The Greening of Climate Models and Their Applications to Understand the Role of Terrestrial Vegetation in the Climate System

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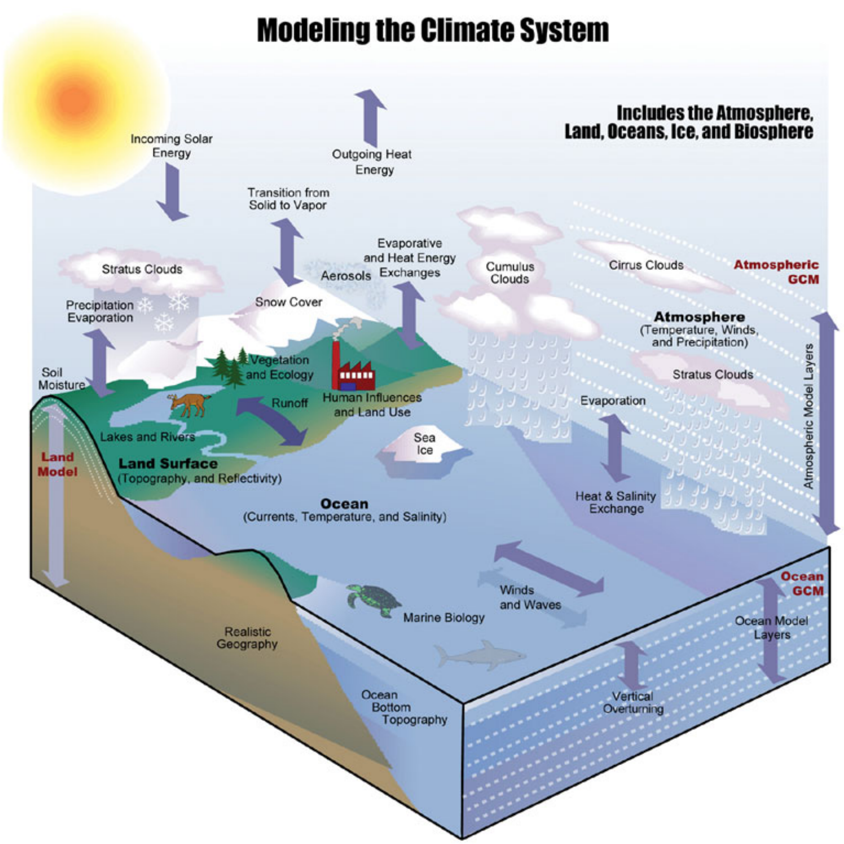
Alternative title:
What have climate models taught us about ecology?

Advanced Study Program Summer Colloquium
National Center for Atmospheric Research
Boulder, CO
5 June 2007

Community Climate System Model (CCSM)



Large community effort (NCAR, DOE national labs, universities)

Uses mathematical formulas to simulate the physical, chemical, and biological processes that drive Earth's climate

- Atmosphere: 2.8° in longitude and latitude with 26 vertical levels (128 × 64 × 26 grid points [212,992 grid points])
- Land: 2.8° in longitude and latitude with 10 soil and 5 snow layers (128 × 64 × 15 grid points)
- Ocean: 1.1° in longitude with 40 vertical levels (320 x 384 x 40 grid points [4,915,200 grid points])
- Sea ice: ~ 1° in longitude and latitude

Equations are solved every 20-minutes for atmosphere and land and every 60-minutes for ocean and sea ice

Typical simulation: several hundred model years

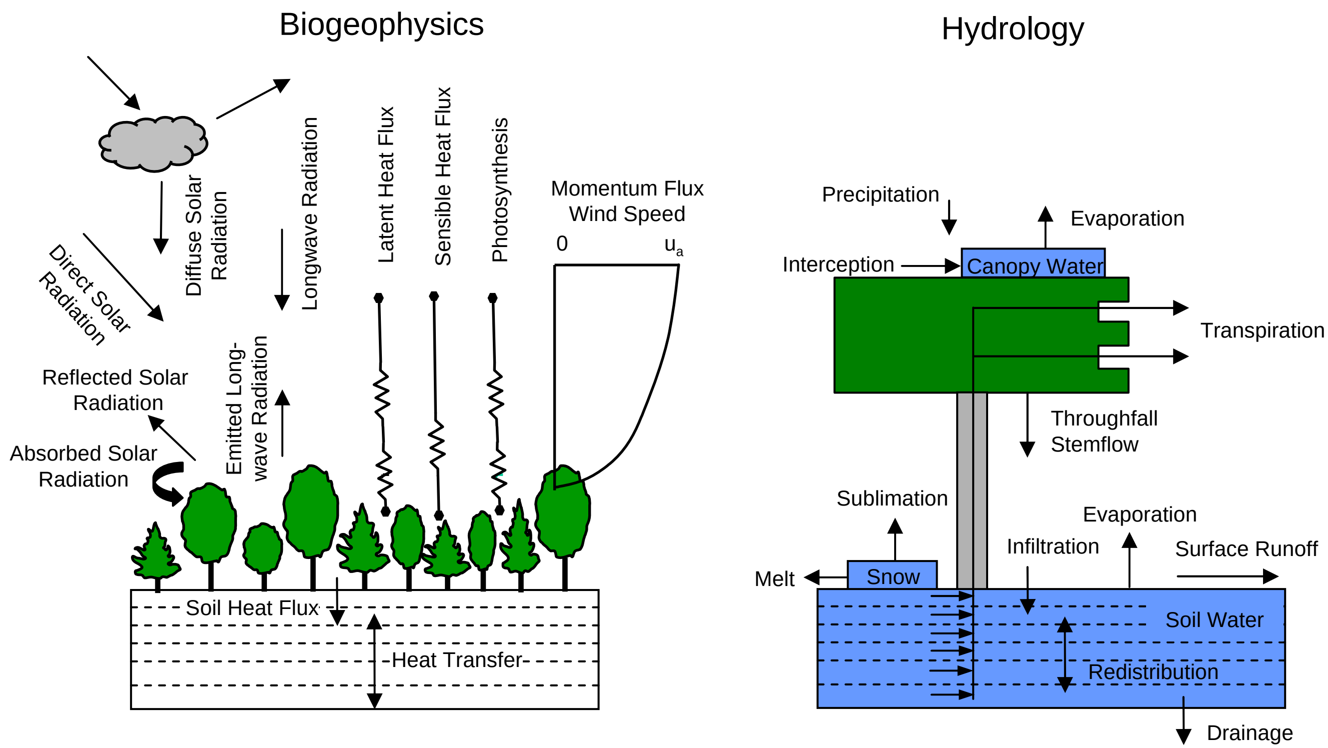
What emerges from trillions of computer calculations is a picture of the world's climate in all its complexity

Other resolutions
Atmosphere: T31, 3.75° (96 × 48 grid); T85, 1.4° (256 × 128 grid)

Ocean: 3.6° in longitude (100 × 116 grid) with 25 vertical levels

Community Land Model

Hydrometeorology



Community Land Model

- Land model for Community Climate System Model
- Developed by the CCSM Land Model Working Group in partnership with university and government laboratory collaborators

Energy fluxes: radiative transfer; turbulent fluxes (sensible, latent heat); heat storage in soil; snow melt

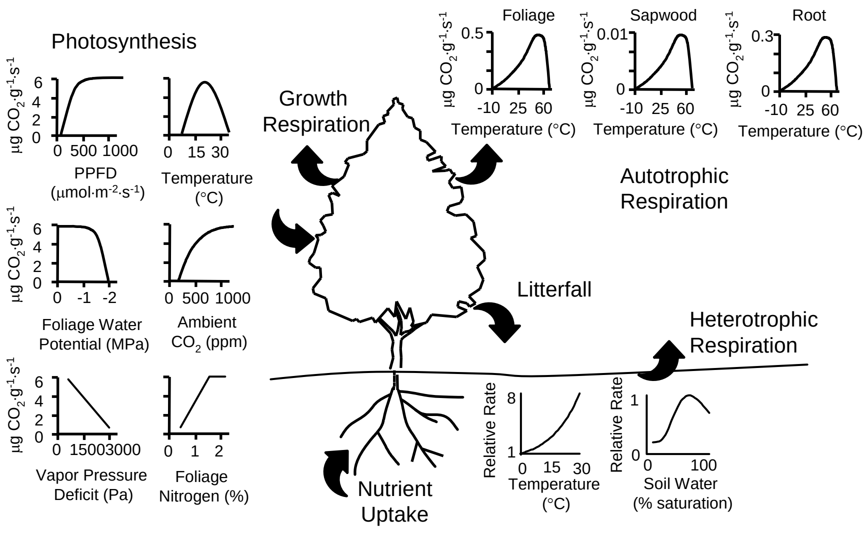
Hydrologic cycle: interception of water by leaves; infiltration and runoff; snow accumulation and melt; multi-layer soil water; partitioning of latent heat into evaporation of intercepted water, soil evaporation, and transpiration

Bonan et al. (2002) J Climate 15:3123-3149
Oleson et al. (2004) NCAR/TN-461+STR
Dickinson et al. (2006) J Climate 19:2302-2324

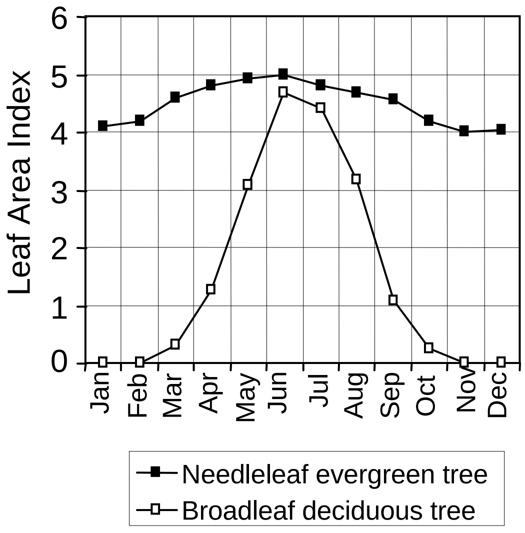
Community Land Model

Carbon cycle and dynamic vegetation

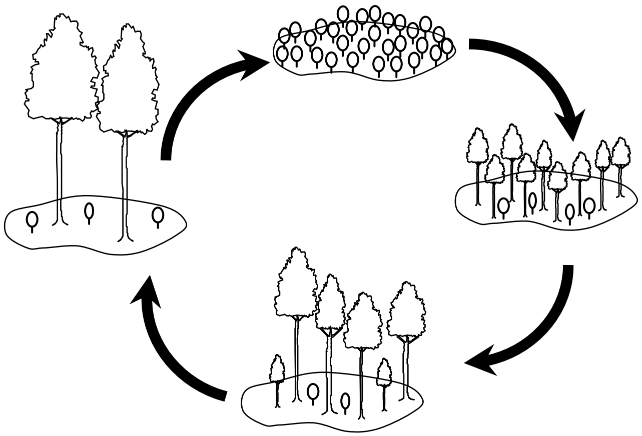
Ecosystem carbon balance



Leaf phenology



Vegetation dynamics

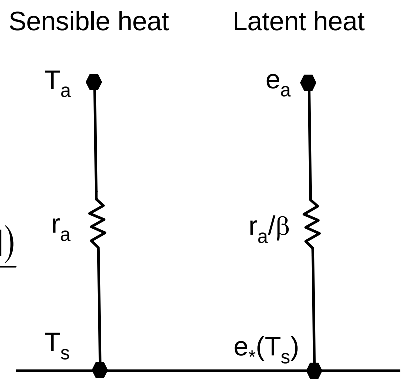


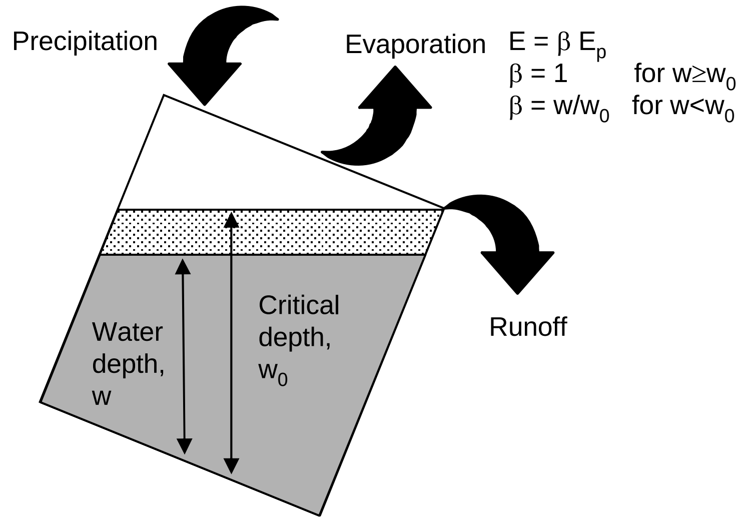
Bonan et al. (2003) Global Change Biology 9:1543-1566
Levis et al. (2004) NCAR/TN-459+IA

First-generation models

$$H = -\rho C_p \frac{(T_a - T_s)}{r_a}$$

$$\lambda E = -\frac{\rho C_p}{\gamma} \frac{(e_a - e_*[T_s])}{r_a / \beta}$$





Simple energy balance model: $(1-r)S\downarrow + \varepsilon L\downarrow = L\uparrow[T_s] + H[T_s] + \lambda E[T_s]$

Prescribed surface albedo

Bulk parameterizations of sensible and latent heat flux

No influence of vegetation on surface fluxes

Prescribed soil wetness factor β or calculated wetness from bucket model

No soil heat storage

Manabe (1969) Monthly Weather Review 97:739-774
Williamson et al. (1987) NCAR/TN-285+STR

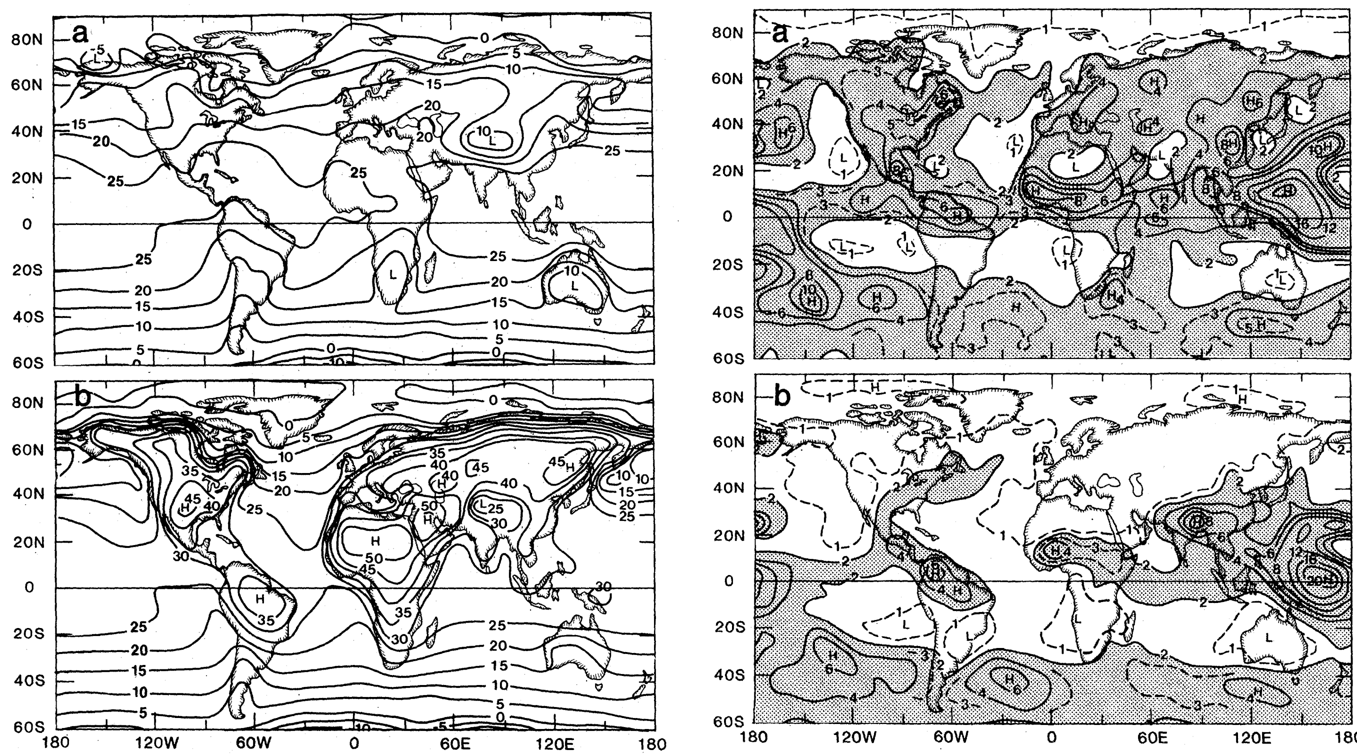
Green world vs desert world

Two climate model experiments
Wet – evapotranspiration not limited by soil water; vegetated planet
Dry – no evapotranspiration; desert planet

July surface temperature (°C) | July precipitation (mm/day)

Wet soil

Dry soil



Wet soil

Dry soil

Dry soil warmer than wet soil

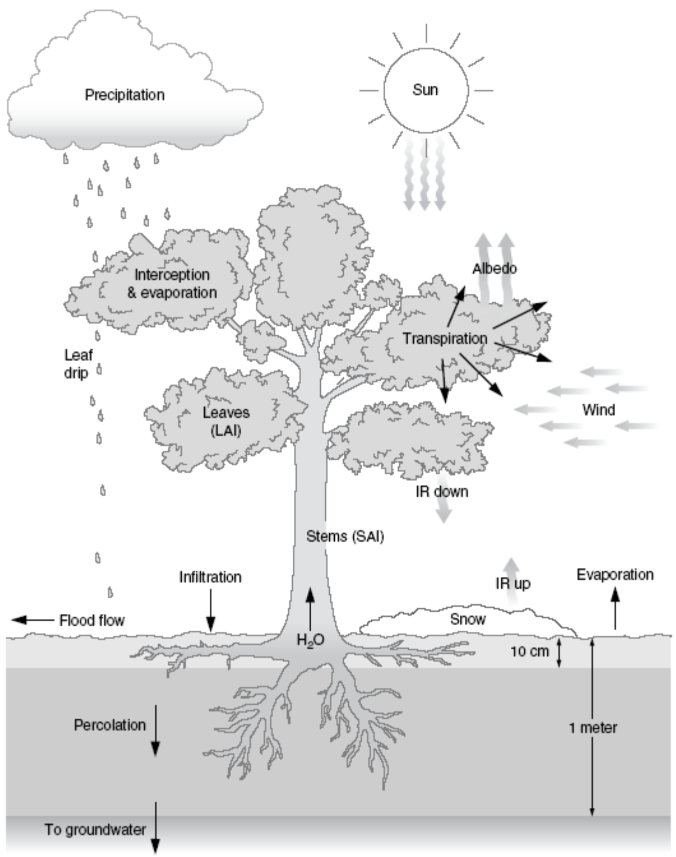
Dry soil has less precipitation

Shukla & Mintz (1982) Science 215:1498-1501

Second-generation models

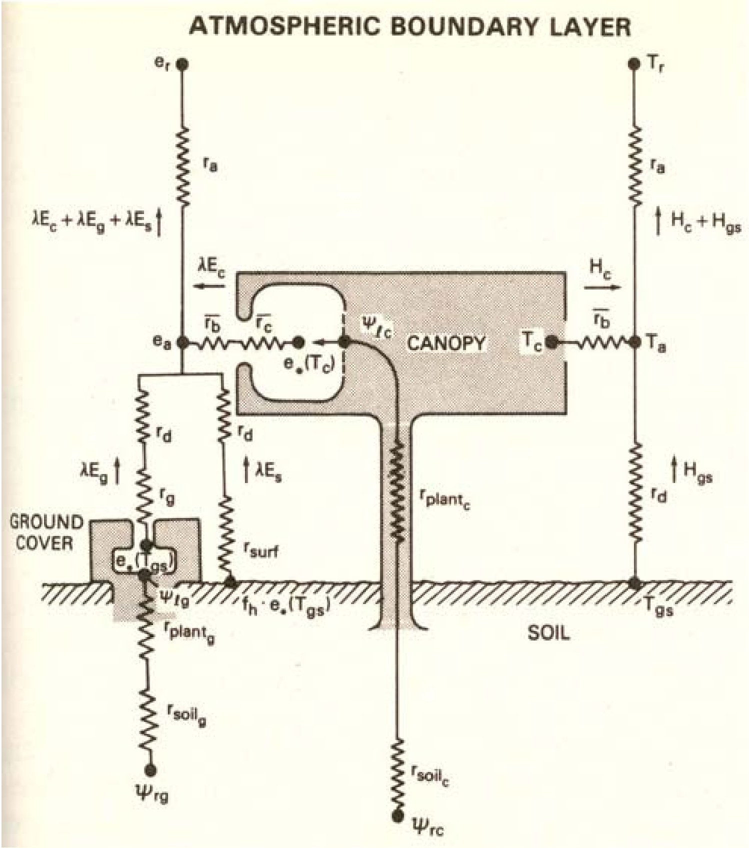
Vegetation and hydrologic cycle

Biosphere-Atmosphere Transfer Scheme (BATS)



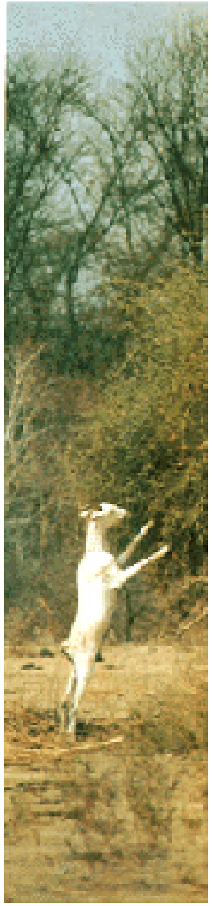
Dickinson et al. (1986) NCAR/TN-275+STR

Simple Biosphere Model (SiB)



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

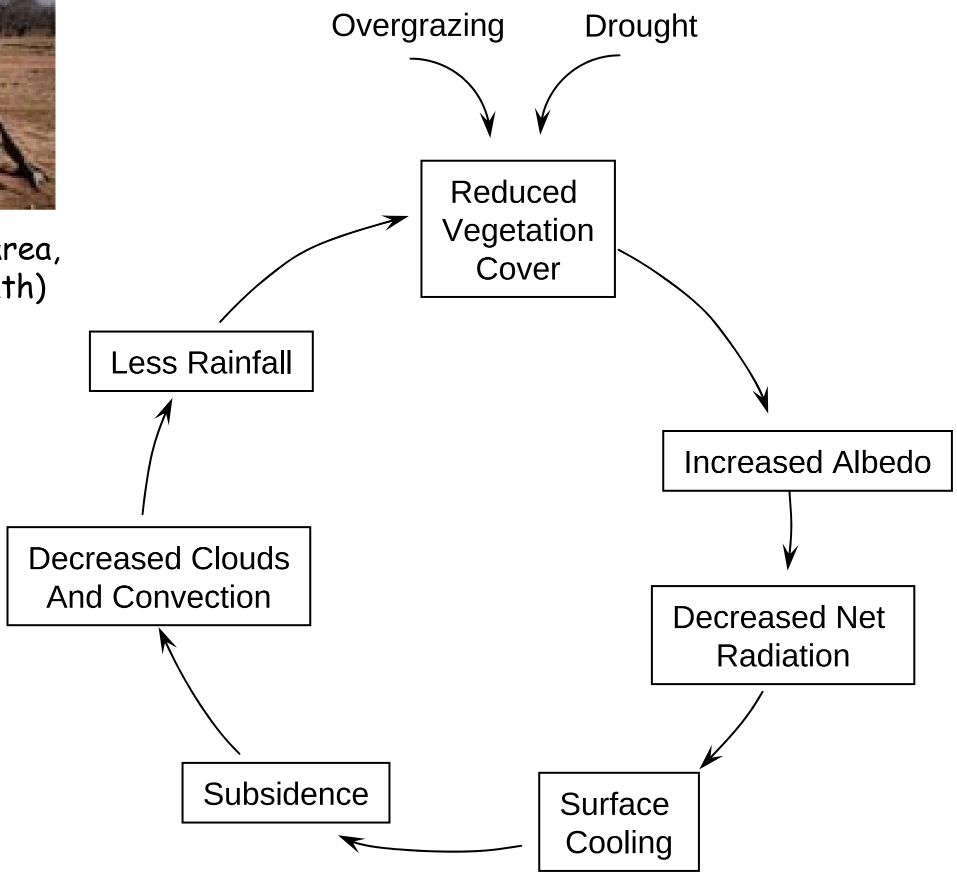
Land degradation



Dead vegetation in drought-stricken area, Sol-Dior area, Senegal (FAO, Ch. Errath)

Goat seeks food in the sparsely vegetated Sahel of Africa (US AID)

Climate feedback

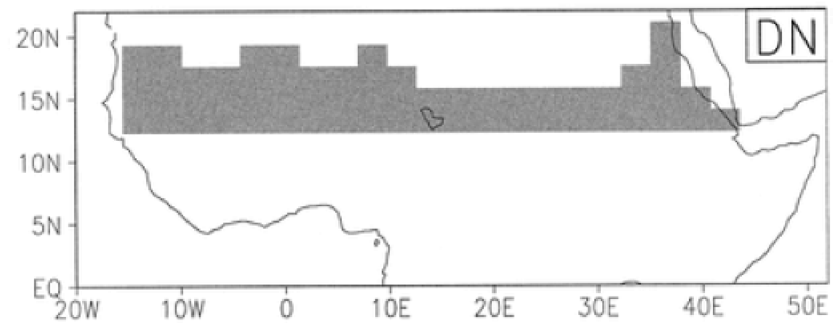


Charney (1975) QJRMS 101:193-202
Charney et al. (1975) Science 187:434-435

Land degradation

Climate model experiments

Degradation scenario - the vegetation type within the shaded area was changed to type 9 to represent degradation: less vegetation, lower LAI, smaller surface roughness length, higher albedo, sandy soil



Broadleaf evergreen tree | Broadleaf tree/ground cover | Broadleaf shrub/ground cover | Broadleaf shrub/bare soil

	Type 1	Type 6	Type 8	Type 9
Surface albedo[a,b]	0.13	0.20	0.20	0.30
Roughness length (m)[a]	2.65	0.95	0.25	0.06
Vegetated fraction	0.98	0.30	0.10	0.10
Leaf area index[a,c]	5.0	4.1	0.9	0.3
Minimum stomatal resistance ($s\ m^{-1}$)	153	165	855	855
Root depth (m)	1.0	0.5	0.5	0.5
Volumetric moisture at wilting point	0.12	0.13	0.05	0.04
Volumetric moisture at saturation	0.42	0.42	0.44	0.44
Hydraulic conductivity at saturation $\times 10^5$ ($m\ s^{-1}$)	2.0	2.0	17.6	17.6
Matric potential at saturation (m)	−0.086	−0.086	−0.035	−0.035

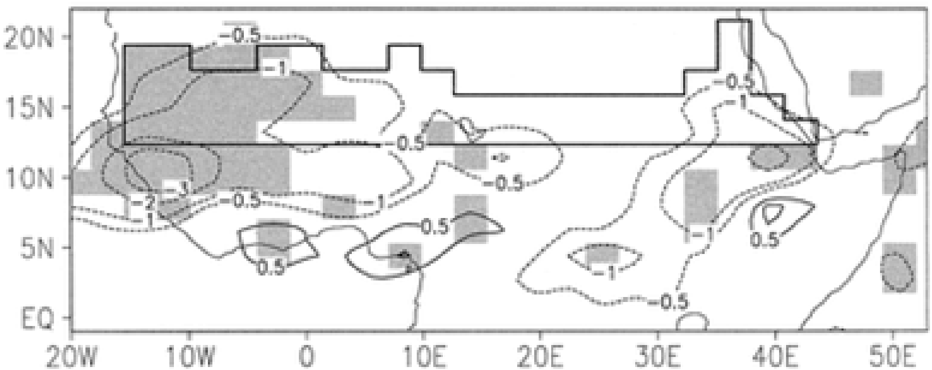
[a] JAS mean value for a parameter with monthly variation.
[b] Surface albedo was as calculated in the control ensemble.
[c] Canopy capacity (mm) is given by 0.1 × leaf area index.

Clark et al. (2001) J Climate 14:1809-1822

Land degradation

Climate impacts

July-August-September precipitation differences (mm/day) due to degradation. Differences that are significant at the 95% confidence level are shaded and the degraded area is enclosed by a solid line.



July-August-September mean differences due to degradation. Values are means over the degraded area. D–C is the difference between degraded and control values.

	Control	D–C
Cloud cover	0.42	−0.06 (−14%)
S_n (W m^{-2})	241	−20** (−8%)
L_n (W m^{-2})	−90	−9 (+10%)
R_n (W m^{-2})	151	−29** (−19%)
H (W m^{-2})	102	−14** (−14%)
LE (W m^{-2})	50	−15* (−30%)
T_s (K)	307.1	+0.2
Boundary layer θ_e (K)	343.4	−2.7
P (mm day^{-1})	2.1	−0.7* (−32%)
E (mm day^{-1})	1.7	−0.5* (−30%)
MC (mm day^{-1})	0.4	−0.2 (−50%)

* Significant at the 90% confidence level.
** Significant at the 95% confidence level.

Clark et al. (2001) J Climate 14:1809-1822

Tropical deforestation

(NASA/GSFC/LaRC/JPL)

Settlement and deforestation surrounding Rio Branco, Brazil (10°S, 68°W) in the Brazilian state of Acre, near the border with Bolivia. The large image covers an area of 333 km x 333 km.

(National Geographic Society)

Tropical deforestation

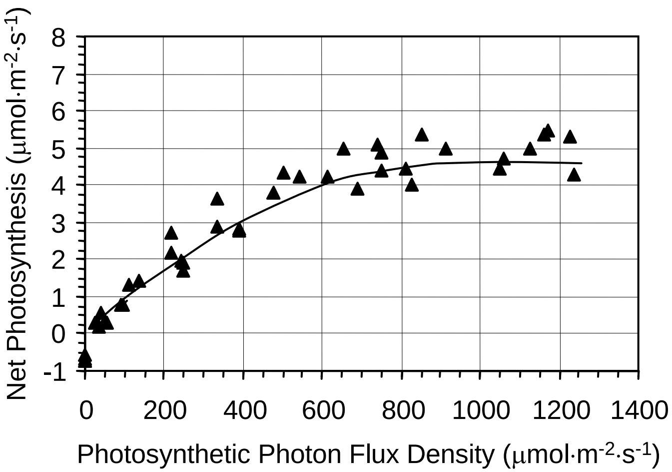
Warmer, drier tropical climate

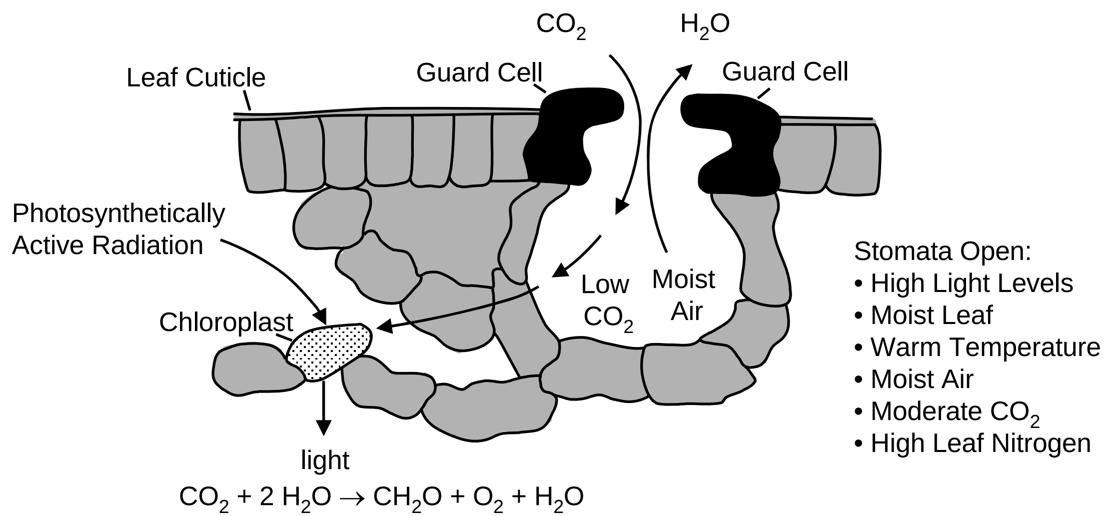
Annual response to Amazonian deforestation in various climate model studies. Δalbedo and Δz_0 indicate the change in surface albedo and roughness due to deforestation (+, increase; -, decrease). ΔT, ΔP, and ΔET are the simulated changes in temperature, precipitation, and evapotranspiration. Shading denotes warmer, drier climate.

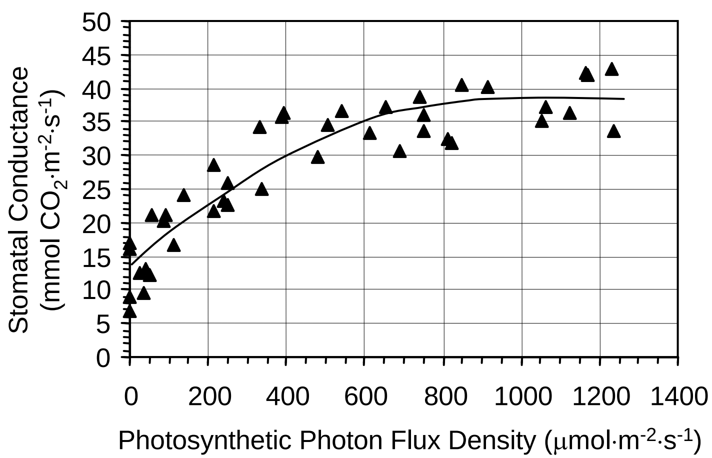
	Surface Change		Climate Change		
Study	Δalbedo	Δz_0	ΔT (°C)	ΔP (mm)	ΔET (mm)
Dickinson and Henderson-Sellers (1988)	+	-	+3.0	0	-200
Lean and Warrilow (1989)	+	-	+2.4	-490	-310
Nobre *et al*. (1991)	+	-	+2.5	-643	-496
Dickinson and Kennedy (1992)	+	-	+0.6	-511	-256
Mylne and Rowntree (1992)	+	unchanged	-0.1	-335	-176
Henderson-Sellers *et al*. (1993)	+	-	+0.6	-588	-232
Lean and Rowntree (1993)	+	-	+2.1	-296	-201
Pitman *et al*. (1993)	+	-	+0.7	-603	-207
Polcher and Laval (1994a)	+	unchanged	+3.8	+394	-985
Polcher and Laval (1994b)	+	-	-0.1	-186	-128
Sud *et al*. (1996)	+	-	+2.0	-540	-445
McGuffie *et al*. (1995)	+	-	+0.3	-437	-231
Lean and Rowntree (1997)	+	-	+2.3	-157	-296
Hahmann and Dickinson (1997)	+	-	+1.0	-363	-149
Costa and Foley (2000)	+	-	+1.4	-266	-223

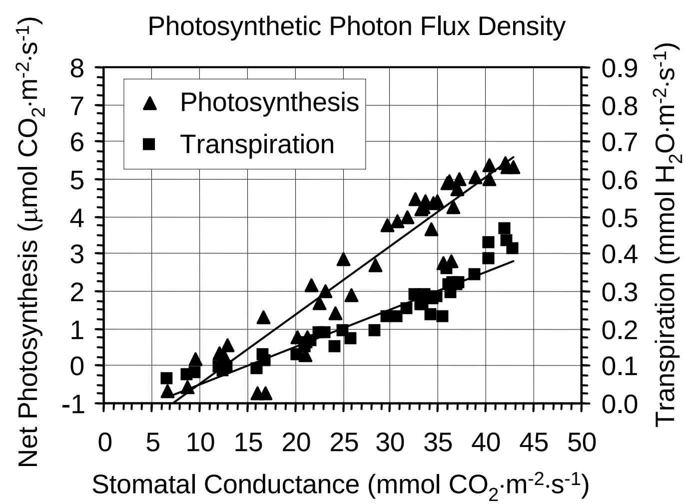
Third-generation models

Stomatal Gas Exchange



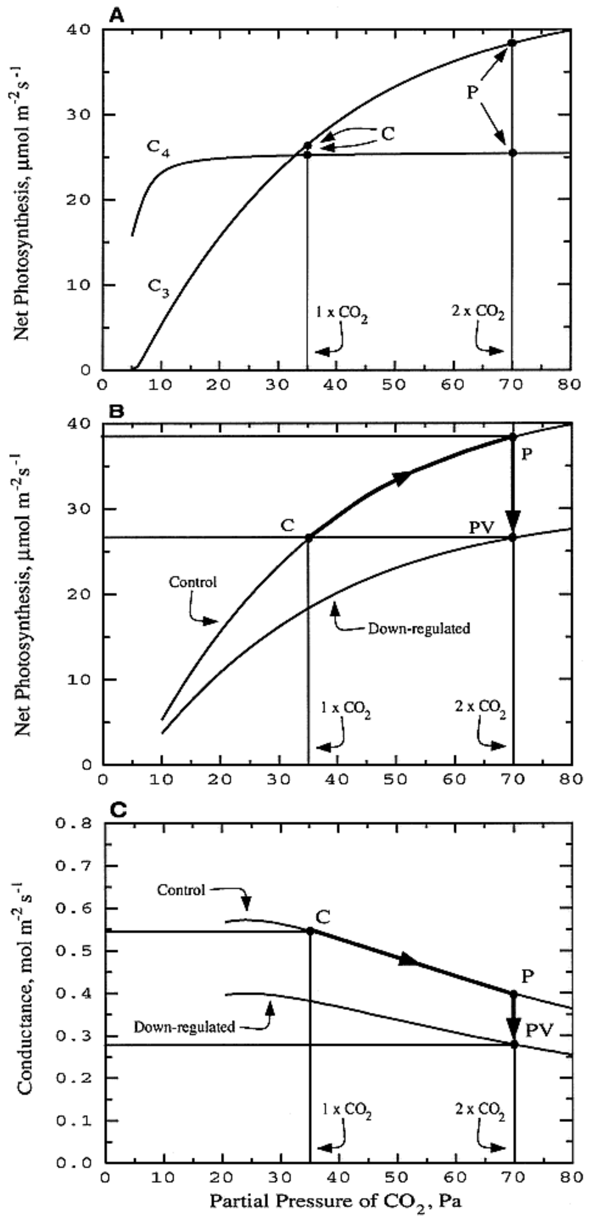






Bonan (1995) JGR 100:2817-2831
Denning et al. (1995) Nature 376:240-242
Denning et al. (1996) Tellus 48B:521-542, 543-567

CO_2 fertilization and stomatal conductance



Leaf photosynthesis and conductance response to atmospheric CO_2 concentration, light-saturated

(a) Dependence of leaf-scale photosynthesis for C_3 and C_4 vegetation on external CO_2 concentration

(b) The C_3 photosynthesis curves for unadjusted (C and P) and down-regulated (PV) physiology

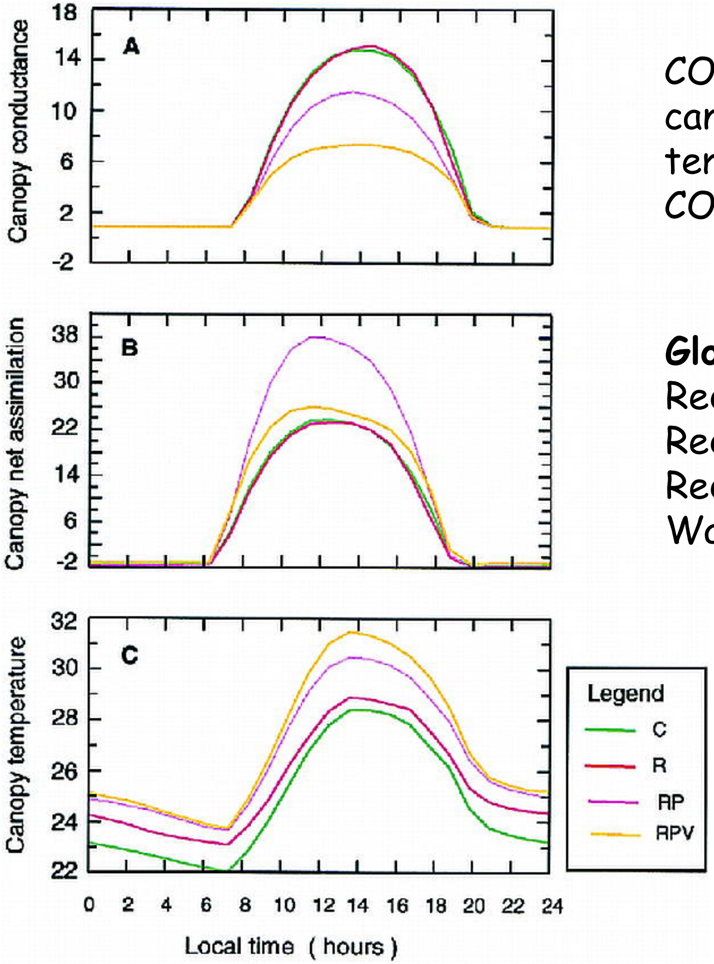
(c) Dependence of stomatal conductance on CO_2 concentration for the unadjusted and down-regulated cases.

Photosynthesis increases and stomatal conductance decreases with higher atmospheric CO_2

Bounoua et al. (1999) J Climate 12:309-324

CO_2 fertilization and stomatal conductance

Amazonian evergreen forest,
diurnal cycle January



CO_2 fertilization (RP, RPV) reduces canopy conductance and increases temperature compared with radiative CO_2 (R)

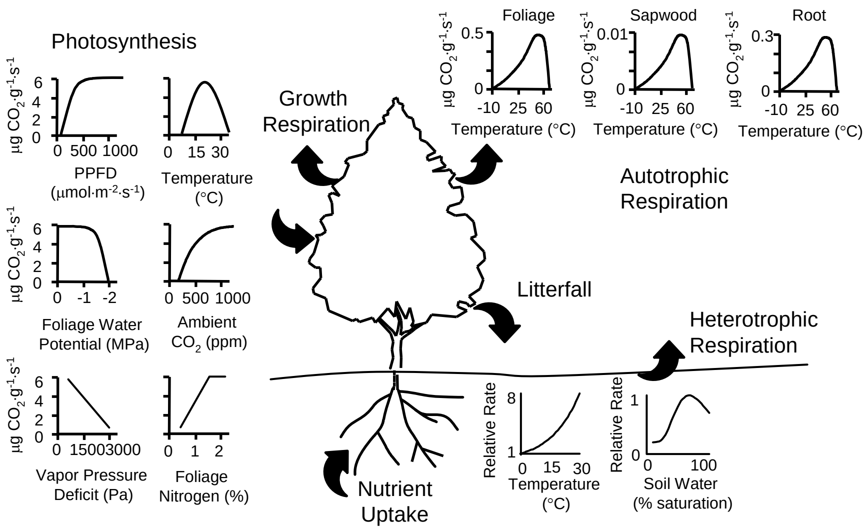
Global climate:
Reduced conductance
Reduced evaporation
Reduced precipitation
Warmer temperature

Bounoua et al. (1999) J Climate 12:309-324

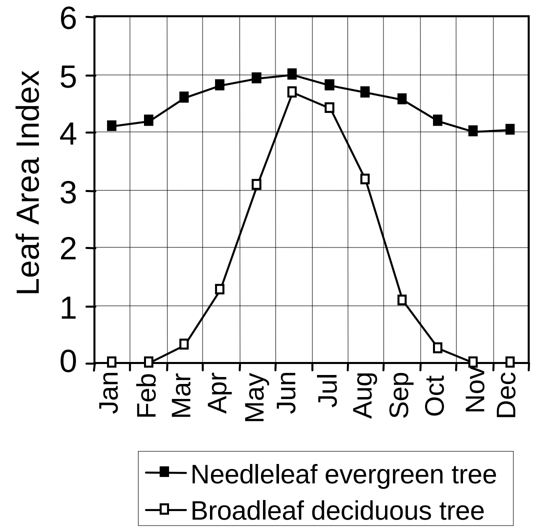
Fourth-generation of models

Dynamic vegetation

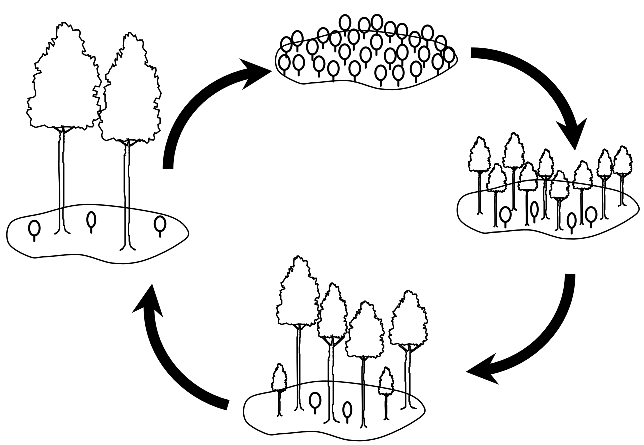
Ecosystem carbon balance



Leaf phenology



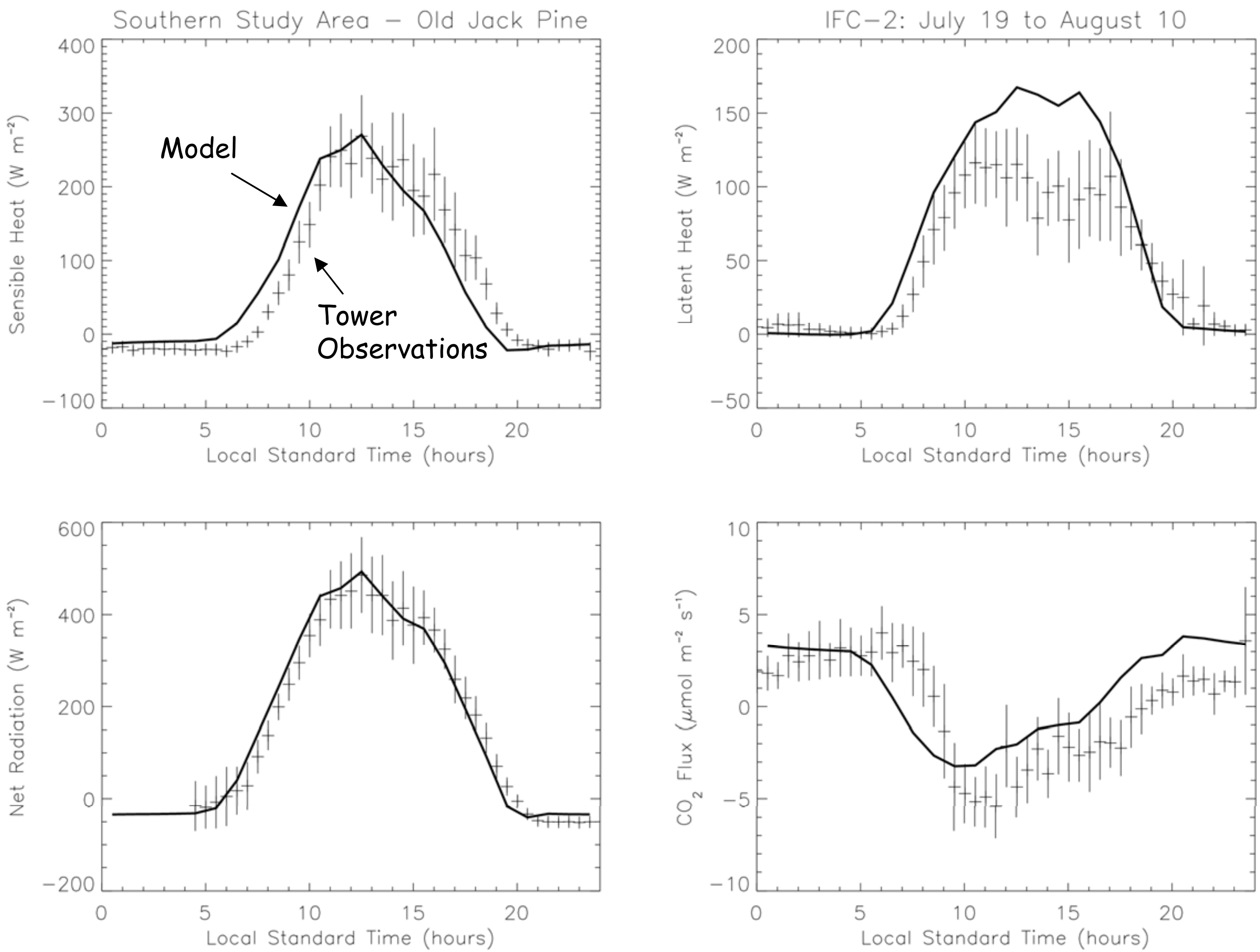
Vegetation dynamics



Foley et al. (1996) GBC 10:603-628
Levis et al. (1999) JGR 104D:31191-31198
Levis et al. (2000) J Climate 13:1313-1325
Cox et al. (2000) Nature 408:184-187

Model validation – tower fluxes

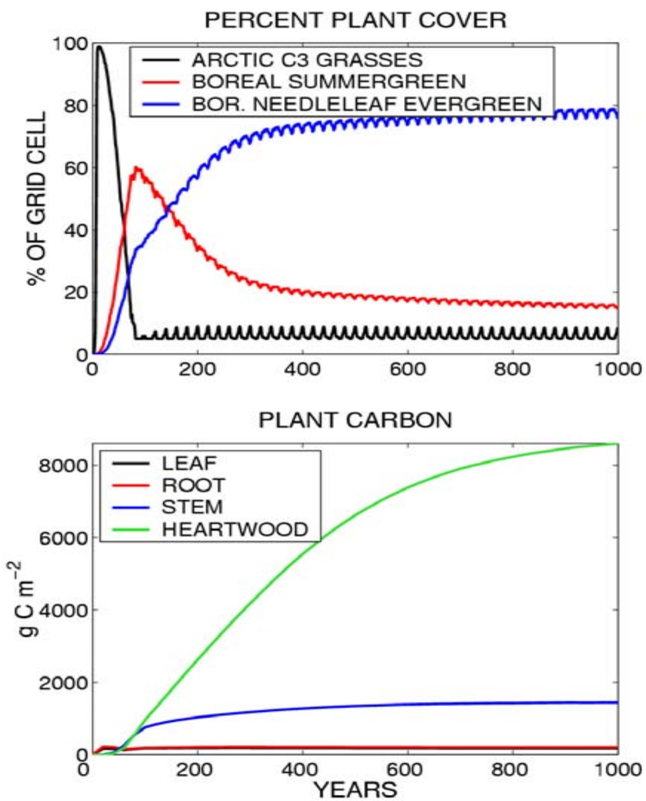
Boreal Ecosystem Atmosphere Study (BOREAS)



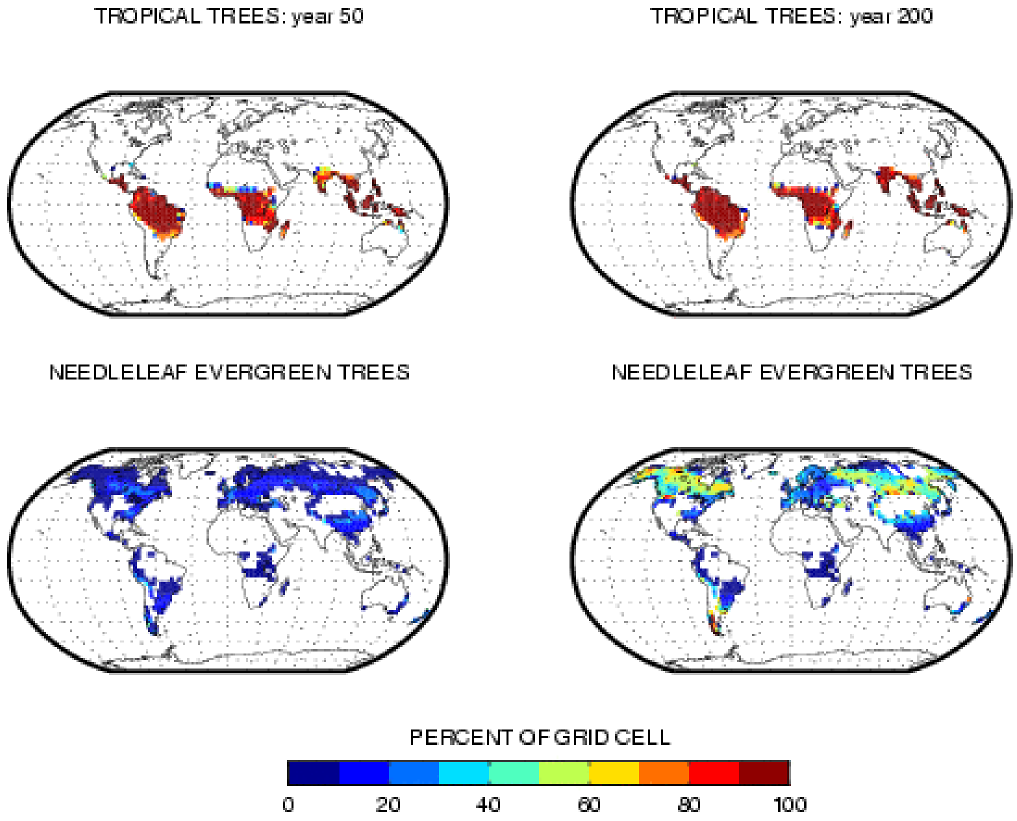
Bonan et al. (1997) J Geophys Res 102D:29065-29075

Vegetation dynamics

Boreal forest succession



Global biogeography



Bonan et al. (2003) Global Change Biology 9:1543-1566

Greening of North Africa

Climate 6000 years BP

Increased Northern Hemisphere summer solar radiation

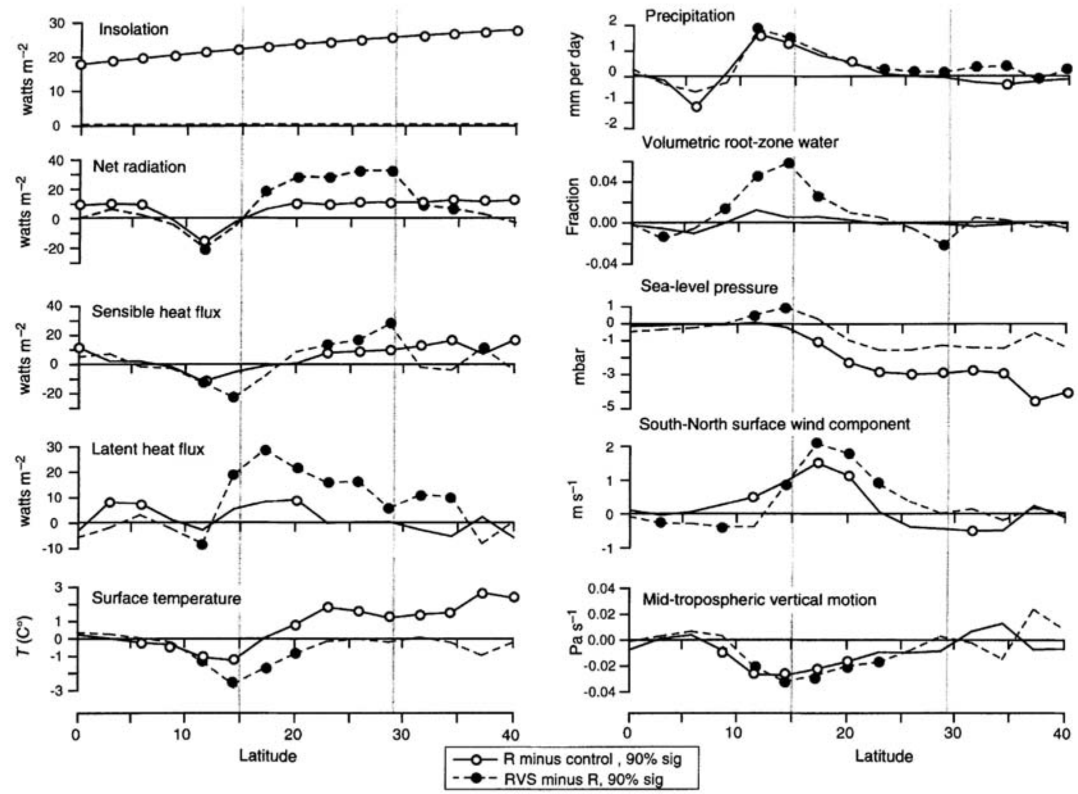
Strengthened African monsoon

Wetter North African climate allowed vegetation to expand

Two climate model experiments

Desert North Africa

Green North Africa



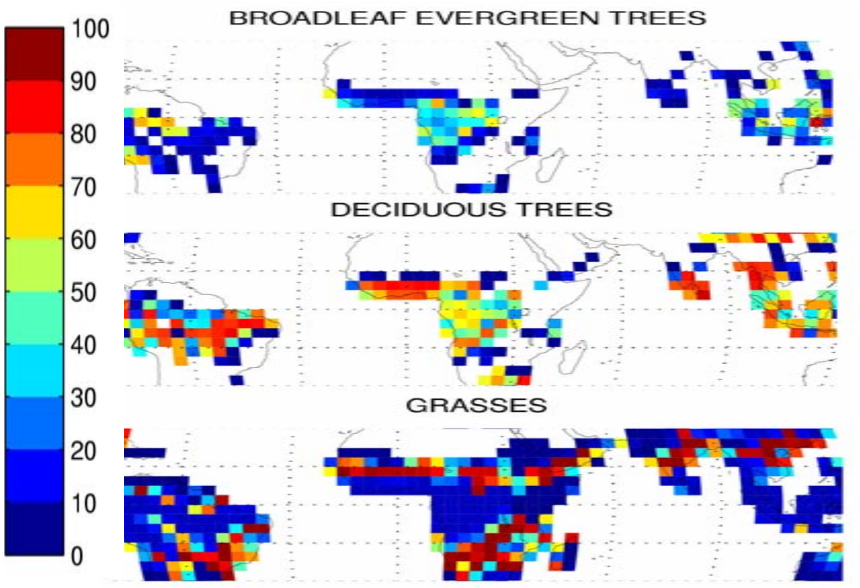
Climate model experiments show:

- Strengthened monsoon due to radiative forcing
- Vegetation forcing similar in magnitude to radiative forcing

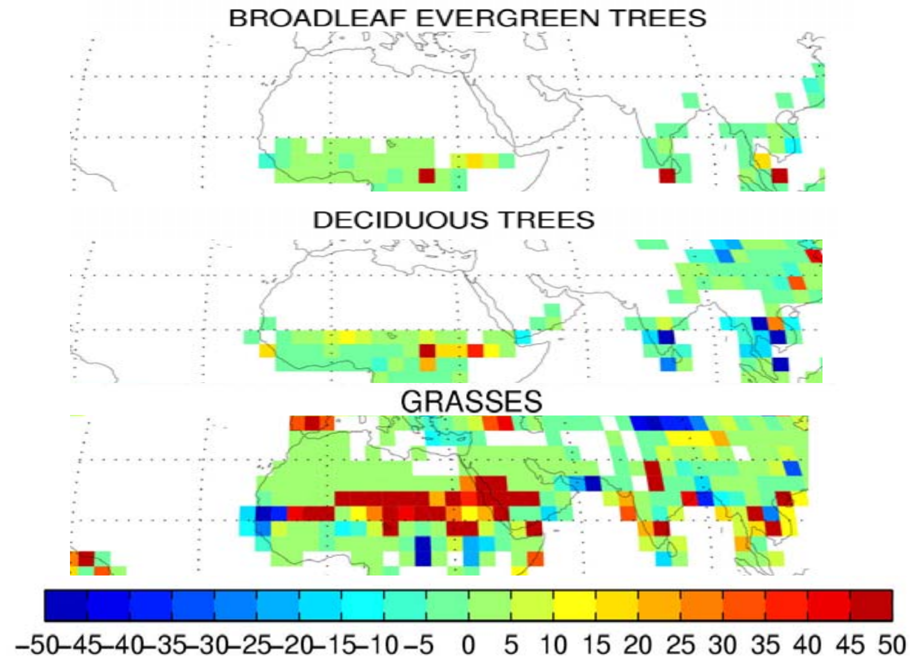
Kutzbach et al. (1996) Nature 384:623-626

Greening of North Africa

Present Day Biogeography
(percent of grid cell)

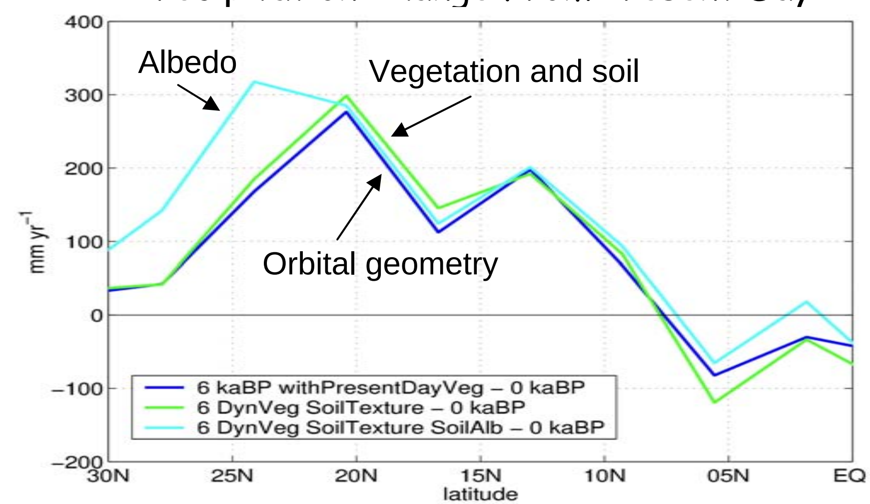


6kaBP DynVeg Soil Texture – 0 kaBP



<u>Dominant forcing</u>
Increase in evaporation
Decrease in soil albedo

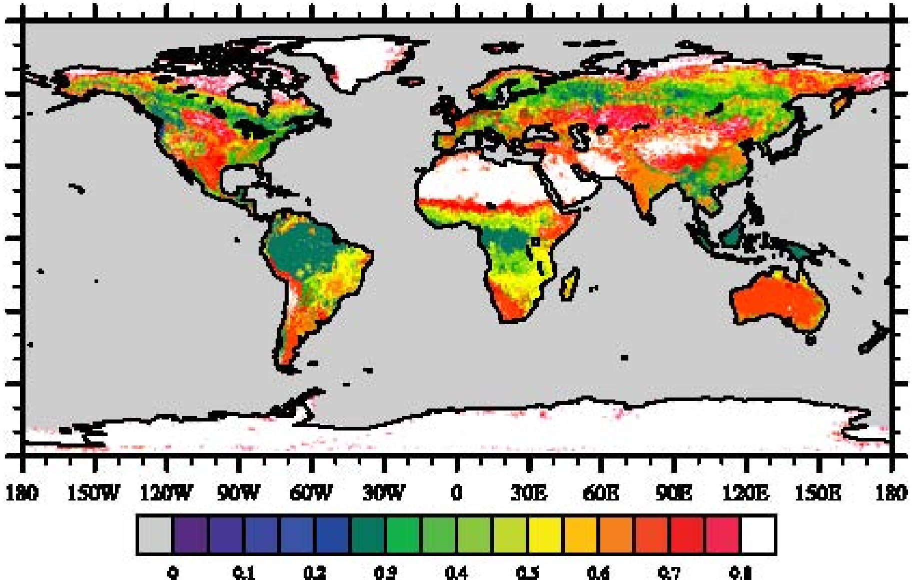
Precipitation Change From Present Day



Levis et al. (2004) Climate Dynamics 23:791-802

Effect of boreal forests on climate

Maximum satellite-derived surface albedo during winter



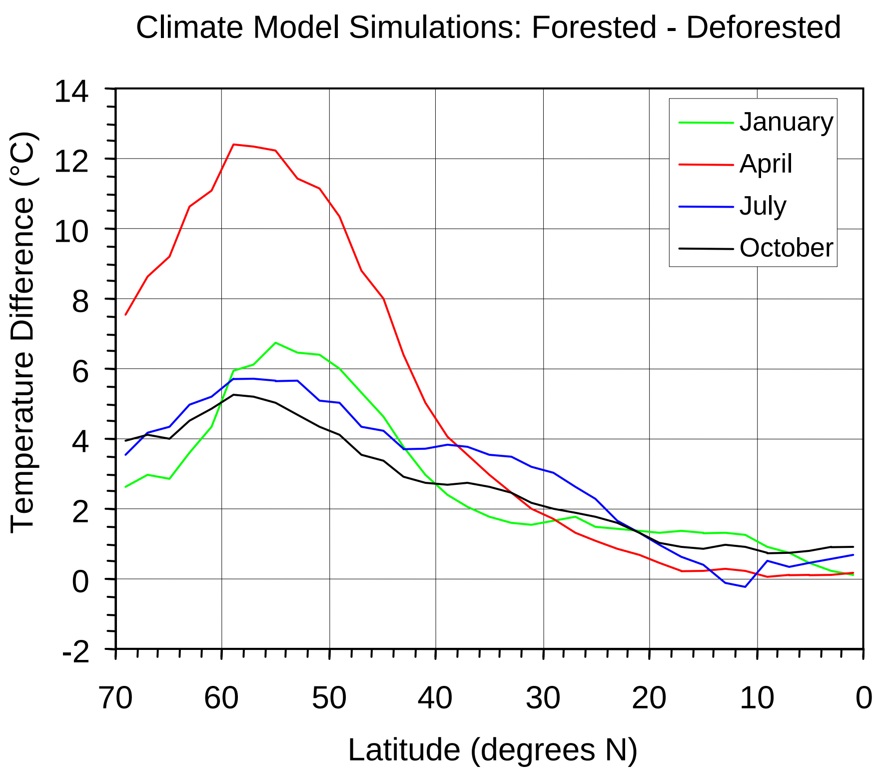
Barlage et al. (2005) GRL, 32, L17405, doi:10.1029/2005GL022881

Colorado Rocky Mountains

Vegetation masking of snow albedo -
Tree-covered land has a low albedo during winter

Effect of boreal forests on climate

Climate model simulations show boreal forest warms climate

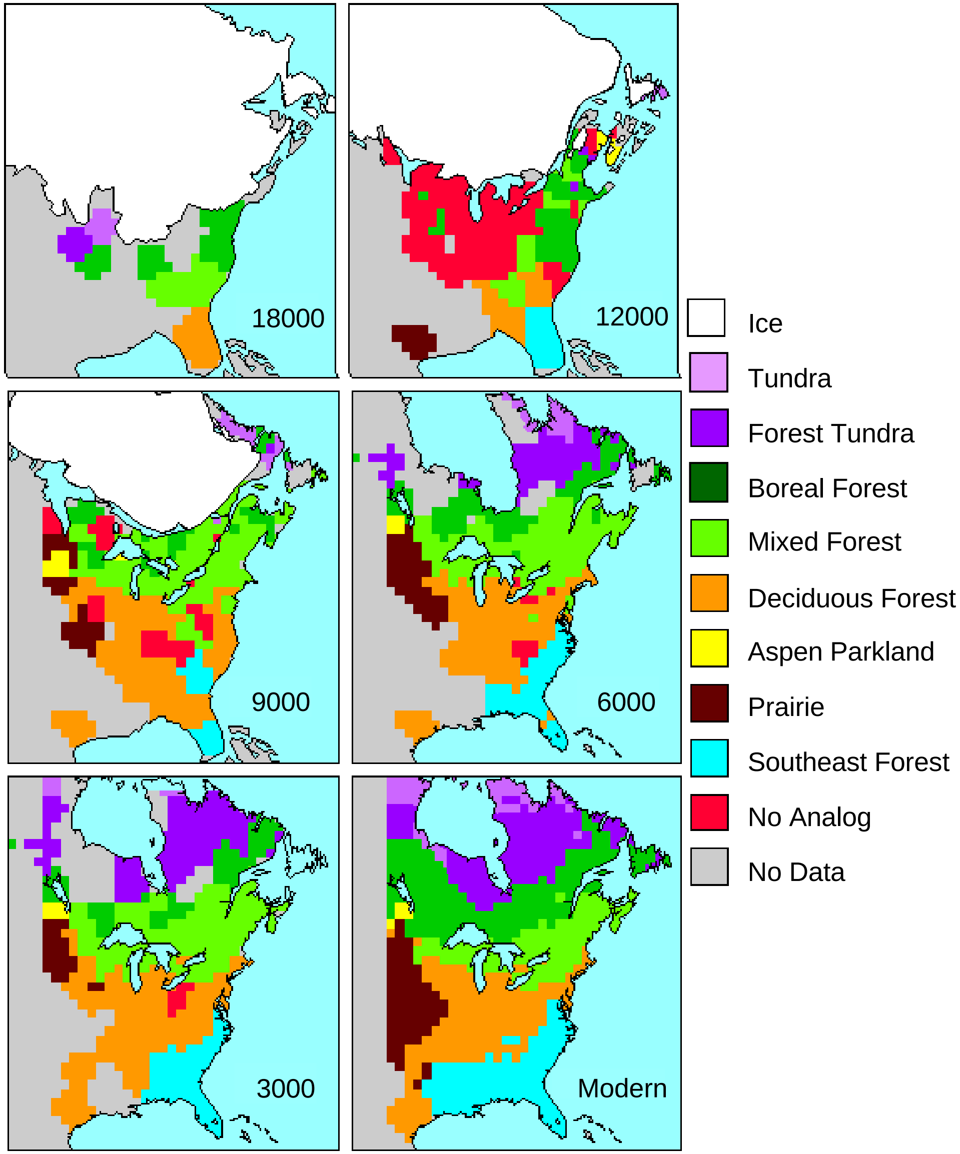


Forest warms climate by decreasing surface albedo
Warming is greatest in spring but is year-round
Warming extends south of boreal forest (about 45°N)

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

Effect of boreal forests on climate

Vegetation change since Last Glacial Maximum

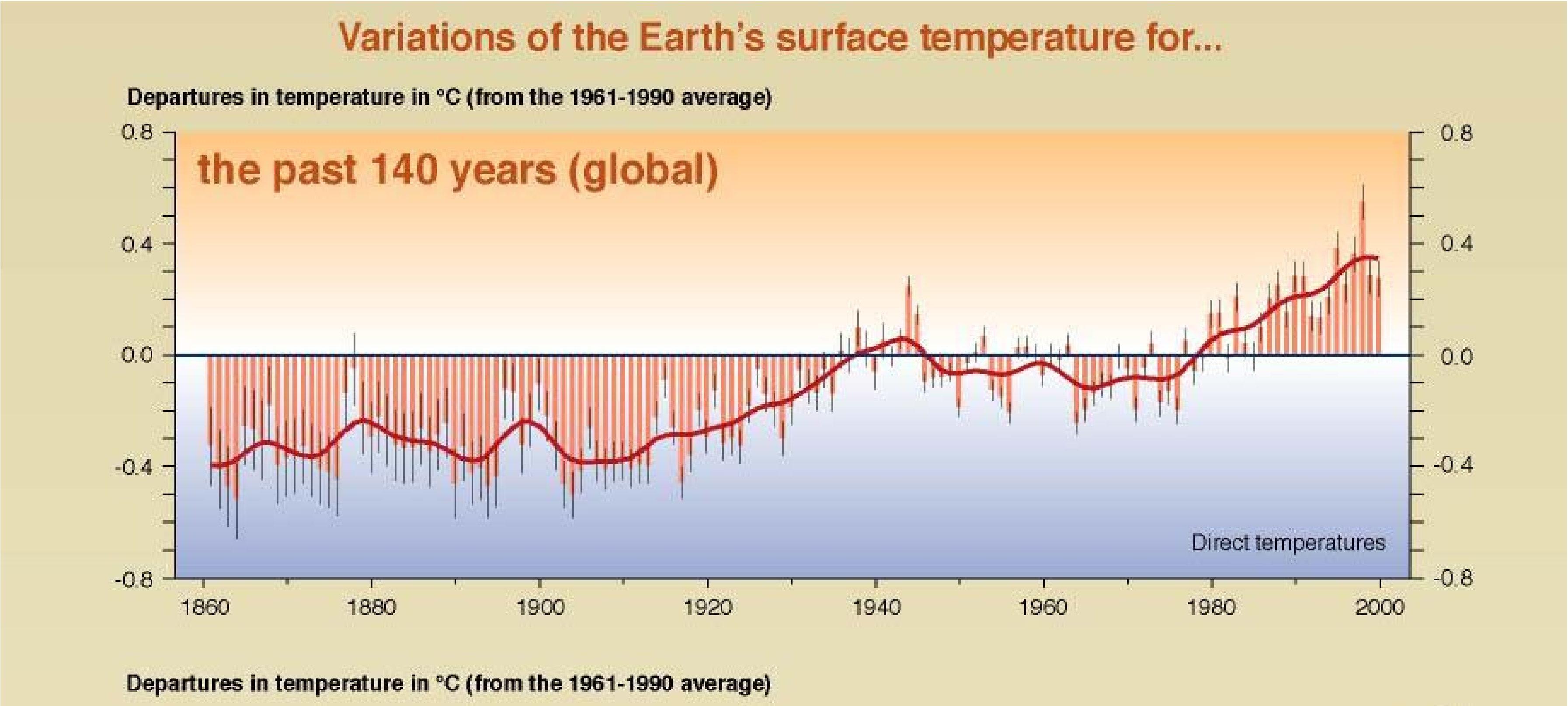


Climate model experiments

Southward retreat of boreal forest is thought to have reinforced glacial climate.

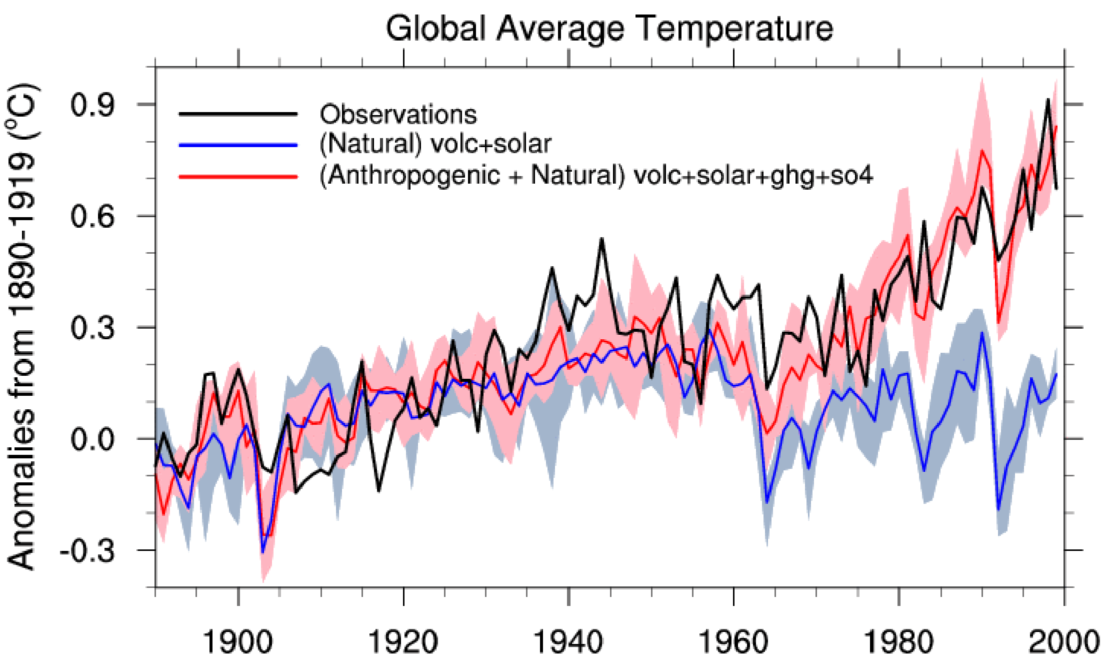
Expansion of boreal forest northward 6000 years BP is thought to have warmed climate.

Climate of the 20th Century



What are the causes of this observed climate change?

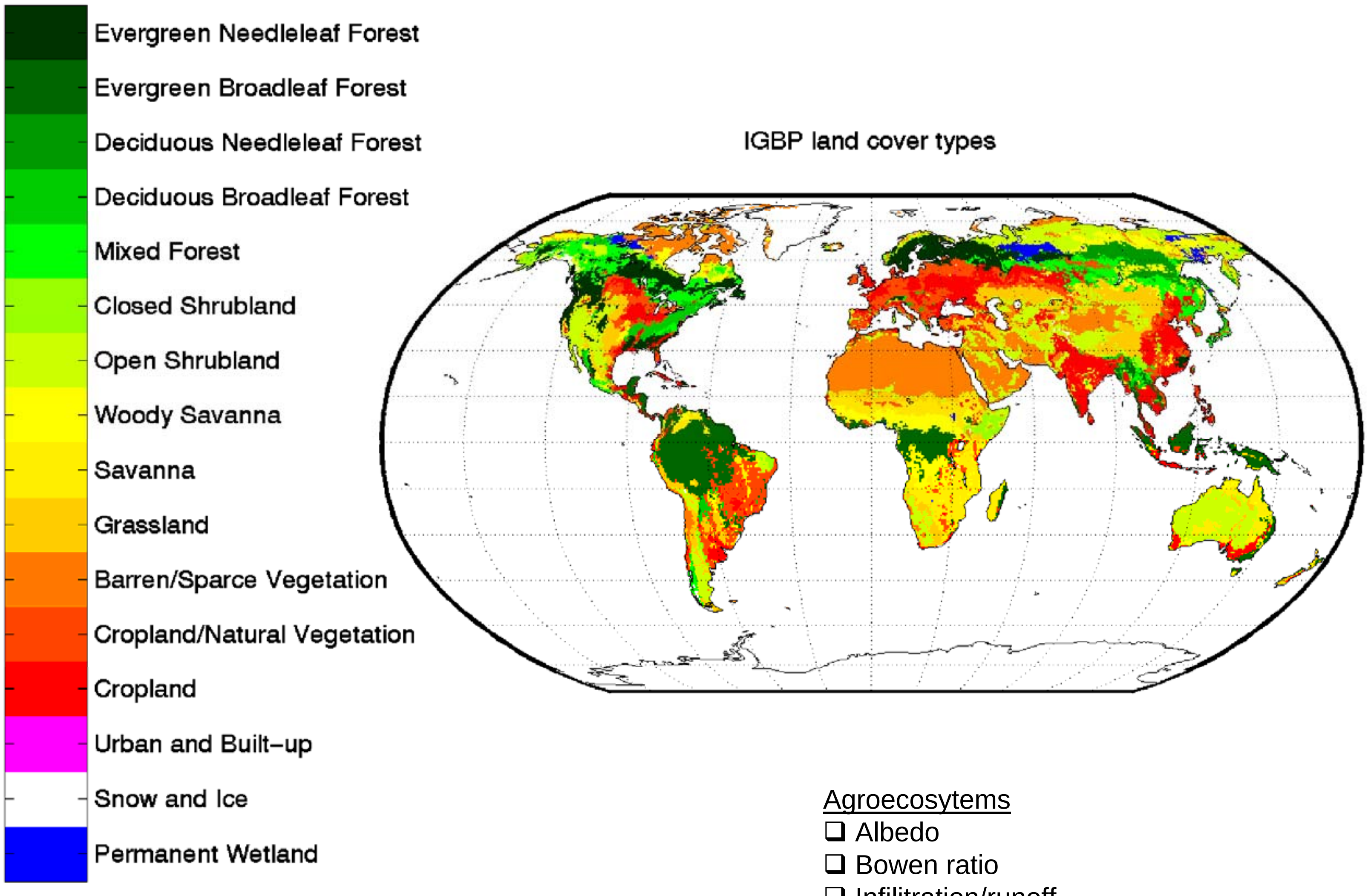
20th Century climate forcings



The combination of natural and anthropogenic forcings can match the observed temperature record

Meehl et al. (2004) J Climate 17:3721-3727

Land use forcing of climate

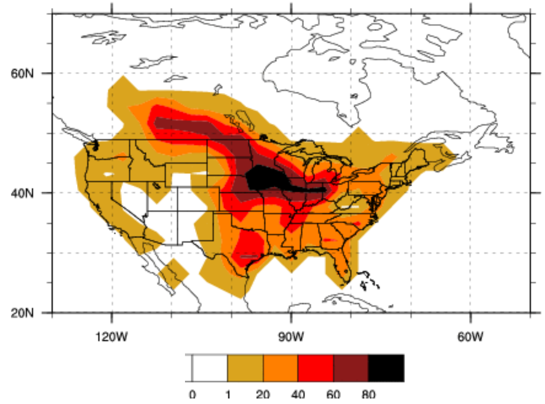


Agroecosytems

- ❑ Albedo
- ❑ Bowen ratio
- ❑ Infilitration/runoff
- ❑ Soil water holding capacity
- ❑ Atmospheric CO_2
- ❑ Nitrogen cycle
- ❑ Dust

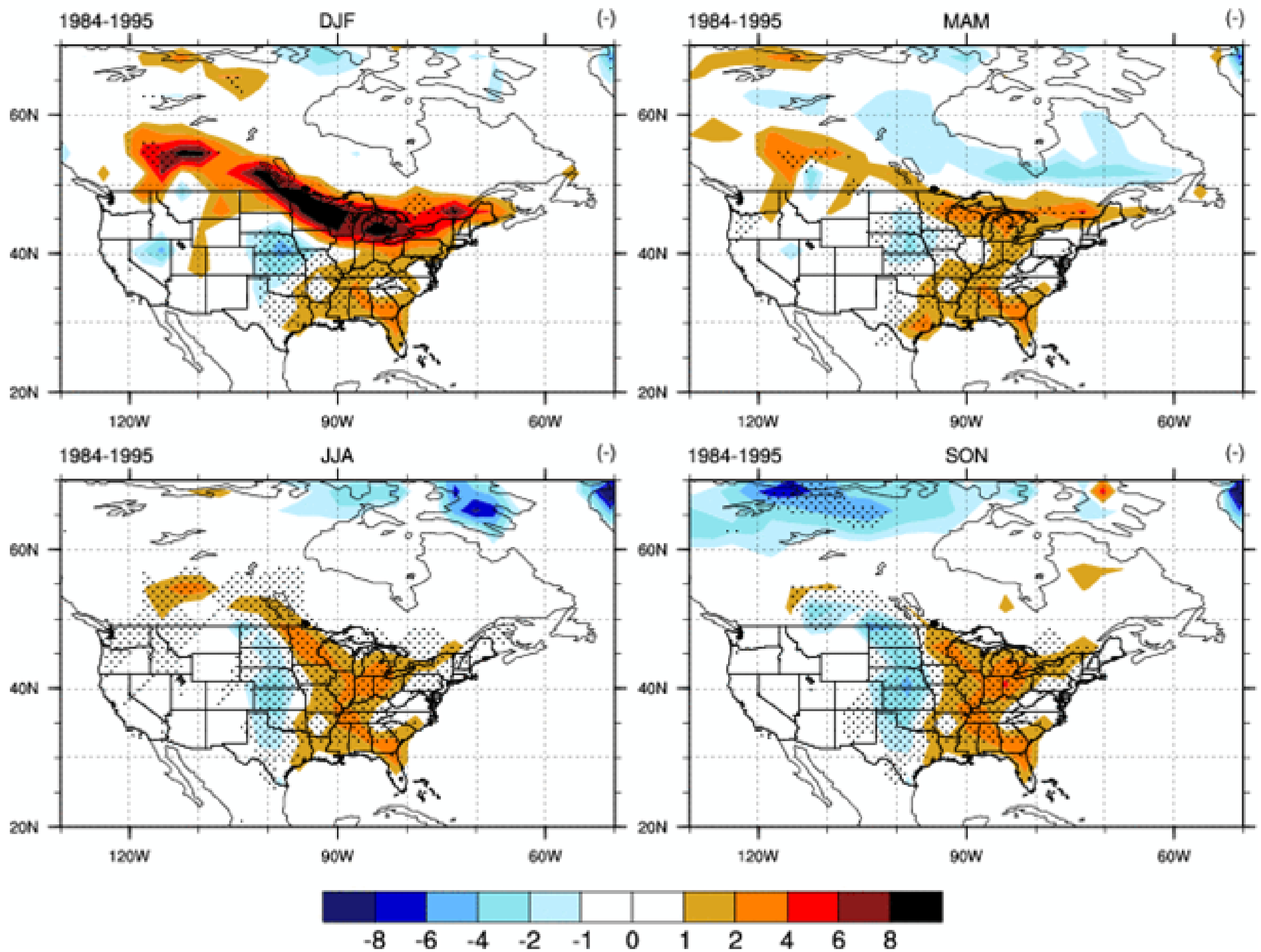
Land use forcing of climate

Cropland extent (%)



Croplands increase albedo

Albedo difference (present day – natural vegetation)

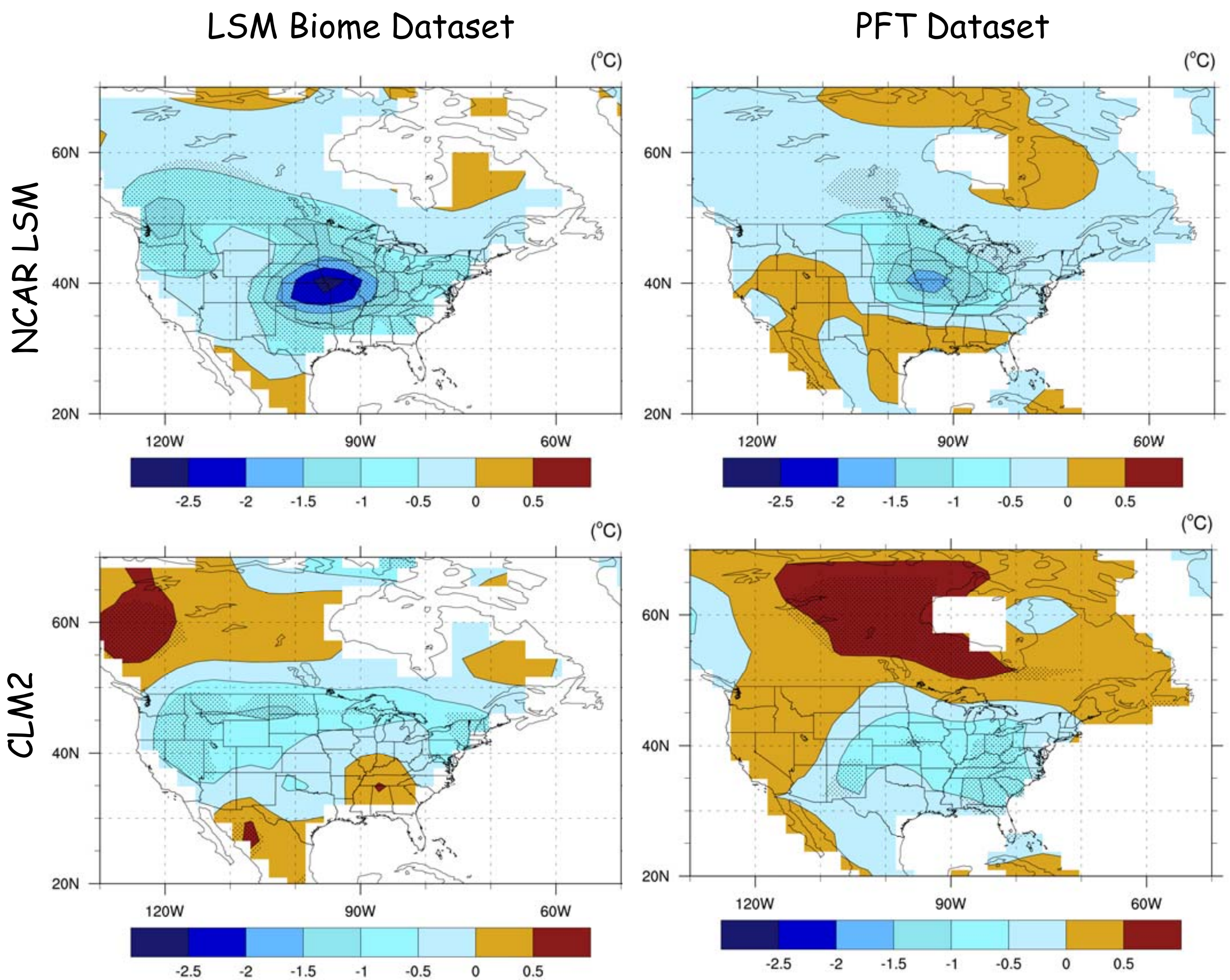


Albedo difference (×100)

Oleson et al. (2004) Climate Dynamics 23:117-132

Land use forcing of climate

Summer Surface Air Temperature Difference (Present Day – Natural Vegetation)



Four paired climate simulations with CAM2 using two land surface models

- NCAR LSM
- CLM2

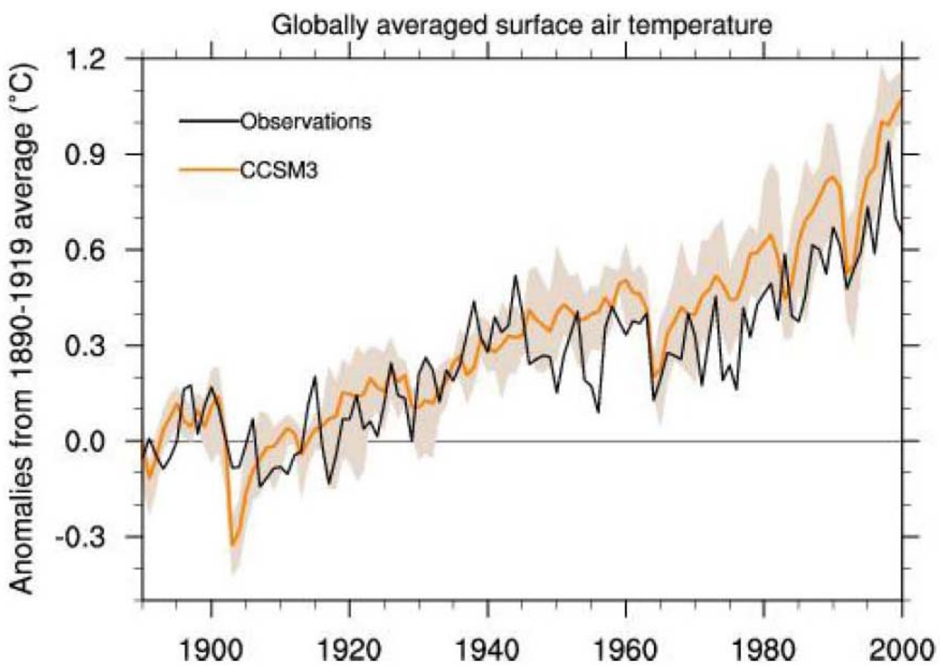
and two surface datasets

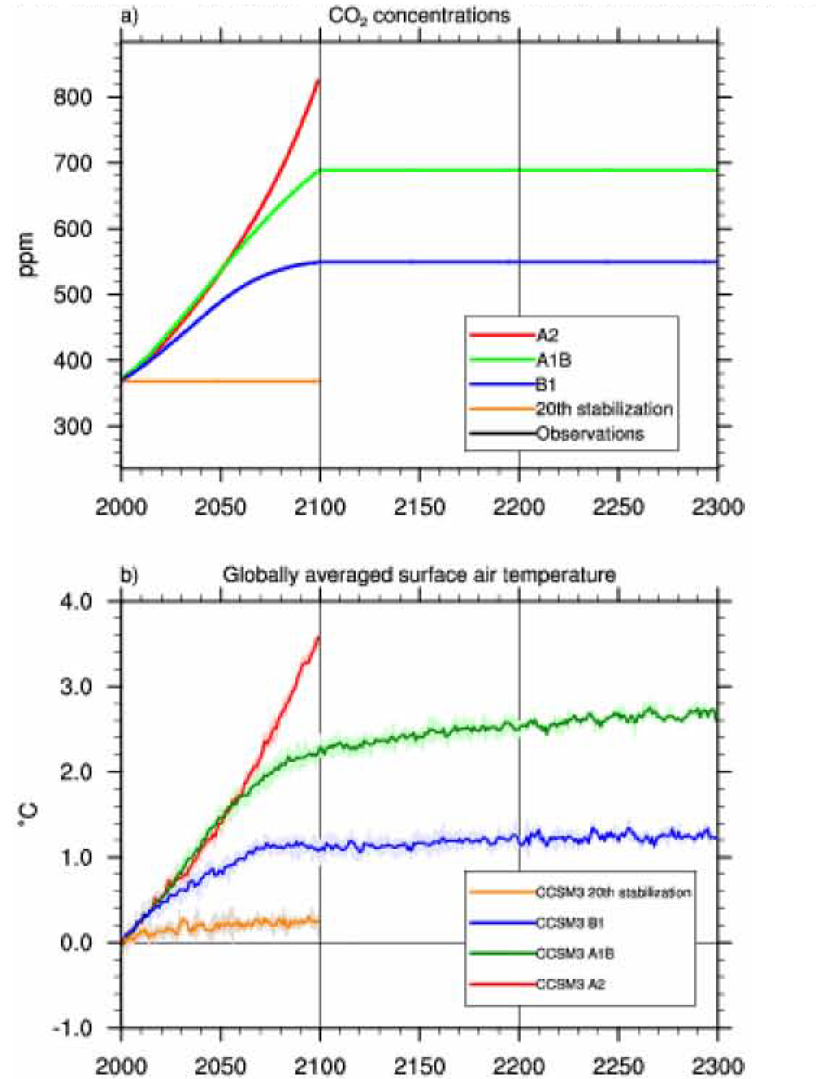
- Biome dataset without subgrid heterogeneity
- Dataset of plant functional types with subgrid heterogeneity

Conclusion
Magnitude of cooling associated with croplands is sensitive to surface datasets and model physics

Oleson et al. (2004) Climate Dynamics 23:117-132

Climate of the 21st century





Climate forcings

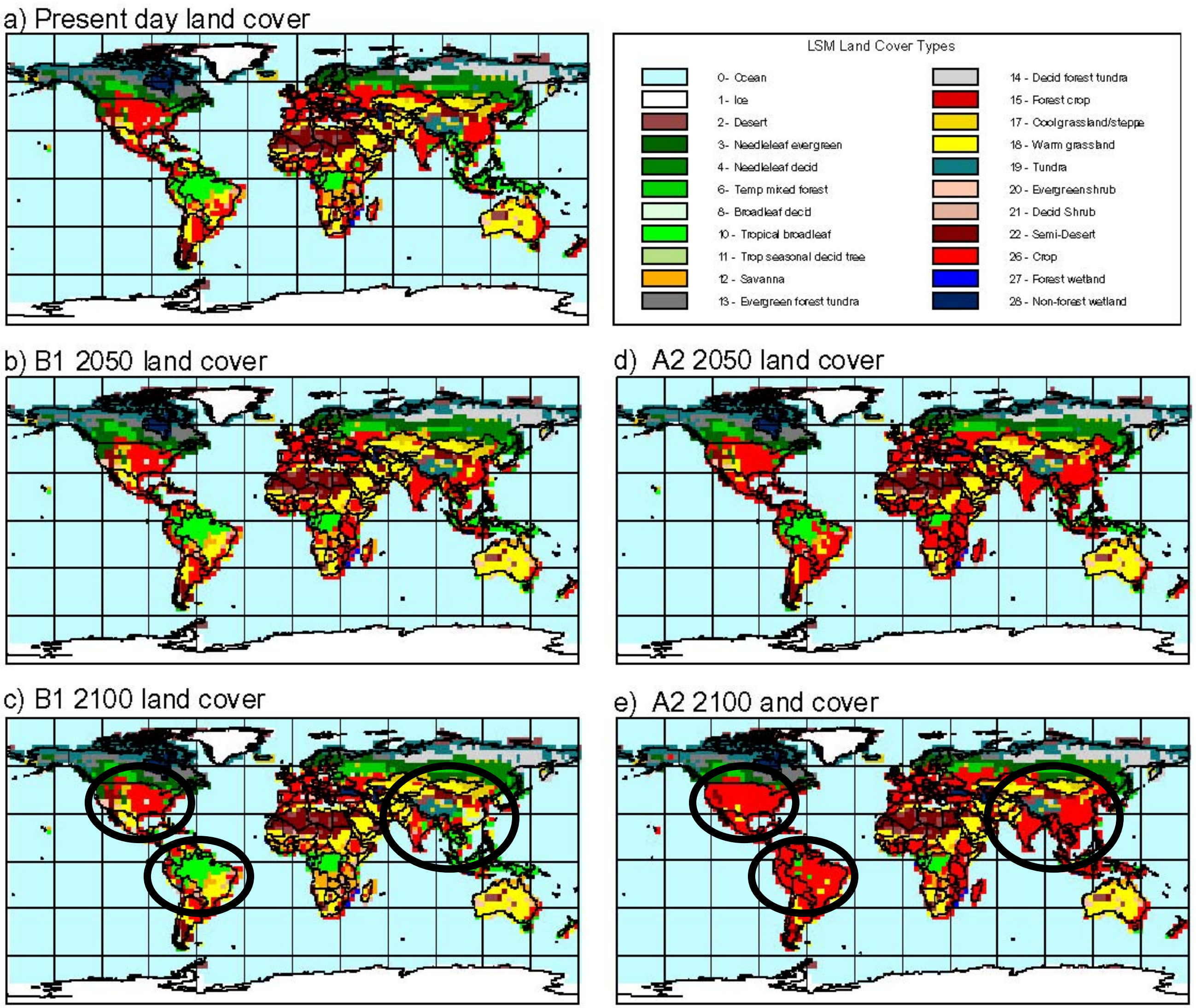
Greenhouse gases
Solar variability
Volcanic aerosols
Ozone
Sulfate aerosols
Black carbon aerosols

What is the vegetation forcing of climate?

Meehl et al. (2006) J Climate 19:2597-2616

Future land cover change as a climate forcing

Future IPCC SRES Land Cover Scenarios for NCAR LSM/PCM



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

Forcing arises from changes in

Community composition
Leaf area
Height [surface roughness]
↓
Surface albedo
Turbulent fluxes
Hydrologic cycle

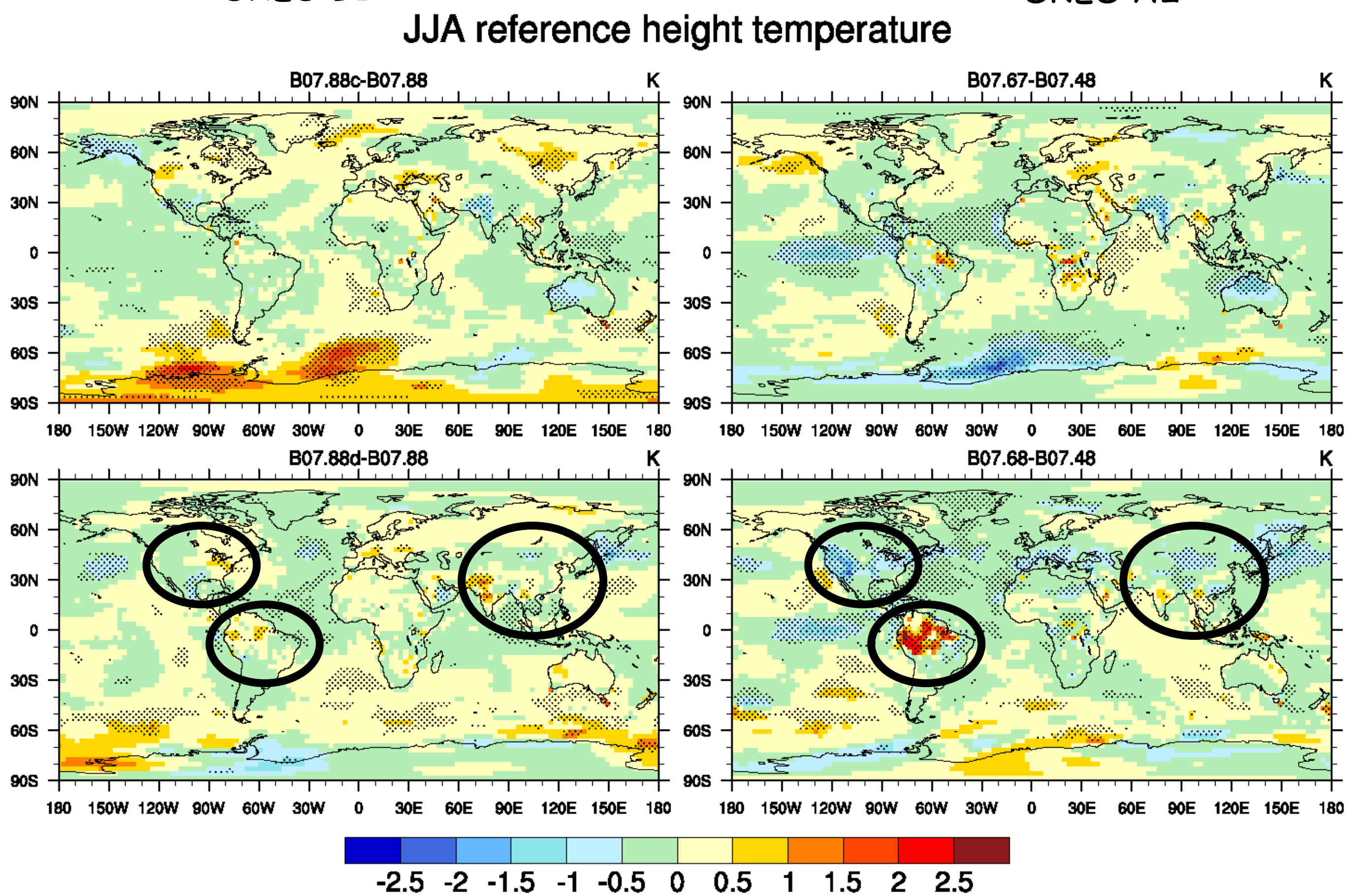
Also alters carbon pools and fluxes, but most studies of land cover change have considered only biogeophysical processes

Future land cover change as a climate forcing

SRES B1 | SRES A2

2050

2100



Dominant forcing
Brazil – albedo, ET
U.S. – albedo
Asia - albedo

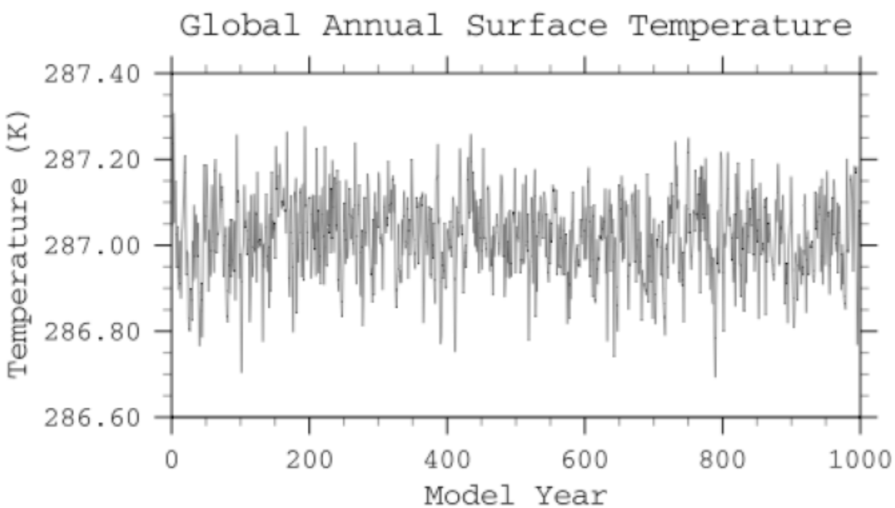
PCM/NCAR LSM transient climate simulations with changing land cover. Figures show the effect of land cover on temperature

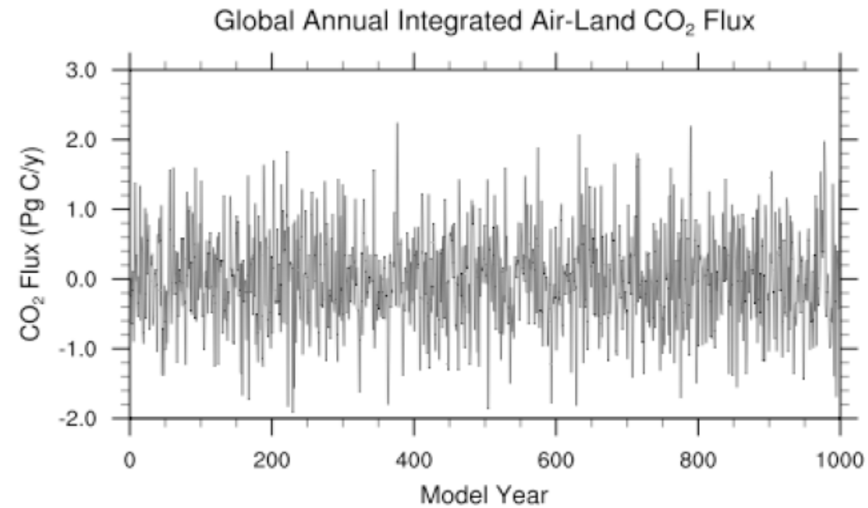
(SRES land cover + SRES atmospheric forcing) - SRES atmospheric forcing

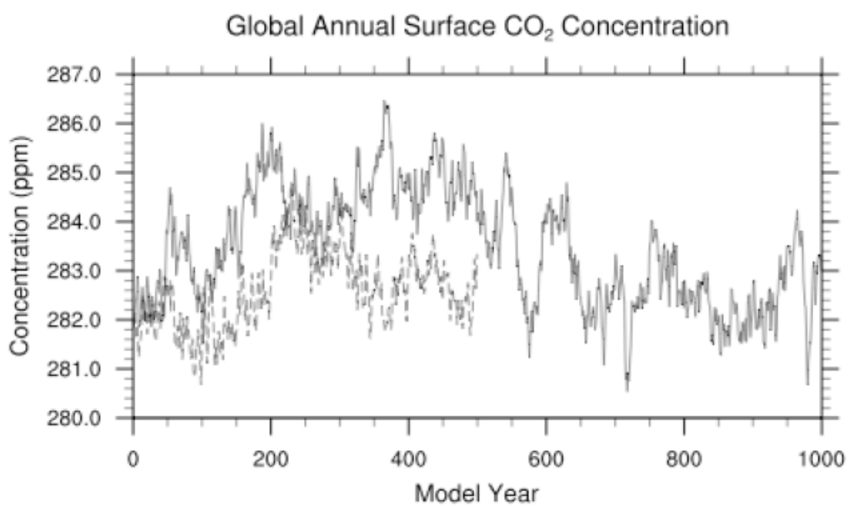
Feddema et al. (2005) Science 310:1674-1678

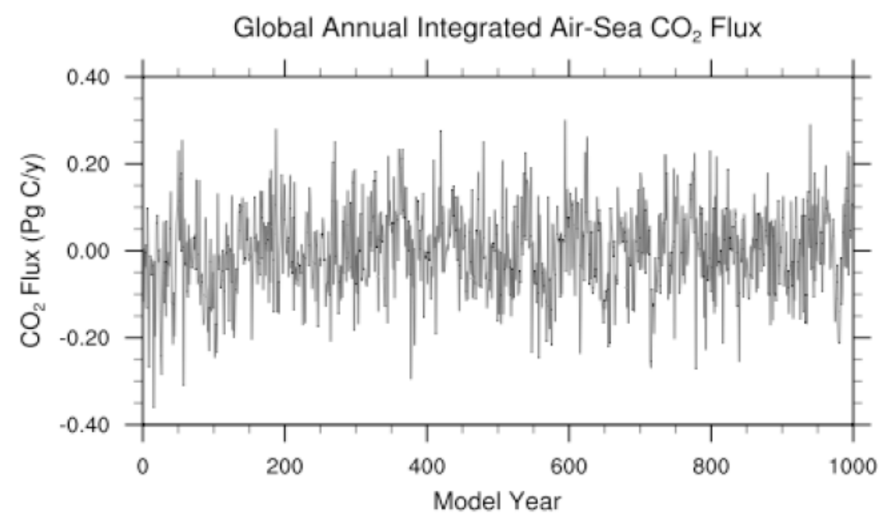
Carbon cycle

CCSM1 – 1000 year climate carbon cycle simulation









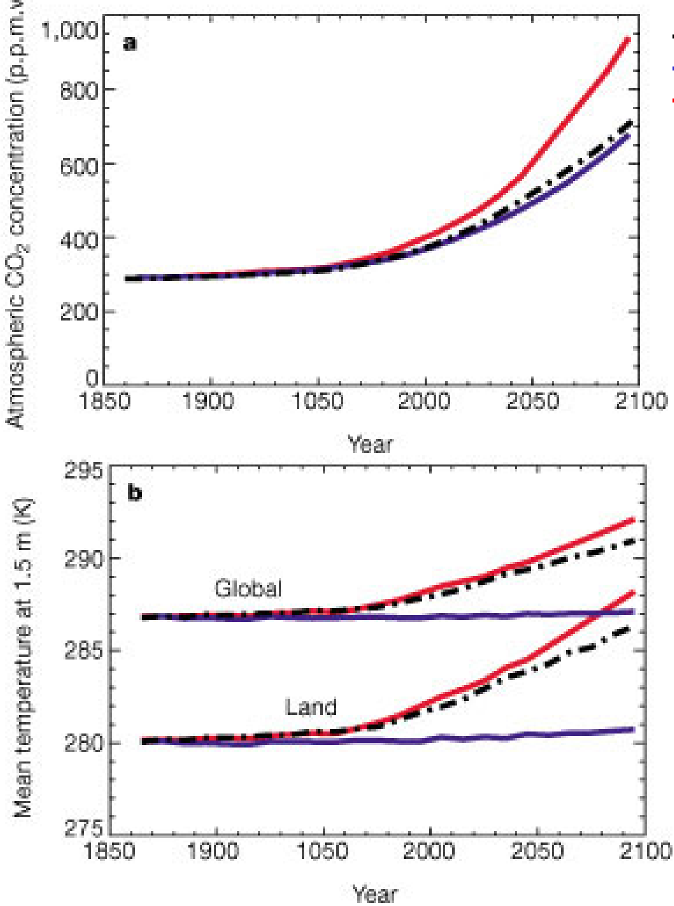
Doney et al. (2006) J Climate 19:3033-3054

Carbon cycle feedback

Three climate model simulations to isolate the climate/carbon-cycle feedbacks

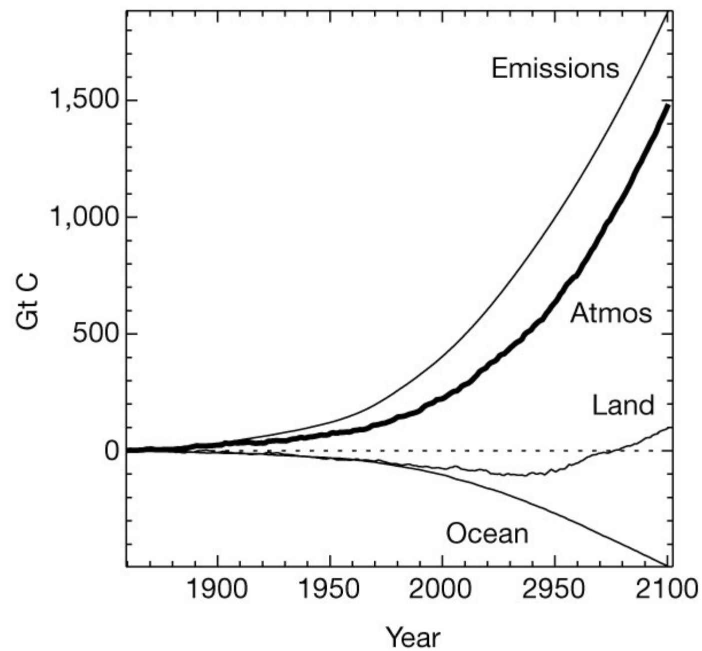
- Prescribed CO_2 and fixed vegetation (a 'standard' GCM climate change simulation)
- Interactive CO_2 and dynamic vegetation but no effect of CO_2 on climate (no climate/carbon cycle feedback)
- Fully coupled climate/carbon-cycle simulation (climate/carbon cycle feedback)

Effect of climate/carbon-cycle feedbacks on CO_2 increase and global warming



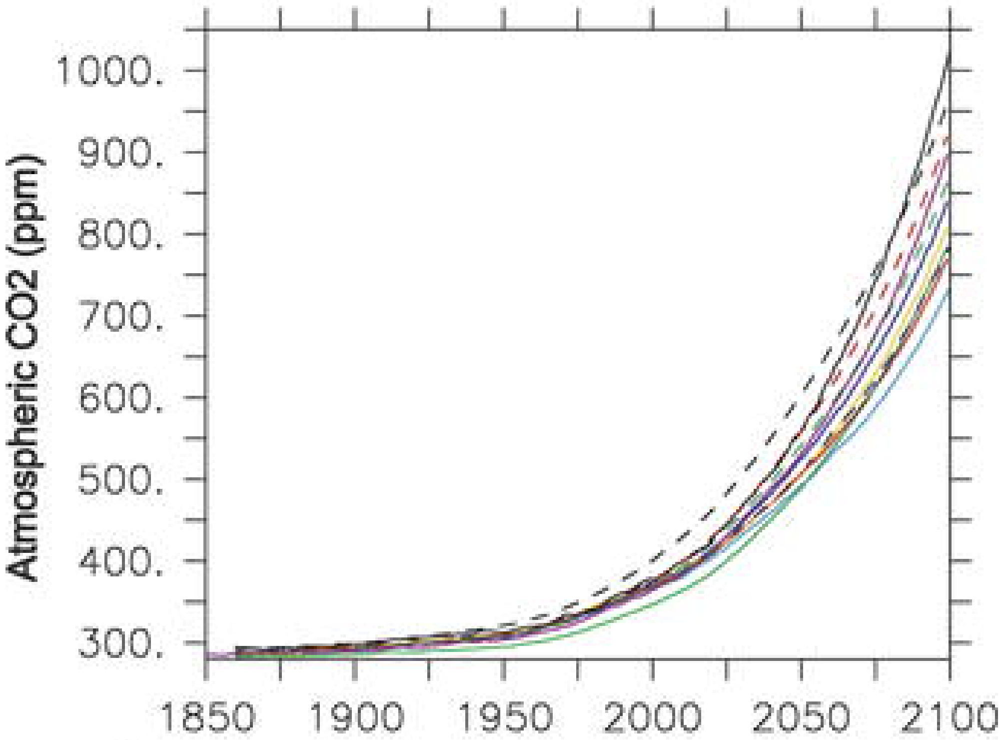
Prescribed CO_2 and fixed vegetation
Interactive CO_2 and vegetation, no climate change
Fully coupled

Carbon budgets for the fully coupled simulation



Cox et al. (2000) Nature 408:184-187

C4MIP – Climate and carbon cycle



Experimental protocol
Eleven climate models of varying complexity with active carbon cycle

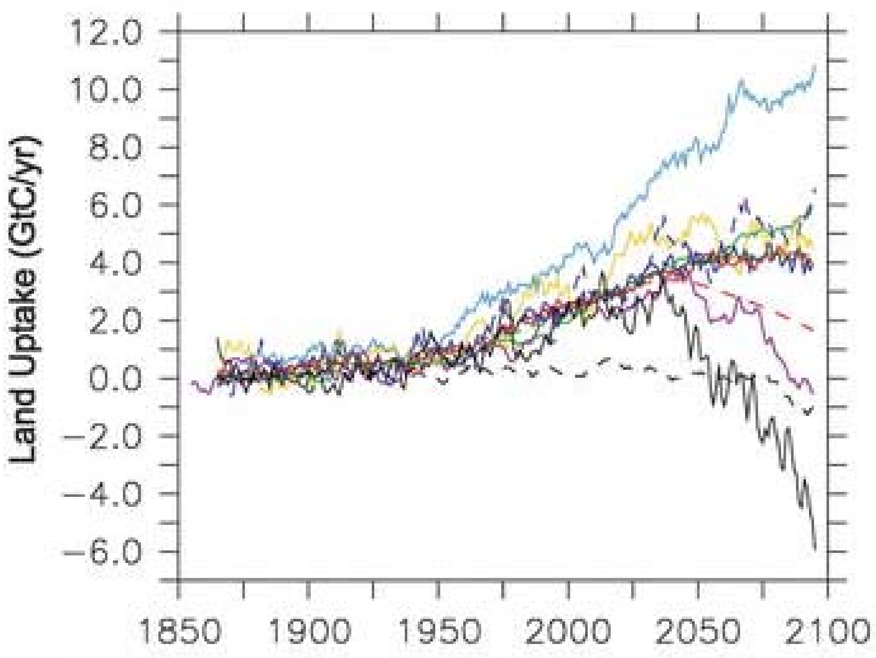
Transient climate simulations through 2100 forced with historical fossil fuel emissions and IPCC SRES A2 emissions

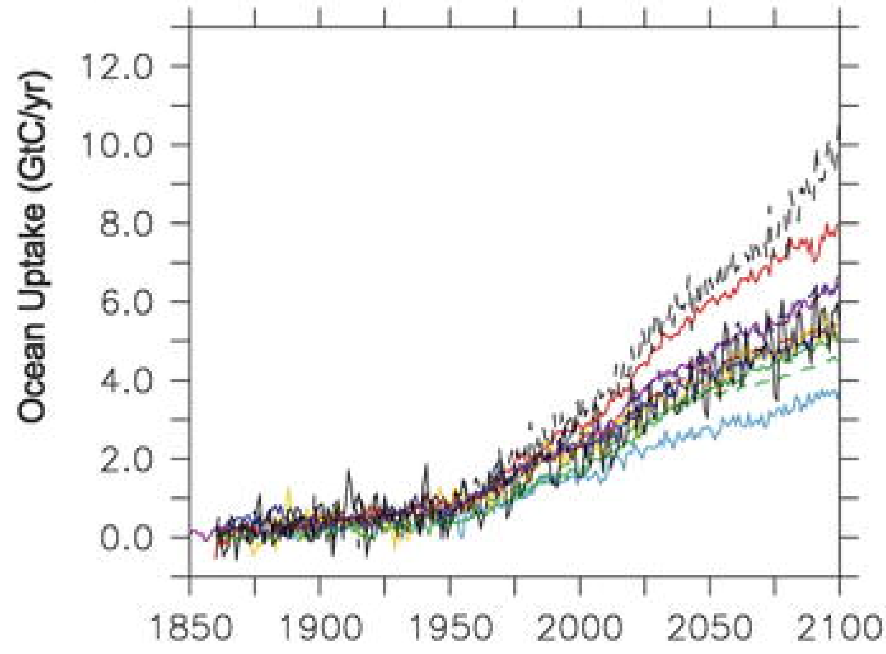
Vegetation forcings of climate
- Direct biogeochemical effect (atmos. CO_2)
- Indirect biogeophysical effect (stomata, leaf area, biogeography)

Results
Models have large uncertainty in simulated atmospheric CO_2 at 2100 (range is from 730 ppm to 1020 ppm)

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

C4MIP – Climate and carbon cycle





Large uncertainty in terrestrial fluxes at year 2100

- 1 model simulates a 6 Gt C/yr source of carbon from land
- 1 model simulates a 11 Gt C/yr terrestrial carbon sink
- 2 models simulate carbon source

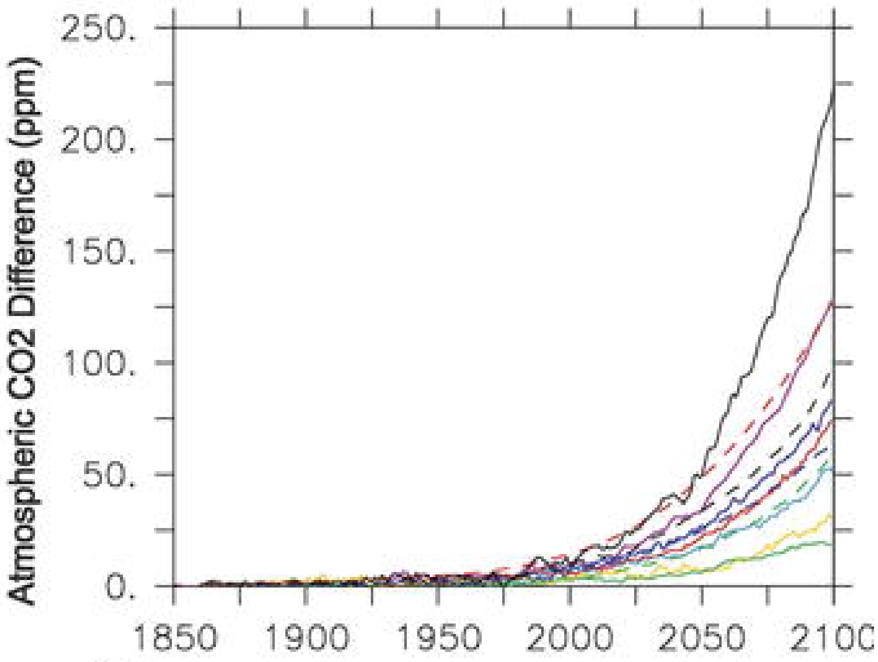
Relatively less uncertainty in ocean fluxes

All models simulate carbon uptake ranging from 4-10 Gt C/yr at year 2100

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

C4MIP – Climate and carbon cycle

Effect of climate change on carbon cycle

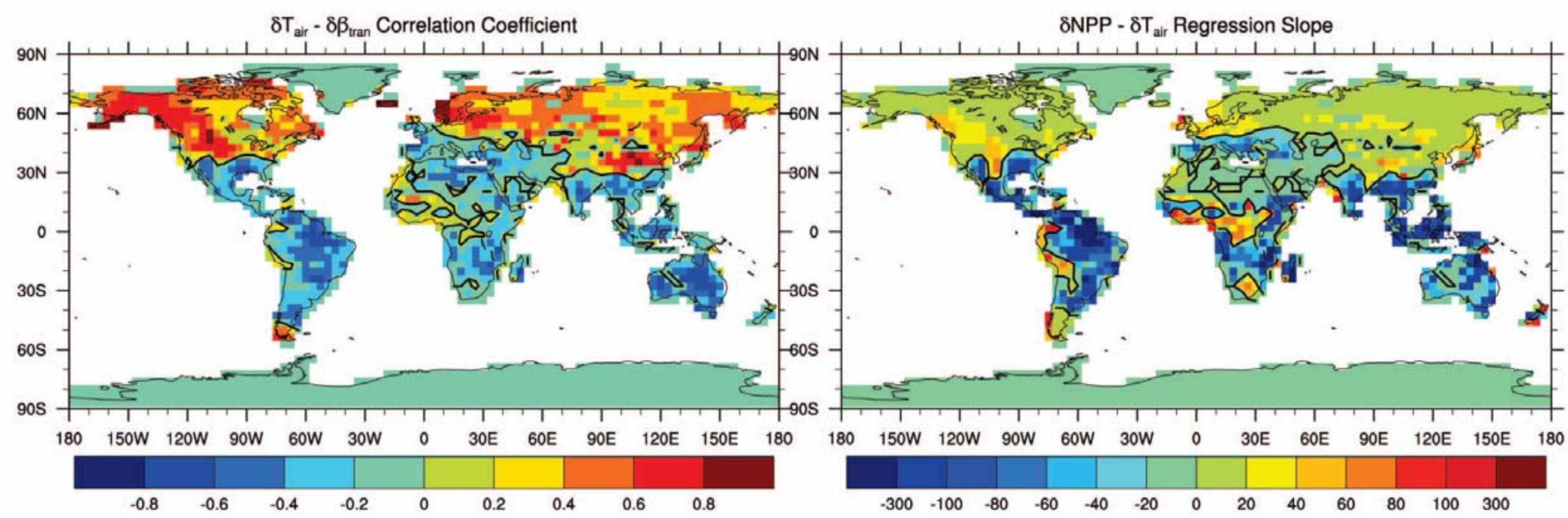


Climate-carbon cycle feedback
- All models show larger atmospheric CO_2 concentration when climate is allowed to change in response to CO_2
- That is, all models have a positive climate-carbon cycle feedback
- This difference between fully coupled climate-carbon cycle simulations and uncoupled simulations (CO_2 has no radiative effect) ranges from 20 ppm to 200 ppm

Conclusion
- Terrestrial carbon cycle can be a large climate feedback
- Considerable more work is needed to understand this feedback
- How will carbon cycle science be advanced? Is there a tradeoff between more complexity (e.g., nitrogen, wildfire, dust fertilization) and understanding?

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

CCSM1 – C4MIP simulation



Correlation of air temperature with soil moisture

Low latitudes
Negative correlation: warming leads to drier soil in warm regions

Middle to high latitudes
Positive correlation: warming leads to wetter soil in cold regions

Correlation of NPP with air temperature

Low latitudes
Negative correlation: NPP decreases with warming because of soil desiccation

Middle to high latitudes
Positive correlation: NPP increases with warming because of more favorable climate

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

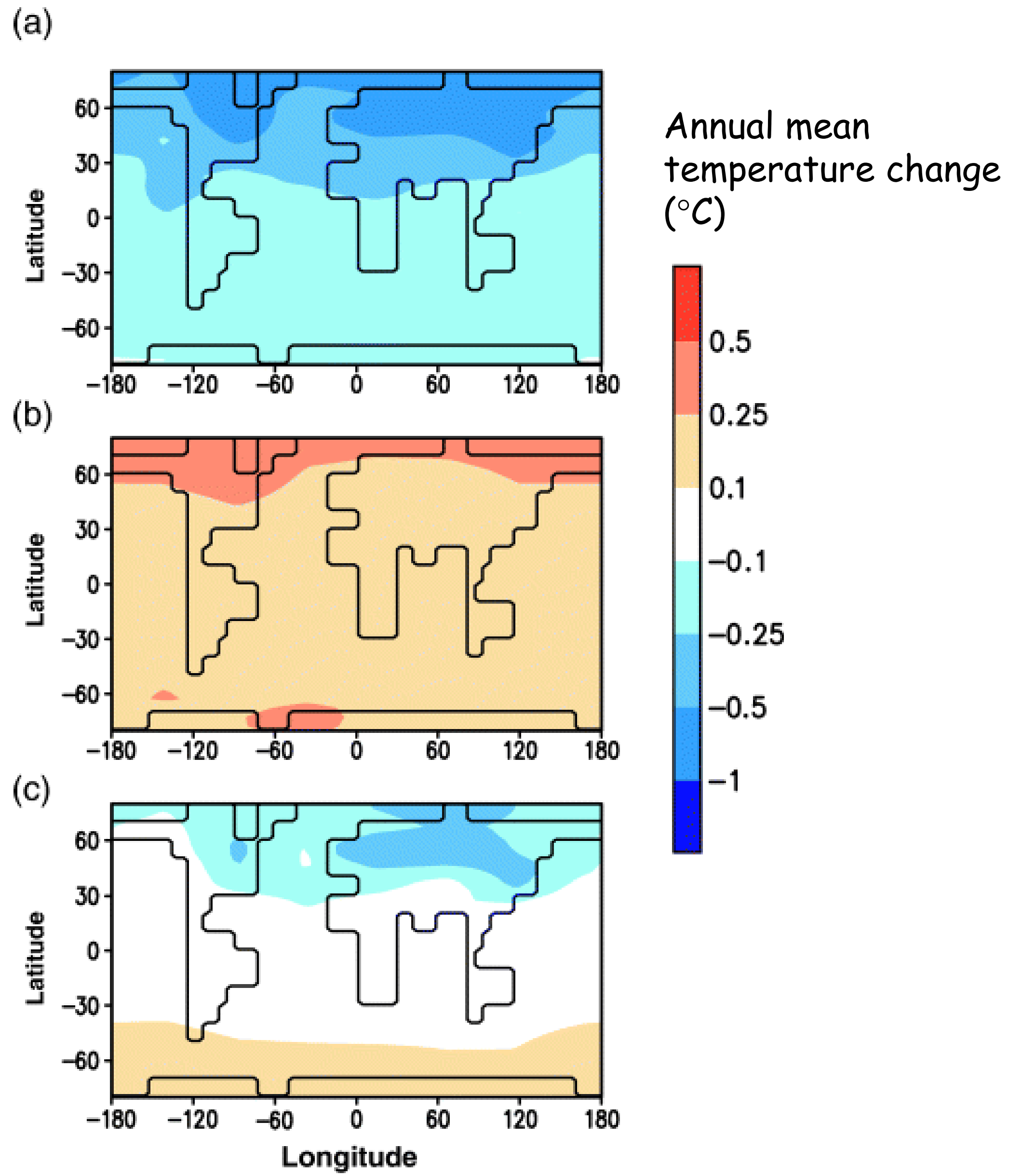
Biogeophysical vs. biogeochemical interactions

Historical land cover change

Biogeophysical cooling

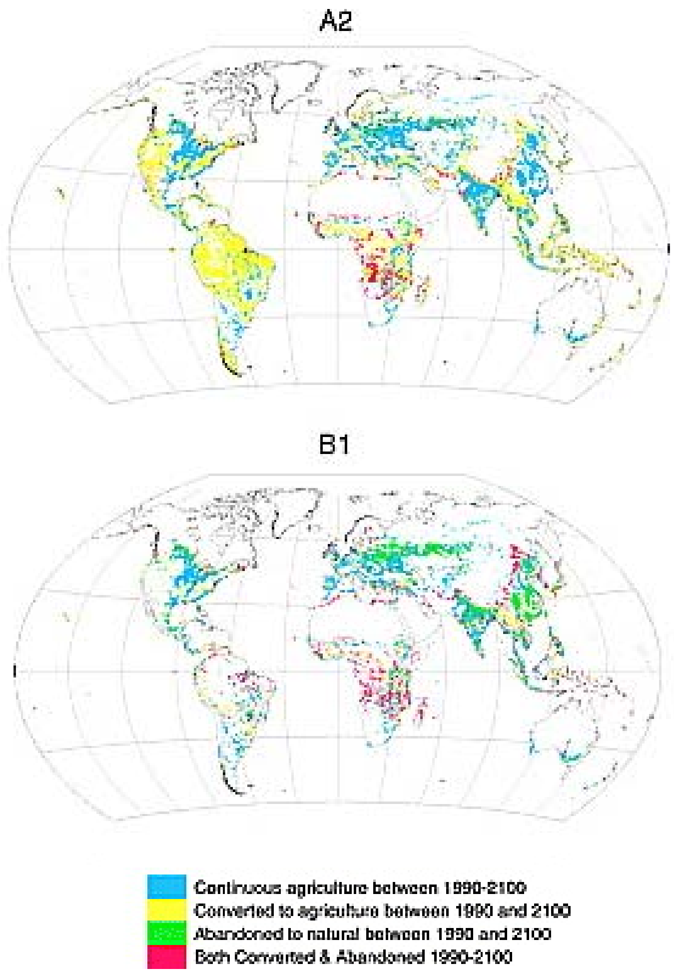
Biogeochemical warming

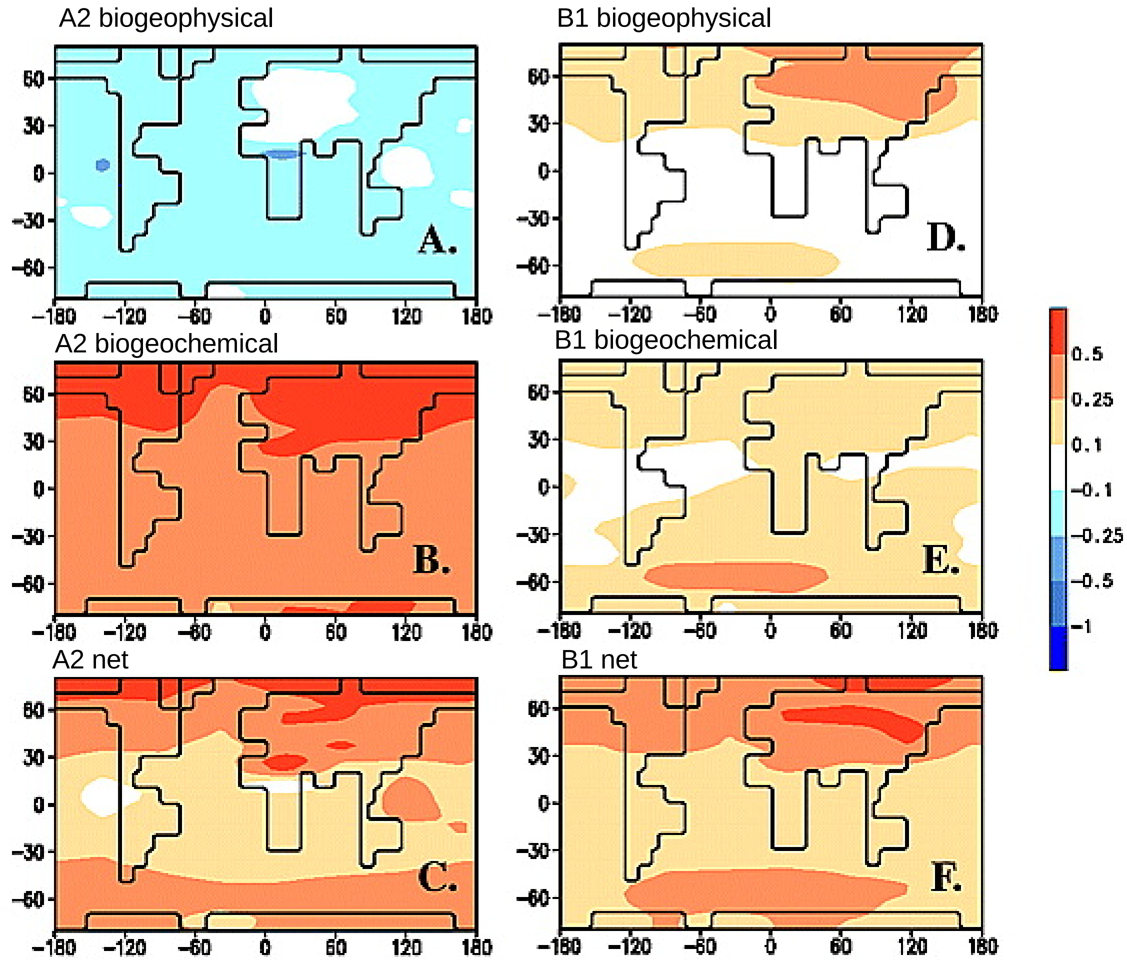
Biogeophysical cooling offsets biogeochemical warming



Brovkin et al. (2004) Global Change Biology 10:1253–1266

Future land cover change





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

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

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

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

Ecology or climatology

Climatic Interpretation

Lamb (1977) Climate: Present, Past and Future. Volume 2, Climatic History and the Future

Lamb (1995) Climate, History and the Modern World

- Painted in the winter of 1565
- Records Bruegel's impression of severe winter
- Start of a long interest in Dutch winter landscapes that coincided with an extended period of colder than usual winters

Ecological Interpretation

Forman & Godron (1986) Landscape Ecology

Defines ecological concept of a landscape
- heterogeneity of landscape elements
- spatial scale
- movement across the landscape

Pieter Bruegel the Elder's 'Hunters in the Snow'

Bonan (2008) Ecological Climatology. 2nd edition (Cambridge Univ. Press)