Ecosystem feedbacks in a 21st century climate: carbon, nitrogen, and land cover change

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

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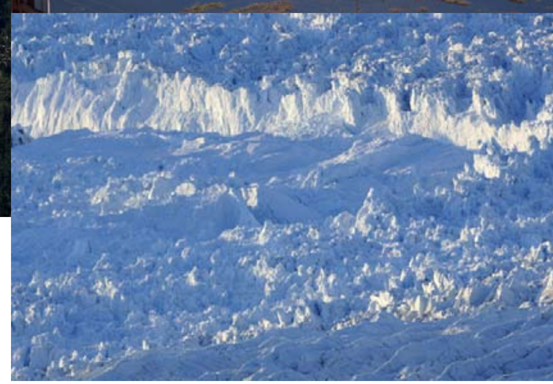
Planetary distress





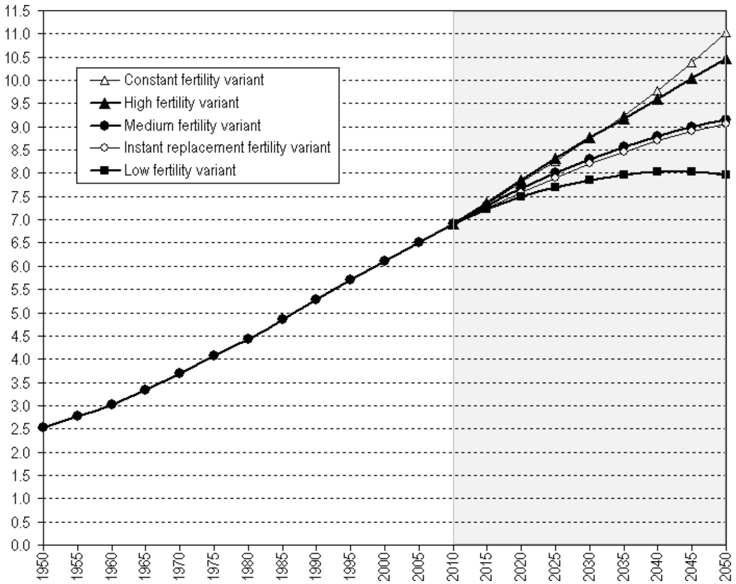





Sea ice retreat (Jonathan Hayward/CP file photo, www.thestar.com)
Drought mortality, Texas (txforestservice.tamu.edu)
Pine beetle, CO (RJ Sangosti/Denver Post)
High Park fire, CO (RJ Sangosti/Denver Post)
Coastal flooding, NC (U.S. Coast Guard)
Texas drought (http://farmprogress.com)
Calving face of the Ilulissat Isfjord, Greenland, 7 June 2007 (www.extremeicesurvey.org)
Habitat loss, NM (UCAR)

The Anthropocene

Population of the world, 1950-2050, according to different projection variants (in billion)



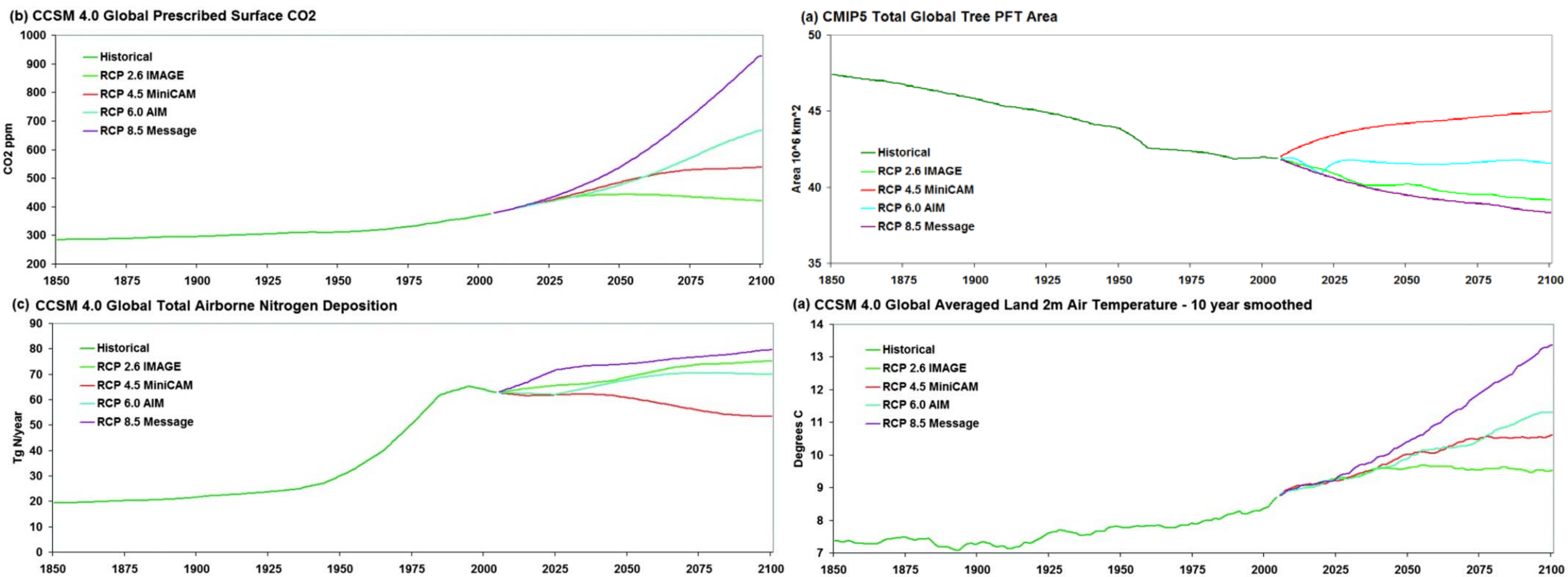
Source: United Nations, Department of Economic and Social Affairs, Population Division (2009): World Population Prospects: The 2008 Revision. New York

Human activities (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 stressors



- ❑ Increasing atmospheric CO_2
- ❑ Land use and land cover change
- ❑ Increasing N deposition
- ❑ Climate change

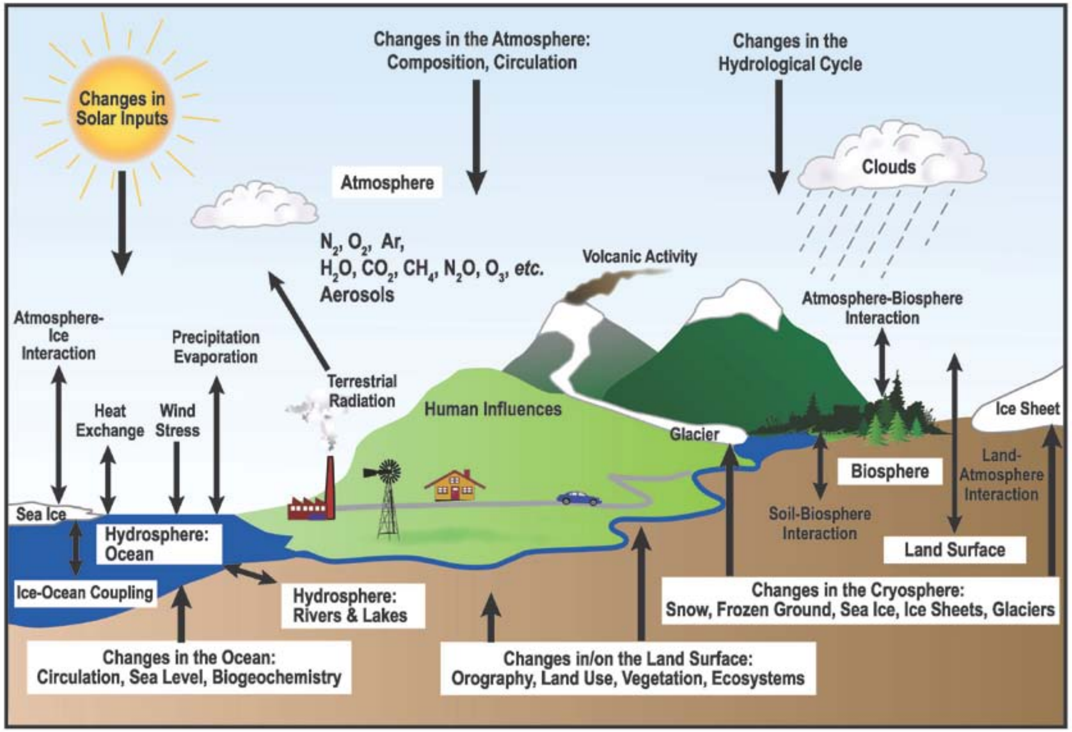
P. Lawrence et al. (2012) J Climate 25:3071-3095

Ecology and climate change

What are the processes and feedbacks by which terrestrial ecosystems contribute to global environmental change?

Can we manage the biosphere to mitigate climate change?

Earth system models



(IPCC 2007)

Prominent biosphere feedbacks

- 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

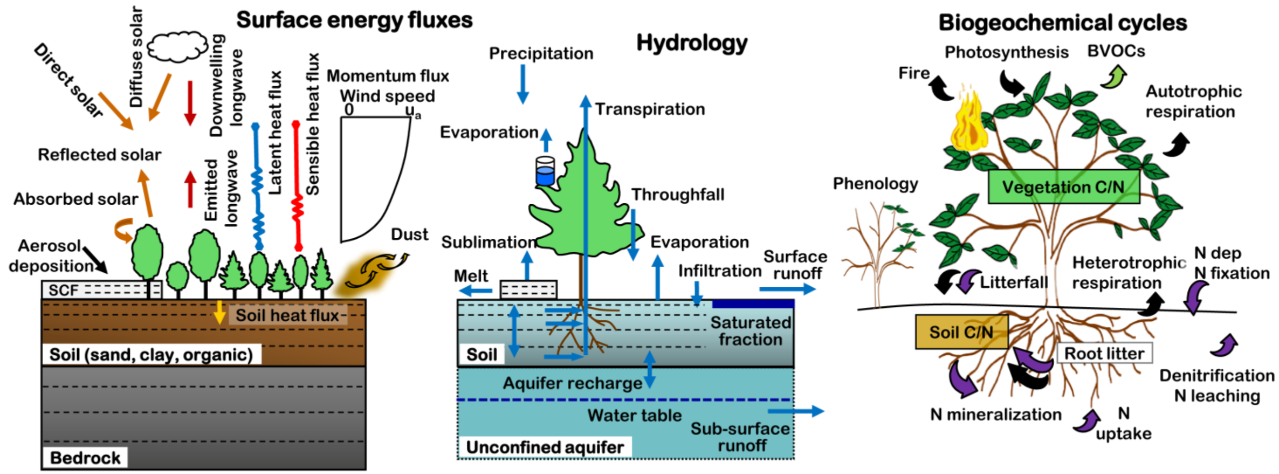
The Community Land Model (CLM4)

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

Oleson et al. (2010) NCAR/TN-478+STR

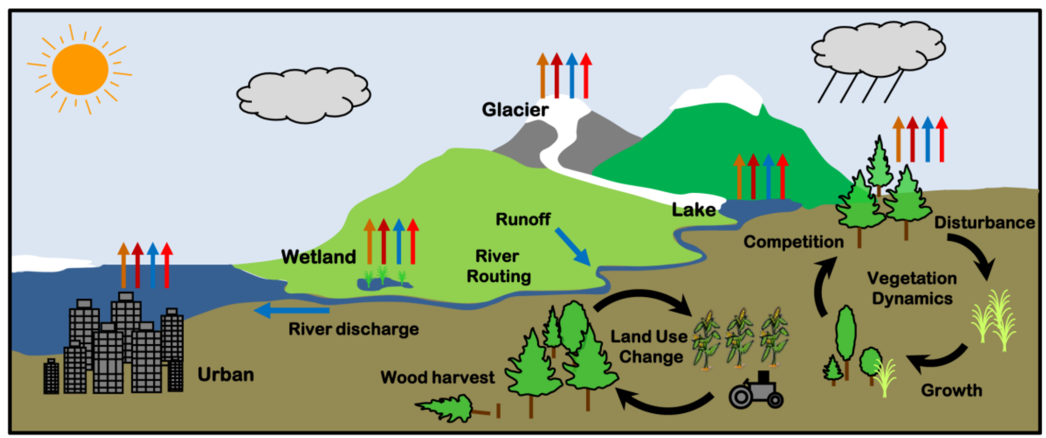
D. Lawrence et al. (2011) JAMES, 3, doi: 10.1029/2011MS000045

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



Spatial scale

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



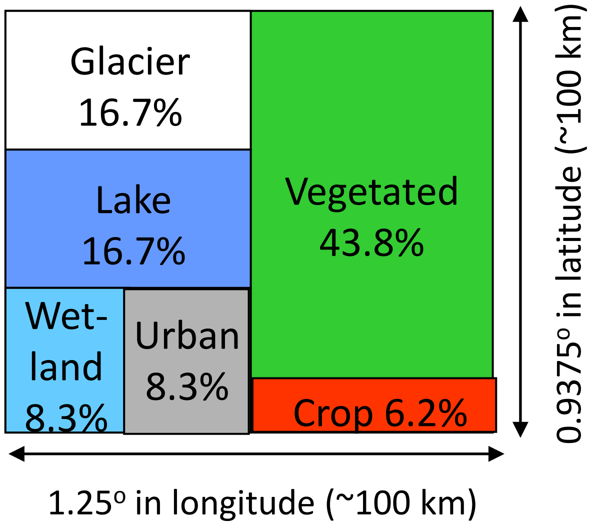
Temporal scale

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

Land surface heterogeneity

The model simulates a column extending from the soil through the plant canopy to the atmosphere. CLM represents a model grid cell as a mosaic of up to 6 primary land cover tiles. Vegetated land is further represented as tiles of individual plant functional types

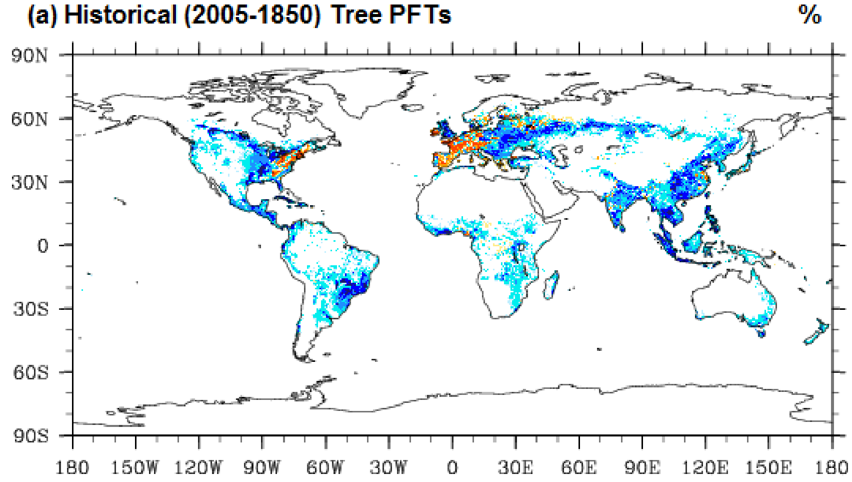
Sub-grid land cover and plant functional types

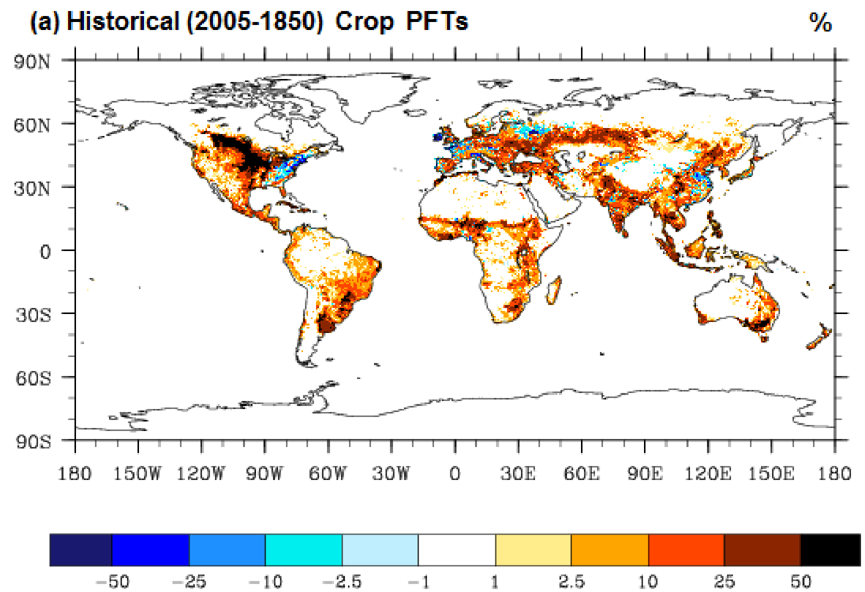


Bonan et al. (2002) GBC, 16, doi:10.1029/2000GB001360

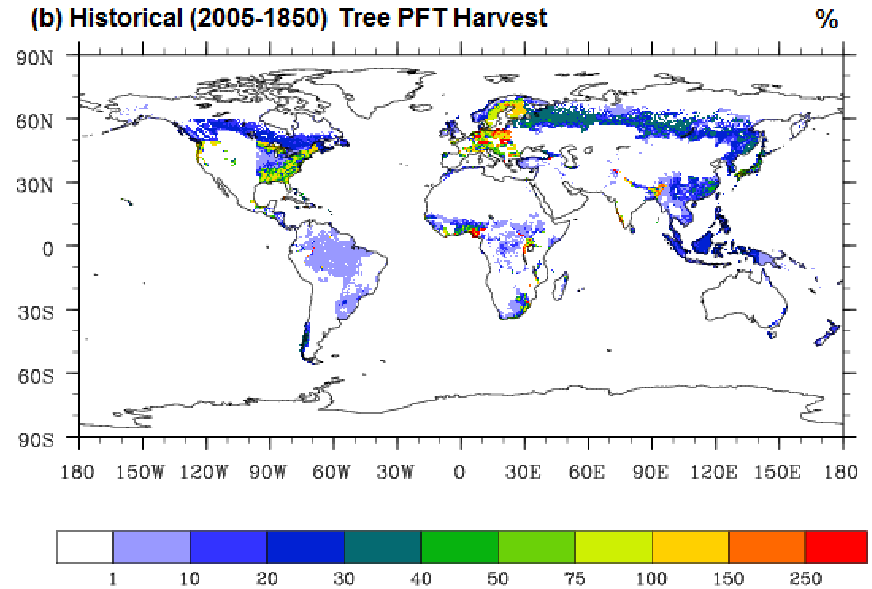
Historical land use and land cover change, 1850 to 2005

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





Cumulative percent of grid cell harvested

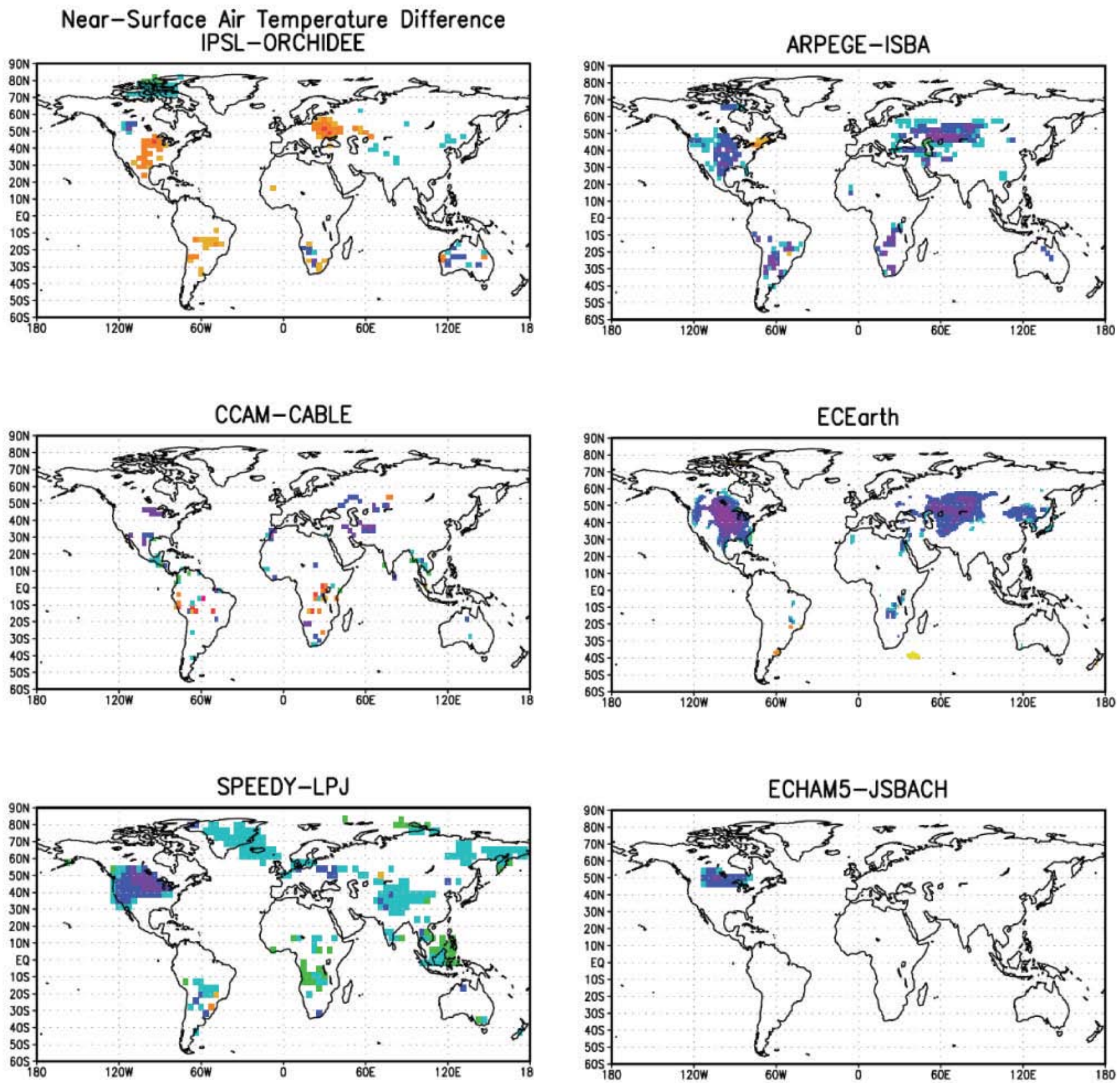


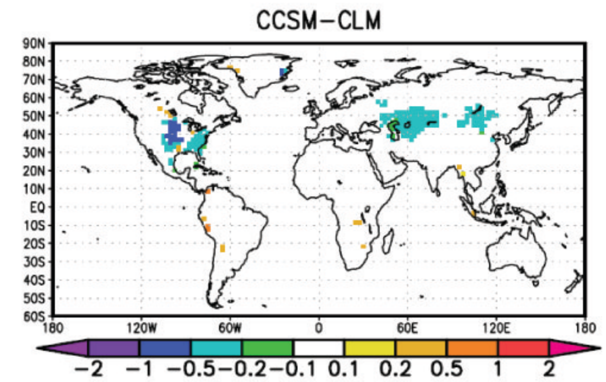
Historical LULCC in CLM4

- ❑ 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

The LUCID intercomparison study





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

Key points:

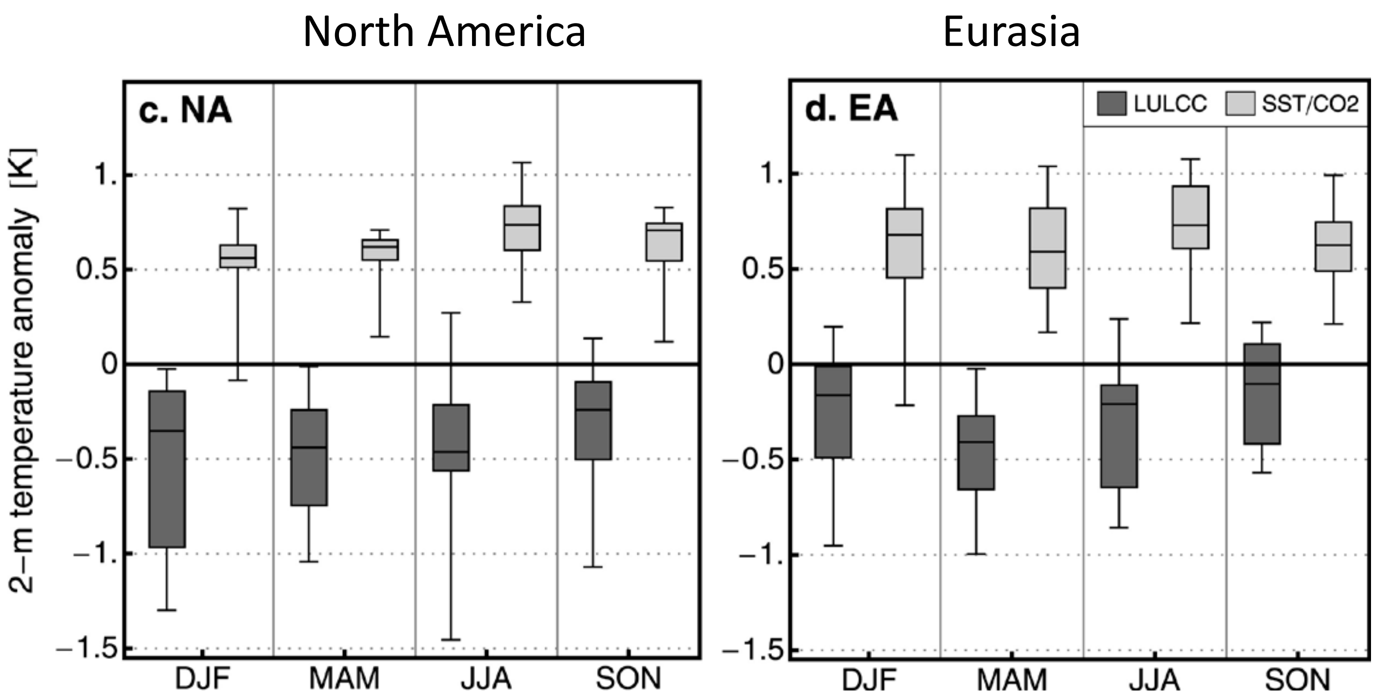
The LULCC forcing is regional

Differences among models matter

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

LULCC relative to greenhouse warming

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



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

Key points:

The LULCC forcing is counter to greenhouse warming

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

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.

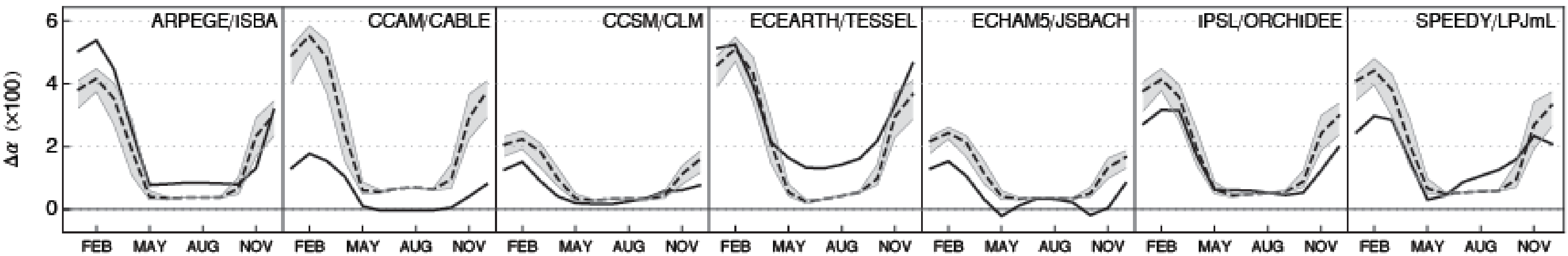
Surface albedo

Colorado Rocky Mountains

LULCC effects

- Forest masking of snow
- High albedo of crops

Surface albedo change due to LULCC



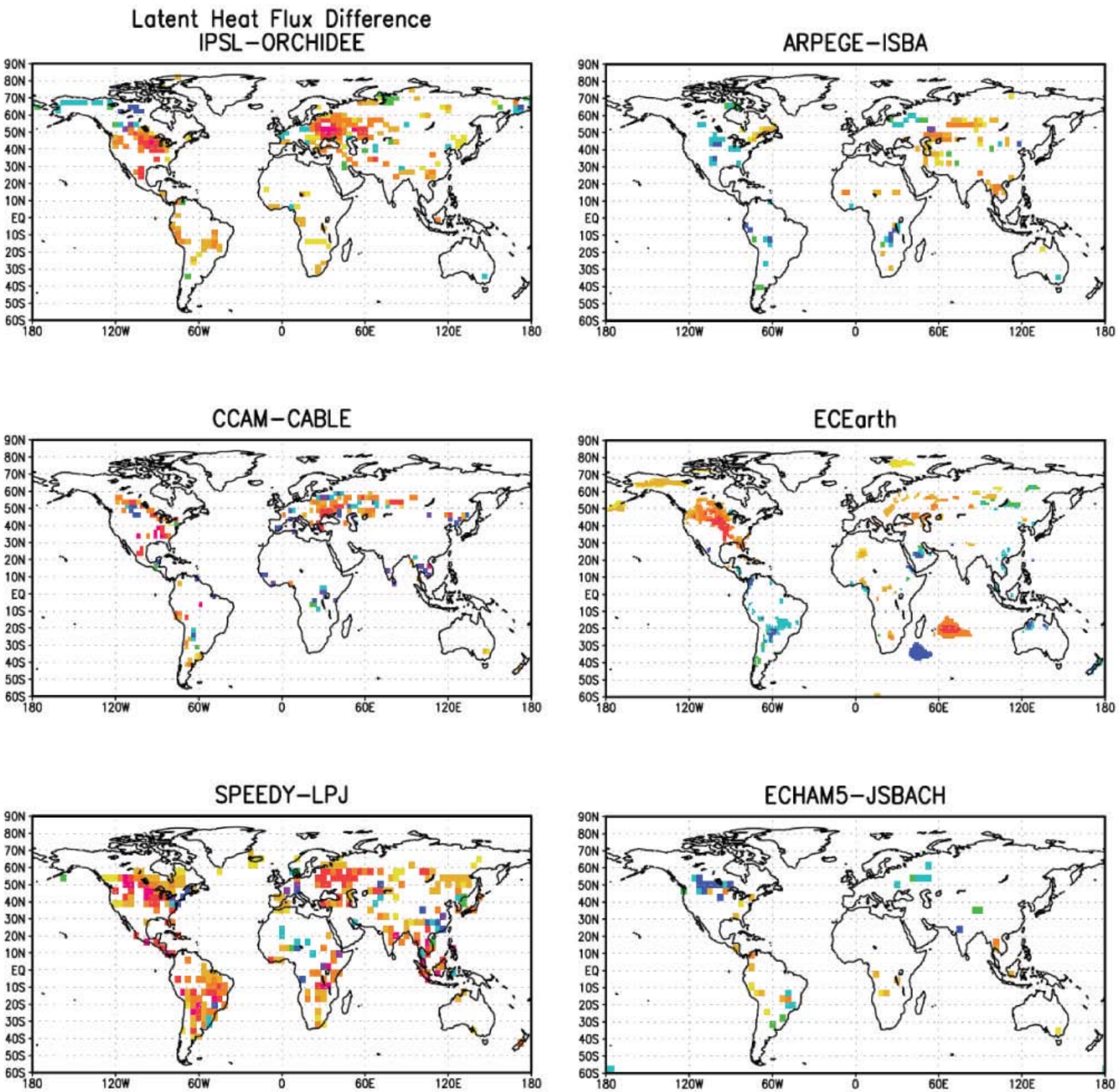
——— Simulated

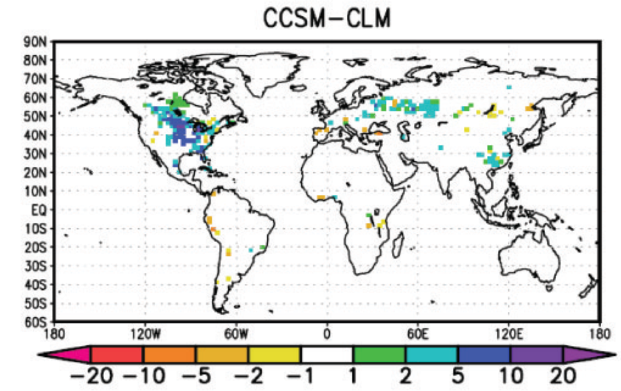
– – – – MODIS reconstruction

- ❑ Models differ in their albedo increase (extent of land cover change, albedo parameterization)
- ❑ Some models are more faithful to MODIS reconstructions than other models

Boisier et al. (2012) Biogeosciences Discuss. 9:12505–12542

Evapotranspiration





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

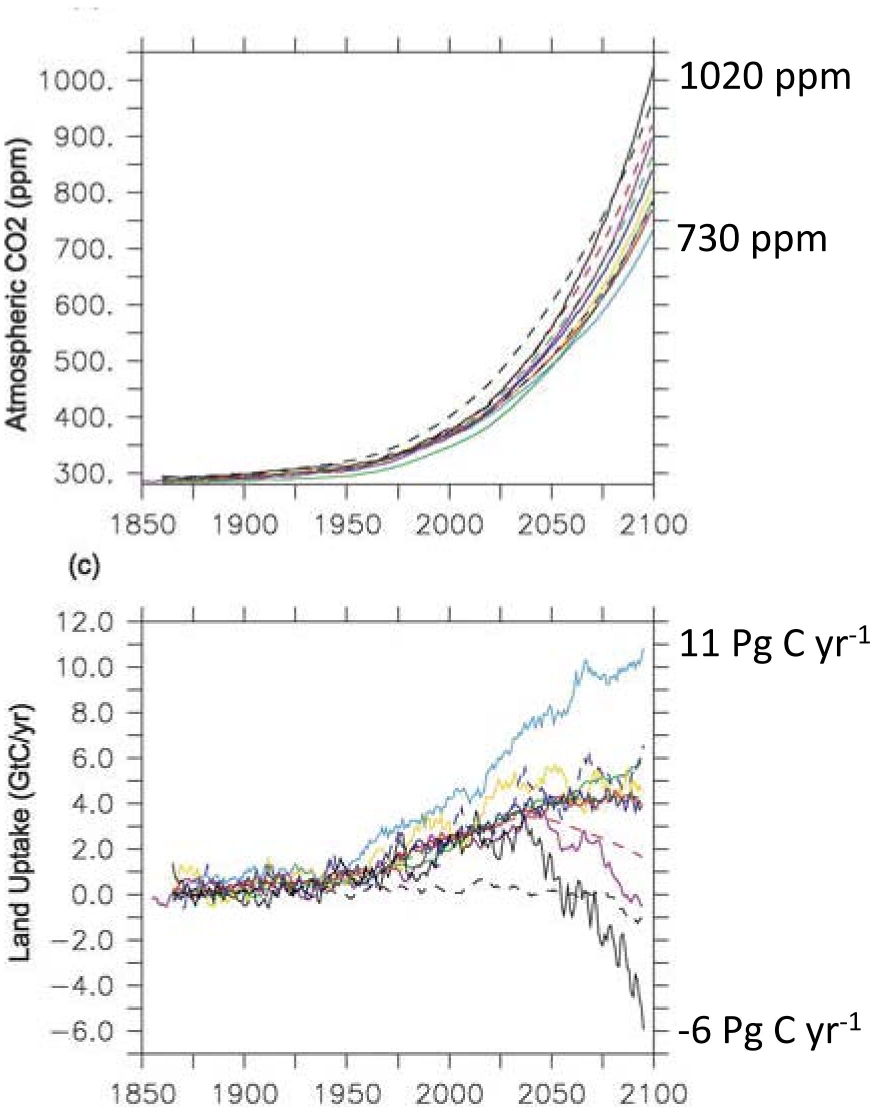
Key points:

The LULCC forcing is regional

Differences among models matter

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

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

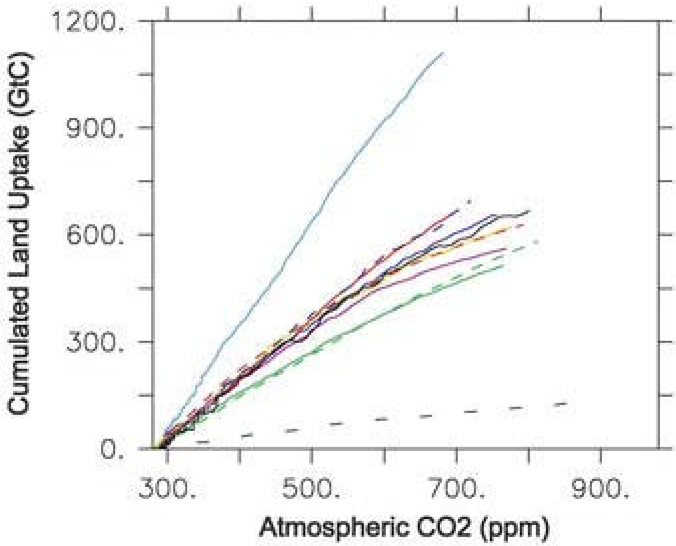
290 ppm difference in atmospheric CO_2 at 2100

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

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

Model uncertainty in feedback is large

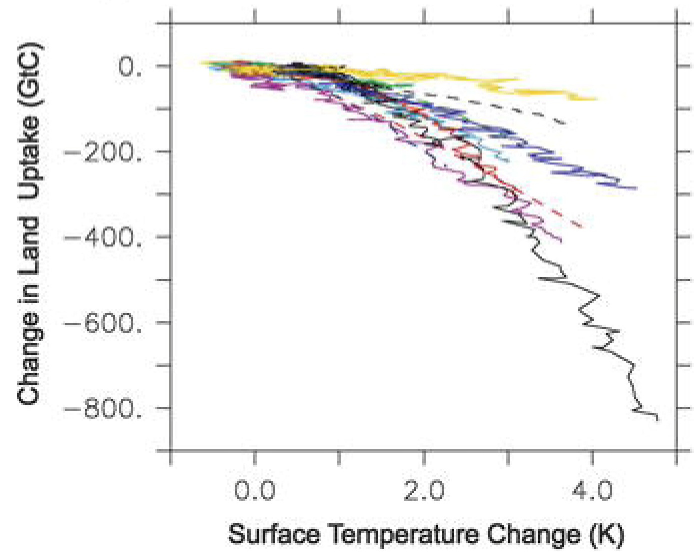
Concentration-carbon feedback



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

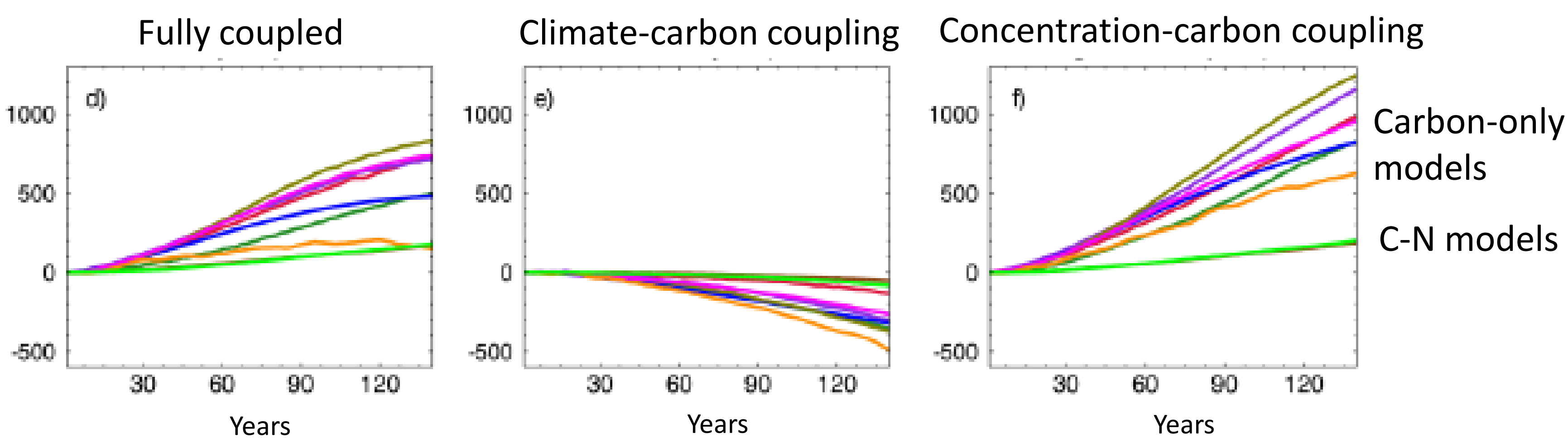
Carbon cycle-climate feedback

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. (2012) J Climate, submitted

Cumulative land-atmosphere CO_2 flux (Pg C)

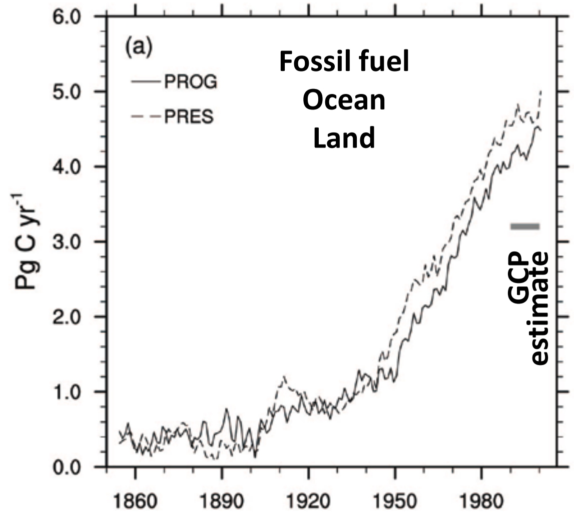


CMIP5: γ_L=-58 Pg C K^{-1} [-16 to -89] β_L=0.9 Pg C ppm^{-1} [0.2-1.5]

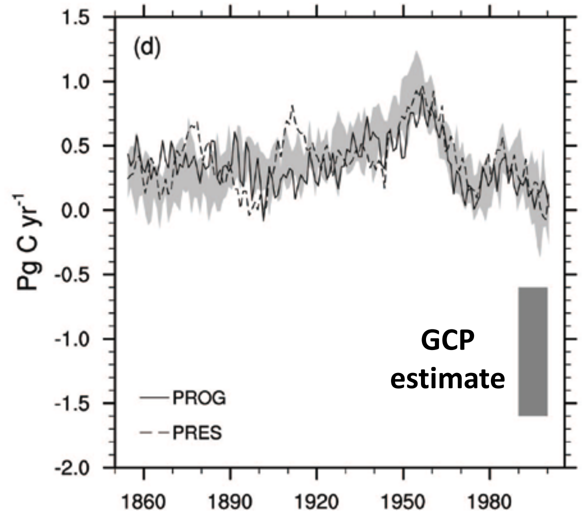
C4MIP: γ_L=-79 Pg C K^{-1} [-20 to -177] β_L=1.4 Pg C ppm^{-1} [0.2-2.8]

CESM/CLM 20th century terrestrial carbon cycle

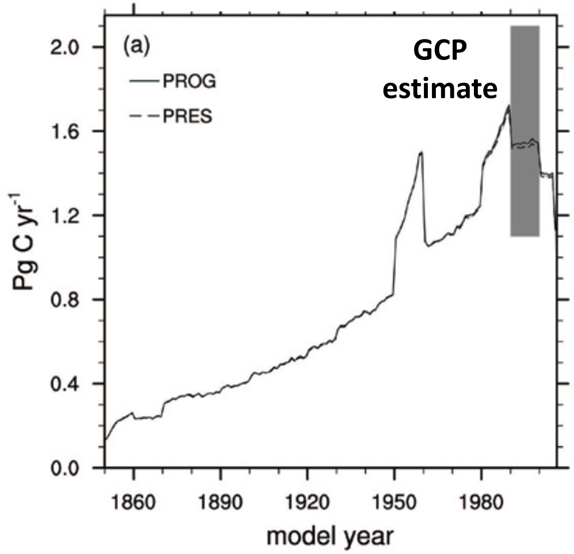
Net atmosphere flux



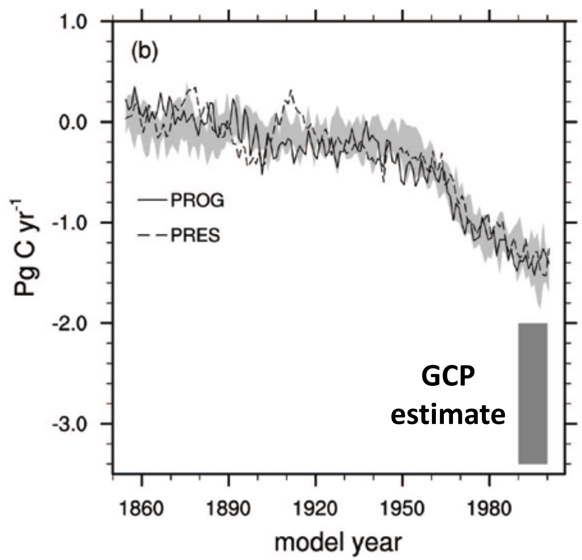
Net land-atmosphere flux



Land use emission



Residual land flux



The atmosphere accumulates too much carbon, because the land is mostly a source of carbon. The net land flux consists of a land use emission and a "residual" uptake. This uptake is too low.

Lindsay et al. (2012) J Climate, submitted

CLM and nitrogen

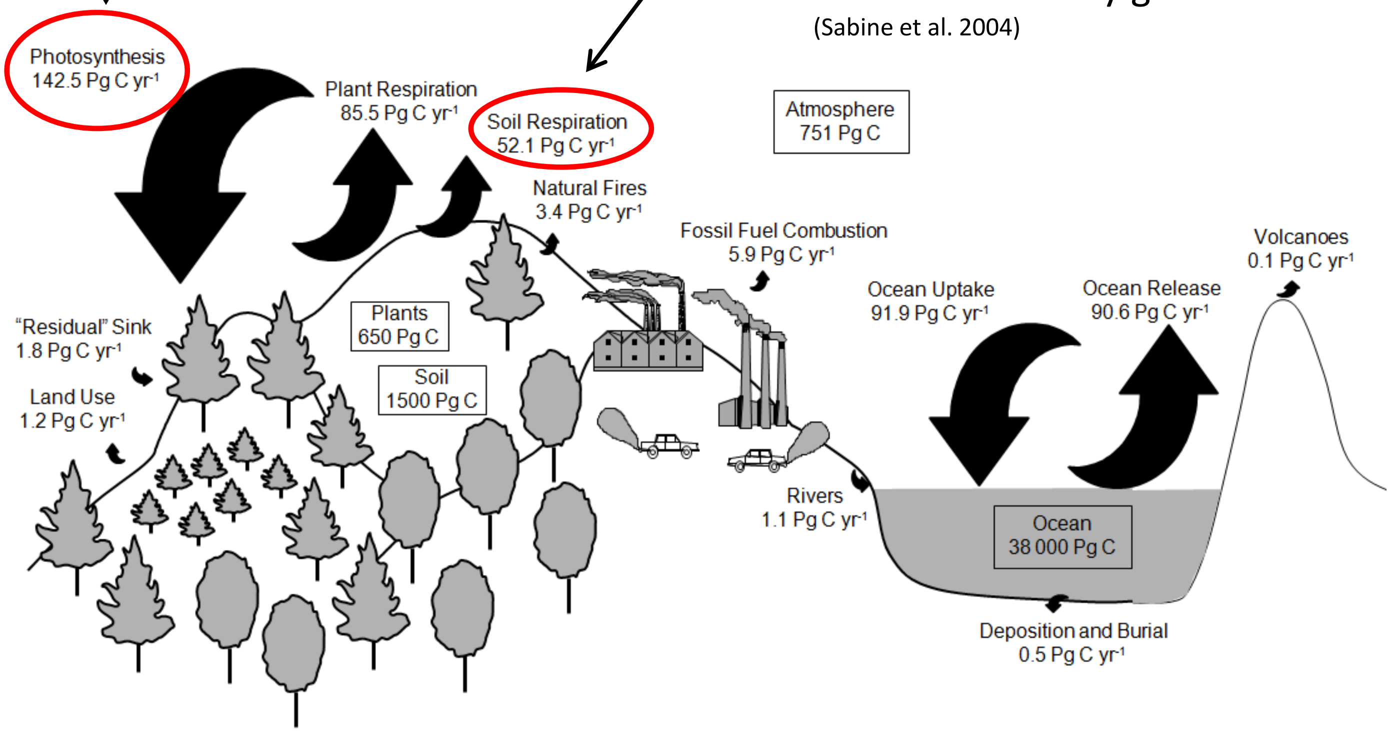
CLM simulates high GPP that must be decreased due to N limitation to match observations. Other approaches (light limitation) can similarly match observations without N limitation

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593
Bonan et al. (2012) JGR, doi:10.1029/2011JG001913

CLM simulates high decomposition rates that must be decreased due to N limitation to match observations. Other models better match observations and do not invoke an N feedback

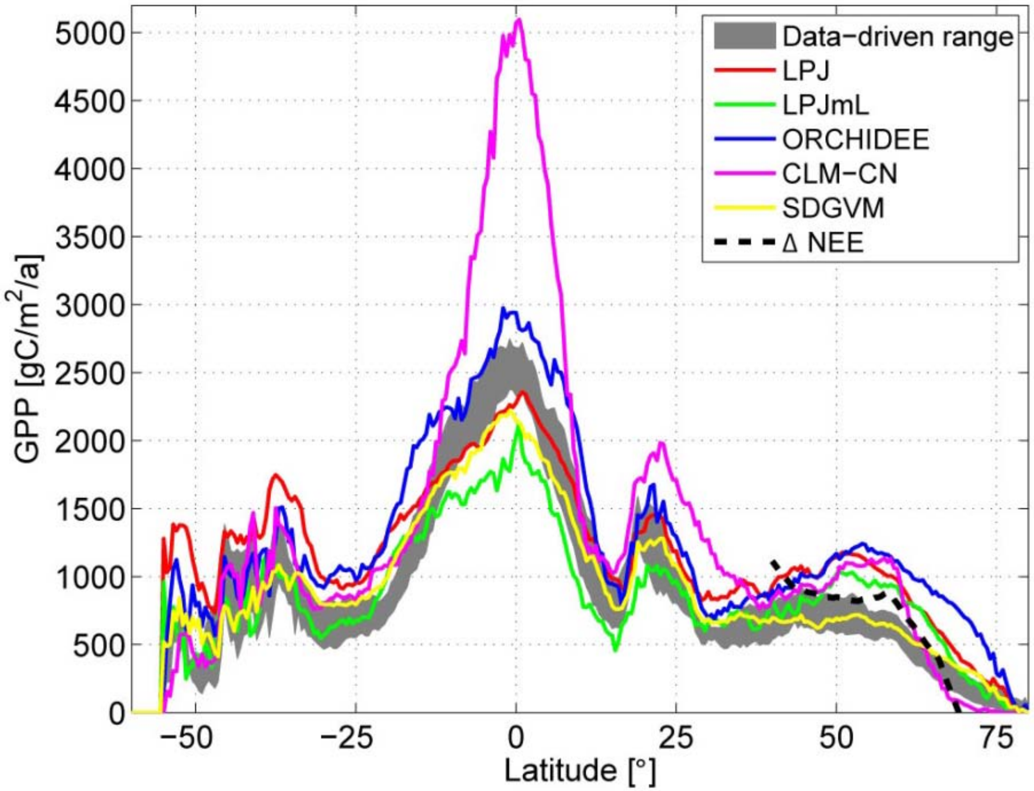
Bonan et al. (2012) GCB, in press

Late-20th century global carbon cycle
(Sabine et al. 2004)



Gross primary production biases

CLM4 (purple line) overestimates annual gross primary production (GPP) compared with data-driven estimates and other models



Beer et al. (2010) Science 329:834-838

Causes of GPP bias

Model structural error

Canopy radiative transfer
- Shaded leaf light absorption

Photosynthesis-stomatal conductance
- Rubisco and RuBP limited rates

Canopy integration
- Nitrogen and photosynthetic capacity

Model parameter uncertainty

V_{cmax}

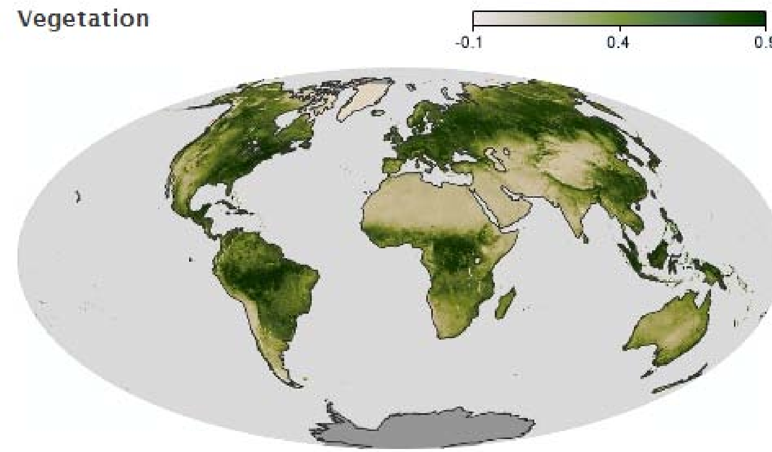
Bonan et al. (2011) JGR, doi:10.1029/2010JG001593
Bonan et al. (2012) JGR, doi:10.1029/2011JG001913

Multi-scale model evaluation

Canopy fluxes

GPP, latent heat flux

Lasslop et al. (2010) GCB 16:187-208



Global vegetation

GPP, latent heat flux

Jung et al. (2011) JGR, 116, doi:10.1029/2010JG001566

Canopy processes

Theory

Numerical parameterization

Profiles of light, leaf traits, and photosynthesis

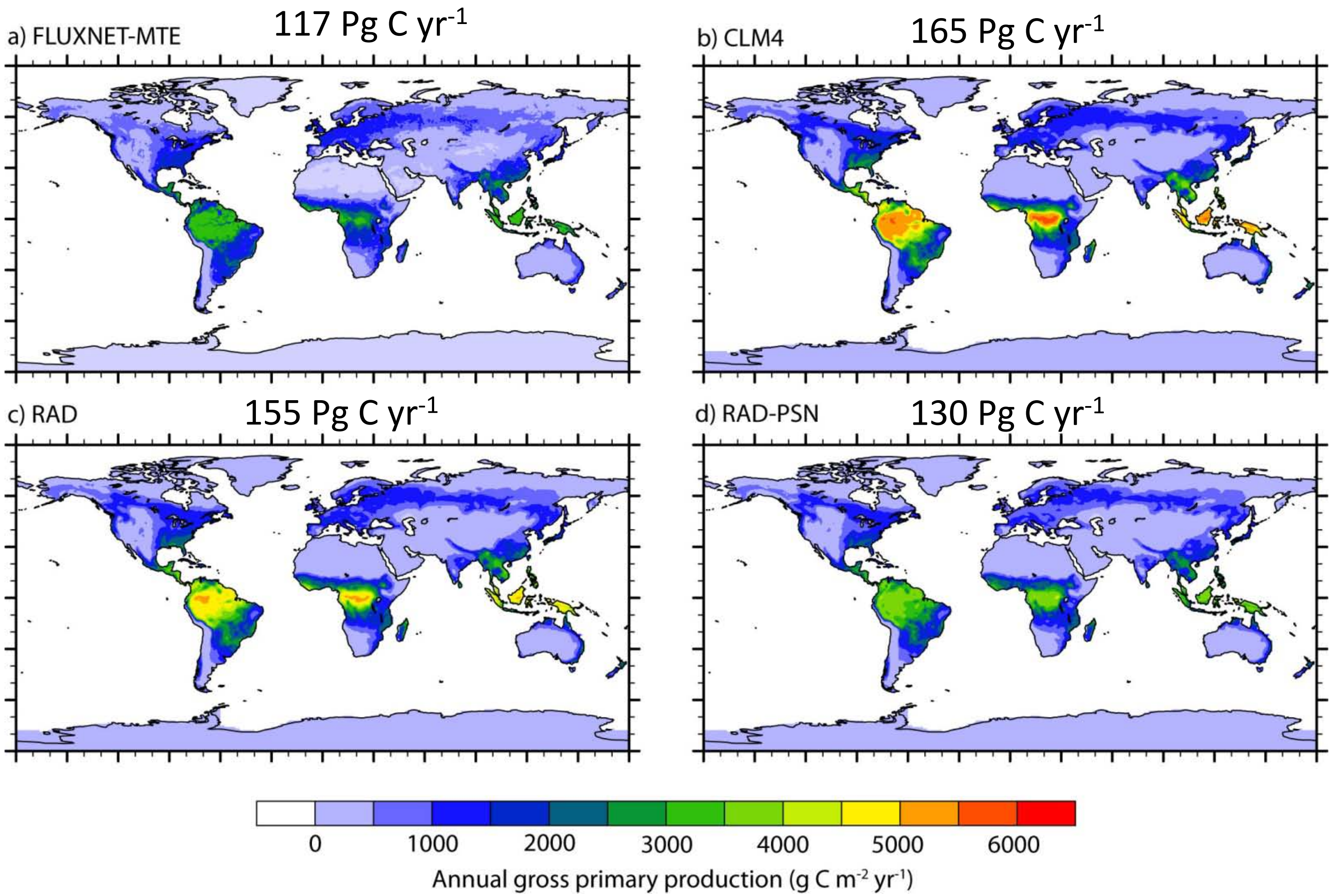
Leaf traits

Nitrogen concentration, V_{cmax}

Kattge et al. (2009) GCB 15:976-991

Global databases of leaf traits and eddy covariance flux datasets allow model testing with observations across multiple scales, from leaf to canopy to global

Gross primary production bias reduction



Control

Radiative transfer for sunlit and shaded canopy

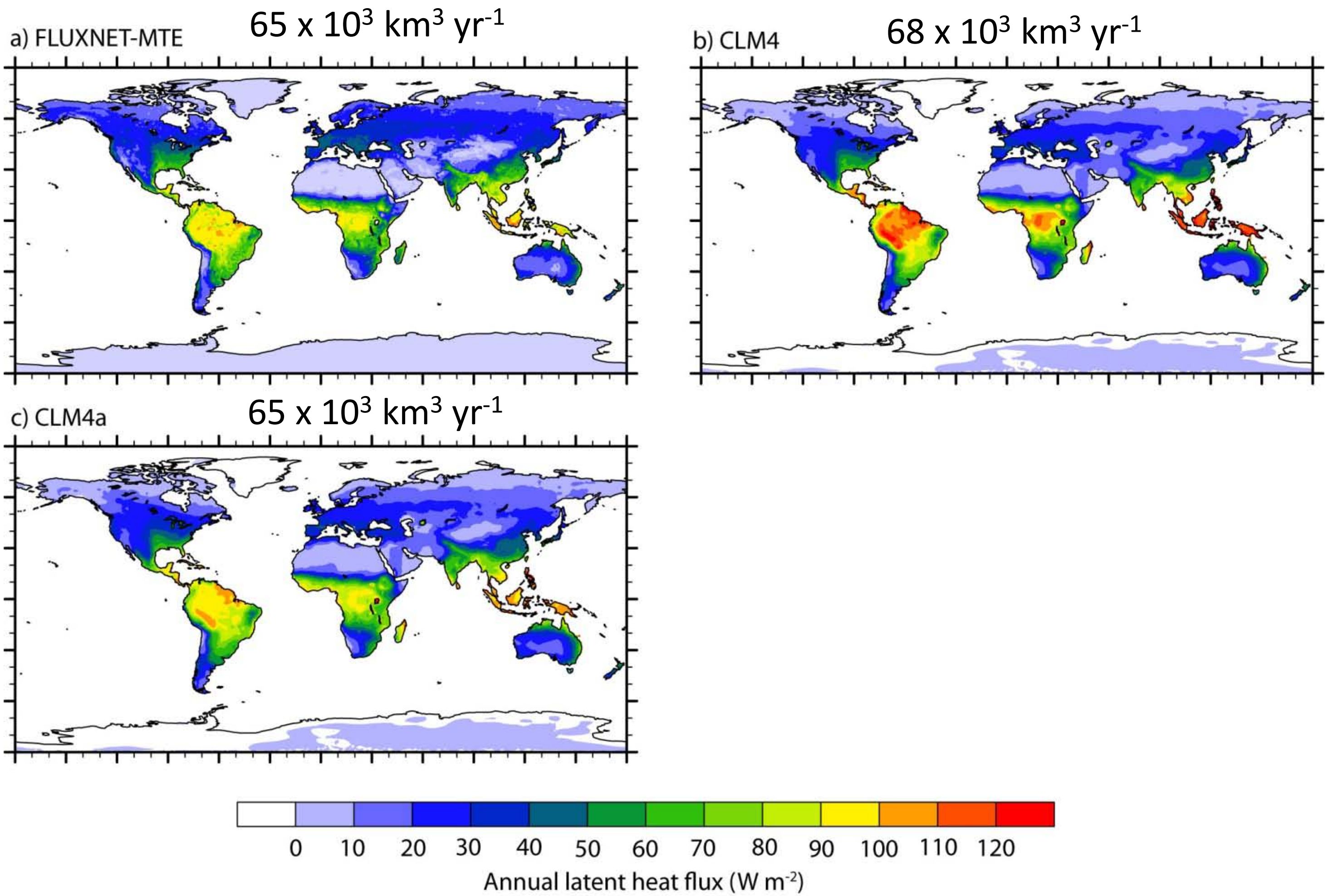
Radiative transfer and photo-synthesis

CLM4 overestimates GPP. Model revisions improve GPP. Similar improvements are seen in evapotranspiration

FLUXNET-MTE data from Martin Jung and Markus Reichstein (MPI-BGC, Jena)

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

Improved annual latent heat flux



Model improvements (CLM4a) reduce ET biases, especially in tropics, and improve monthly fluxes

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

Is the CLM4 photosynthetic capacity consistent with observations?

To match observed GPP, CLM4 needs to infer strong N reduction of GPP (with therefore reduced photosynthetic capacity)

How does this compare with observations of photosynthetic capacity, including N limitation?

Global databases of leaf traits provide an answer

Global Change Biology (2009) **15**, 976–991, doi: 10.1111/j.1365-2486.2008.01744.x

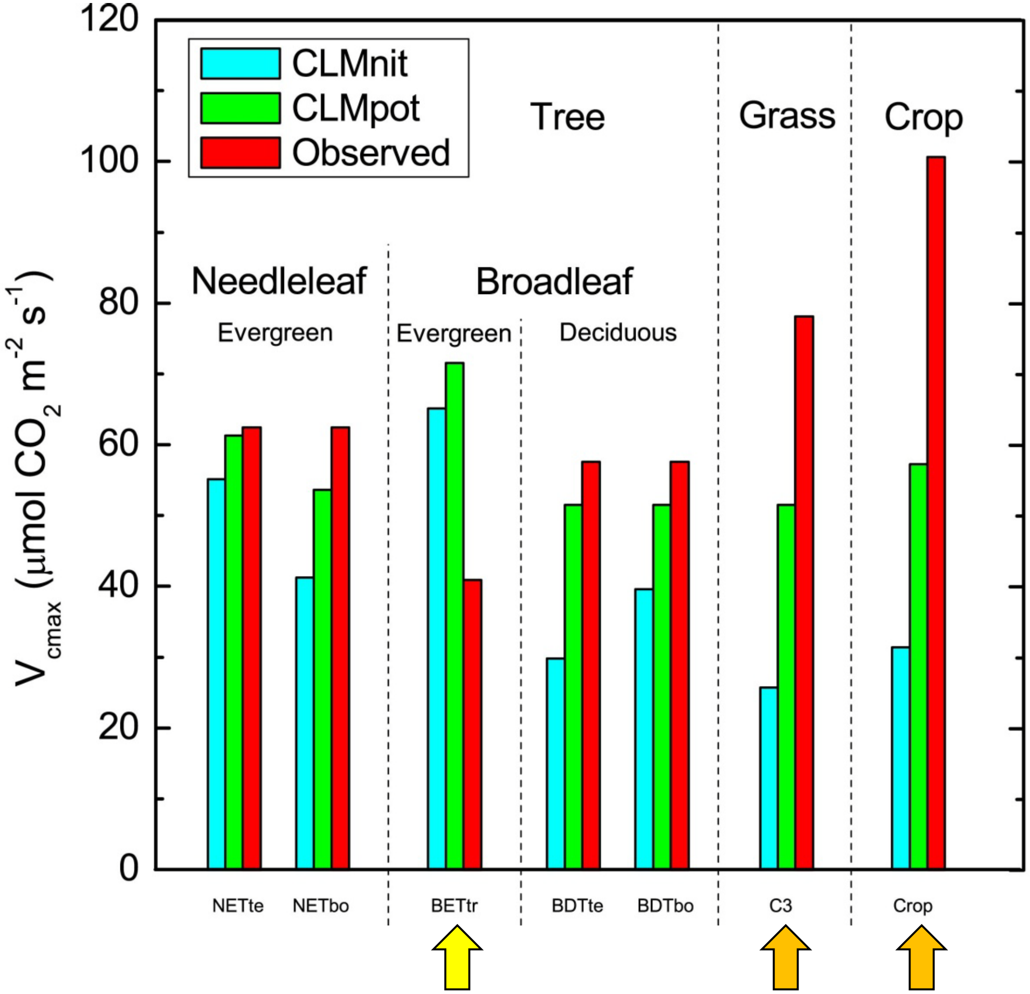
Quantifying photosynthetic capacity and its relationship to leaf nitrogen content for global-scale terrestrial biosphere models

JENS KATTGE*, WOLFGANG KNORR†, THOMAS RADDATZ‡ and CHRISTIAN WIRTH*
*Max-Planck-Institute for Biogeochemistry, Hans-Knöll Street 10, 07745 Jena, Germany, †QUEST, Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, BS8 1RJ, UK, ‡Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg, Germany

- Derived the relationship between photosynthetic parameter V_{cmax} and leaf N from V_{cmax} (723 data points) and A_{max} (776 data points) studies
- Used measured leaf N in natural vegetation to estimate V_{cmax} for various PFTs
- Most comprehensive estimates of V_{cmax} available
- Includes the effects of extant N availability

CLM4 photosynthetic capacity

Observed and model V_{cmax} (25 °C) for several CLM plant functional types



- CLM4 reduces a potential GPP for simulated N availability
- CLM4 realized V_{cmax} after N down-regulation is less than Kattge observed V_{cmax}, except for tropical forest
- CLM4 potential V_{cmax} before N down-regulation is comparable to Kattge observed V_{cmax}, with some exceptions

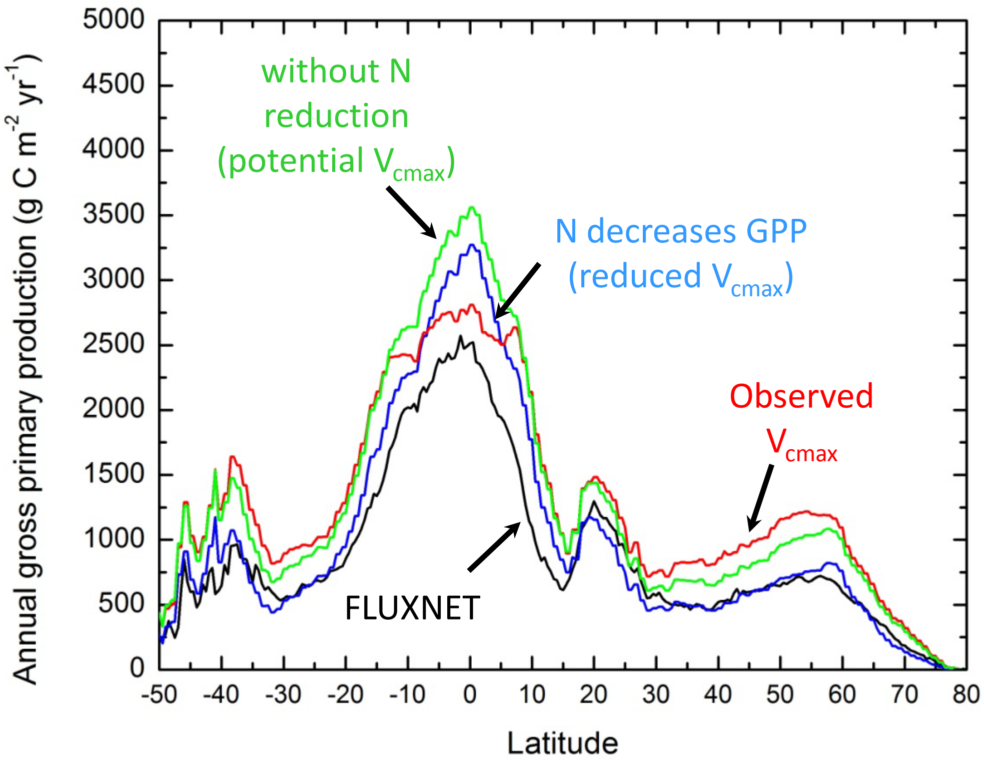
CLM4 requires low V_{cmax}

What happens when we use these V_{cmax} values?

Best simulation uses low V_{cmax}. When we remove the N down-regulation, the model is too productive

Kattge observed V_{cmax} increases GPP except in the tropics, which declines because of lower V_{cmax}

Why is GPP so high if we are using the correct enzyme-limited photosynthetic capacity? What is missing in the model?



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

Canopy light absorption

Hypothesis: CLM4 is too productive (high GPP) in the absence of N down-regulation because of deficiencies in the canopy parameterization. The CLM nitrogen down-regulation compensates for this deficiency

Model simulations

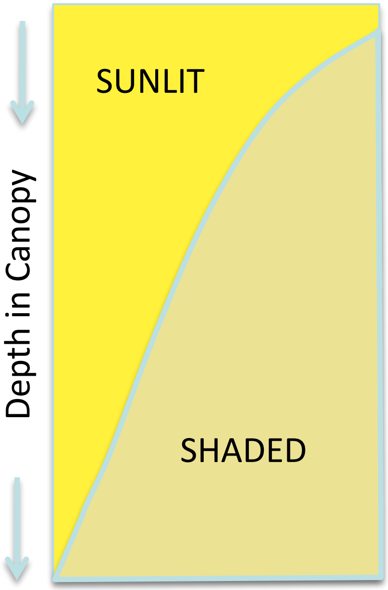
- Without C-N biogeochemistry
- With satellite leaf area and prescribed V_{cmax}

Investigate why CLM requires low V_{cmax} and why it performs poorly with the Kattge et al. (2009) values

Photographs of Morgan Monroe State Forest tower site illustrate two different representations of a plant canopy: as a "big leaf" (below) or with vertical structure (right)

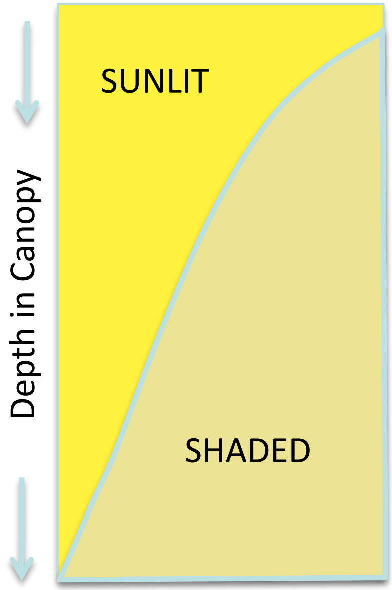
Multi-layer canopy

CLM4



- Two “big-leaves” (sunlit, shaded)
- Radiative transfer integrated over LAI (two-stream approximation)
- Photosynthesis calculated for sunlit and shaded big-leaves
- Quasi -scaling over canopy using a gradient in specific leaf area

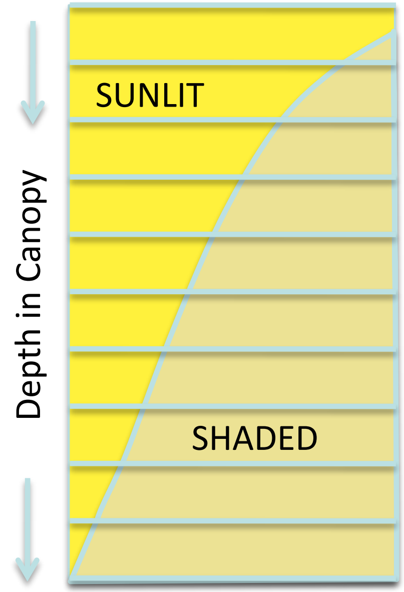
CLM4a



Same model structure as CLM4, but with revisions described by Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

- Corrected radiative transfer for sunlit and shaded canopy
- Corrected A and g_s
- Nitrogen (V_{cmax}) scales exponentially with cumulative LAI (K_n=0.11)

CLM4b

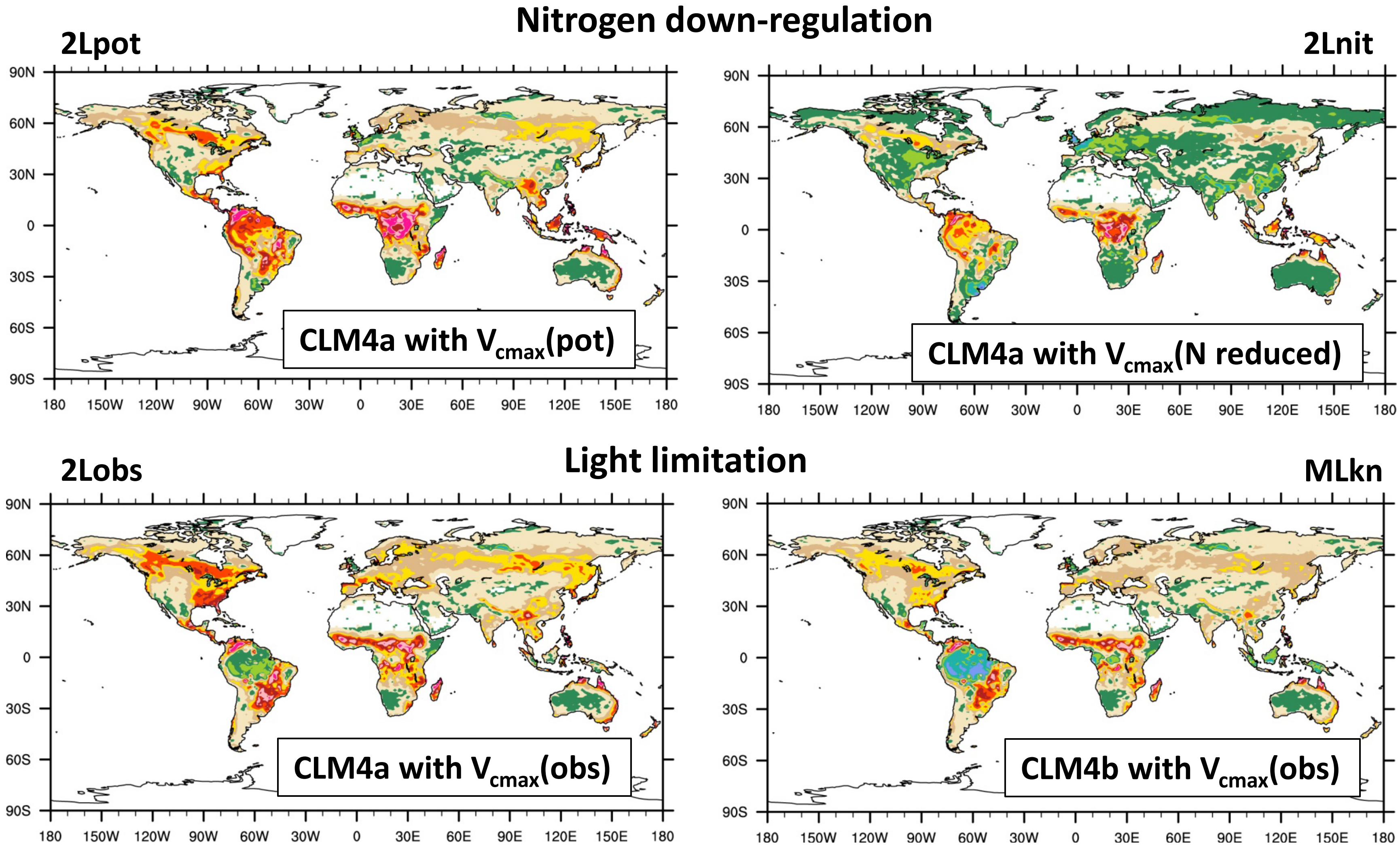


CLM4a and multi-layer canopy

Multi-layer model

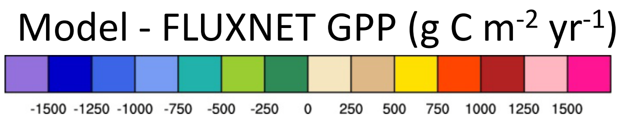
- Two-stream approximation for light profile at each layer
- Resolves direct and diffuse radiation at each layer
- Resolves sunlit and shaded leaves at each layer
- Explicit definition of photosynthetic capacity (V_{cmax}) at each layer
- Nitrogen scaled exponentially with cumulative LAI. K_n dependant on V_{cmax} (Lloyd et al. 2010)
- V_{cmax} from Kattge et al. (2009)
- Bonan et al. (2012) JGR, doi:10.1029/2011JG001913

Two ways to get similar GPP

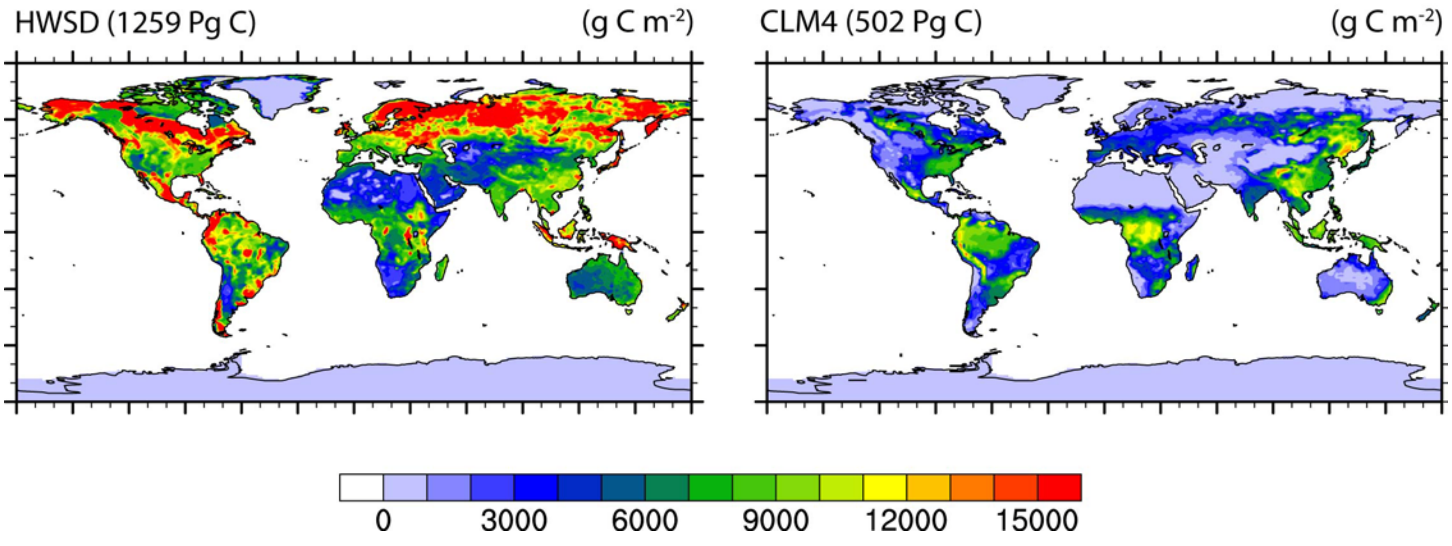


Biases in CLM4b are comparable to, though of opposite sign, those of CLM4a

Two-leaf canopy does not capture non-linearity of radiative transfer and photosynthesis



Soil carbon biases



CLM4 has far too little soil carbon

Possible causes of soil carbon bias

Litter fall

Turnover rates

- Model structure (pools)
- Abiotic controls (temperature, moisture, pH, texture, N)

Long-Term Intersite Decomposition Experiment (LIDET)

Observations

10-year study of litter dynamics for a variety of litter types placed in different environments

- 20 sites: 2 tundra, 2 boreal forest, 5 conifer forest, 3 deciduous forest, 3 tropical forest, 2 humid grassland, 3 arid grassland
- 9 litter types (6 species of leaves, 3 species of root) that vary in chemistry

Litter bags sampled once a year for C and N

Model simulations

- CLM-cn, DAYCENT
- Follow a cohort of litter (100 g C m^{-2}) deposited on October 1
- Specified climatic decomposition index (CDI) to account for temperature and moisture
- Soil mineral nitrogen

  DAYCENT

  SOM C:N ratios vary with mineral N. Use low and high C:N ratios

  CLM-cn

  Configure simulations so that N does not limit decomposition & immobilization (fpi=1) and so that N is rate limiting (fpi<1)

Bonan et al. (2012) GCB, in press

The models

CLM-cn

3 litter pools (labile, cellulose, lignin)

- Base turnover = 20 h – 71 d

4 SOM pools

- Base turnover = 14 d – 27 y
- C:N = 10-12

Rapid decomposition rates
Low SOM C:N ratios (high immobilization)

DAYCENT

Surface (leaf)

2 litter pools (metabolic, structural)

- Turnover = 46 d – 182 d

2 SOM pools

- Turnover = 61 d – 12 y
- C:N = 10-20

Belowground (root)

2 litter pools (metabolic, structural)

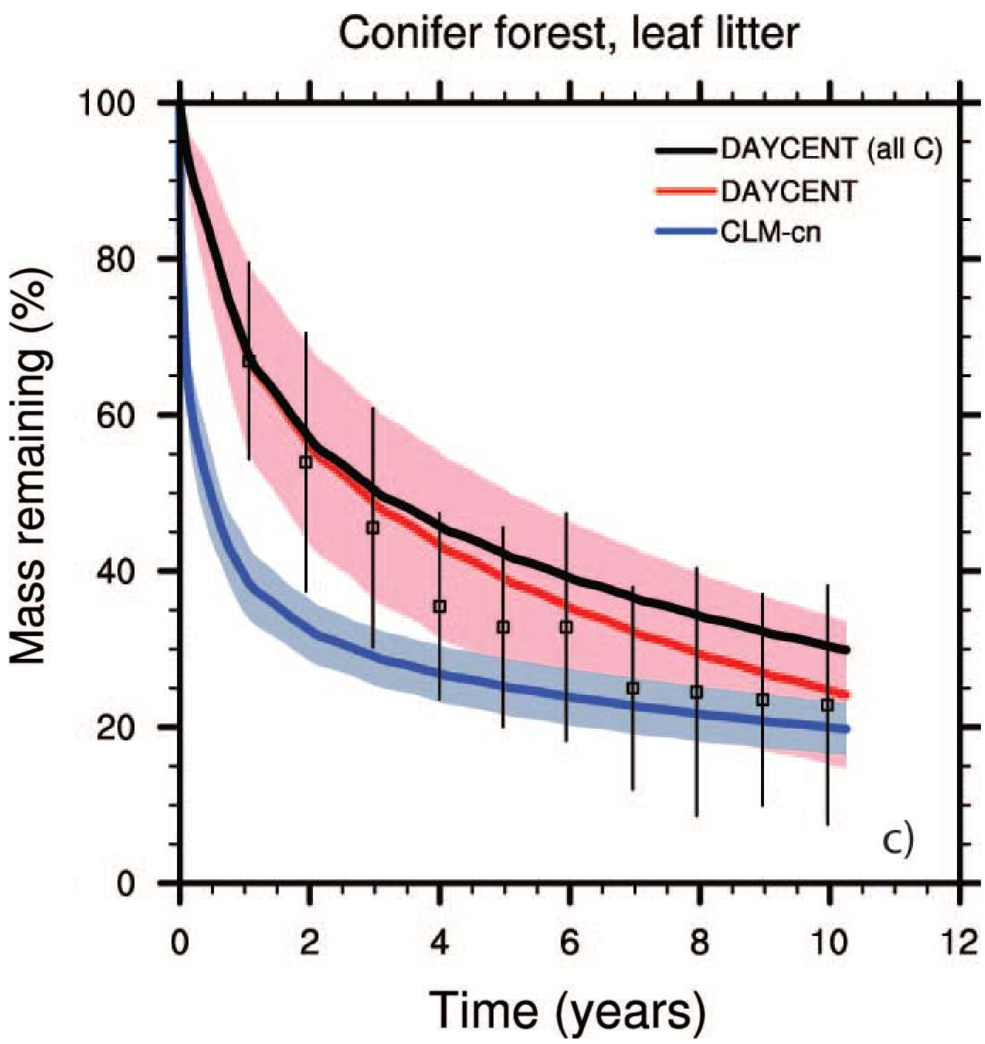
- Turnover = 20 d – 74 d

3 SOM pools

- Turnover = 33 d – 303 y
- C:N = 6-40

Slow decomposition rates
pH, lignin, L/N, soil texture
High SOM C:N ratios (low immobilization)

Leaf litter mass loss – conifer forest



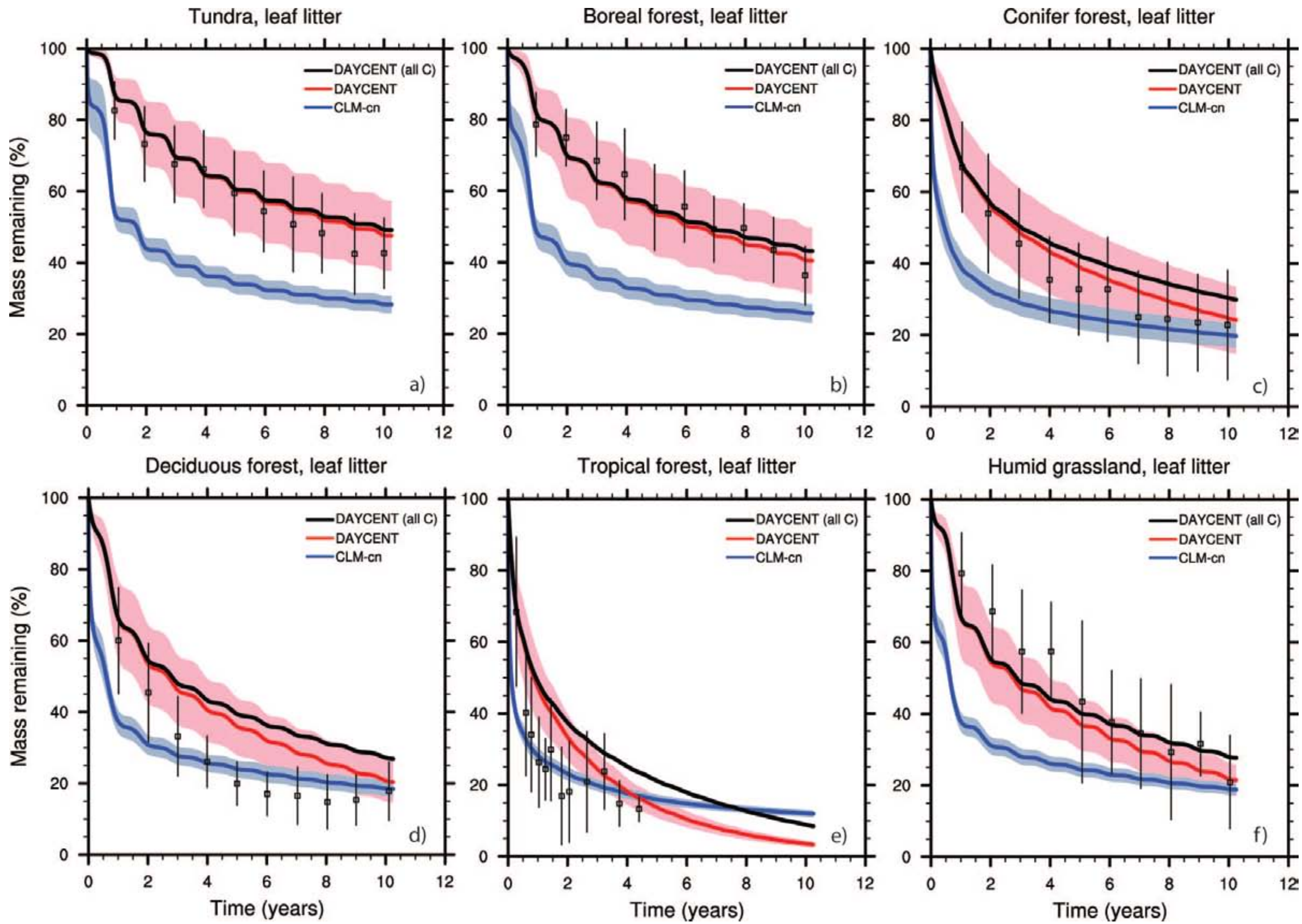
5 sites
6 leaf litter types
Shown are the site x litter mean and ± 1 SD

DAYCENT simulations show surface C and all C (surface and soil)

CLM underestimates carbon mass remaining (overestimates mass loss), especially during first several years. This is common to all sites.

Bonan et al. (2012) GCB, in press

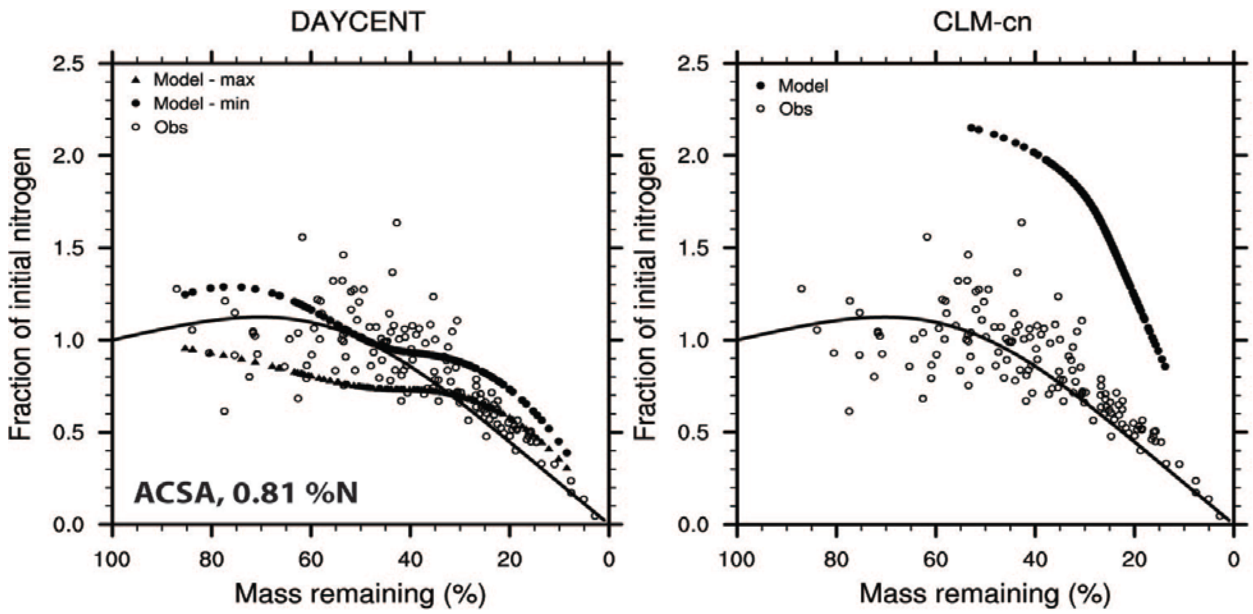
Leaf litter mass loss – all sites



Bonan et al. (2012) GCB, in press

Nitrogen dynamics

Maple, 0.81 %N

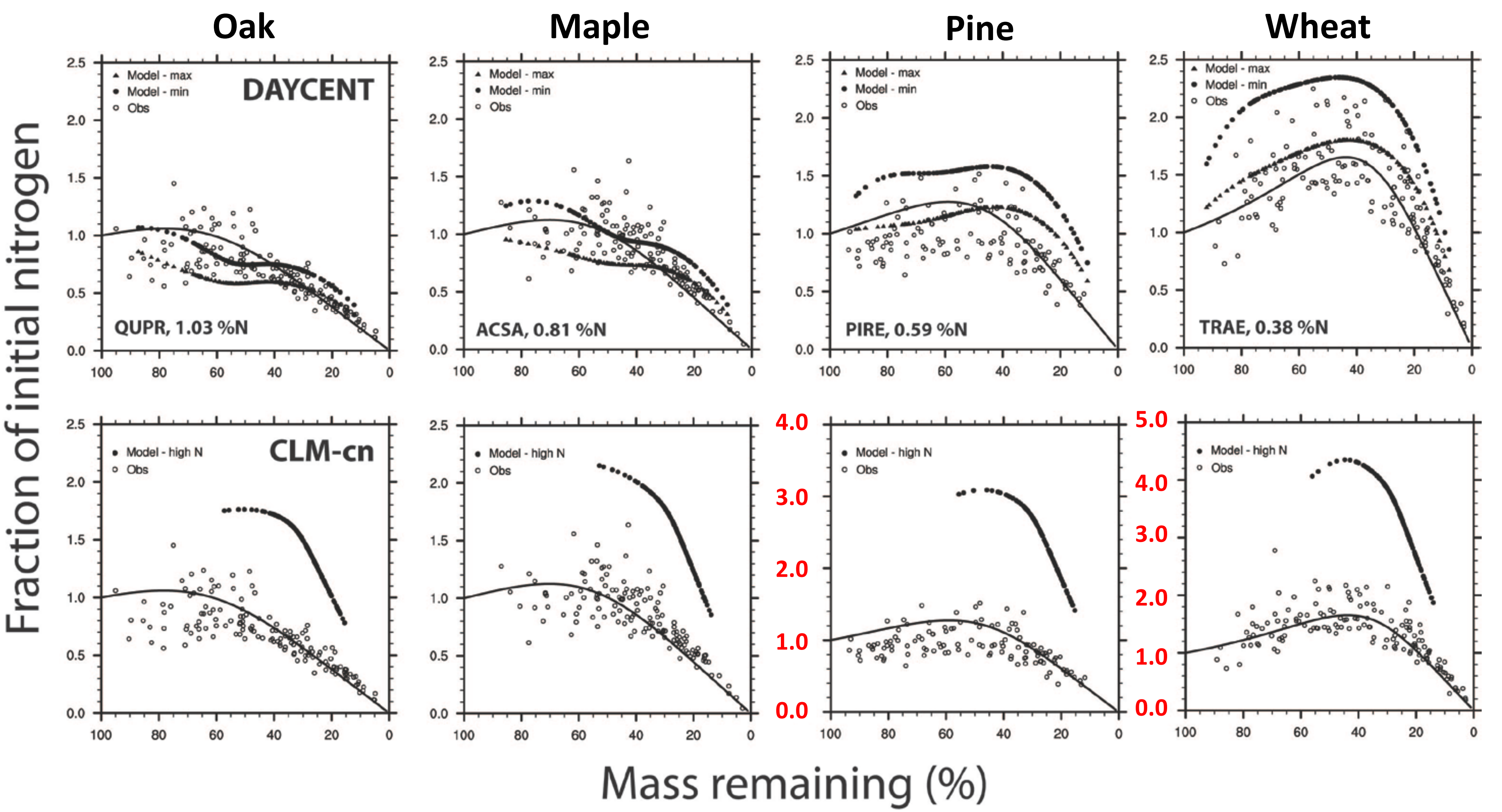


Observations are sampled once per year. Shown are data for maple leaf litter at all biomes except arid grassland. Model data are sampled similar to the observations.

CLM overestimates immobilization. Larger bias for leaf litter with lower initial %N

Bonan et al. (2012) GCB, in press

Nitrogen dynamics



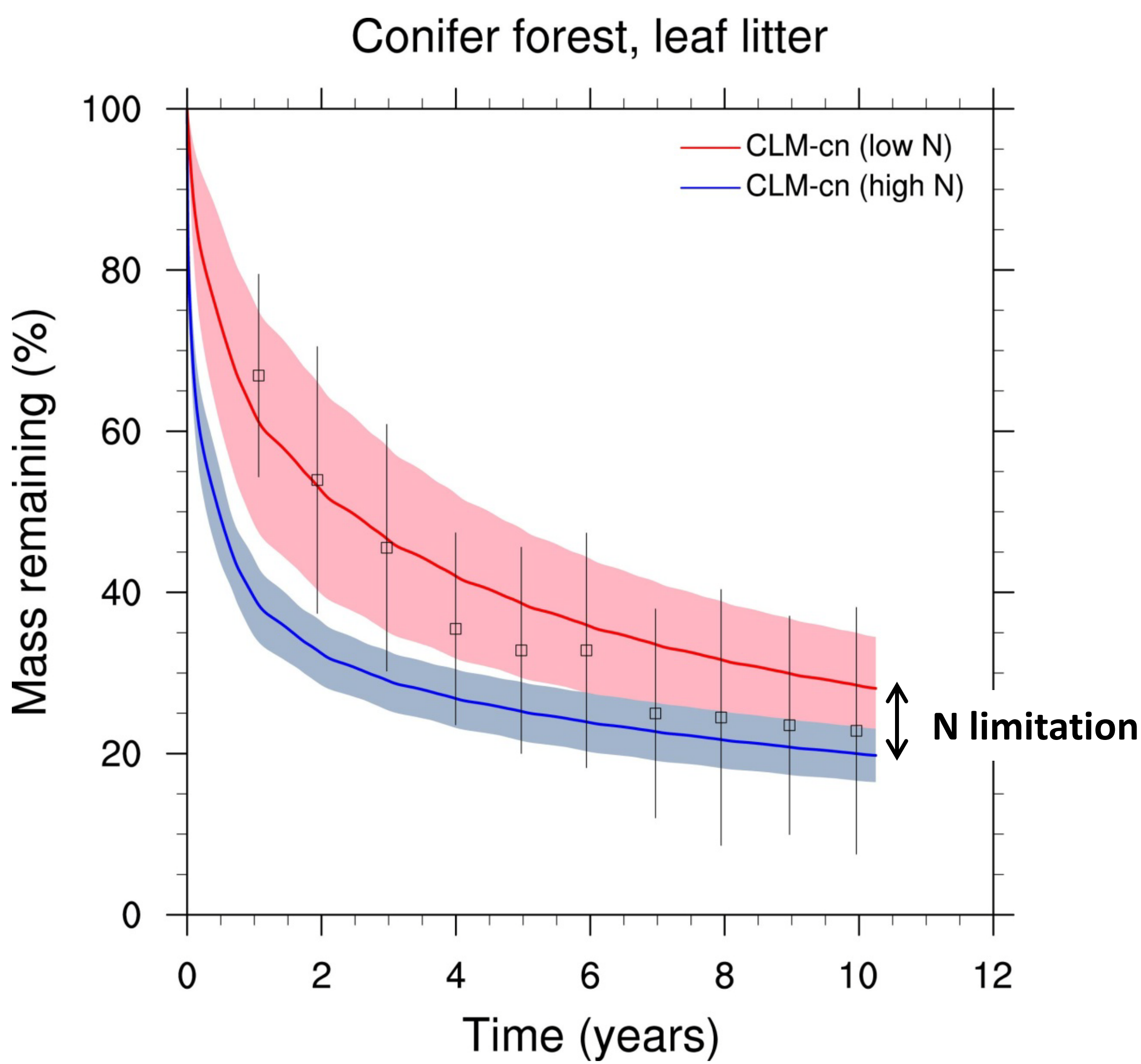
Bonan et al. (2012) GCB, in press

CLM-cn nitrogen limitation

N limitation reduces decomposition rates in CLM-cn and improves carbon dynamics. Here we use fpi = 0.05. Similar results can be obtained for other biomes using fpi=0.05-0.20

Decomposition rates in DAYCENT do not need to be similarly reduced

Different underlying philosophies for the two models, particularly with respect to the influence of soil mineral N on litter C-N dynamics



Bonan et al. (2012) GCB, in press

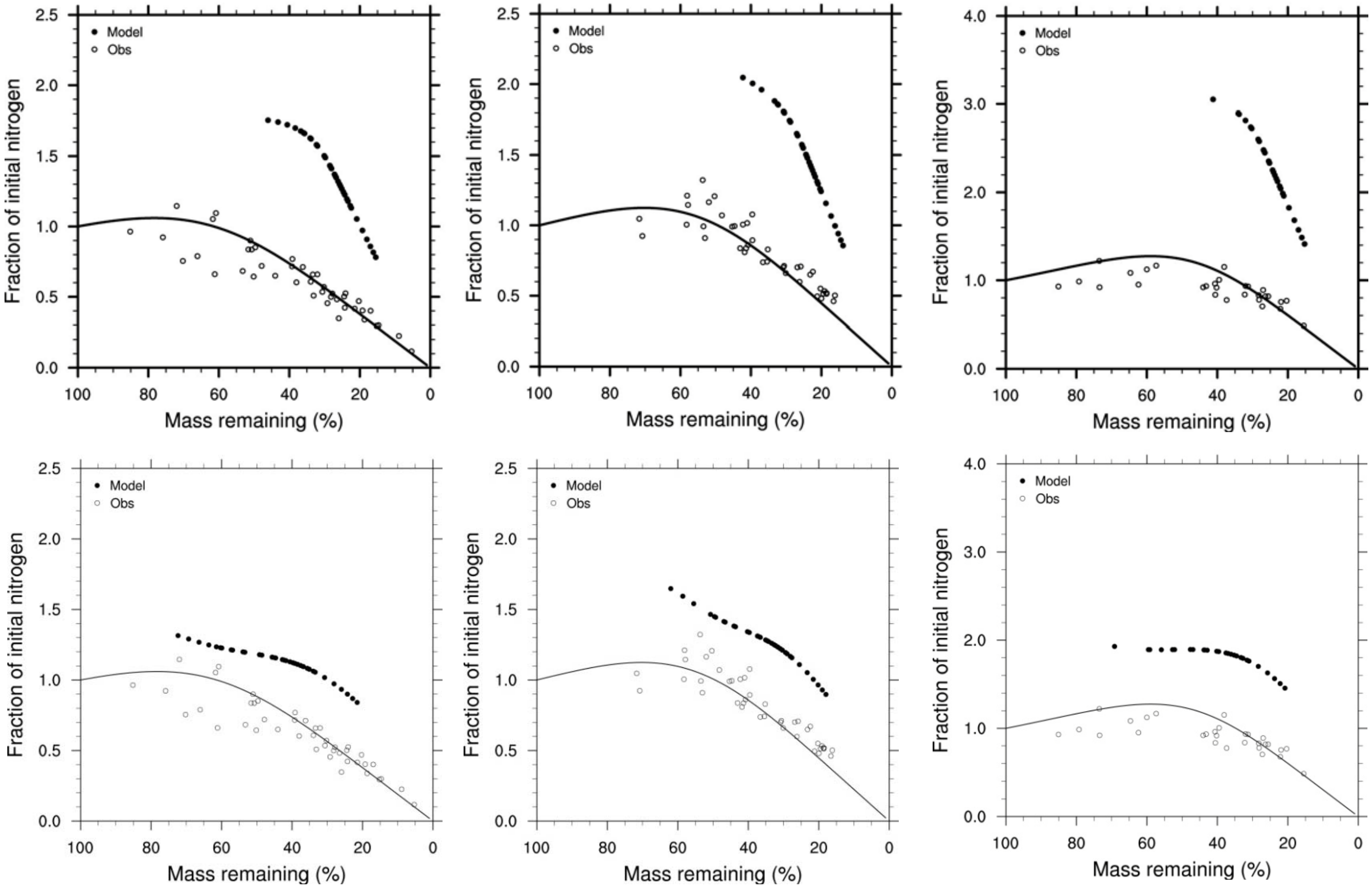
CLM-cn nitrogen limitation

Conifer forest

Oak, 1.03 % N | **Maple, 0.81 % N** | **Pine, 0.59 % N**

N not limiting

N limiting



N limitation (fpi=0.05) reduces bias. Similar results can be obtained for other biomes using fpi=0.05-0.20

Conclusions

- o Climate models have evolved to earth system models with much ecology
- o Prominent biosphere feedbacks, but much uncertainty
  - • land use and land cover change (albedo, ET, carbon)
  - • carbon cycle (GPP, heterotrophic respiration)
  - • reactive nitrogen (N gas emissions)
- o Confidence in model simulations from:
  - • physical/chemical/ecological principles
  - • mean state (e.g., present-day carbon cycle)
  - • historical trends (e.g., 20th century warming)
  - • processes (e.g., CO_2 enrichment, N fertilization, soil warming , deforestation)

Integrate ecological studies with earth system models

Environmental Monitoring

Eddy covariance flux tower

Hubbard Brook Ecosystem Study

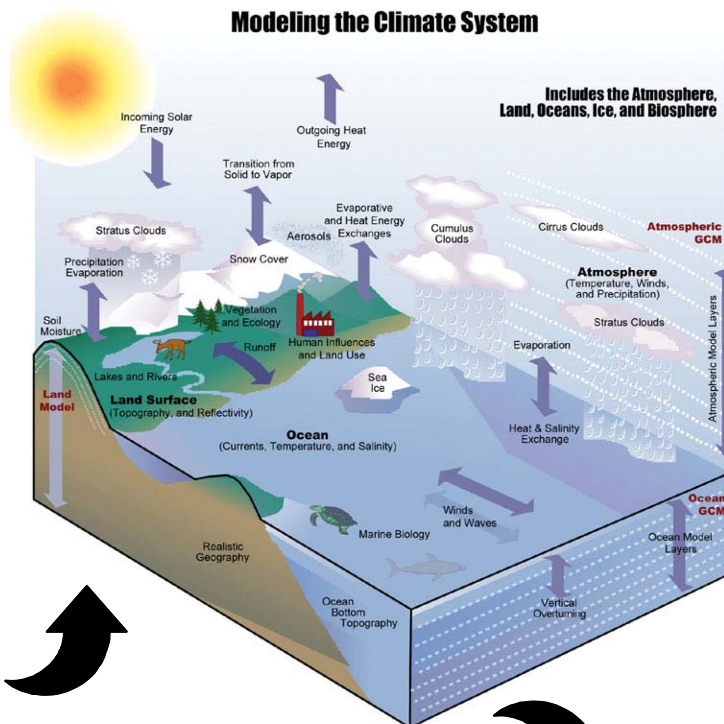
Experimental Manipulation

Soil warming, Harvard Forest

CO_2 enrichment, Duke Forest

$CO_2 \times N$ enrichment, Cedar Creek

Test model-generated hypotheses of earth system functioning with observations



Planetary energetics
Planetary ecology
Planetary metabolism