Modeling the Biosphere in 2050: Successes and Failures, Consensus and Controversies (v2)

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National Center for Atmospheric Research
Boulder, Colorado, USA

CESM Land Model Working Group Meeting
Boulder, CO
11 February 2019

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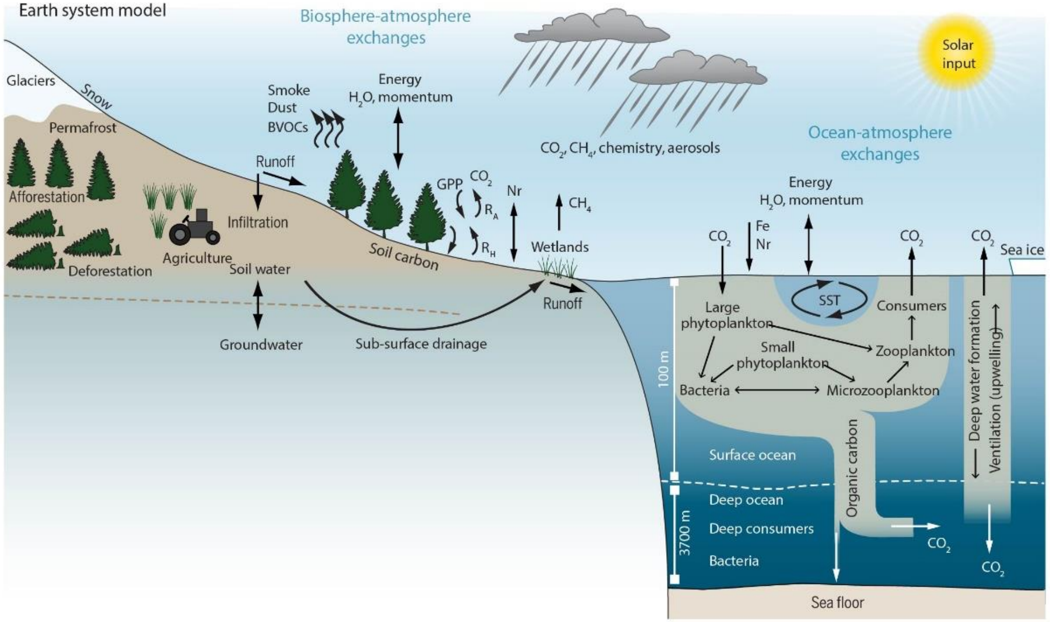
Earth system models

Earth system perspective with terrestrial ecosystems and biogeochemical cycles



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

Earth system prediction

What are the consequences of alternative socioeconomic pathways?

Scientific discovery

Identify ecological processes that determine climate

Advance theory

Test generality of ecological theories at the macroscale

NCAR models circa 1993

NCAR/TN-382+STR
NCAR TECHNICAL NOTE

June 1993

Description of the
NCAR Community Climate Model (CCM2)

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

CLIMATE AND GLOBAL DYNAMICS DIVISION

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

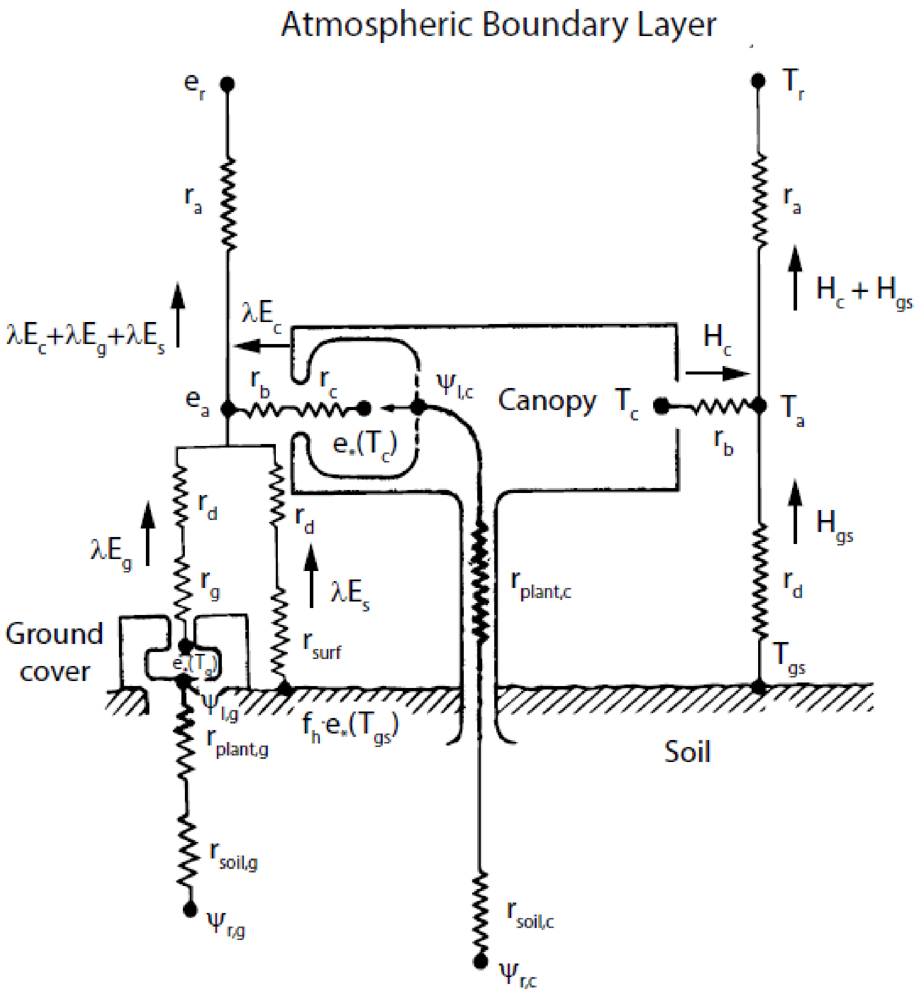
- Prescribed soil wetness and snow depth
- Prescribed surface albedos
- No plant canopies (no leaves or stomata)

Advent of land surface models

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

Diffusive fluxes as controlled by plant canopies:

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



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

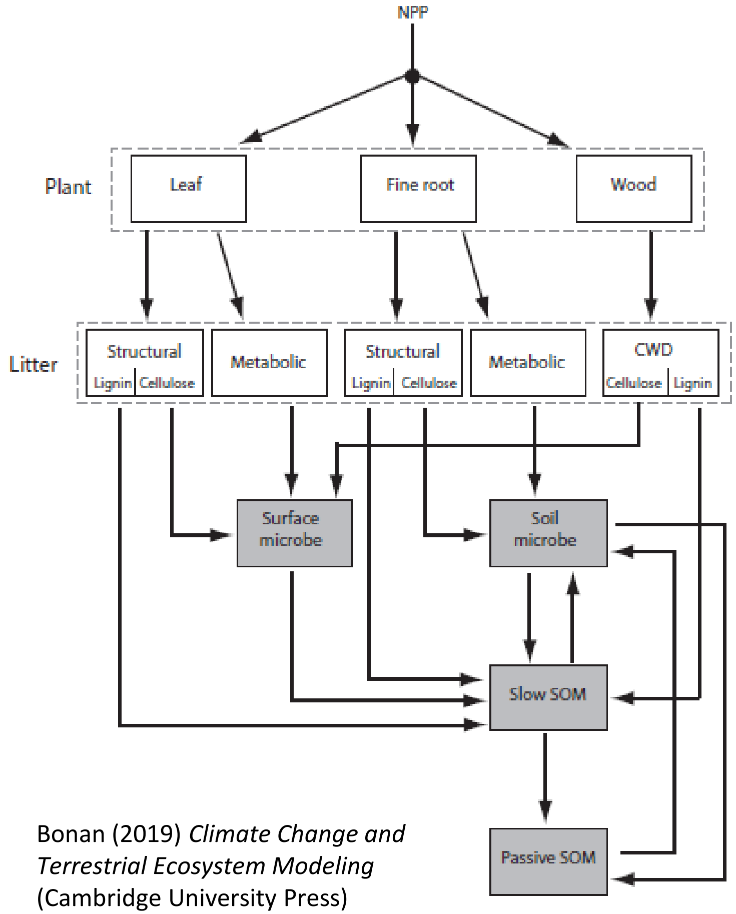
Biogeochemical perspective

Evolution of carbon sinks in a changing climate

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

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

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



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

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

- Simple 12-pool model

Centennial research

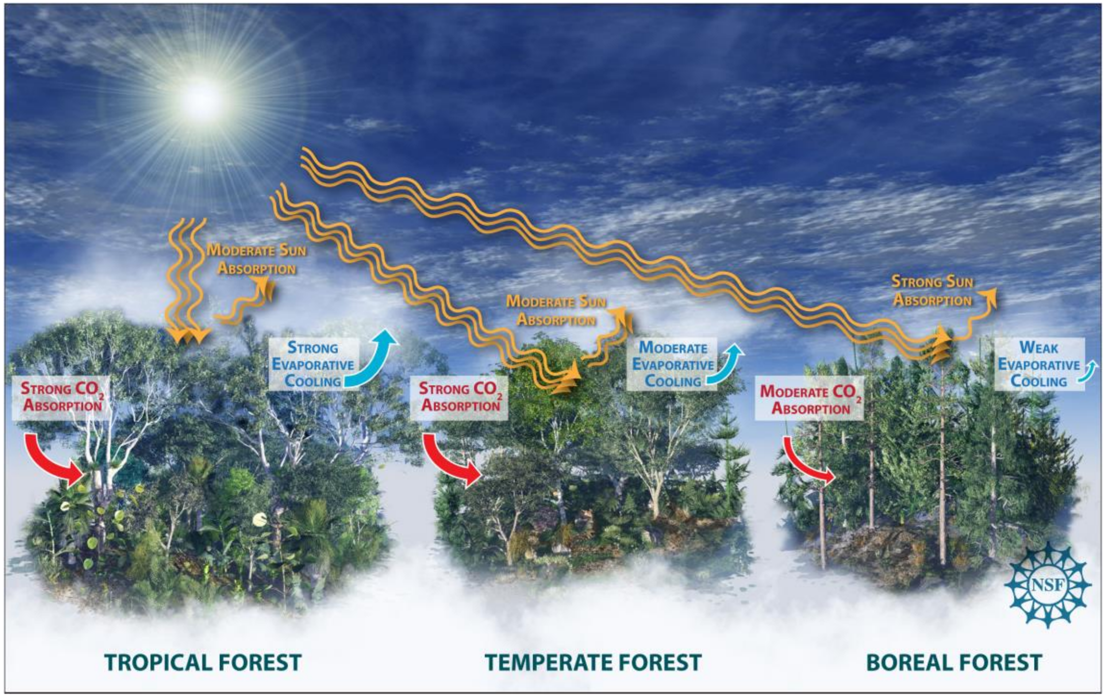
Past

“rational climatology gives no basis for the much-talked of influence upon the climate of a country produced by the growth or destruction of forests … and the cultivation of crops over a wide extent of prairie”

Abbe (1889) Is our climate changing? *Forum*, 6(Feb.), 678-688

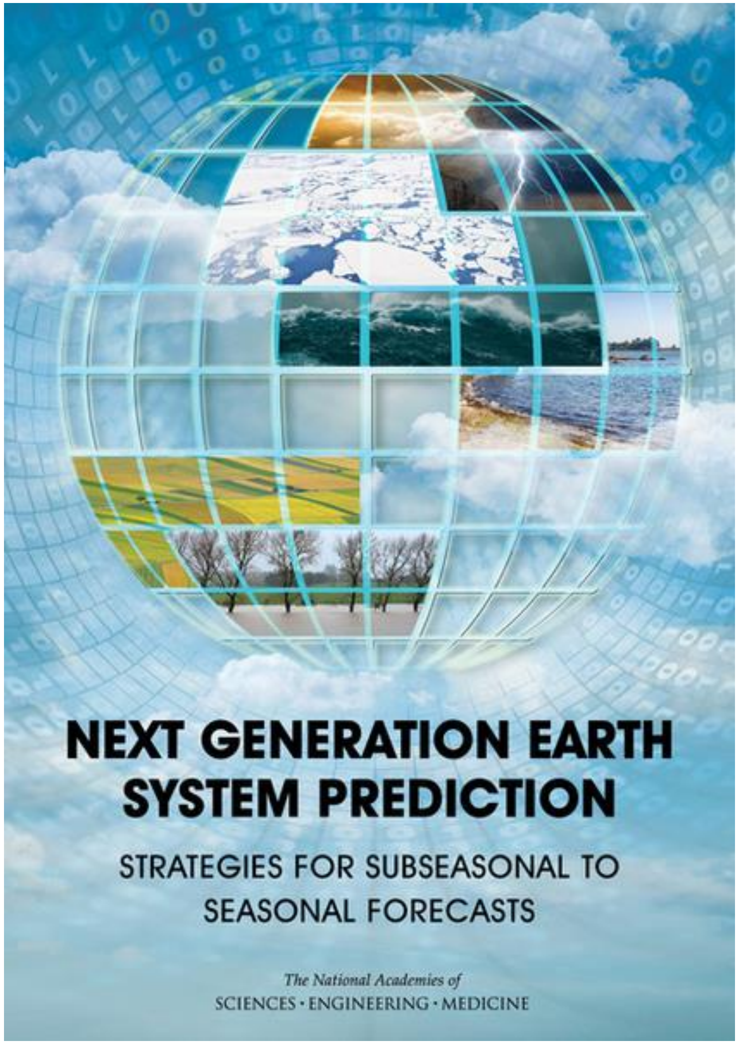
(the AMS recognizes Abbe’s contributions with the Cleveland Abbe Award For Distinguished Service to Atmospheric Science)

Present: climate services of forests



Bonan (2008) *Science*, 320, 1444-1449 Credit: *Nicolle Rager Fuller, National Science Foundation*

Earth system prediction

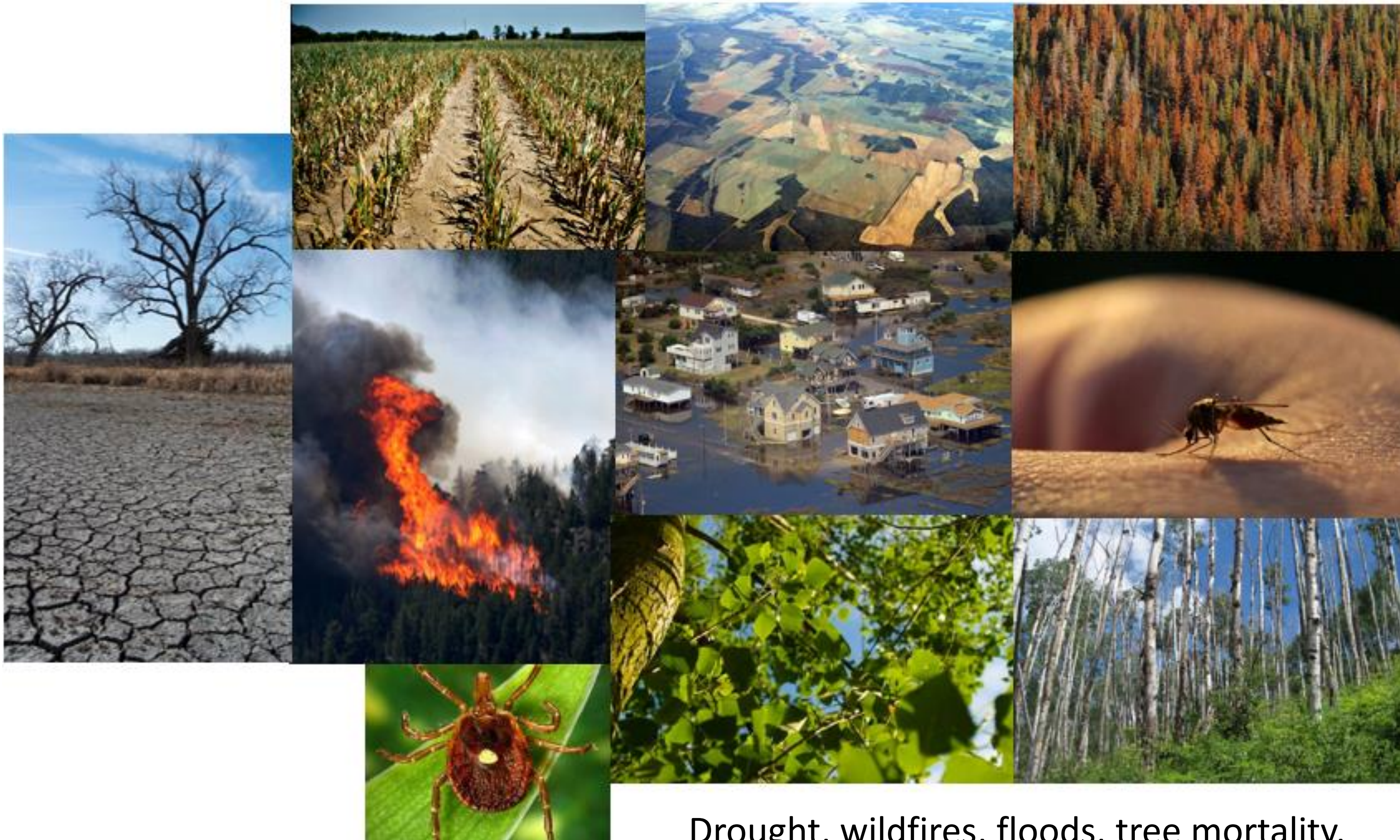


Land as a source of atmospheric predictability
- Soil moisture
- Snow
- Vegetation state (leaf area)

(NAS, 2016)

Earth system change

… or predictability of land state and fluxes

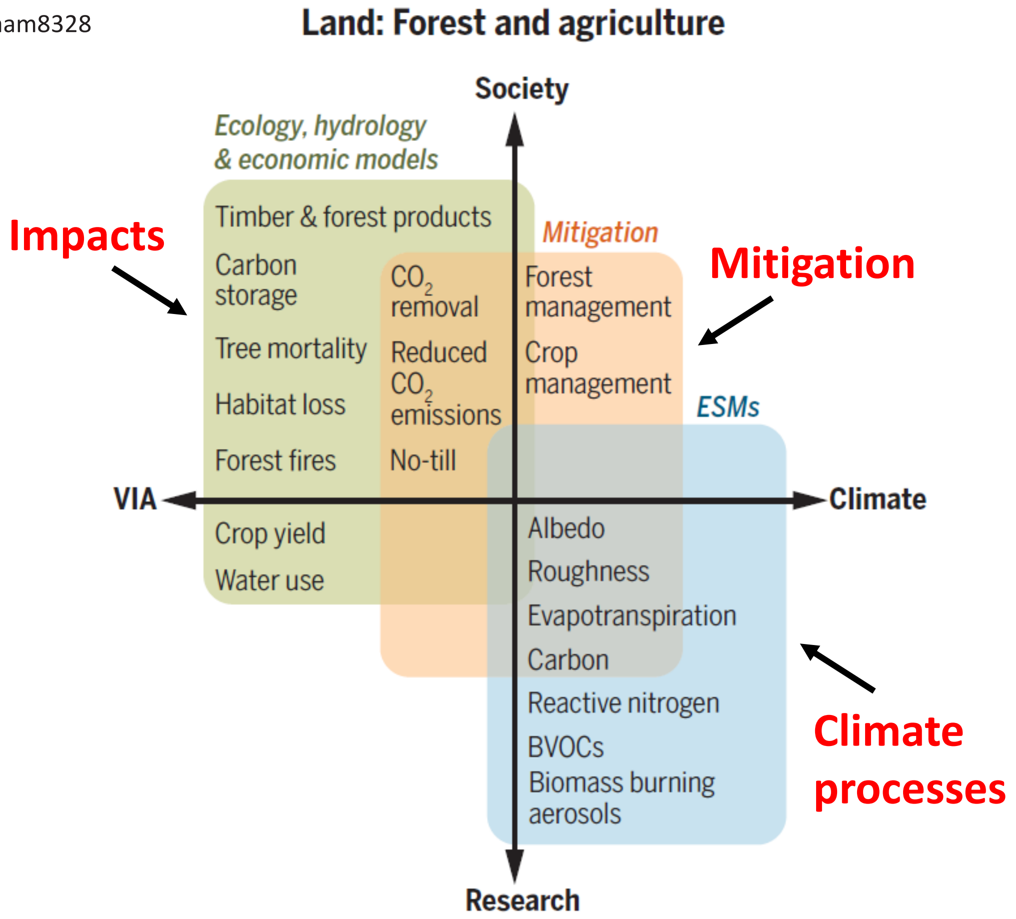


Drought, wildfires, floods, tree mortality, vegetation greening, habitat loss, infectious disease

Earth system prediction

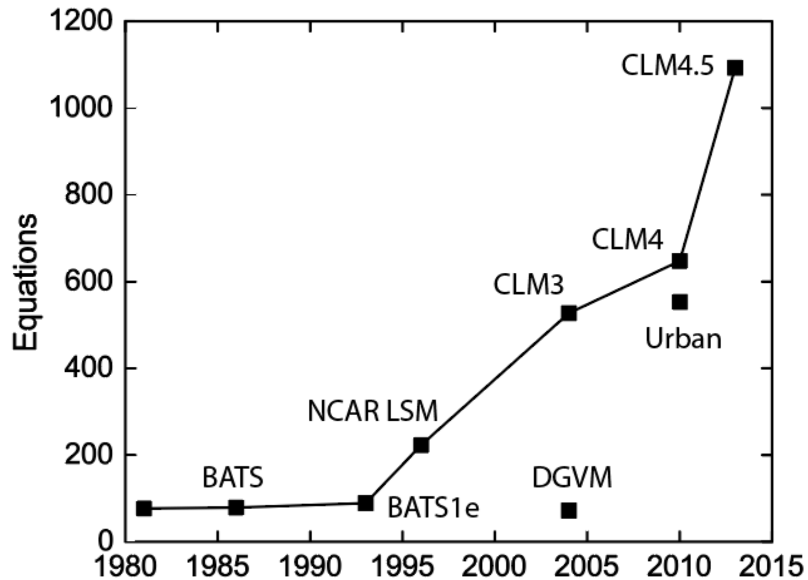
The various models used for climate projections, mitigation, and impacts (VIA) overlap in scope and would benefit from a broad perspective of Earth system prediction

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



Increasing model complexity

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

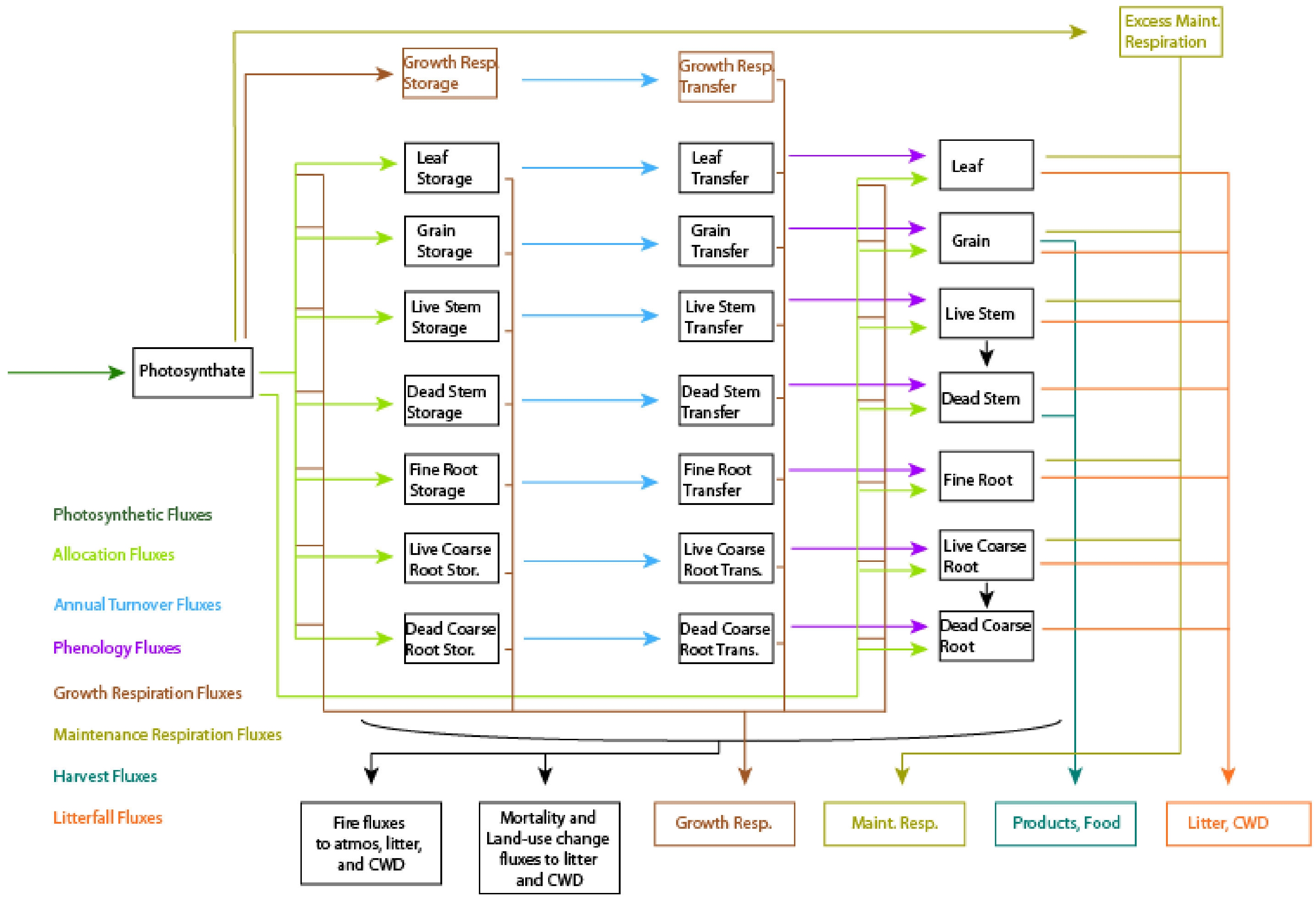


Bonan (2019) *Climate Change and Terrestrial Ecosystem Modeling* (Cambridge University Press)

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

Increasing model complexity

Vegetation carbon pools and fluxes in the Community Land Model



CLM4.5: 70 carbon balance equations (including vertically resolved soil carbon in 10 soil layers)

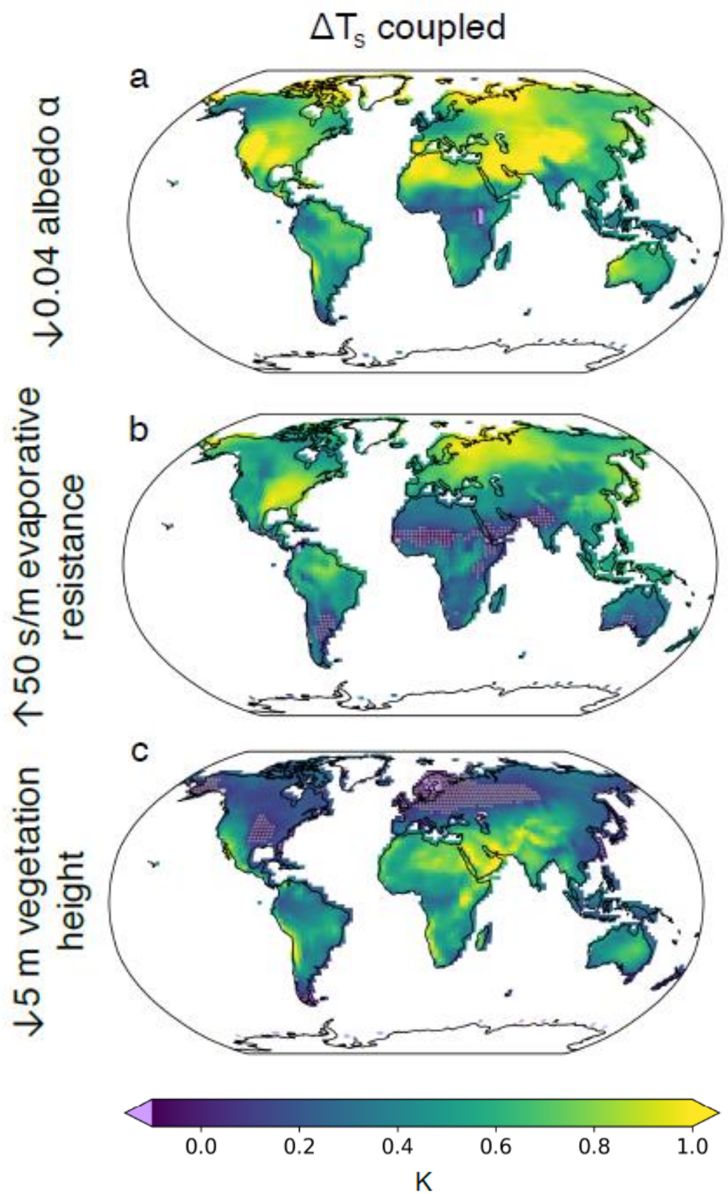
CLM5.0 Technical Description:
cesm.ucar.edu/models/cesm2/land

Hierarchy of models

Simple Land Interface Model (SLIM)
(Marysa Lägue, Univ. of Washington)

Lägue, Bonan & Swann, *J. Clim.*, submitted

Allows separation of albedo, evaporation, and roughness effects on climate



Deconstructing models

deconstruct: to take apart or examine (something) in order to reveal the basis or composition often with the intention of exposing biases, flaws, or inconsistencies
(Merriam-Webster)

Monin-Obukhov similarity theory $$\frac{k(z-d)}{u_*}\frac{\partial u}{\partial z} = \phi_m\left(\frac{z-d}{L_{MO}}\right)$$

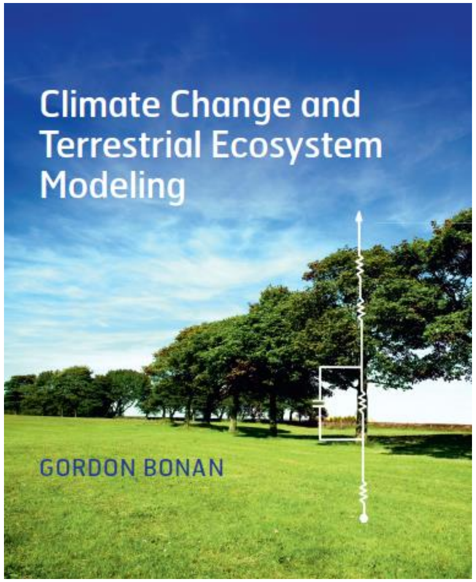
Richards equation $$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial \psi}{\partial z}\right] + \frac{\partial K}{\partial z}$$

FvCB photosynthesis $$A_c = \frac{V_{c\max}(c_i - \Gamma_*)}{c_i + K_c(1 + o_i/K_o)} - R_d$$

$$A_j = \frac{J}{4}\left(\frac{c_i - \Gamma_*}{c_i + 2\Gamma_*}\right) - R_d$$

Ball-Berry stomatal conductance $$g_{sw} = g_0 + g_1 \frac{A_n}{c_s} h_s$$

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



Modeling photosynthesis

Planta 149, 78–90 (1980)

Planta

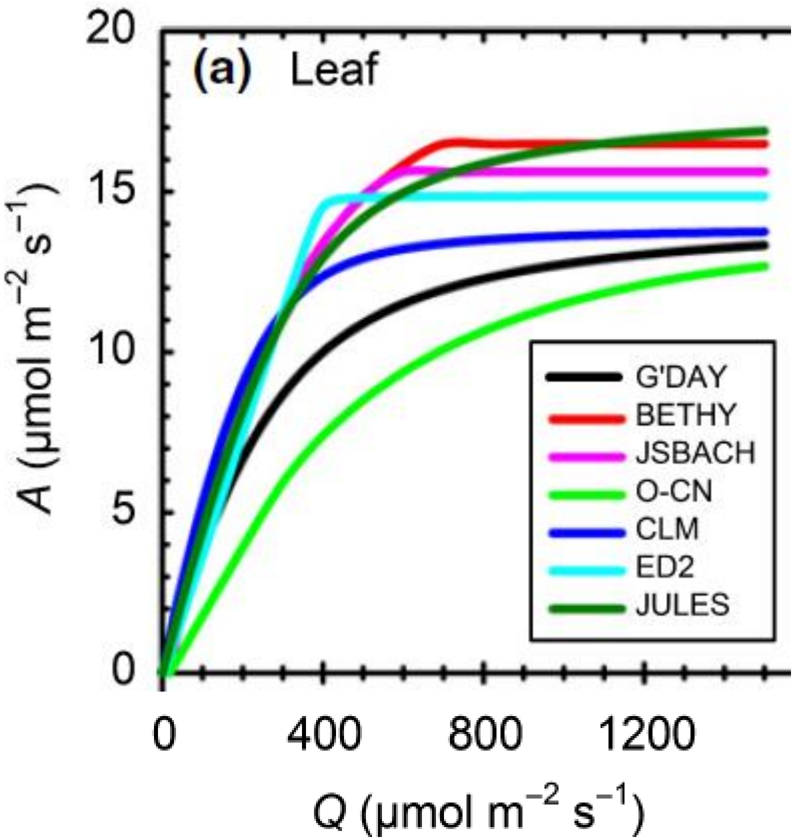
A Biochemical Model of Photosynthetic CO_2 Assimilation in Leaves of C_3 Species

G.D. Farquhar[1], S. von Caemmerer[1], and J.A. Berry[2]

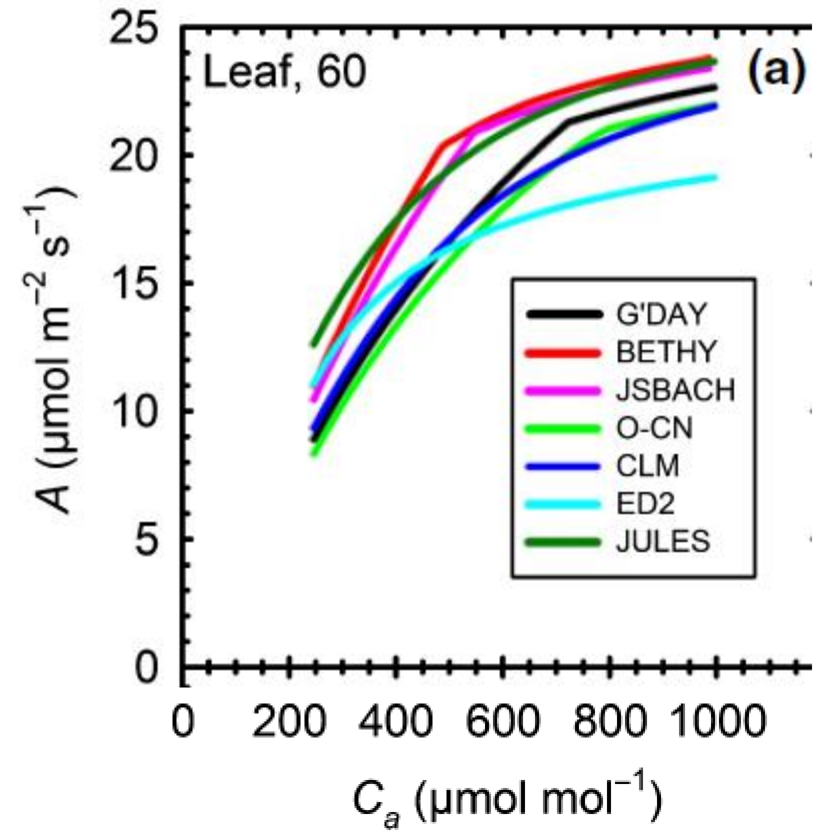
[1] Department of Environmental Biology, Research School of Biological Sciences, Australian National University, P.O. Box 475, Canberra City ACT 2601, Australia and
[2] Carnegie Institution of Washington, Department of Plant Biology, Stanford, Cal. 94305, USA

Are we modeling the same thing?

Light response



CO_2 response



Rogers et al. (2017) *New Phytol.,* 213, 22-42

Stomatal conductance

Ball, Woodrow & Berry (1987)

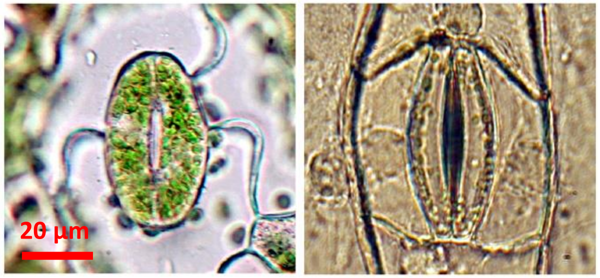
$g_{sw} = \underbrace{g_0 + g_{1B}}_{\text{Empirical parameters}} A_n h_s / c_s$

Empirical relationship between stomatal conductance and photosynthesis. Parameter g_{1B} obtained from leaf gas exchange data.

Medlyn et al. (2011)

$g_{sw} = g_0 + 1.6\,(1 + g_{1M} / D_s^{1/2})\, A_n / c_s$

Derived from optimality theory after many simplifying assumptions. Uses empirical parameter g_{1M}.



Franks & Farquhar (2007) *Plant Physiol.* ,143, 78-87

Optimization theory (Cowan & Farquhar 1977)

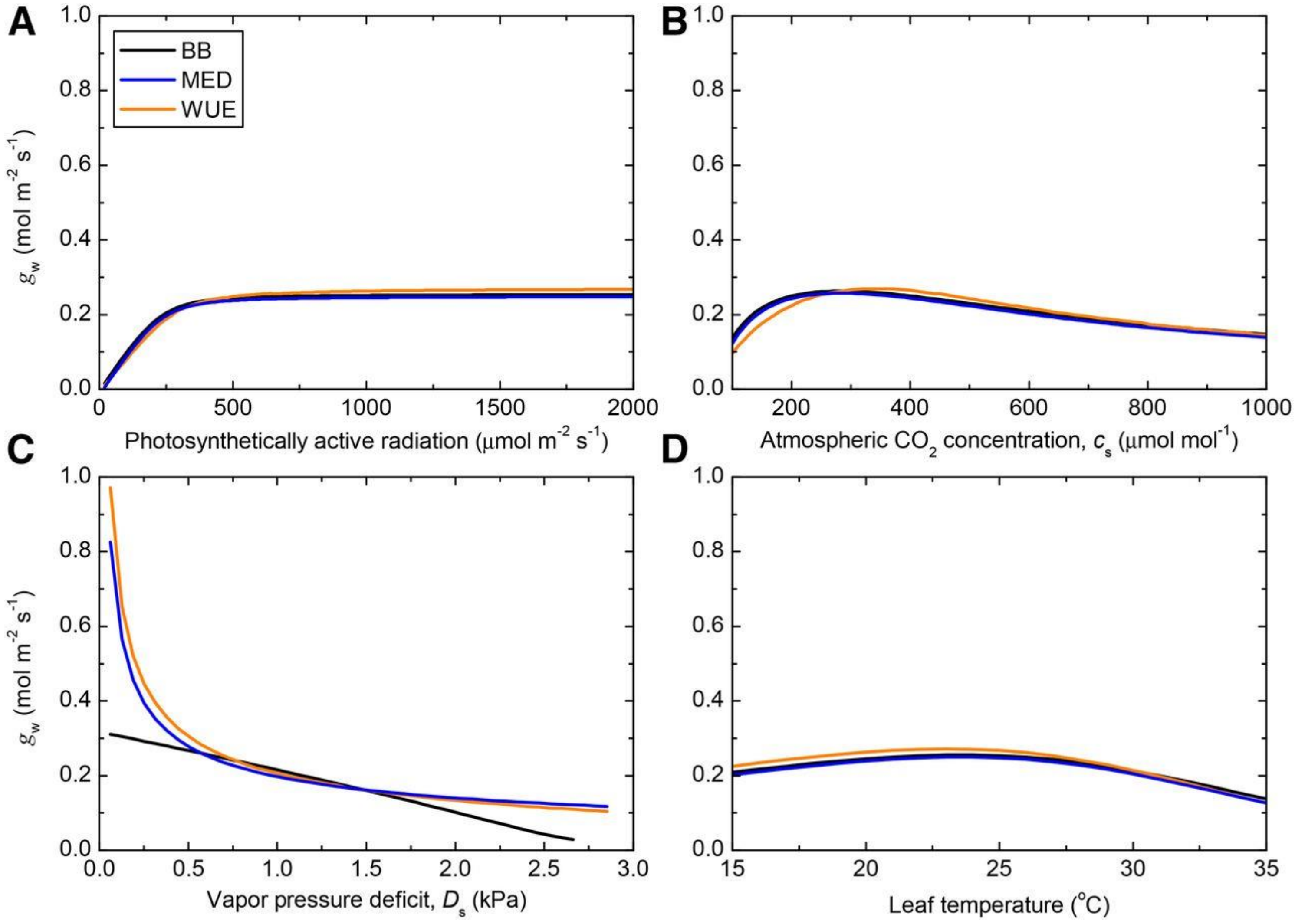
Stomata optimize photosynthetic carbon gain per unit transpiration water loss:

$\partial A_n / \partial E = \iota$

Need to specify ι (marginal water-use efficiency)

Similar model behavior

Using comparable g_{1B}, g_{1M}, and ι values gives similar results



Franks et al. (2017) *Plant Physiol.*, 174, 583-602

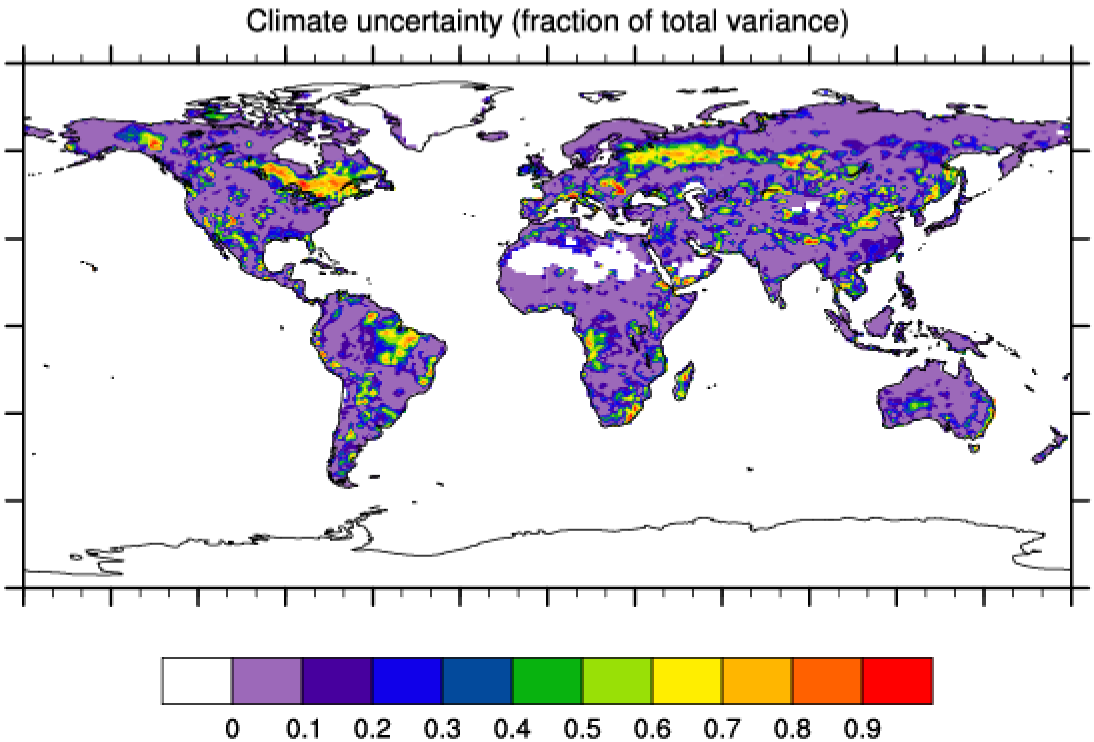
Sources of uncertainty

Ensemble of 6 land-only CLM historical simulations

- 3 models: CLM4, CLM4.5 & CLM5 (very different carbon cycles)
- 2 climate forcings: CRUNCEP & GSWP3
- Partition variance across 6 simulations into model structure and climate forcing

GPP (2000-2009)

Uncertainty in climate forcing exceeds that from model structure in many regions. Similar results for NPP and carbon stocks



Bonan et al. (2019) *Global Biogeochem. Cycles*, submitted

Two viewpoints

Data will solve the problem

Earth system models disagree wildly about the magnitude and frequency of carbon-climate feedback events, and data to this point have been astonishingly ineffective at reducing this uncertainty.

Sellers, Schimel, et al. (2018) *PNAS*, 115, 7860-68

The equifinality thesis

Science … is supposed to be an attempt to work towards a single correct description of reality. It is not supposed to conclude that there must be multiple feasible descriptions of reality. The users of research also do not (yet) expect such a conclusion and might then interpret the resulting ambiguity of predictions as a failure (or at least an undermining) of the science.

Beven (2006) *J. Hydrology*, 320, 18-36

Reconstructing CLM

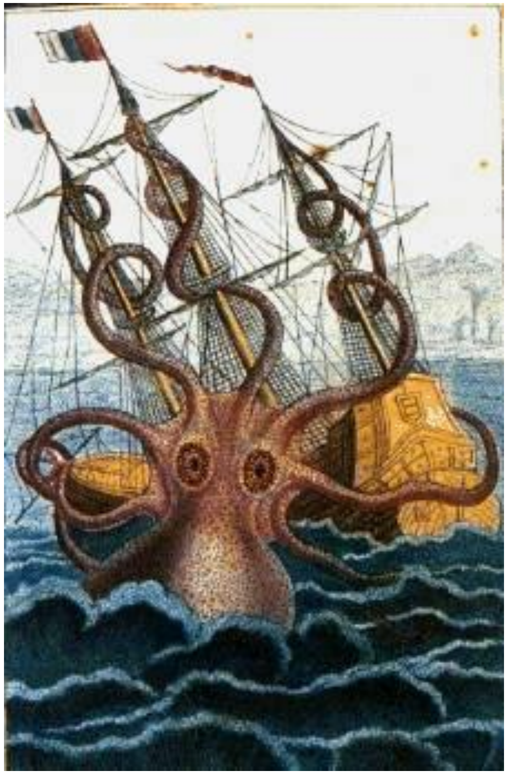
CLM5 surface fluxes

Many interconnected routines

- CanopyHydrology
- CanopySunShadeFracs
- SurfaceRadiation
- CanopyTemperature
- BareGroundFluxes
- CanopyFluxes
    - FrictionVelocity
    - Photosynthesis
    - PhotosynthesisHydraulicStress
    - Fractionation
    - CalcOzoneStress
    - LUNA
- VOCEmission
- SoilTemperature
- SoilFluxes
- DryDepVelocity
- SurfaceAlbedo

A knot to untangle …

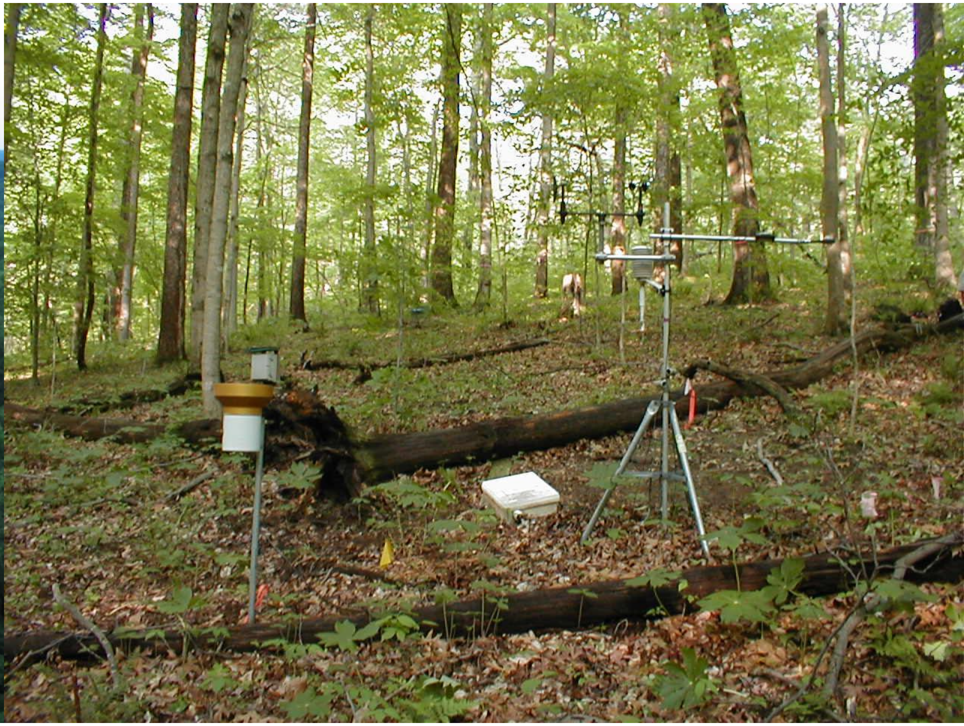
… or the kraken devouring a ship



Colossal octopus attacking a ship (Pierre Denys de Montfort, 1801)

Two ways to model plant canopies

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)



A carpet of leaves

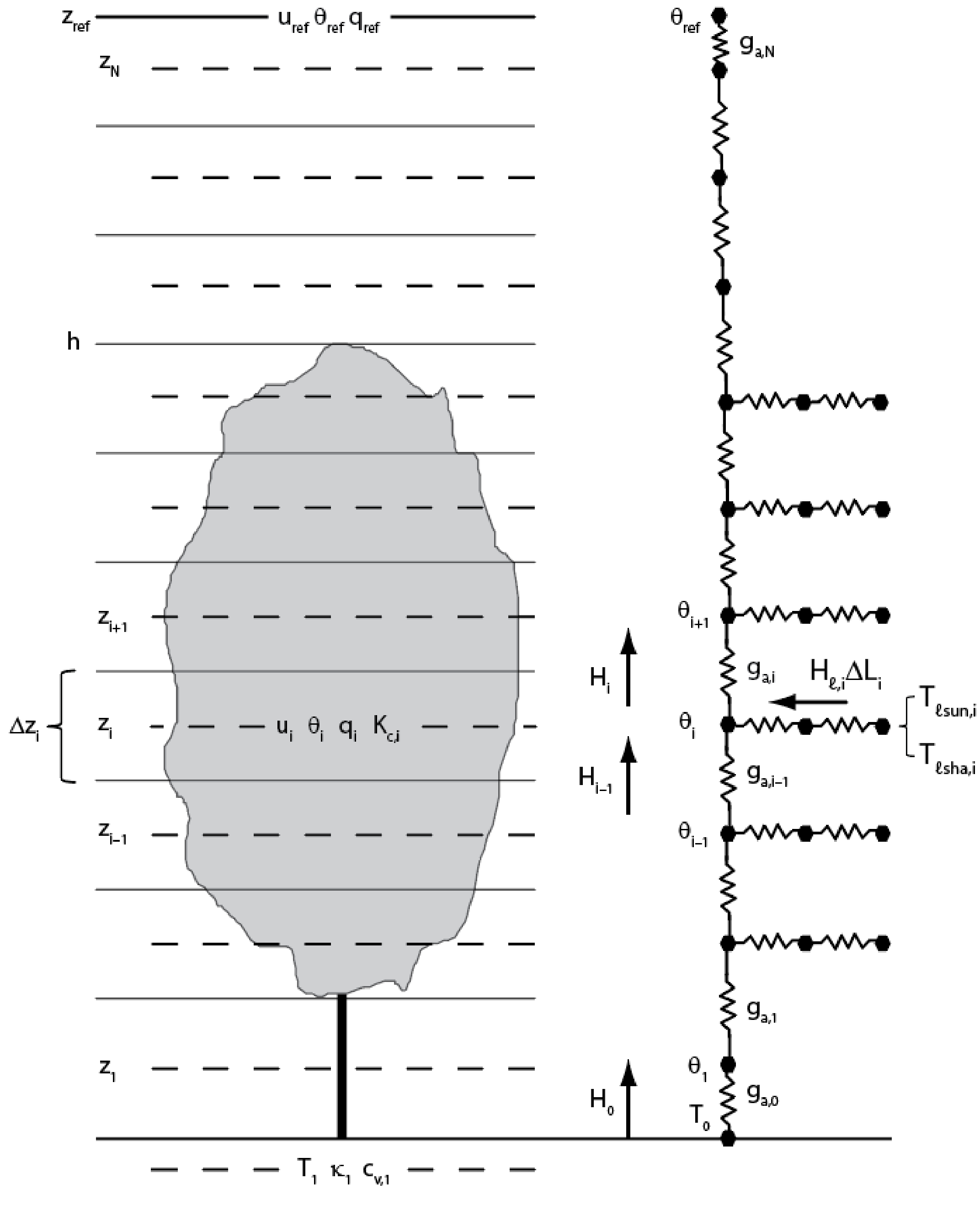
“incorrect but useful”

A vertically-structured canopy

“correct but useless”

Raupach & Finnigan (1988) *Aust. J. Plant Physiol.*, 15, 705-716

Multilayer canopy



Water-use efficiency optimization while preventing leaf desiccation ($\psi_\ell > \psi_{\ell min}$; plant hydraulics)

Williams et al. (1996) *Plant Cell Environ.*, 19, 911-27
Bonan et al. (2014) *Geosci. Model Dev.*, 7, 2193-2222

Canopy turbulence and roughness sublayer

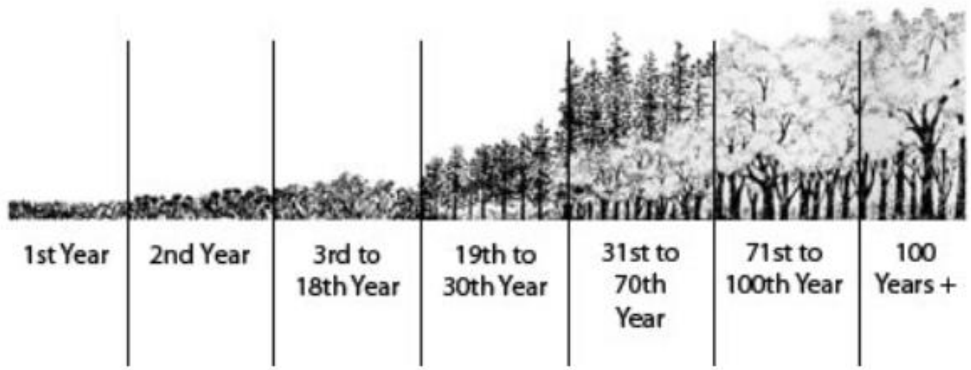
Harman & Finnigan (2007, 2008) *Boundary-Layer Meteorol.*, 123, 339-63; 129, 323-51

Bonan et al. (2018) *Geosci. Model Dev.*, 11, 1467-96

The physics and physiology of the multilayer canopy are simpler and more consistent with theory than is the CLM5 big-leaf canopy (with many ad-hoc parameterizations and much technical debt)

Forest succession and community organization

Succession in the North Carolina Piedmont



https://dukeforest.duke.edu/forest-environment/forest-succession/

Ecosystems as superorganisms with emergent properties representing a distinct level of ecological organization

Clements (1916) *Plant Succession: An Analysis of the Development of Vegetation*

Clements (1928) *Plant Succession and Indicators*

Ecosystems as the sum of its individual organisms interacting with each other and the environment

Gleason (1917) *Bulletin of the Torrey Botanical Club*, 44, 463-481

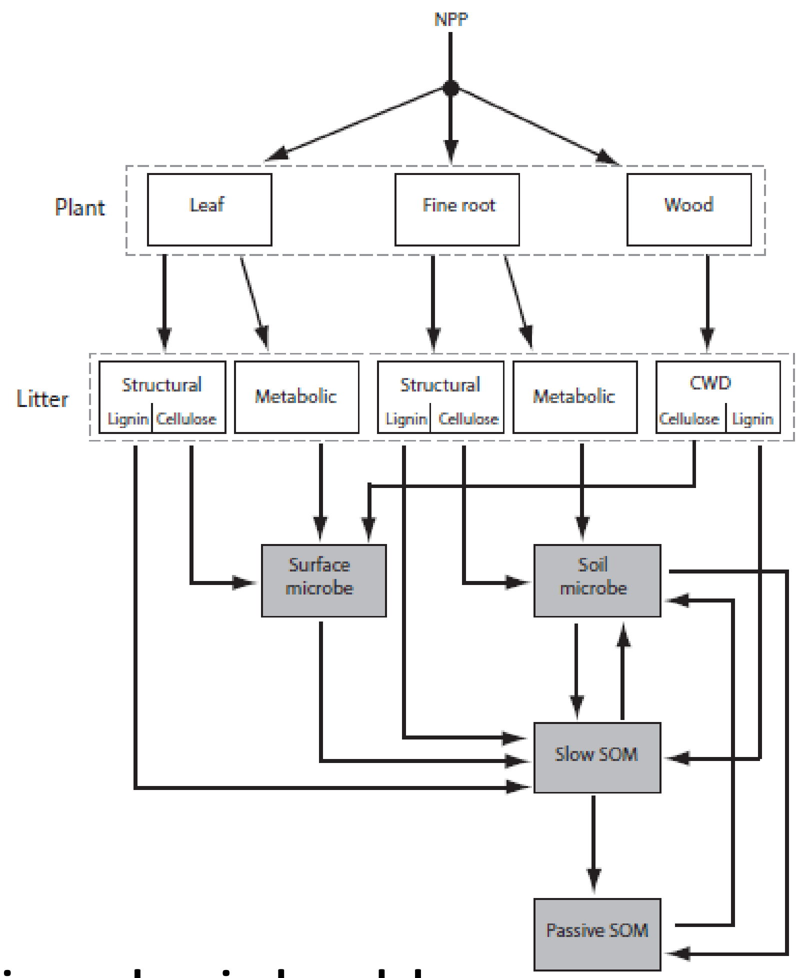
Gleason (1926) *Bulletin of the Torrey Botanical Club*, 53, 7-26

Tansley (1935) first coined the term ecosystem as part of this debate

Tansley (1935) *Ecology*, 16, 284-307

Contrasting views of ecosystems

Clementsian view



Biogeochemical model

Ecosystem as system of interconnected pools

Gleasonian view

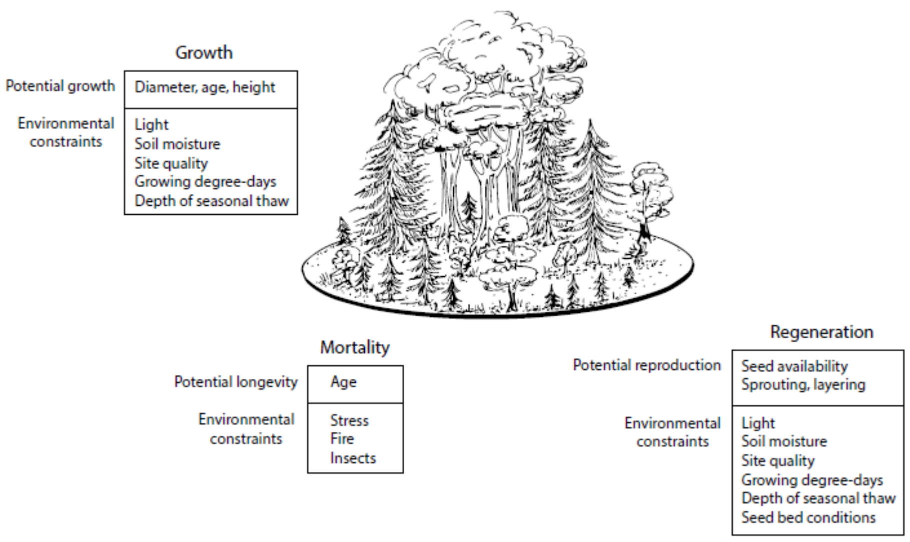
Individual based model

Ecosystem as individual trees

Demography

Life history characteristics

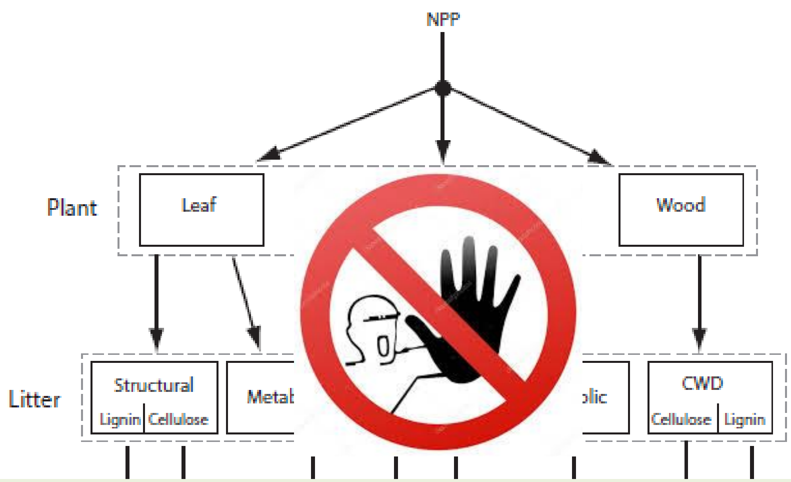
Functional traits



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

Contrasting views of ecosystems

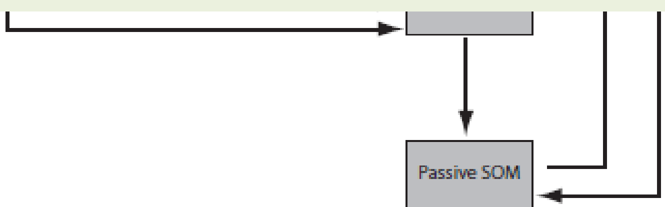
Clementsian view



International Biological Program (late-1960s to early-1970s)

Seen as too large and unnecessarily mathematically complex but biologically simple

Golley (1993) *A History of the Ecosystem Concept in Ecology*



Biogeochemical model

Ecosystem as system of interconnected pools

Gleasonian view

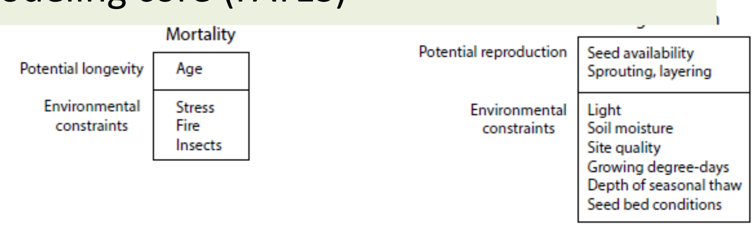
Individual based model

Ecosyst … dual trees
Demog
Life hist … eristics
Functio

Reaction to biogeochemical models

Ecologically authentic, but not yet implemented in global models

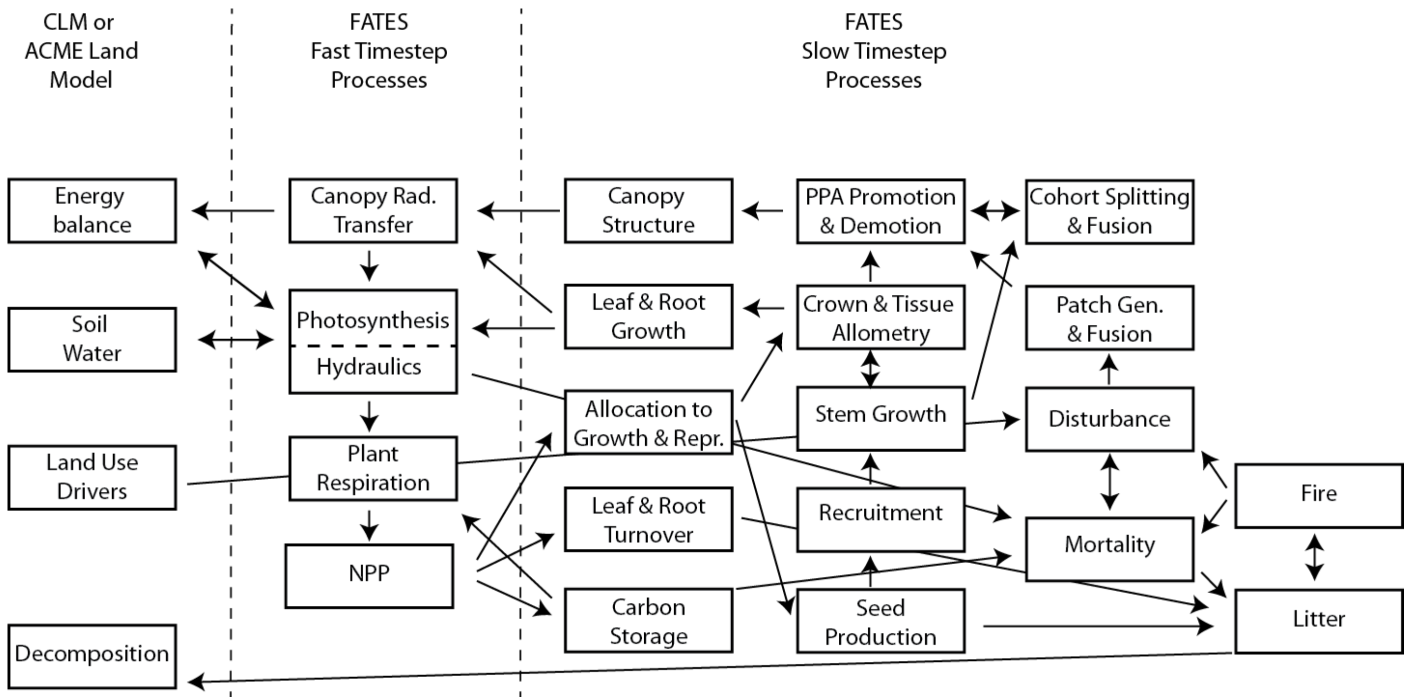
Cohort-based ecosystem demography as modeling core (FATES)



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

Complexity itself is not the problem

Simplified FATES with separate timescales

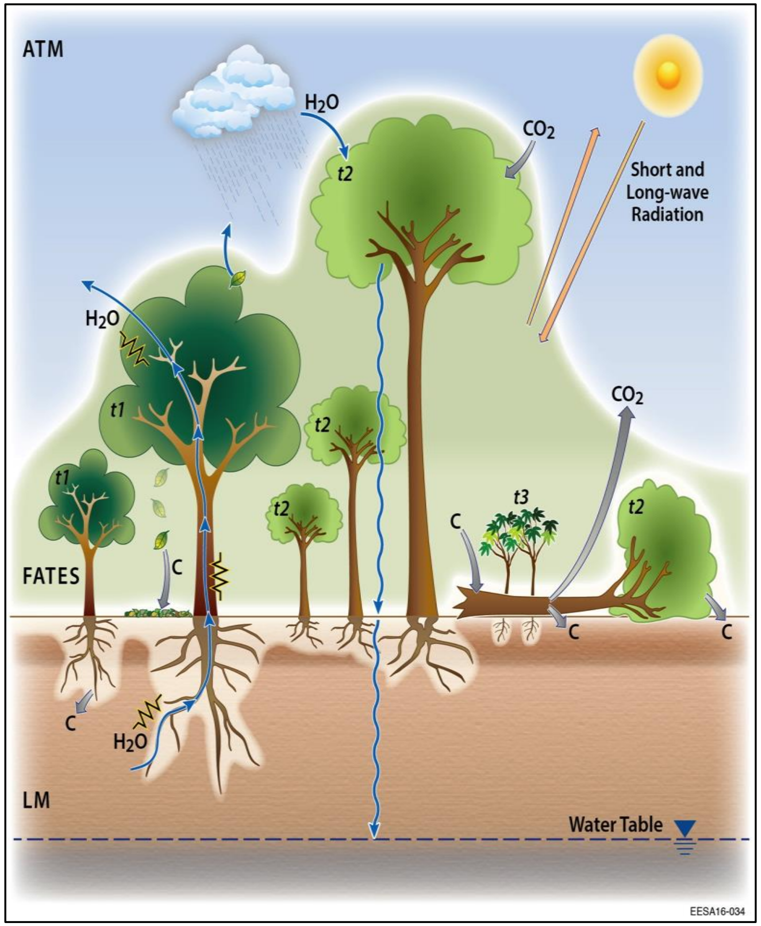


Charlie Koven (LBNL)

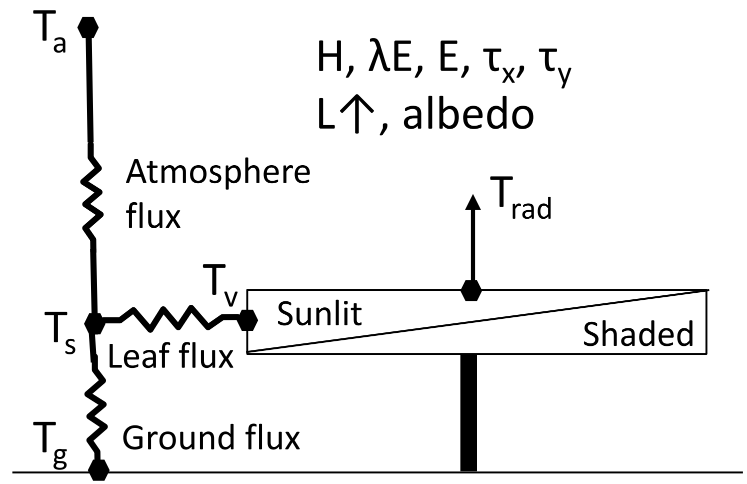
Static stand structure:
Hold the slow processes constant and calculate only fast timescale canopy biophysics and physiology

Coupling FATES and CLM

FATES = vertically-structured canopy



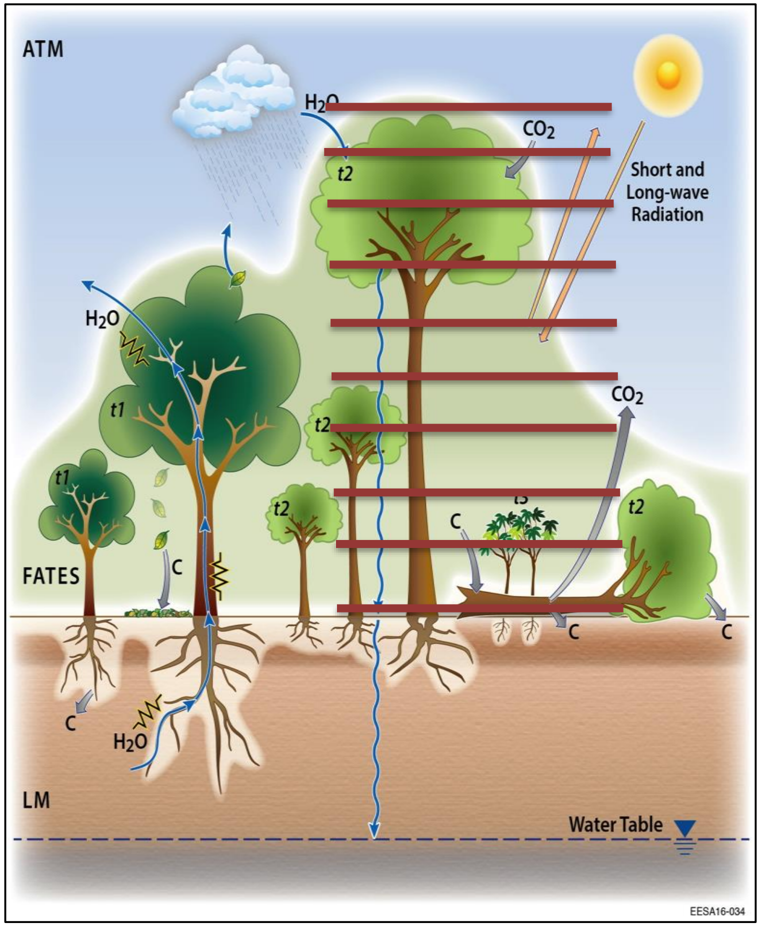
CLM5 = Dual source, big-leaf canopy without vertical structure



Enhances technical debt and perpetuates expedient coding practices

Coupling FATES and CLM

Ecosystem demography / multilayer canopy



Reducing uncertainty

- Will simplify surface flux code and BGC code
- Based on fundamental physical, physiological, and biological principles
- Uses observable parameters, not ad hoc corrections