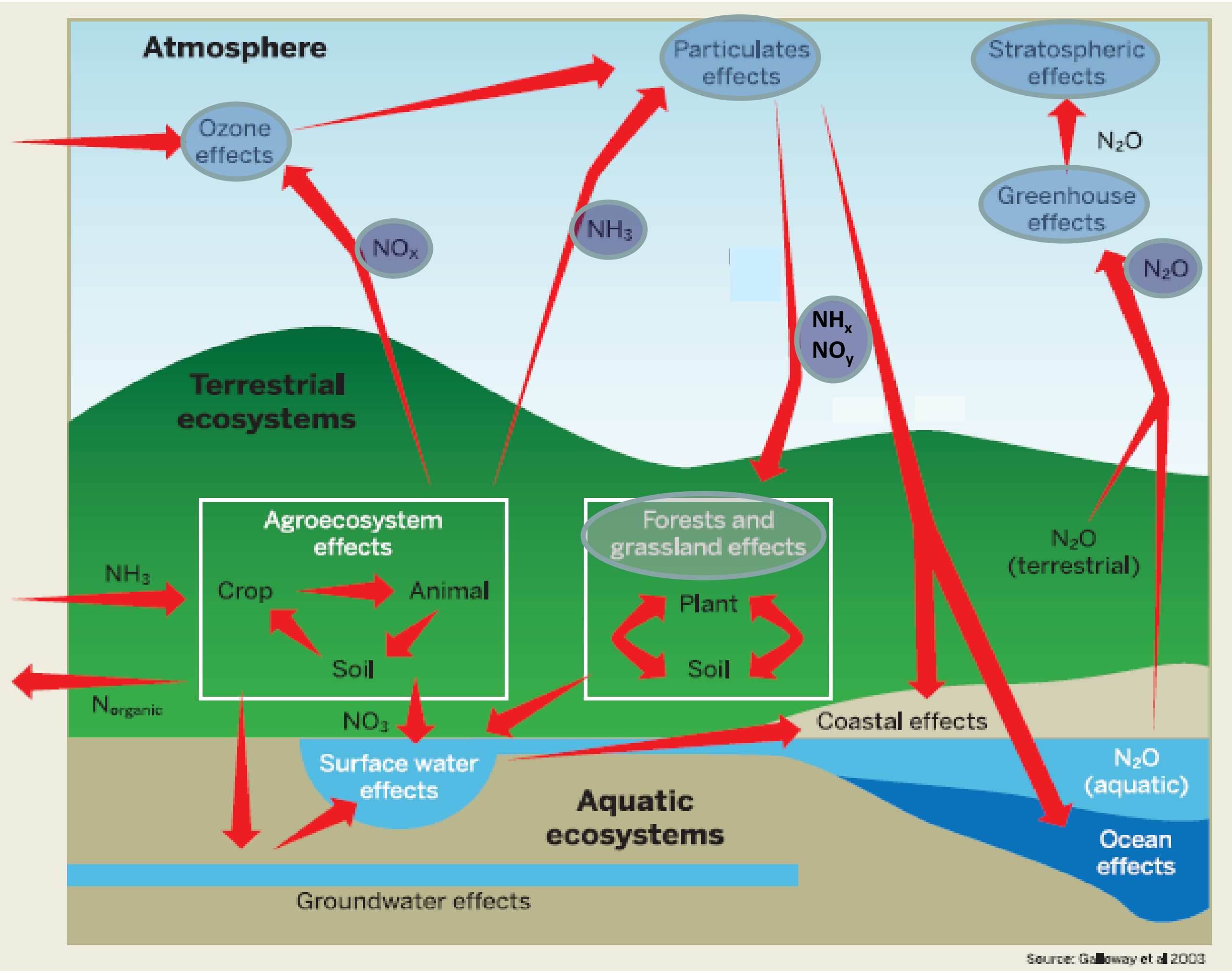
Nitrogen cascade and climate



Science

Increasing emissions of nitrogen oxides (NO_x), ammonia (NH_3), and nitrous oxide (N_2O) alter atmospheric composition and chemistry

- ❑ N_2O, O_3, CH_4, and aerosols

Deposition of NH_x and NO_y on land alters ecosystems

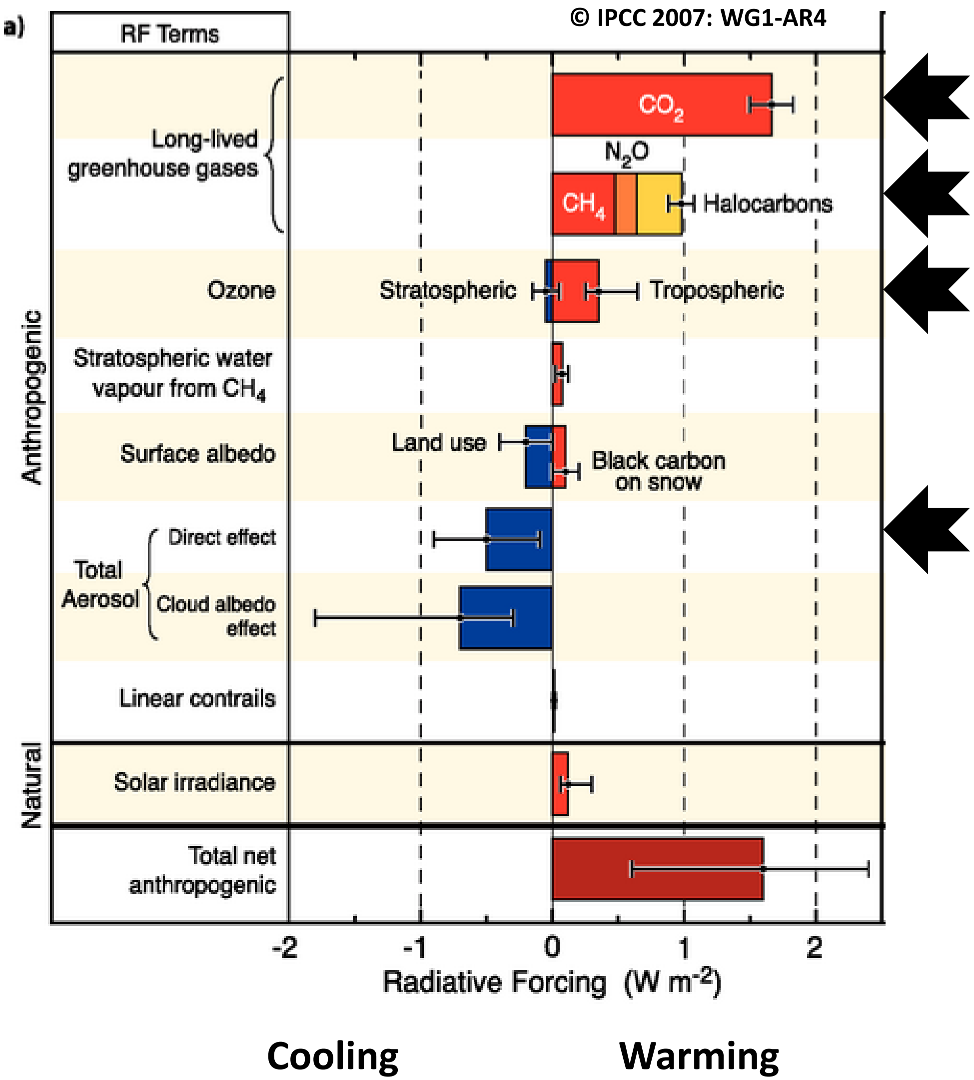
- ❑ Carbon storage, biodiversity

Indirect effects, e.g., higher surface 0_3 reduces plant productivity

Policy

Nitrogen management strategies for global climate change mitigation, and concomitant benefits to society through the N cascade

Effect of additional N on global mean radiative forcings

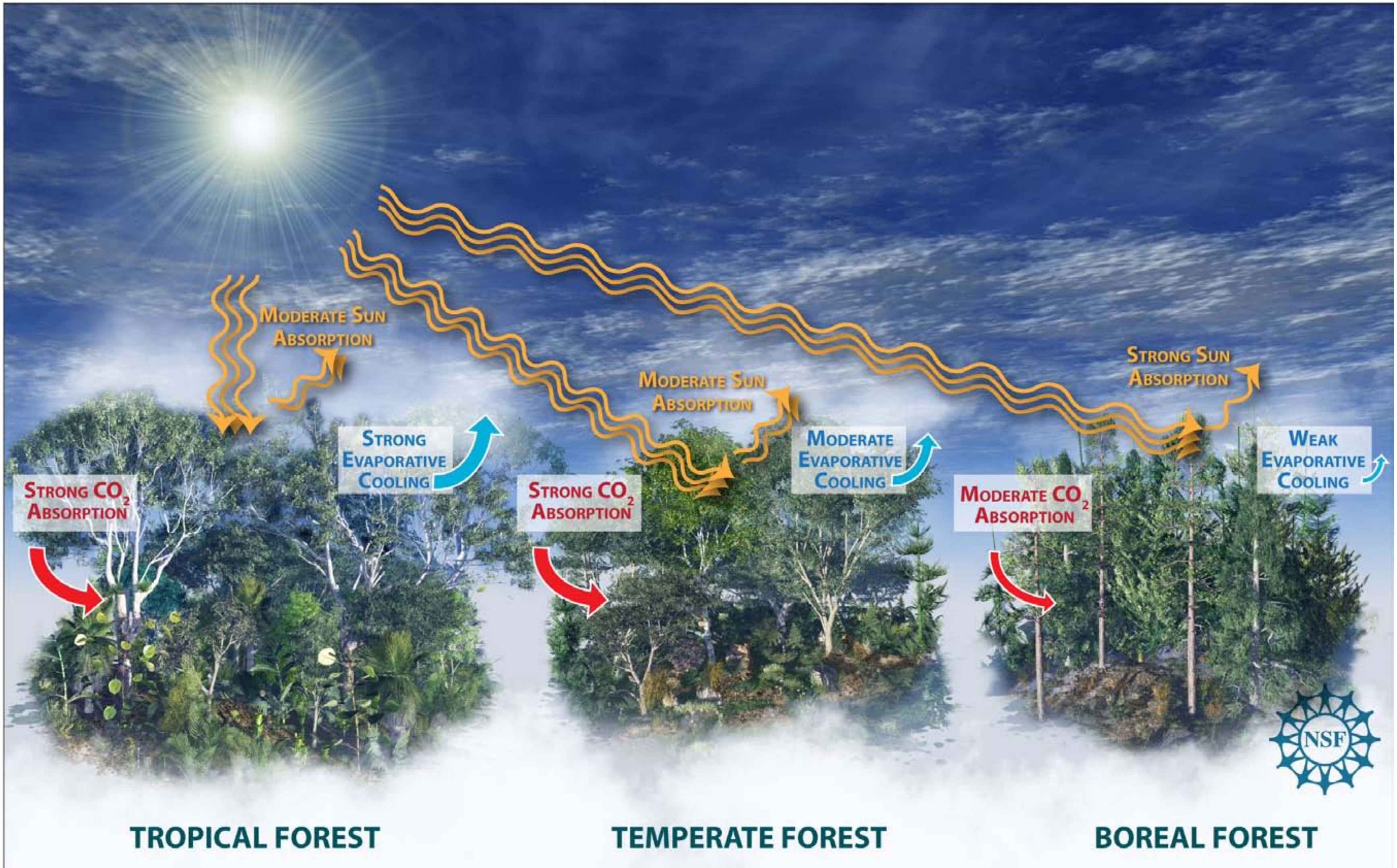


Nitrogen addition:	**Change in radiative forcing**
Increases land CO_2 uptake	(-)
N_2O emission: Increases N_2O	(+)
NO_X emission: Decreases CH_4	(-)
NO_X emission: Increases tropospheric O_3	(+)
N_2O emission: Decreases stratospheric O_3	(+)
NH_3 emission: Increases aerosols	(-)

Nitrogen addition alters the composition and chemistry of the atmosphere, and changes the radiative forcing. The net radiative forcing varies regionally.

Terrestrial ecosystems and global environmental change

Multiple competing influences of forests – albedo, ET, C, and also Nr, aerosols



Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*