Land Surface Models for Climate Models: Description and Application

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Role of land surface models in GCMs

- Provides the boundary conditions at the land-atmosphere interface
  - e.g. albedo, surface temperature, surface fluxes
- Partitions available energy at the surface into sensible and latent heat flux components
- Partitions rainfall into runoff and evaporation
  - Evaporation provides surface-atmosphere moisture flux
  - River runoff provides freshwater input to the oceans
- Provides the carbon fluxes at the surface (photosynthesis, respiration)
- Updates state variables which affect surface fluxes
  - e.g. snow cover, soil moisture, soil temperature, vegetation cover, leaf area index

- LSM cost is actually not that high (~10% of full coupled model)

Role of land surface models in GCMs

The land-surface model solves (at each timestep)

- **Surface energy balance** (and other energy balances, e.g. in canopy, snow, soil)
  - $S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G$
    - $S^{\downarrow}$, $S^{\uparrow}$ are down(up)welling solar radiation
    - $L^{\downarrow}$, $L^{\uparrow}$ are down(up)welling longwave radiation
    - λ is latent heat of vaporization, E is evaporation
    - H is sensible heat flux
    - G is ground heat flux

- **Surface water balance** (and other water balances such as snow and soil water)
  - $P = E_S + E_T + E_C + R_{Surf} + R_{Sub\text{-}Surf} + \Delta SM / \Delta t$
    - P is rainfall
    - E_S is soil evaporation, E_T is transpiration, E_C is canopy evaporation
    - R_{Surf} is surface runoff, $R_{Sub\text{-}Surf}$ is sub-surface runoff
    - $\Delta SM / \Delta t$ is the change in soil moisture over a timestep

- **Carbon balance** (and plant and soil carbon pools)
  - $NPP = GPP - Ra = (\Delta C_f + \Delta C_s + \Delta C_r) / \Delta t$
  - $NEP = NPP - Rh$
  - $NBP = NEP - Combustion$
    - NPP is net primary production, GPP is gross primary production
    - Ra is autotrophic (plant) respiration, Rh is heterotrophic (soil) respiration
    - ΔC_f, ΔC_s, ΔC_r are foliage, stem, and root carbon pools
    - NEP is net ecosystem production, NBP is net biome production
    - Combustion is carbon loss during fire

Surface energy balance and surface temperature

Surface energy balance

$(S\downarrow - S\uparrow) + \varepsilon L\downarrow = L\uparrow[T_s] + H[T_s] + \lambda E[T_s] + G[T_s]$

$$L\uparrow = \varepsilon\sigma(T_s + 273.15)^4 + (1-\varepsilon)L\downarrow$$

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

$$\lambda E = -\frac{\rho C_p}{\gamma}\frac{\left(e_a - e_*[T_s]\right)}{r_{aW}}$$

$$G = k\frac{\left(T_s - T_{soil}\right)}{\Delta z}$$

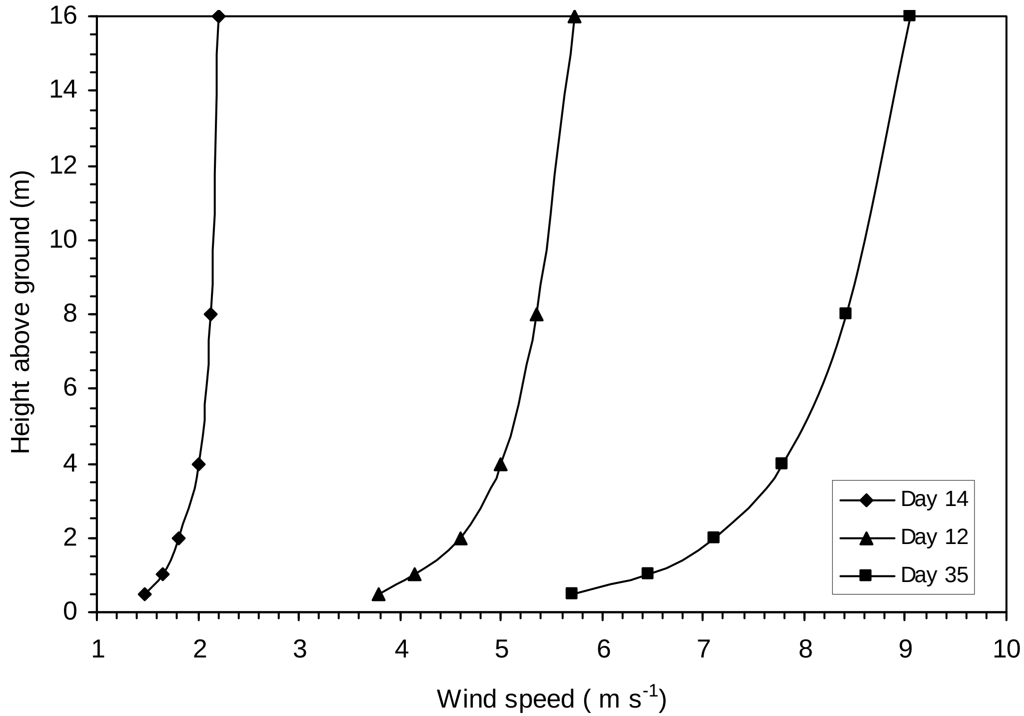
Atmospheric forcing
$S\downarrow$ - incoming solar radiation
$L\downarrow$ - incoming longwave radiation
T_a – air temperature
e_a – vapor pressure

Surface properties
$S\uparrow$ - reflected solar radiation (albedo)
ε - emissivity
raH – aerodynamic resistance (roughness length)
raW – aerodynamic resistance (roughness length)
T_{soil} – soil temperature
k – thermal conductivity
Δz – soil depth

With atmospheric forcing and surface properties specified, solve for temperature T_s that balances the energy budget

Turbulent fluxes

Logarithmic wind profile in atmosphere near surface



$$\left(z/u_*\right)\partial\overline{u}/\partial z = 1/k \;\Rightarrow\; \overline{u}_2 - \overline{u}_1 = \left(u_*/k\right)\ln\left(z_2/z_1\right) \;\Rightarrow\; \overline{u}(z) = \left(u_*/k\right)\ln\left(z/z_{0M}\right)$$

$$\overline{u}(z) = \left(u_*/k\right)\ln\left[\left(z-d\right)/z_{0M}\right]$$

Similar logarithmic profiles for temperature and vapor pressure

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

Turbulent fluxes

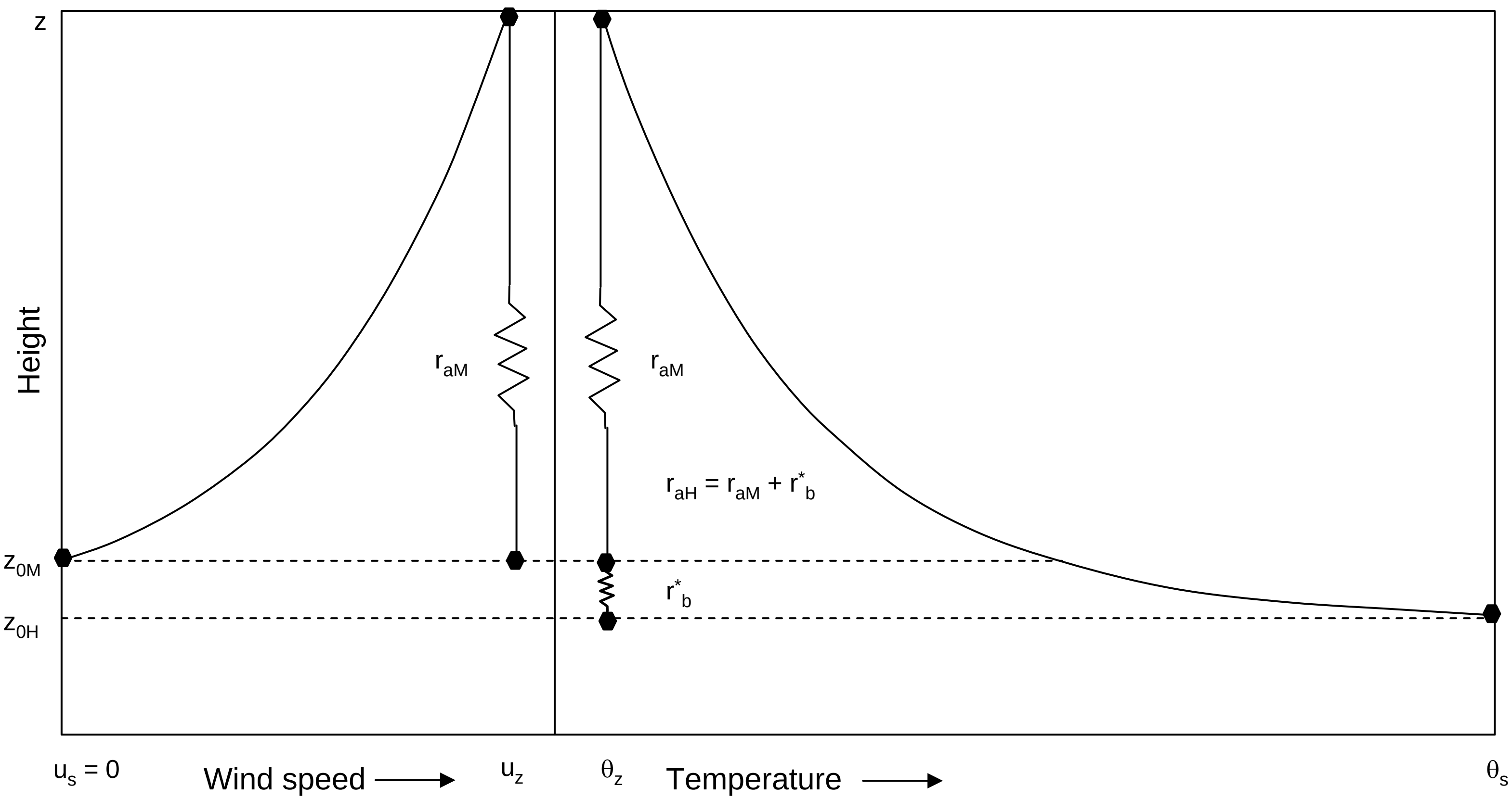
$$\tau = \rho(\bar{u} - \bar{u}_s)/r_{aM} = \rho\bar{u}/r_{aM}$$

$$H = -\rho C_p \frac{(\theta_a - T_s)}{r_{aH}}$$

$$r_{aM} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]^2$$

$$r_{aH} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]\left[\ln\left(\frac{z-d}{z_{0H}}\right) - \psi_h(\zeta)\right]$$

$$r_{aW} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]\left[\ln\left(\frac{z-d}{z_{0W}}\right) - \psi_w(\zeta)\right]$$



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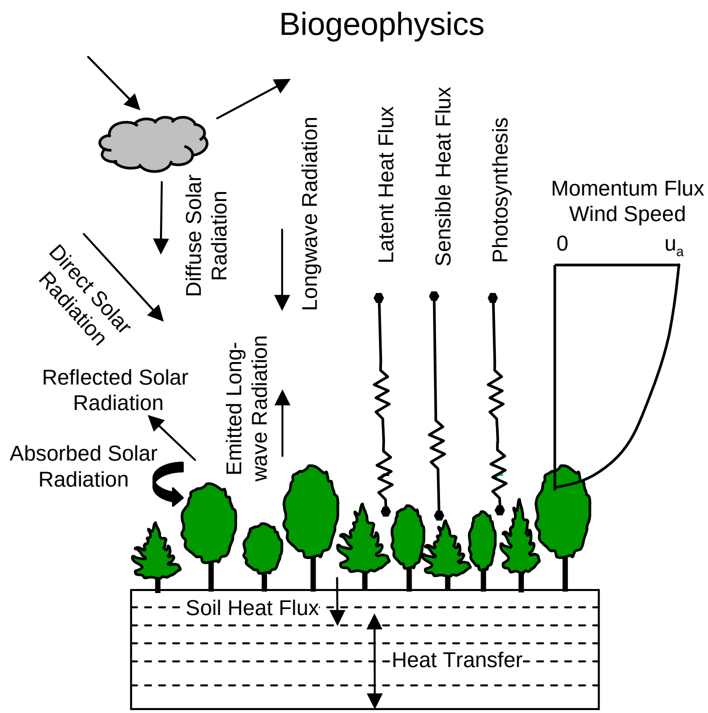
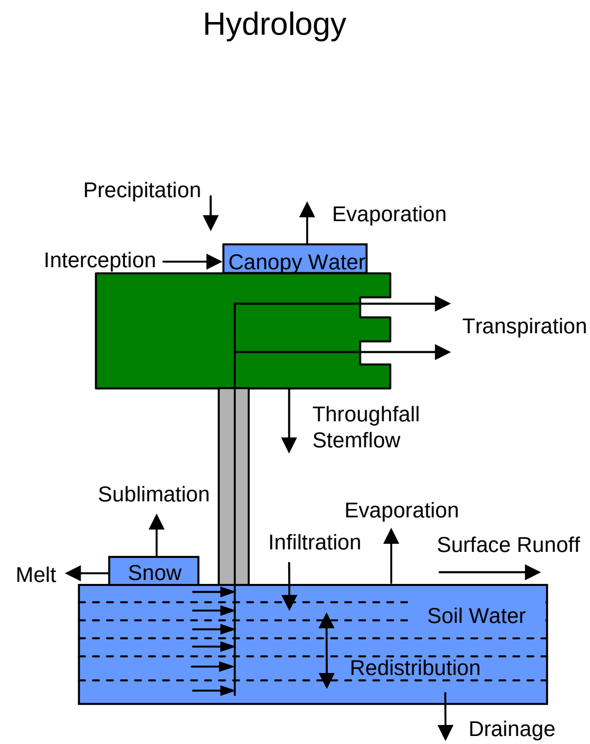
Community Land Model

Hydrometeorology





<u>Community Land Model</u>

- 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

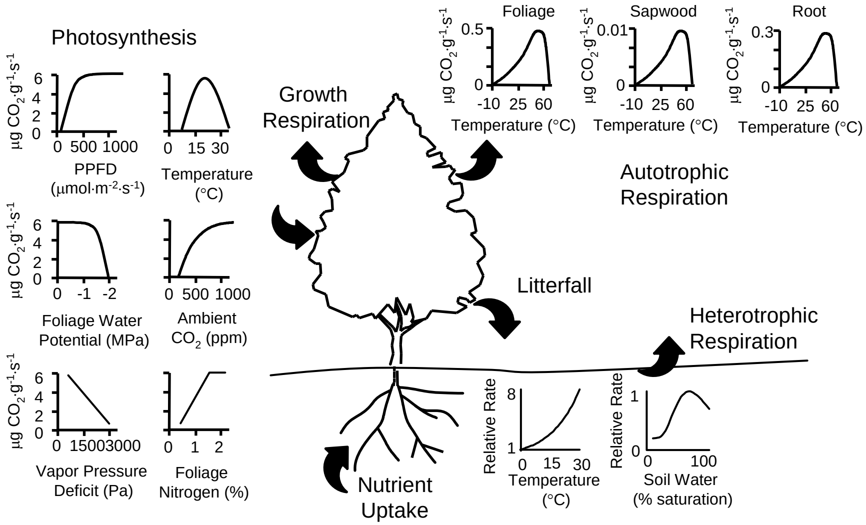
Hydrologic cycle: interception of water by leaves; infiltration and runoff; snow accumulation and melt; multi-layer soil water; partitioning of latent heat into evaporation of intercepted water, soil evaporation, and transpiration

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

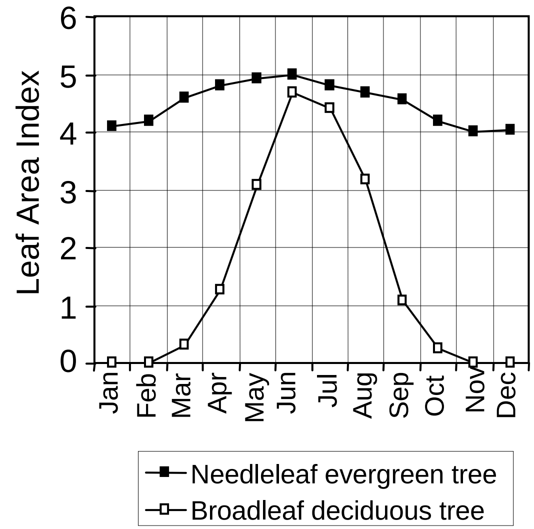
Community Land Model

Dynamic vegetation

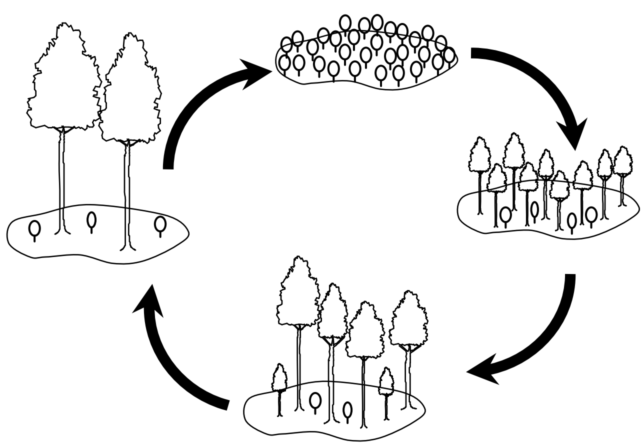
Ecosystem carbon balance



Leaf phenology



Vegetation dynamics

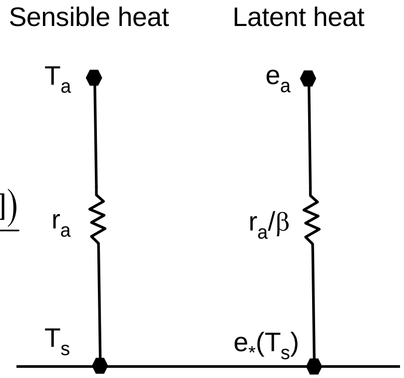


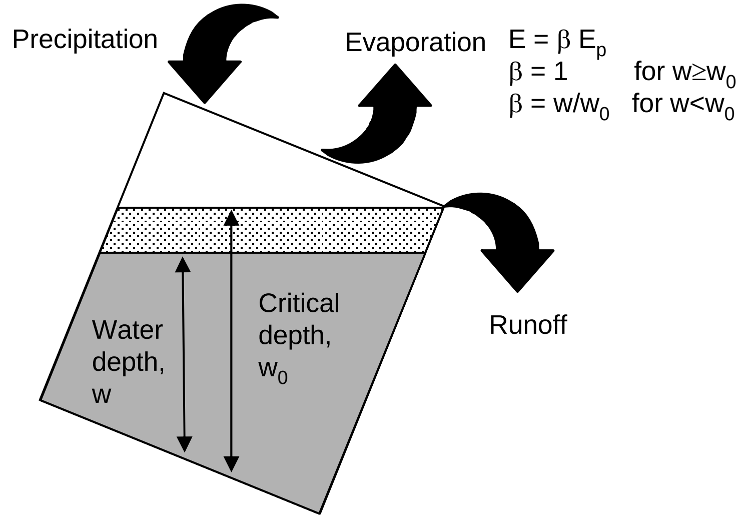
Bonan et al. (2003) Global Change Biology 9:1543-1566
Levis et al. (2004) NCAR/TN-459+IA
Bonan & Levis (2006) J Climate 19:2290-2301

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

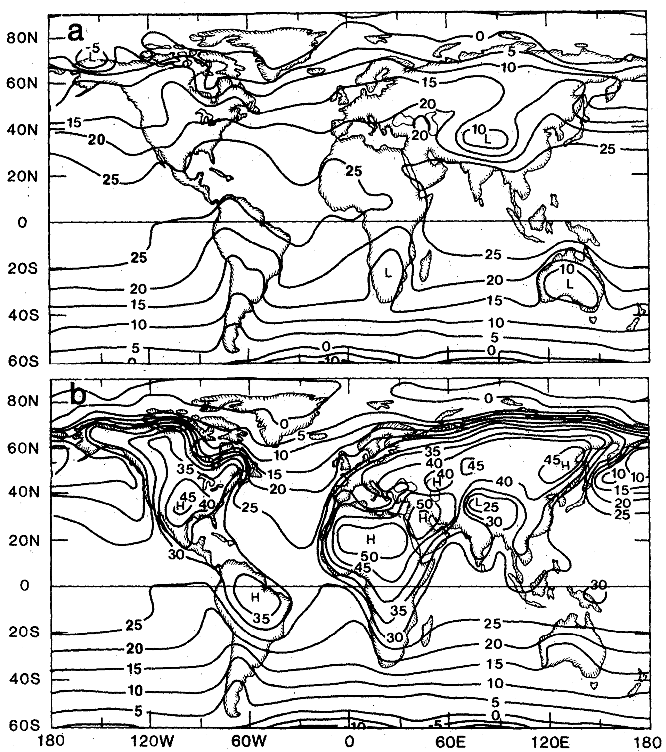
Wet – evapotranspiration not limited by soil water; vegetated planet

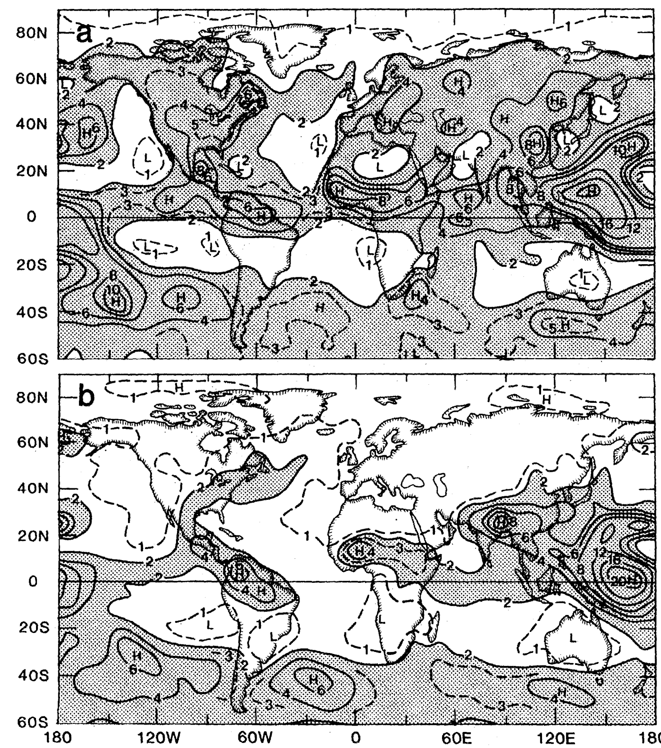
Dry – no evapotranspiration; desert planet

July surface temperature (°C)

July precipitation (mm/day)

Wet soil





Wet soil

Dry soil

Dry soil

Dry soil warmer than wet soil

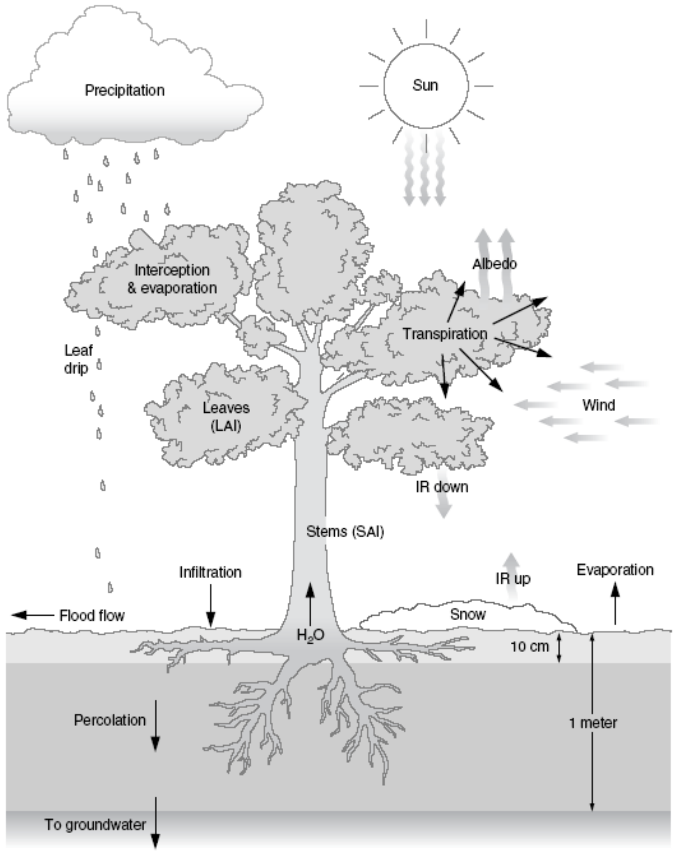
Dry soil has less precipitation

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

Second-generation models

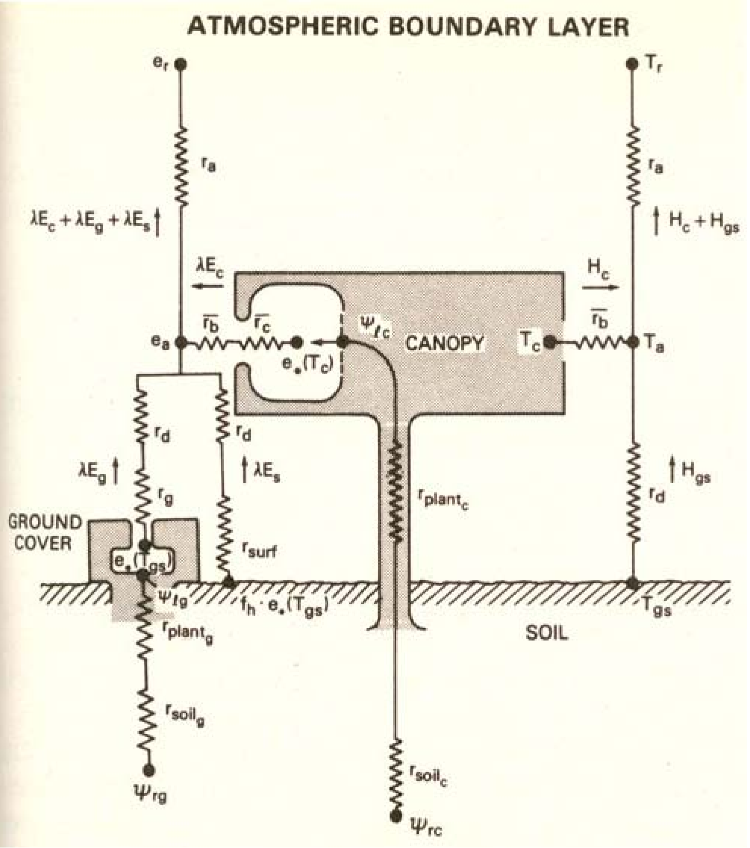
Vegetation and hydrologic cycle

Biosphere-Atmosphere Transfer Scheme (BATS)



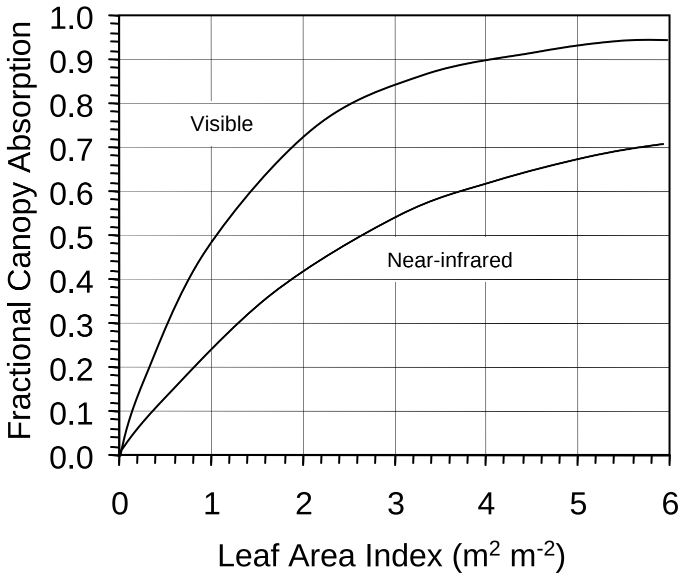
Dickinson et al. (1986) NCAR/TN-275+STR

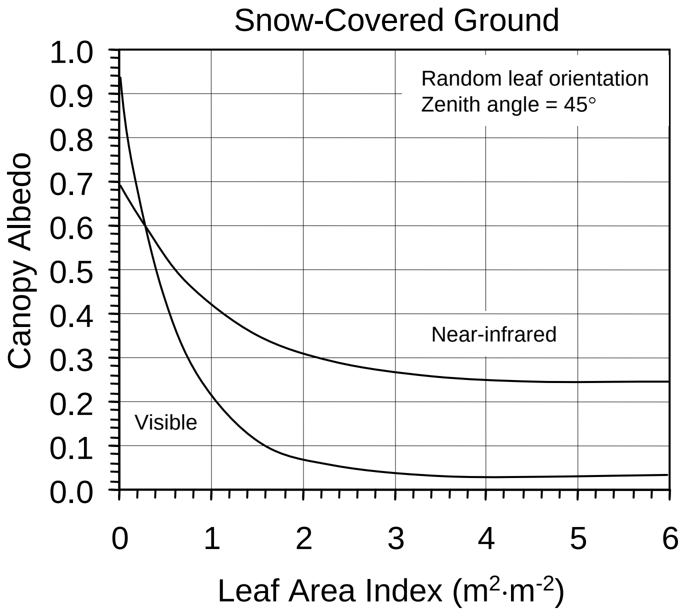
Simple Biosphere Model (SiB)

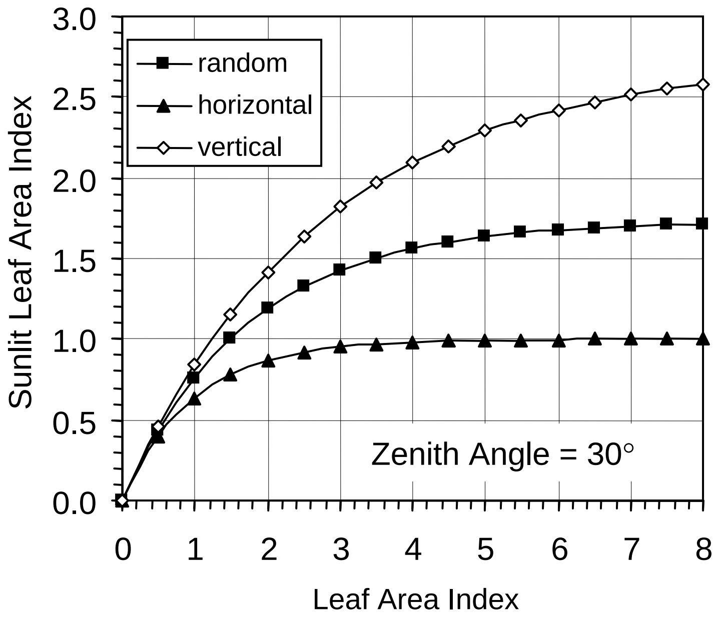


Sellers et al. (1986) J Atmos Sci 43:505-531

Radiative transfer

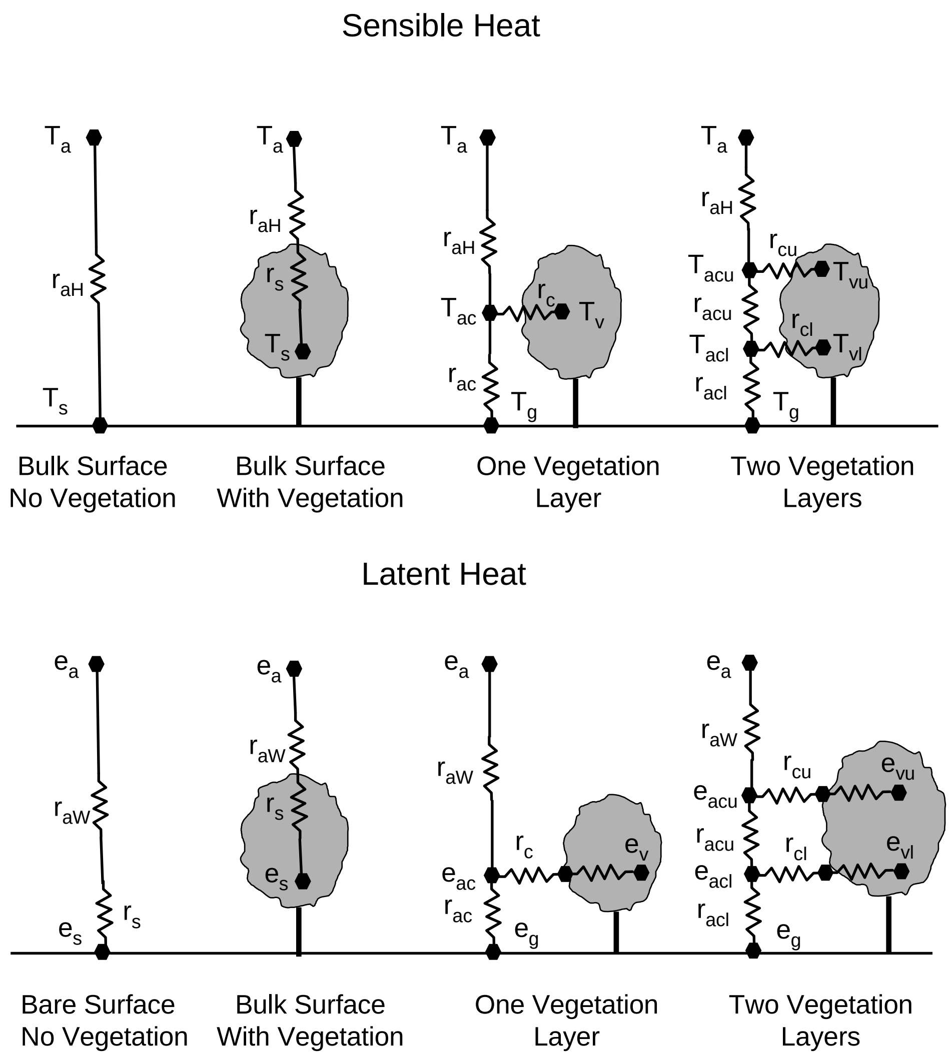






Bonan (2008) Ecological Climatology. 2nd edition (Cambridge Univ. Press)

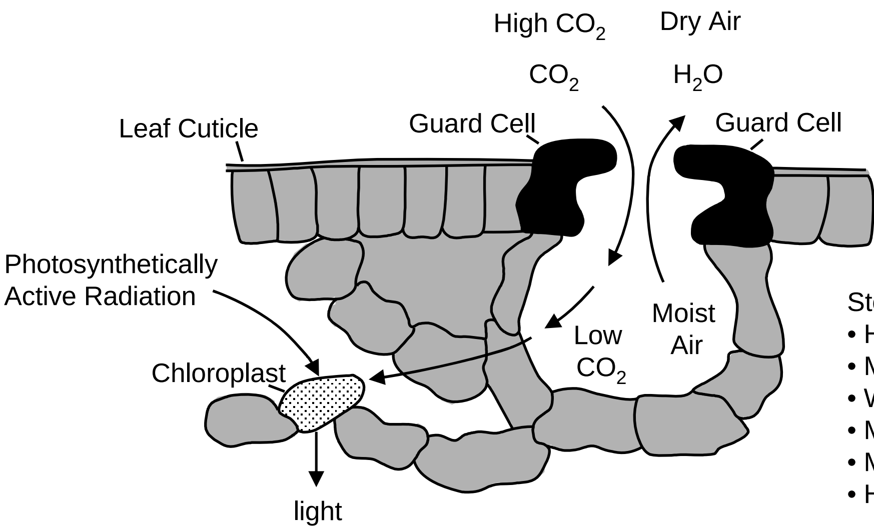
Plant canopy



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

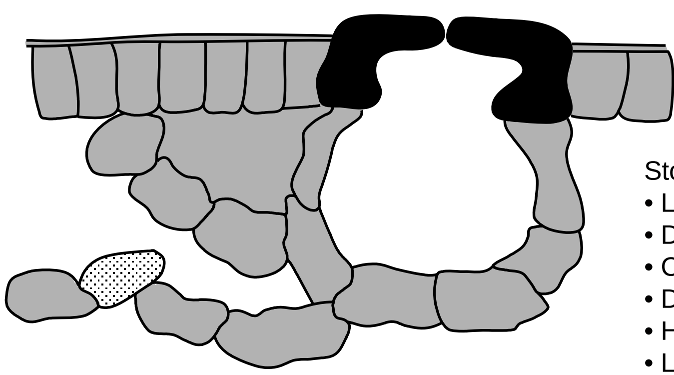
Leaf stomatal resistance

Stomatal Gas Exchange



$$CO_2 + 2\ H_2O \rightarrow CH_2O + O_2 + H_2O$$

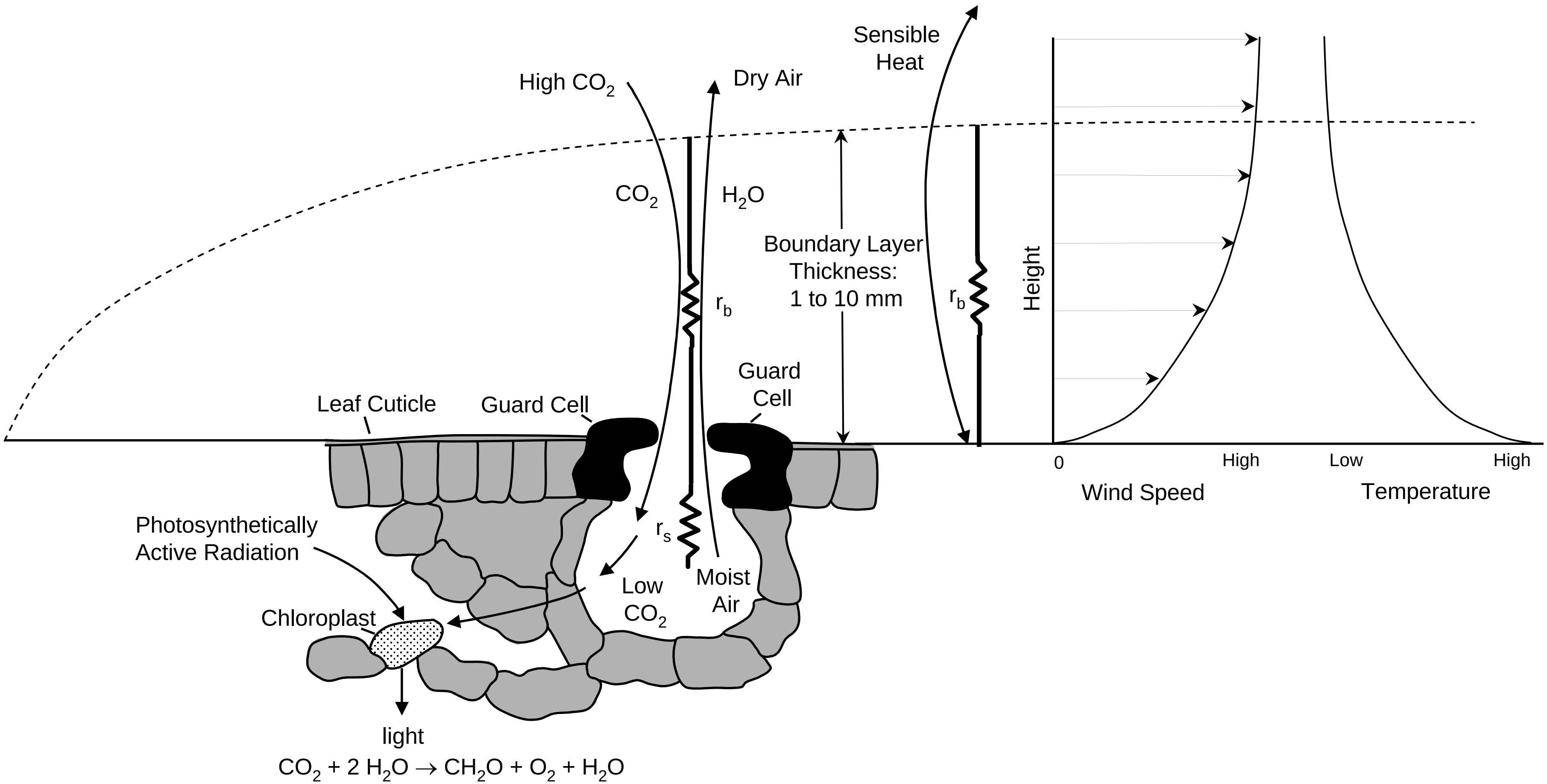
Stomata Open:
- High Light Levels
- Moist Leaf
- Warm Temperature
- Moist Air
- Moderate CO_2
- High Leaf Nitrogen



Stomata Close (Smaller Pore Opening):
- Low Light Levels
- Dry Leaf
- Cold Temperature
- Dry Air
- High CO_2
- Low Leaf Nitrogen

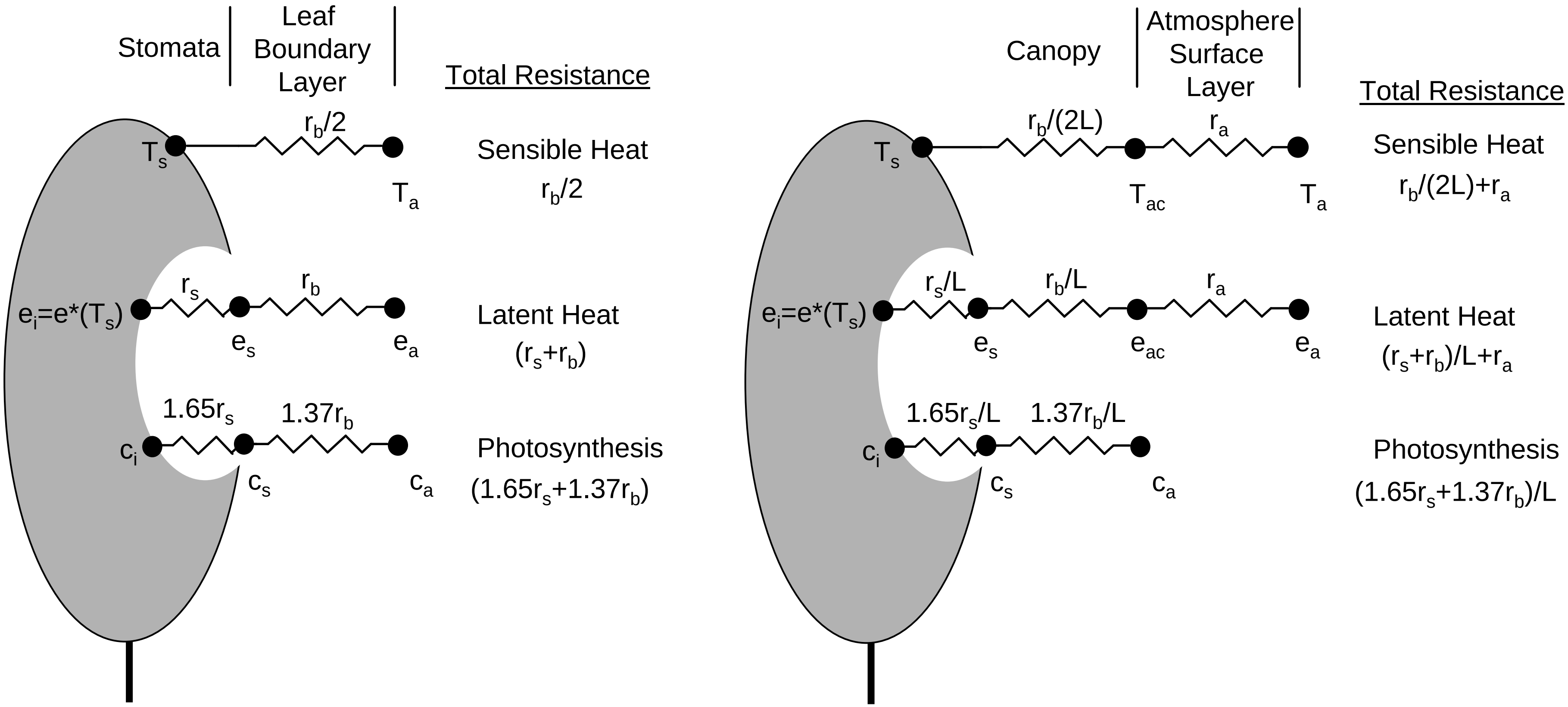
Bonan (2008) Ecological Climatology. 2nd edition (Cambridge Univ. Press)

Leaf boundary layer



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

Plant canopy



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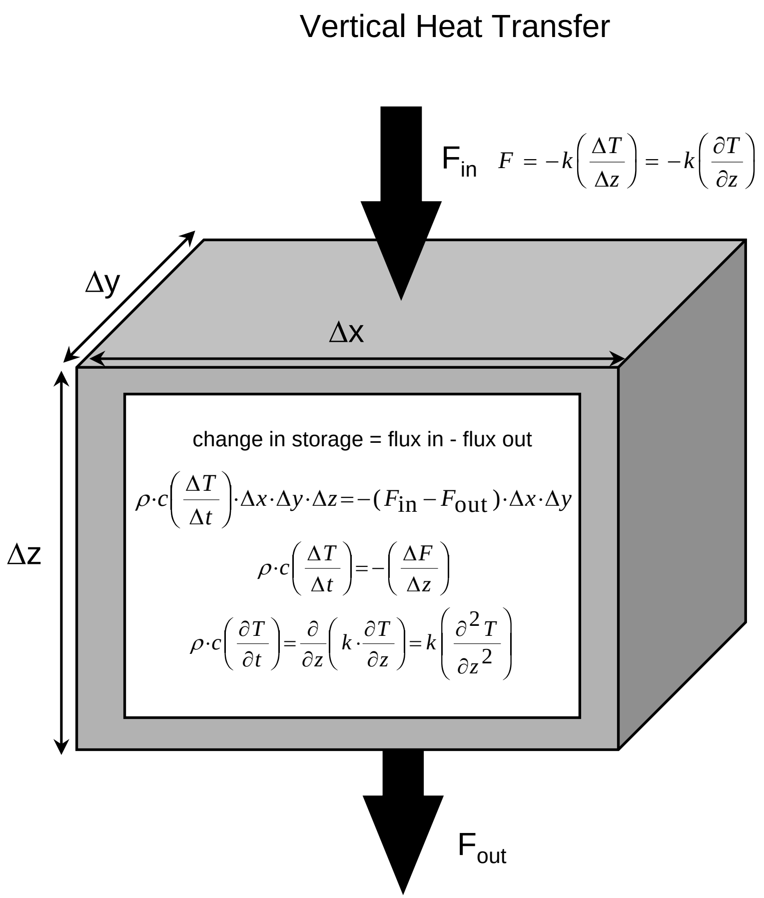
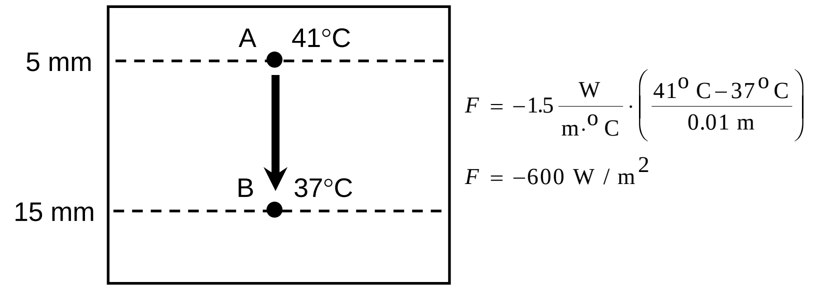
Soil temperature





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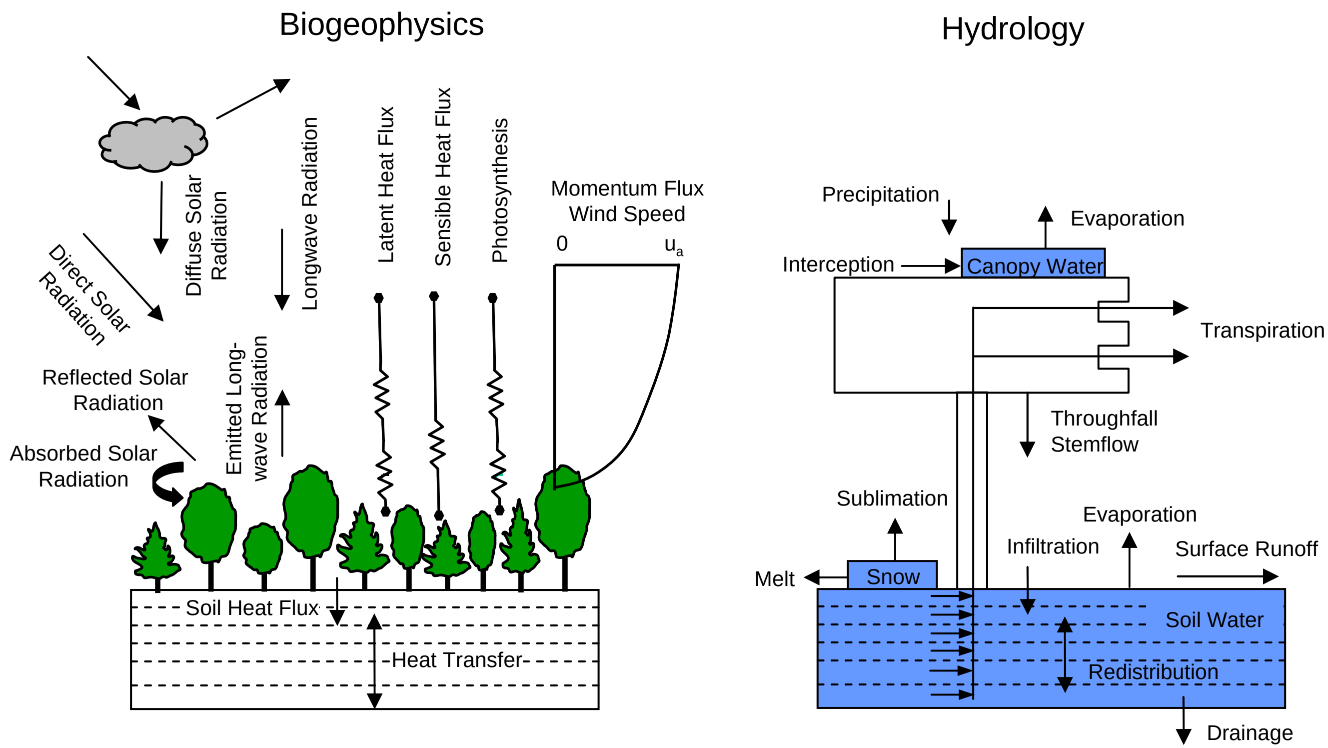
Hydrologic cycle



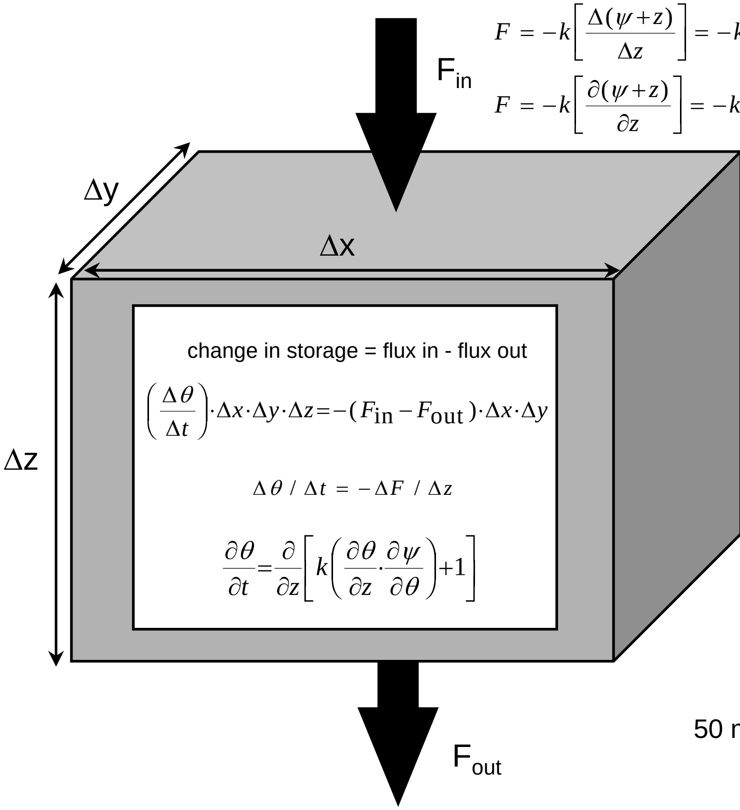
Bonan (2008) Ecological Climatology. 2nd edition (Cambridge Univ. Press)

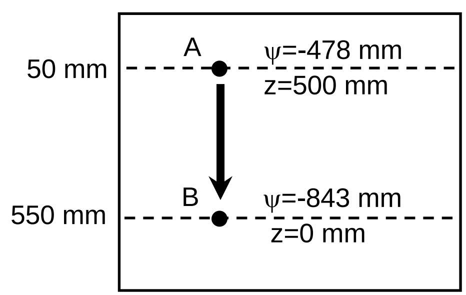
Soil water – Richards equation

Vertical Water Flow

$$F = -k\left[\frac{\Delta(\psi+z)}{\Delta z}\right] = -k\left(\frac{\Delta\psi}{\Delta z}+1\right)$$

$$F = -k\left[\frac{\partial(\psi+z)}{\partial z}\right] = -k\left(\frac{\partial\psi}{\partial z}+1\right) = -k\left(\frac{\partial\theta}{\partial z}\cdot\frac{\partial\psi}{\partial\theta}+1\right)$$



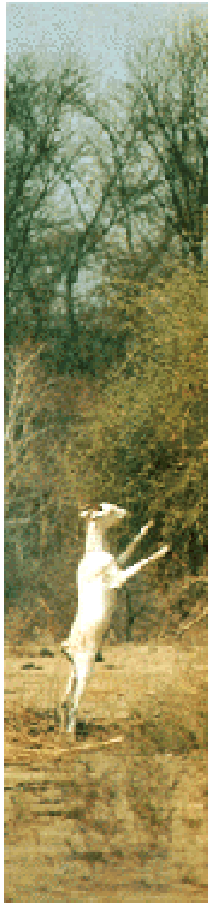


$$F = -2\,\frac{\text{mm}}{\text{hr}}\cdot\left[\frac{(-478\text{ mm}+500\text{ mm})-(-843\text{ mm}+0\text{ mm})}{500\text{ mm}}\right]$$

$$F = -3.46\text{ mm / hr}$$

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

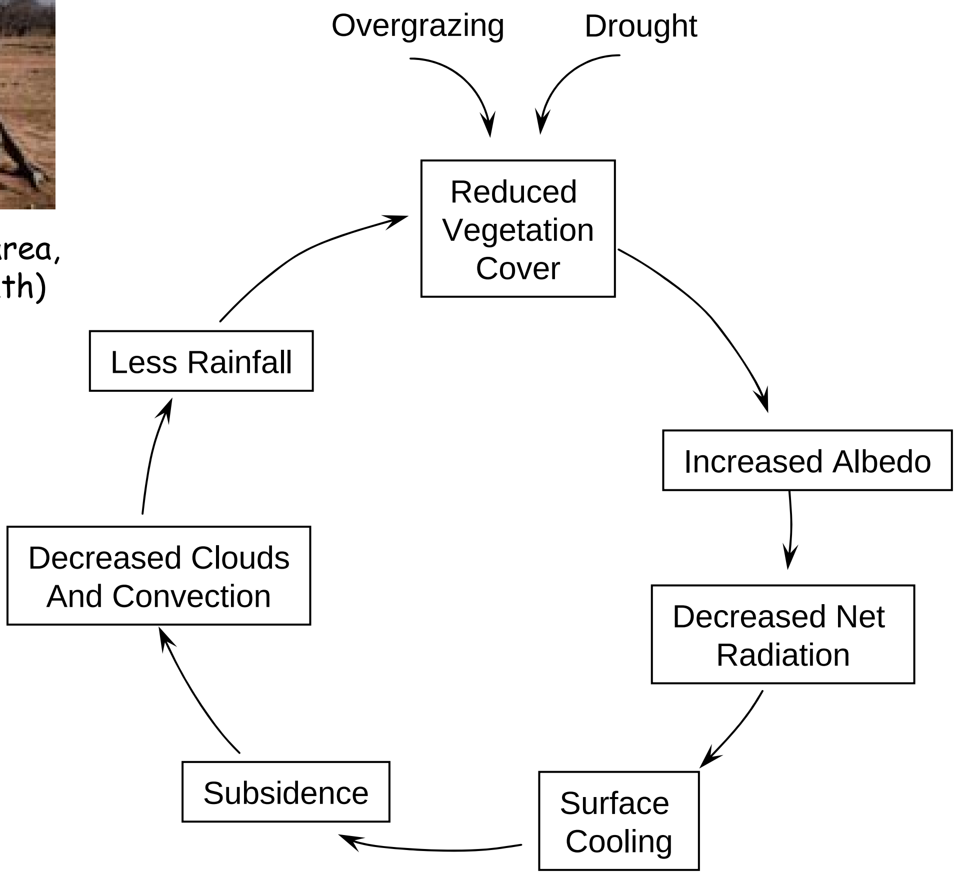
Land degradation



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

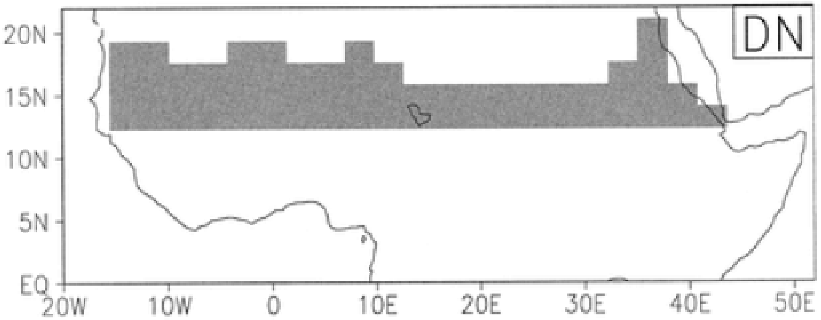


Charney (1975) QJRMS 101:193-202
Charney et al. (1975) Science 187:434-435

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



	Type 1	Type 6	Type 8	Type 9
	Broadleaf evergreen tree	Broadleaf tree/ground cover	Broadleaf shrub/ground cover	Broadleaf shrub/bare soil
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

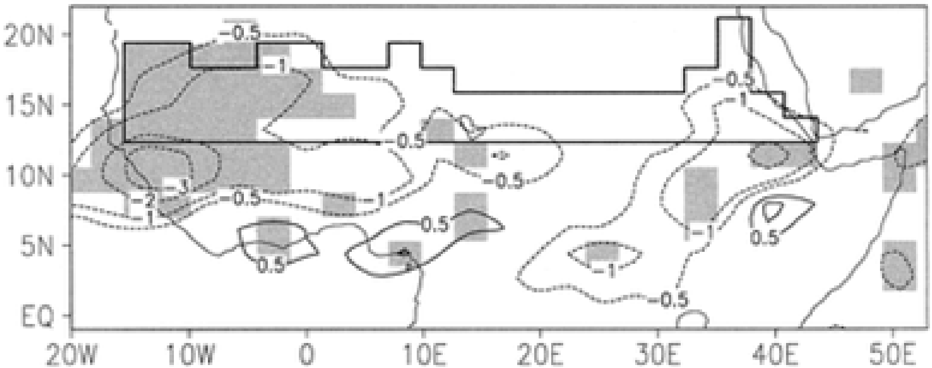
[a] JAS mean value for a parameter with monthly variation.
[b] Surface albedo was as calculated in the control ensemble.
[c] Canopy capacity (mm) is given by 0.1 × leaf area index.

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

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.

July 28, 2000

(NASA/GSFC/LaRC/JPL)

(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

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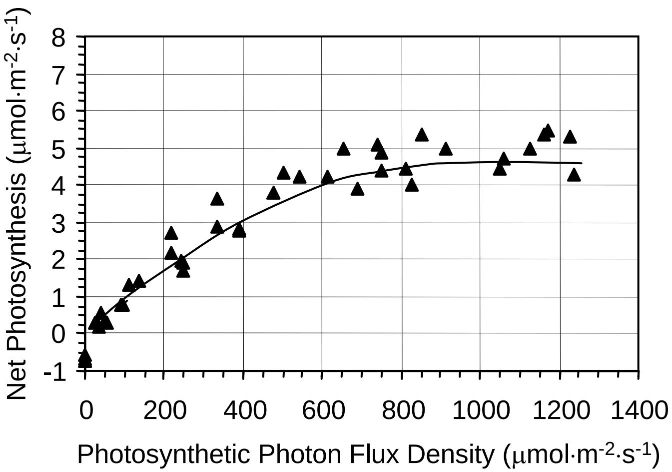
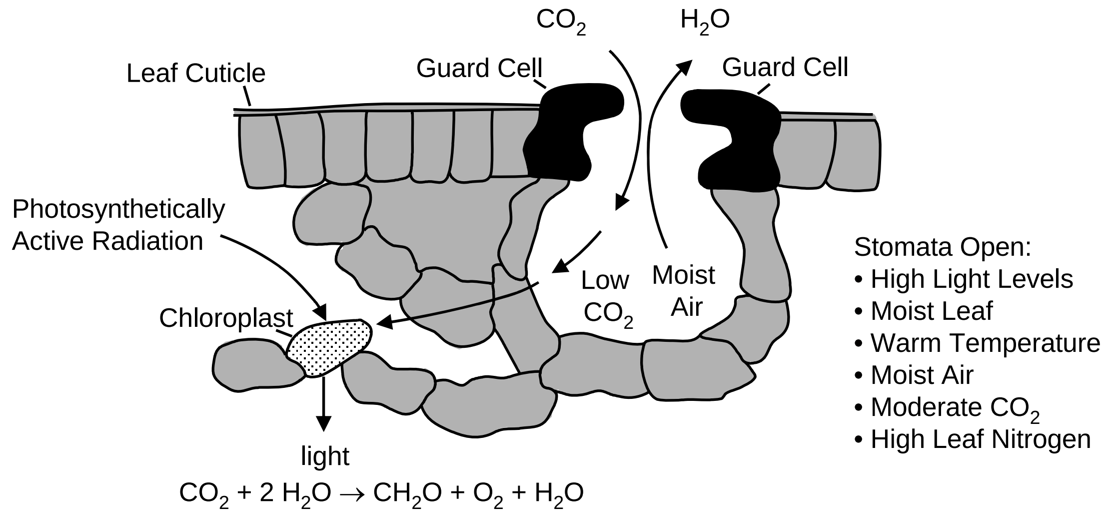
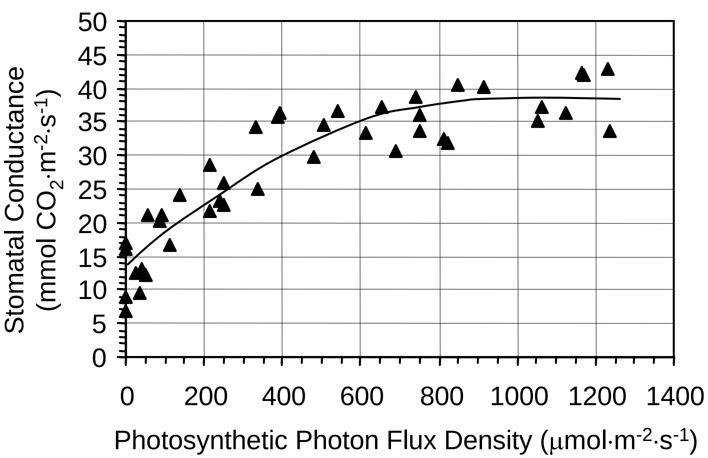
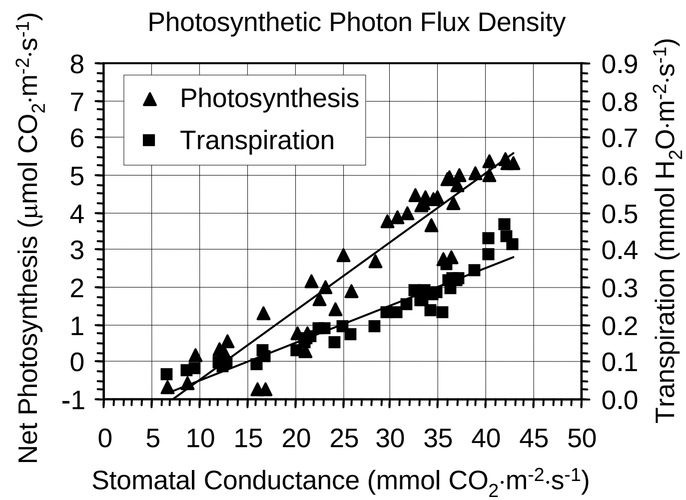
Third-generation models

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

Leaf stomatal resistance

$$\frac{1}{r_s} = g_s = m\frac{A_n(h_s/100)P}{c_s} + b$$

$$A_n = \min(w_c, w_j) - R_d$$

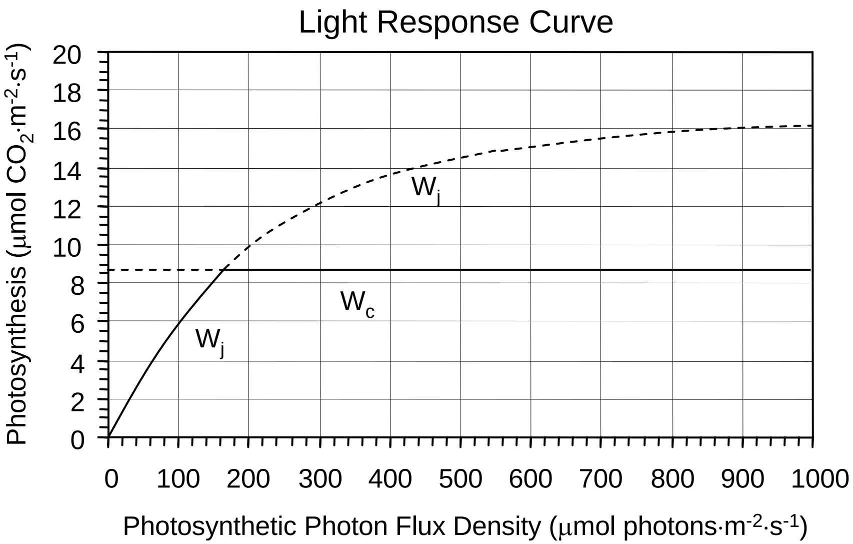
w_c is the rubisco-limited rate of photosynthesis, w_j is light-limited rate allowed by RuBP regeneration

rubisco-limited rate is

$$w_c = \frac{V_{max}(c_i - \Gamma_*)}{c_i + K_c(1 + O_i/K_o)}$$

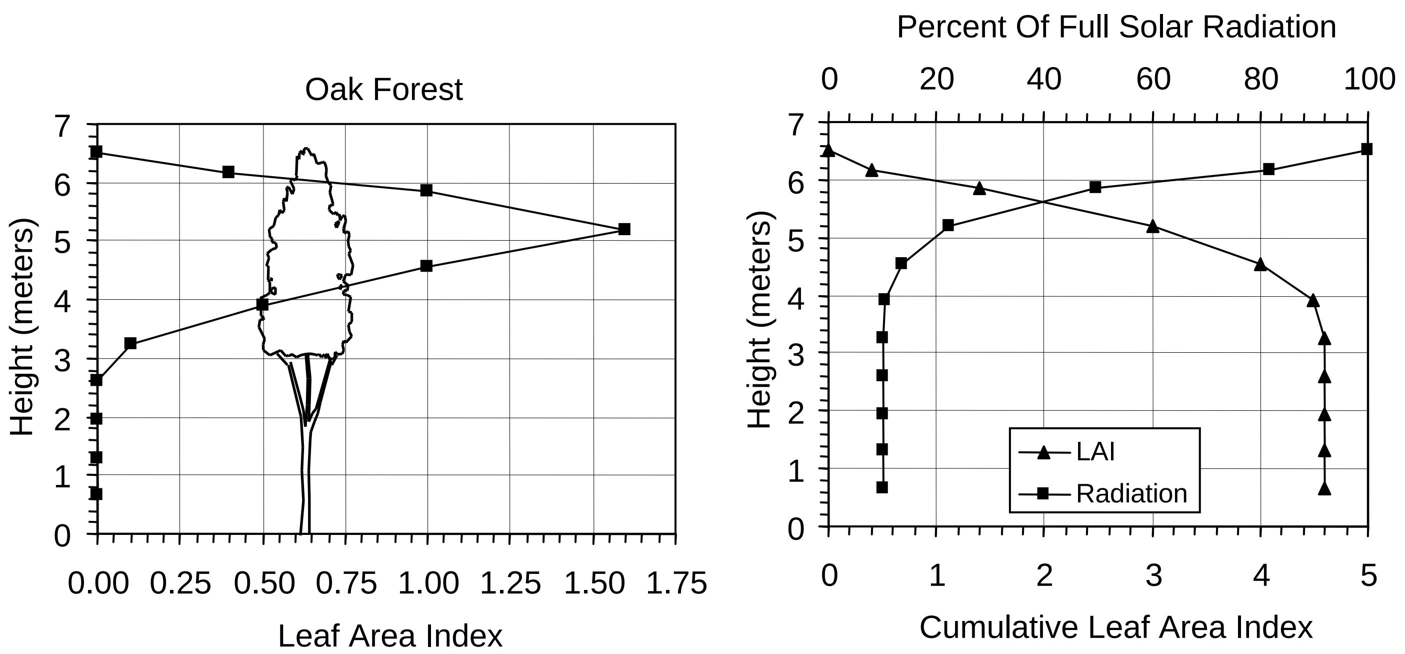
RuBP regeneration-limited rate is

$$w_j = \frac{J(c_i - \Gamma_*)}{4(c_i + 2\Gamma_*)}$$



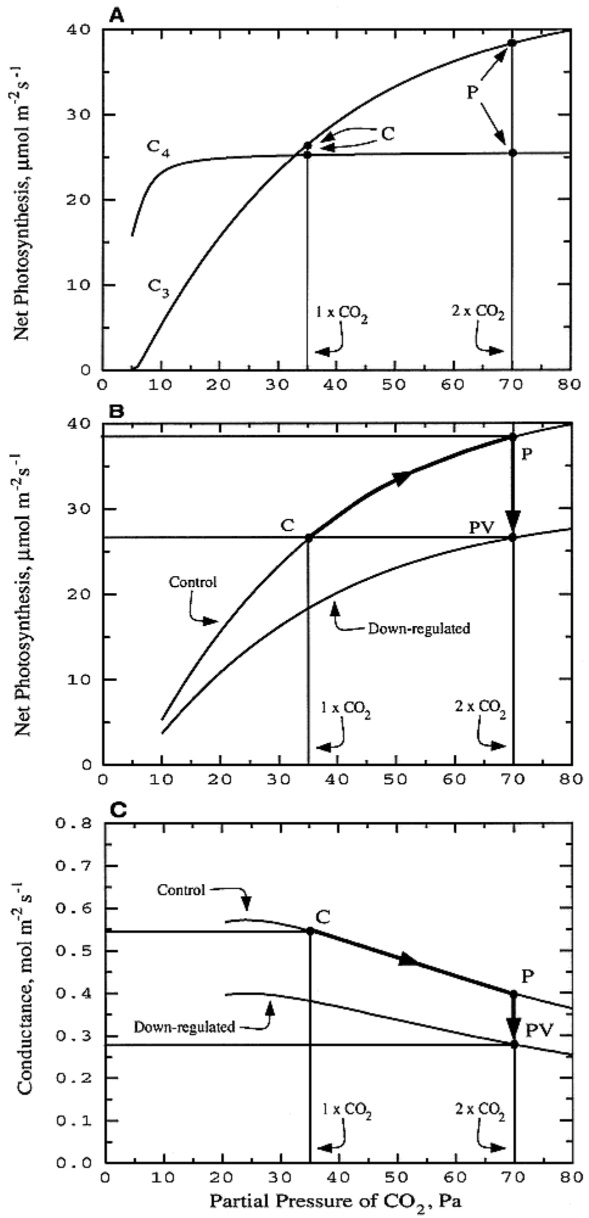
Bonan (2008) Ecological Climatology. 2nd edition (Cambridge Univ. Press)

Canopy resistance



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

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.

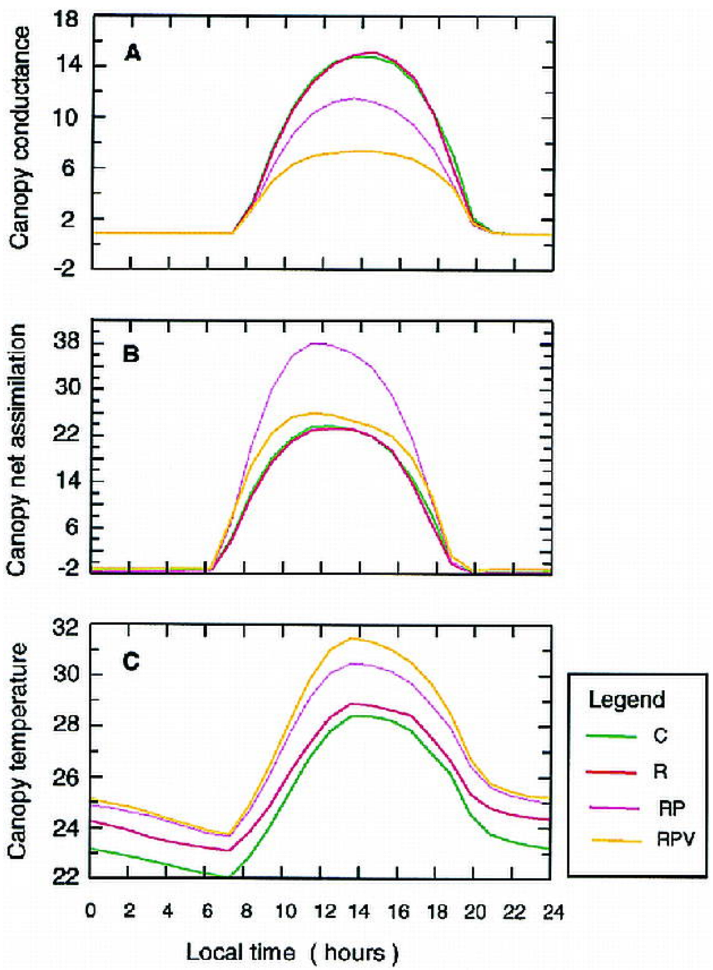
Photosynthesis increases and stomatal conductance decreases with higher atmospheric CO_2

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

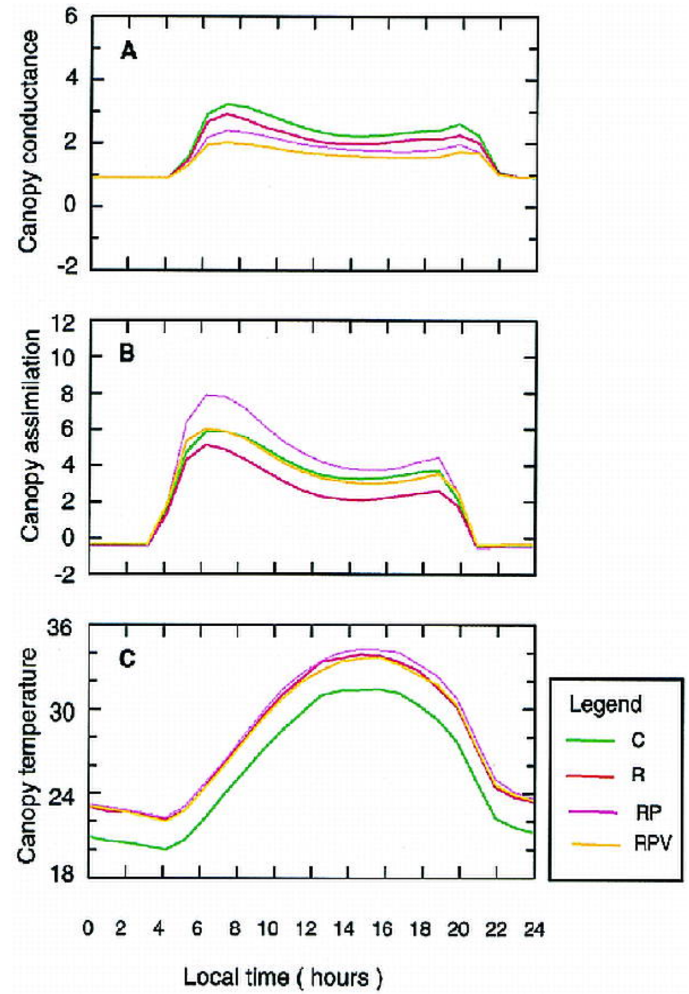
CO_2 fertilization and stomatal conductance

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

Amazonian evergreen forest, diurnal cycle January



Canadian evergreen forest, diurnal cycle July



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

CO_2 fertilization and stomatal conductance

TABLE 2. Summary of results from the six experiments described in test: C-control (1 × CO_2 for radiation and physiology); P (1 × CO_2 for radiation, 2 × CO_2 for physiology); PV (1 × CO_2 for radiation, 2 × CO_2 for down-regulated physiology); R (2 × CO_2 for radiation, 1 × CO_2 for physiology); RP (2 × CO_2 for radiation, 2 × CO_2 for physiology); RPV (2 × CO_2 for radiation, 2 × CO_2 for down-regulated physiology). Values in table are means for the last 10 yr of the 30-yr simulations. The values in parentheses are the percent differences from C except in the case of surface air temperature, which are the differences from C.

	Location				
Experiment	Tropics 14.4°S–14.4°N	Midlatitudes 28.8–50.4°N	North latitudes 50.4–72.0°N	All land points	Global land + ocean
	Assimilation (μmol m^{-2} s^{-1})				
C	6.04	1.77	1.67	2.65	
P	7.96 (31.7)	2.62 (48.3)	2.26 (35.6)	3.59 (35.3)	
PV	6.87 (13.8)	1.96 (10.8)	1.76 (6.0)	2.93 (10.6)	
R	6.08 (0.6)	1.72 (−2.5)	1.63 (−2.0)	2.65 (0.0)	
RP	8.10 (35.1)	2.53 (43.4)	2.25 (35.0)	3.59 (35.5)	
RPV	6.71 (11.0)	2.02 (14.1)	1.81 (8.9)	2.94 (11.0)	
	Canopy conductance (mm s^{-1})				
C	2.79	0.79	0.92	1.21	
P	2.06 (−26.1)	0.61 (−23.4)	0.68 (−25.9)	0.90 (−25.1)	
PV	1.82 (−34.8)	0.49 (−38.3)	0.59 (−35.7)	0.78 (−35.2)	
R	2.81 (0.6)	0.79 (−0.9)	0.91 (−0.6)	1.21 (0.2)	
RP	2.12 (−24.1)	0.61 (−23.8)	0.69 (−24.5)	0.92 (−23.8)	
RPV	1.79 (−35.9)	0.51 (−35.9)	0.62 (−32.4)	0.79 (−34.1)	
	Evapotranspiration (W m^{-2})				
C	100.8	49.6	38.6	58.9	96.0
P	96.7 (−4.0)	49.3 (−0.6)	37.7 (−2.2)	57.6 (−2.3)	95.8 (−0.2)
PV	96.5 (−4.2)	48.1 (−3.1)	37.0 (−4.1)	56.9 (−3.5)	96.0 (0.1)
R	105.9 (5.1)	52.3 (5.4)	41.2 (6.8)	62.3 (5.8)	100.1 (4.2)
RP	102.6 (1.9)	51.5 (3.8)	39.9 (3.4)	60.9 (3.3)	99.9 (4.0)
RPV	100.0 (−0.8)	50.4 (1.6)	39.0 (1.0)	59.1 (0.3)	99.1 (3.3)
	Precipitation (mm day^{-1})				
C	4.36	2.70	2.35	2.90	3.29
P	4.34 (−0.4)	2.69 (−0.2)	2.33 (−1.1)	2.89 (−0.3)	3.28 (−0.2)
PV	4.35 (−0.2)	2.78 (3.0)	2.34 (−0.6)	2.94 (1.3)	3.29 (0.1)
R	4.58 (5.0)	2.91 (7.7)	2.54 (7.8)	3.10 (7.0)	3.43 (4.2)
RP	4.58 (5.0)	2.89 (6.8)	2.49 (5.8)	3.09 (6.5)	3.42 (4.0)
RPV	4.45 (2.1)	2.79 (3.1)	2.43 (3.4)	2.99 (3.0)	3.40 (3.3)
	Surface air temperature (°C)				
C	28.1	17.4	4.8	19.6	18.5
P	28.5 (0.4)	17.7 (0.3)	5.1 (0.3)	19.8 (0.3)	18.7 (0.1)
PV	28.8 (0.7)	17.9 (0.5)	5.9 (1.1)	20.2 (0.7)	18.9 (0.3)
R	29.8 (1.7)	20.0 (2.6)	8.8 (4.0)	22.2 (2.6)	20.4 (1.9)
RP	30.2 (2.1)	20.3 (2.9)	8.7 (3.9)	22.4 (2.8)	20.5 (1.9)
RPV	30.6 (2.6)	20.0 (2.6)	8.1 (3.3)	22.2 (2.7)	20.4 (1.8)

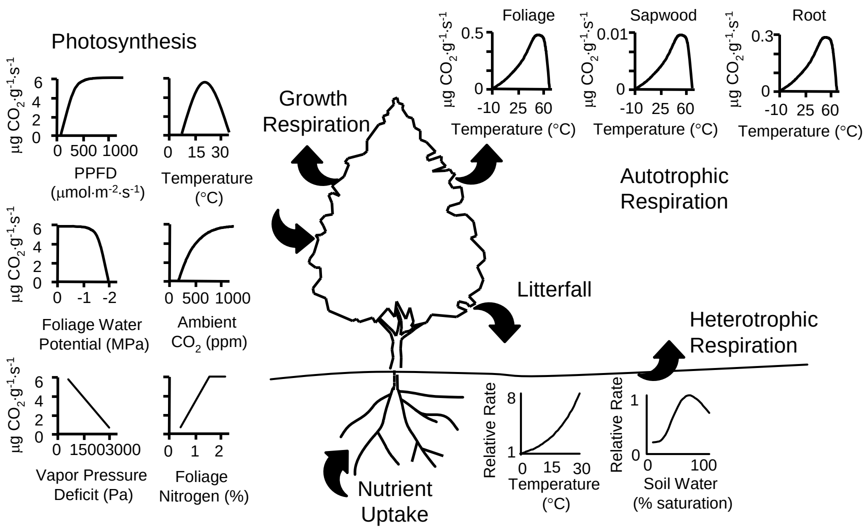
Global climate:
Reduced conductance
Reduced evaporation
Reduced precipitation
Warmer temperature

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

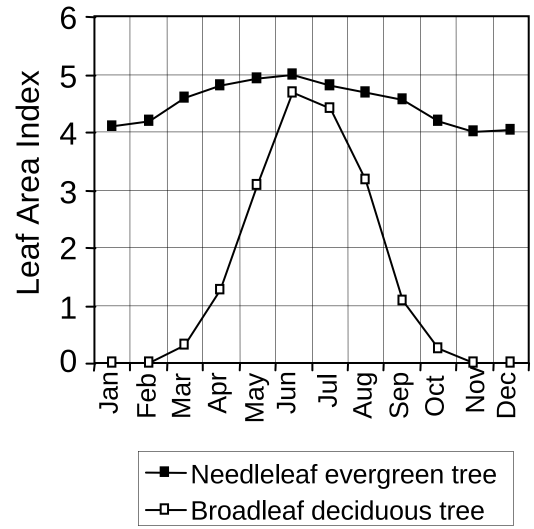
Fourth-generation of models

Dynamic vegetation

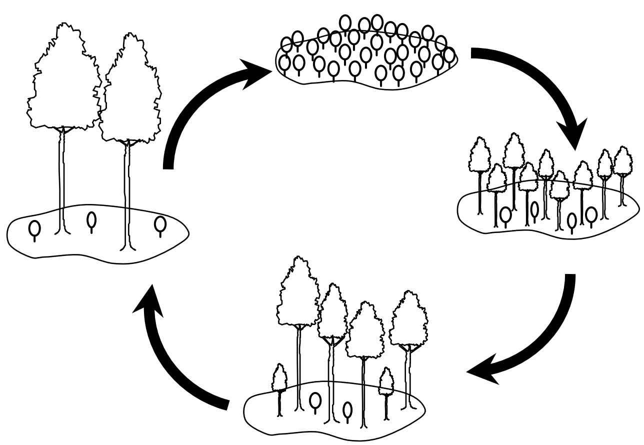
Ecosystem carbon balance



Leaf phenology

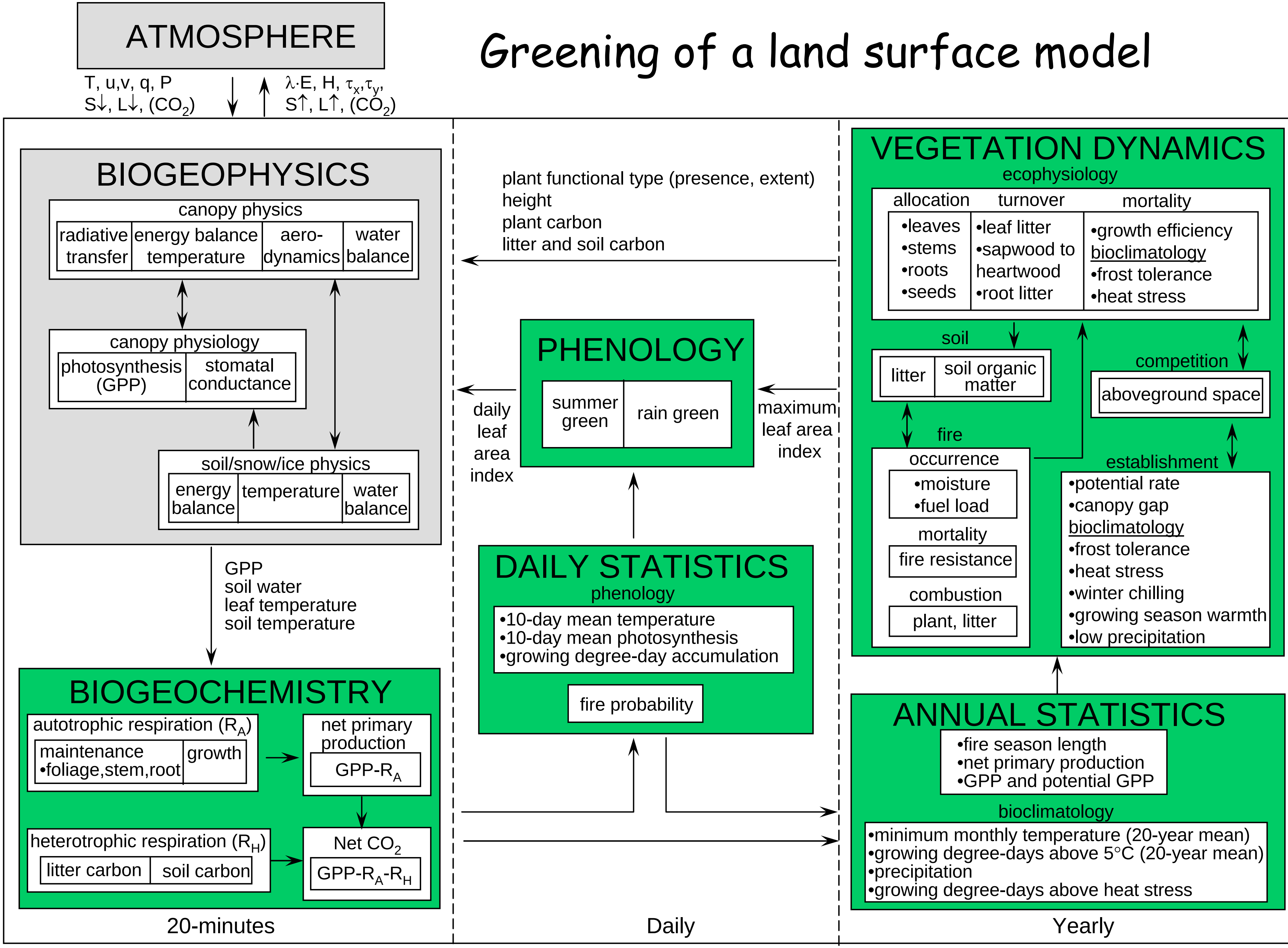


Vegetation dynamics



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

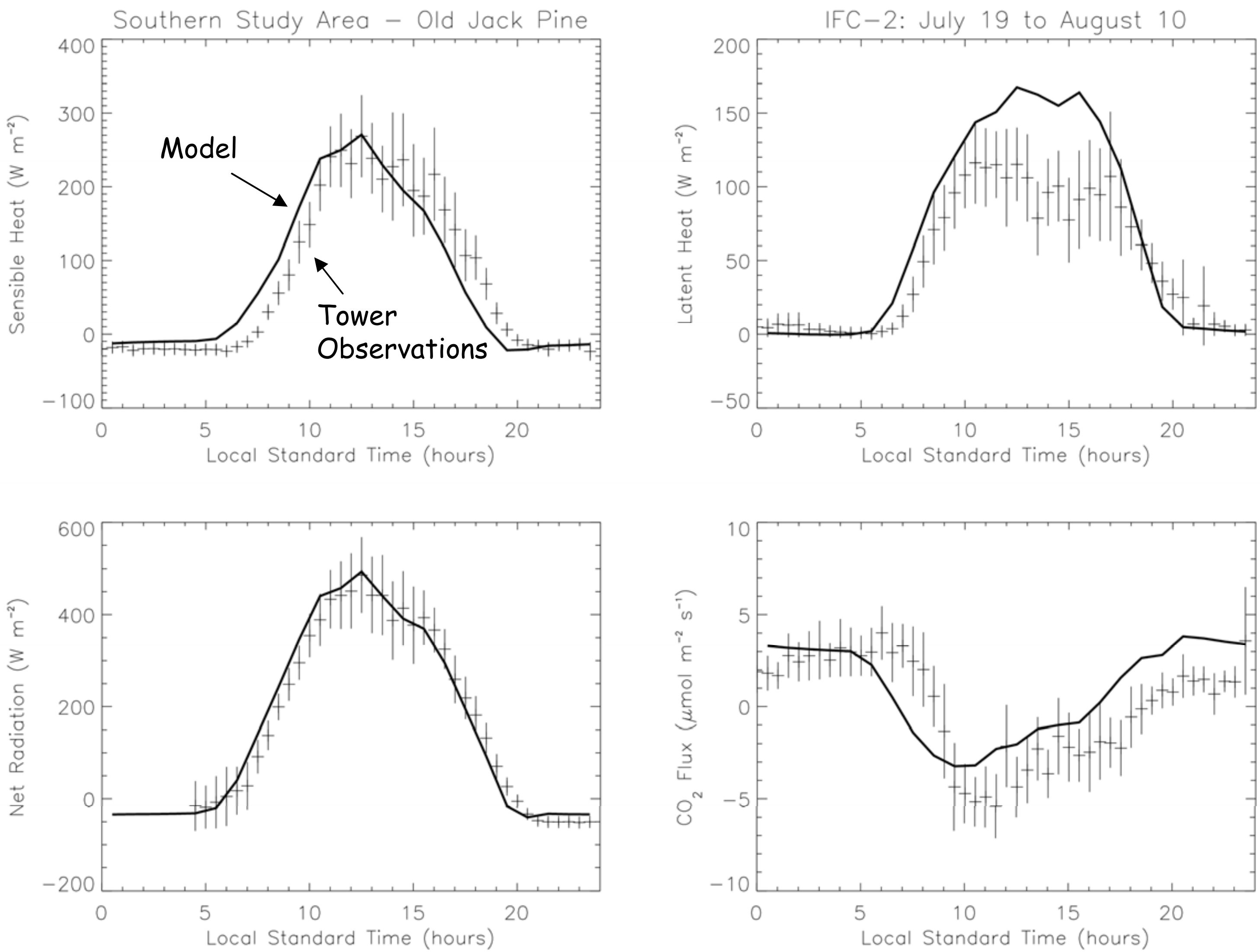
Greening of a land surface model



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

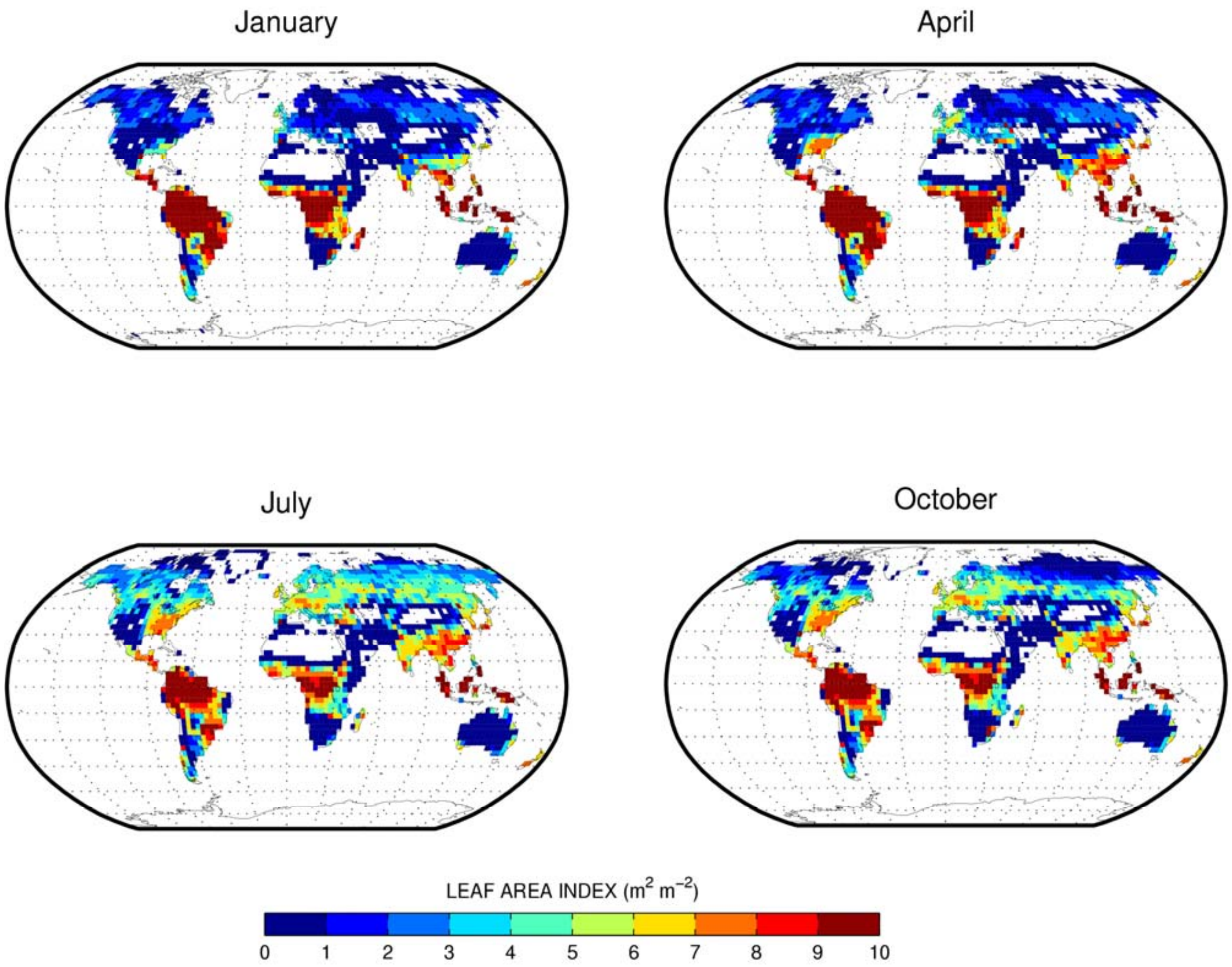
Model validation – tower fluxes

Boreal Ecosystem Atmosphere Study (BOREAS)



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

Simulated Leaf Area Index



Three types of phenology

- Evergreen
- Raingreen
- Summergreen

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

Model validation – global net primary production

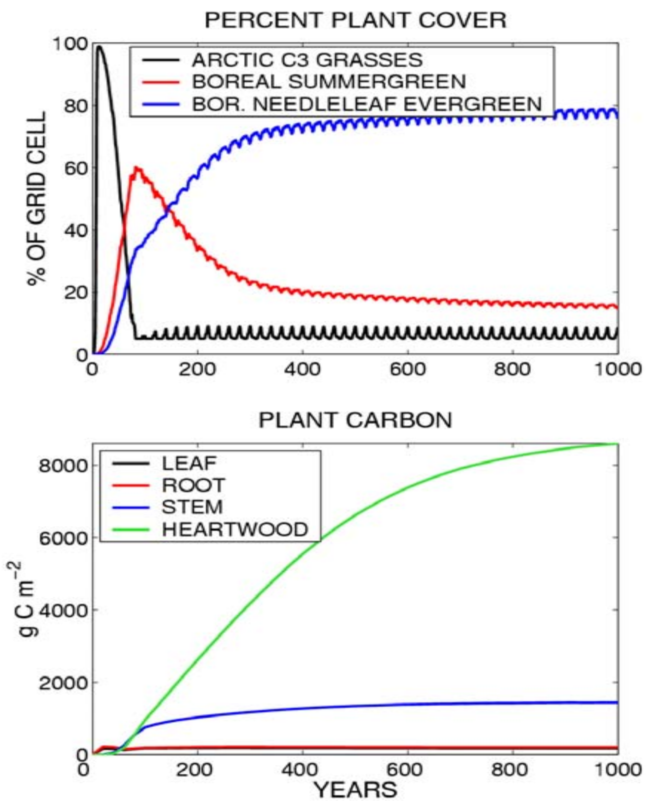
Annual net primary production (g C m^{-2} yr^{-1})

Vegetation Type	Simulated	Observed
Tropical broadleaf evergreen forest	1278	1250±900
Tropical broadleaf deciduous forest	886	825±475
Temperate broadleaf deciduous forest	579	600±325
Boreal deciduous forest	346	425±200
Boreal needleleaf evergreen forest	385	325±200
Temperate/boreal mixed forest	576	525±275
Grassland	175	575±475
Tundra	159	150±200

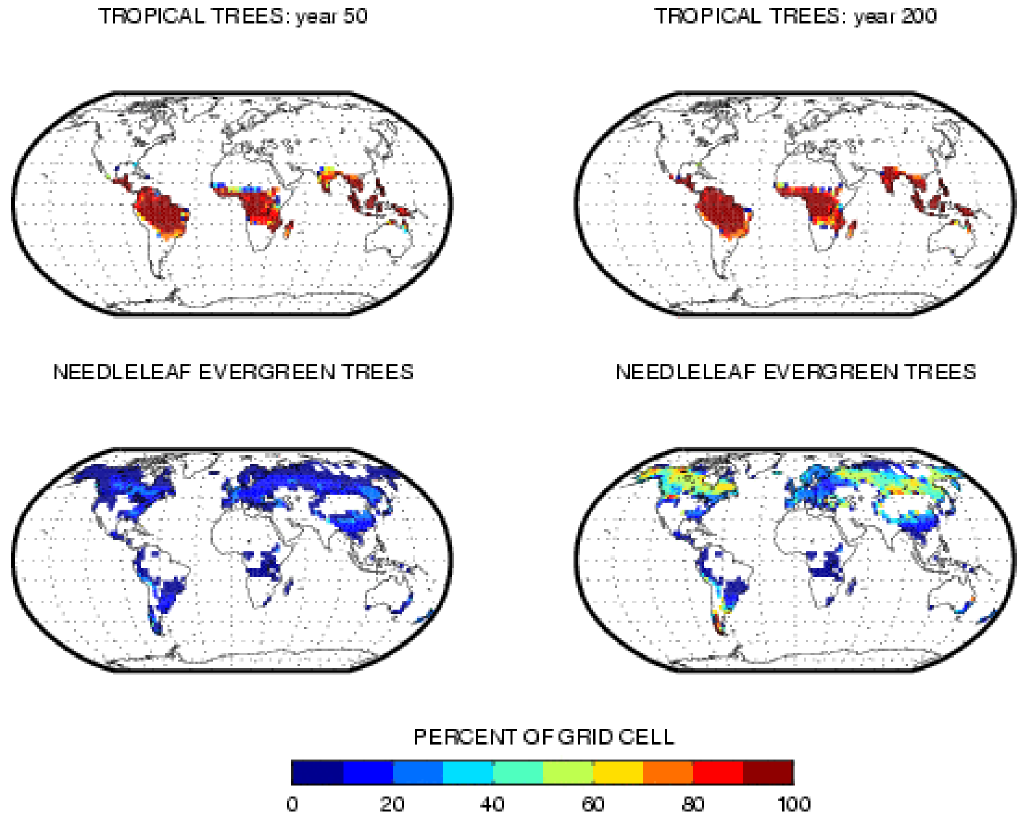
Bonan et al. (2003) Global Change Biology 9:1543-1566

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

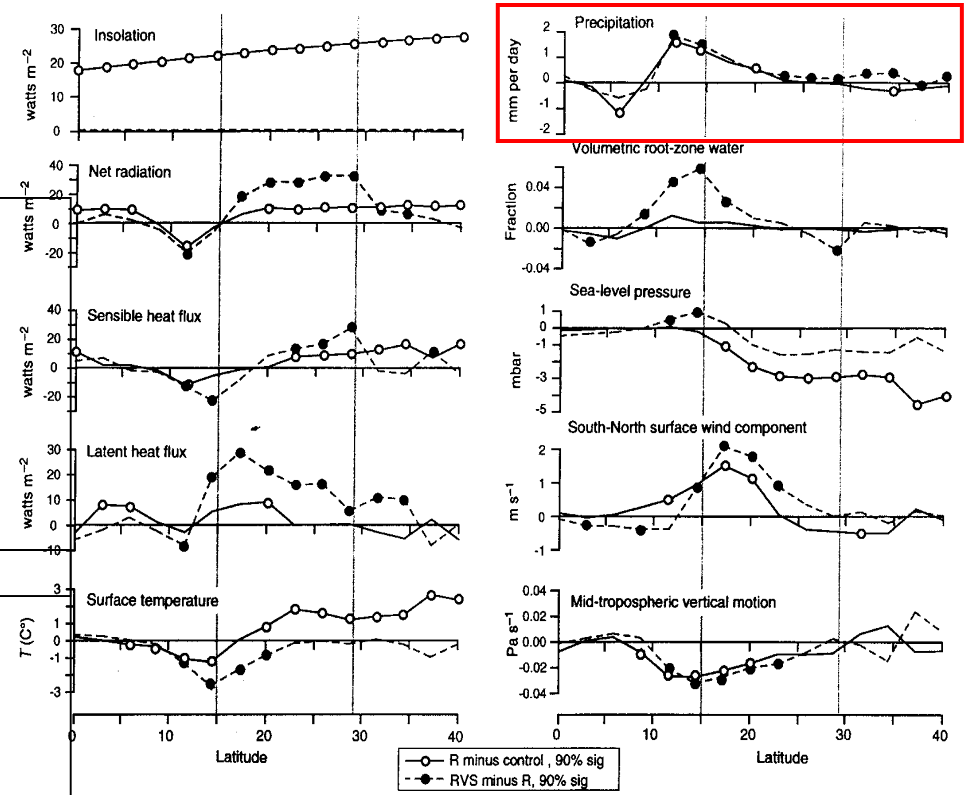
Strengthened African monsoon

Wetter North African climate allowed vegetation to expand

Two climate model experiments

Desert North Africa

Green North Africa



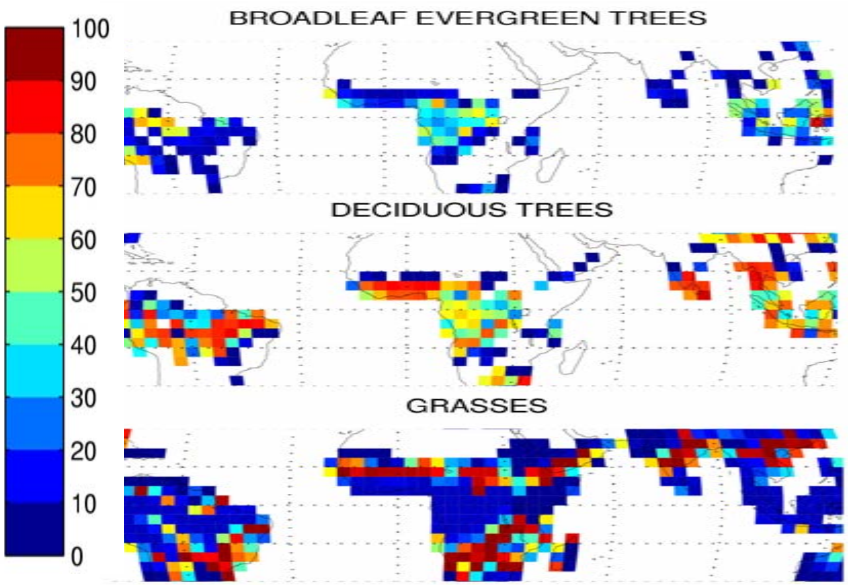
Climate model experiments show:

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

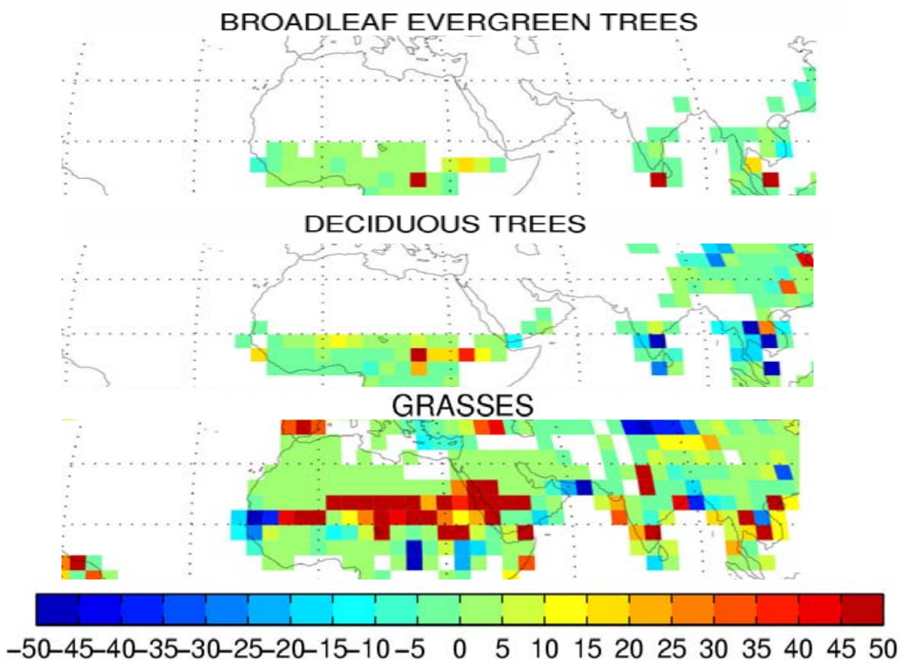
Kutzbach et al. (1996) Nature 384:623-626

Greening of North Africa

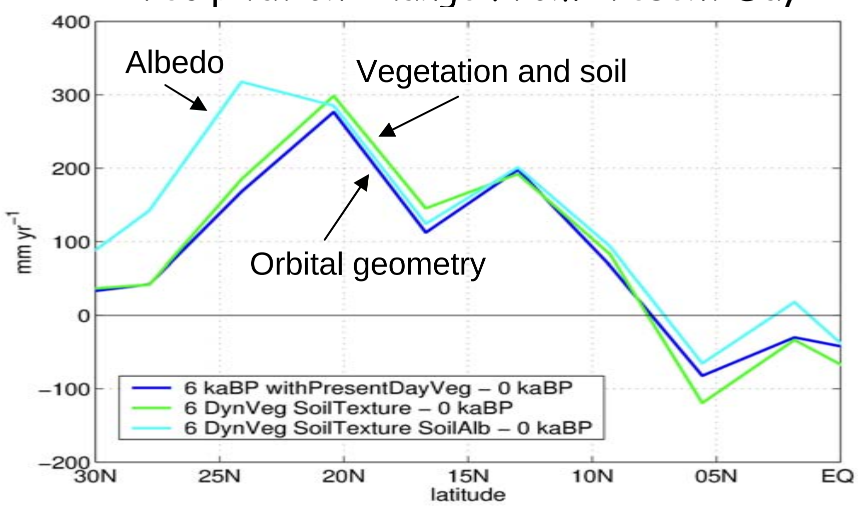
Present Day Biogeography
(percent of grid cell)



6kaBP DynVeg Soil Texture – 0 kaBP



Precipitation Change From Present Day



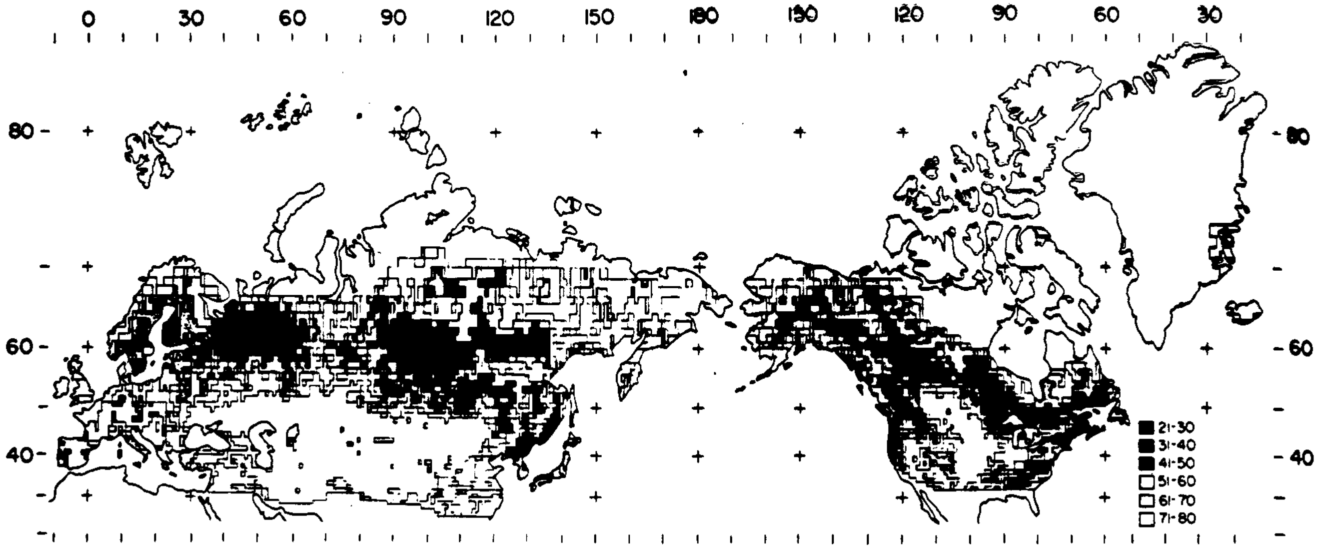
<u>Dominant forcing</u>
Increase in evaporation
Decrease in soil albedo

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

Effect of boreal forests on climate

Vegetation masking of snow albedo

Maximum satellite-derived surface albedo during winter



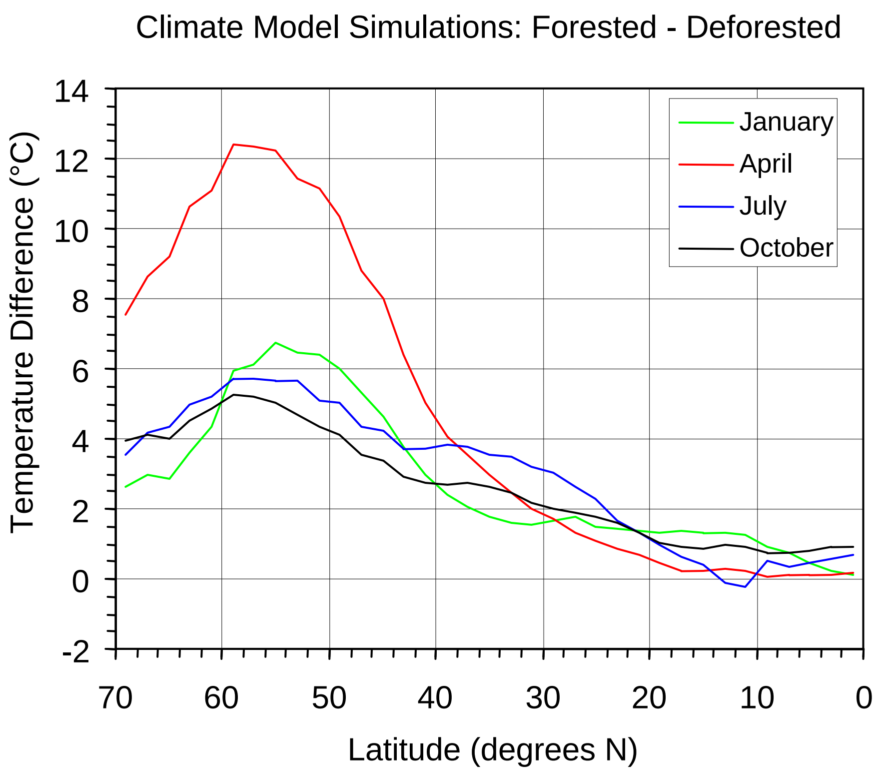
Robinson & Kukla (1985) J Climate Appl Meteor 24:402-411

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

Colorado Rocky Mountains

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)

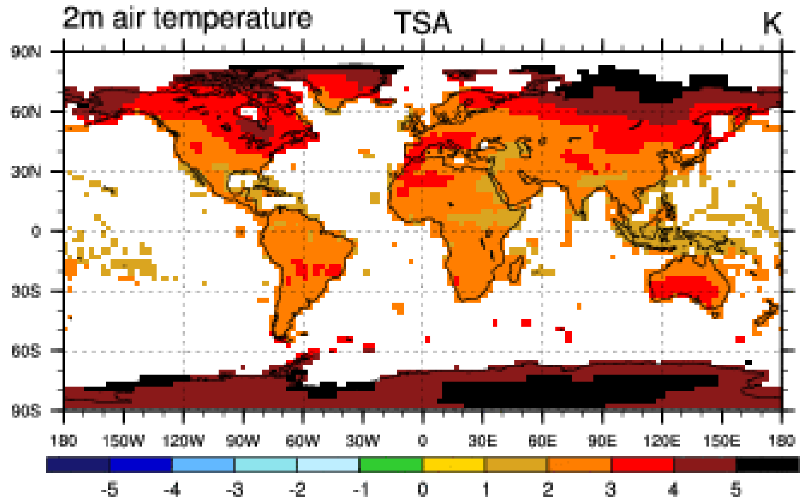
Bonan et al. (1992) Nature 359:716-718

Effect of boreal forests on climate

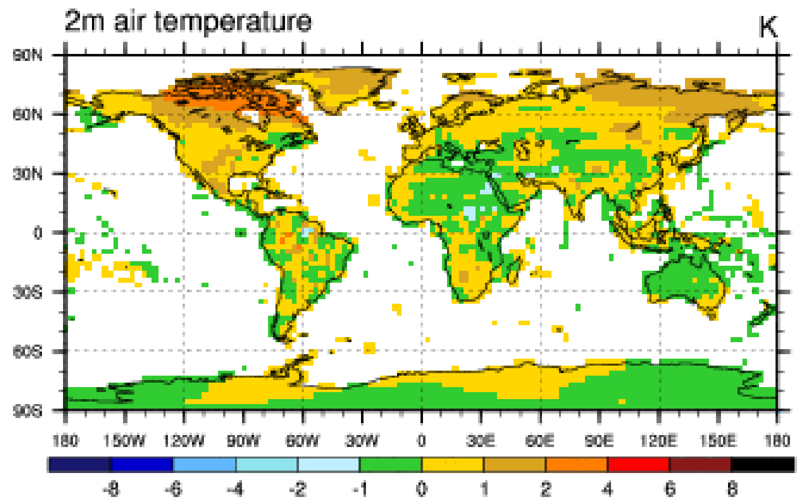
Boreal forest expansion with $2\times CO_2$ warms climate

Dominant forcing
Decrease in albedo
[Carbon storage could mitigate warming]

Mean annual temperature ($2\times CO_2$)

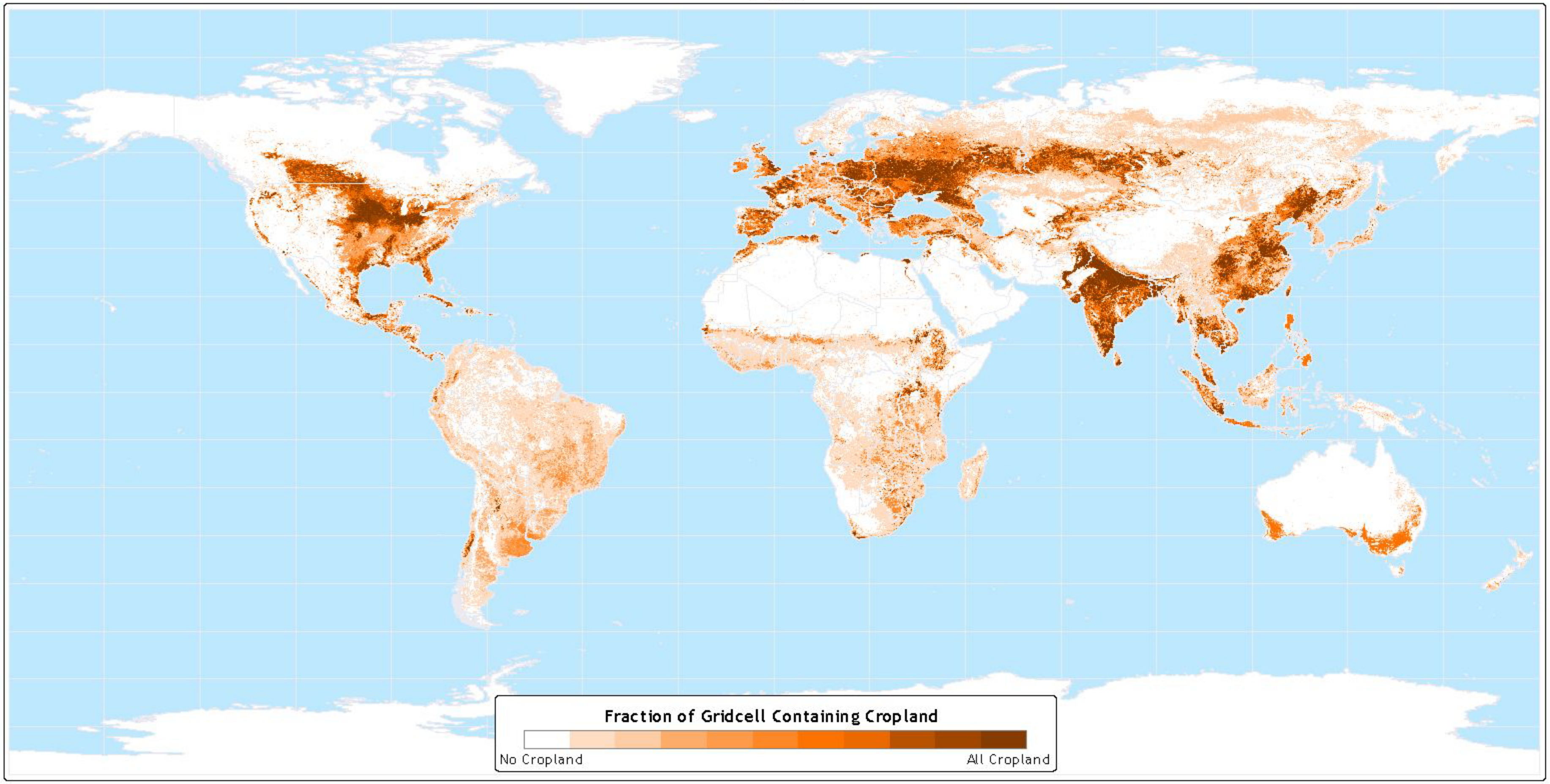


Additional temperature change with vegetation



Bonan & Levis, unpublished

Land cover change as a climate forcing

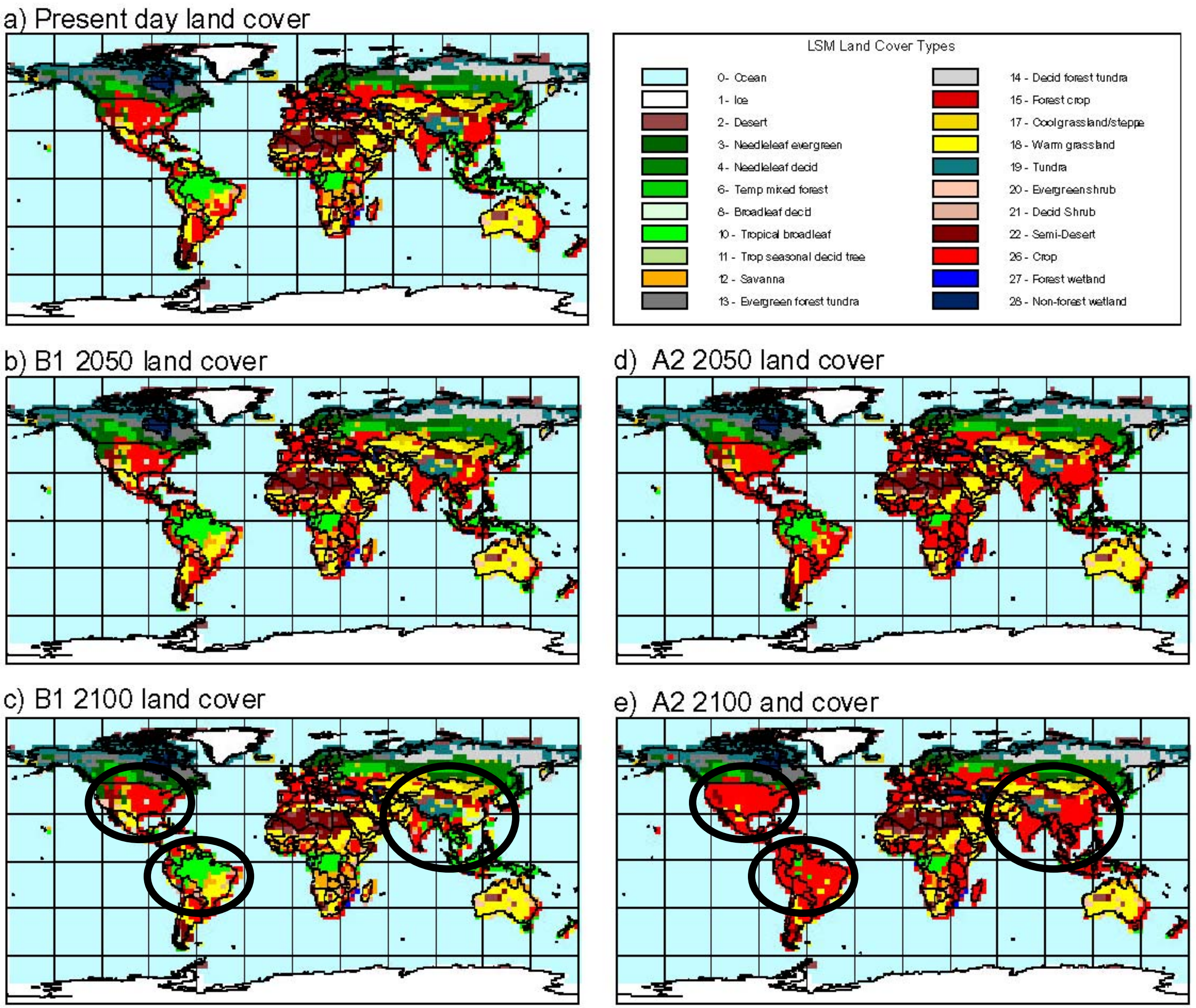


Data taken from: Ramankutty and Foley 1999

Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison

Land cover change as a climate forcing

Future IPCC SRES Land Cover Scenarios for NCAR LSM/PCM



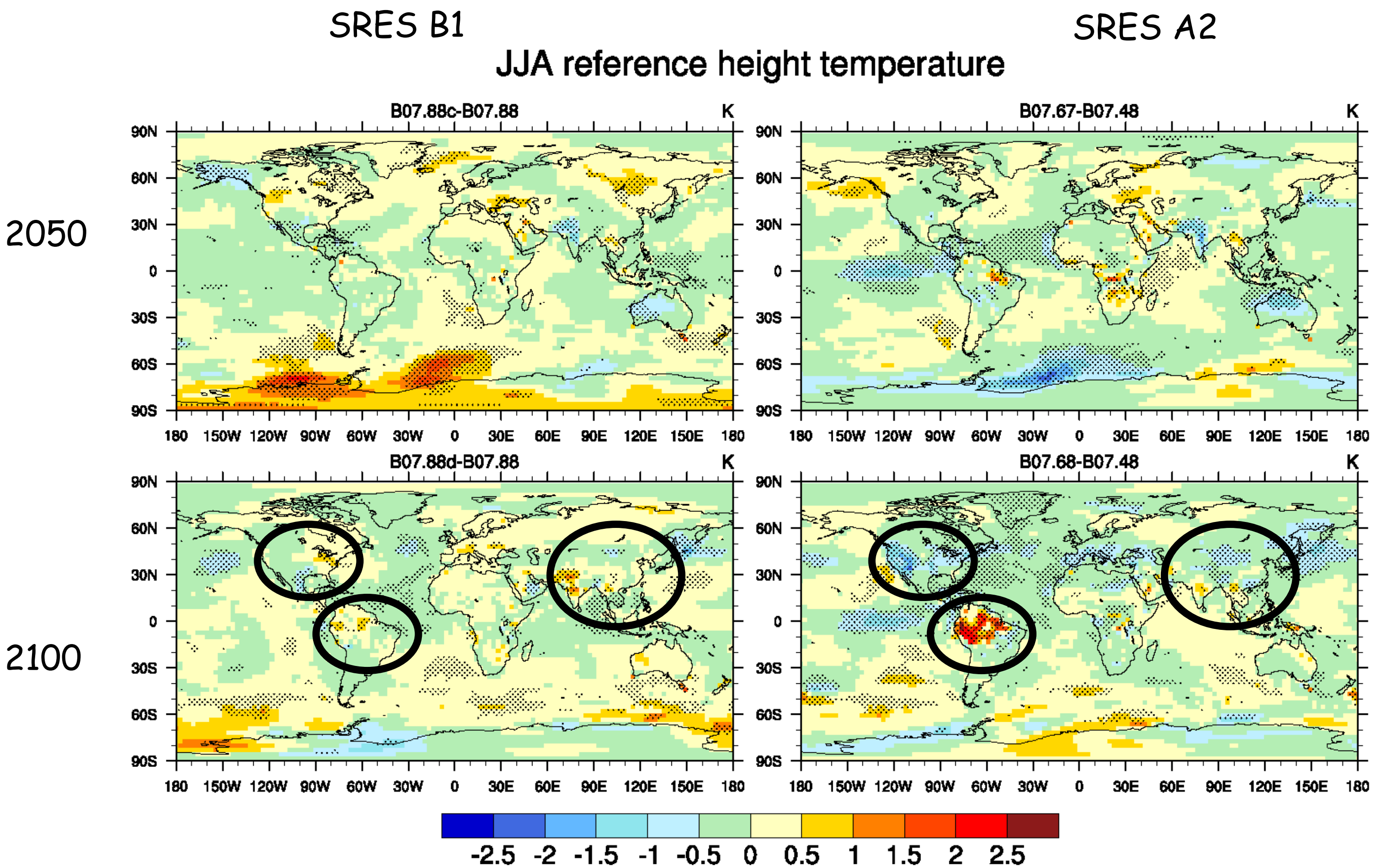
Forcing arises from changes in

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

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

Land use climate forcing



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

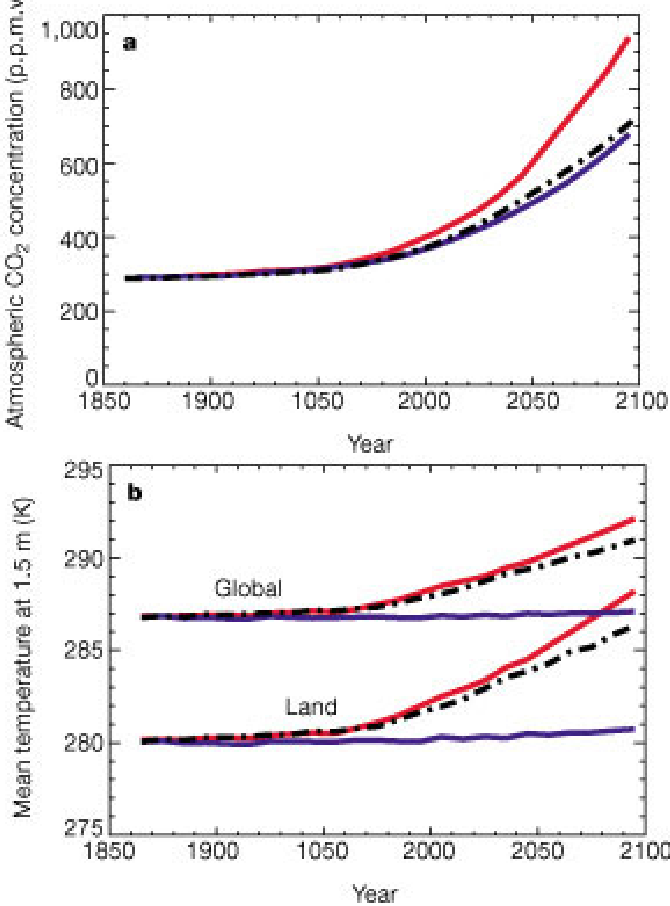
Feddema et al. (2005) Science 310:1674-1678

Carbon cycle feedback

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

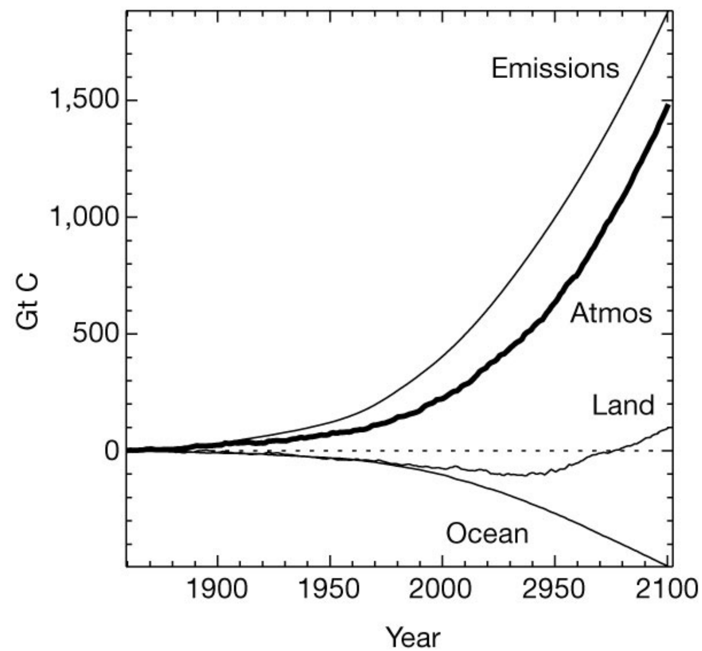
- Prescribed CO_2 and fixed vegetation (a 'standard' GCM climate change simulation)
- Interactive CO_2 and dynamic vegetation but no effect of CO_2 on climate (no climate/carbon cycle feedback)
- Fully coupled climate/carbon-cycle simulation (climate/carbon cycle feedback)

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