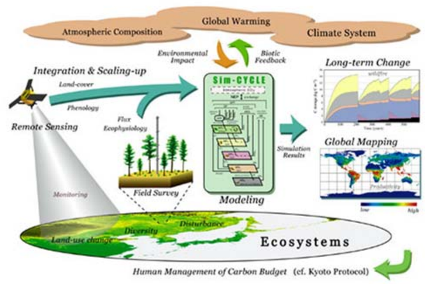
Ecosystem Modeling

- Rationale
- Concepts
  - Hierarchy
  - Components
- History
- General Features
- Performance



Dennis Baldocchi
ESPM
UC Berkeley

Ecosystem Modeling is an important tool for digesting data, making predictions and to interpolate and extrapolate in time and space.

While this lecture will focus on Ecosystem models per se, so far through this class you have been slowly exposed to a variety of models. Here we pull the ideas together

Why Model Ecosystems?

- Diagnose and Understand Complex sets of Measurements
  - Tease apart convoluted and confounding processes and attributes
  - Provides Paradigm or Hypothesis on how Ecosystem Functions

- Assess behavior in situations and/or at scales or conditions beyond which measurements can be made
  - Regional and Global Scales
  - Reconstruction with Past Climate Data
  - Elevated CO_2, Acid Deposition, Droughts, Warming, Fertilization
  - Long-Term Successional Sequences

- Integrate Information across time and space
  - Interpolate and Extrapolate information
- Predict future conditions and states
- Make Management and Policy Decisions
  - What If Exercises
    - Logging, Gap Size, Fire, Species Removal/Addition, Rate of Spread or Retreat

All models are wrong; some models are useful

Attributed to George Box, statistician

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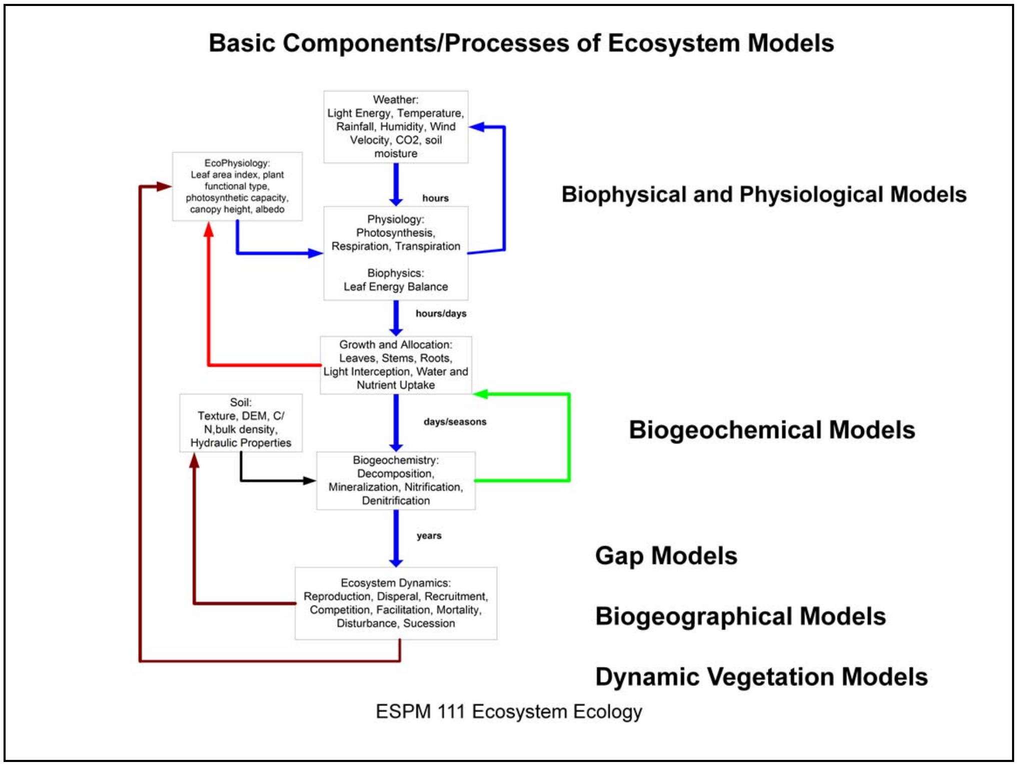
Since all models are wrong the scientist cannot obtain a "correct" one by excessive elaboration. On the contrary following William of Occam, we should seek an economical description of natural phenomena. Just as the ability to devise simple but evocative models is the signature of the great scientist, so is over-elaboration and over-parameterization often the mark of mediocrity.

This quotation by Box has re-calibrated my perspective on the value of different types of models. I see value in simple toy models, with a few equations and interactions, to tease out some basic understanding of a system. There is merit is simple statistical models for management decisions and there is need for highly mechanistic and theoretical models for prediction and fuller understanding. The type of model you chose and use depends upon you application and the data in hand.

George E. P. Box (1976) *Science and Statistics* *Journal of the American Statistical Association*, Vol. 71, No. 356. (Dec., 1976), pp. 791-799



As shown early in the semester, this is the conceptual ecosystem ‘model’ we have been dealing with throughout the semester. This is coupled, nested and includes a variety of model classes, including biophysical and physiological models, biogeochemical models, gap, biogeographical and vegetation dynamic models

Set of Ecosystem Topics that are Modeled to different degrees of detail

- Light
- Water
- Carbon Pools
- Nutrients (N, P)
- Climate Interactions (Warming, CO2)
- Disturbance (Fire, Logging, Grazing)
- Land Use Change
- Pollution and Acid Deposition

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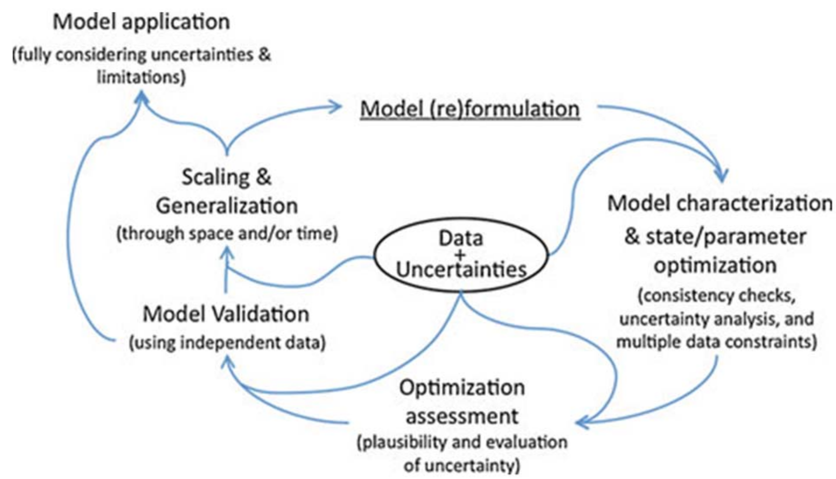
Different types of ecosystem models serve different purposes. Here is a list of the type of processes these models can address

Sources of Model Uncertainty

- System Complexity
  - Appropriate Set of Equations Must be Applied
- Model Parameters
- Driving Input Variables
- Temporal and Spatial Resolution
  - Time Step, Pixel Resolution, Number of Layers
- Validation Data

Implementation of Models



Williams et al

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Modeling is an iterative process, balanced by data, experimentation and hypothesis testing. Models tend to represent a 'best' view of a system given current knowledge. But as model algorithms become falsified, we acquire more data and the models and their parameters evolve and improve, new knowledge is achieved.

There remains debate on the merits and demerits of model data fusion, using Bayesian statistics, in this era of big data vs mechanistic models. If there are big datasets to mine and the questions remain within the domain of the dataset, model data fusion has strengths. How well they can predict future states outside the bounds of the data remain contentious. Here is where mechanistic models may have an advantage.

Art of Modeling

- Use Model Hierarchy Assessments to address 'how good is good enough' regarding model detail
- Use Multiple constraints to Minimize over fitting
- Use Independent Data to Fit and to Validate Models
- Consider Representativeness of Data
- Use Good Numeric Methods

Model Pitfalls

- Garbage In = Garbage Out
- Watch out for Non-Linearities
  - Apply at Proper Time-Step and Space-Scale
- Validate, Validate, Validate
- Don't Parameterize Model Algorithms with the Same data used to Validate
- Equifinality, a combination of parameters yield the same answer
  - An appeal to Multiple Constraints
- Closure: Equal number of Equations and Unknowns is needed
- Avoid Auto-Correlation, y =f(y)
- Avoid Extrapolating Empirical Regression models beyond the range of the dataset
- Use Mechanistic and Prognostic Models to predict the future and to upscale information
- Are Driving Variables Representative of the Conditions Experienced by the Organ or Organism?

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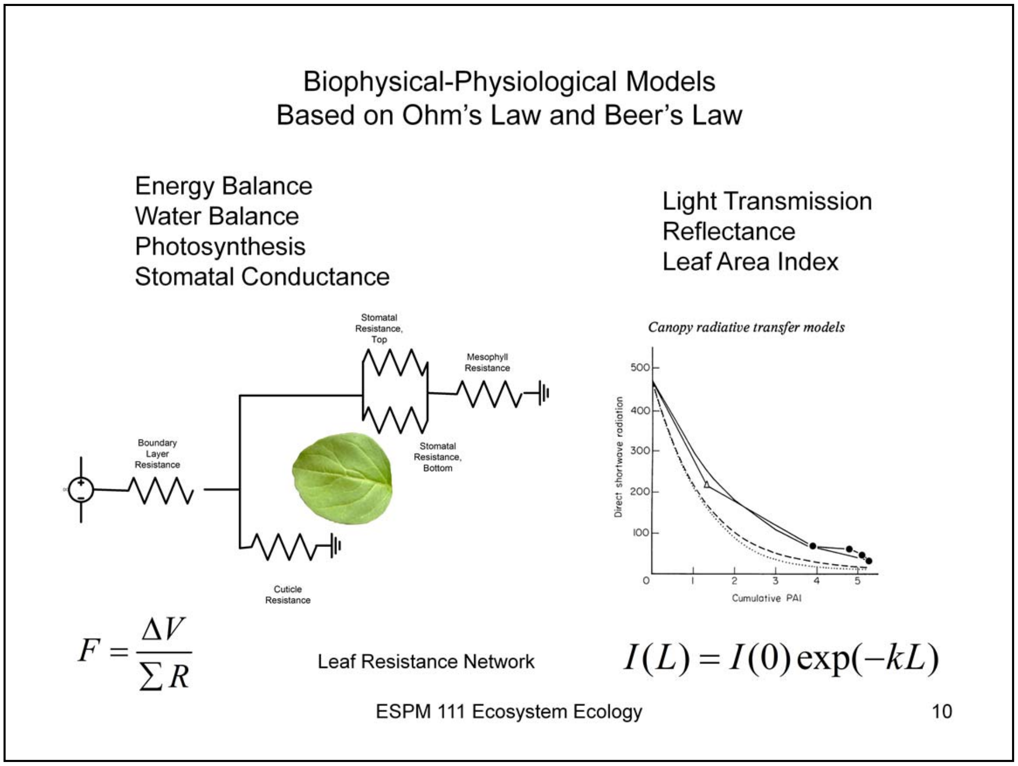
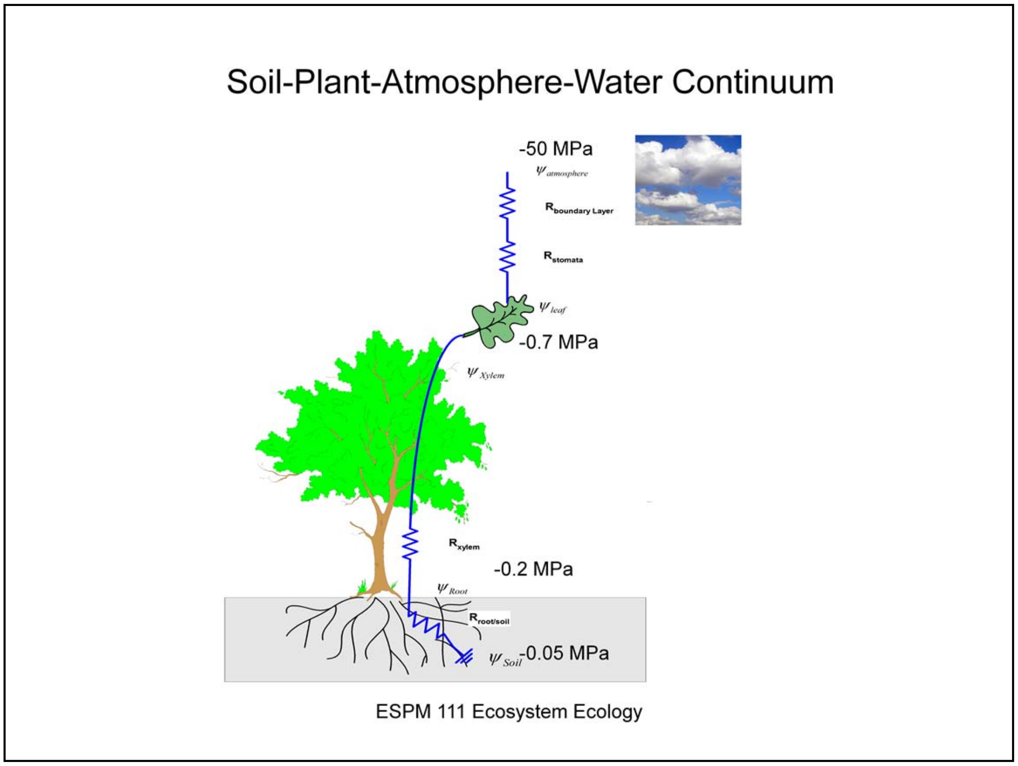
My experience over the years of some model pitfalls, as well and ideas from a great paper by Belinda Medlyn et al. in Tree Physiology



Ohm's Law is often applied to compute fluxes between leaves/canopies and the atmosphere

Beer's law is important for telling us how much sunlight is available at different locations in the plant canopy. We need to combine Beer's Law and Ohm's law to upscale flux information from the leaf to the canopy



Resistance Analog model for water transport through the soil-plant-atmosphere continuum

Mathematical Representation: Model Algorithms

1. Empirical, Regression Based
   1. Multiplicative
   2. Additive
2. Mechanistic/Diagnostic
3. Prognostic

$$f(t,x,y) = af(t) \cdot bf(x) \cdot cf(y)$$

$$f(t,x,y) = af(t) + bf(x) + cf(y)$$

$$Rn = H + \lambda E + G$$

$$\frac{dc}{dt} = f(c,t)$$

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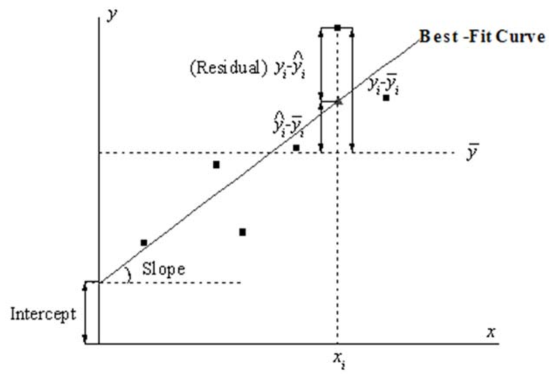
Models can be very simple

Minimize the Sum of the Squares

$$\sum (y_i - \widehat{y_i})^2 = \sum (y_i - \beta_0 + \beta_1 x_i)^2$$



$$y = \beta_0 + \beta_1 x$$

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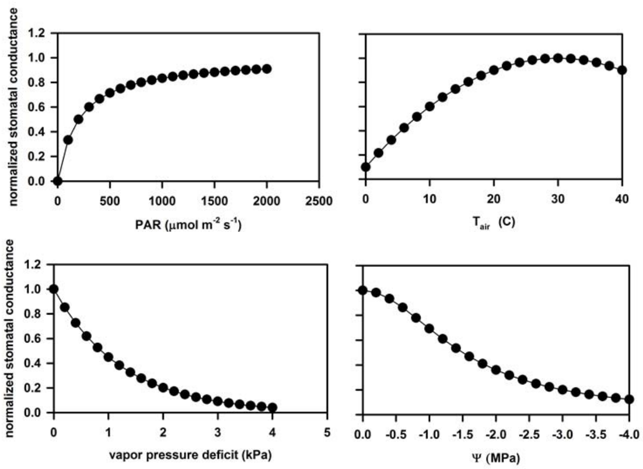
Least squares fit models, be they linear, non-linear, and multi-variate, are ways of fitting data to simple equations

http://www.originlab.com/www/helponline/origin/en/UserGuide/Illustration_of_the_Least_Squares_Method.html

Multiplicative Model

$$g_s(PAR, VPD, T, \psi) = g_{s,\max} \cdot f_1(PAR) \cdot f_2(VPD) \cdot f_3(T) \cdot f_4(\psi)$$



Concepts of Jarvis Model for Stomatal Conductance

ESPM 129 Biometeorology

Example of Boundary Line Analysis
To fit the Jarvis-Reed Model

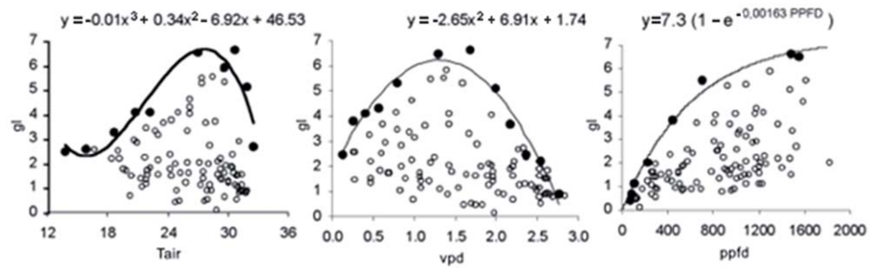


Figure 4. Scatter diagrams of the measurements of leaf diffusive conductance plotted against air temperature, air vapor pressure deficit and photosynthetic photon flux density, with the hypothetical boundary line fitted for each environmental variable.

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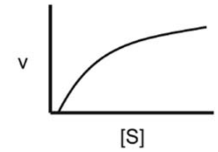
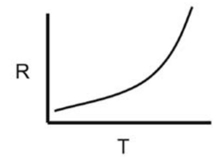
http://dx.doi.org/10.1590/S1677-04202004000100008

Non-Linear Biophysical Processes

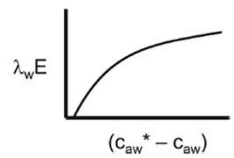
$$v = \frac{V_{max}\,[S]}{K_m + [S]}$$



$$R = R_0\, e^{\left(\ln Q_{10}/10\right)\Delta T}$$



$$\lambda_w E = \frac{s(R_n - G) + \rho_a\, c_p (c_{aw}^* - c_{aw}) / r_H}{s + \gamma \frac{r_v}{r_H}}$$



Monson and Baldocchi, 2014 ESPM 111 Ecosystem Ecology

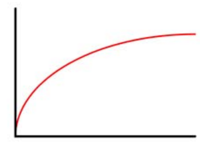
Examples of other models we commonly use to calculate processes like enzyme kinetics, respiration and latent heat of evaporation

Other Non-Linear Biophysical Processes

Photosynthesis

$$A \sim \frac{aI}{b+cI}; \frac{dC}{e+fC}$$

$$aA^3 + bA^2 + cA + d = 0$$



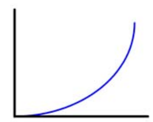
Transpiration

$$e_s(T) \sim \exp(T)$$

$$aLE^2 + bLE + c = 0$$

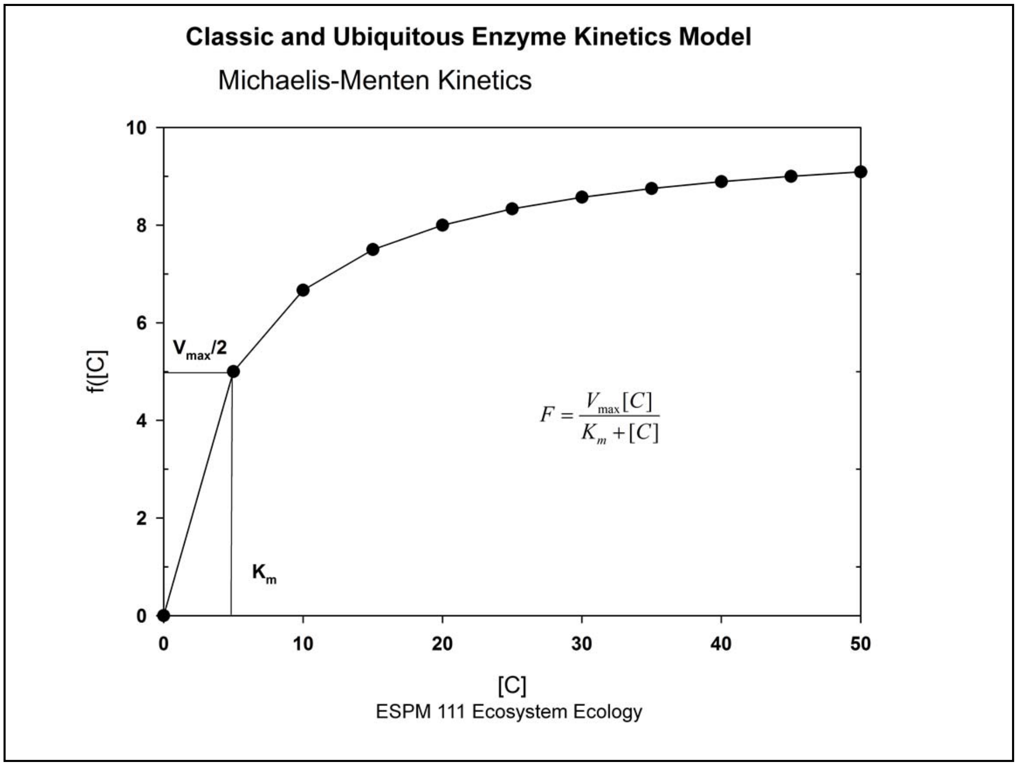
Respiration

$$R_d \sim \exp(T)$$

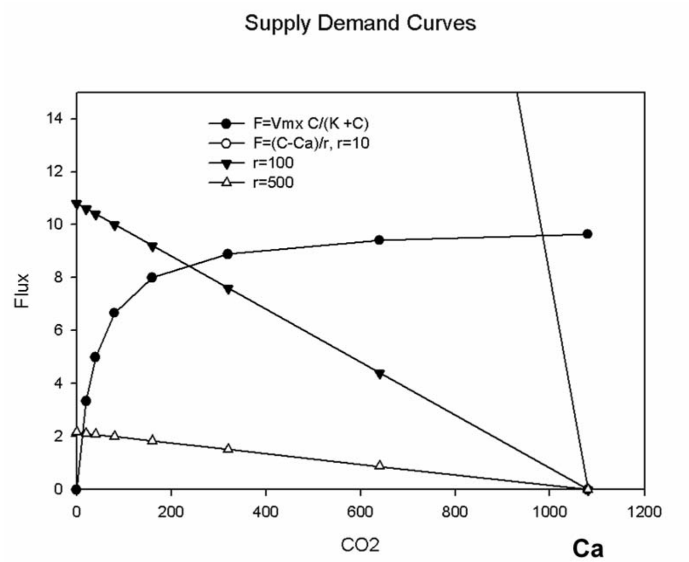


Leaf Temperature

$$L\uparrow \sim T_s^4$$



Parameters must be fit to use these models. K is the C value at one-half Vmax



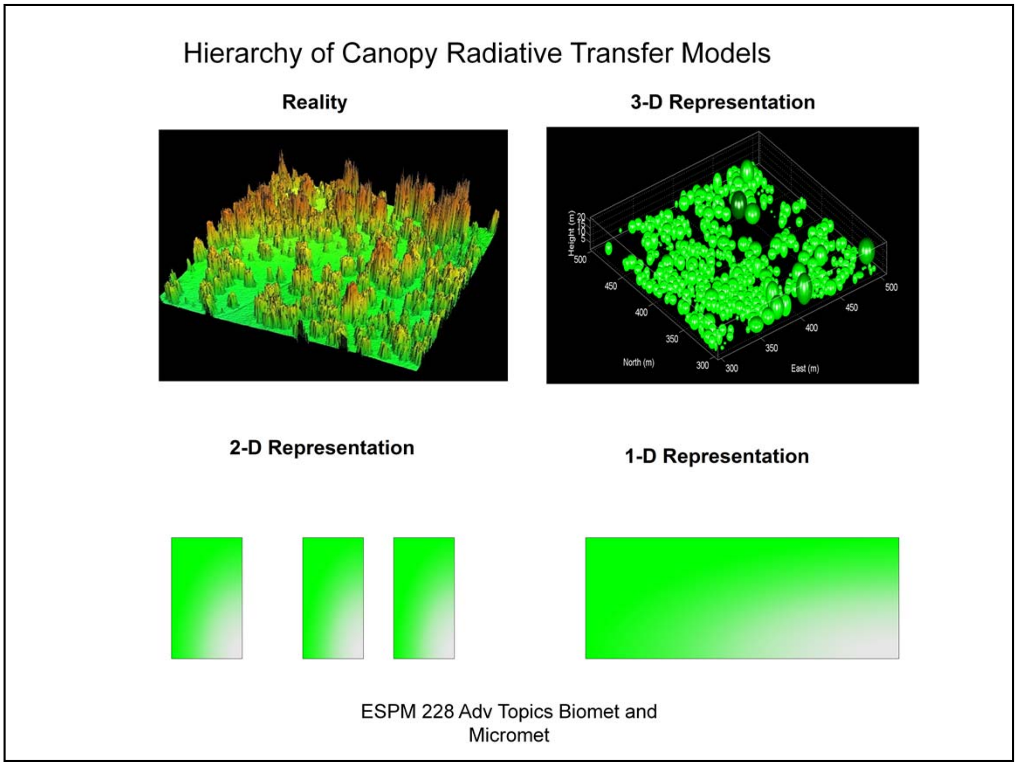
$$F = \frac{C_a - C}{r} = \frac{F_{\max} C}{K + C}$$

In many gas exchange processes there becomes a balance or equilibrium between the supply provided by the diffusion and turbulent transport of a gas from the free atmosphere through the boundary layers and stomata to the site of biochemical consumption in the leaf. In turn the rate of biochemical consumption is a function of the local concentration of C. Ultimately the flux that occurs is at the intersection between the supply and demand curves. If the resistance is nearly zero and the conductance infinite then the intersection occurs at Ca = C

Canopy Representation

Canopy as a Turbid Medium, with Randomly Distributed Leaves

How do we treat a plant canopy? Do we have to know where every leaf and plant is? This can be done. But for practical applications we use statistical models. We assume a canopy is a turbid medium, with randomly distributed leaves, in space, with known leaf inclination angle distributions

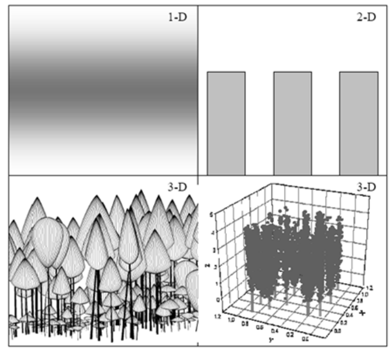


Here are various treatments of light transmission models. The most general is the 1D representation. It works well for closed canopies.

Geometrical Abstraction of the Canopy

- One-Dimensional
  - Big-Leaf
  - Dual Source, Sun-Shade
  - 2-Layer
    - Vegetation and soil
  - Multi-Layered
- Two-Dimensional
  - Dual source
    - sunlit and shaded
    - Vegetated vs Bare Soil
- Three-Dimensional
  - Individual Plants and Trees

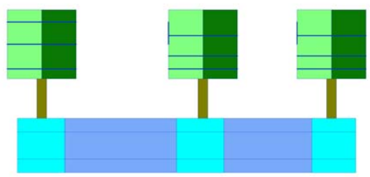
Cescatti A. and Niinemes Ü. - Light harvesting: from leaf to landscape -



Hierarchy of Ecosystem Models:

Big-Leaf Vegetation/Bucket Soil

Multi-layer Vegetation/Soil & Sun/Shade



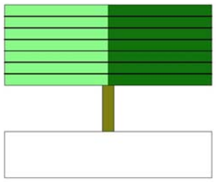
Space:

- Big-Leaf Vegetation/Bucket Soil
- Sun/Shade Vegetation
- Layered Vegetation and Soil

Time:

- Hour
- Day
- Month

CANOAK



Role of Proper Model Abstraction

J.M. Chen et al. / Ecological Modelling 124 (1999) 99–119 117

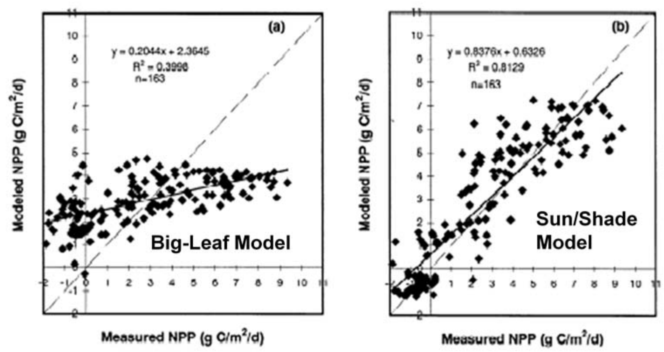
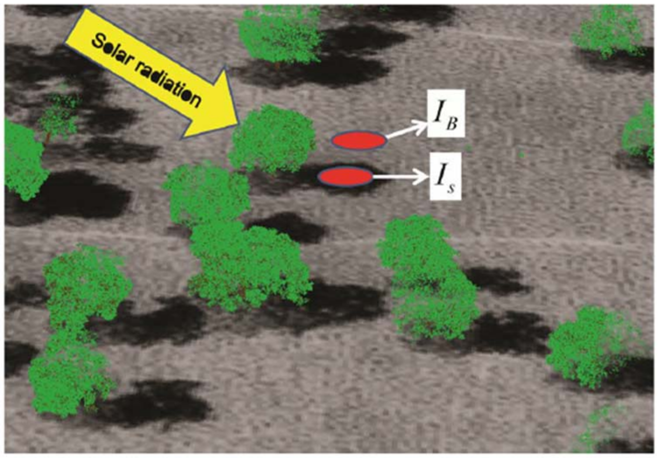


Fig. 9. One-to-one comparison of the measured NPP with the modeled NPP for a mature aspen stand. (a) big-leaf model, and (b) daily integrated model with sunlit–shaded leaf separation.

High-Resolution Voxel Based Trees



Courtesy of Martin Beland

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With LIDAR we can now measure where every tree is and assess the distribution of foliage using voxels of varying size. As we go to more open canopies it is better to treat the light environment in better detail

Model Input GIS:f(x,y,z,t)

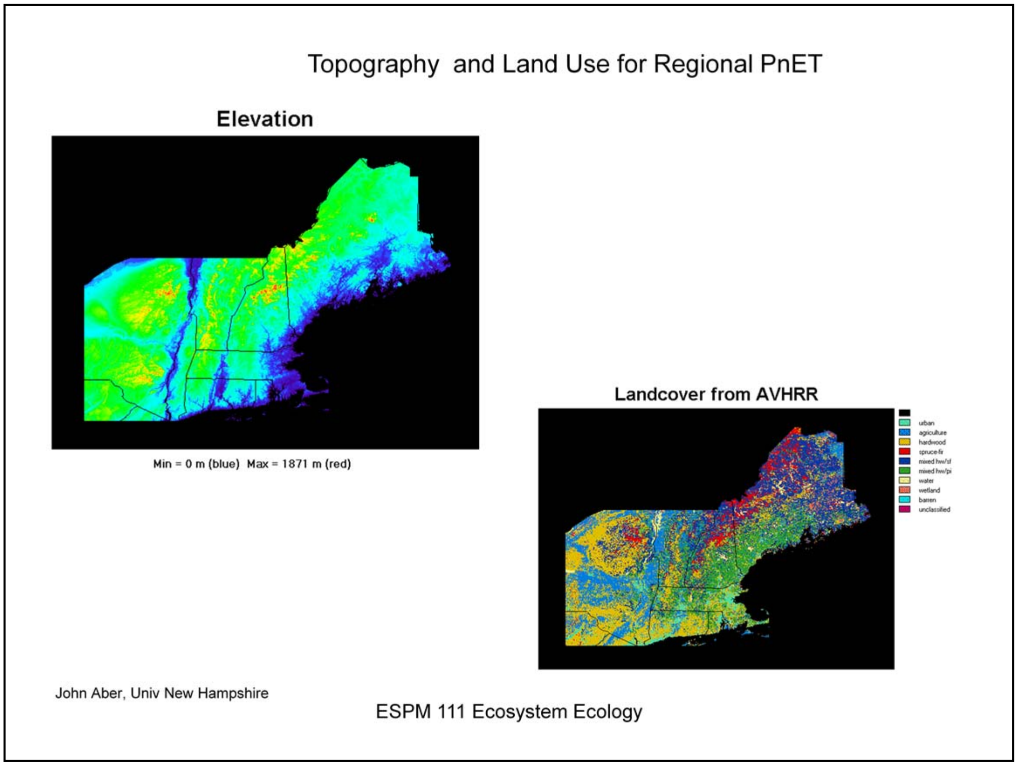
- Climate and Weather
  - Solar radiation, precipitation, temperature
- Topography
  - Digital Elevation Model
- Soils
  - Bulk density
  - hydraulic/thermodynamic properties
  - C/N
  - Soil moisture/temperature
  - Roots
- Vegetation
  - LandUse
  - Structure
    - LAI, biomass (C)
  - Function
    - Ps and gs Capacity

- Spatial Resolution
  - 0.5 Degree?
  - 30 km?
  - 1 km?
  - 1 m?

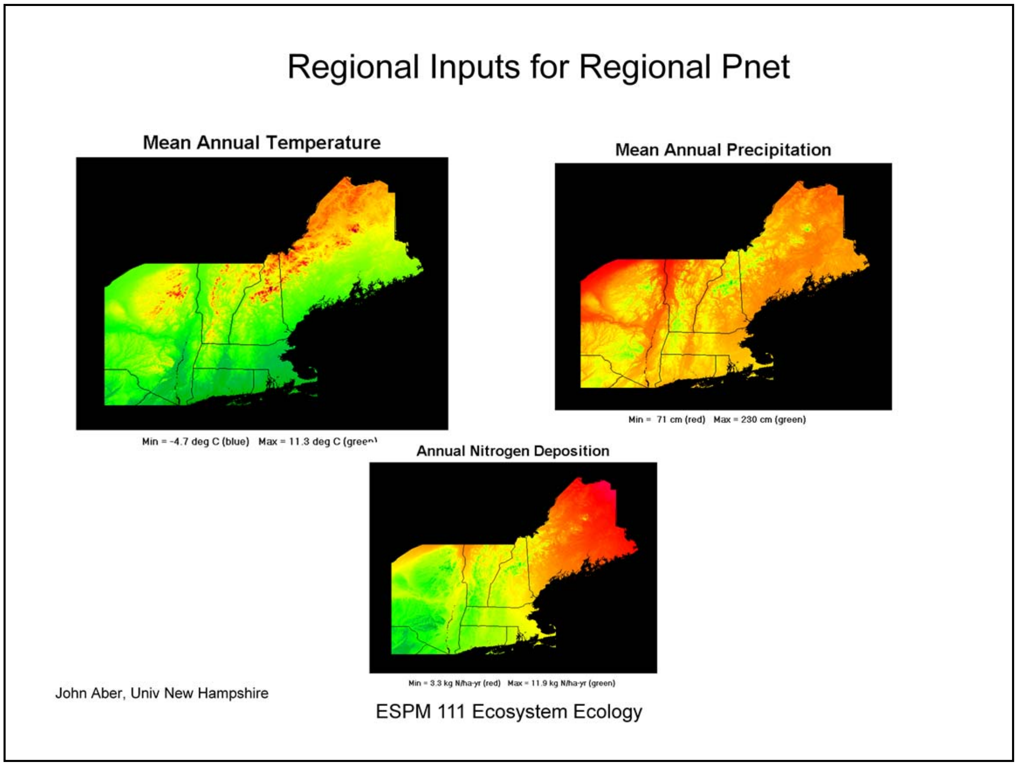
- Temporal Resolution
  - hourly?
  - daily?
  - annual?
  - Decadal?

- Disturbance
  - Fire
  - Logging
  - pests

Be careful about representativeness of inputs. Is the temperature at a weather station the same as that of a forest, 10 km away?
What about sub grid spatial variability?



Examples of maps of inputs needed to drive regional ecosystem models



More variables

New Data Layers on Stand Age and Disturbance History

Y. Pan et al.: Age structure and disturbance legacy of North American forests 719

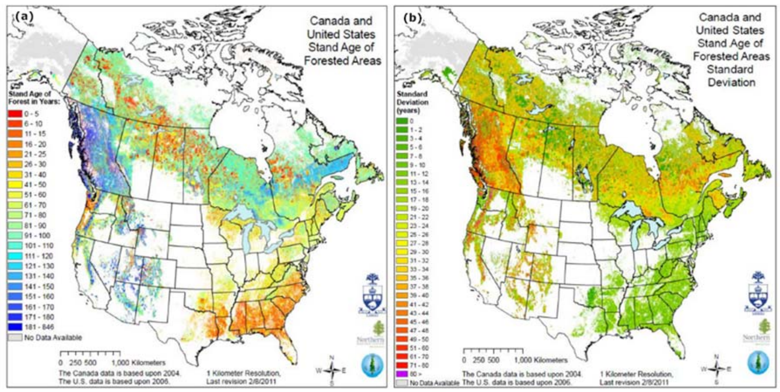


Fig. 1. **(a)** Forest age distribution in North America (excluding Alaska and Mexico), which was developed by combining forest inventory data (of US and Canada) with several remote sensing based disturbance data sources. **(b)** The standard deviations of forest ages that characterize uncertainty in the age map **(a)**.

Pan et al 2011 Biogeoscience

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Exciting and new data layer on disturbance

Sources of Geospatial Information for Ecosystem Models

Atlas of the Biosphere
Land Use,Climate,etc

http://www.sage.wisc.edu/atlas/

International Soil Moisture Network

https://ismn.geo.tuwien.ac.at/

Flux Networks, Fluxnet

http://www.fluxdata.org/default.aspx

Gridded Climate Data

http://www.cru.uea.ac.uk/data

http://www.esrl.noaa.gov/psd/data/gridded/

http://www.prism.oregonstate.edu/

http://daymet.ornl.gov/

NASA Land Products

https://lpdaac.usgs.gov/data_access

Carbon Dioxide Information Center

http://cdiac.esd.ornl.gov/

Climate Change in California

http://cal-adapt.org/

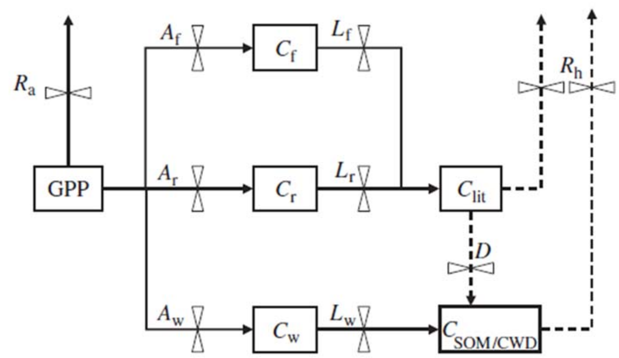
National Atmospheric Deposition Program

http://nadp.sws.uiuc.edu/mdn/

Ecosystem Models, Examples/Types

- Gap Models
  - Jabowa
  - FORET
  - SORTIE/ED/ED-2
- Biogeochemical
  - Century/DayCent
  - TEM
  - CASA
  - Forest/BIOME-BGC
  - PnET
- Biophysical
  - MAESTRA/CANVEG/CUPID
  - SIB/BATS
  - LSM/CLM
  - SIPNET
- Biogeographical
  - Miami
  - DOLY
  - MAPSS
  - BIOME
- Dynamic Global Vegetation Models
  - Hybrid
  - Lund-Potsdam-Jena (LPJ)
  - IBIS
- Next Generation Land-Climate Models
  - JULES
  - ORCHIDEE
  - CASA-CLM
  - JSBACH

Simple Coupled Ecosystem Carbon Pool Model



Williams et al.

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Very simple 4 pool carbon model. Considers the gains and losses of Carbon by photosynthesisi, GPP, how photosynthesis (A) is partitioned into the foliage, root and wood fractions, how these pools (C) change as there are respiratory losses. Then litter either is lost by respiration or turned into soil detritus, which respires, too.

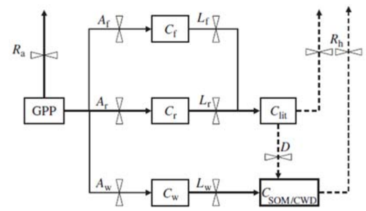
Simple Set of Coupled Differential Equations to Solve the problem

$$V_a \rho_a \frac{dC_a}{dt} = -P_{plant} + R_{plant} + R_{soil}$$

$$V_{plant} \frac{dC_{plant}}{dt} = P_{plant} - R_{plant} - F_{litter}$$

$$V_{litter} \frac{dC_{litter}}{dt} = F_{litter} - R_{litter}$$

$$V_{soil} \frac{dC_{soil}}{dt} = F_{litter} - R_{litter} - R_{soil}$$



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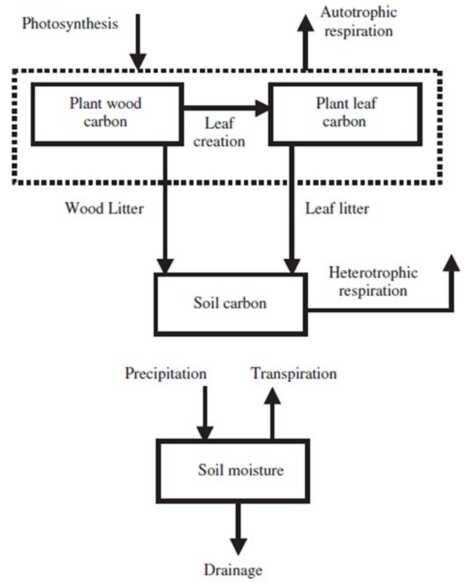
Closure is important. We need the same number of equastions as unknowns. And we need to define model parameters



Braswell et al

Model Validation
How Good is Good Enough?

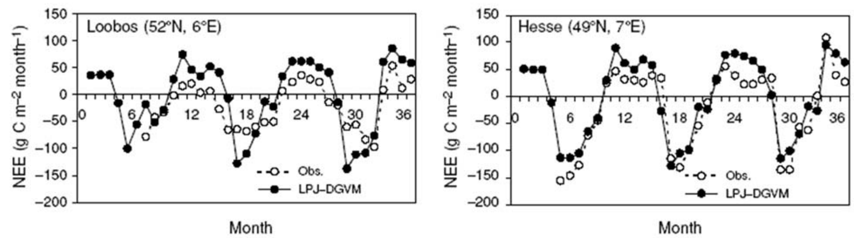


Fig. 3 Observed vs. simulated monthly fields of Net Ecosystem Exchange (NEE, g C m^{-2}; here and elsewhere positive values represent a flux to the atmosphere; negative values a flux to the biosphere), at six EUROFLUX sites.

Sitch et al. 2003 GCB

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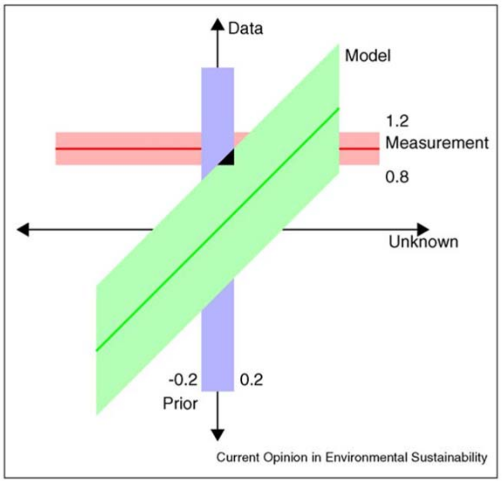
How good is good enough

Model Data Fusion
Why Data or Models May be Correct, or Incorrect

Figure 1



There are imperfections
In model, parameters,
And measurements

The Black Triangle is the
Intersection of data, model
And measurements

Rayner 2010 Current Opinions in Environment Sustainability

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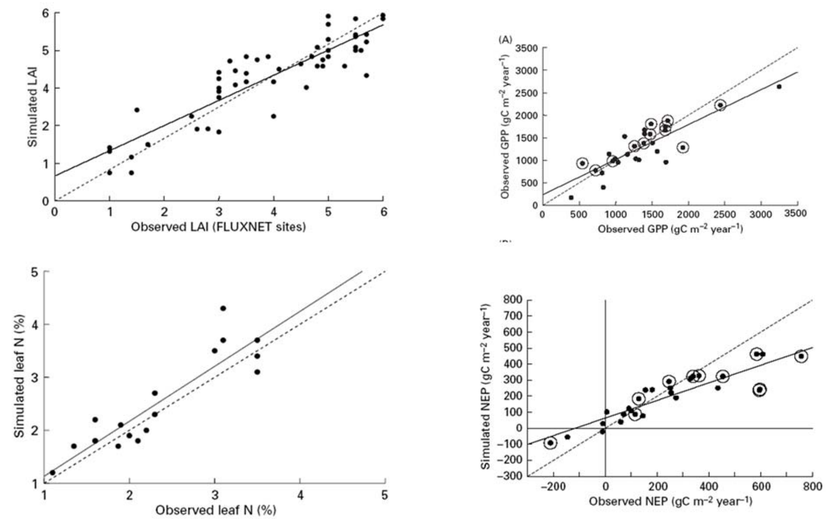
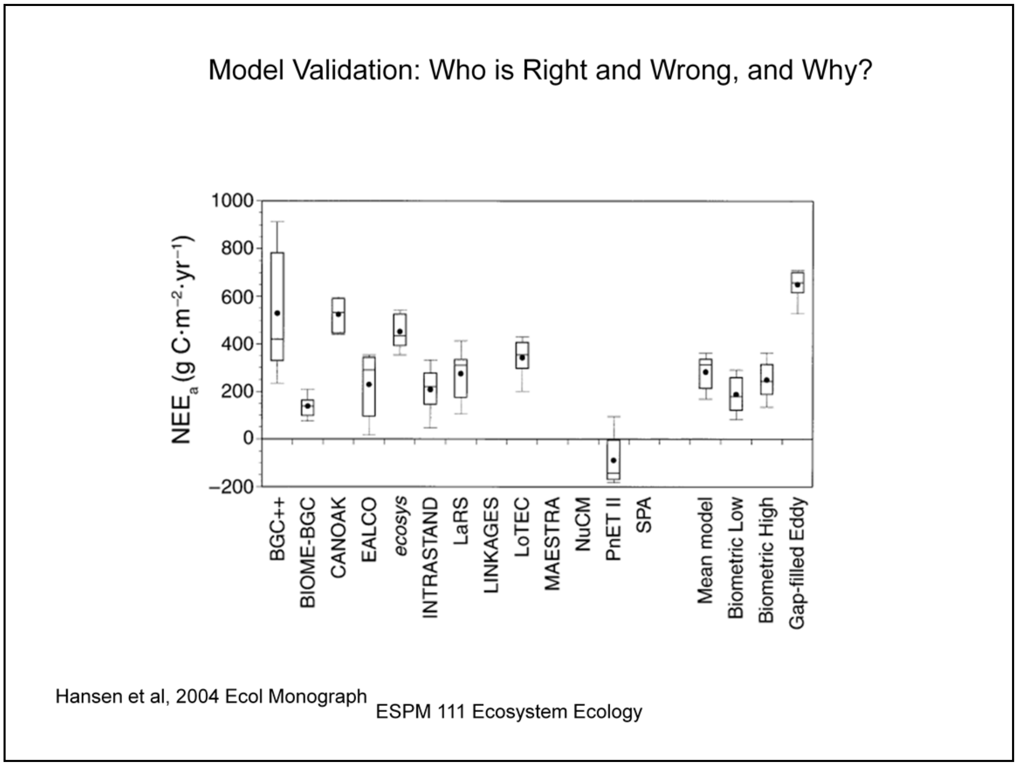
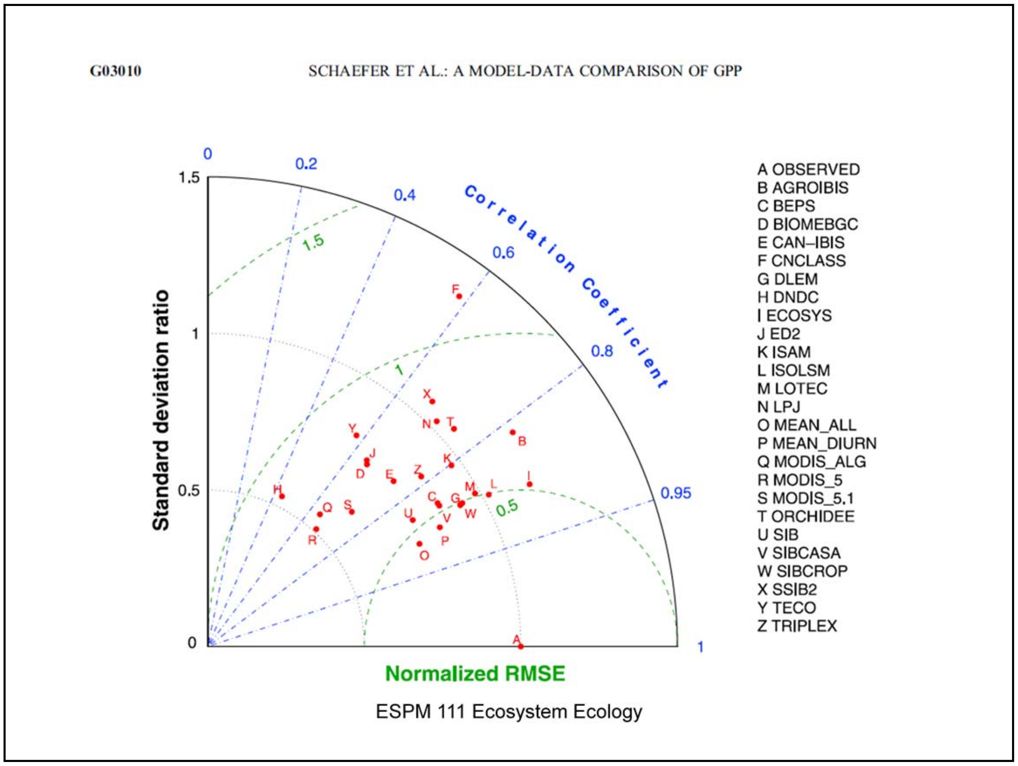
How Good is Good Enough, part 2



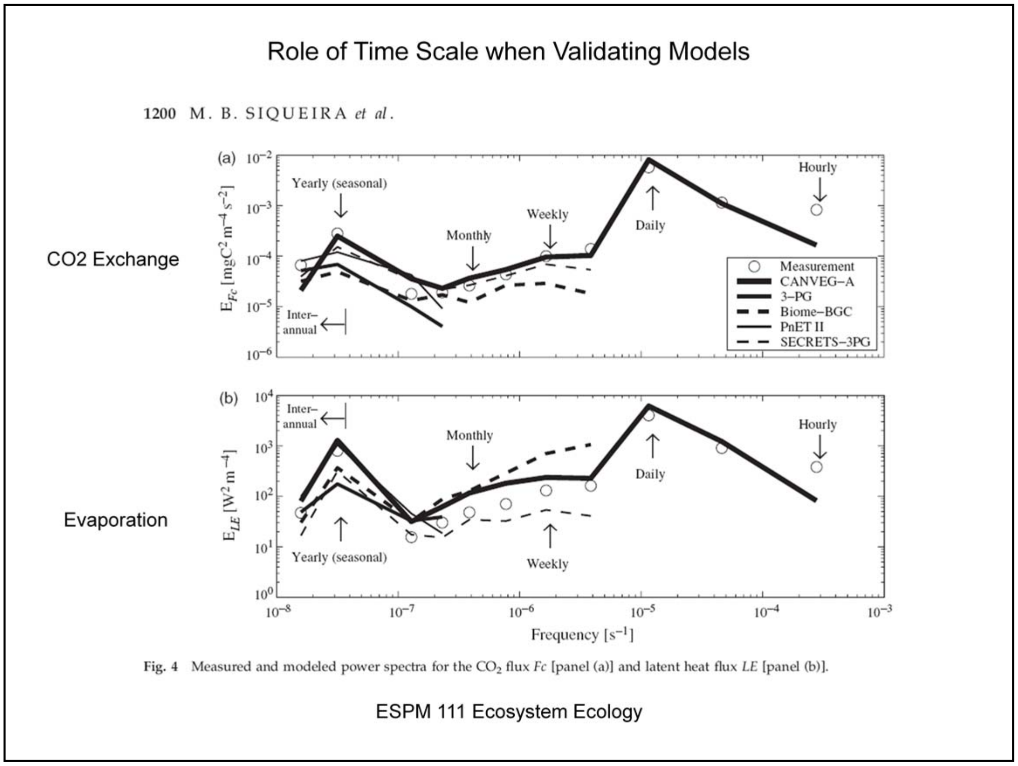
Woodward and Lomas, 2004



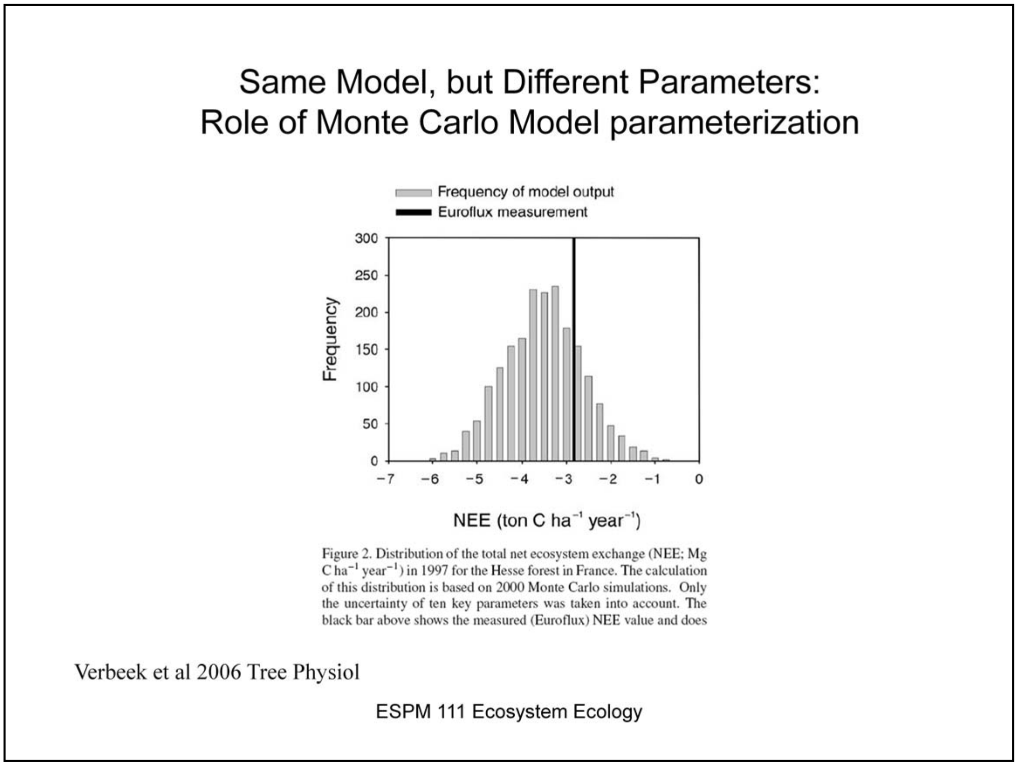
Test of Models at Walker Branch, a deciduous forest



Ways to test groups of models with data from flux networks, using lots of data and lots of models. Here it looks like most of the 'best' models are not doing well when tested with data.



The time scale at which you test a model is important too. Some models may get short term fluxes wrong, and long integrations right, due to offsetting errors.



Models have many uncertainties and it is important to quantify this uncertainty

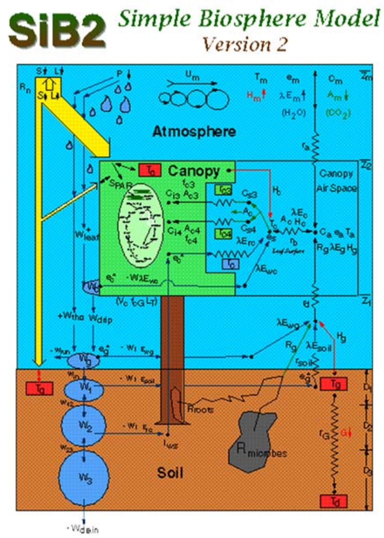
Will Be?

- Even Better Coupled Biophysical-Biogeochemical-Ecosystem Dynamics Models [e.g. LPJ (Prentice et al.); IBIS, (Foley et al.]; ORCHIDEE; CASA/CLM
- Predict Functional type, LAI, Structure, phenology, soil moisture + Ecosystem responses to CO2,T, ppt + N perturbations and disturbance
- Improved Coupling of Biogeochemistry to Climate Models
- Better Spatial Inputs of Climate and Plant Drivers
  - Lidar Mapping of Forests and Vegetation
- Better Model Parameterization
- Fire Probabilities
- Better Phenology
- Better Allocation
- Better Disturbance Maps

Big-Leaf Model

Ohm's Law Analog for Fluxes

$$F = \frac{V}{\Sigma R}$$



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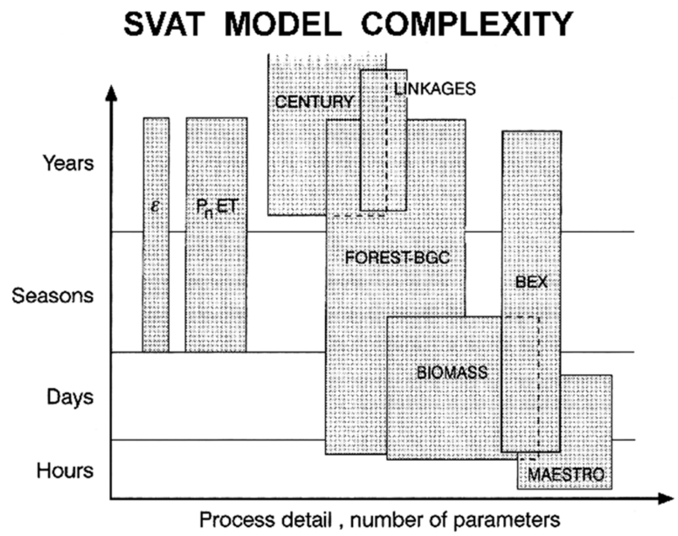

Landsberg and Gower, 1997

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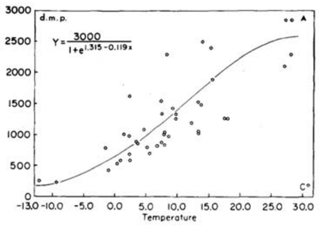
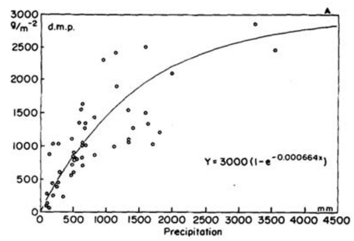
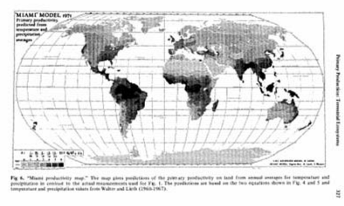
First Global Ecosystem Model
Miami Model, Helmut Lieth







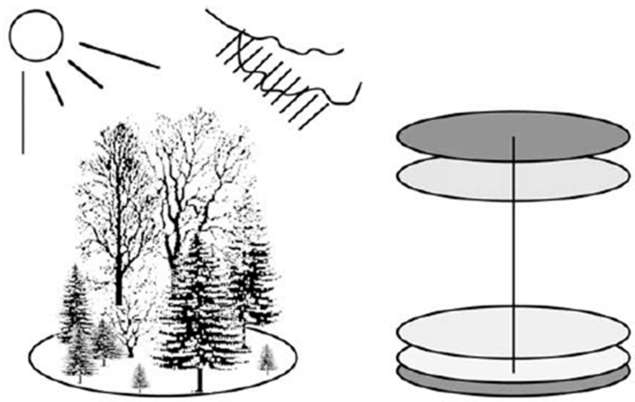
Lieth, 1973, Human Ecology

Jabowa/FORET

The Grand-Daddy of Ecosystem Gap Dynamic Models

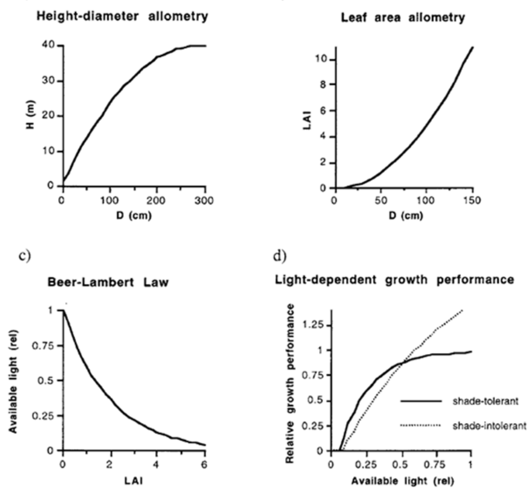
- Abstraction
  - Forest is abstracted as composite patches and gaps
  - Patches are horizontally homogeneous
    - ~100 m2
  - Leaves in a thin disk at top of tree
  - No interaction among patches
  - Individual Based
- Growth
  - Competition for Light and Resources (soil moisture, Temperature, N)
- Mortality
  - Stochastic
- Establishment and Recruitment
  - Stochastic
  - All seeds available
  - Ample water for establishment

Gap Models, JABOWA, etc



Bugmann, Climatic Change, 2001

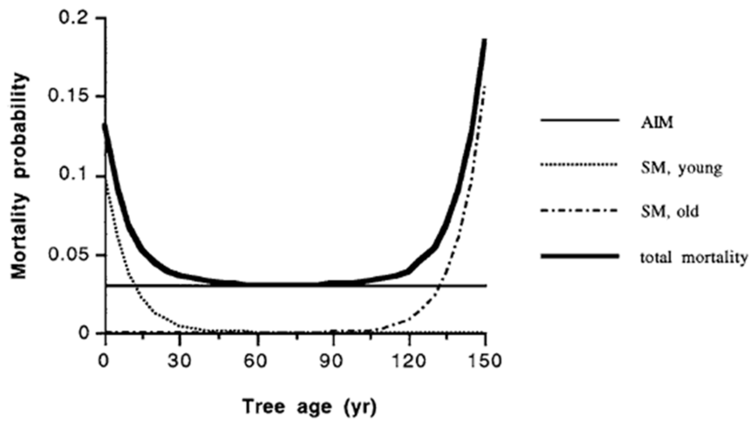
Conceptual Forcing Functions by Species



Highly Parameterized!

Bugmann, 2001 Climatic Change   ESPM 111 Ecosystem Ecology

Mortality Functions



Bugmann, 2001 Climatic Change

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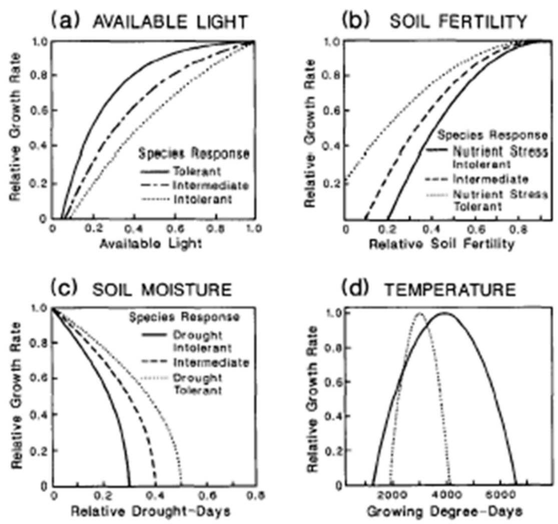
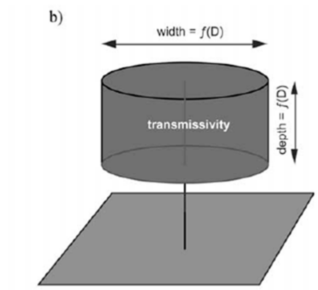
Conceptual Forcing Functions, part 2



Shugart et al, 1992 Ann Rev Ecol

SORTIE

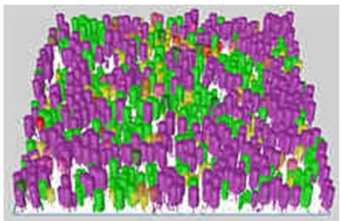
- Follows fate of individual trees
- Four submodels
  - Resource Limitations (light, water, N)
  - Growth =f(species, diameter and light index)
  - Mortality=f(species, carbon balance)
  - Recruitment (number, size seeds, germination, survival, root sprouting)
- Parameterization
  - Field data
  - Regression equations
  - Maximum Likelihood



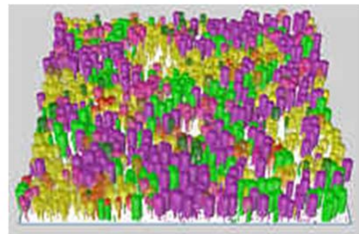
Pacala 1996 Ecol Monograph

Spatial Representation of Trees in SORTIE

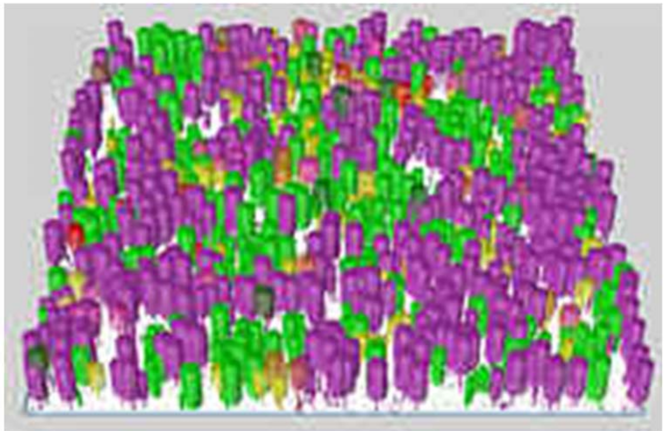
Undisturbed, 500 years



Disturbed, 500 years

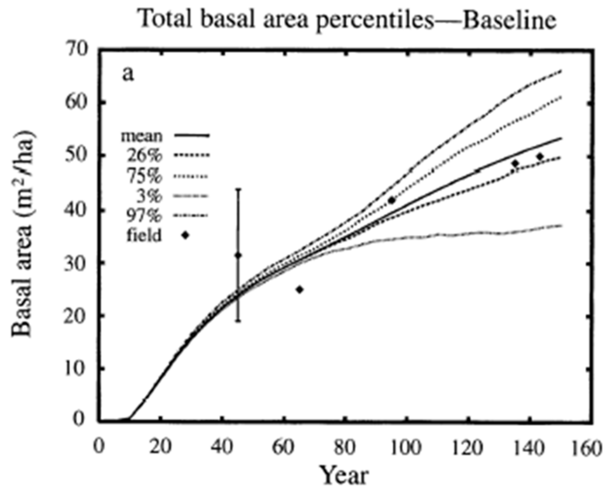


Pacala 1996 Ecol Monograph; Deutschman et al 1997 Science http://www.sciencemag.org/feature/data/deutschman/index.htm



Open MPEG HyperLink

Testing SORTIE



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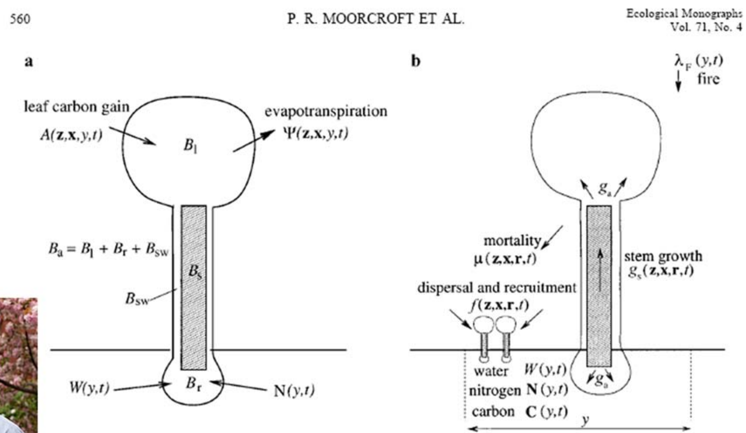
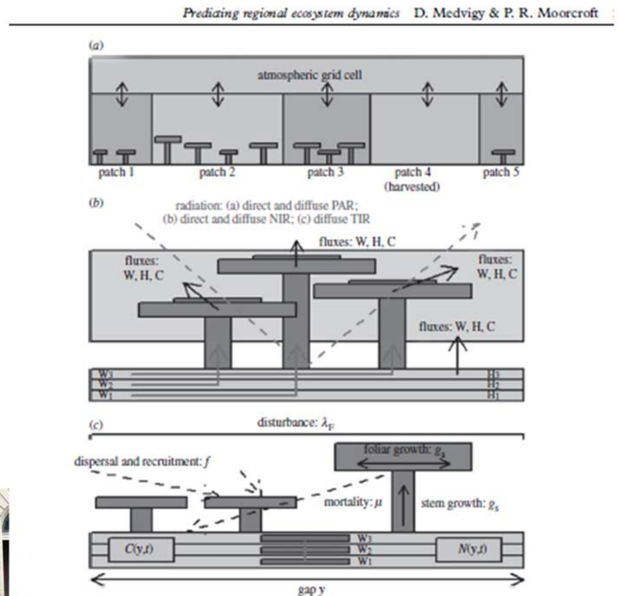
Ecosystem Dynamic Model, ED
SORTIE with EcoPhysiology



Moorcroft et al 2001, Ecol Monograph

ED-2



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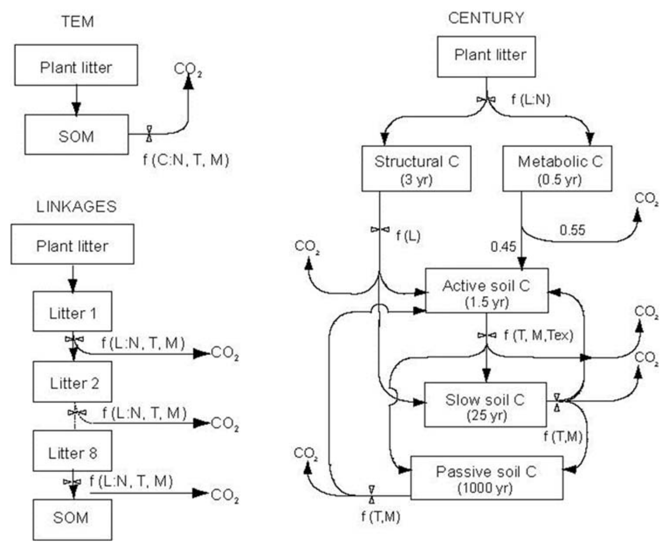
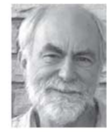
Multi-Pooled Biogeochemical Cycling Models





Chapin et al.

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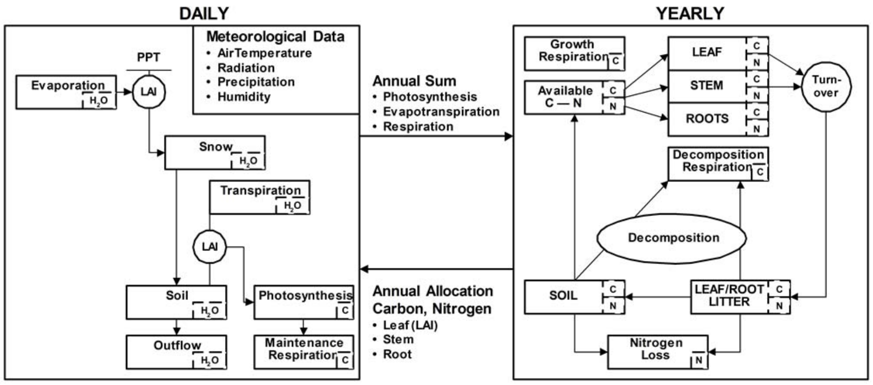
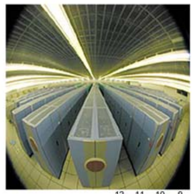
Biogeochemical Cycling Model at Daily and Annual Time Steps

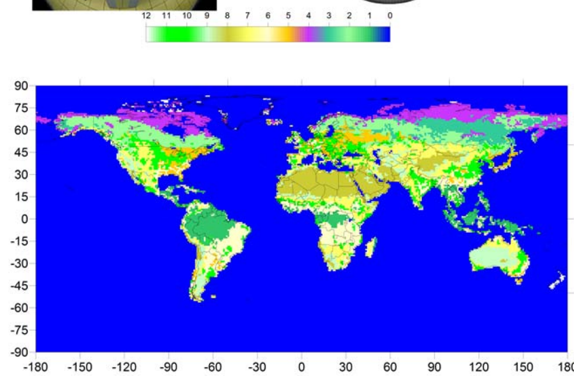
Forest — BGC



Coughlan and Running, 1988

Dynamic Vegetation-Climate Computer Models





deFries Global 1x1 degree land cover map

Coupled Climate-CASA, Contemporary Global Biogeochemical Cycling Model

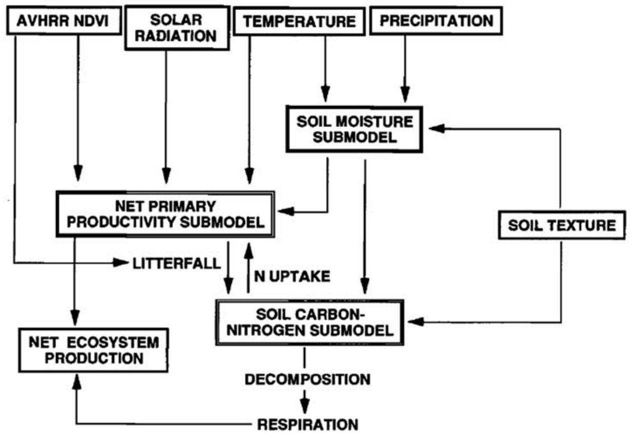
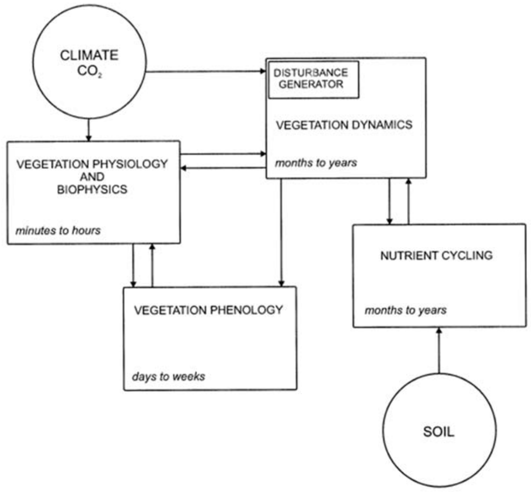


Fig. 1. Model integration framework. Global climate data sets are combined with soil texture settings to compute the monthly water balance, which controls NPP and soil microbial activity.

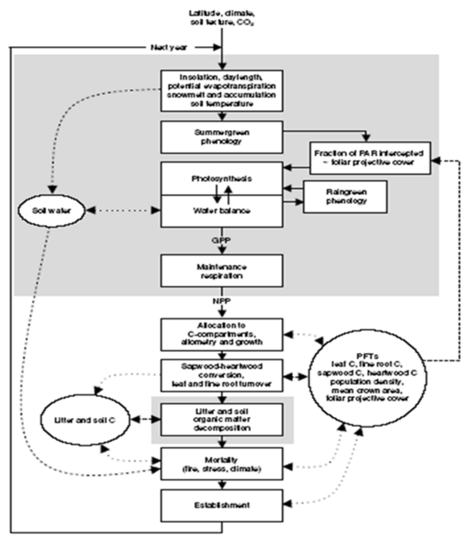
Dynamic Global Vegetation Model



Cramer et al 2001, GCB

LPJ Global Dynamic Vegetation Model

164 S. SITCH *et al.*



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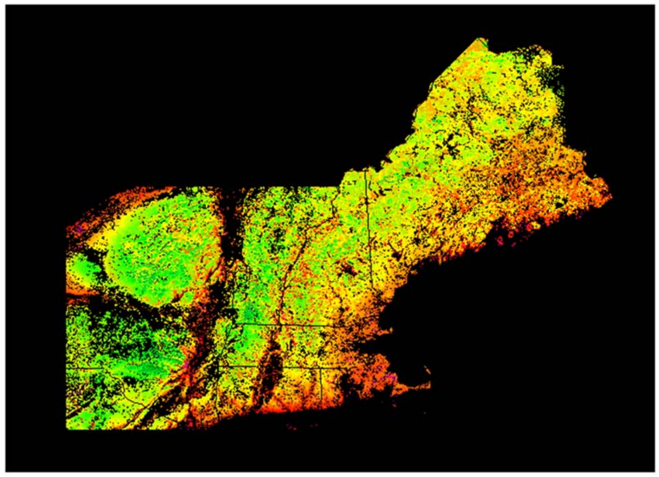
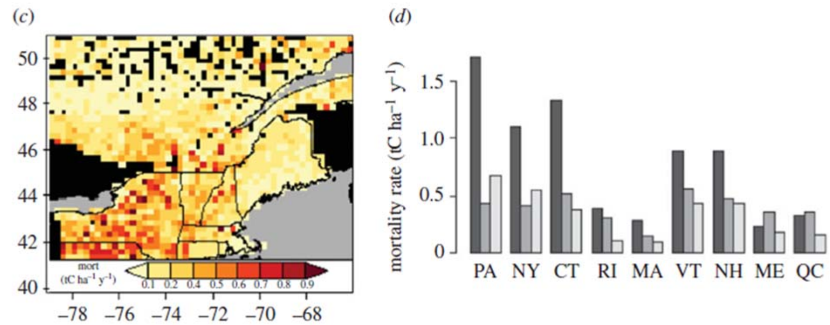
Annual Net Ecosystem Production



Min = -271 g C/m2-yr (black)   Max = 345 g C/m2-yr (green)

http://www.pnet.sr.unh.edu/subpages/graphics/bkg8.gif PnET

Computing Mortality Maps with Optimized ED-2 Model



Medvigy and Moorcroft, 2012 Phil Trans Royal Soc B

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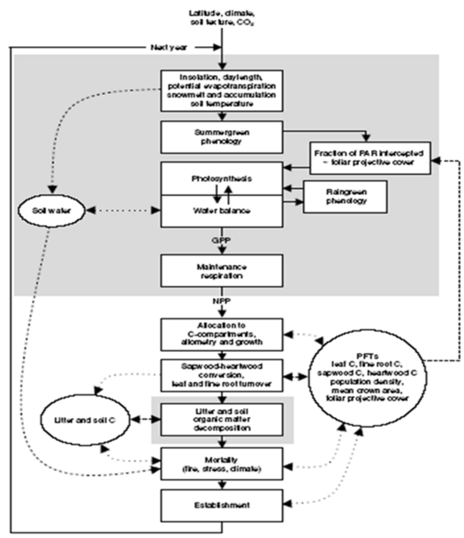
More on data assimilation

LPJ Global Dynamic Vegetation Model

164 S. SITCH *et al.*



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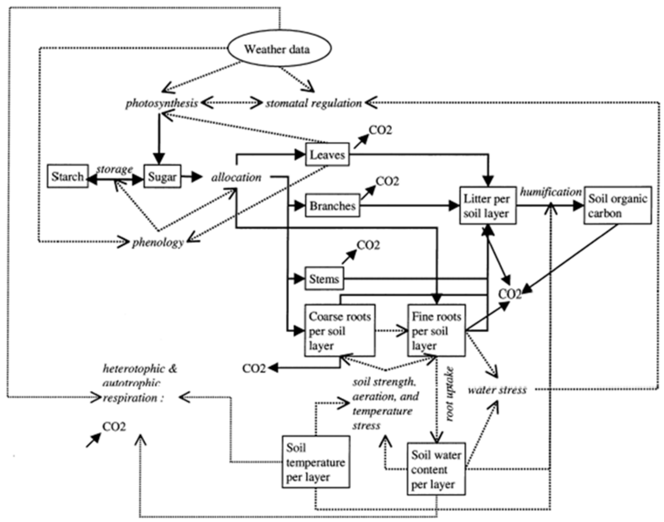
ASPECTS: Coupled Forest Ecosystem Model
Rasse et al, Ecol Modeling



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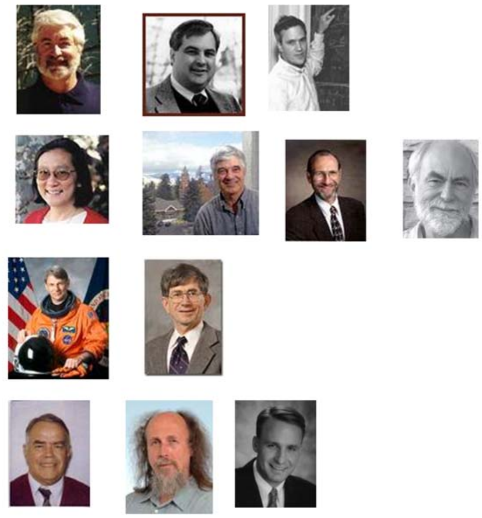
Ecosystem Models, Examples

- Gap Models
  - Jabowa
  - FORET
  - SORTIE
  - ED
- Biogeochemical
  - Century
  - TEM
  - CASA
  - Forest/BIOME-BGC
  - PnET
- Biophysical
  - SIB
  - BATS
  - LSM
  - Canveg
  - SPA
- Biogeographical
  - Miami
  - DOLY
  - MAPSS
  - BIOME
- Dynamic Global Vegetation Models
  - Hybrid
  - Lund-Potsdam-Jena (LPJ)
  - IBIS



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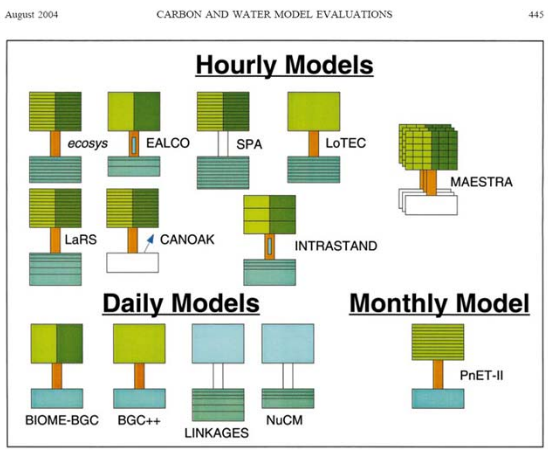
Hierarchy of Models:



Space:

Big-Leaf Vegetation
Bucket Soil

Sun/Shade Vegetation

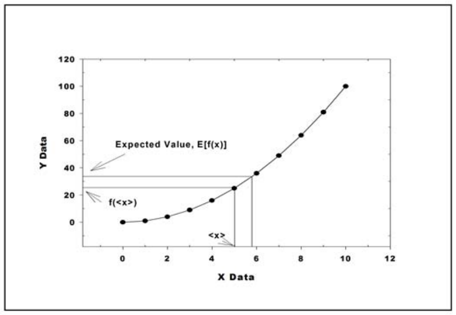
Layered Vegetation and Soil

Time:

Hour
Day
Month

After Hanson et al Ecol Appl 2004

Why Non-linearity is Important?



Jensen's Inequality

$$f([x]) \neq [f(x)]$$

Taylor's Series Expansion

$$E[f(x)] = f(\bar{x}) + \frac{1}{2}\frac{\partial^2 f(\bar{x})}{\partial x^2}\sigma(\bar{x})^2$$