Biosphere–atmosphere interactions in Earth system models

Gordon Bonan
National Center for Atmospheric Research
Boulder, Colorado, USA

CLM Tutorial 2019

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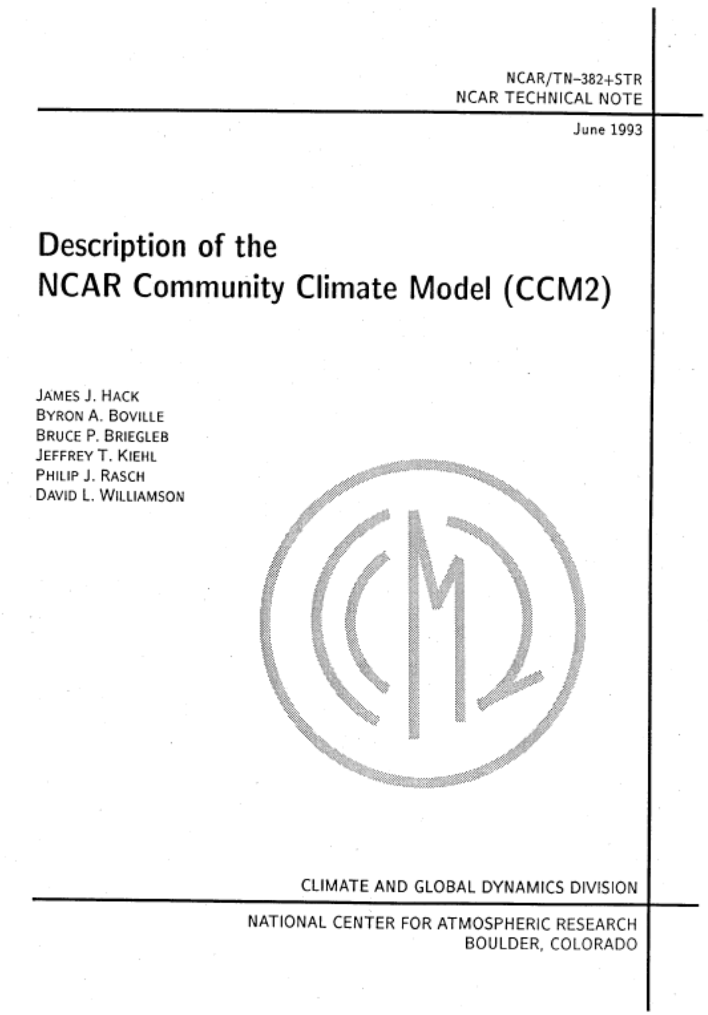
4 February 2019

NCAR is sponsored by the National Science Foundation

NCAR models circa 1993


NCAR/TN-382+STR
NCAR TECHNICAL NOTE

June 1993

Description of the
NCAR Community Climate Model (CCM2)

JAMES J. HACK
BYRON A. BOVILLE
BRUCE P. BRIEGLEB
JEFFREY T. KIEHL
PHILIP J. RASCH
DAVID L. WILLIAMSON

CLIMATE AND GLOBAL DYNAMICS DIVISION

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

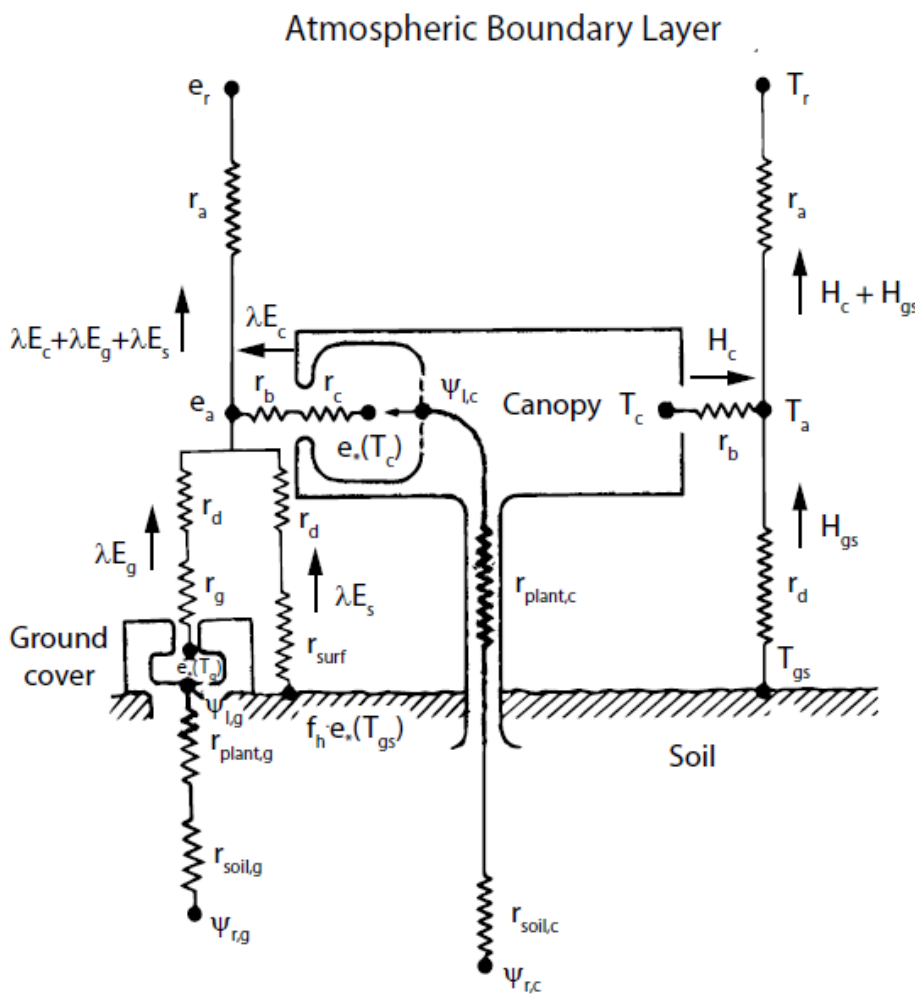
- Prescribed soil wetness and snow depth
- Prescribed surface albedos
- No plant canopies (no leaves or stomata)

Advent of land surface models

Simple Biosphere Model (SiB) (Sellers et al. 1986, 1996)
Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1986, 1993)

Diffusive fluxes as controlled by plant canopies:

- Radiative transfer
- Turbulent energy fluxes
- Stomata
- Hydrology
- Momentum transfer



Sellers et al. (1986) *J. Atmos. Sci.*, 43, 505-531

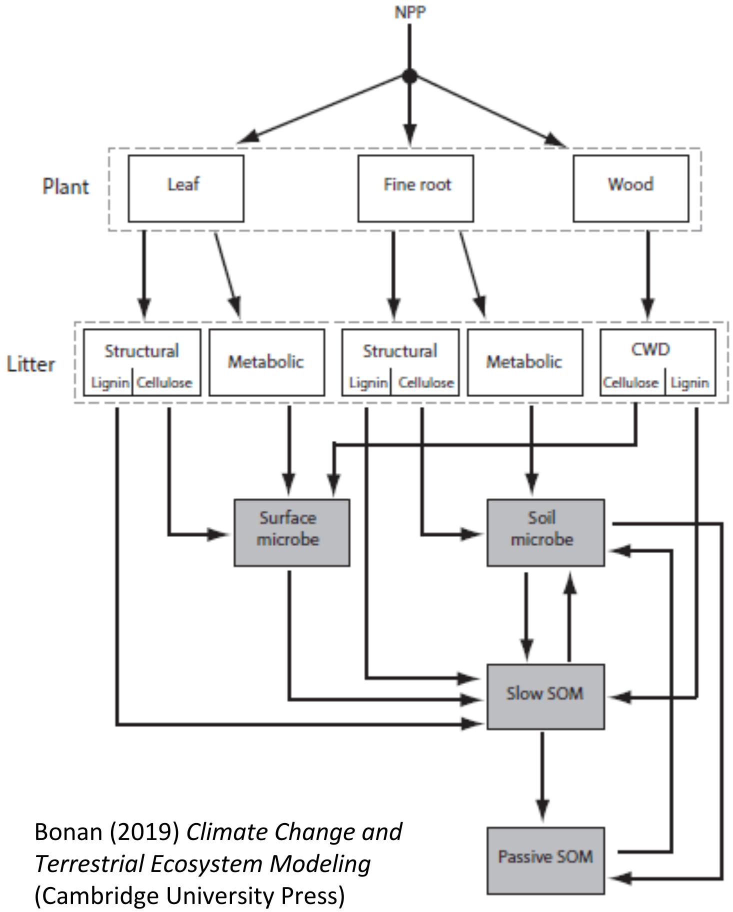
Biogeochemical perspective

Evolution of carbon sinks in a changing climate

Inez Y. Fung*†, Scott C. Doney‡, Keith Lindsay§, and Jasmin John*

*Berkeley Atmospheric Sciences Center, University of California, Berkeley, CA 94720-4767; ‡Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA 02543; and §National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307

Fung et al. (2005) *PNAS*, 102, 11201-11206

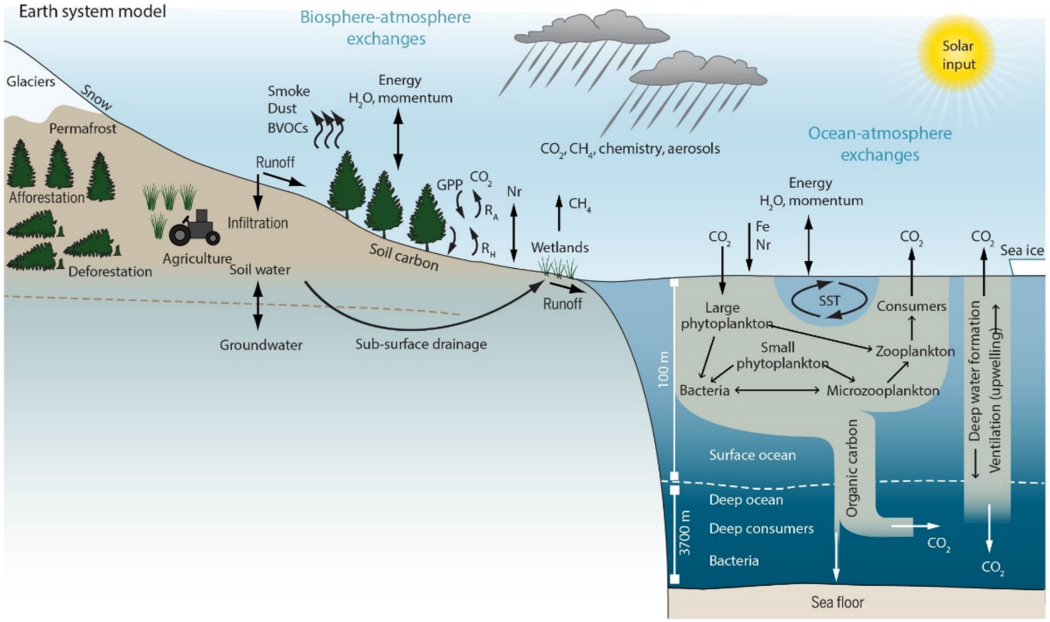


Bonan (2019) *Climate Change and Terrestrial Ecosystem Modeling* (Cambridge University Press)

First coupled carbon cycle-climate model at NCAR using CASA‘ adaptation of CASA biogeochemical model

- Simple 12-pool model

Earth system models



Bonan & Doney (2018) *Science*, 359, eaam8328, doi:10.1126/science.aam8328

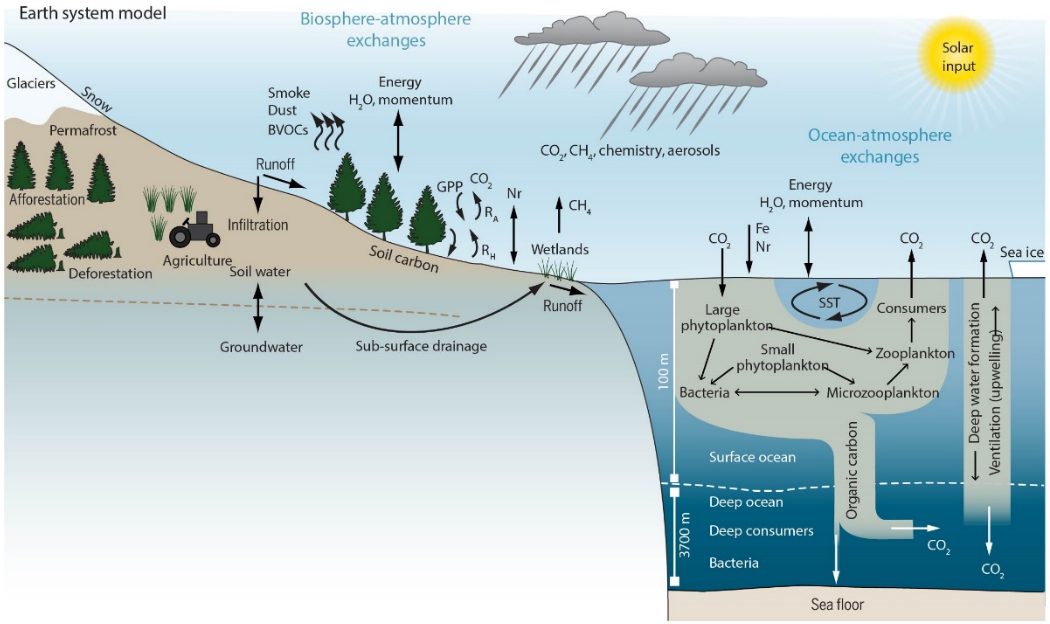
Earth system models use mathematical formulas to simulate the **physical**, **chemical**, and **biological** processes that drive Earth's atmosphere, hydrosphere, biosphere, and geosphere

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



Bonan & Doney (2018) *Science*, 359, eaam8328, doi:10.1126/science.aam8328

Earth system prediction

What are the consequences of alternative socioeconomic pathways?

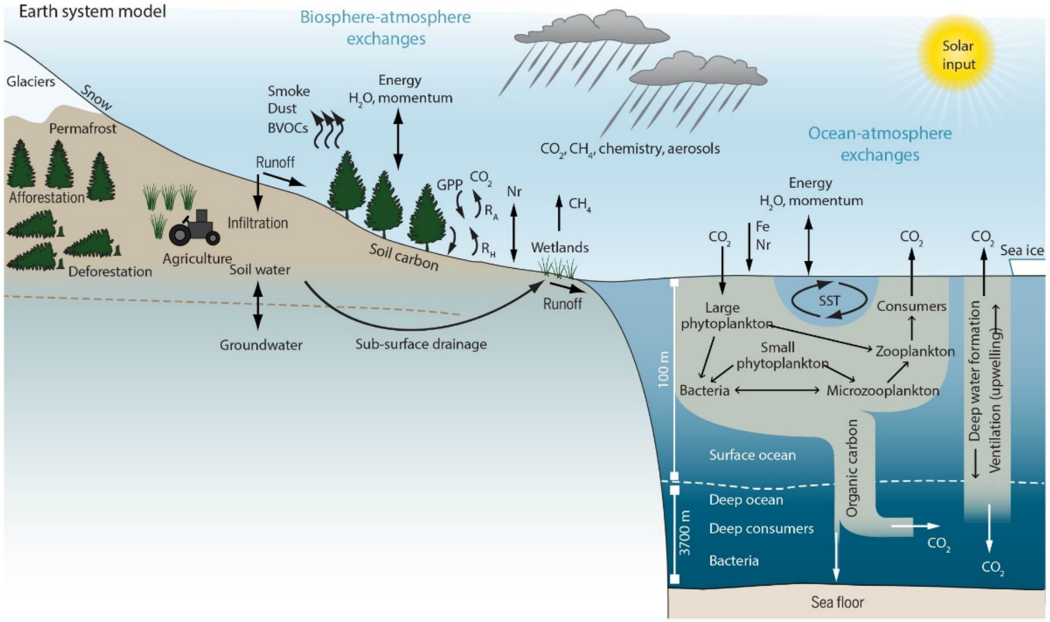
Scientific discovery

Identify ecological processes that determine climate

Advance theory

Test generality of ecological theories at the macroscale

Earth system models

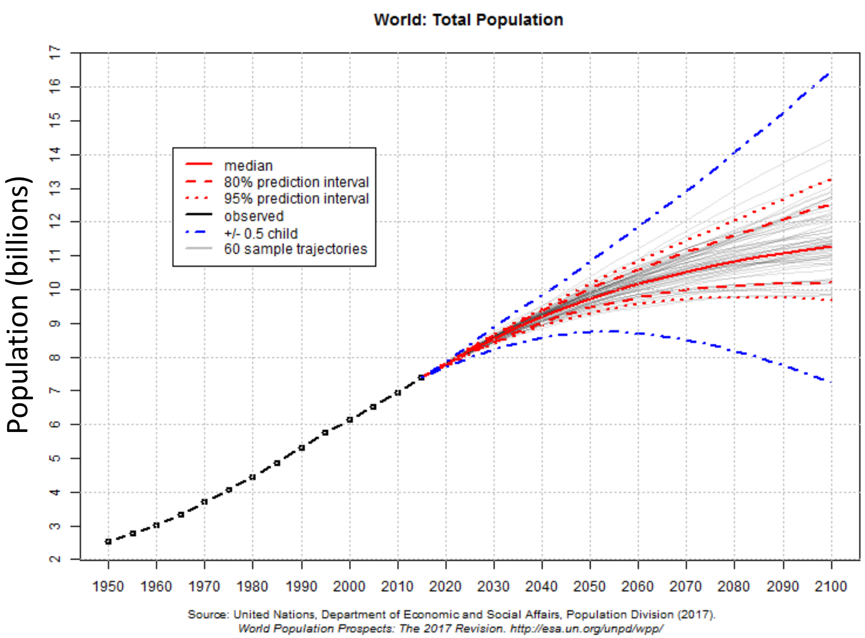


Bonan & Doney (2018) *Science*, 359, eaam8328, doi:10.1126/science.aam8328

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

The Anthropocene

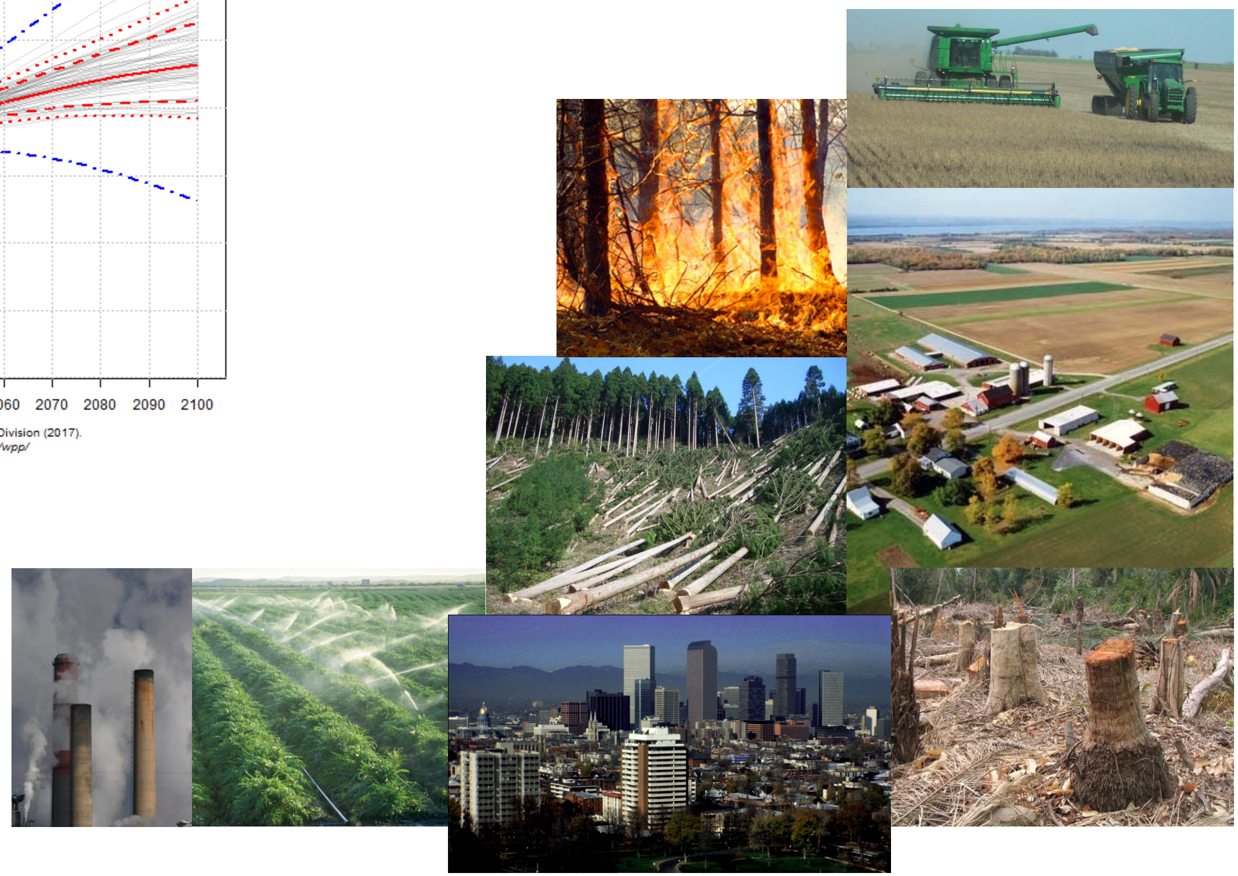
Human domination of Earth system



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?

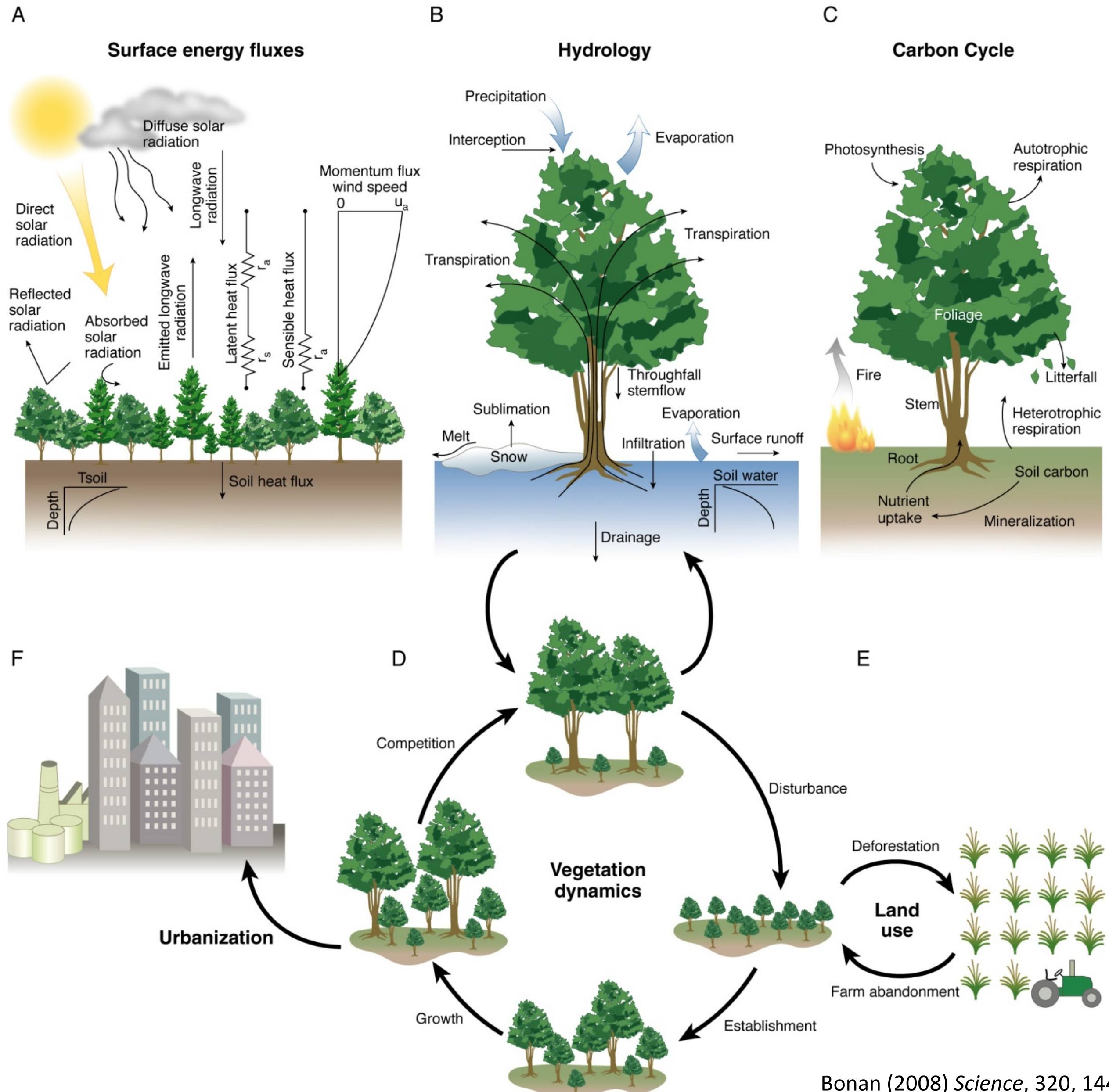


Ecosystems and climate

Multiple processes at many timescales

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, 1444-49

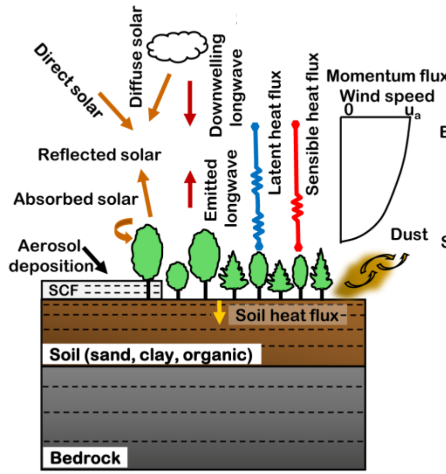
The Community Land Model

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

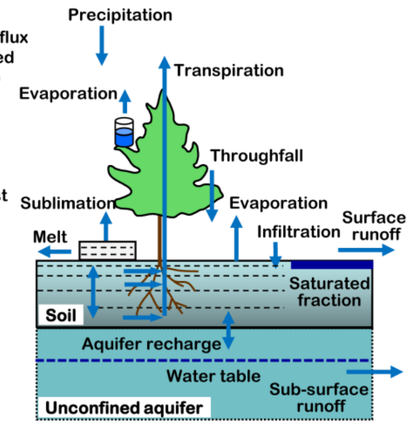
Lawrence et al. (2019) *J. Adv. Mod. Earth Syst.*, submitted

CLM5 documentation: cesm.ucar.edu/models/cesm2/land

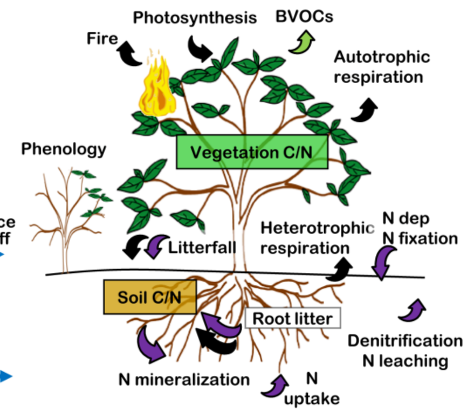
Surface energy fluxes



Hydrology



Biogeochemistry

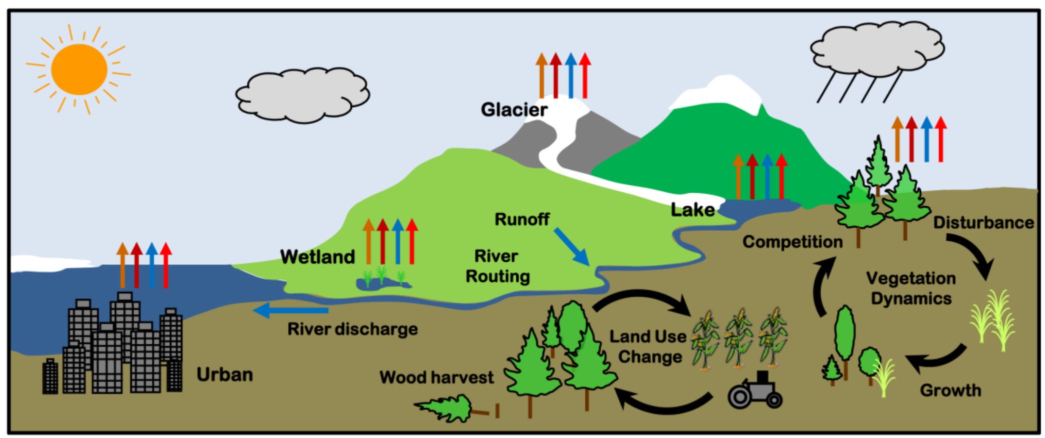


Spatial scale

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)



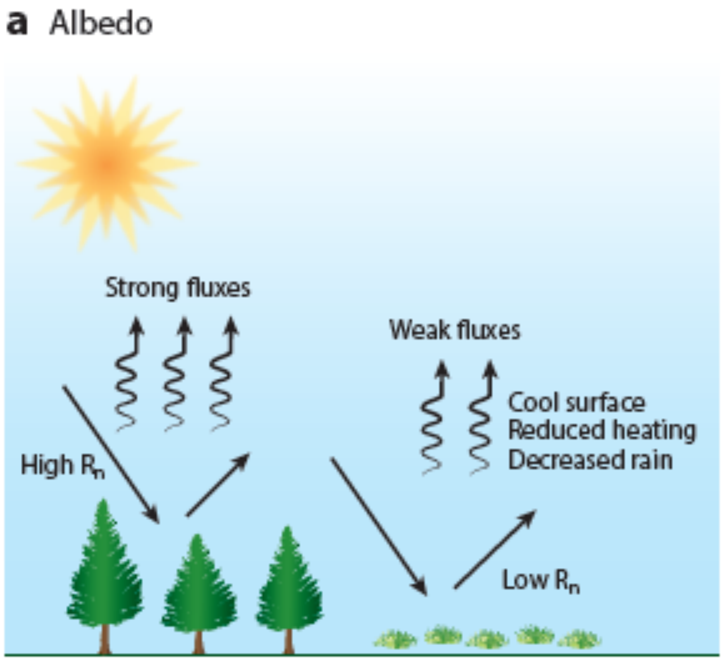
Landscape dynamics

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

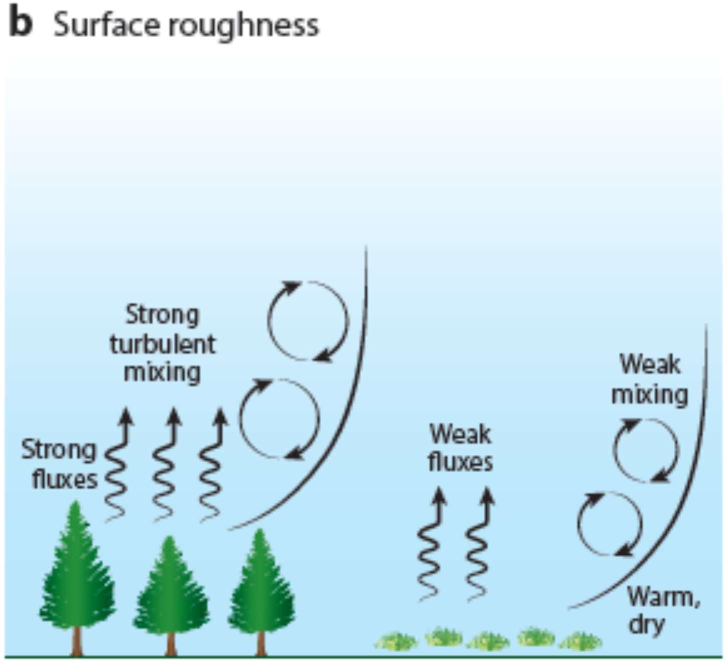


Bonan (2016) *Ecological Climatology*, 3rd ed (Cambridge Univ. Press)
Bonan (2016) *Annu. Rev. Ecol. Evol. Syst.*, 47, 97-121

Biogeophysical processes

Trees are tall (aerodynamically rough)

Cowling Arboretum, Carleton College

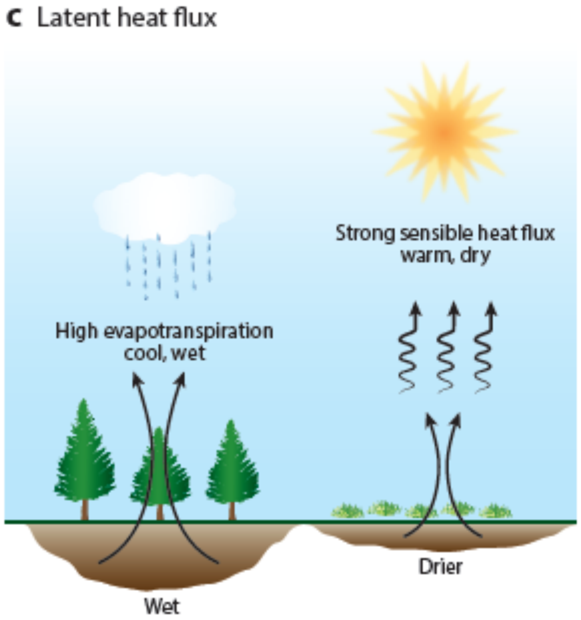


Bonan (2016) *Ecological Climatology*, 3rd ed (Cambridge Univ. Press)
Bonan (2016) *Annu. Rev. Ecol. Evol. Syst.*, 47, 97-121

Biogeophysical processes

Soil moisture and evapotranspiration

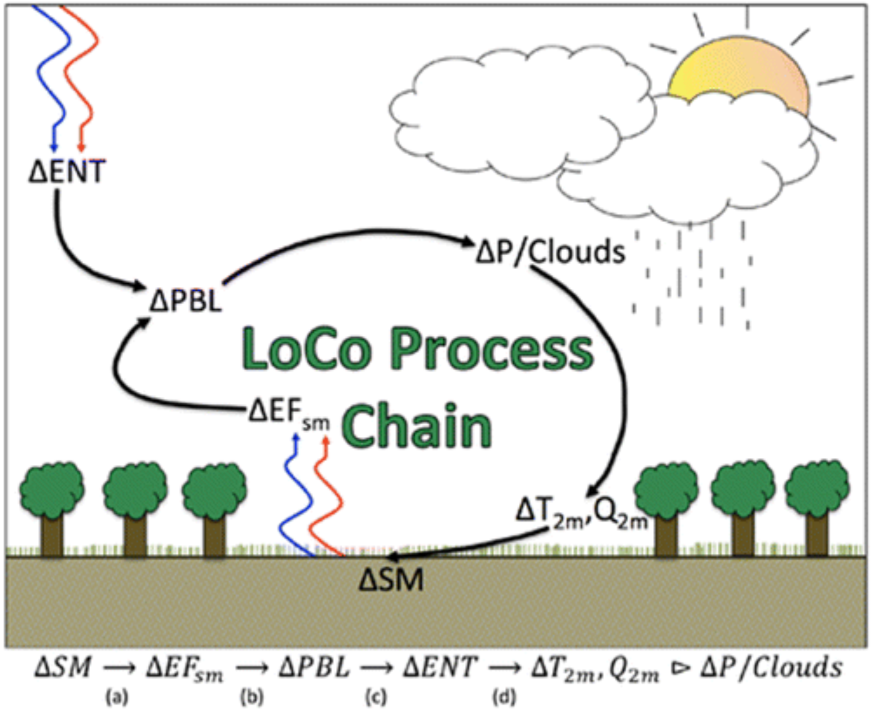
2012 drought, Waterloo, NE (Nati Harnik, AP)



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

Land-atmosphere coupling

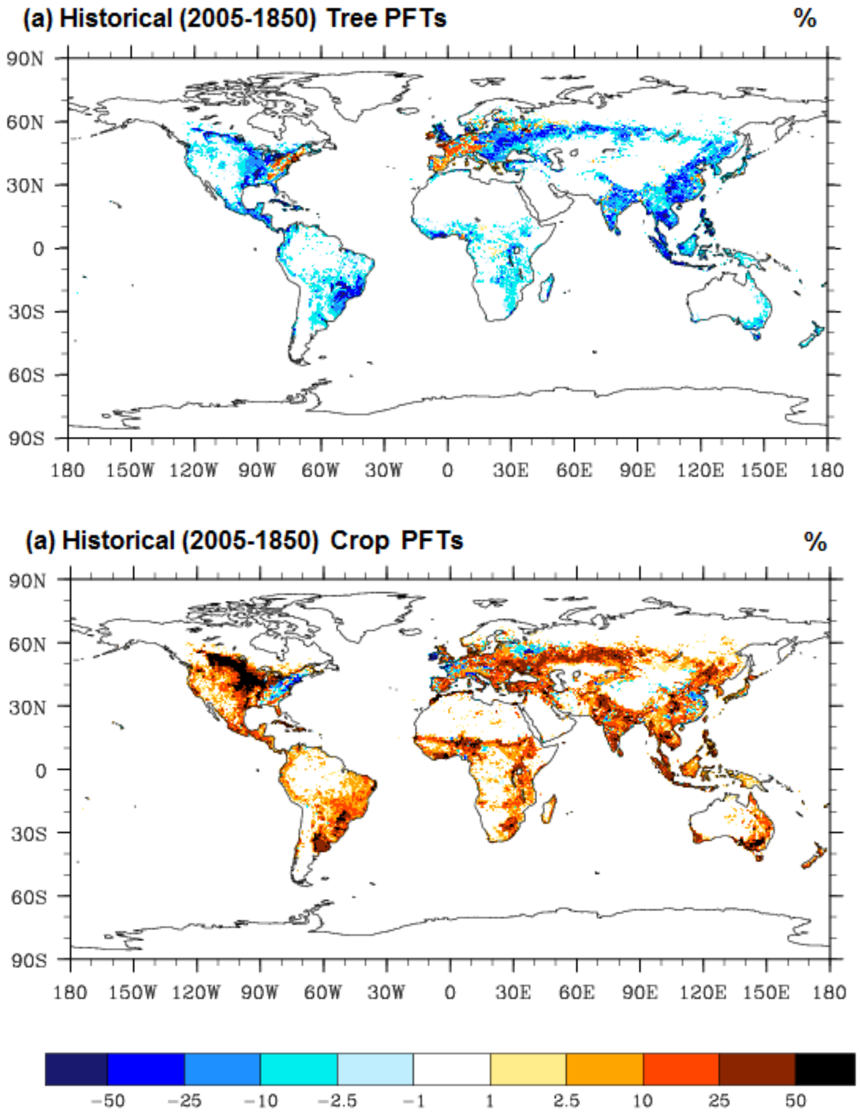
Hydrometeorological coupling at short timescales (sub-seasonal to seasonal); e.g. soil moisture and atmospheric predictability



Santanello et al. (2018) *Bull. Amer. Meteor. Soc.*, 99, 1253-72

Historical land use & land cover change, 1850-2005

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



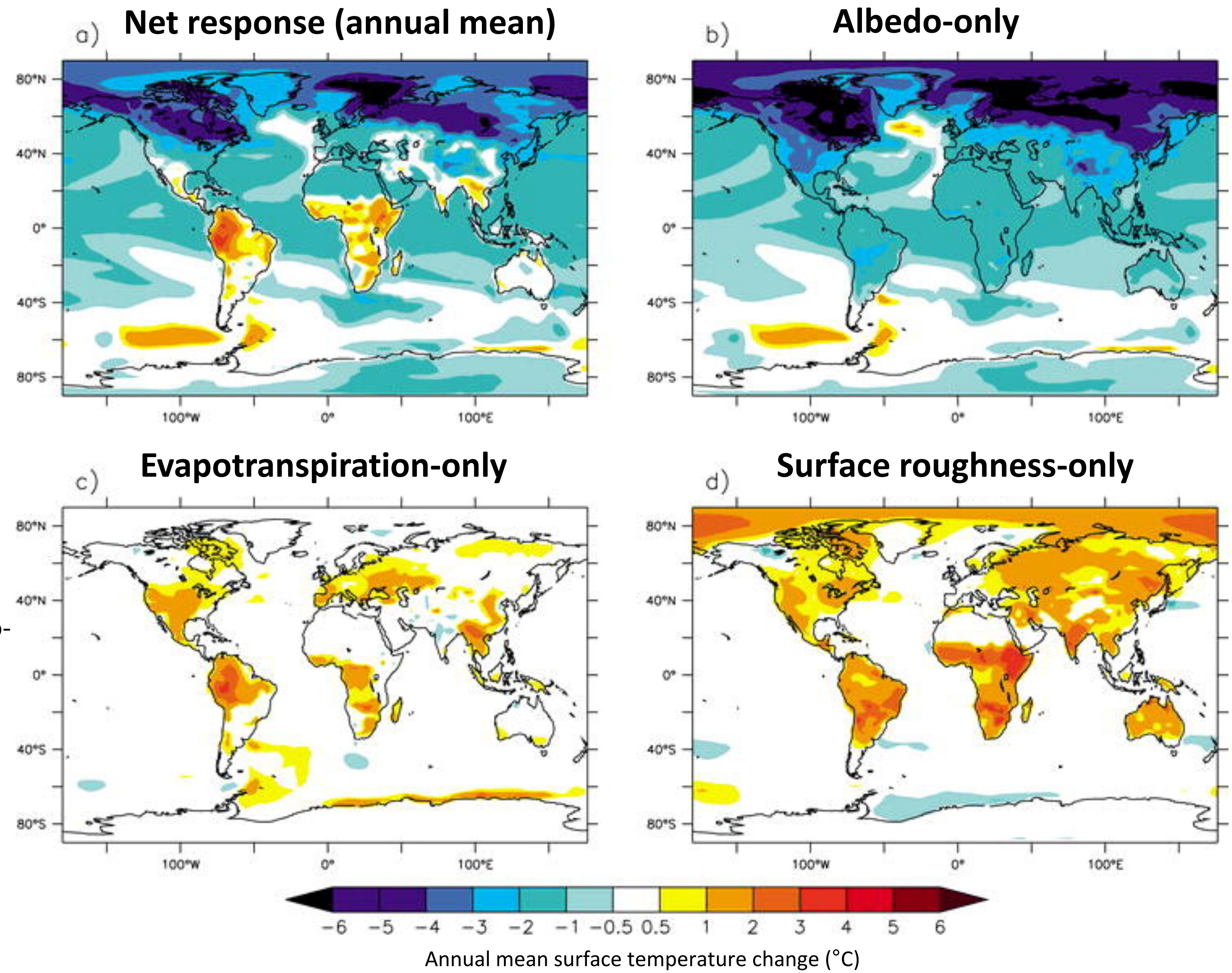
<u>Historical land use & land-cover change</u>

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

Lawrence et al. (2012) *J. Clim.*, 25, 3071-95

Forests influences on global climate

What happens when forests are replaced with grassland?



Higher albedo = cooling

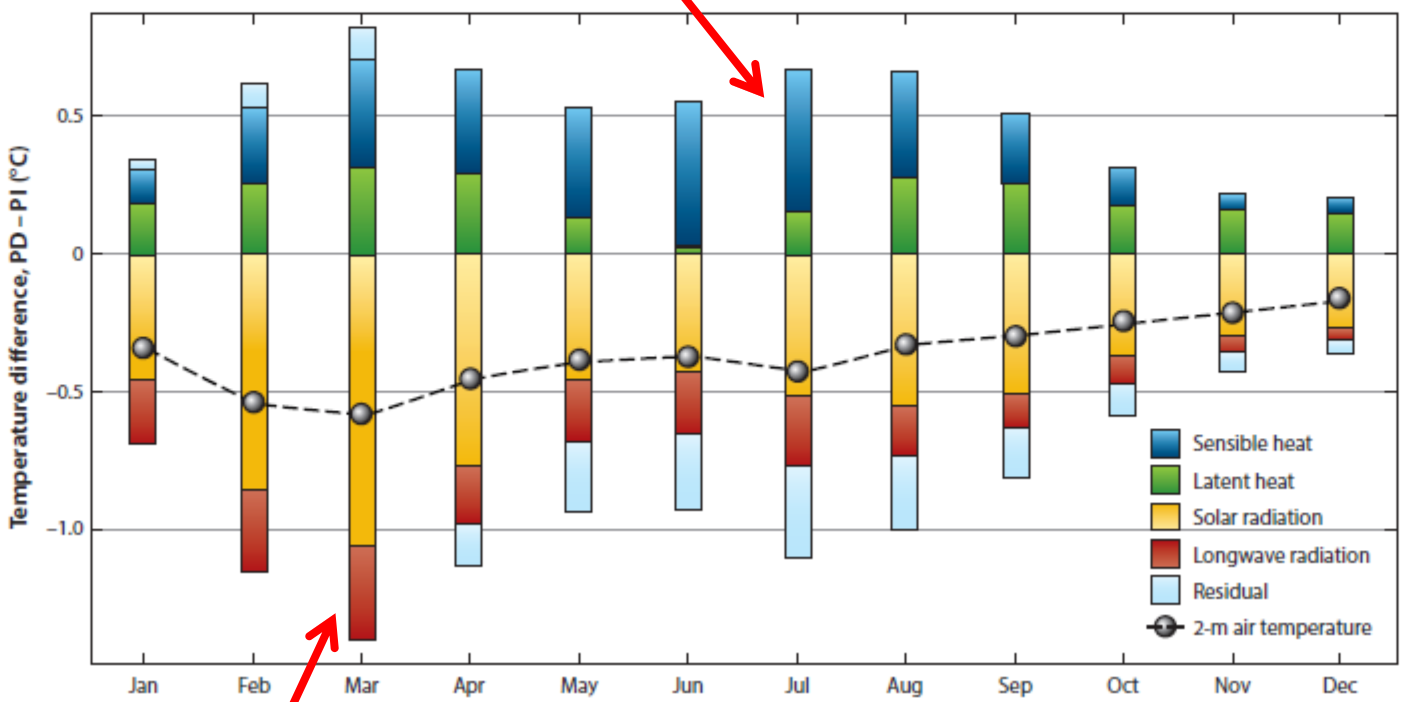
Reduced evapo-transpiration = warming

Reduced surface roughness = warming

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

Historical land use & land cover change

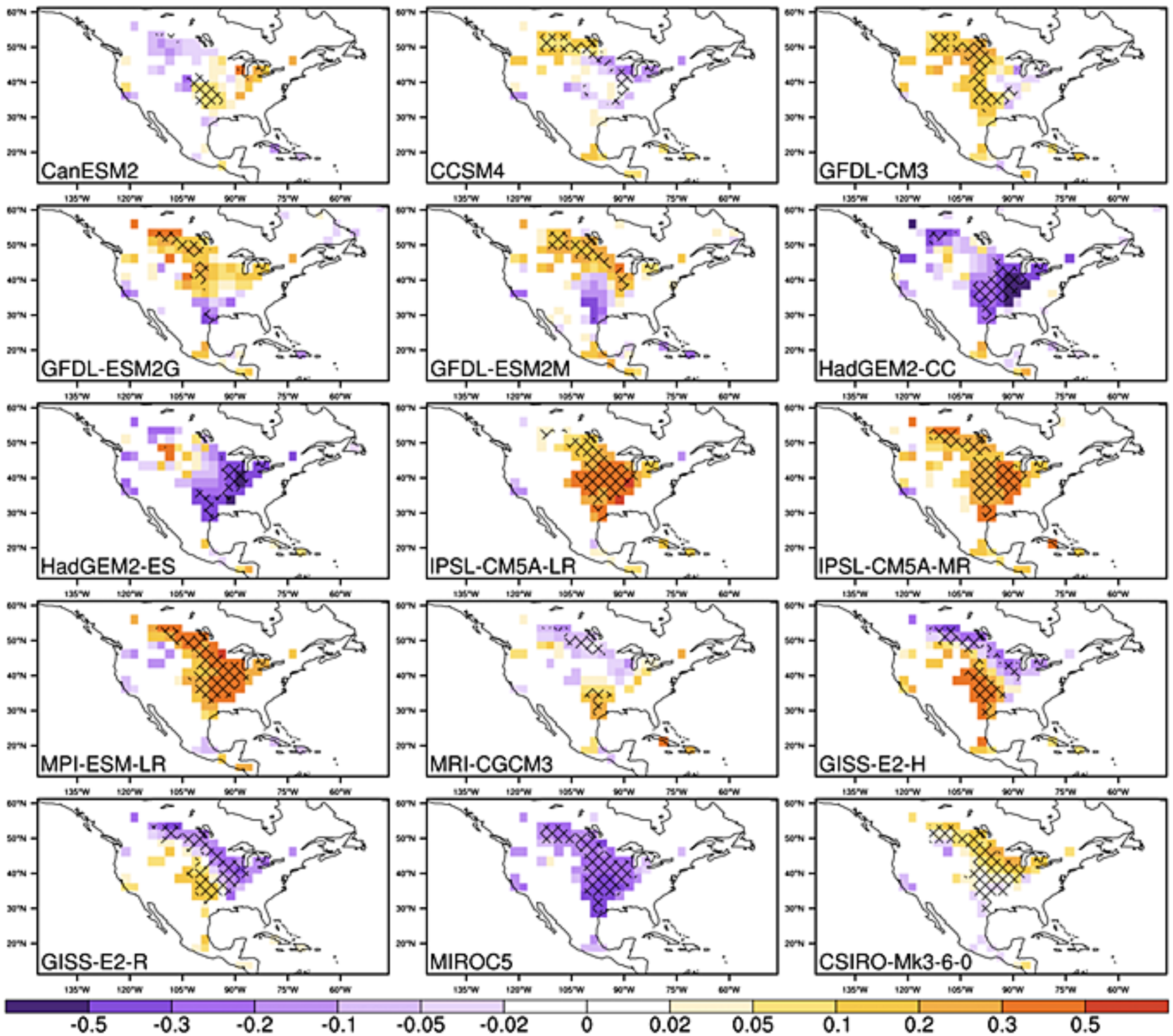
Warming from sensible and latent heat fluxes



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

- Atmosphere model
- Land model
- How land cover change is implemented

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

Observationally based analyses

Radiative forcing

- Change in surface albedo and carbon storage with disturbance

Randerson et al. (2006) *Science*, 314, 1130-32

Climate regulation value

- Evaporative cooling is a positive climate service
- Surface warming from low albedo is a negative climate service
- Biogeochemical processes; e.g., carbon storage is a positive climate service

Anderson-Teixeira et al. (2012) *Nature Clim. Change*, 2, 177-81

Flux tower analyses

- Change in surface temperature for paired sites

Lee et al. (2011) *Nature,* 479, 384-87
Luyssaert et al. (2014) *Nature Clim. Change*, 4, 389-93

MODIS surface temperature, albedo and evapotranspiration

Zhao & Jackson (2014) *Ecol. Monogr.*, 84, 329-53

Alkama & Cescatti (2016) *Science*, 351, 600-604

How do these analyses constrain models?

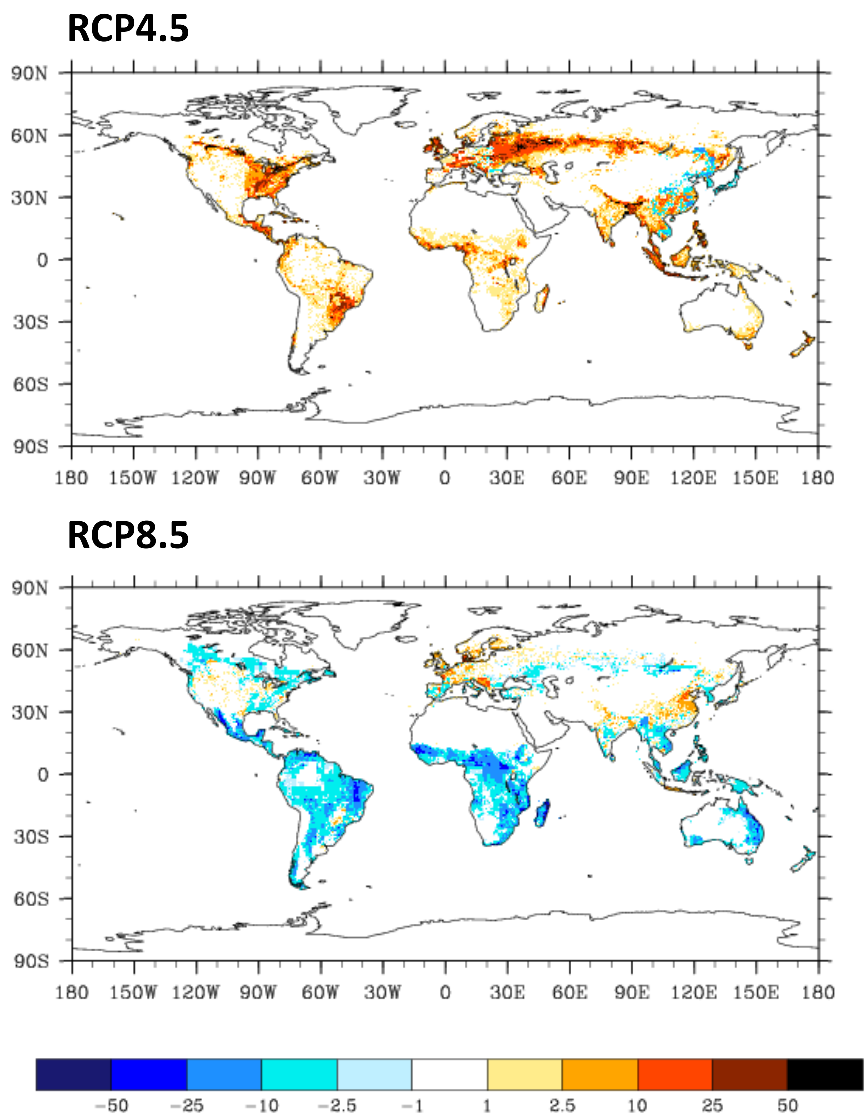
Bonan (2016) *Annu. Rev. Ecol. Evol. Syst.*, 47, 97-121

Twenty-first century land-cover change

Mitigation - afforestation to enhance the terrestrial carbon sink

Business as usual - continued deforestation

Change in tree cover (percent of grid cell)



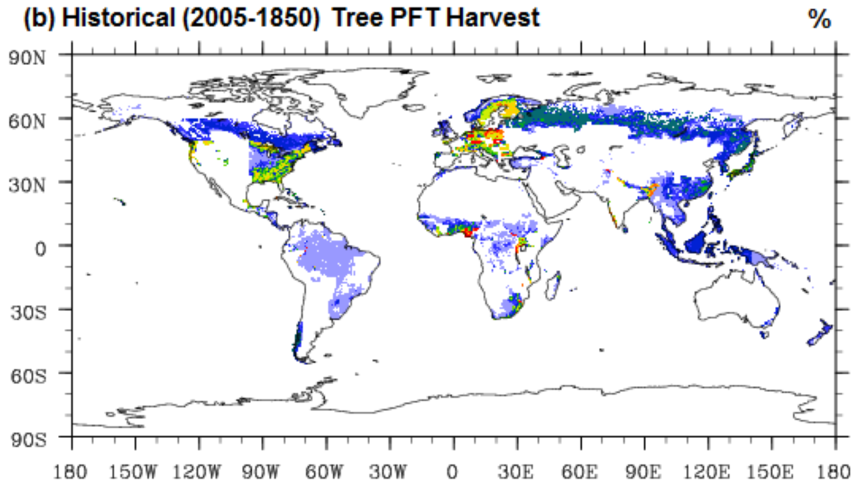
Percent of grid cell

Lawrence et al. (2012) *J. Clim.*, 25, 3071-95

Land management

Forest management

Cumulative percent of grid cell harvested



Lawrence et al. (2012) *J. Clim.*, 25, 3071-95

Agricultural management

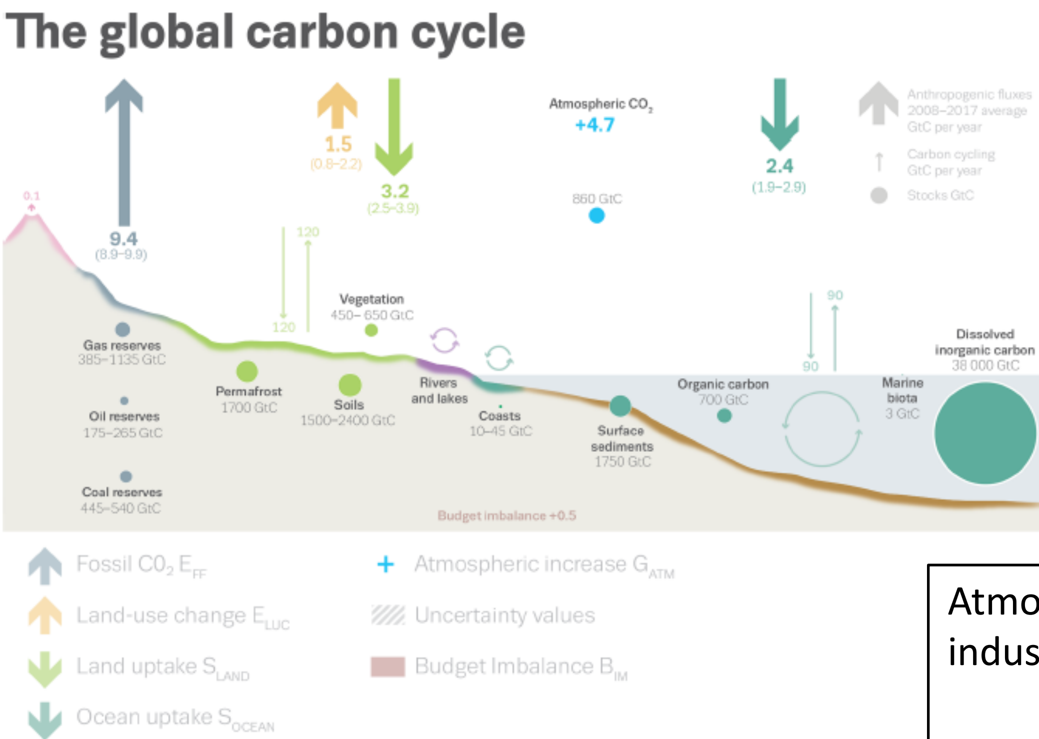
Crop selection
Irrigation
Fertilizer use
Tillage

8 crop functional types:

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

Lombardozzi et al. (2019) *JGR: Biogeosci.*, submitted

Carbon cycle



Le Quéré et al. (2018) *Earth Syst. Sci. Data*, 10, 2141-94

Atmospheric CO_2 has increased over the industrial era as the balance of:

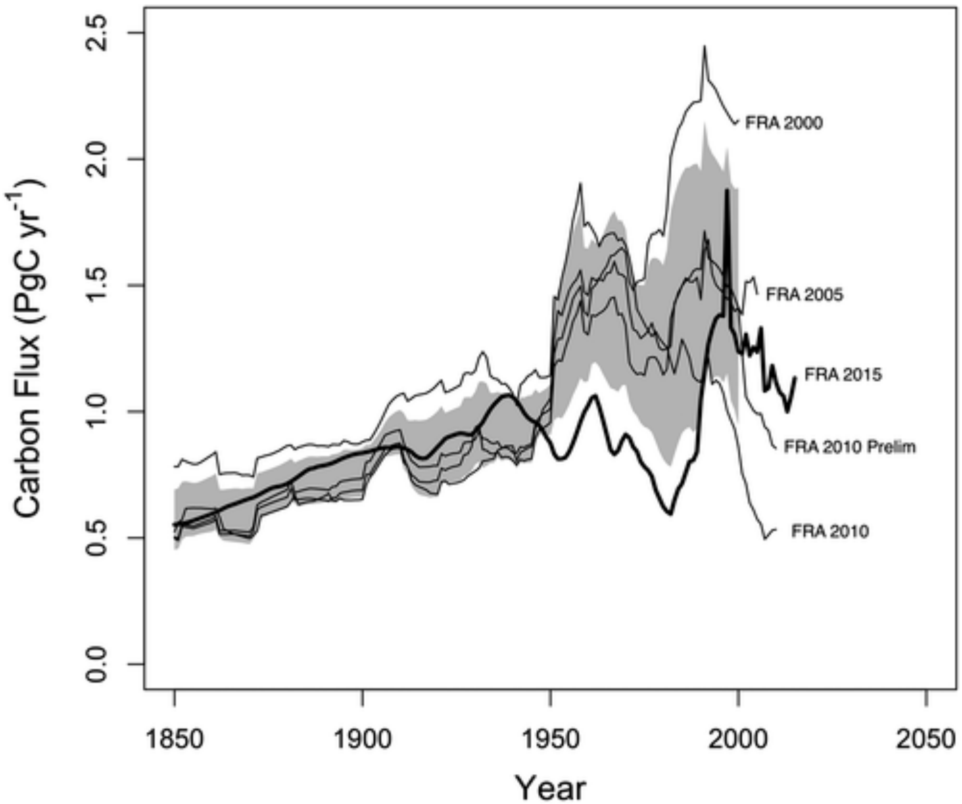
- Fossil fuel emissions
- Land-use and land-cover change emissions
- Terrestrial and oceanic sinks

How will the global carbon cycle change in the future?

Will the terrestrial biosphere continue to be a carbon sink?

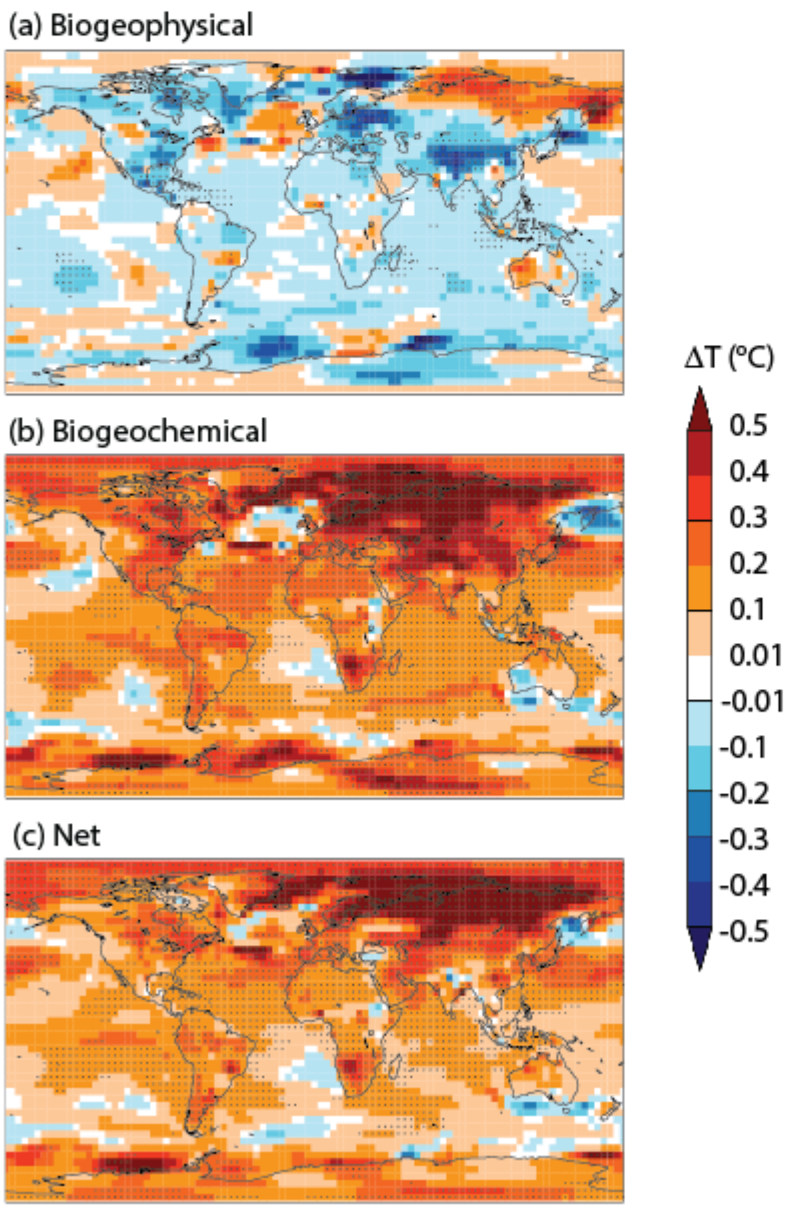
Land use emissions

Global flux of carbon from land use and land cover change 1850-2015



Houghton & Nassikas (2017) *Global Biogeochem. Cycles*, 31, 456-472

Biogeophysics and biogeochemistry



Historical land use & land-cover change

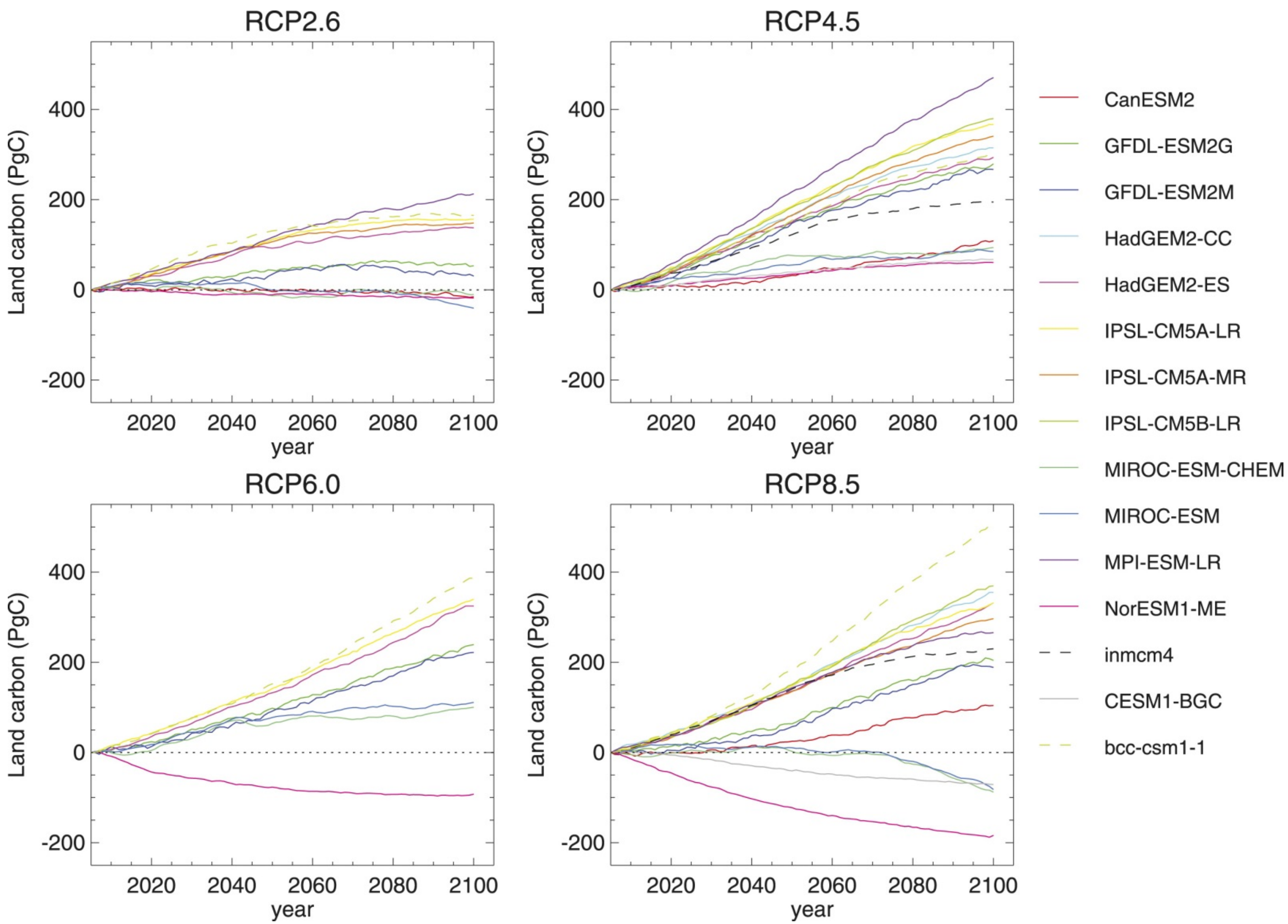
- ❑ Biogeophysical processes decrease annual mean temperature (albedo)
- ❑ Deforestation releases carbon (warms temperature)
- ❑ Biogeochemical warming exceeds biogeophysical cooling

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

Carbon cycle projections



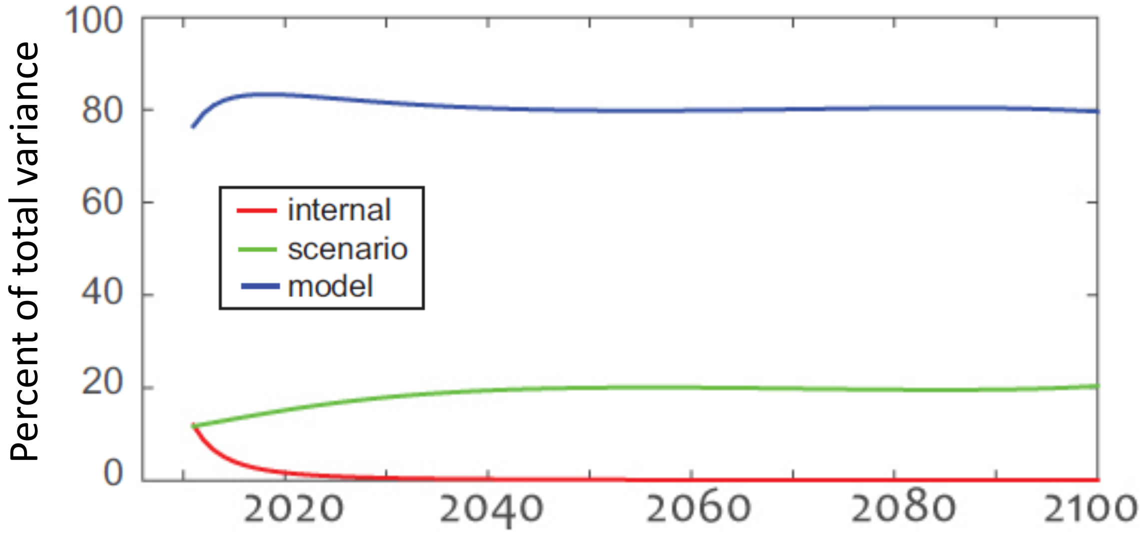
Uncertainty in land carbon uptake due to differences among models is considerably larger than the spread across scenarios

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

CMIP5 model uncertainty

Sources of uncertainty
- Internal variability
- Model structure
- Scenarios

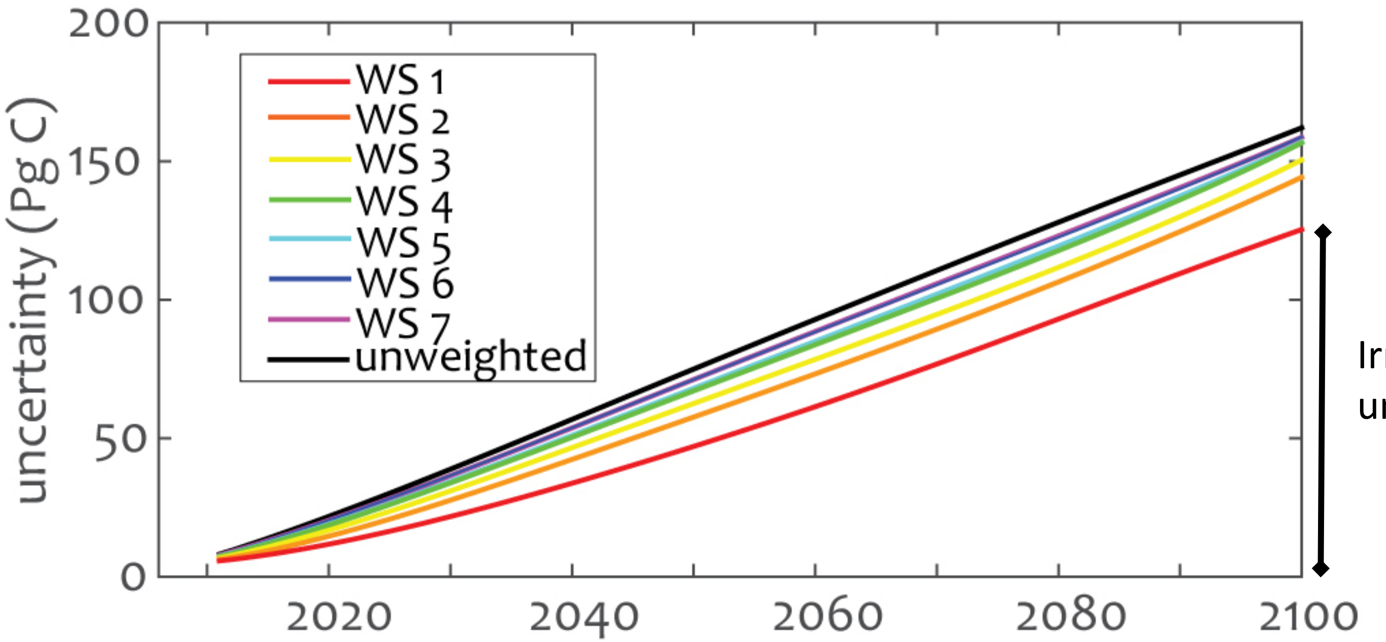
Hawkins & Sutton (2009) *BAMS*, 90, 1095-1107



Lovenduski & Bonan (2017) *Environ. Res. Lett.*, 12, 044020

CMIP5 model uncertainty

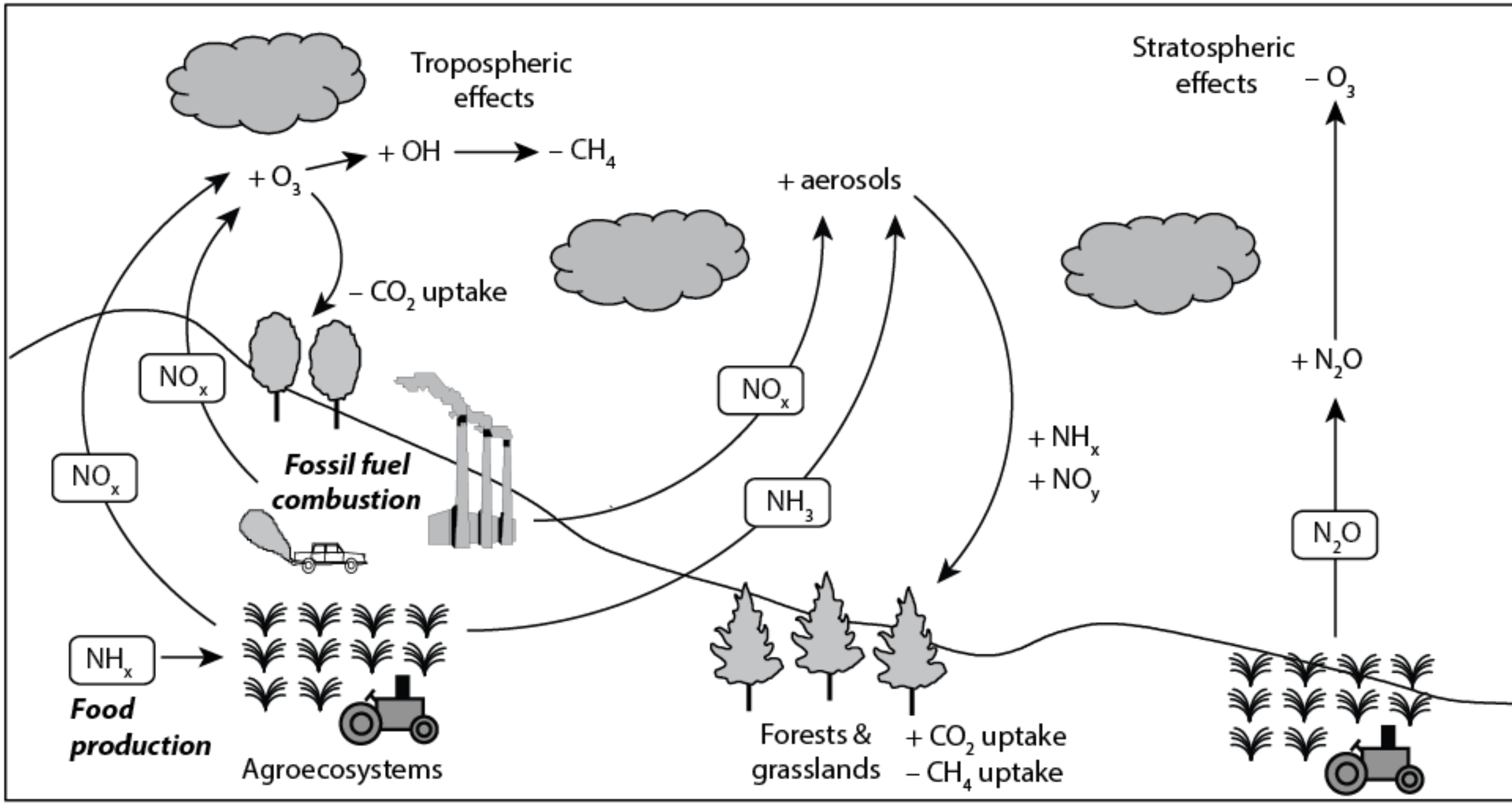
Weighting models does not substantially reduce uncertainty



Irreducible uncertainty?

Lovenduski & Bonan (2017) *Environ. Res. Lett.*, 12, 044020

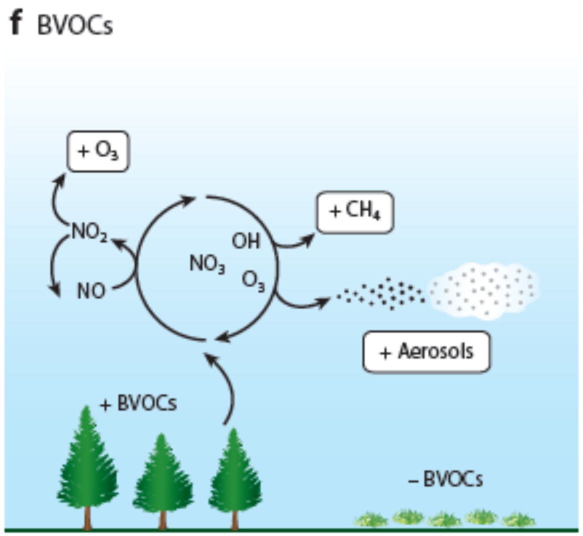
Reactive nitrogen



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

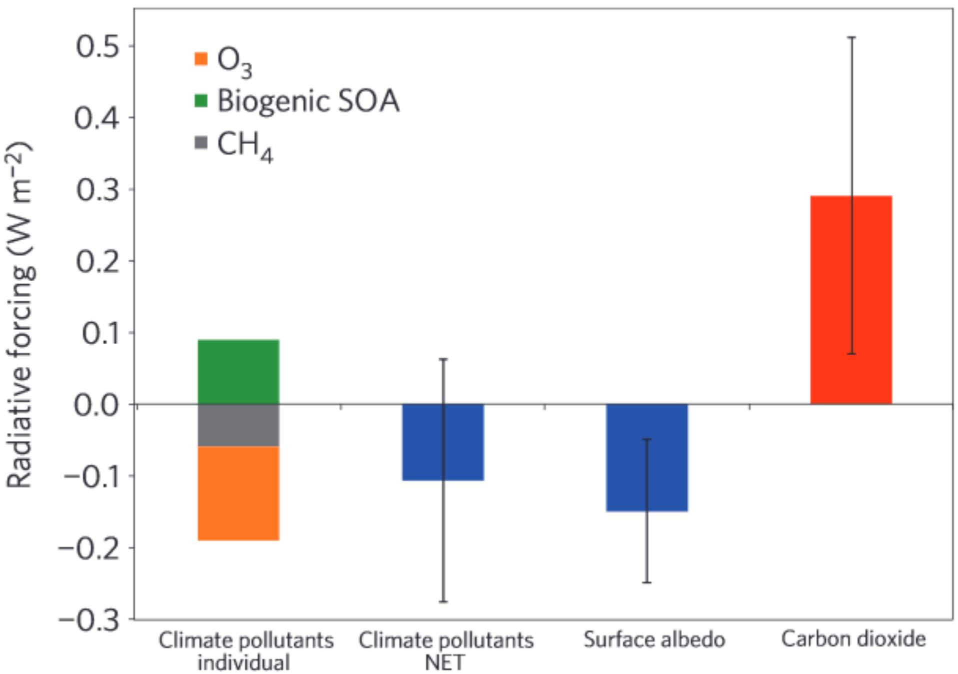
Nitrogen addition alters the composition and chemistry of the atmosphere, and changes the radiative forcing. The net radiative forcing varies regionally.

Chemistry – climate interactions



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

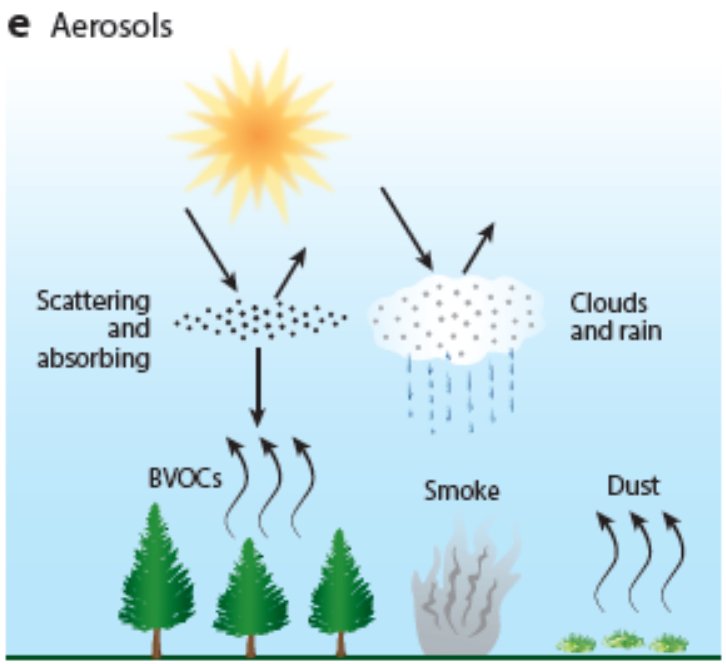
Global climate effects of historical cropland expansion



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

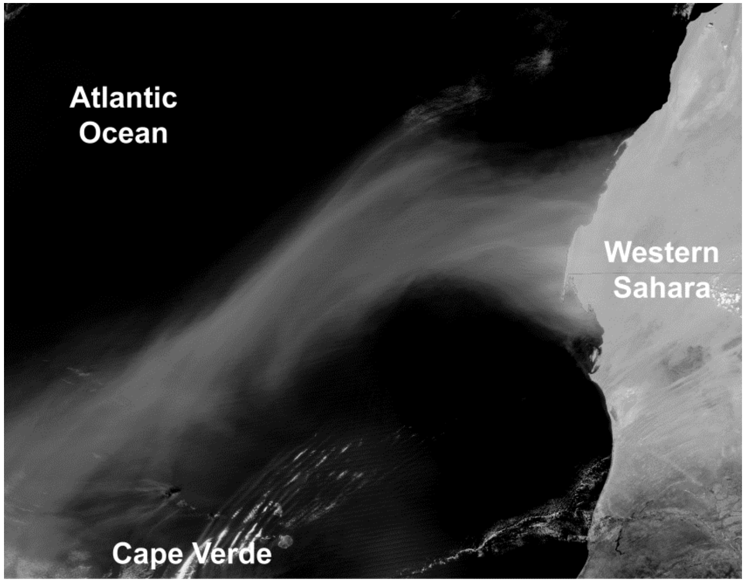
- Loss of forests and increase in croplands reduces global BVOC emissions
- Decreases ozone, CH_4, and secondary organic aerosols
- Net radiative forcing is –0.11 W m^{-2}

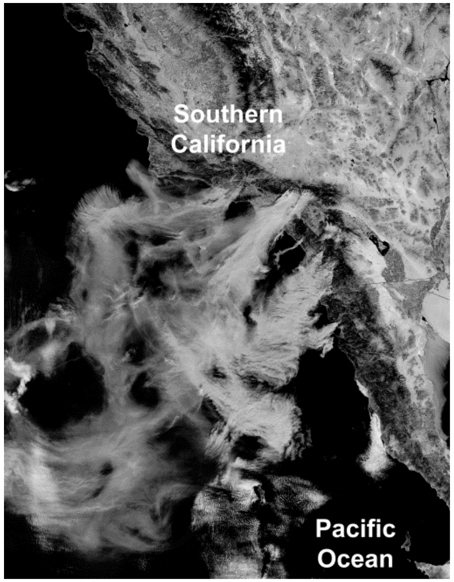
Biomass burning and dust



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

Dust plume off Africa





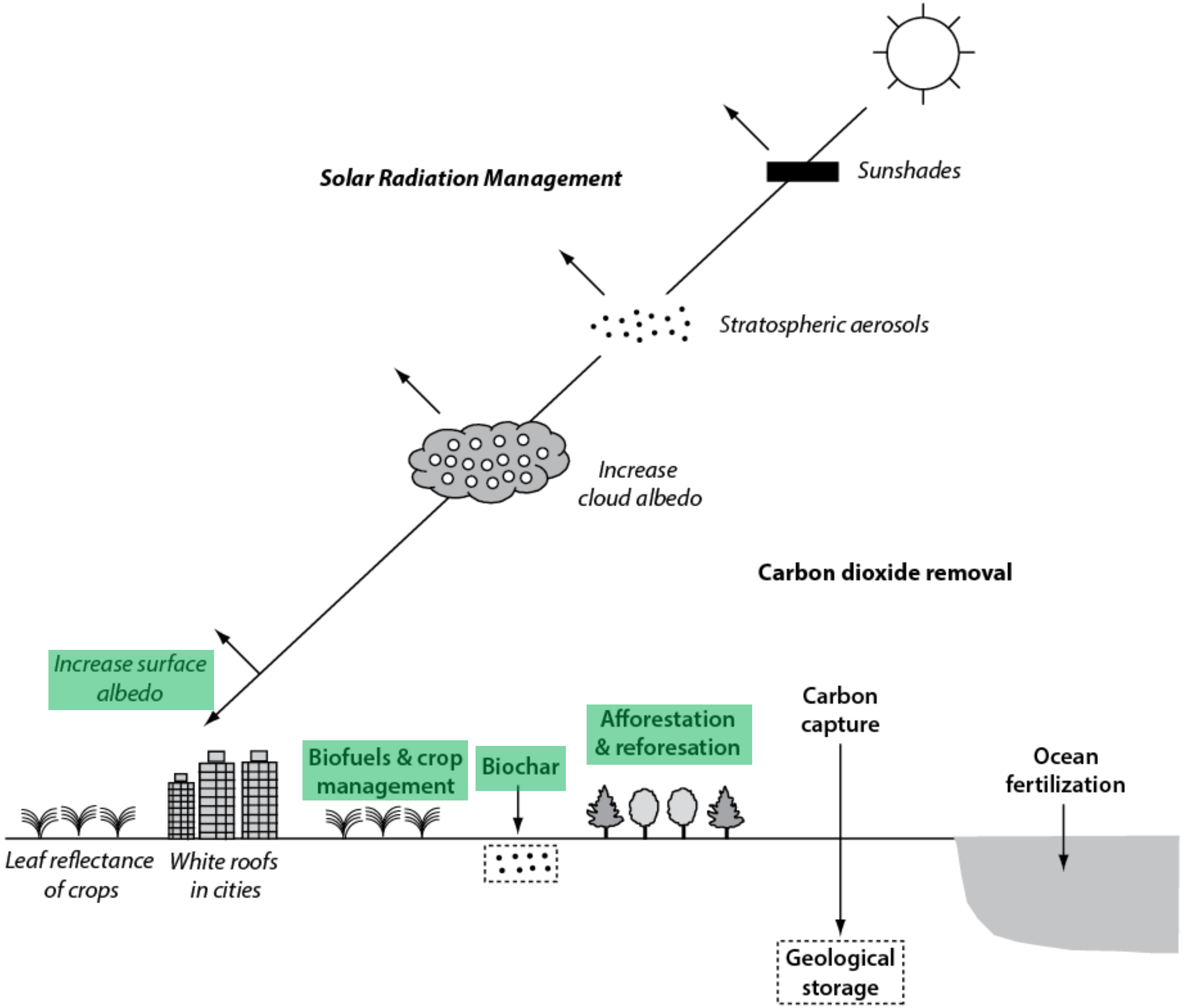
Smoke plume
off California

Atmospheric radiation
Atmospheric chemistry
Surface albedo

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

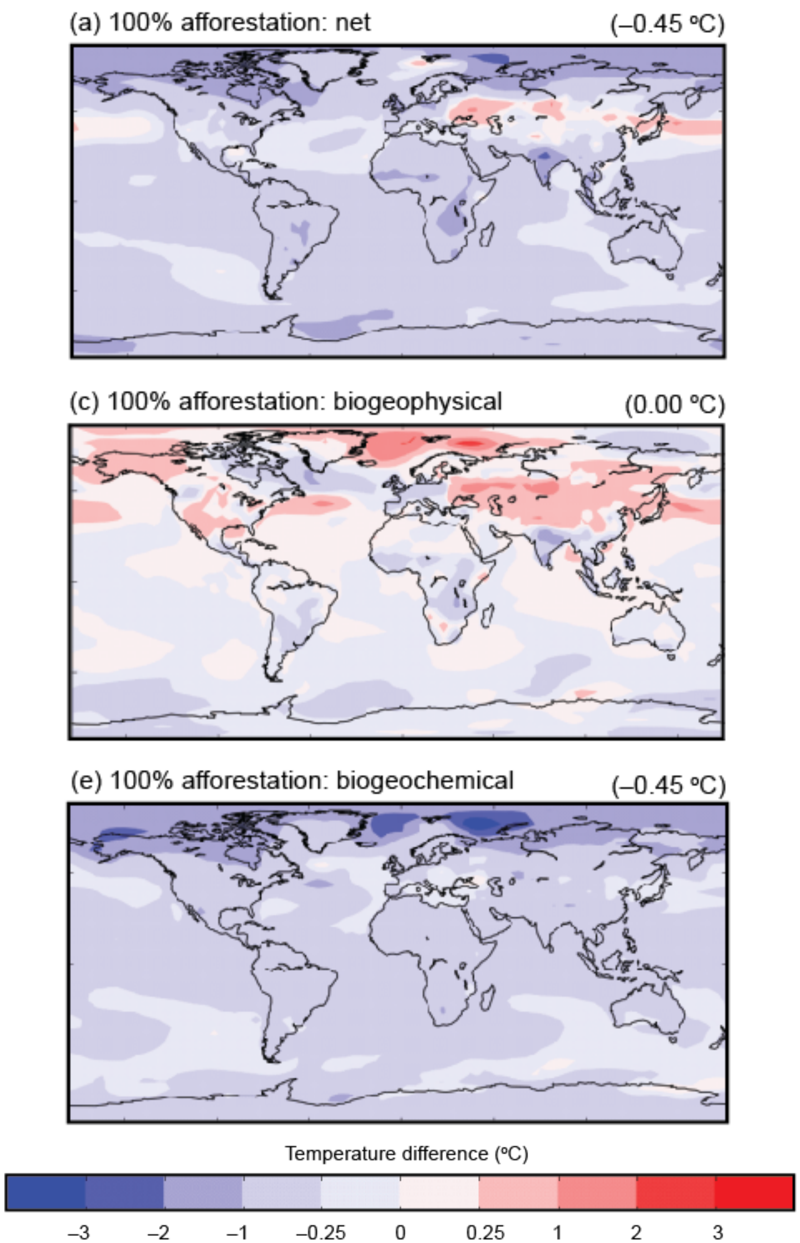
Terrestrial ecosystems and geoengineering

Green solutions to mitigate climate change



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

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

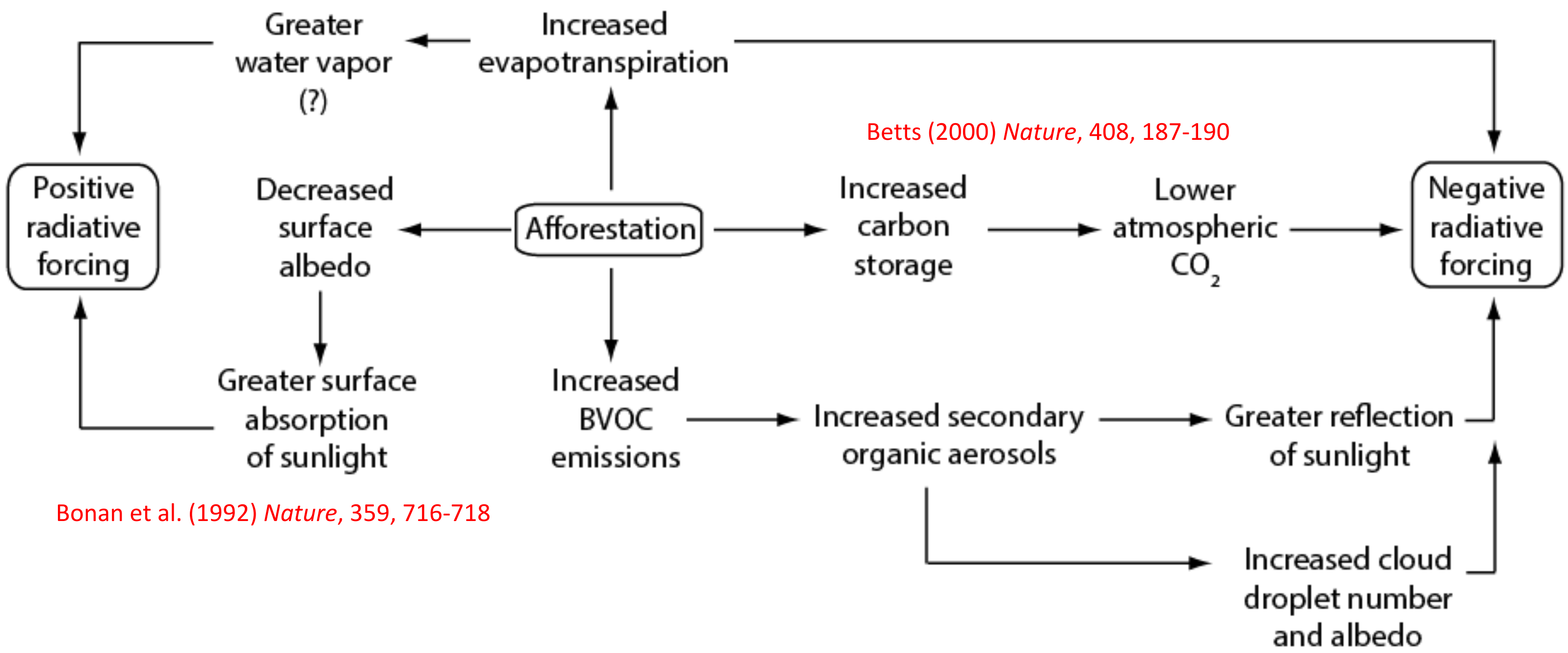
Arora & Montenegro (2011) *Nature Geosci.*, 4, 514–518

Net radiative forcing

Consequences of boreal afforestation

Swann et al. (2010) *PNAS*, 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, 4613-26

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

Forests and climate

But can (should) forests be managed for climate services?

Trade-offs in using European forests to meet climate objectives

Sebastiaan Luyssaert[1,2*], Guillaume Marie[1], Aude Valade[3,5], Yi-Ying Chen[2,6], Sylvestre Njakou Djomo[4], James Ryder[2,7], Juliane Otto[2,8], Kim Naudts[2,9], Anne Sofie Lansø[2], Josefine Ghattas[3] & Matthew J. McGrath[2]

Nature, 562, 259-262 (2018)

SCIENCE ADVANCES | RESEARCH ARTICLE

ENVIRONMENTAL STUDIES

Natural climate solutions for the United States

Fargione et al. (2018) *Sci. Adv.*, 4, eaat1869

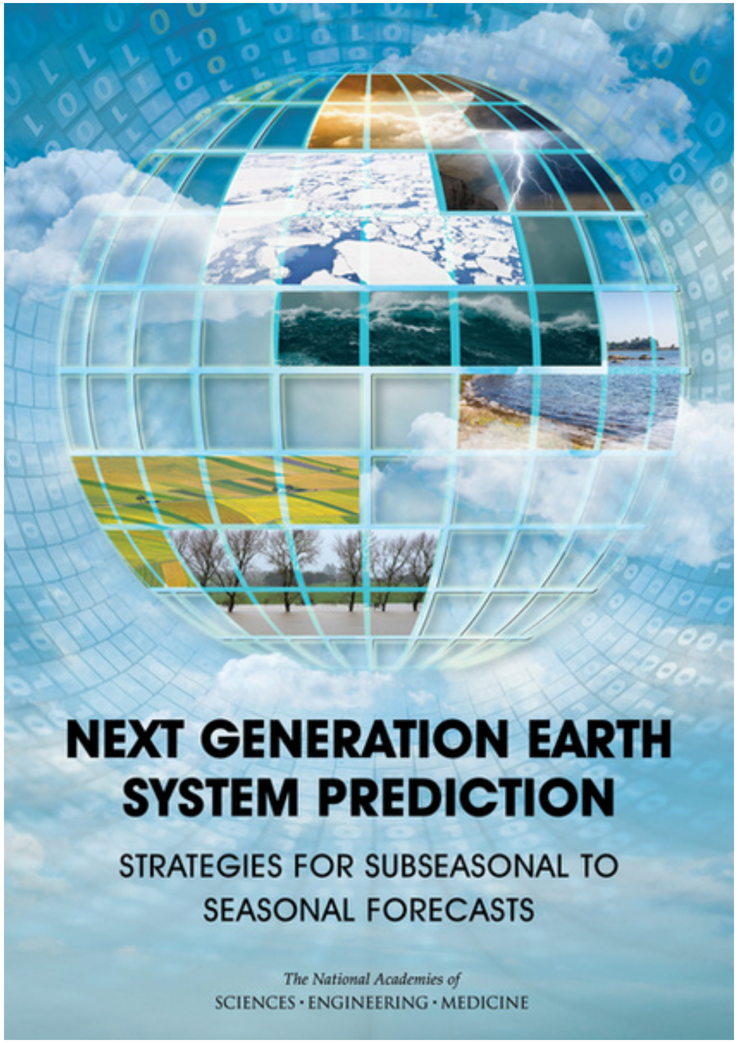
Harvard Forest (Rose Abramoff)

The forest question

Trees are supposed to slow global warming, but growing evidence suggests they might not always be climate saviours.

Popkin (2019) *Nature*, 565, 280-282

Earth system prediction



Land as a source of atmospheric predictability

- Soil moisture
- Snow
- Vegetation state (leaf area)

(NAS, 2016)

Earth system change

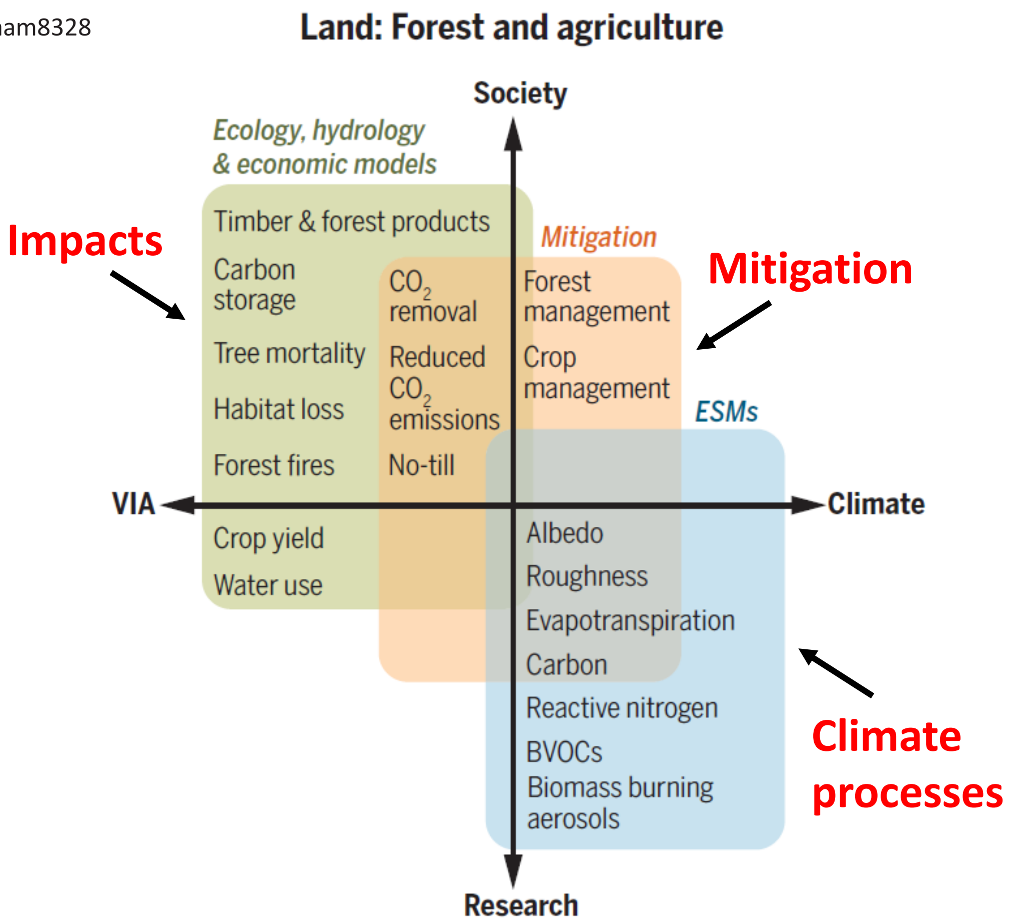
… or predictability of land state and fluxes

Drought, wildfires, floods, tree mortality, vegetation greening, habitat loss, infectious disease

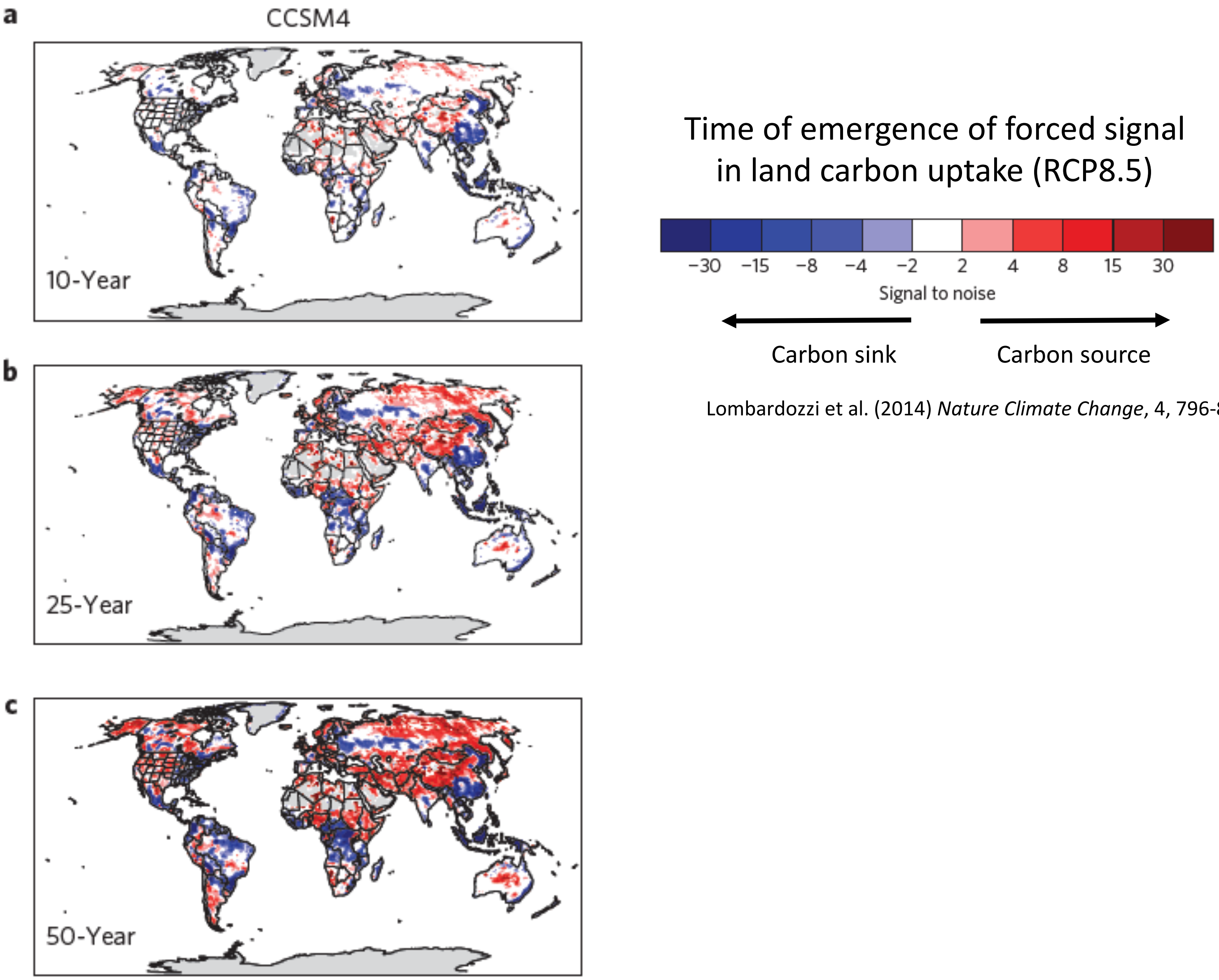
Earth system prediction

The various models used for climate projections, mitigation, and impacts (VIA) overlap in scope and would benefit from a broad perspective of Earth system prediction

Bonan & Doney (2018) *Science*, 359, eaam8328, doi:10.1126/science.aam8328



Earth system prediction

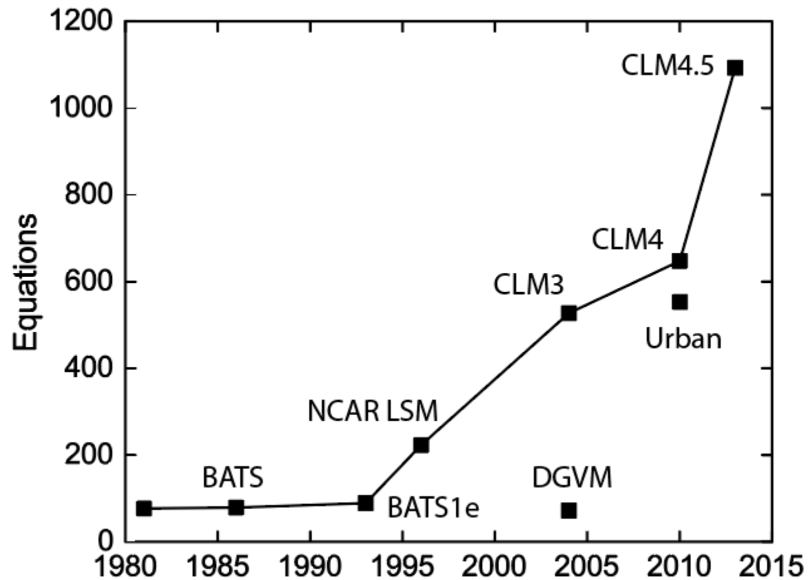


Time of emergence of forced signal in land carbon uptake (RCP8.5)

Lombardozzi et al. (2014) *Nature Climate Change*, 4, 796-800

Increasing model complexity

Breadth and complexity of land surface models
as documented by NCAR technical notes



Bonan (2019) *Climate Change and Terrestrial Ecosystem Modeling* (Cambridge University Press)

Do more complexity and more authentic process parameterizations provide a better model?

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
CLM5; process models (multilayer canopy, MIMICS); simple models (Marysa Lägue)

Model deconstruction
Take apart into sub-components to expose biases, flaws, or inconsistencies

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
- Just because a process is in the model does not mean it is correct
- CLM is a very complex, multidisciplinary model that requires a broad perspective of the Earth system