Biosphere–atmosphere interactions in Earth system models

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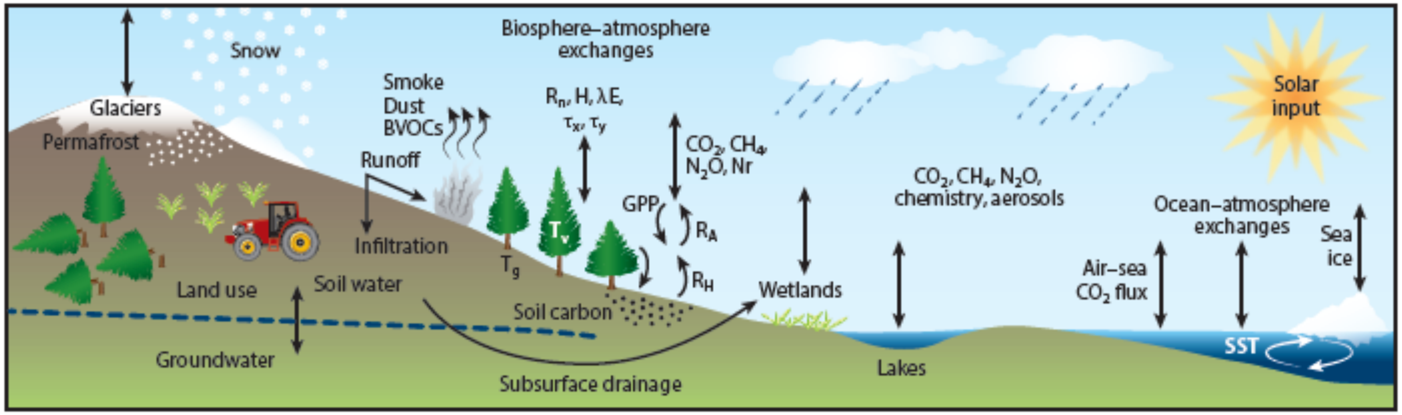
Earth system models



Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)
Bonan (2016) Annu. Rev. Ecol. Evol. Syst. 47:97-121

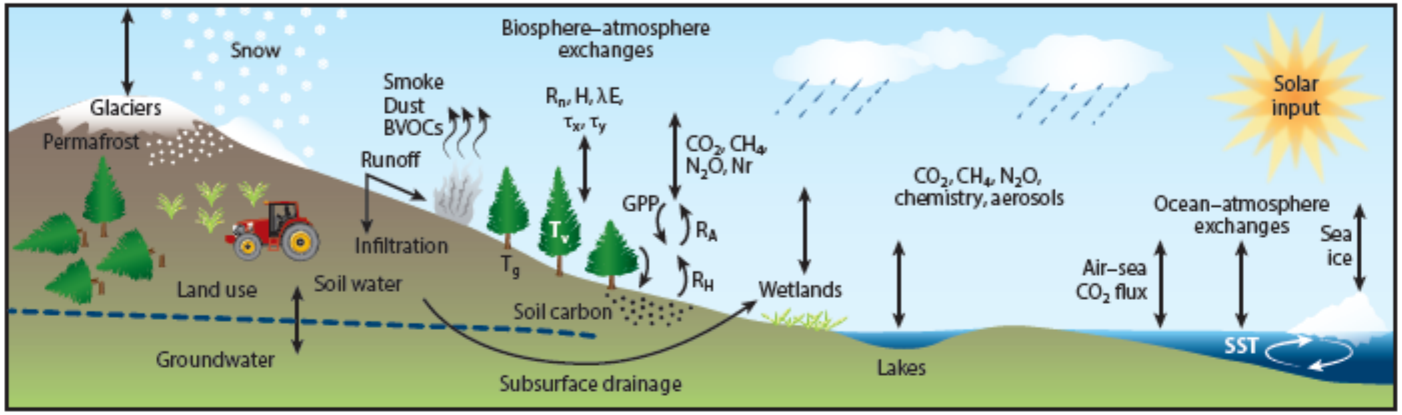
Earth system models use mathematical formulas to simulate the **physical**, **chemical**, and **biological** processes that drive Earth's atmosphere, hydrosphere, biosphere, and geosphere

A typical Earth system model consists of coupled models of the **atmosphere**, **ocean**, **sea ice**, **land**, and **glaciers**

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 environmental change

Earth system models



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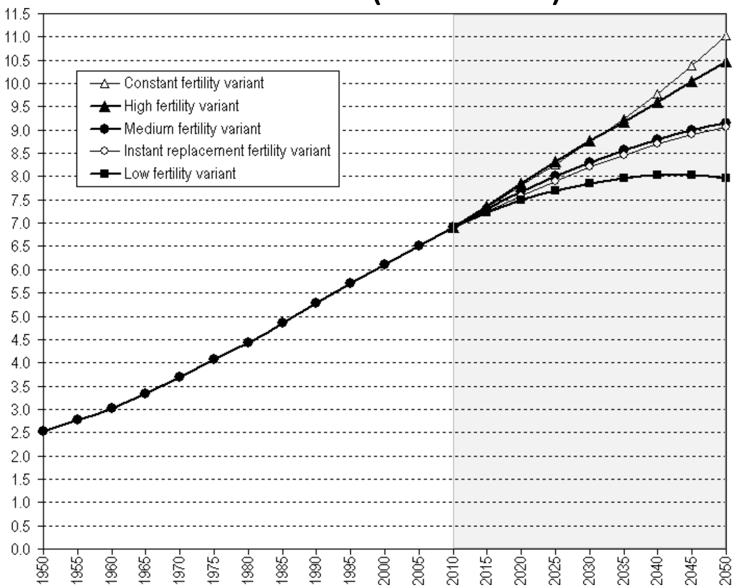
Bonan (2016) Annu. Rev. Ecol. Evol. Syst. 47:97-121

Prominent terrestrial feedbacks

- Snow cover and climate
- Soil moisture-evapotranspiration-precipitation
- Land use and land cover change
- Carbon cycle
- Reactive nitrogen
- Chemistry-climate (BVOCs, O_3, CH_4, aerosols)
- Biomass burning

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?

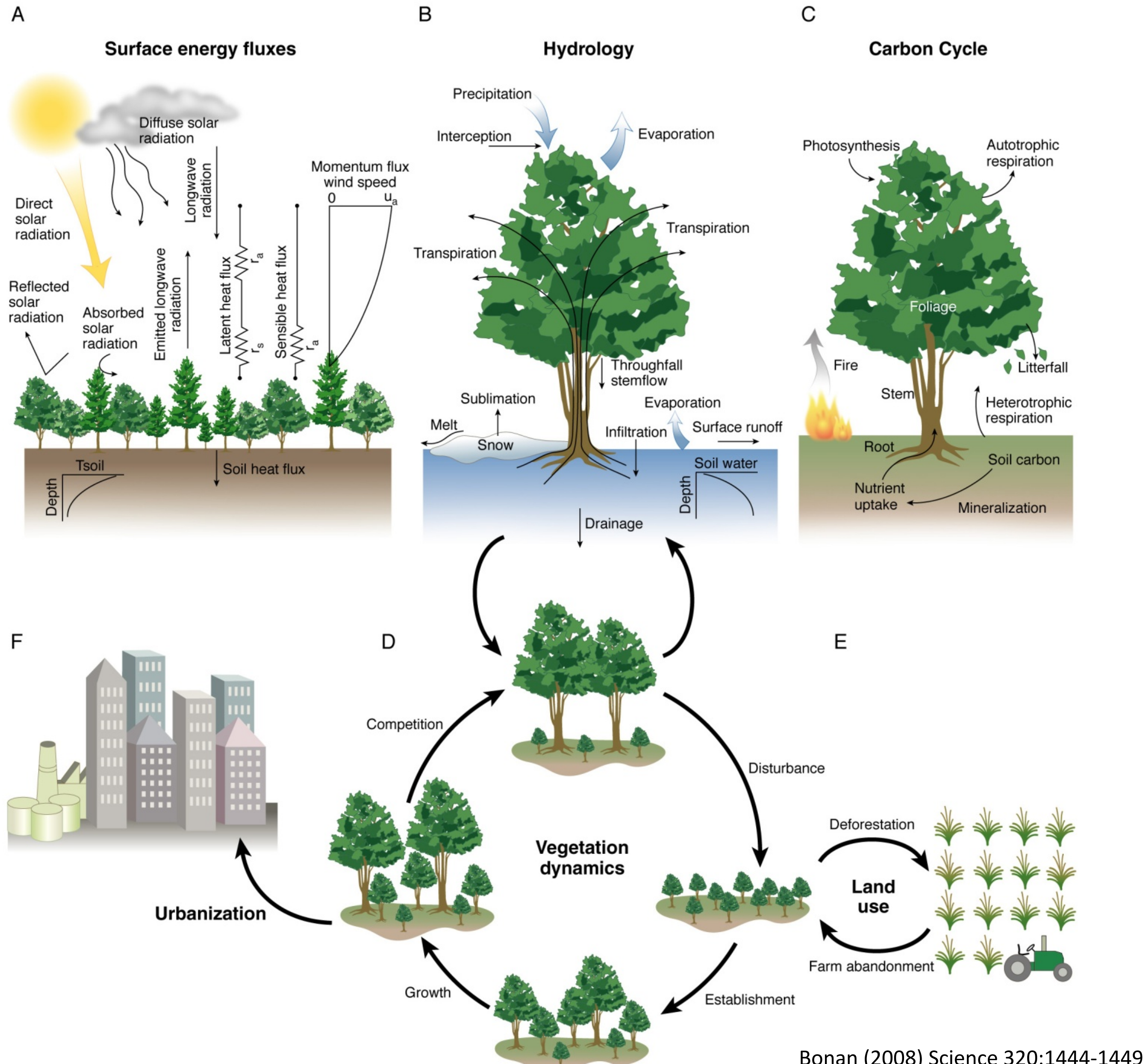
Planetary distress

Drought, Waterloo, NE (Nati Harnik, AP)
Corn production, Midwest US (Daniel Acker/Bloomberg)
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)
Glacial calving (www.extremeicesurvey.org)
Midway-Sunset oil field, CA (Jim Wilson/The New York Times)

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)

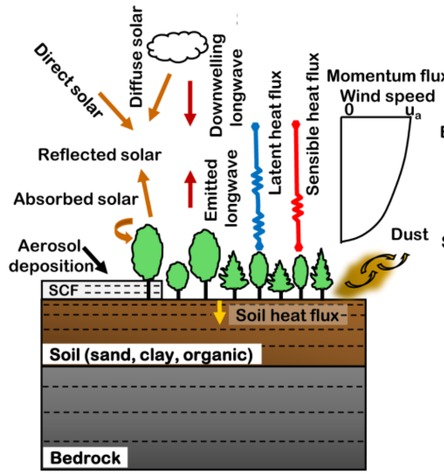


Bonan (2008) Science 320:1444-1449

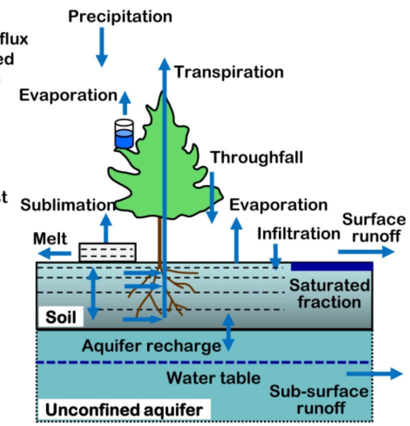
The Community Land Model

Fluxes of energy, water, CO_2, CH_4, BVOCs, and Nr and the processes that control these fluxes in a changing environment

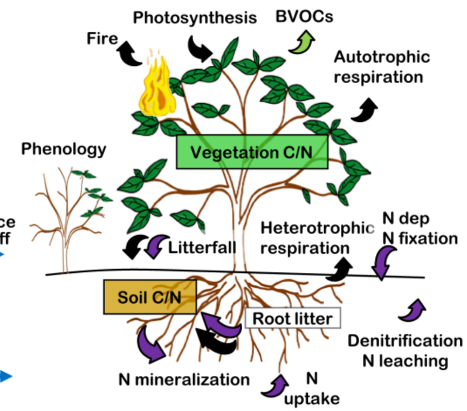
Surface energy fluxes



Hydrology



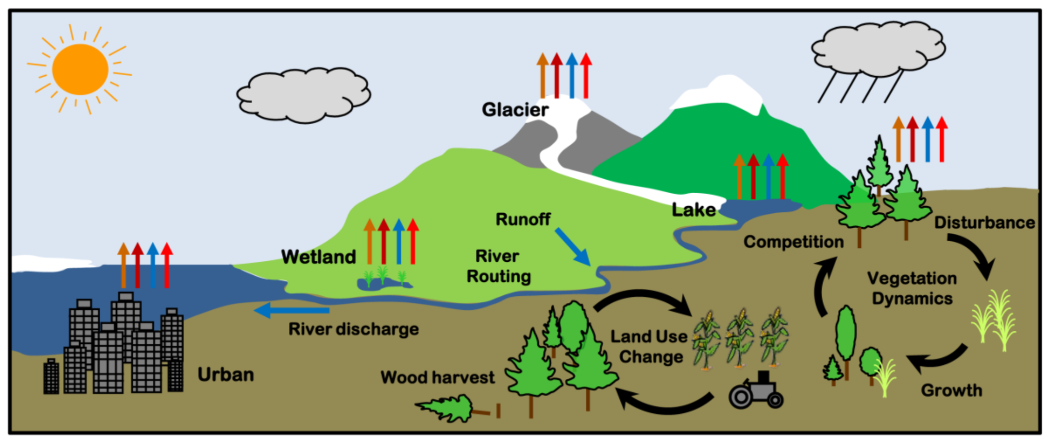
Biogeochemistry



Oleson et al. (2013) NCAR/TN-503+STR (420 pp)

Lawrence et al. (2011) J. Adv. Mod. Earth Syst., 3, doi: 10.1029/2011MS000045

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



Landscape dynamics

Spatial scale

1.25° longitude ? 0.9375° latitude (288 ? 192 grid), ~100 km ? 100 km

Temporal scale

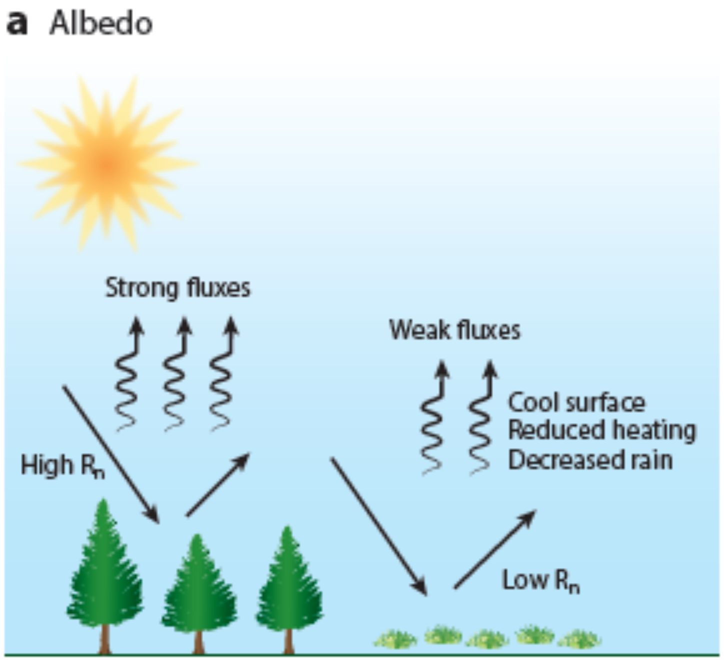
- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century (disturbance, land use, succession)
- Paleoclimate (biogeography)

Biogeophysical processes

Trees have a low albedo

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

Colorado Rocky Mountains



Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)
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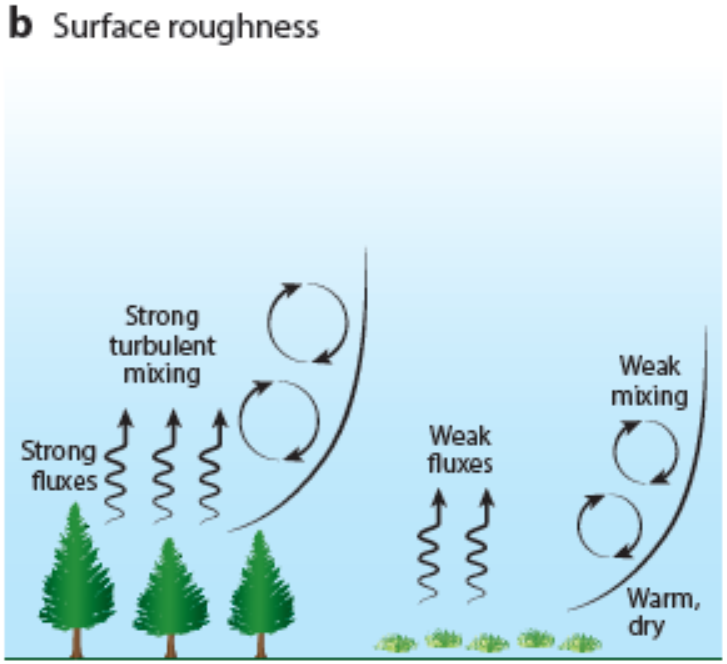
Biogeophysical processes

Trees are tall (aerodynamically rough)

Cowling Arboretum, Carleton College

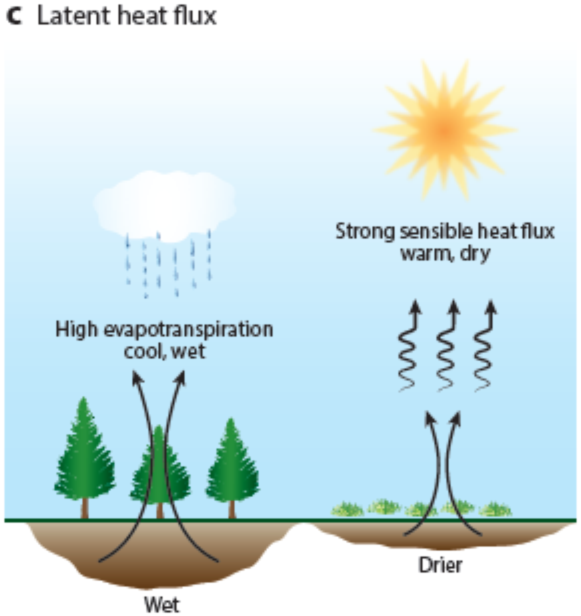


Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)
Bonan (2016) Annu. Rev. Ecol. Evol. Syst. 47:97-121

Biogeophysical processes

Soil moisture and evapotranspiration

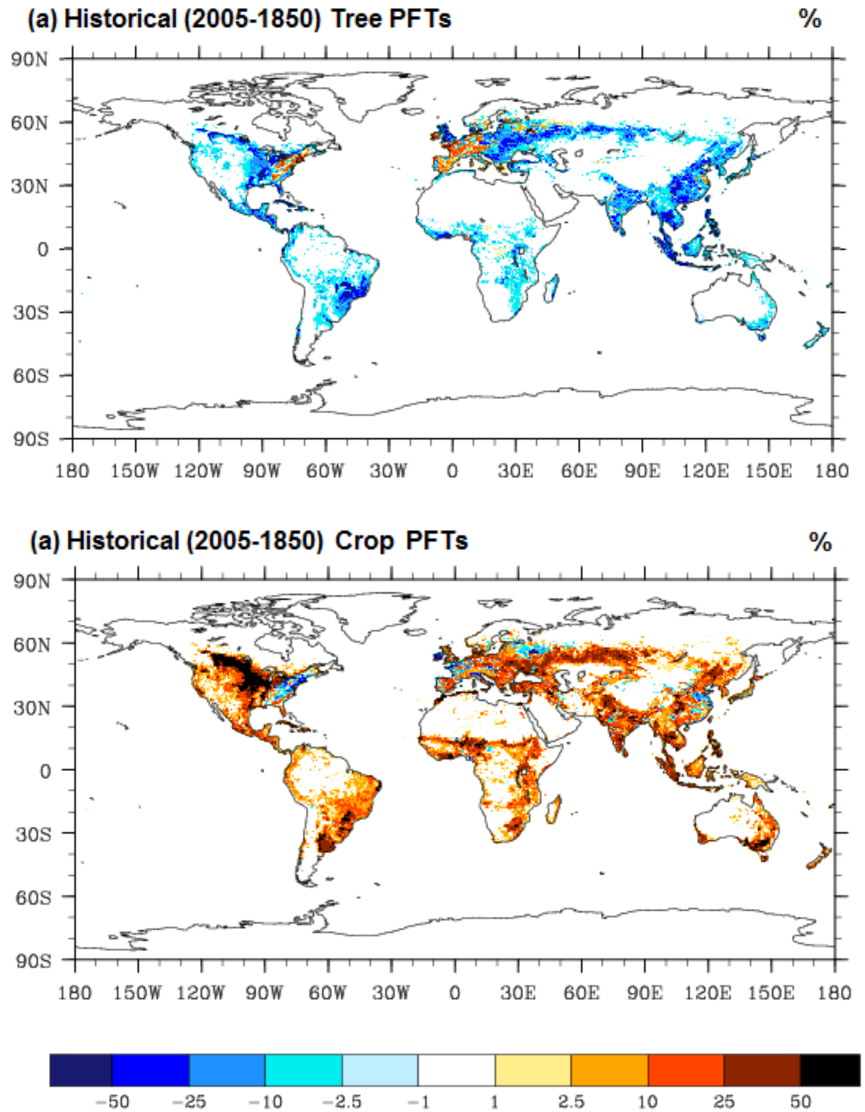
2012 drought, Waterloo, NE (Nati Harnik, AP)



Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)
Bonan (2016) Annu. Rev. Ecol. Evol. Syst. 47:97-121

Historical land use & land cover change, 1850-2005

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

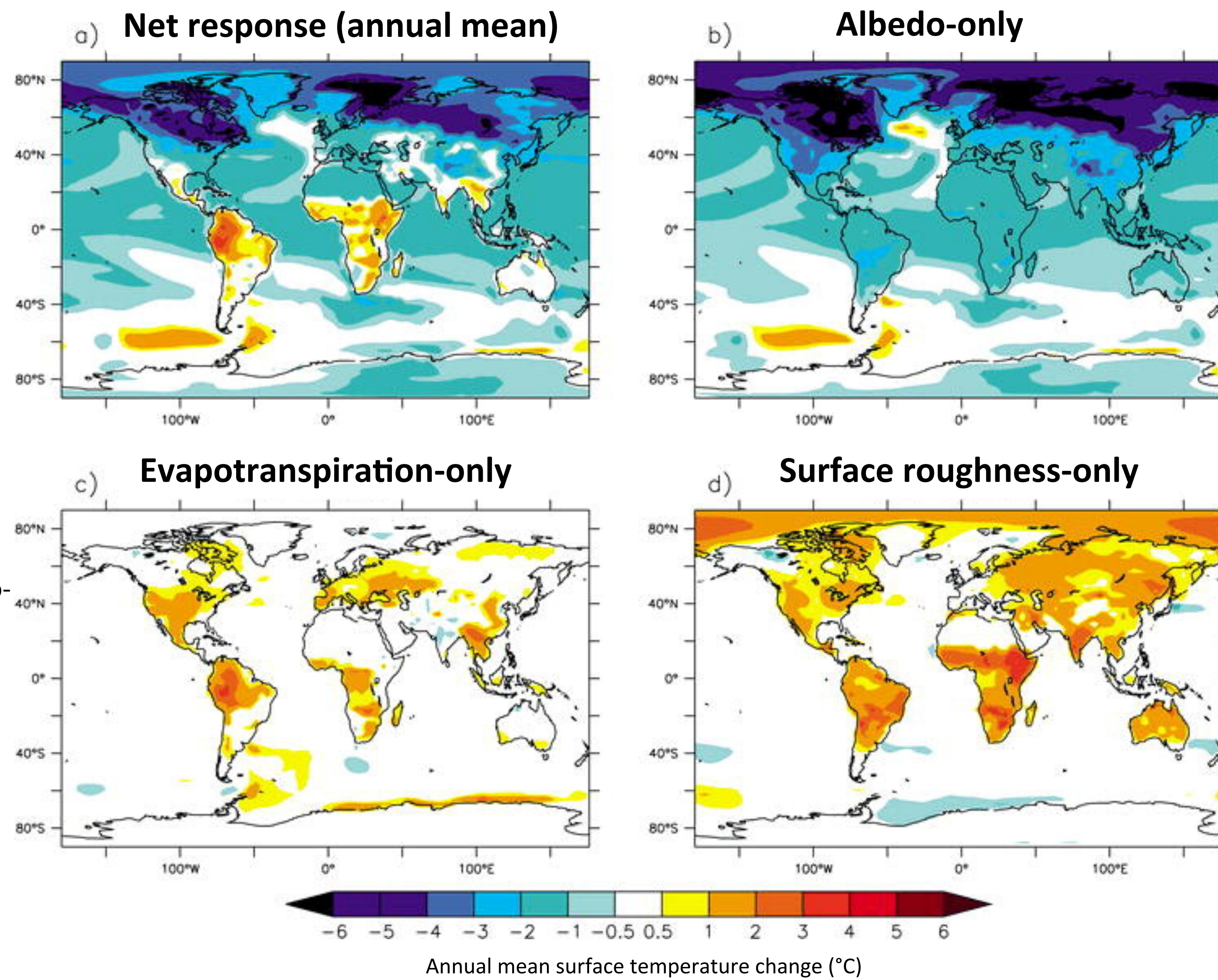


Historical land use & land-cover change

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

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

Forests influences on global climate



Higher albedo with deforestation

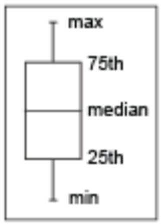
Reduced evapo-transpiration

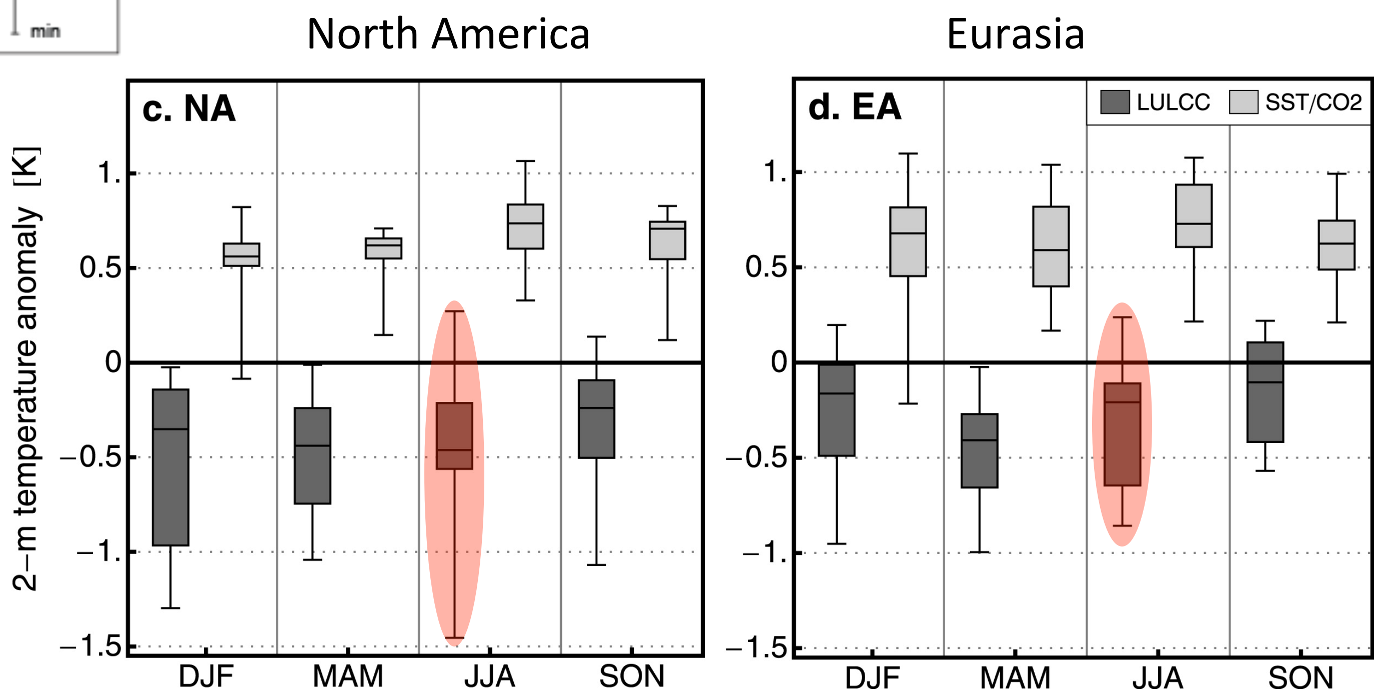
Reduced surface roughness

Davin & de Noblet-Ducoudré (2010) J Clim. 23:97-112

The LUCID intercomparison study

Multi-model ensemble (7) of the simulated changes between the pre-industrial time period and present-day





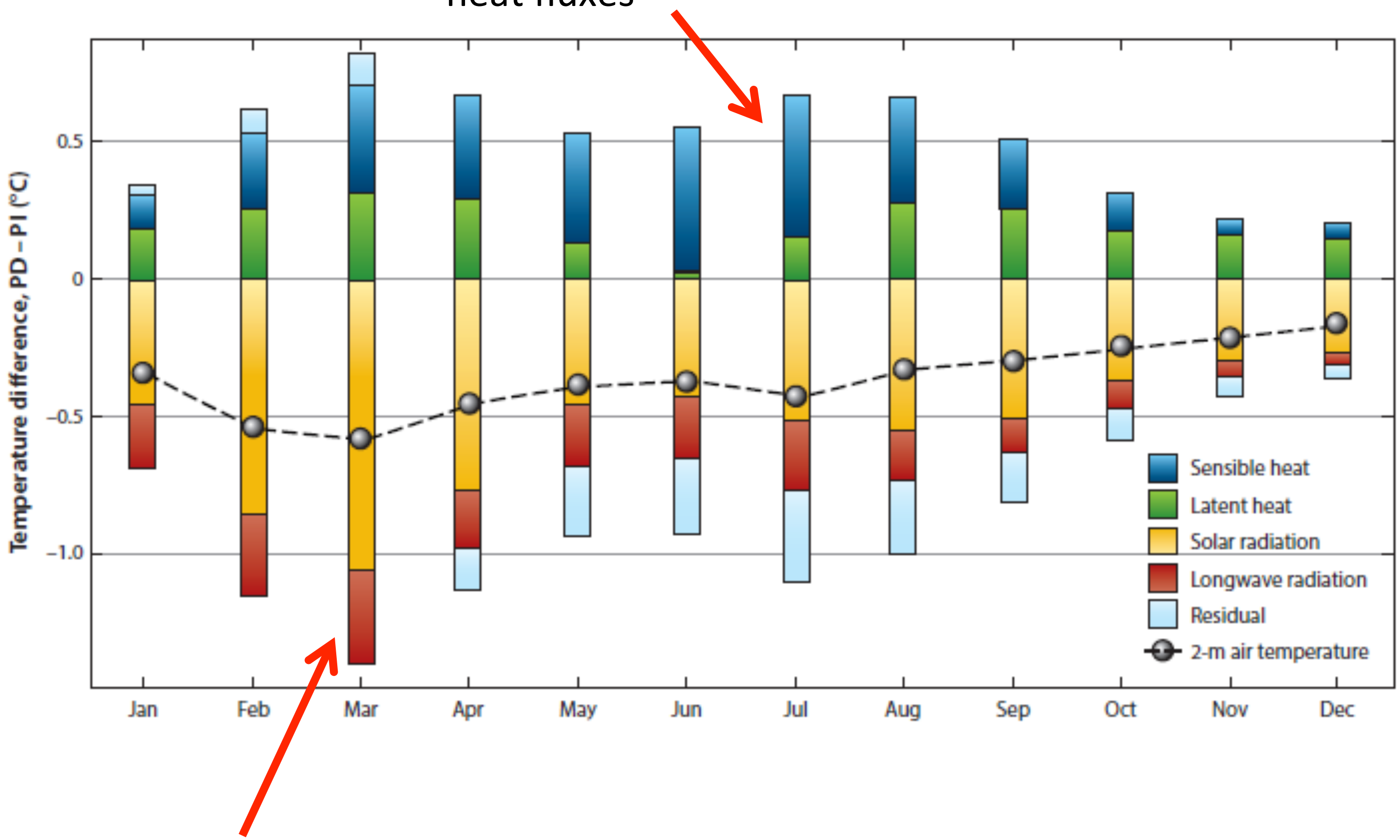
CO_2 + SST + SIC forcing leads to warming

Land-cover change leads to cooling

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

Biogeophysical mechanisms

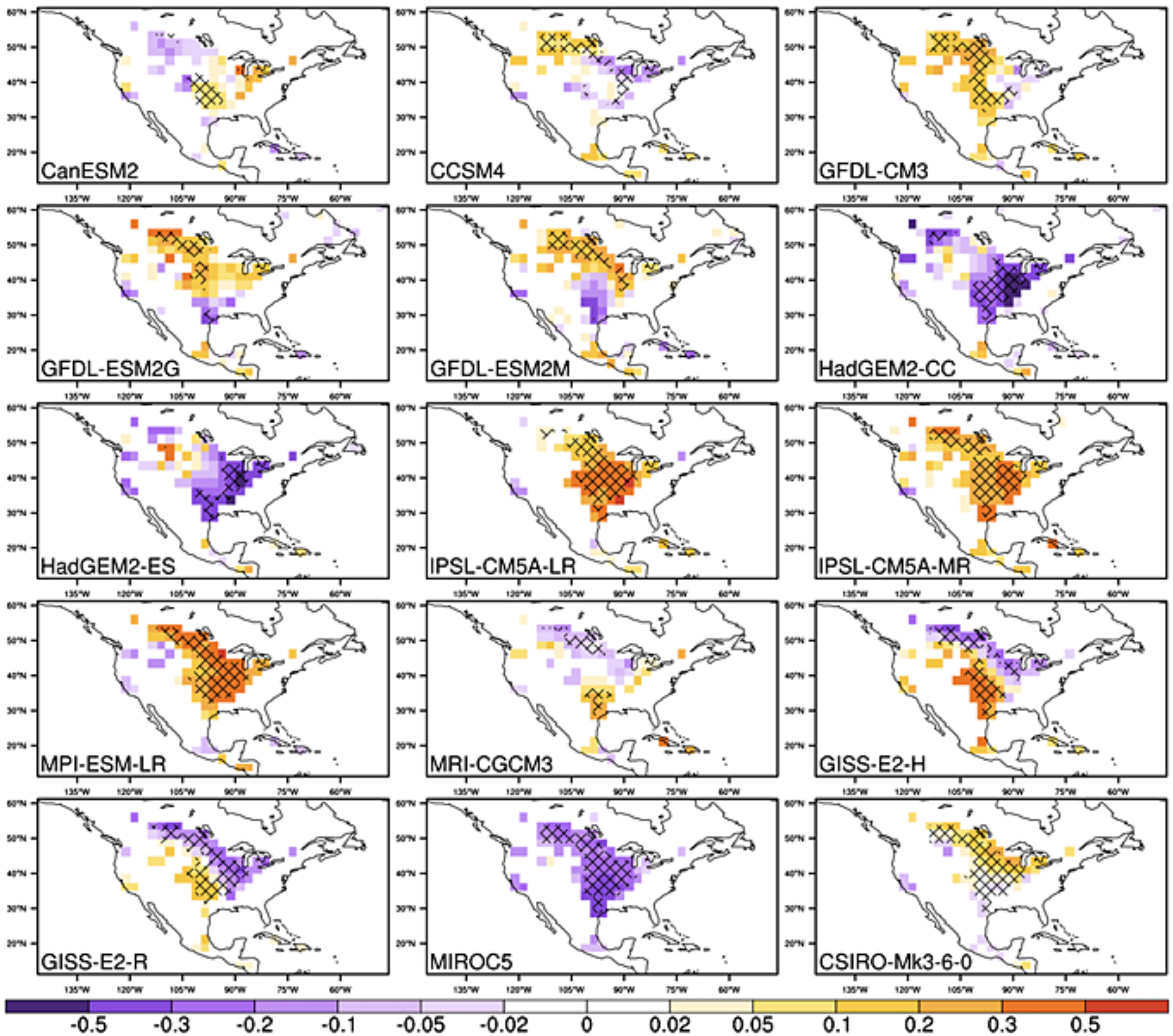
Warming from sensible and latent heat fluxes



Radiative cooling

Boisier et al. (2012) JGR, 117, doi:10.1029/2011JD017106

Model variability

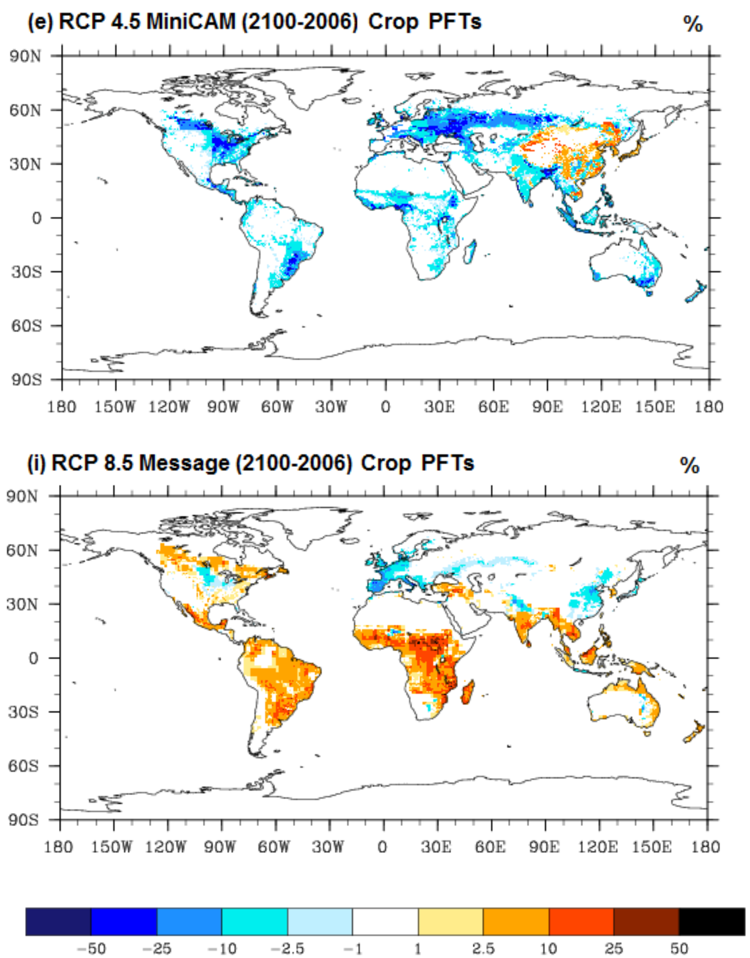


15 CMIP5 models: Change in JJA temperature (°C) with 20th century land-cover change

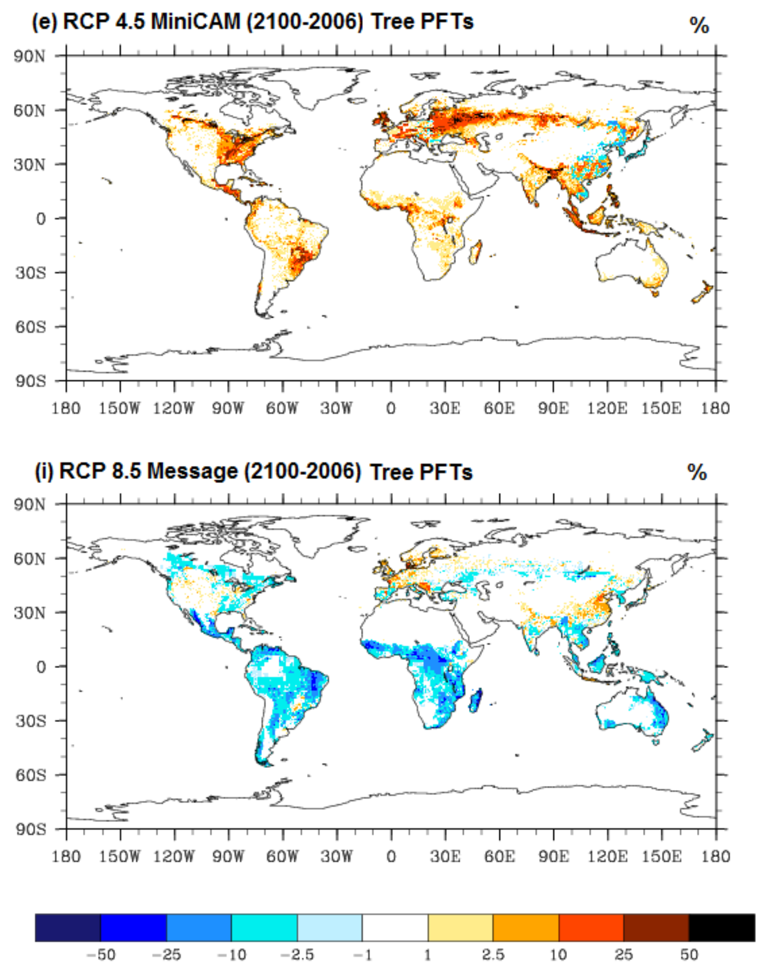
Kumar et al. (2013) JGR: Atm, 118, doi:10.1002/jgrd.50463

Twenty-first century land-cover change

Change in crop cover (percent of grid cell)



Change in tree cover (percent of grid cell)

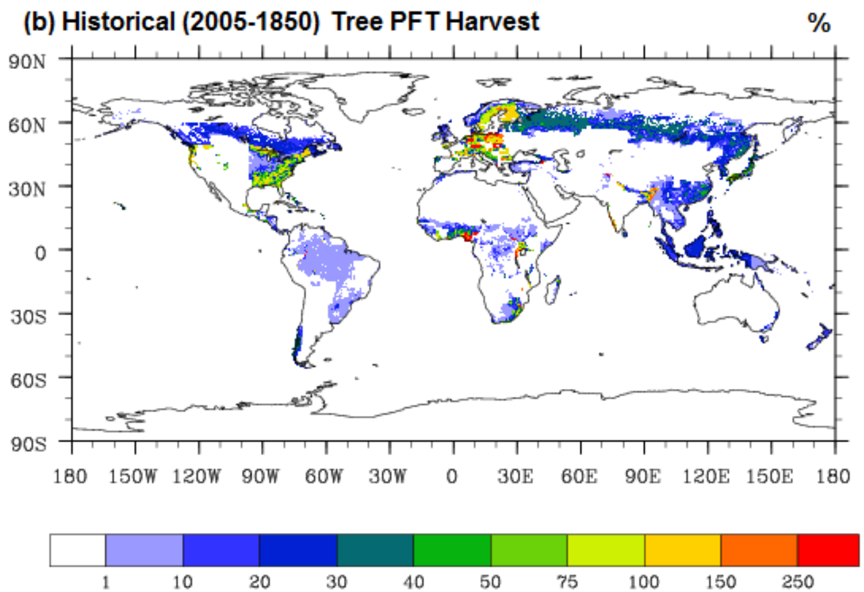


Lawrence et al. (2012) J Clim. 25:3071-3095

Land management

Forest management

Cumulative percent of grid cell harvested



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

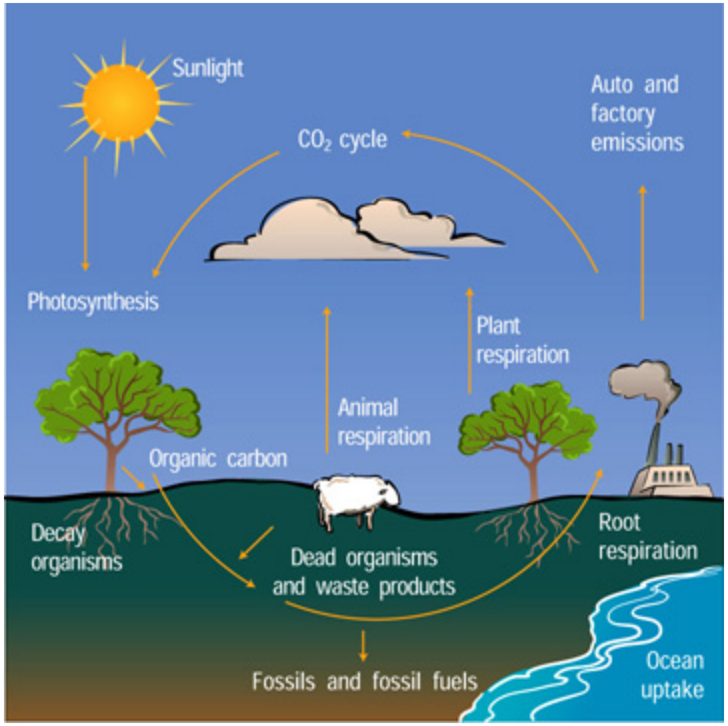
Agricultural management

Tillage
Crop selection
Irrigation
Fertilizer use

<u>8 crop functional types</u>:

Maize (temperate, tropical)	Sugarcane
Soybean (temperate, tropical)	Cotton
Spring wheat	Rice

Carbon cycle and climate change



(UCAR)

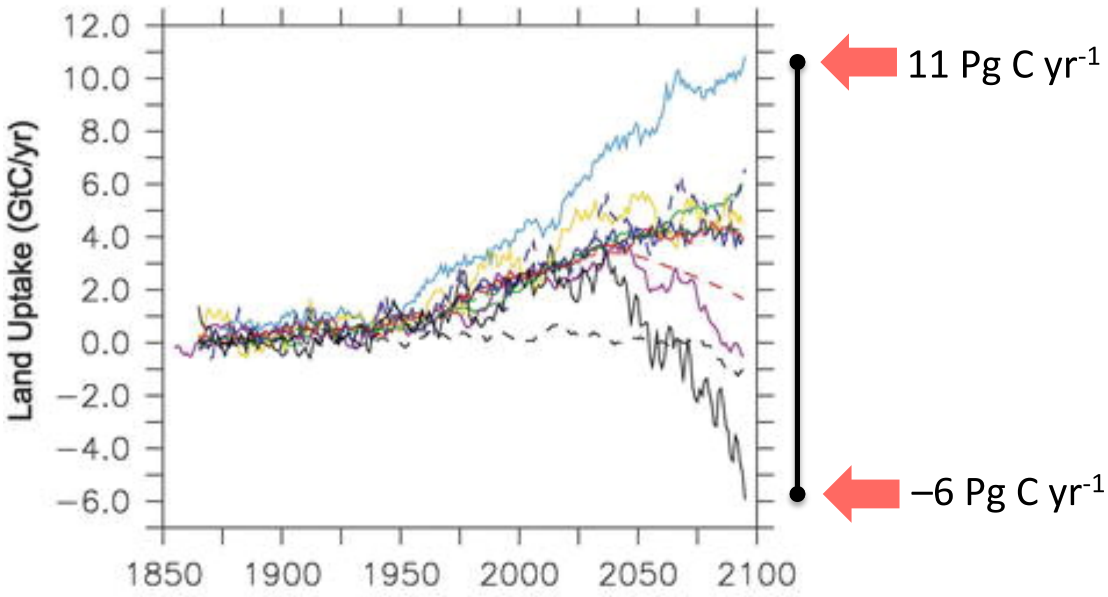
Atmospheric CO_2 has increased by 112 ppm (1750-2011) as a balance of:

- Fossil fuel emissions
- Land-use and land-cover change emissions
- Terrestrial and oceanic sinks

How will the global carbon cycle change in the future?

Will the terrestrial biosphere continue to be a carbon sink?

C4MIP – Climate and carbon cycle



Carbon cycle-climate feedback

11 carbon cycle-climate models of varying complexity

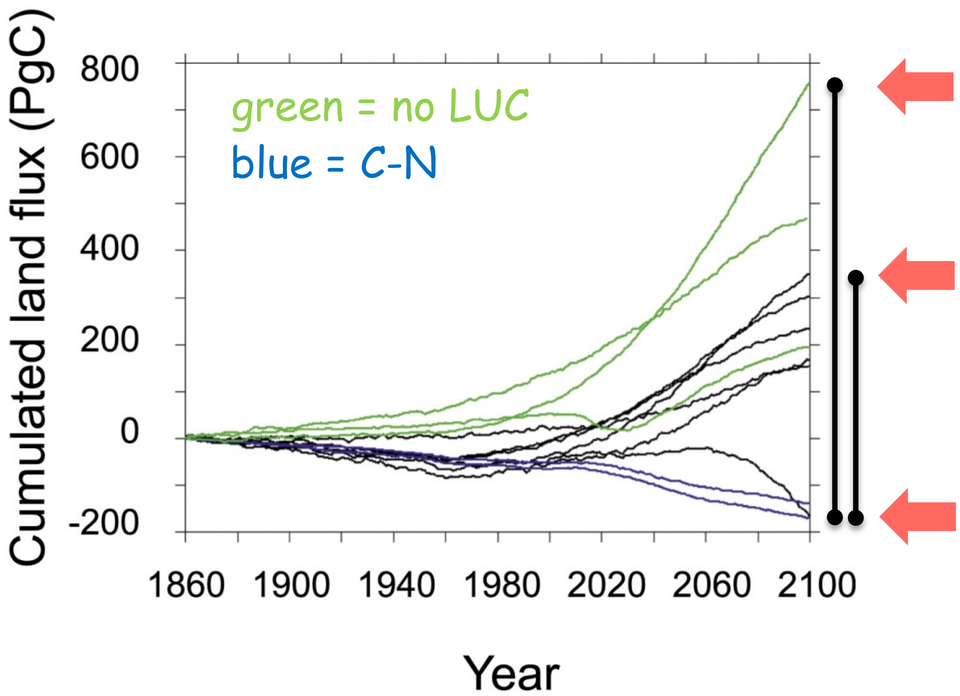
CO_2 fertilization enhances carbon uptake, diminished by decreased productivity and increased soil carbon loss with warming

Large model spread (uncertainty):

- 17 Pg C yr^{-1} difference in land uptake at 2100

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

CMIP5 model uncertainty



758 Pg C

(sink: 8 models)

352 Pg C

(sink: 5 models, all with LUC)

–173 Pg C

(source: 3 models)

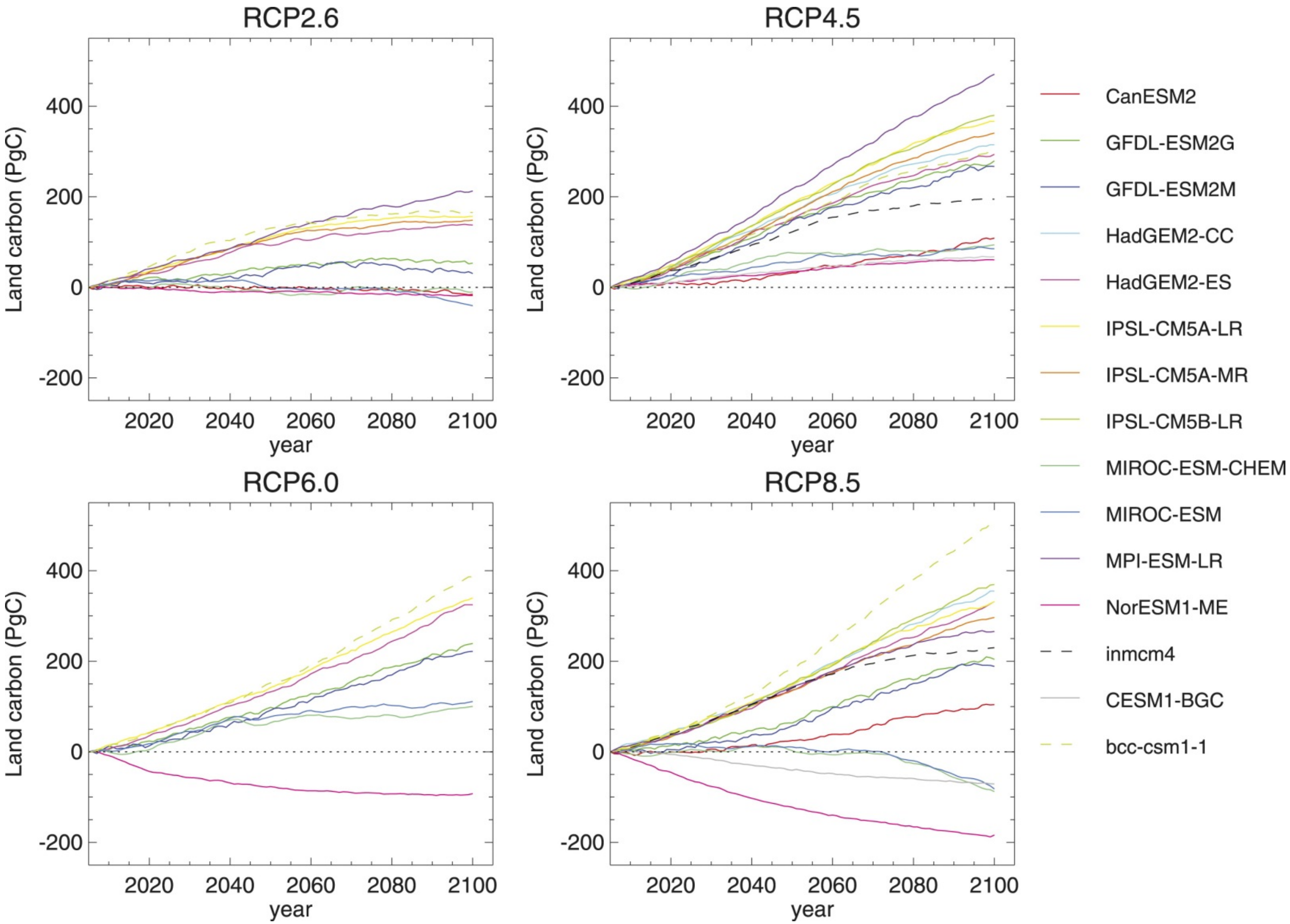
11 Earth system models with RCP8.5

CO_2 fertilization enhances C uptake, diminished by C loss with warming, N cycle reduces CO_2 fertilization

Large uncertainty in cumulative land uptake (Δ525 Pg C)

Friedlingstein et al. (2014) J. Clim. 27:511-526

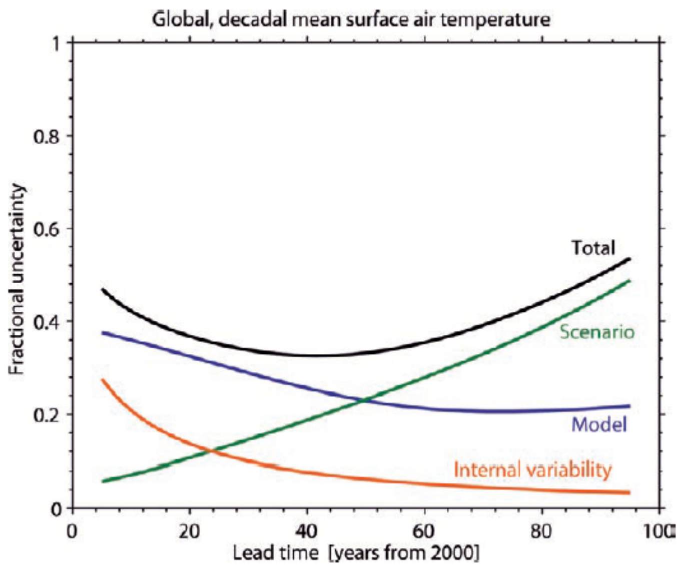
CMIP5 model uncertainty



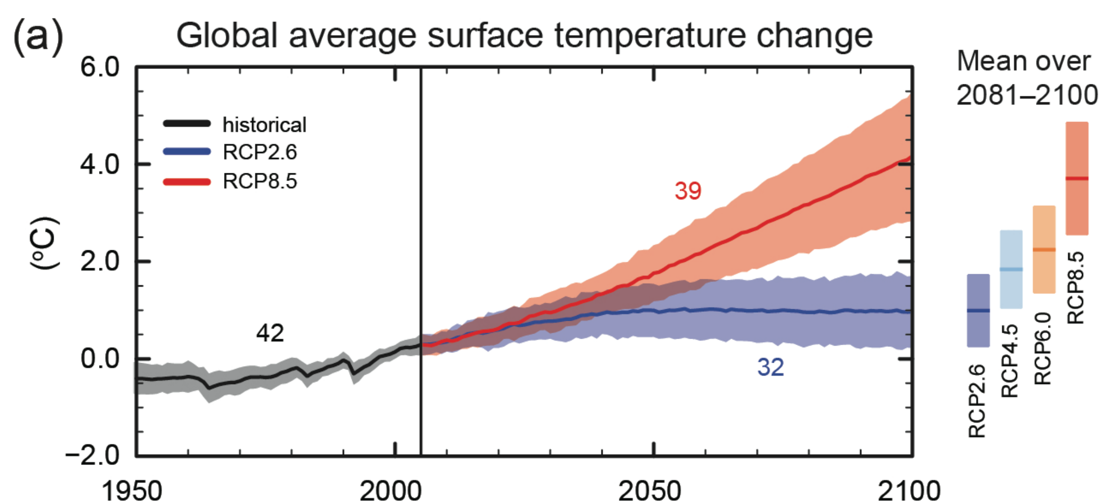
Uncertainty in land carbon uptake due to differences among models is considerably larger than the spread across scenarios

Jones et al. (2013) J. Clim. 26:4398-4413

Model uncertainty



Hawkins & Sutton (2009) BAMS 90:1095-1107



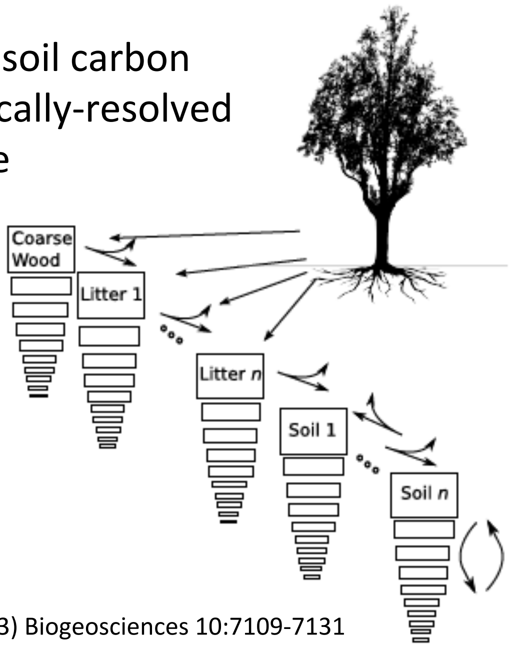
IPCC (2013) *Cli-mate Change 2013: The Physical Science Basis*

Process understanding improves models

Leaf to canopy scaling

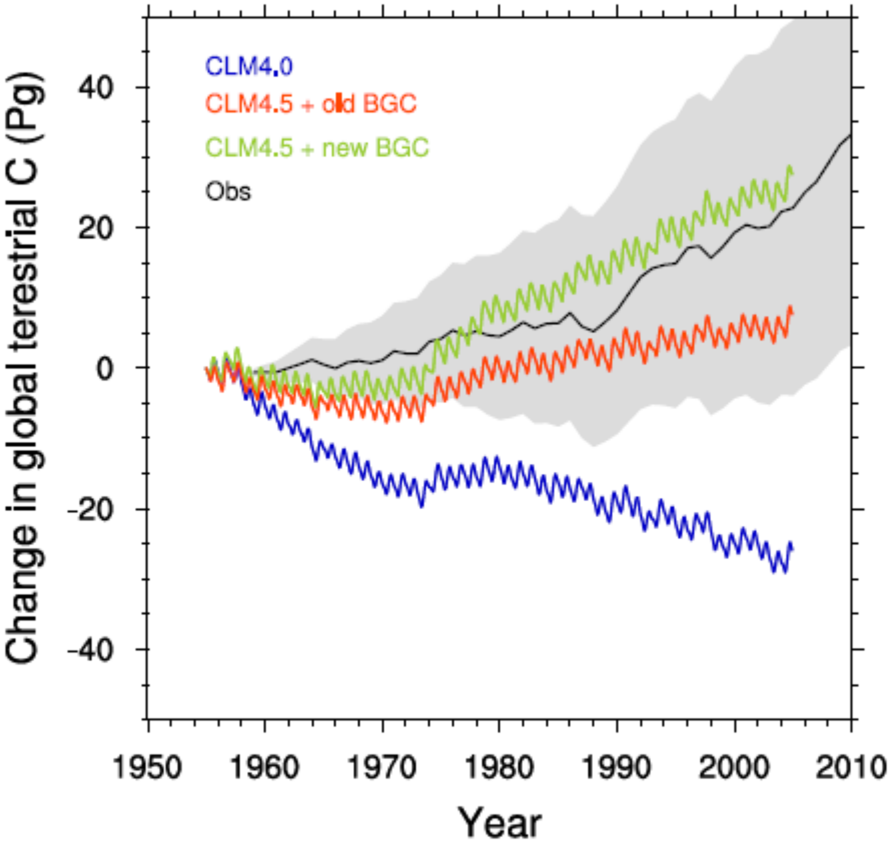
Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

CENTURY soil carbon with vertically-resolved soil profile



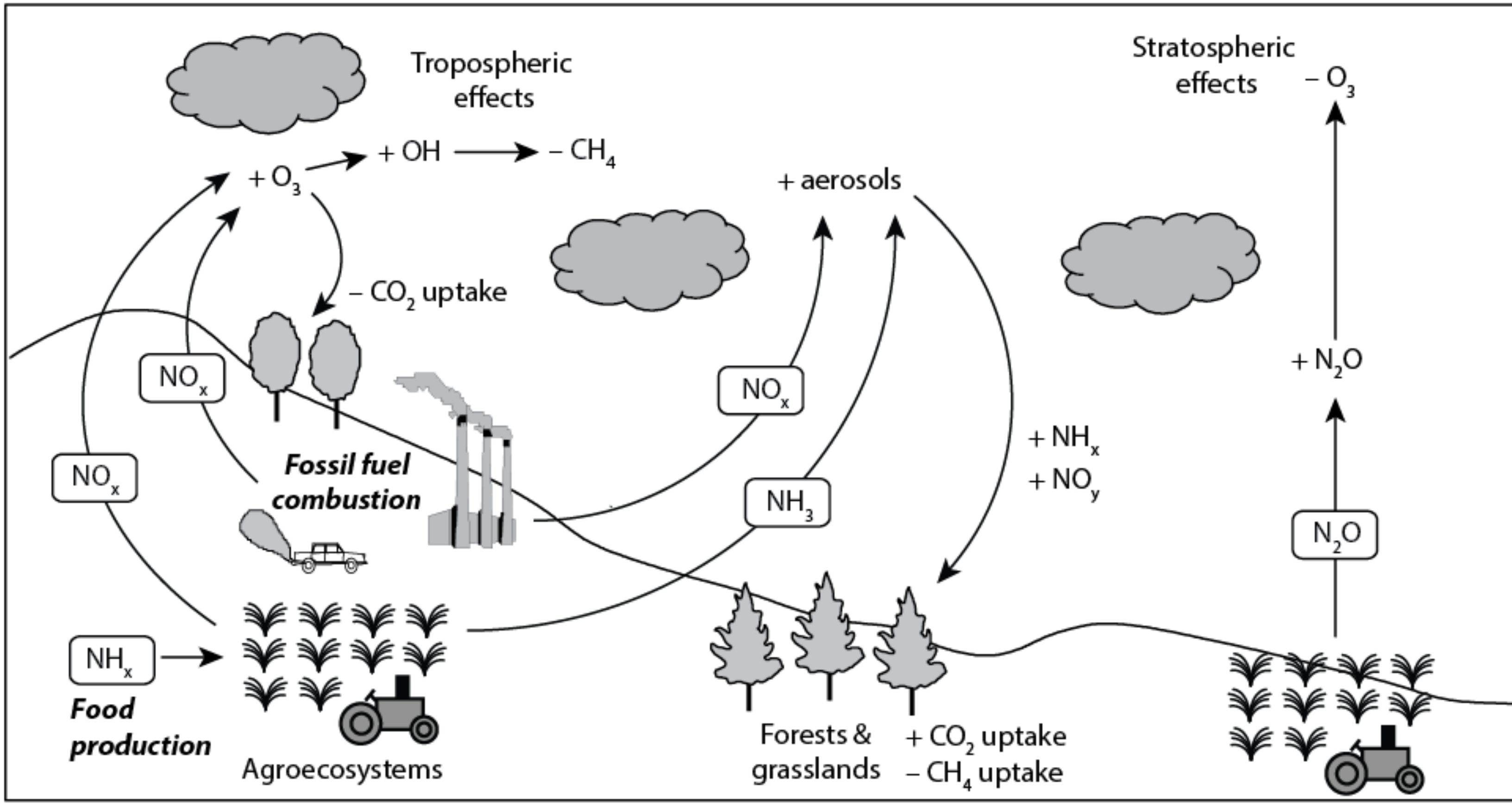
Koven et al. (2013) Biogeosciences 10:7109-7131

CLM4cn → CLM4.5bgc



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

Reactive nitrogen

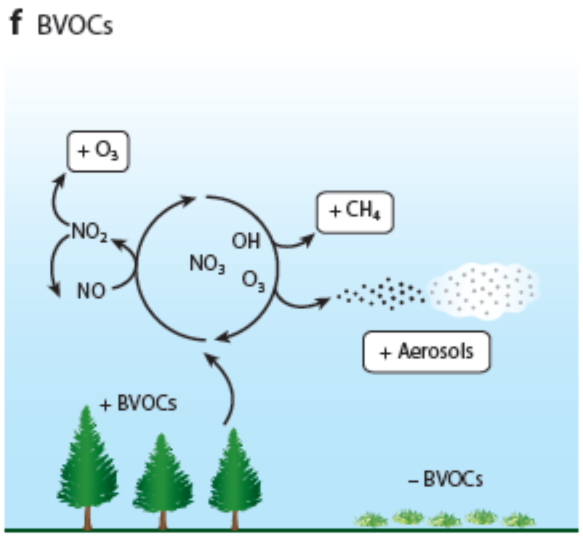


Erisman et al. (2011) Curr. Opin. Environ. Sustain. 3:281-290

Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

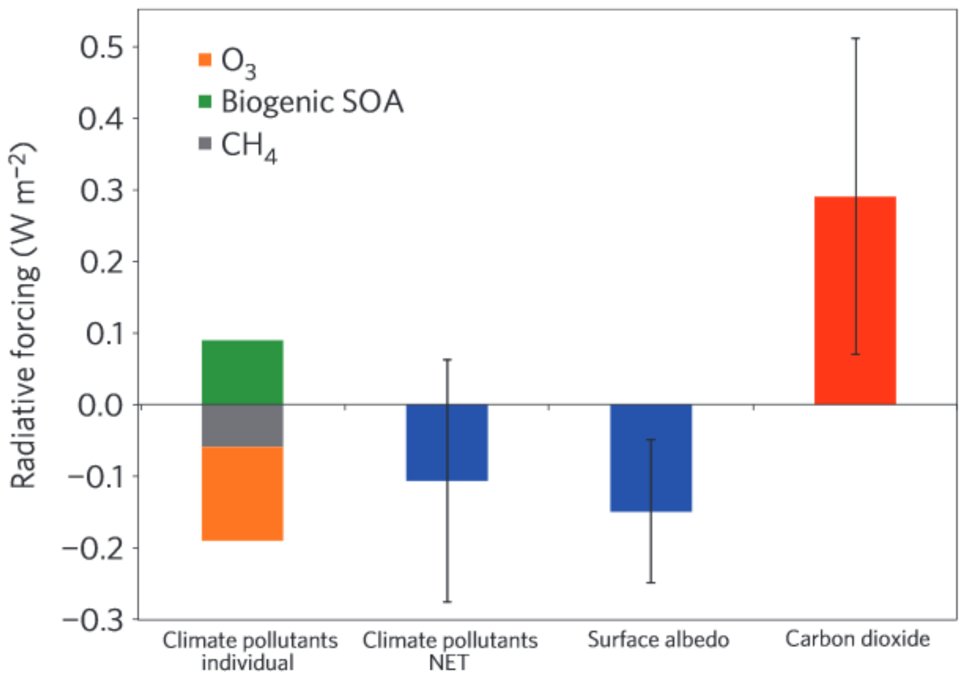
Nitrogen addition alters the composition and chemistry of the atmosphere, and changes the radiative forcing. The net radiative forcing varies regionally.

Chemistry – climate interactions



Bonan (2016) Annu. Rev. Ecol. Evol. Syst. 47:97-121
Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

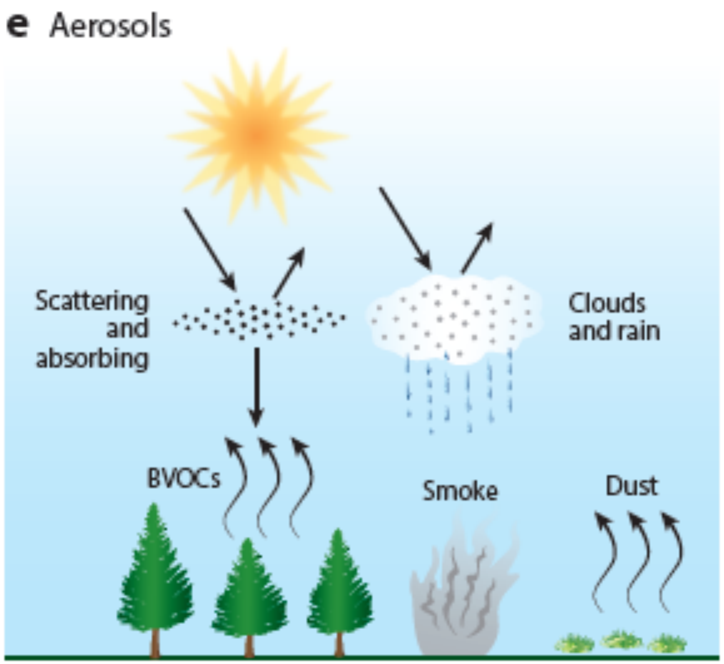
Global climate effects of historical cropland expansion



Unger (2014) Nature Clim. Change 4:907-910

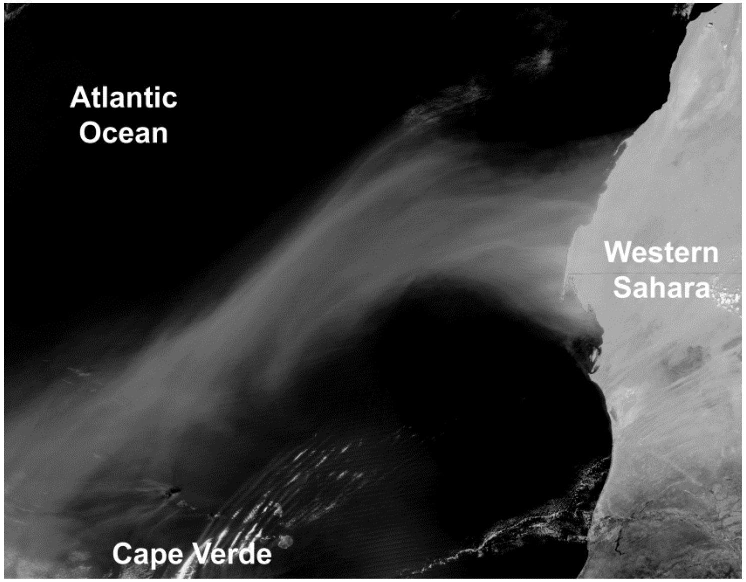
- Loss of forests and increase in croplands reduces global BVOC emissions
- Decreases ozone, CH_4, and secondary organic aerosols
- Net radiative forcing is –0.11 W m^{-2}

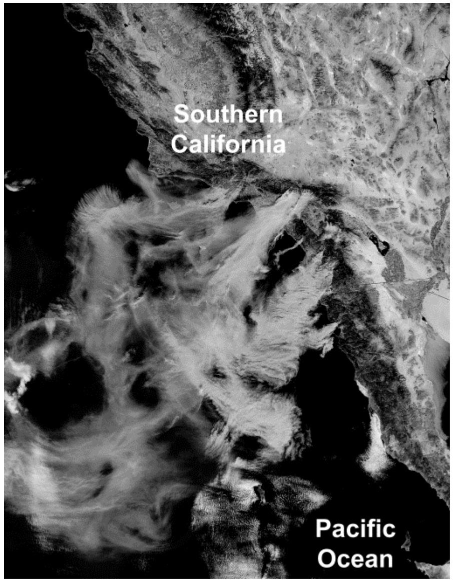
Biomass burning and dust



Bonan (2016) Annu. Rev. Ecol. Evol. Syst. 47:97-121

Dust plume off Africa





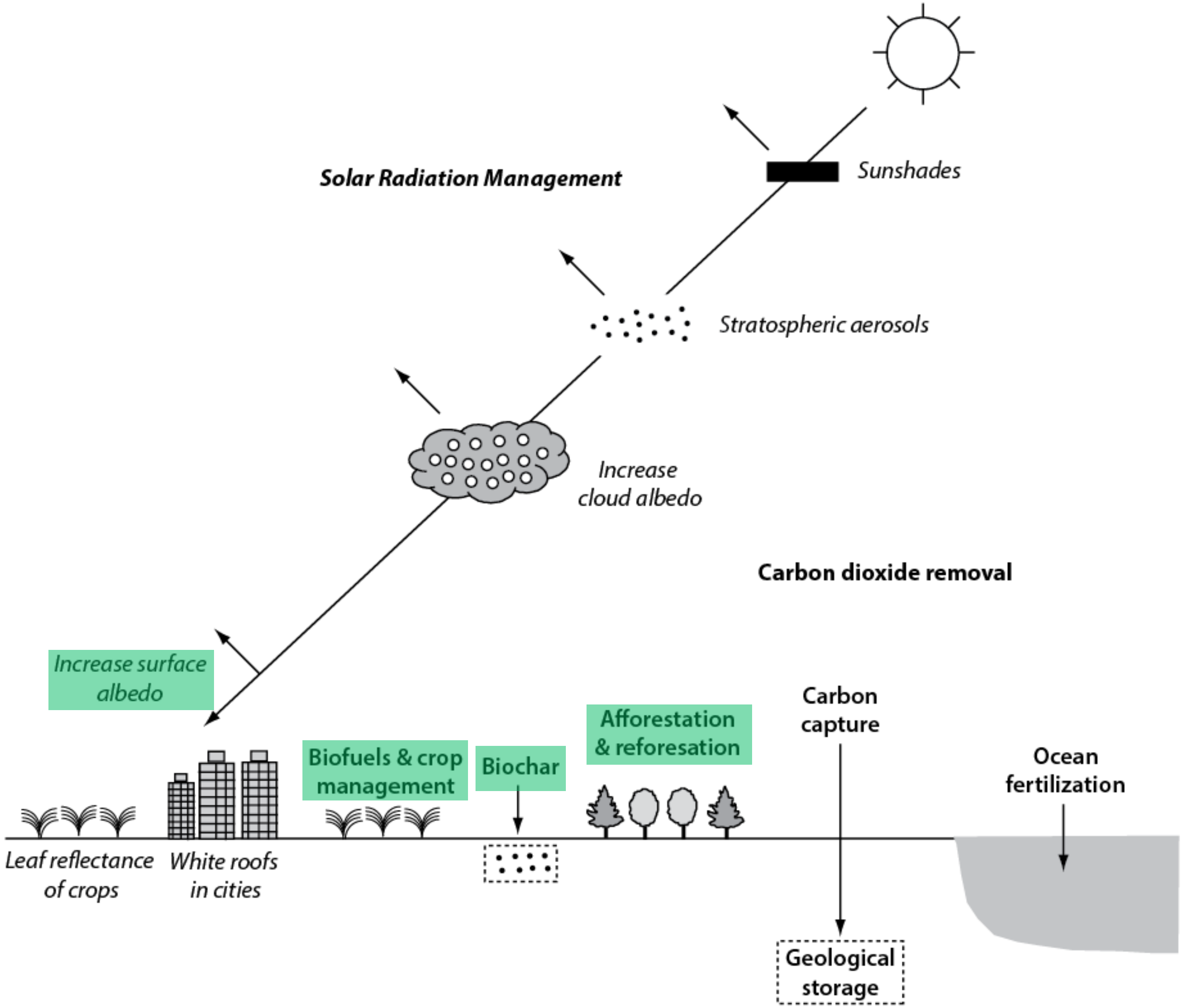
Smoke plume off California

Atmospheric radiation
Atmospheric chemistry
Surface albedo

Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

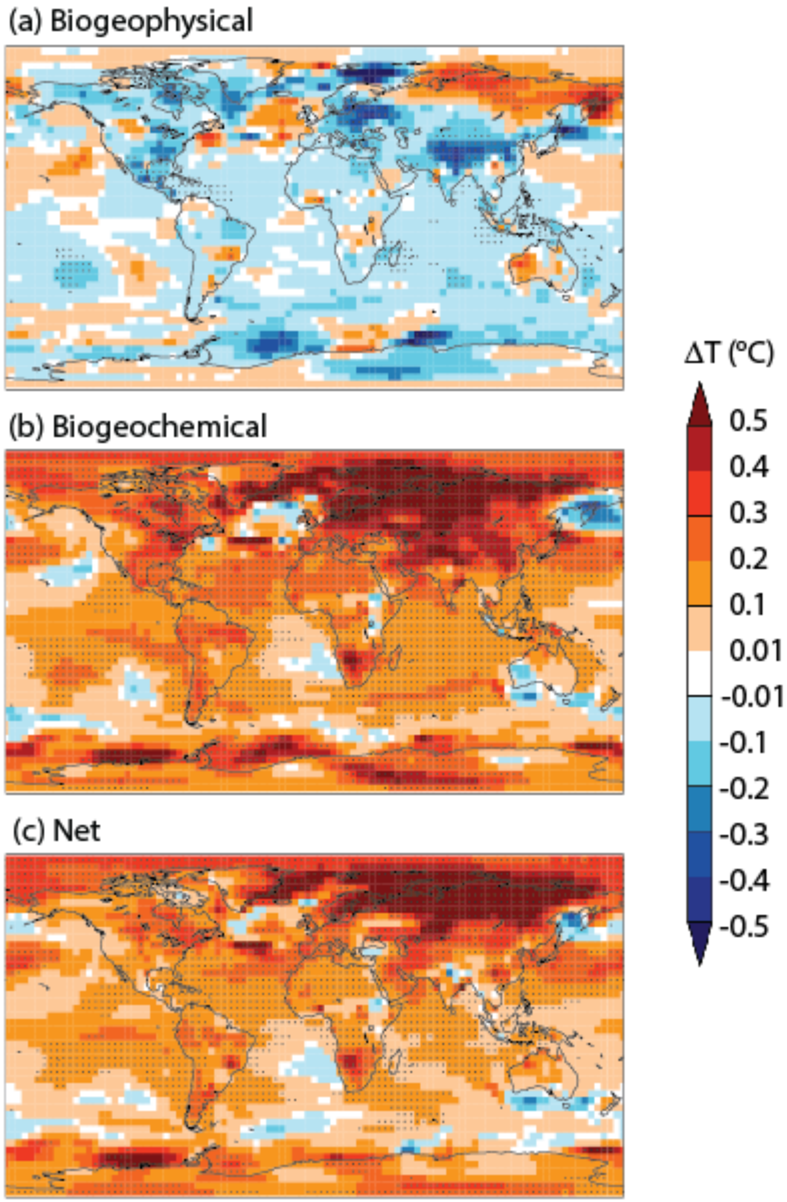
Terrestrial ecosystems and geoengineering

Green solutions to climate change mitigation



Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

Biogeophysics and biogeochemistry



<u>Historical land use & land-cover change</u>

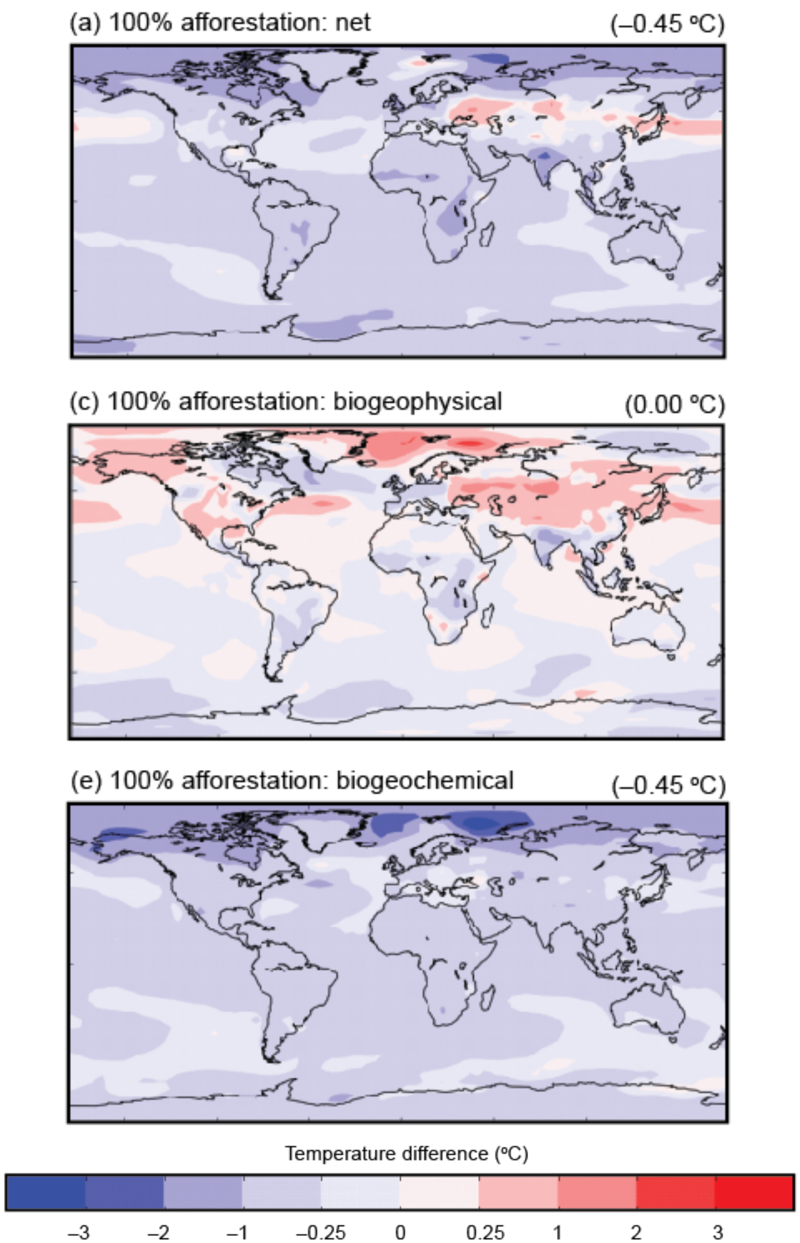
- ❑ Biogeophysical processes decrease annual mean temperature (albedo)
- ❑ Deforestation releases carbon (warms temperature)
- ❑ Biogeochemical warming exceeds biogeophysical cooling

Prevailing paradigm

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

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

Afforestation over the 21st century



Areas of the world that are presently occupied by cropland but which could potentially support forests were allowed to be afforested

Biogeophysical warming is prominent in northern high latitudes, where the warming from the lower albedo is important and initiates loss of sea ice

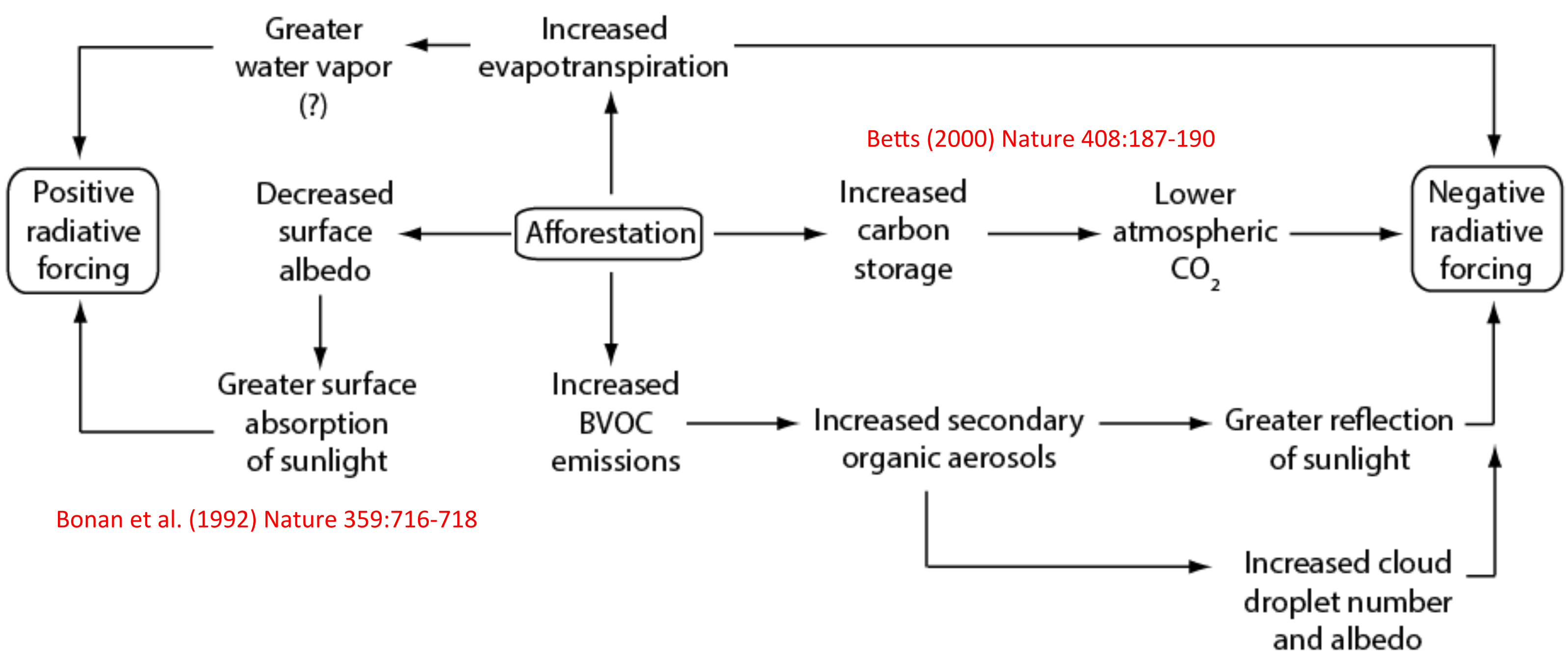
Afforestation increases the land carbon uptake over the twenty-first century and reduces atmospheric CO_2 compared with the control simulation

Arora & Montenegro (2011) Nature Geosci. 4:514–518

Net radiative forcing

Consequences of boreal afforestation

Swann et al. (2010) 107:1295-1300



Betts (2000) Nature 408:187-190

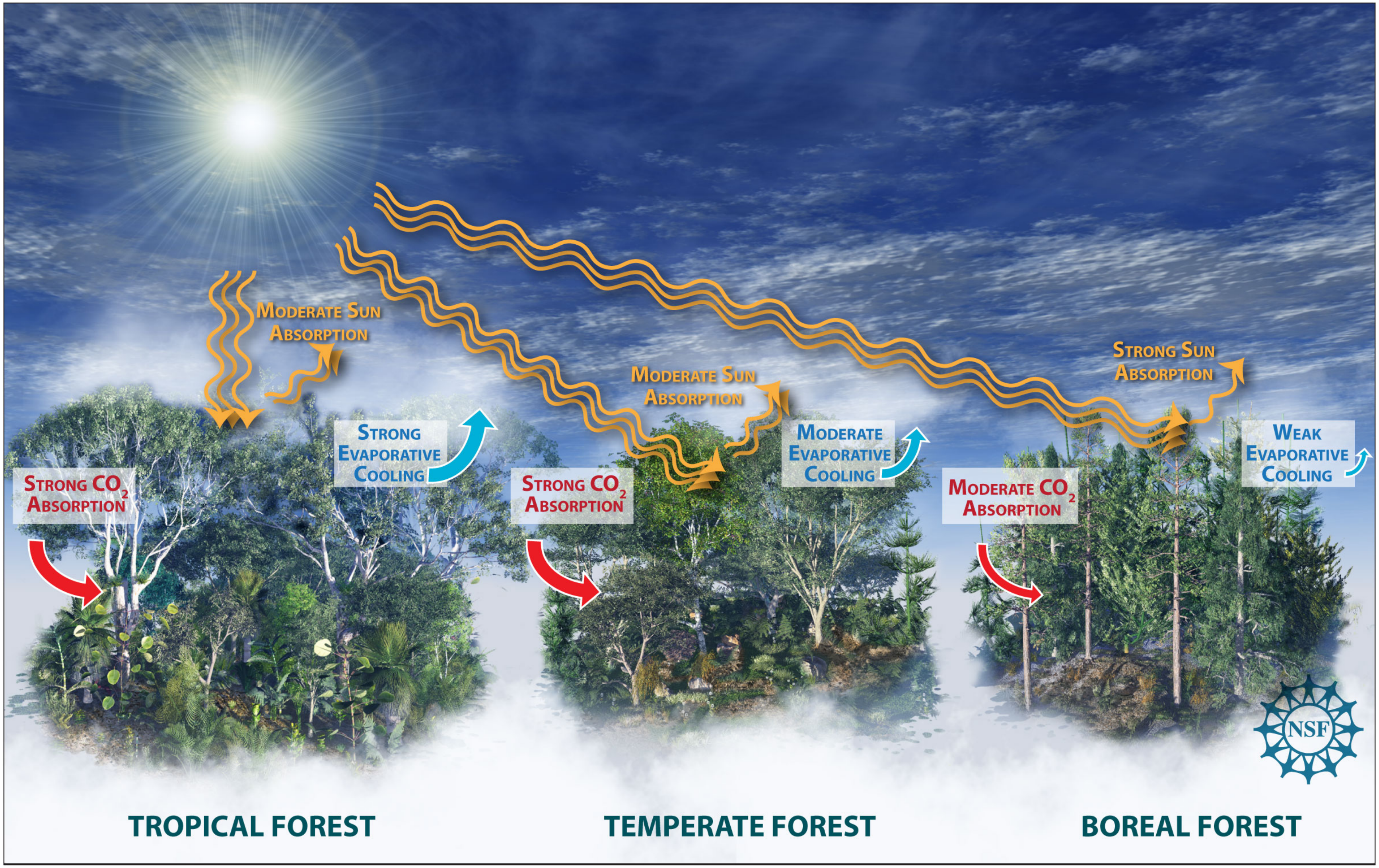
Bonan et al. (1992) Nature 359:716-718

Spracklen et al. (2008) Phil. Tran. R. Soc. A 366:4613-4626

Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

Forests and climate change

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



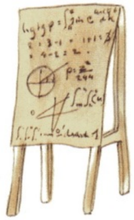
Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*

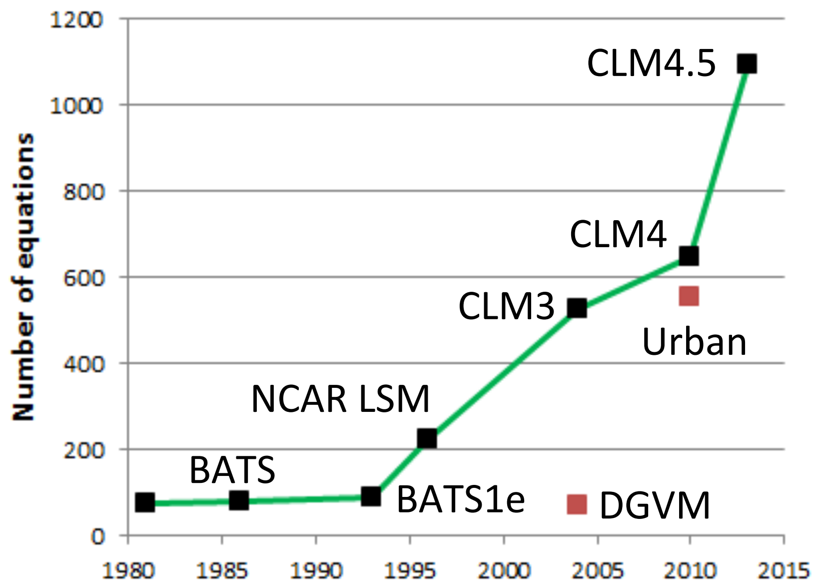
Modeling caveats

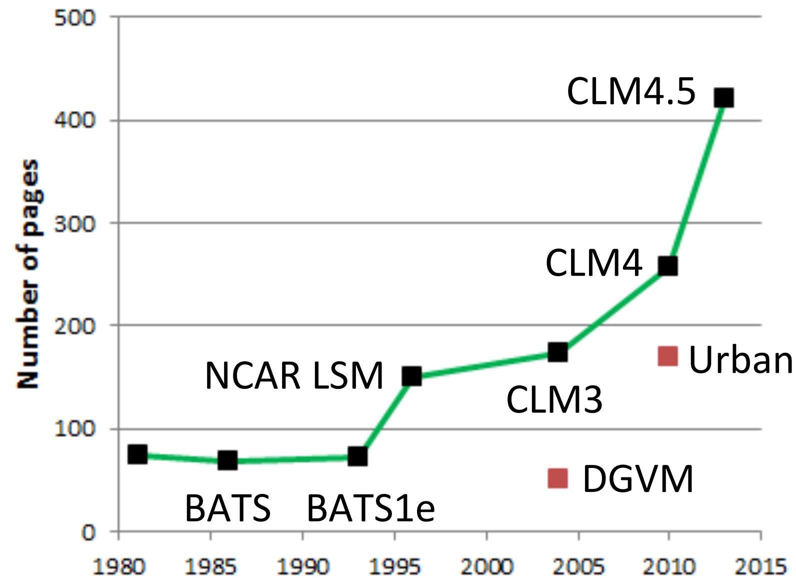
CLM is just a starting point for the science. It is not the science itself

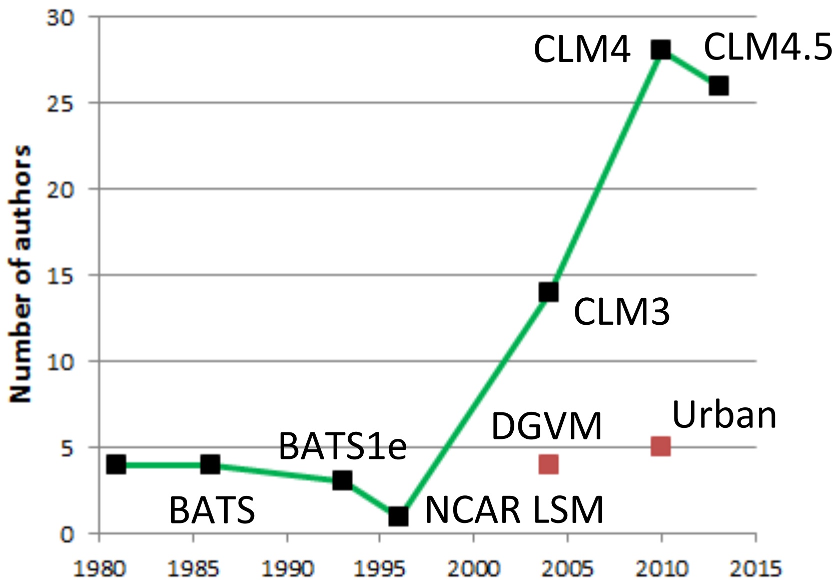
- Easy to run the model and get an answer
- Much harder to understand why you got that answer
- CLM is a very complex, multidisciplinary model



Breadth and complexity of land surface models







Many paths to reduce model uncertainty

Model intercomparisons (MIPs)
CMIP6: carbon cycle, land use, land-atmosphere coupling, …
Range of plausible outcomes, but more models ≠ better results

Model benchmarking
Comprehensive model evaluation against observations

Real-world experiments and models
FACE, N addition

Model-data fusion
Data assimilation, parameter estimation

"Discover" critical missing process
Add another process that is ecologically important but poorly known at the global scale.
Tune a key parameter to get a good simulation.

Model intracomparison
Focus on model structural uncertainty to identify processes contributing to uncertainty

Model hierarchy
CLM
Process models (multilayer canopy, MIMICS)
Simple land models (Marysa Lague)