Terrestrial Ecosystem Forcings and Feedbacks in the Climate System

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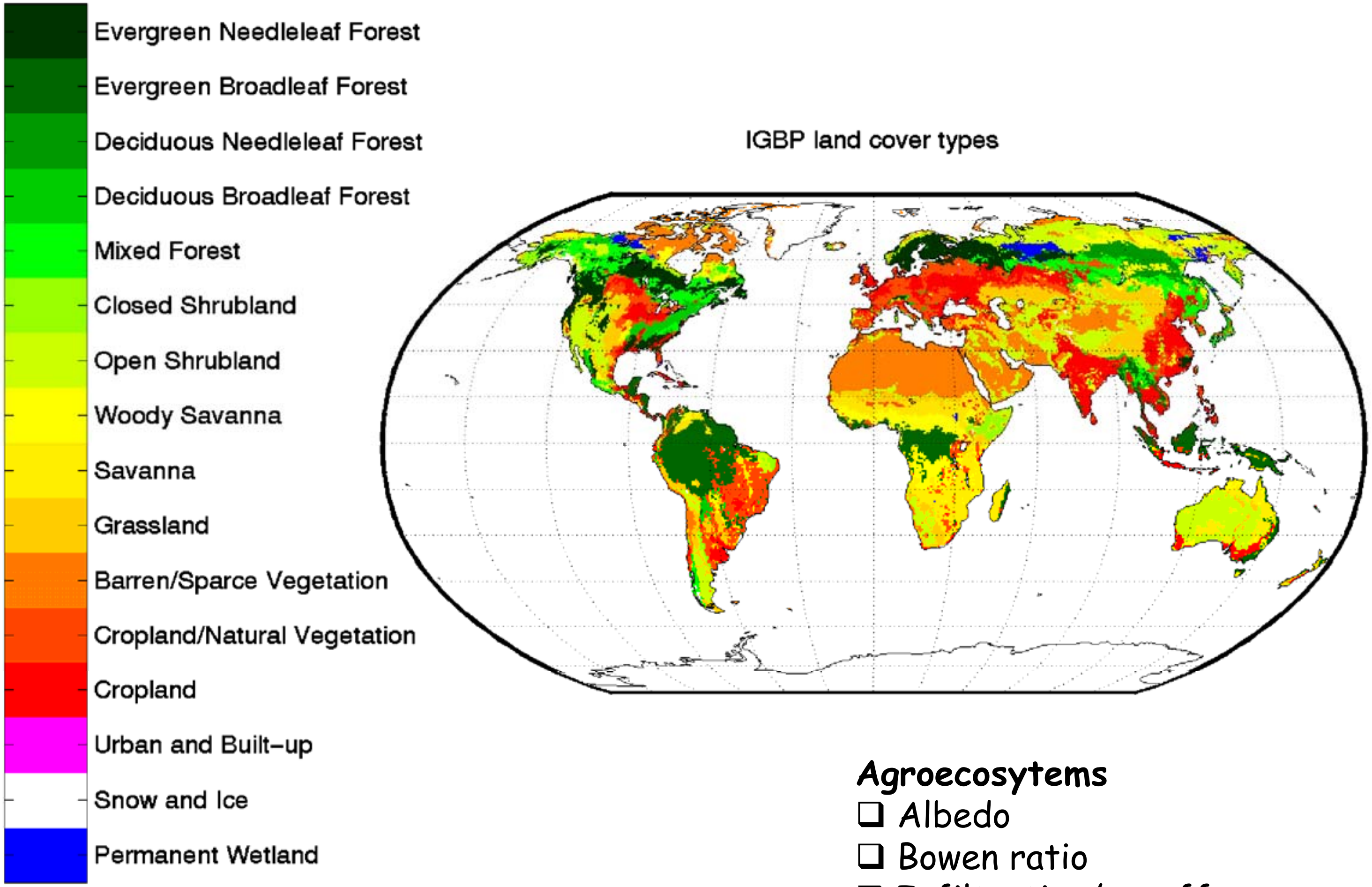
Friday Harbor Laboratories, San Juan Island, WA
13 September 2007

Anthropogenic land cover change



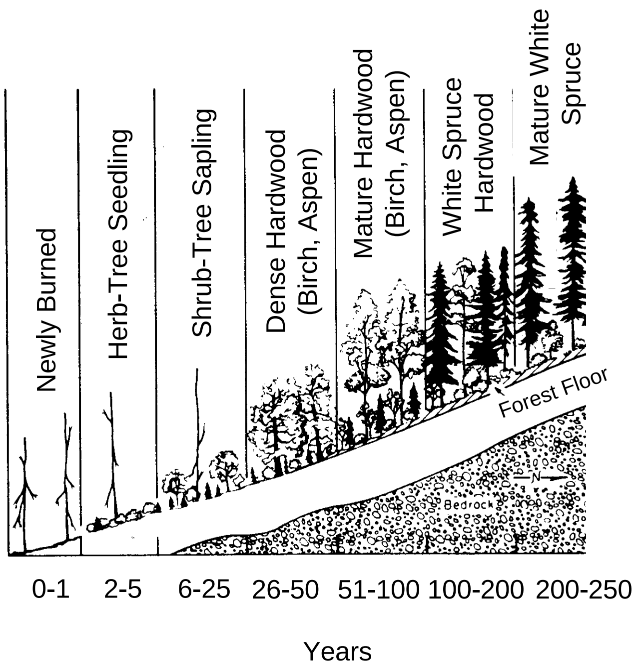
Land cover change occurs from human uses of land

Agroecosytems

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

Natural vegetation dynamics

Upland boreal forest succession, Fairbanks, Alaska



Van Cleve & Viereck (1981) in *Forest Succession: Concepts and Application*, West et al., Eds., 185-211

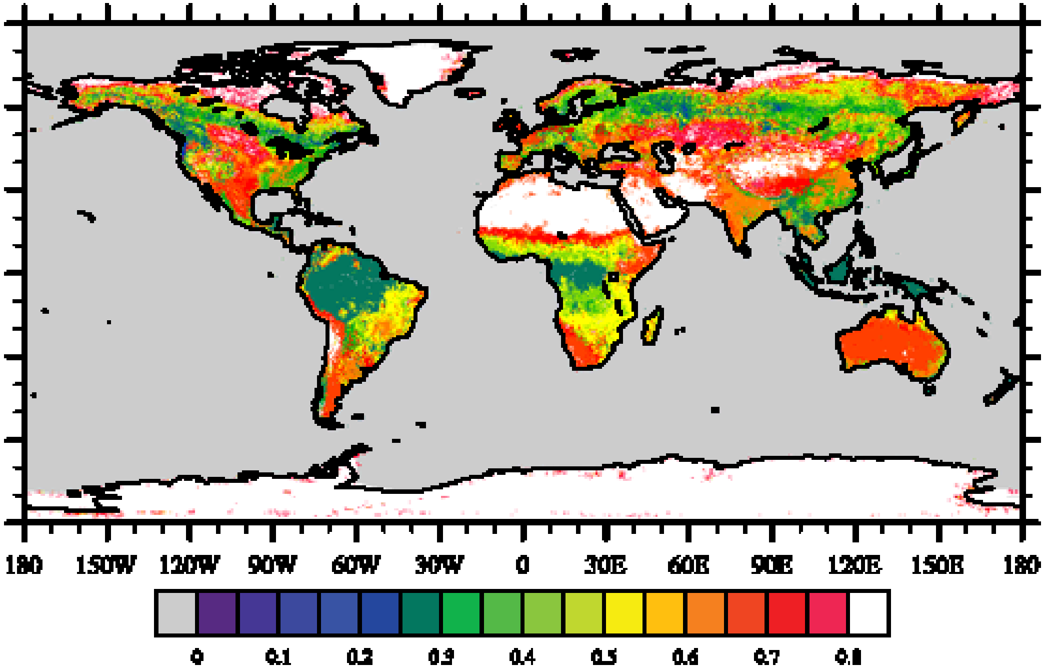
Land cover change occurs from natural ecological processes

Vegetation dynamics

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

Vegetation masking of snow albedo

Maximum satellite-derived surface albedo during winter



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

Colorado Rocky Mountains

Tree-covered land has a lower albedo during winter than other snow-covered land

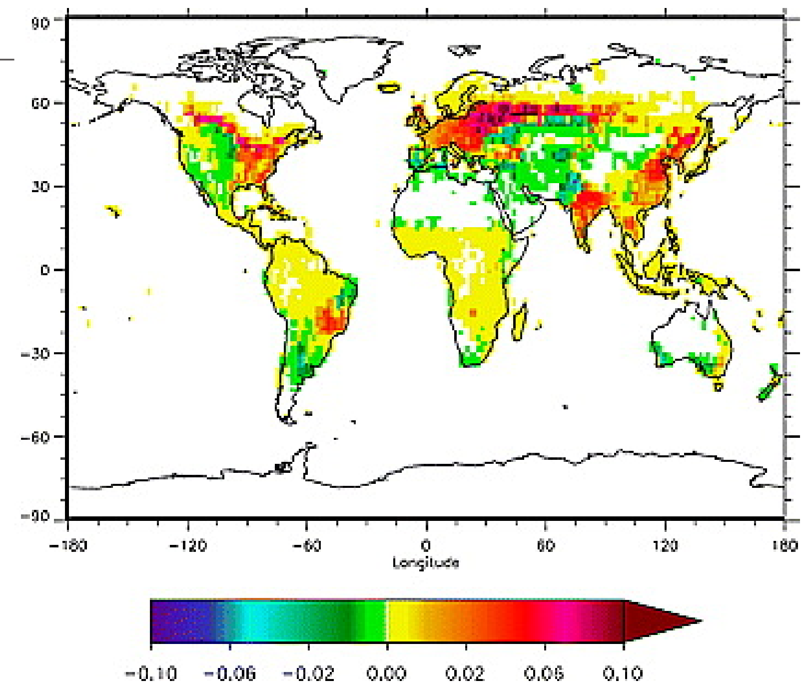
Cropland increases surface albedo

Table 1. Black-Sky Snow Free Surface Albedo Values for Various Land Cover Types According to the IGBP Vegetation Classes Given for 4 Months as 4 Years Mean[a]

Vegetation Type	February	May	August	November
Evergreen needleleaf (1)	0.096	0.090	0.096	0.092
Evergreen broadleaf in Amazonas (2)	0.122	0.119	0.124	0.127
Evergreen broadleaf excluding Amazonas (2)	0.121	0.116	0.118	0.127
Deciduous needleleaf (3)	0.103	0.095	0.110	0.103
Decidious broadleaf (4)	0.116	0.137	0.140	0.119
Mixed forest(5)	0.096	0.101	0.119	0.100
Open shrubland 35S–45N (7)	0.220	0.219	0.209	0.217
Open shrubland Australia (7)	0.177	0.177	0.177	0.173
Open shrubland other (7)	0.137	0.126	0.141	0.129
Woody savanna (8)	0.106	0.117	0.110	0.112
Savanna (9)	0.140	0.141	0.142	0.133
Grassland (10)	0.185	0.165	0.165	0.178
Cropland Eurasia (12)	0.144	0.140	0.150	0.139
Cropland East Asia, India (12)	0.162	0.161	0.151	0.156
Cropland other (12)	0.162	0.151	0.165	0.159
Barren in Sahara and the Arabian desert (16)	0.365	0.356	0.353	0.365
Barren in Asia (16)	0.222	0.229	0.232	0.228
Barren excluding Sahara, the Arabian desert and Asia (16)	0.208	0.215	0.175	0.215

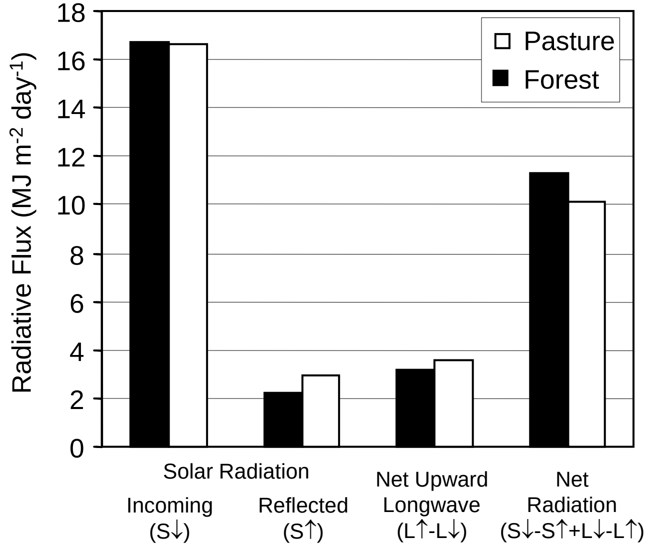
[a]Data in the analysis are based on high quality and snow free quality assurance flag.

Annual mean surface albedo change caused by anthropogenic vegetation changes

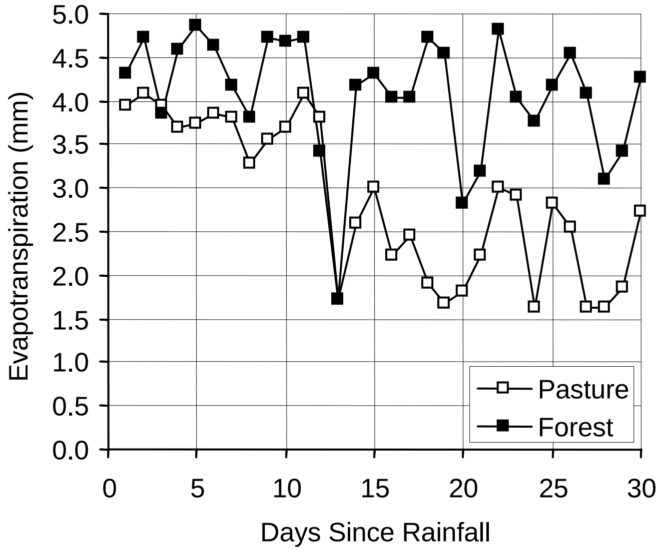


Myhre et al. (2005) GRL, 32, L21410, doi:10.1029/2005GL024004

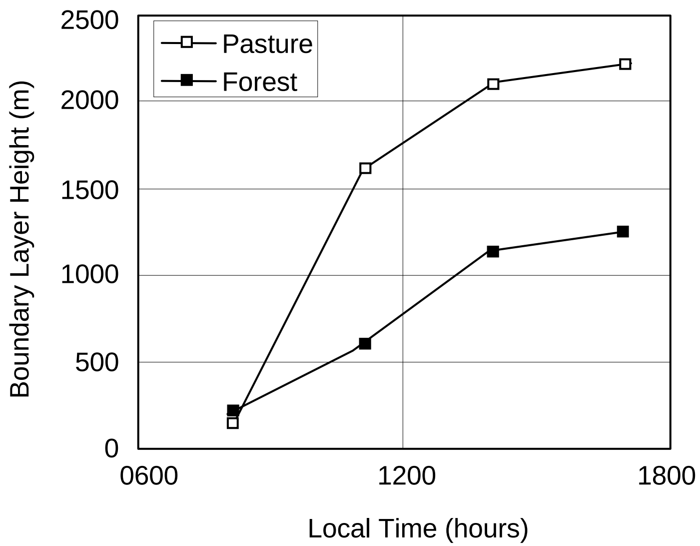
Surface energy fluxes



Culf et al. (1996) in *Amazonian Deforestation and Climate*, Gash et al., Eds., 175-191



Wright et al. (1992) QJRMS 118:1083-1099

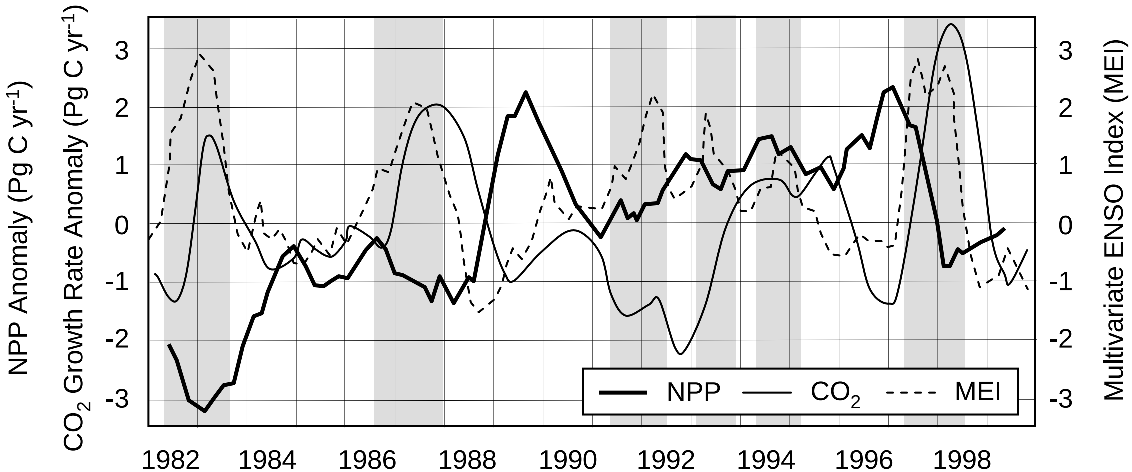


Gash & Nobre (1997) BAMS 78:823-830

Observations taken in nearby forest and pasture sites in Amazonia during the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS)

Observations taken during the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) show similar results

Atmospheric CO_2 and ENSO



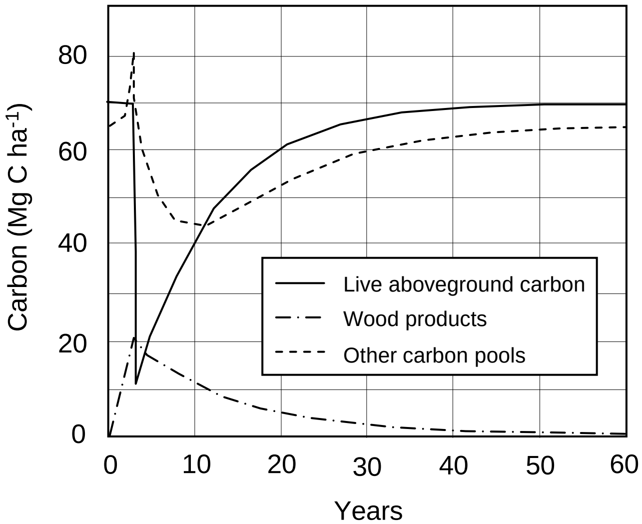
Global net primary production (NPP) and CO_2 growth rate during the period 1982-1999 in relation to the multivariate ENSO index (MEI). High MEI indicates the warm phase of ENSO. Highlighted in grey are El Niños of 1982-83, 1986-87, 1991-92, 1993, 1994-95, and 1997-98.

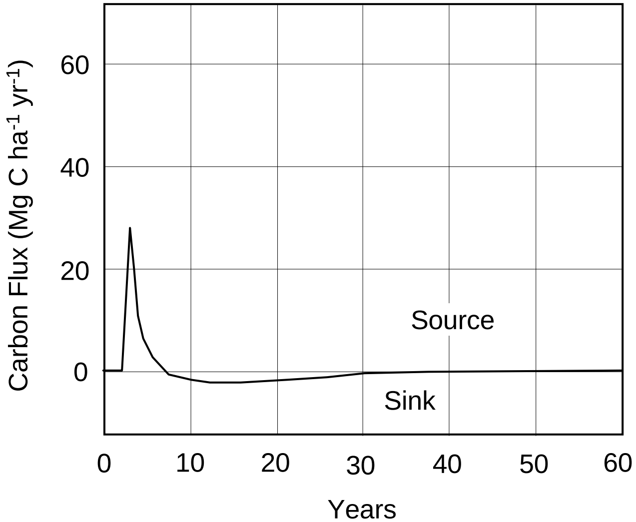
Global NPP on land decreased during El Niño events with corresponding increases in atmospheric CO_2 growth rate.

The period 1991-1993, following the eruption of Mount Pinatubo, is an exception to the general relationship between ENSO and NPP.

Hashimoto et al. (2004) JGR, 109, D23110, doi:10.1029/2004JD004959

Deforestation is a carbon source

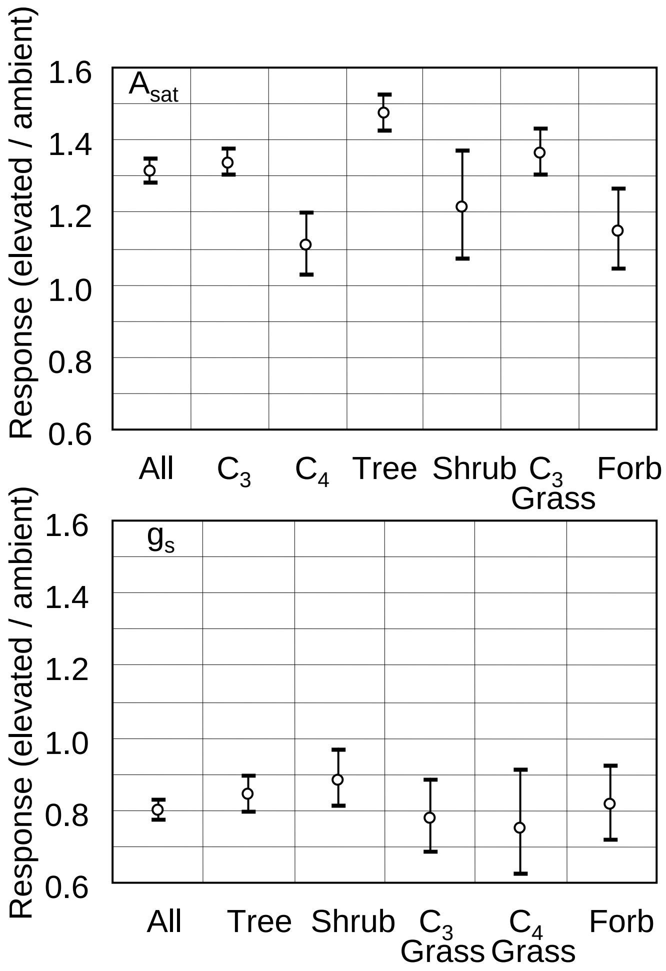




Idealized changes in ecosystem carbon pools (top) and resulting carbon flux (bottom) due to harvest and regrowth in a temperate forest. 10 Mg ha^{-1} = 1 kg m^{-2}

Houghton (2005) Global Change Biology 11:945-958

CO_2 fertilization and stomatal conductance



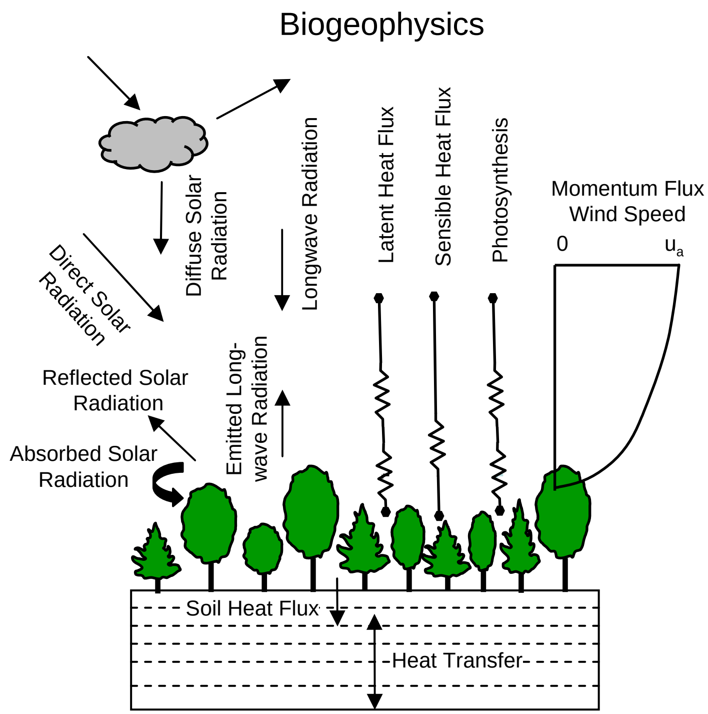
Synthesis results from 12 FACE studies in forest, grassland, desert, and agricultural ecosystems exposed to CO_2 concentrations of 475-600 ppm. Data are the mean response (circles) and 95% confidence intervals (bars) for all species and by plant functional type for light-saturated leaf photosynthetic rate (A_{sat}) and stomatal conductance (g_s).

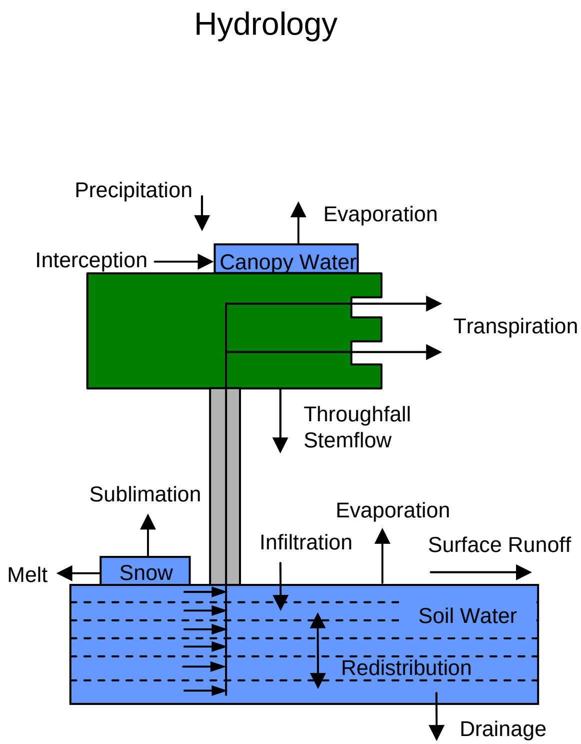
Photosynthesis increases and stomatal conductance decreases with higher atmospheric CO_2.

Ainsworth & Long (2005) New Phytologist 165:351-372

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

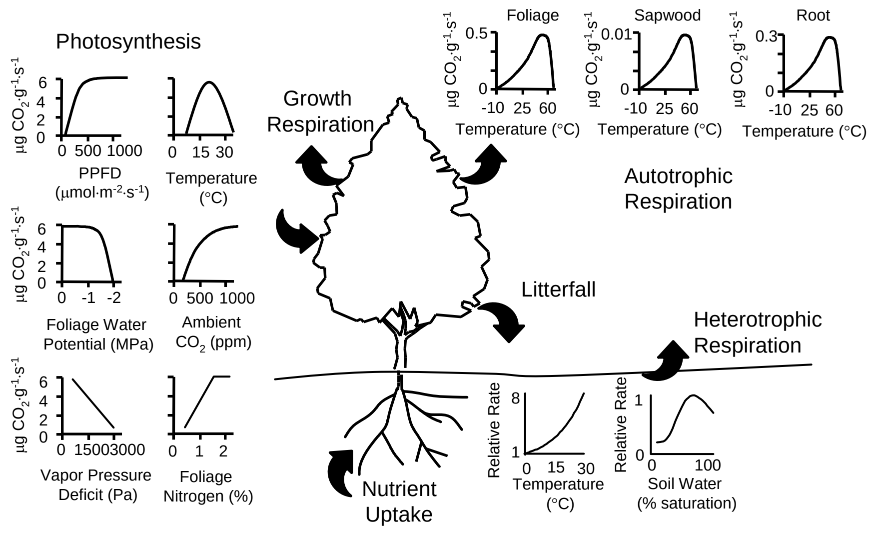
Hydrologic cycle: interception of water by leaves; infiltration and runoff; snow accumulation and melt; multi-layer soil water; partitioning of latent heat into evaporation of intercepted water, soil evaporation, and transpiration

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

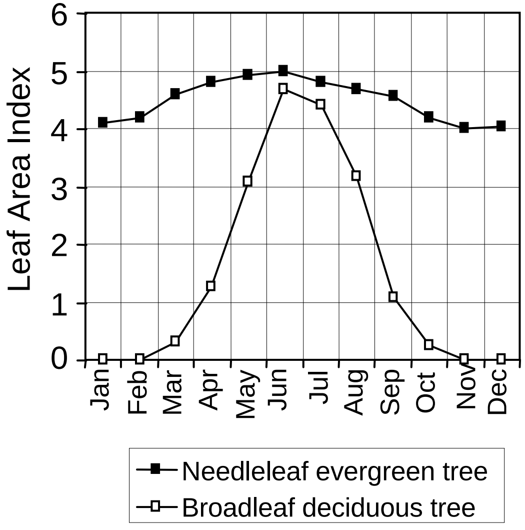
Community Land Model

Carbon cycle and dynamic vegetation

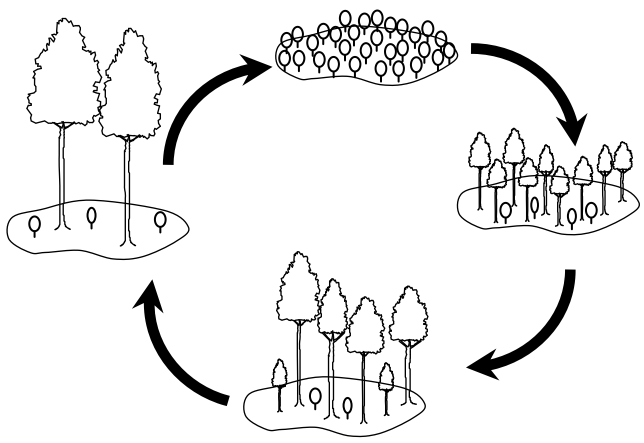
Ecosystem carbon balance



Leaf phenology



Vegetation dynamics



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

Tropical deforestation

July 28, 2000

(NASA/GSFC/LaRC/JPL)

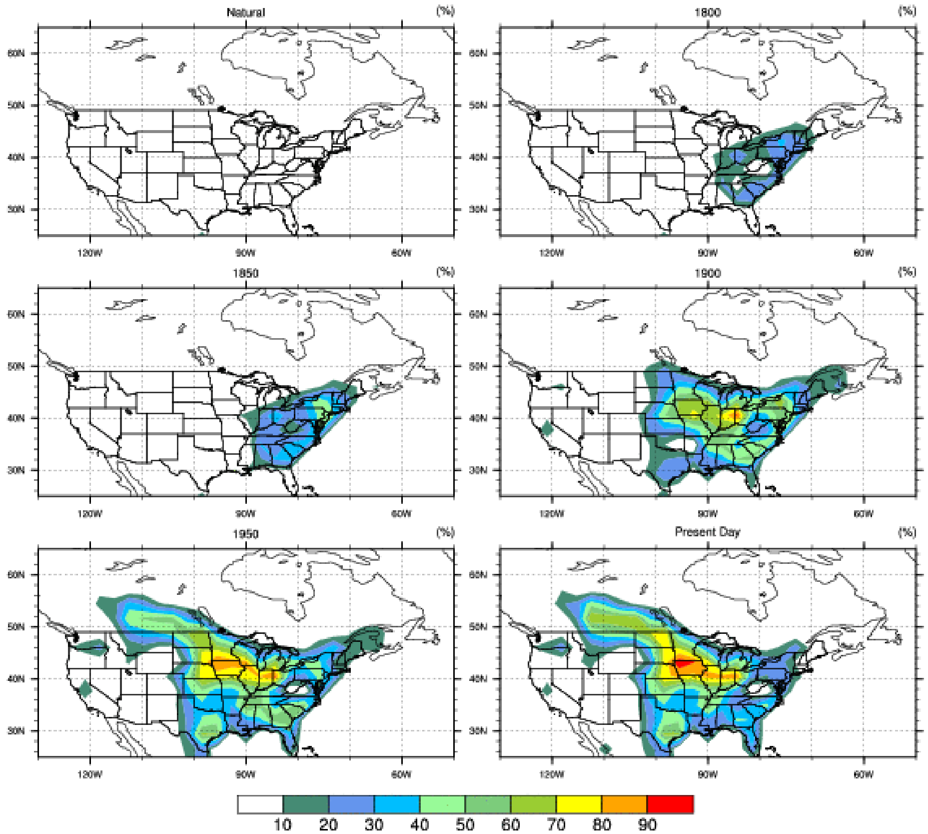
Settlement and deforestation surrounding Rio Branco, Brazil (10°S, 68°W) in the Brazilian state of Acre, near the border with Bolivia. The large image covers an area of 333 km x 333 km.

Numerous climate model studies find a warmer, drier tropical climate following deforestation

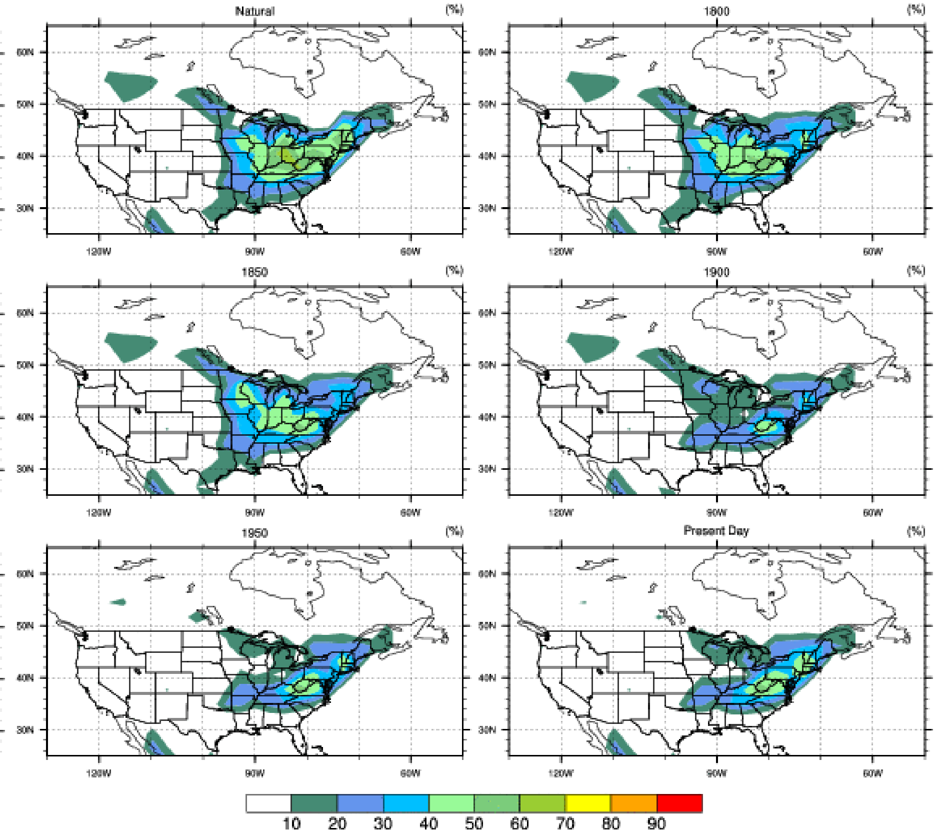
(National Geographic Society)

U.S. deforestation

Cropland (percent of grid cell)



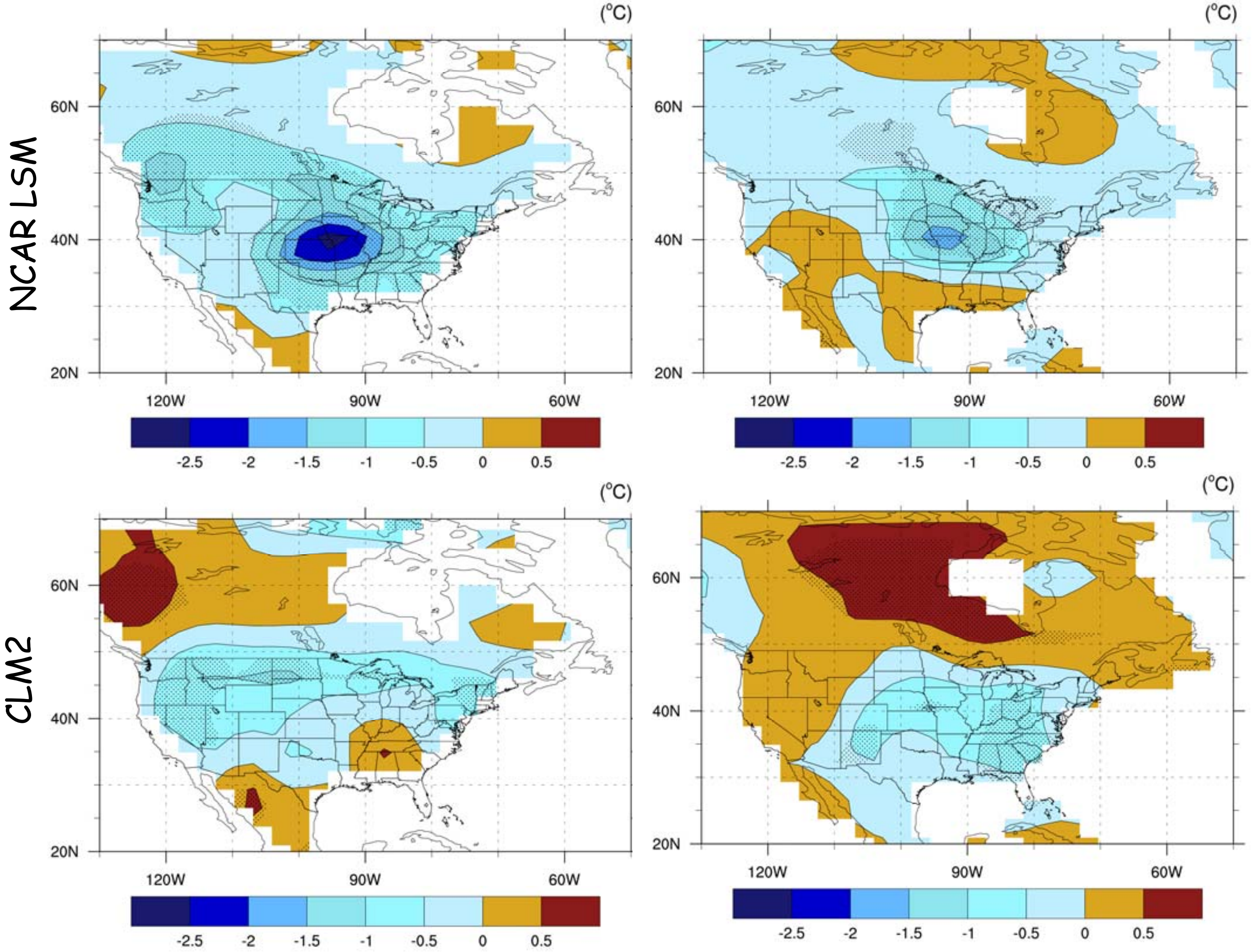
Broadleaf deciduous tree (percent of grid cell)



U.S. deforestation

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

LSM Biome Dataset | PFT Dataset



Four paired climate simulations with CAM2 using two land surface models

- NCAR LSM
- CLM2

and two surface datasets

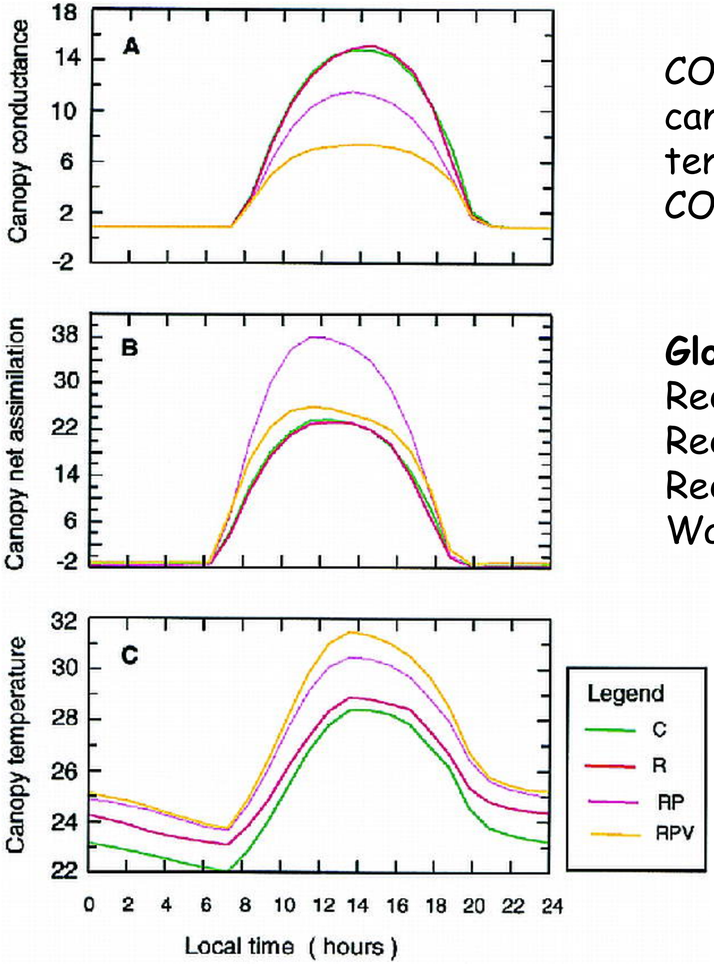
- Biome dataset without subgrid heterogeneity
- Dataset of plant functional types with subgrid heterogeneity

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

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

CO_2 fertilization and stomatal conductance

Amazonian evergreen forest,
diurnal cycle January

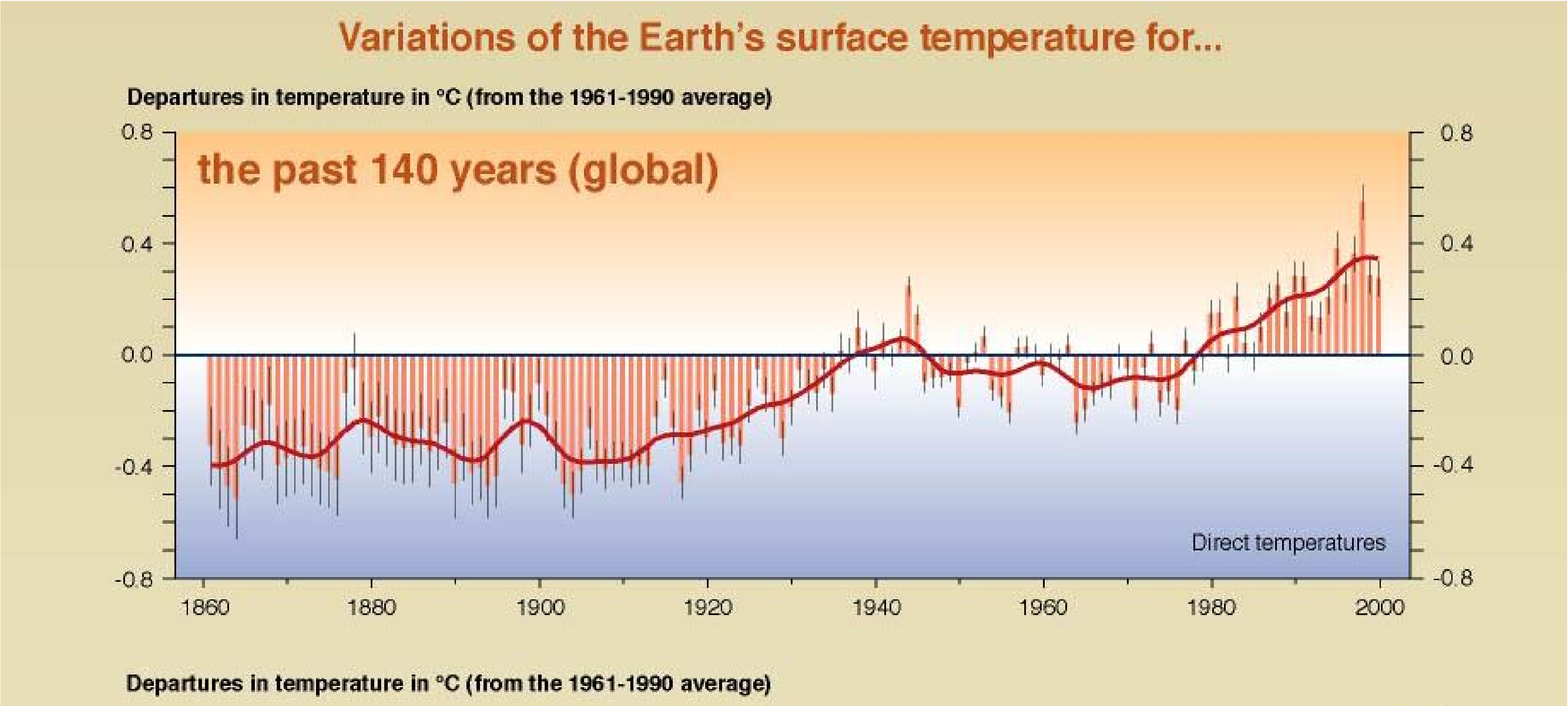


CO_2 fertilization (RP, RPV) reduces canopy conductance and increases temperature compared with radiative CO_2 (R)

Global climate:
Reduced conductance
Reduced evaporation
Reduced precipitation
Warmer temperature

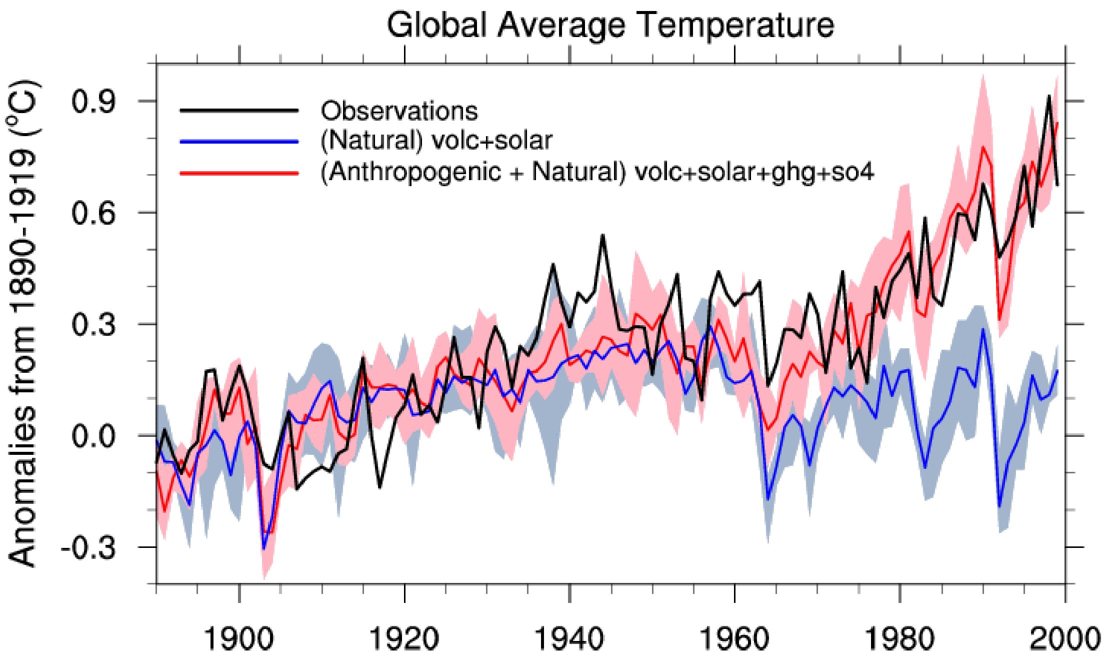
Bounoua et al. (1999) J Climate 12:309-324

Climate of the 20th century



What are the causes of this observed climate change?

20th century climate forcings

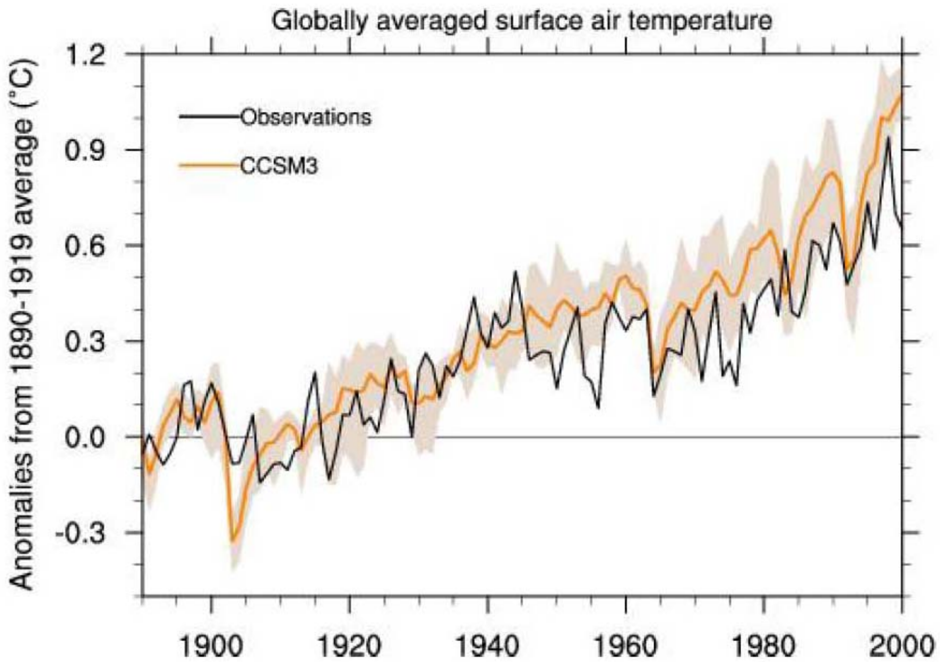


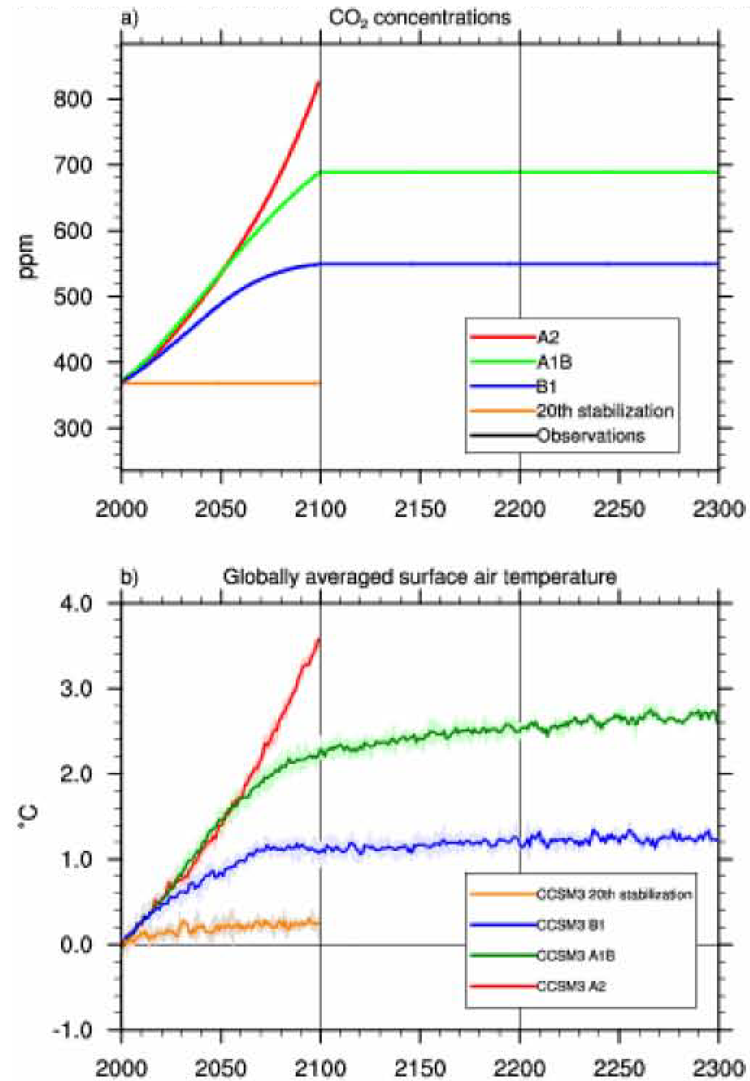
The combination of natural and anthropogenic forcings can match the observed temperature record

What is the vegetation forcing of climate over this period?

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

Climate of the 21st century





Climate forcings

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

What is the vegetation forcing of climate?

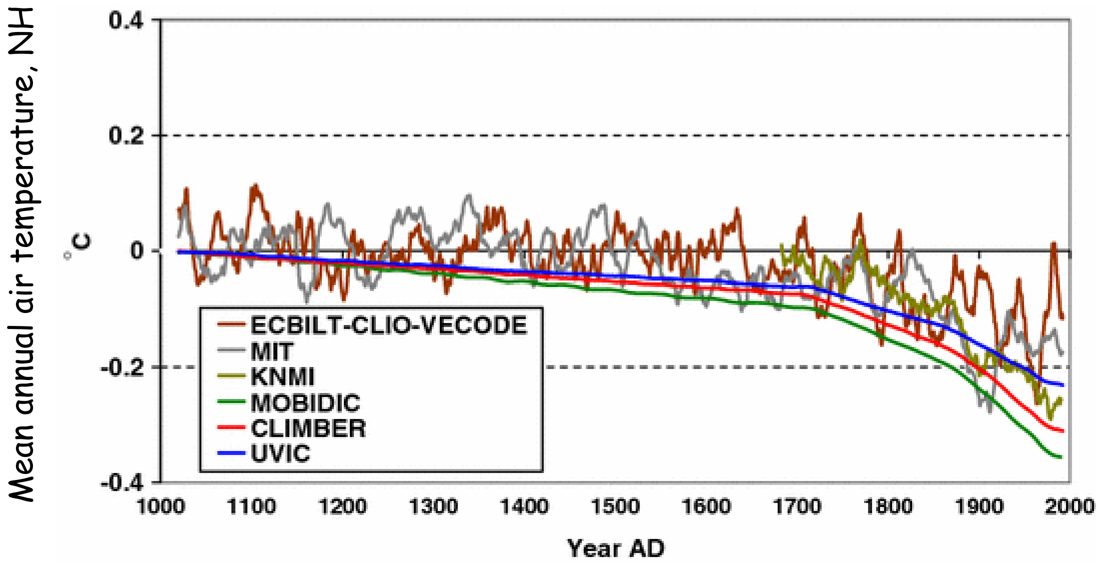
Meehl et al. (2006) J Climate 19:2597-2616

Historical land use forcing of climate

Many studies have examined the global climate forcing due to historical changes in land cover. The emerging consensus is that land cover change in middle latitudes has cooled the Northern Hemisphere (primarily because of higher surface albedo)

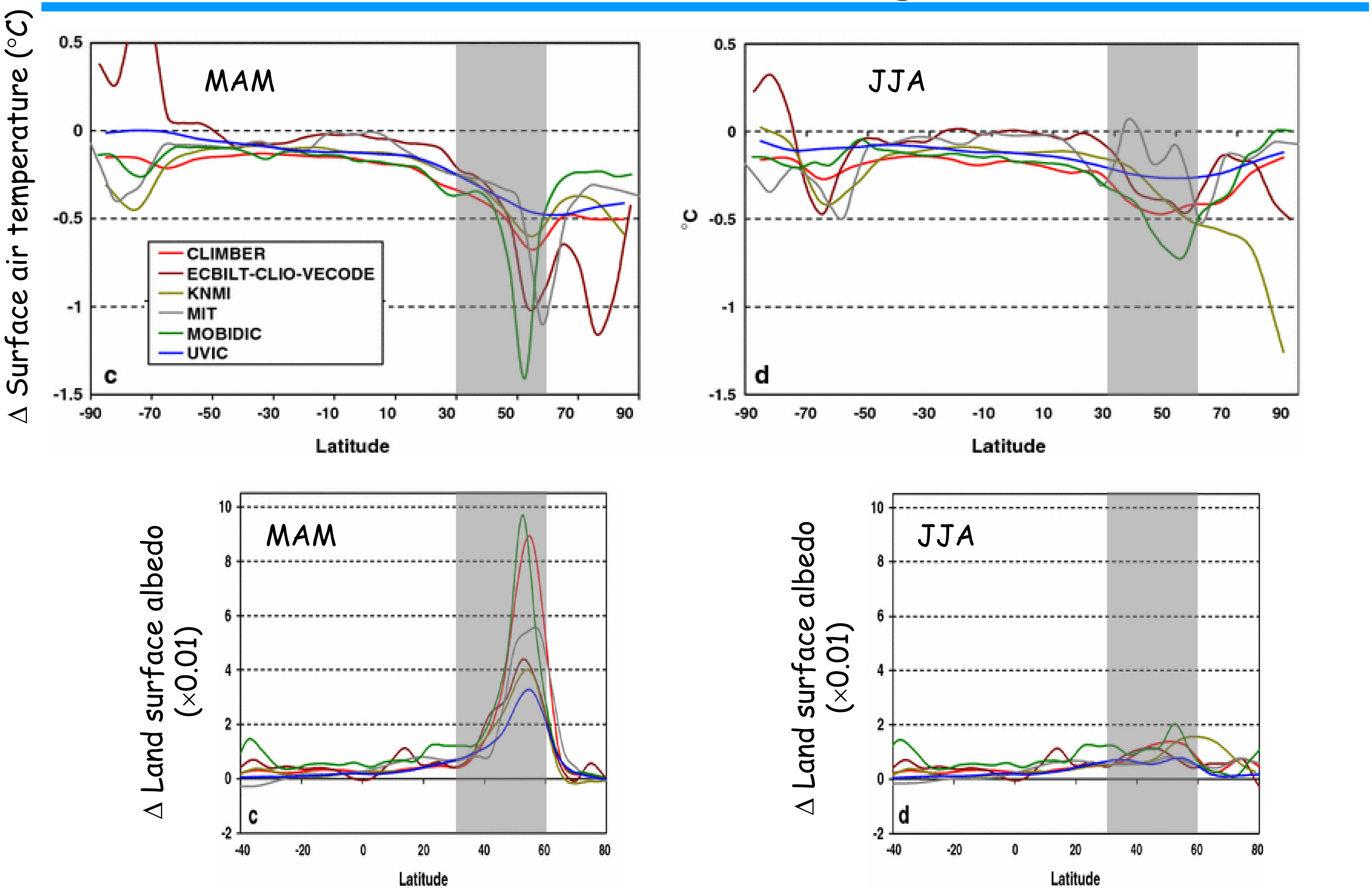
Comparison of 6 earth system models of intermediate complexity forced with historical land cover change, 1000-1992…

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



Brovkin et al. (2006) Climate Dynamics 26:587-600

Historical land use forcing of climate



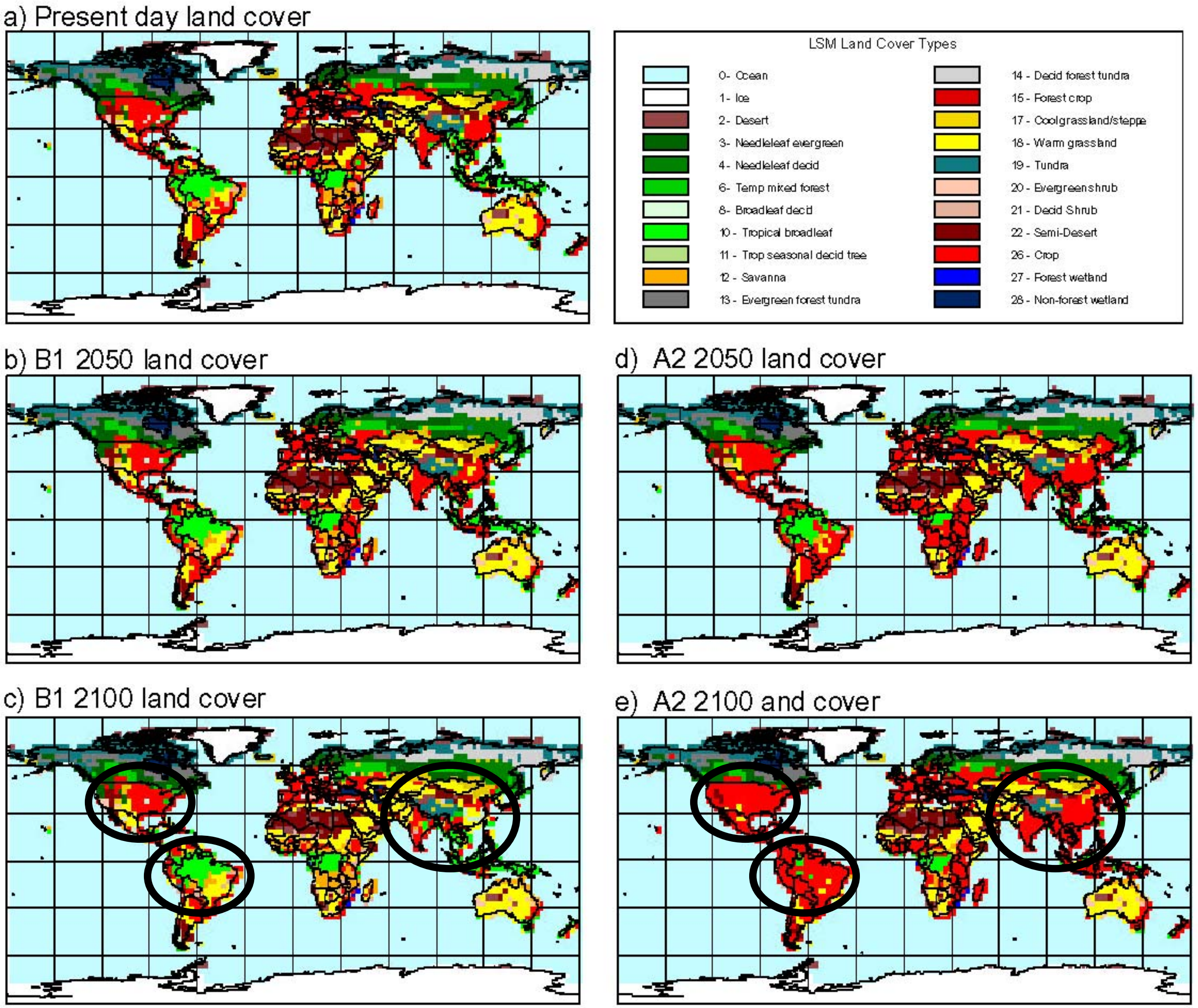
Loss of snow-masking by forests

Higher albedo of crop

Brovkin et al. (2006) Climate Dynamics 26:587-600

Future land cover change as a climate forcing

Future IPCC SRES Land Cover Scenarios for NCAR LSM/PCM



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

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

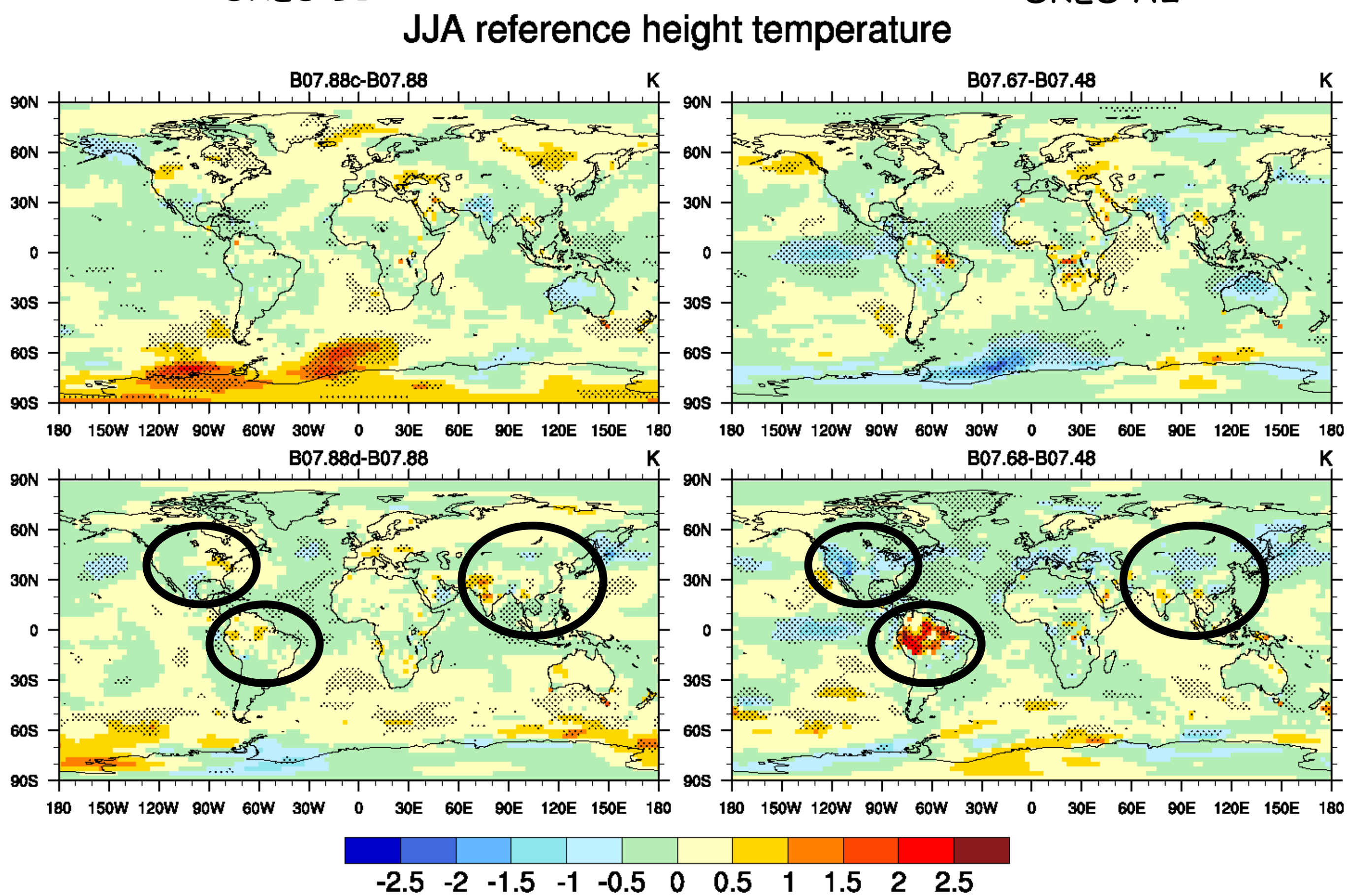
Feddema et al. (2005) Science 310:1674-1678

Future land cover change as a climate forcing

SRES B1 | SRES A2

2050

2100



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

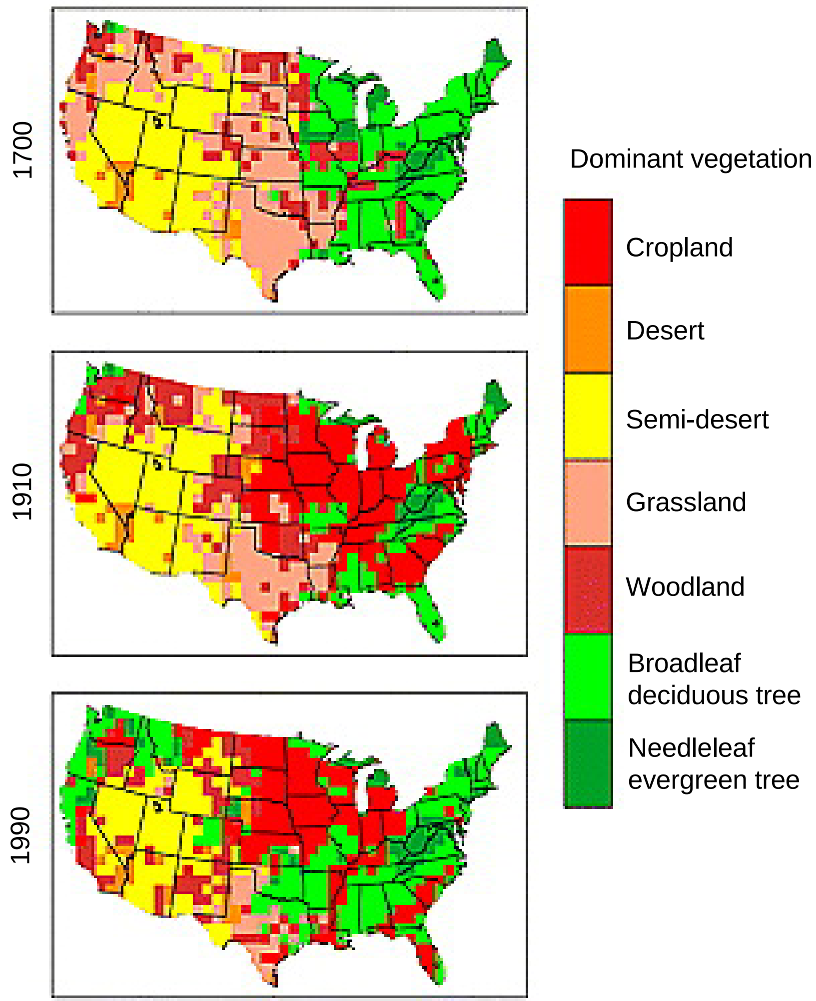
PCM/NCAR LSM transient climate simulations with changing land cover. Figures show the effect of land cover on temperature

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

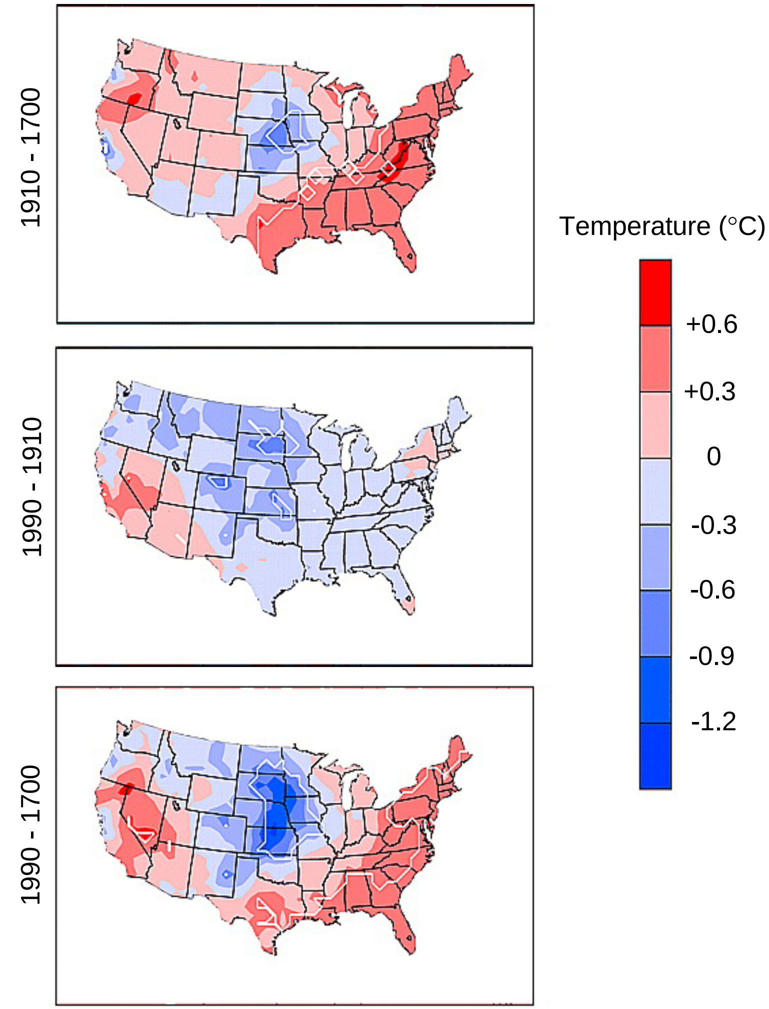
Feddema et al. (2005) Science 310:1674-1678

U.S. deforestation warms climate

Land cover RAMS with LEAF-2



July temperature difference

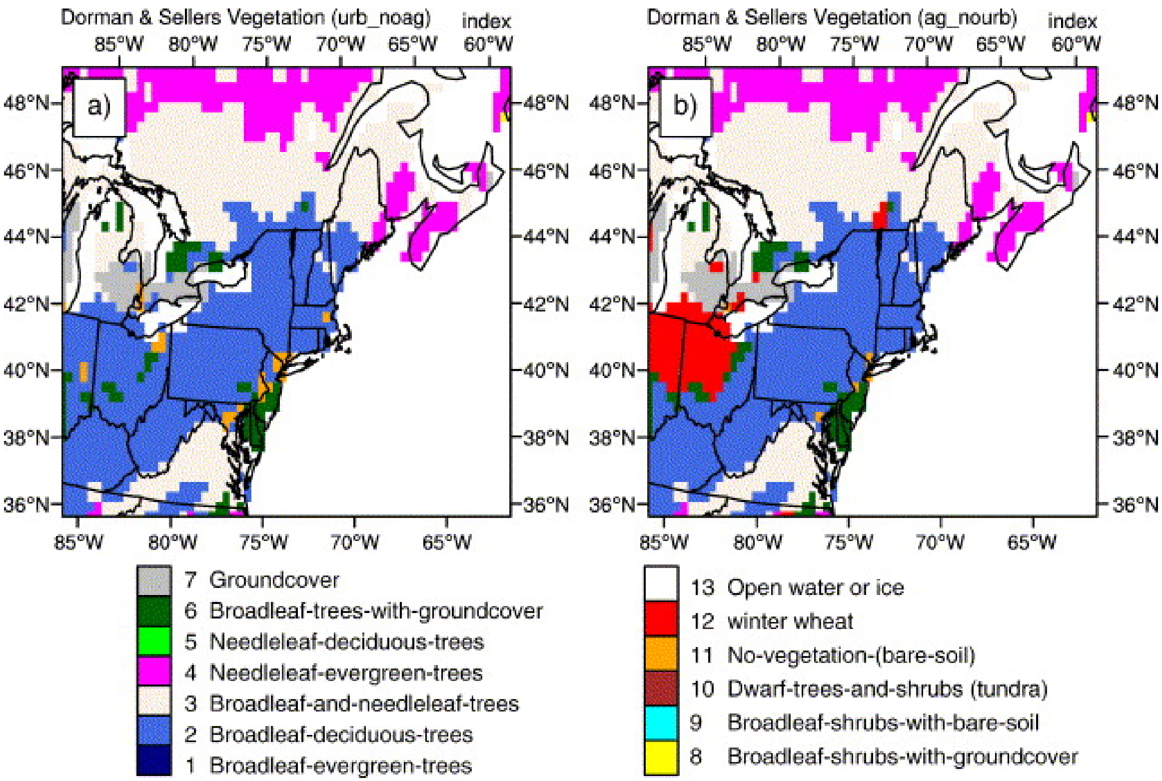


1700 → 1910: Forest → cropland in east
Grass → cropland in central US
1910 → 1990: Reforestation in east
Greater cropland in central US

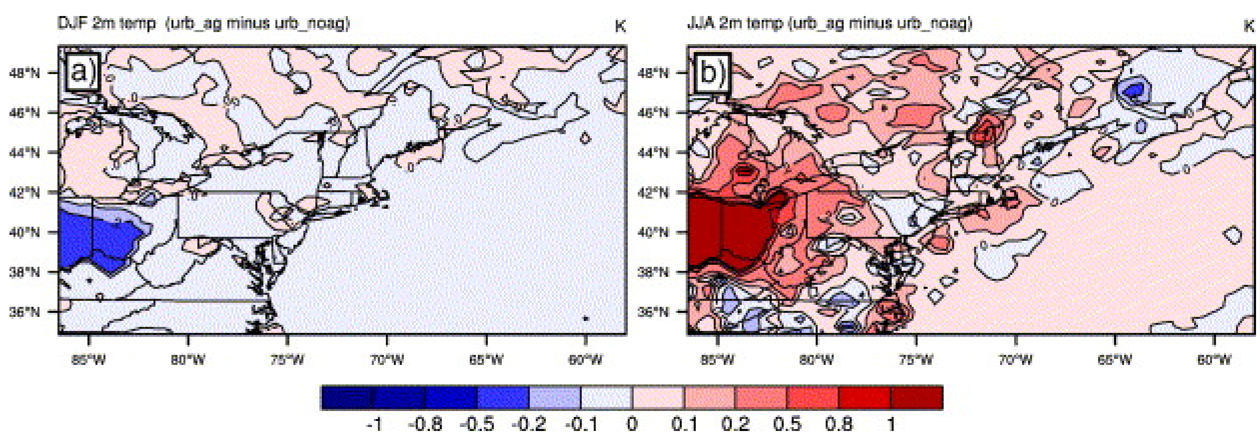
Grass → crop: Increased ET
Forest → crop: Increased albedo, reduced z0, reduced ET (rooting depth)

Baidya Roy et al. (2003) JGR, 108D, 4793, doi:10.1029/2003JD003565

Winter wheat warms temperature

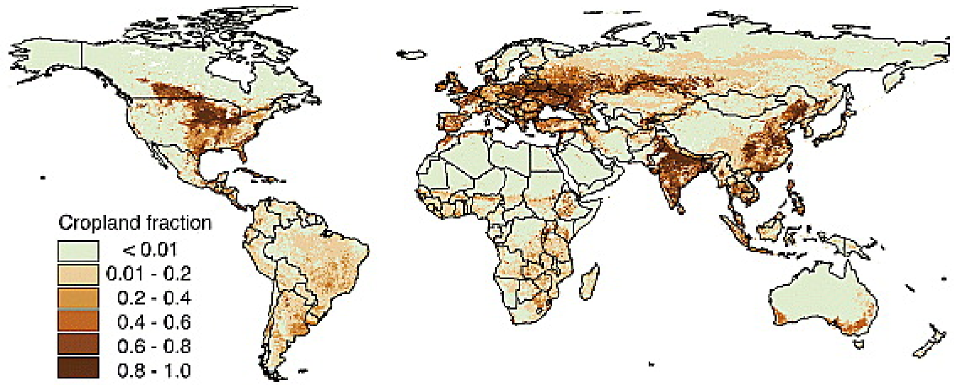


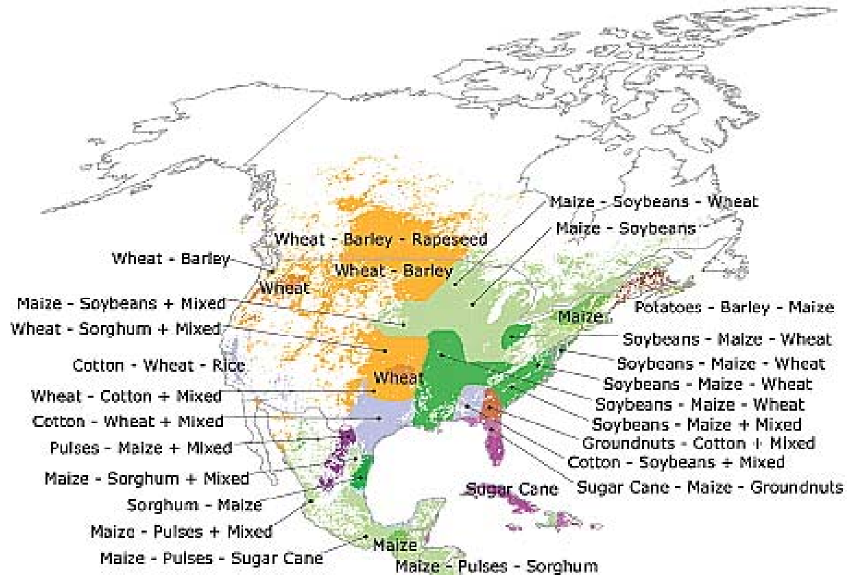
MM5 with LSX

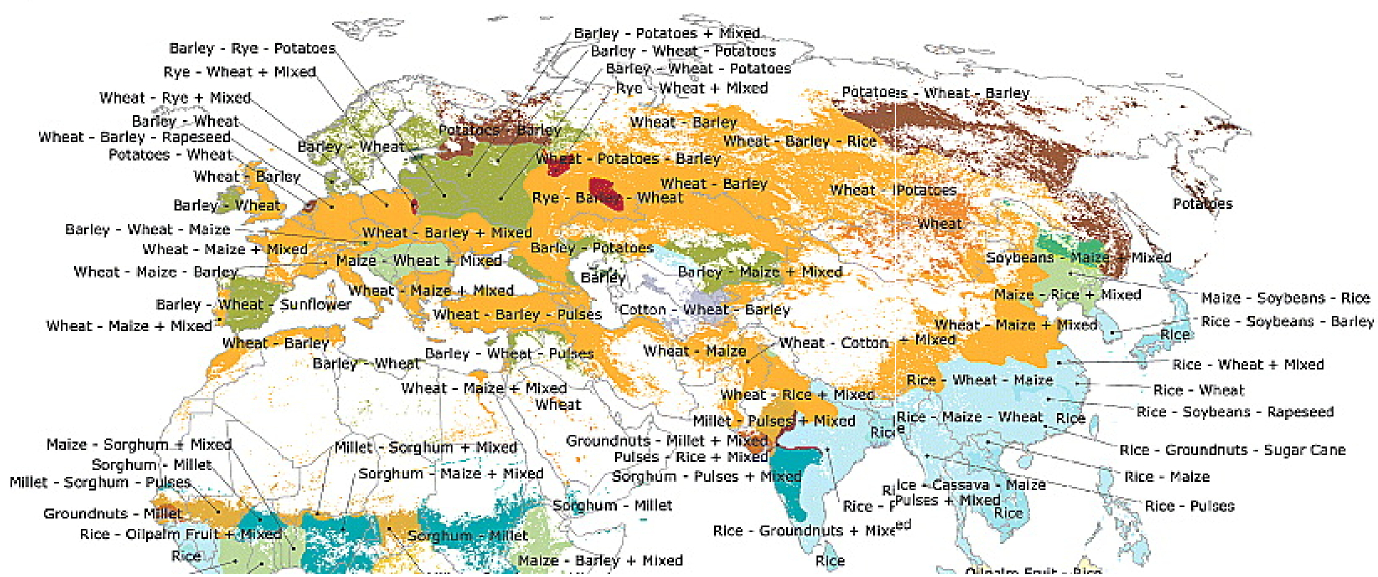


Lamptey et al. (2005) Global and Planetary Change 49:203-221

A broad diversity of crops worldwide







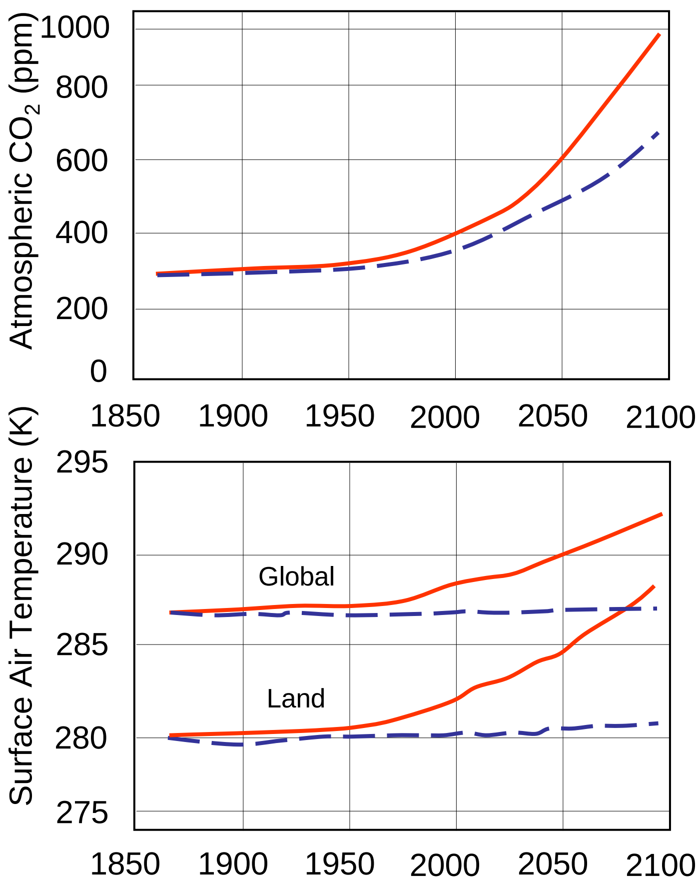
Leff et al. (2004) *GBC*, 18, GB1009, doi:10.1029/2003GB002108

Carbon cycle feedback

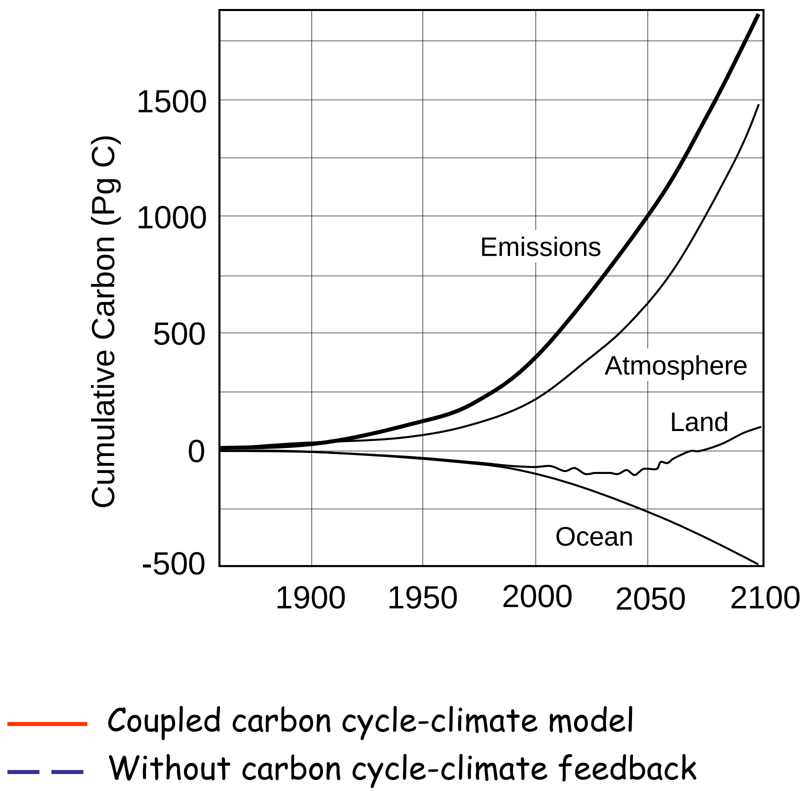
Transient simulations 1860-2100 with a carbon cycle, forced with anthropogenic CO_2 emissions
Two simulations to isolate the carbon cycle feedback:

- Coupled carbon cycle-climate simulation (with carbon cycle-climate feedback)
- Carbon cycle-climate simulation but no effect of CO_2 on climate (no carbon cycle-climate feedback)

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

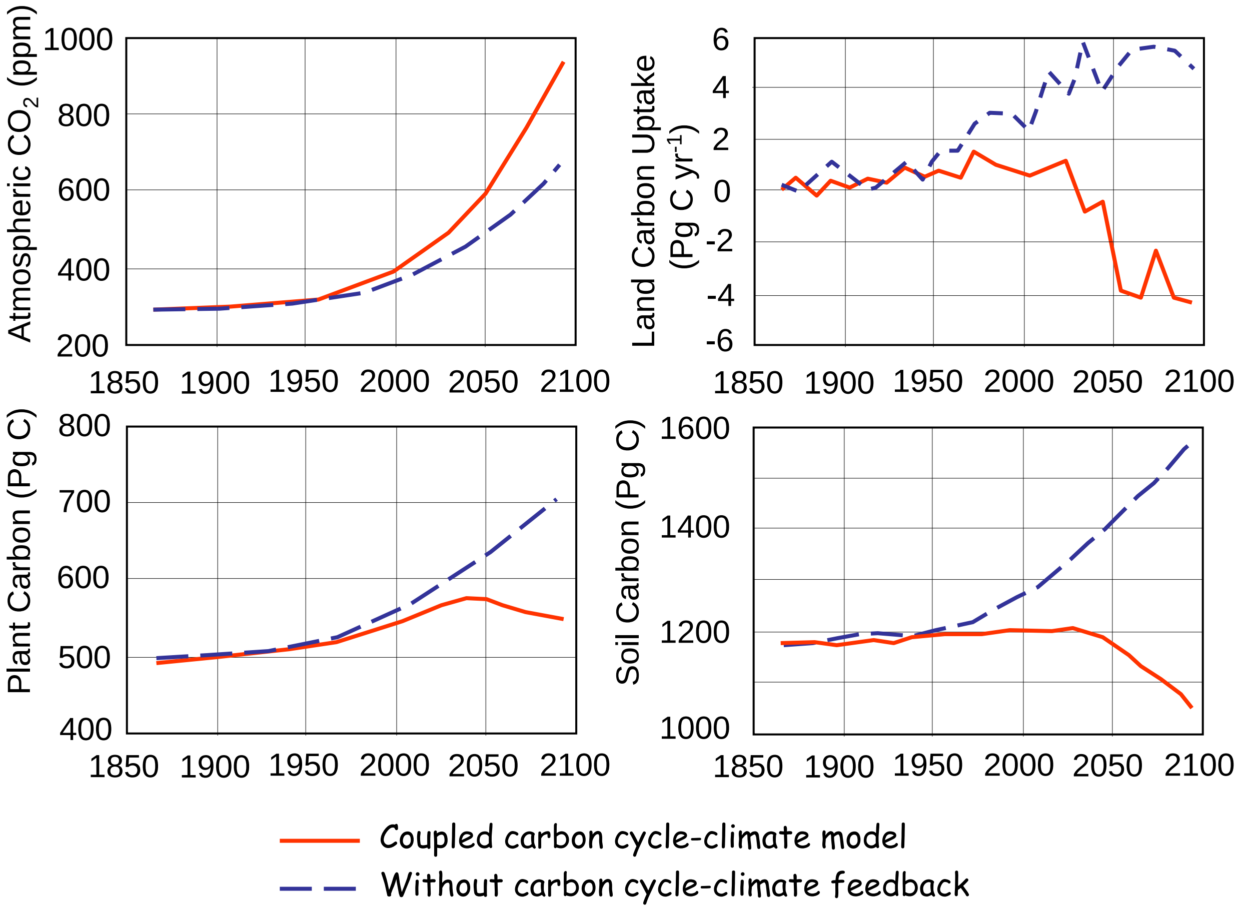


Carbon budgets for the fully coupled simulation



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

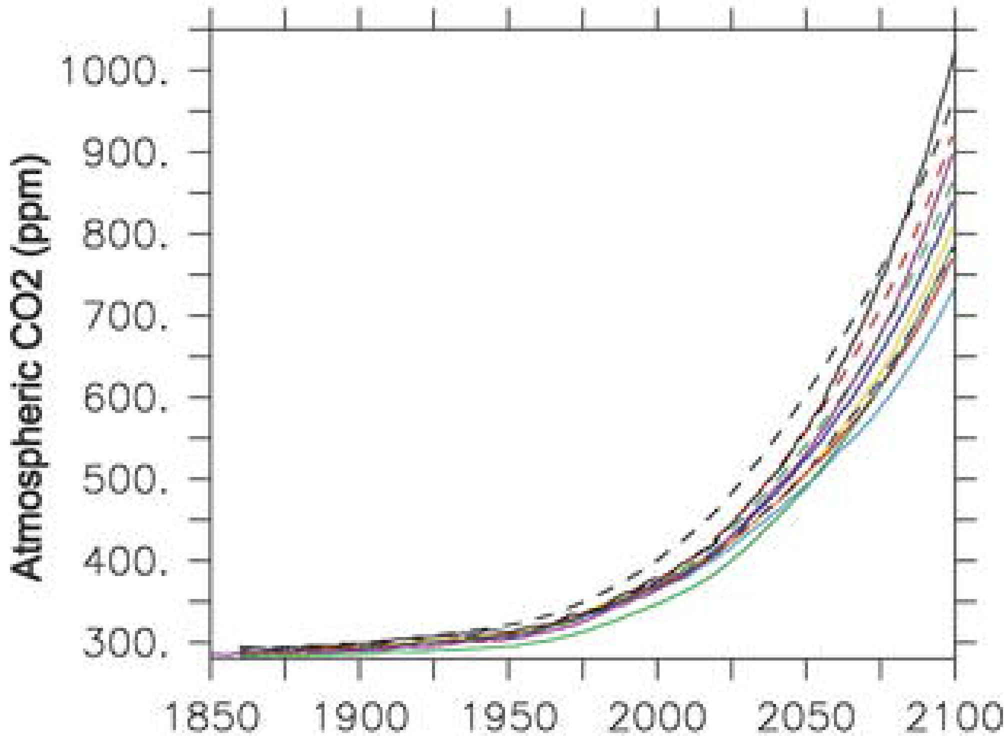
Carbon cycle feedback



Without climate change (i.e., without carbon cycle-climate feedback), CO_2 fertilization of plant growth increases carbon uptake by the terrestrial biosphere throughout the 20th and 21st centuries. In the fully coupled model, climate change decreases the terrestrial carbon sink, and the biosphere becomes a source of carbon by the middle of the 21st century.

Cox et al. (2004) Theoretical Applied Climatol. 78:137-156

C4MIP – Climate and carbon cycle



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

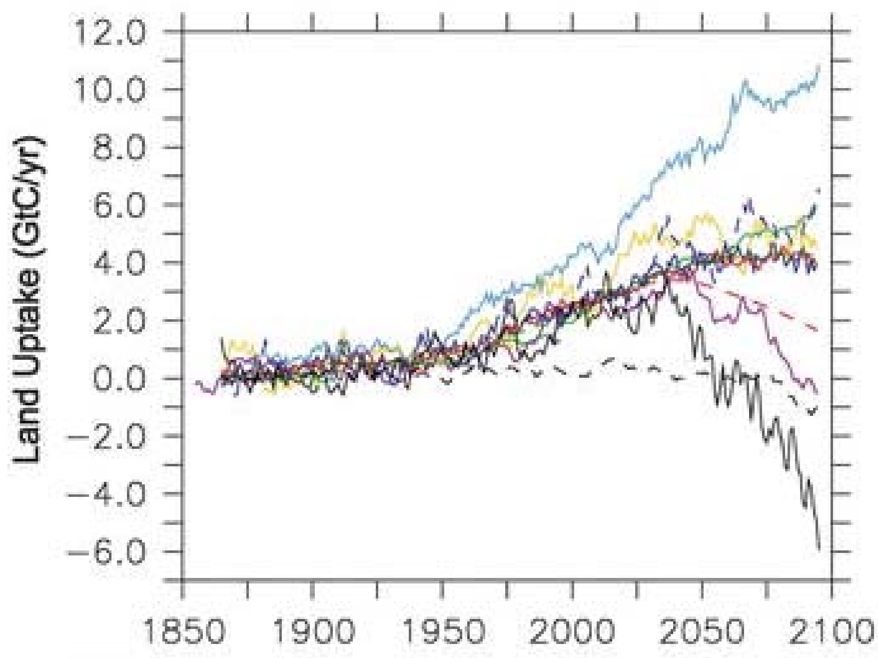
Transient climate simulations through 2100 forced with historical fossil fuel emissions and IPCC SRES A2 emissions

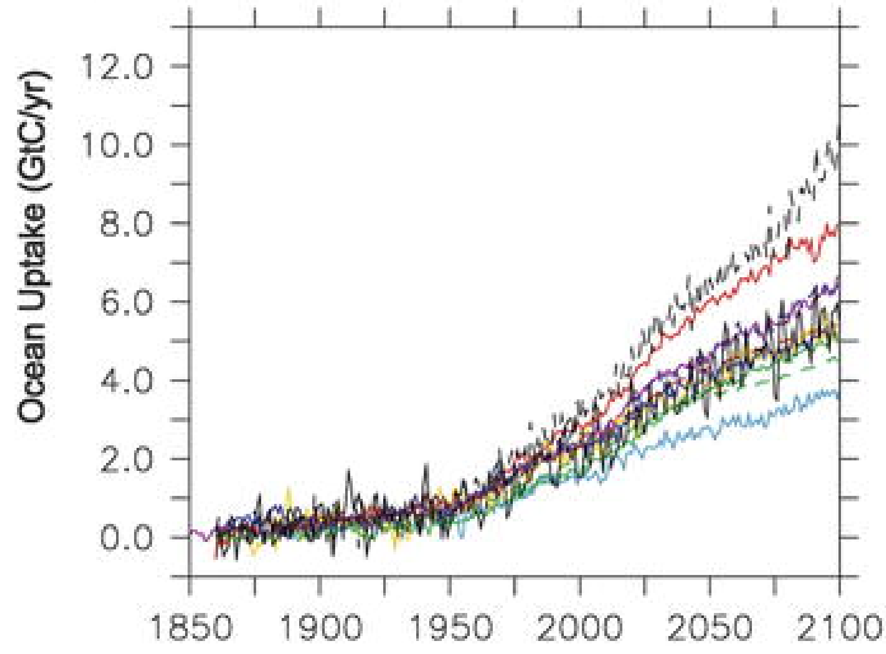
Vegetation forcings of climate
- Direct biogeochemical effect (atmos. CO_2)
- Indirect biogeophysical effect (stomata, leaf area, biogeography)

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 Pg C/yr source of carbon from land
- 1 model simulates a 11 Pg C/yr terrestrial carbon sink
- majority of models simulate a modest carbon sink

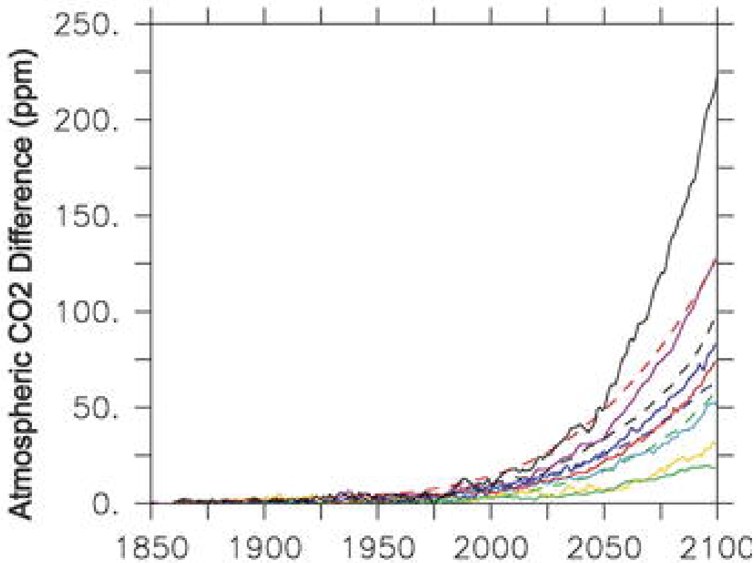
Relatively less uncertainty in ocean fluxes

All models simulate carbon uptake ranging from 4-10 Pg 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

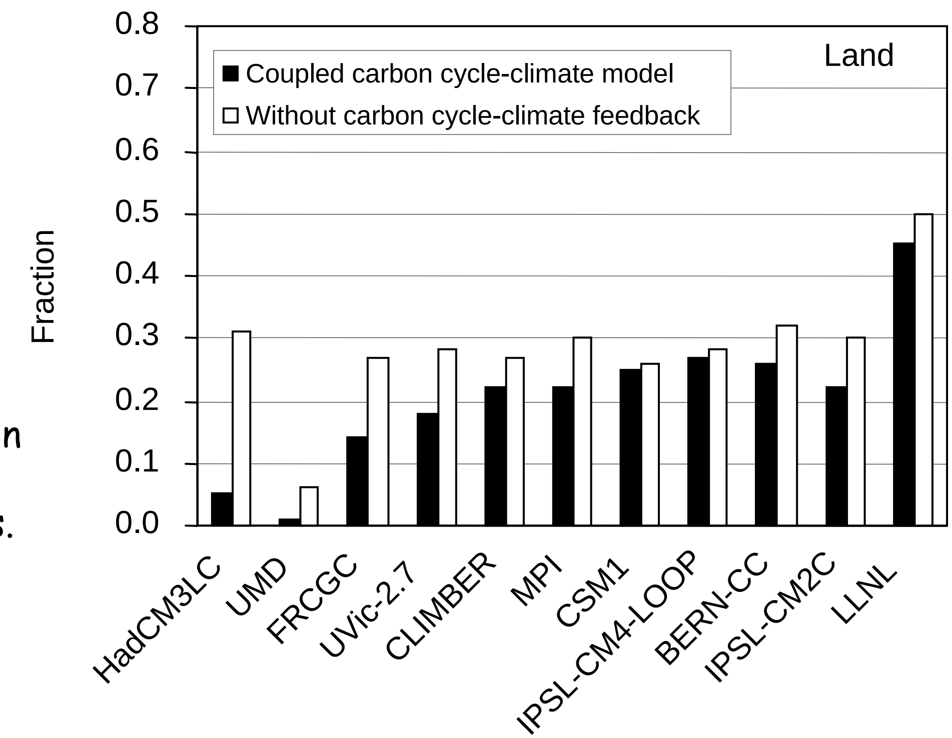


Climate-carbon cycle feedback

- All models have a positive climate-carbon cycle feedback
- The difference between fully coupled carbon cycle climate simulations and uncoupled simulations (CO_2 has no radiative effect) ranges from 20 ppm to 200 ppm

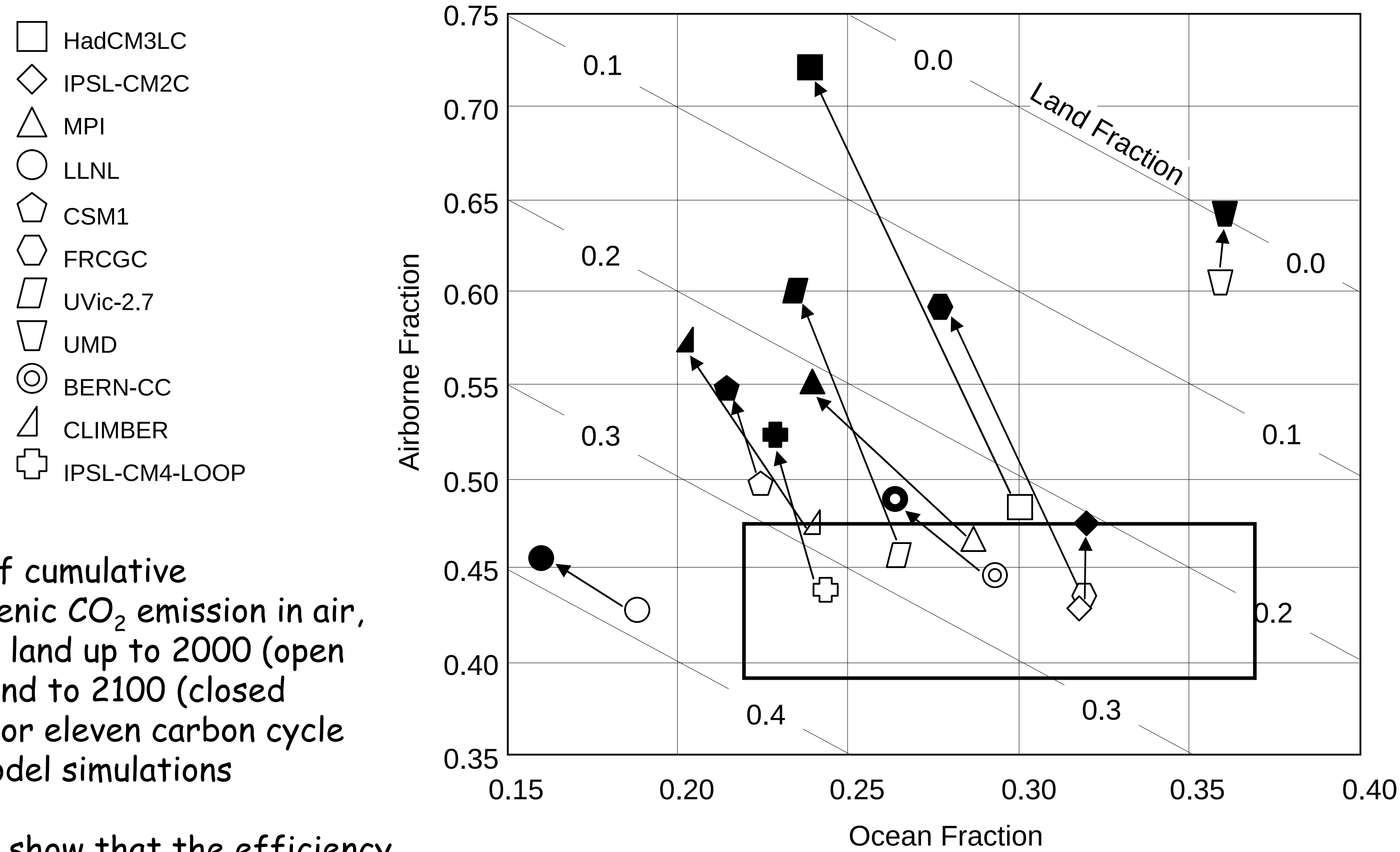
Distribution at 2100 of cumulative anthropogenic carbon emissions

The amount of carbon stored in the atmosphere increases in each model compared with the comparable simulation without climate-carbon cycle feedback, while the land carbon storage decreases.



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

C4MIP – Climate and carbon cycle



Fraction of cumulative anthropogenic CO_2 emission in air, ocean, and land up to 2000 (open symbols) and to 2100 (closed symbols) for eleven carbon cycle climate model simulations

All models show that the efficiency of the carbon cycle to store anthropogenic CO_2 in ocean and land decreases in the future

Denman et al. (2007) in *Climate Change 2007: The Physical Science Basis*, Solomon et al., Eds., 499-587

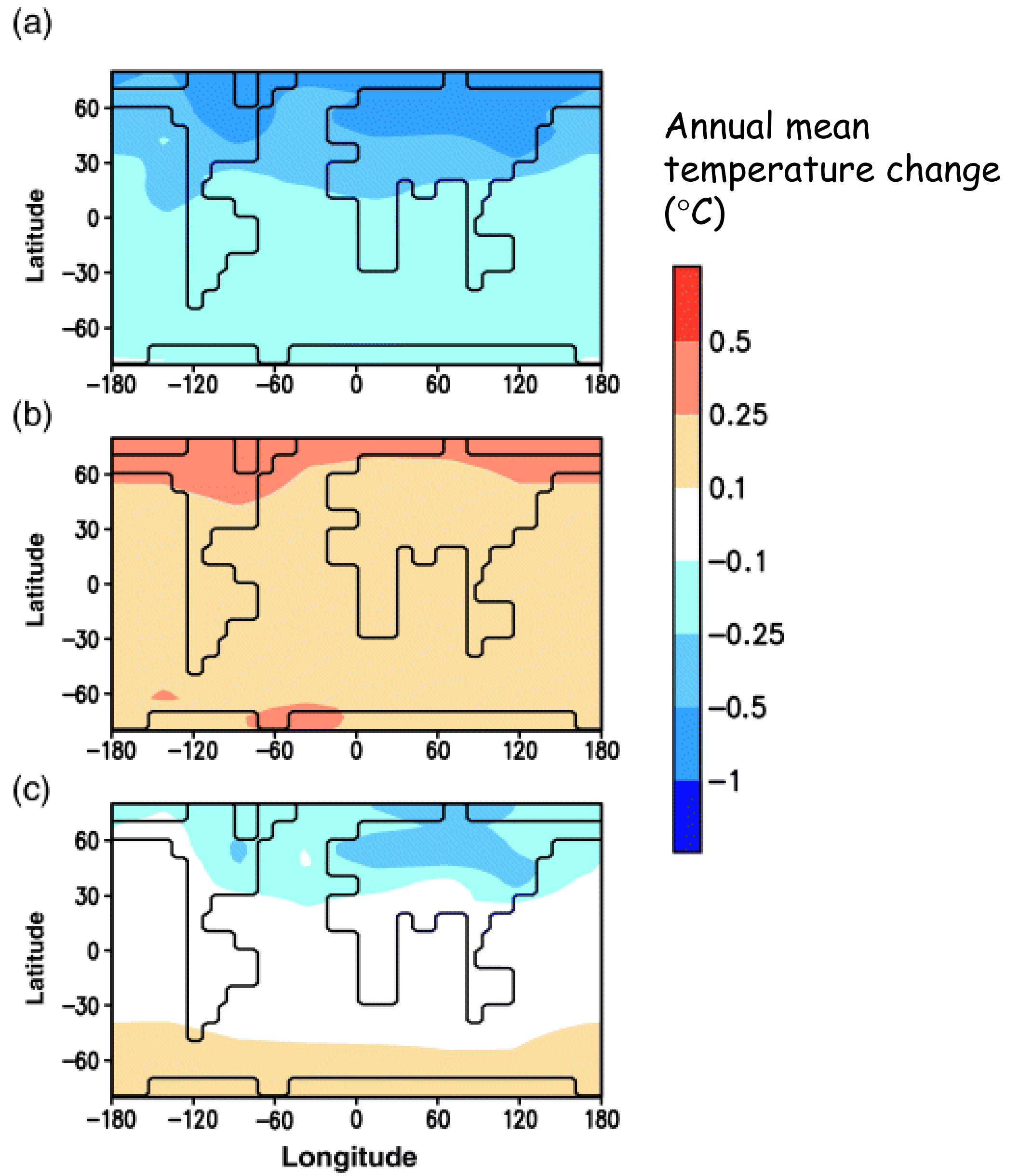
Biogeophysical vs. biogeochemical interactions

Historical land cover change

Biogeophysical cooling

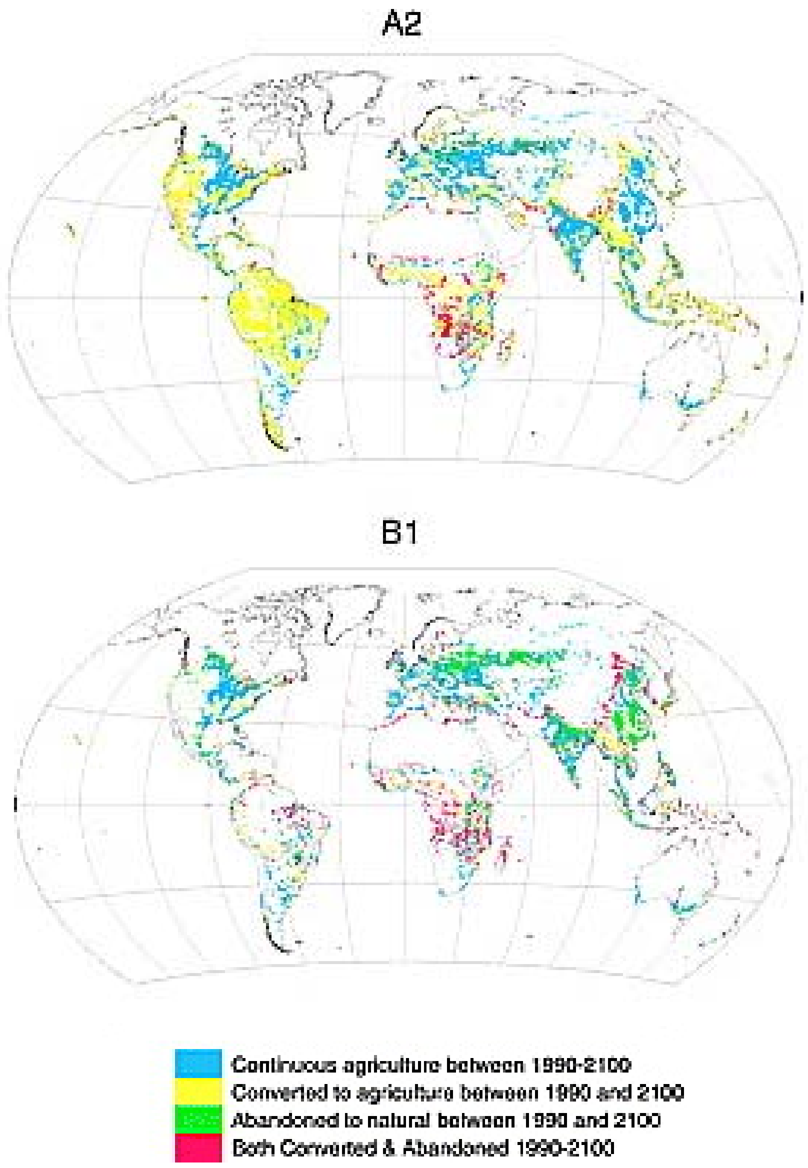
Biogeochemical warming

Biogeophysical cooling offsets biogeochemical warming



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

Future land cover change



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

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

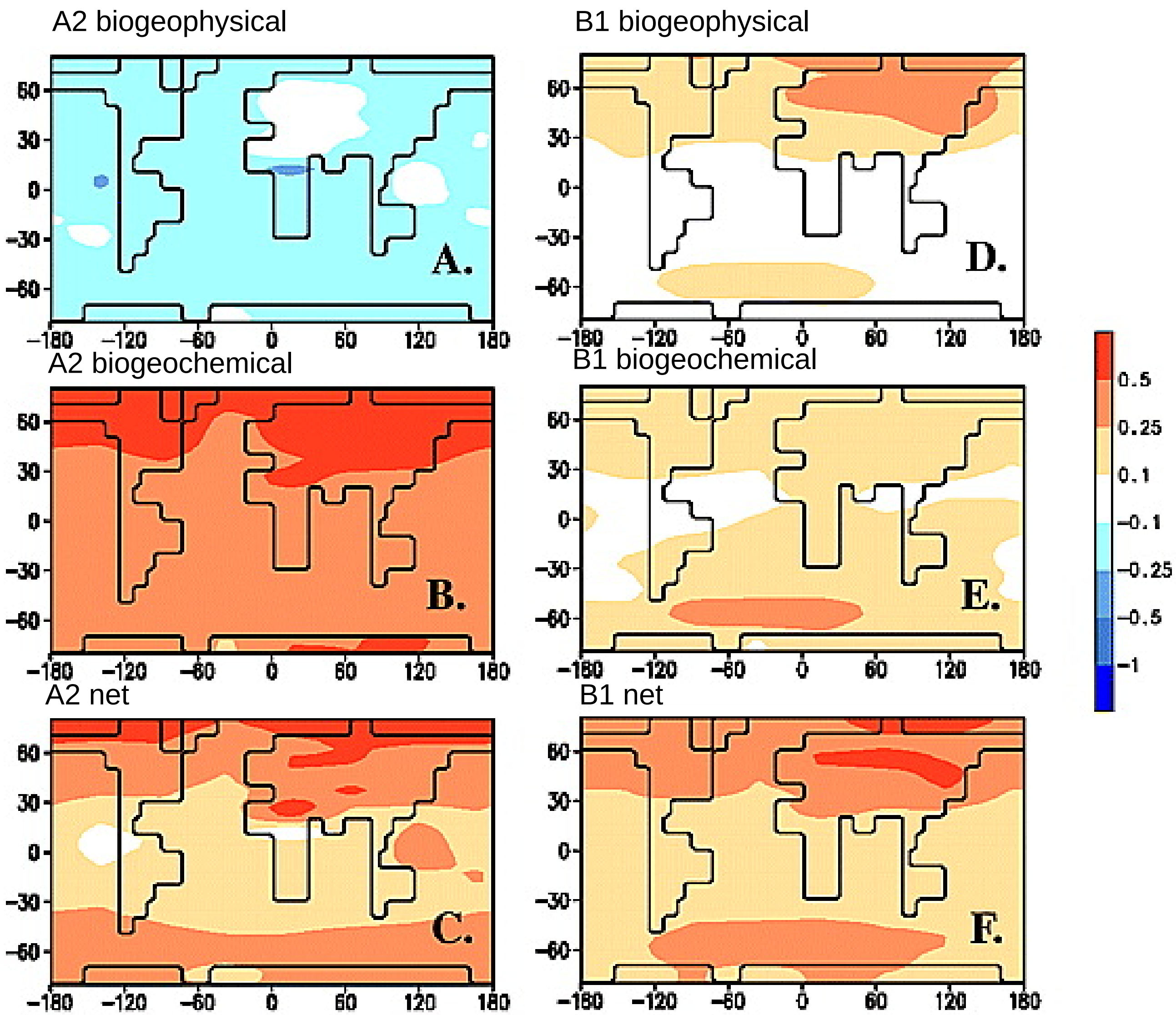
Sitch et al. (2005) GBC, 19, GB2013, doi:10.1029/2004GB002311

Future land cover change

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

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

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



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

Permissible anthropogenic CO_2 emissions

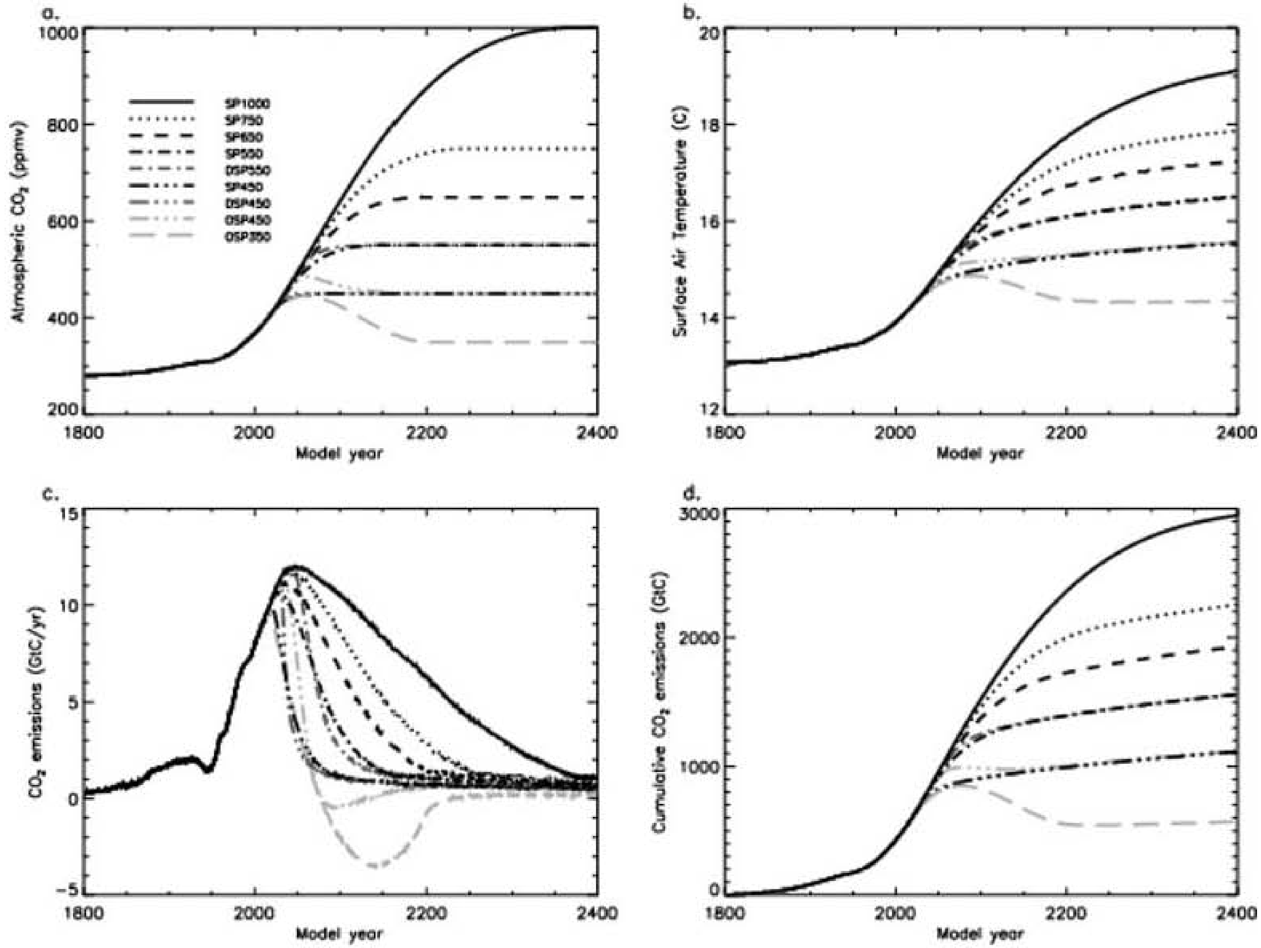


Fig. 1. Results from nine CO_2 stabilization scenario runs: (a) prescribed atmospheric CO_2; (b) modelled global mean surface air temperature; (c) calculated annual CO_2 emissions and (d) calculated cumulative CO_2 emissions.

Permissible anthropogenic CO_2 emissions to achieve a targeted atmospheric CO_2 are derived from specified atmospheric CO_2 concentration and simulated land and ocean carbon fluxes.

The positive carbon cycle-climate feedback reduces the ability of the biosphere to store anthropogenic carbon emissions and necessitates reductions in emissions to achieve stabilization goals.

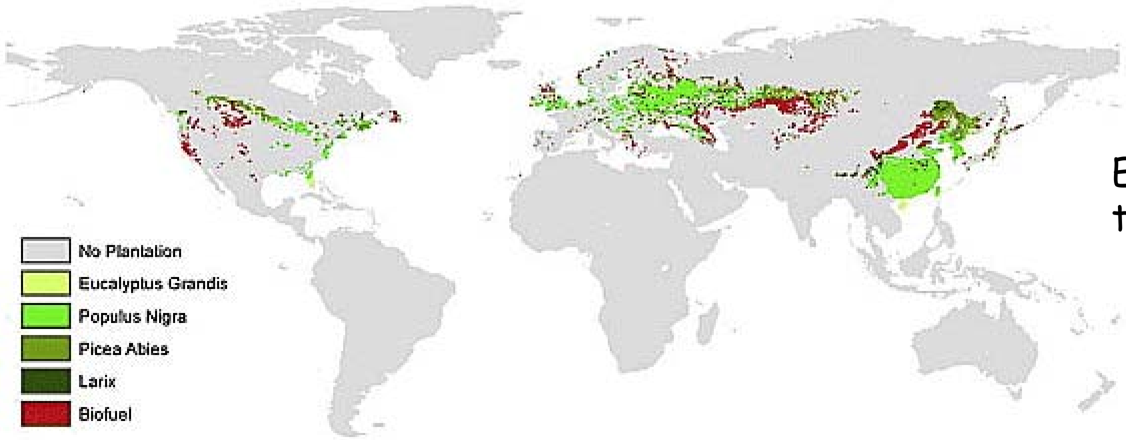
The CO_2 fertilization effect is particularly important as this increases the terrestrial carbon sink and allows high anthropogenic emissions.

Matthews (2006) Tellus 58B:591-602

Land management policies to mitigate climate change

Reforestation might be chosen as an option for the enhancement of terrestrial carbon sequestration or biofuel plantations as a substitute for fossil fuels

2100 land management, IPCC A1b scenario

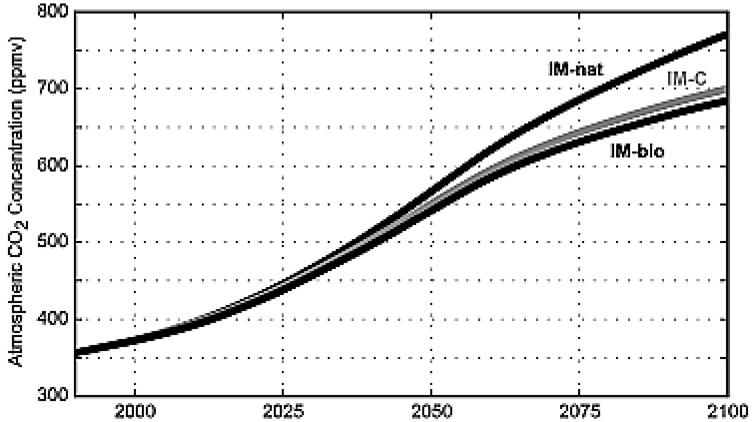


Excess agricultural land converted to carbon storage or biofuels

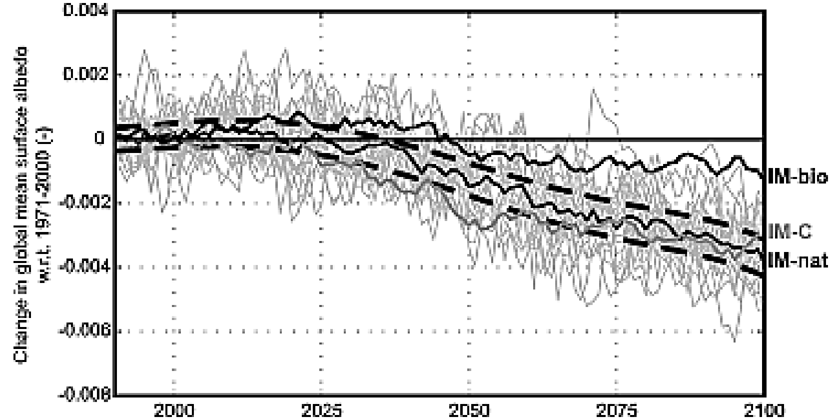
Green = carbon plantations
Green + red = biofuel plantations

Schaeffer et al. (2006) GBC, 20, GB2020, doi:10.1029/2005GB002581

Land management policies to mitigate climate change



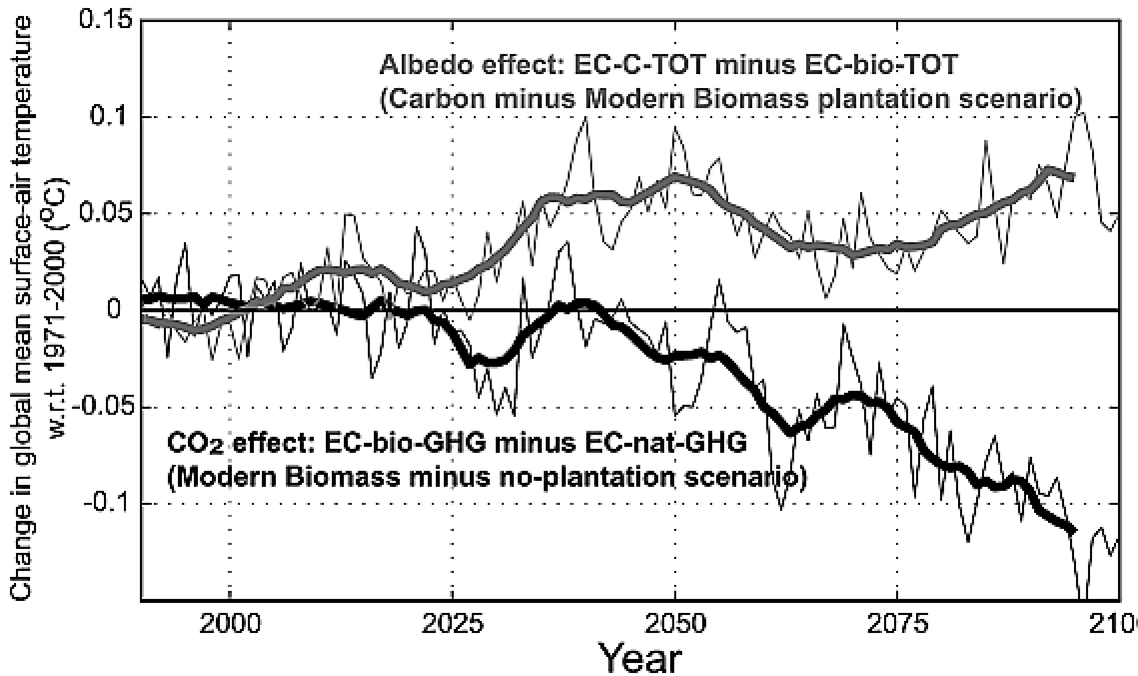
Carbon plantations (IM-C) and biofuels (IM-bio) reduce CO_2 by 70-80 ppm



Natural vegetation (IM-nat) and carbon plantations (IM-C) have lower albedo than biofuels (IM-bio)

Carbon plantations and biofuel plantations reduce atmospheric CO_2, leading to cooling.

Carbon plantations have lower albedo than biofuels, leading to warming



Schaeffer et al. (2006) GBC, 20, GB2020, doi:10.1029/2005GB002581

Colonial Americans and forests

Thomas Cole – "View from Mount Holyoke, Northampton, Massachusetts, after a Thunderstorm (The Oxbow)", 1836

Conveys the views Americans at that time felt toward forests. The forest on the left is threatening. The farmland on the right is serene.

Forest – dark, sinister, forbidding, lacking order, threat to survival

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)