Integrating Information on 'Biosphere Breathing' from Chloroplast to the Globe

Dennis Baldocchi,
University of California, Berkeley

Spring 2016

3/7/16

ESPM 228 Adv Topics Biomet and Micromet

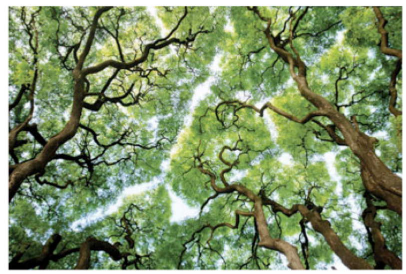
How do we sum fluxes from the scale of leaves to plant canopies, to landscapes and the globe it the quest of this set of lectures

Outline

- Overview on Principles of Leaf-Canopy Scaling and Integration Concepts
- Show Tests of Such Models over Multiple Time Scales
- Use the CANVEG Model to Ask Ecophysiological and Micrometeorological Questions Relating to Trace Gas Fluxes

A Challenge for Leaf to Landscape Upscaling, and Beyond:

Transform Weather Conditions from
a Weather Station to that of the **Leaves** in a Canopy with Their Assortment of Angles and Layers Relative to the Sun and Sky

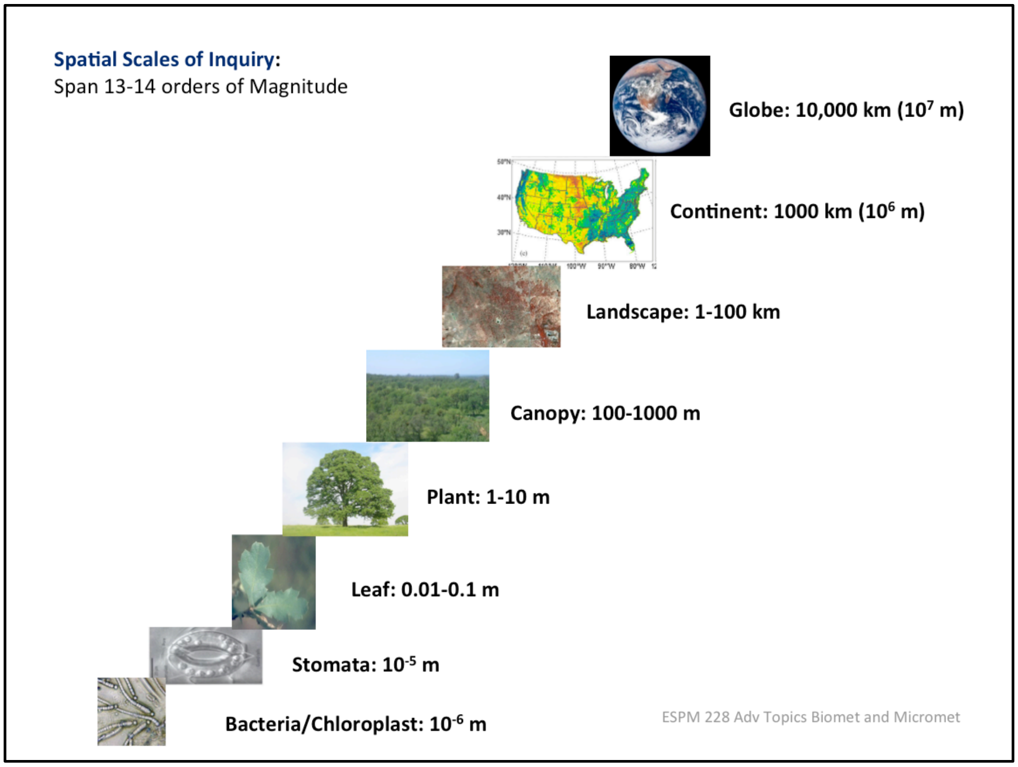


Challenge for Landscape to Global Upscaling

Converting Virtual ‘Cubism’ into Virtual ‘Reality’

Realistic Spatialization of Flux Data
Requires the Merging Numerous Data Layers with varying Time Stamps (hourly, daily, weekly), Spatial Resolution (1 km to 0.5 degree) and Data Sources (Satellites, Flux Networks, Climate Stations)

Can we apply principles learned in this class to chase problems at the landscape, region, continent and global scales?

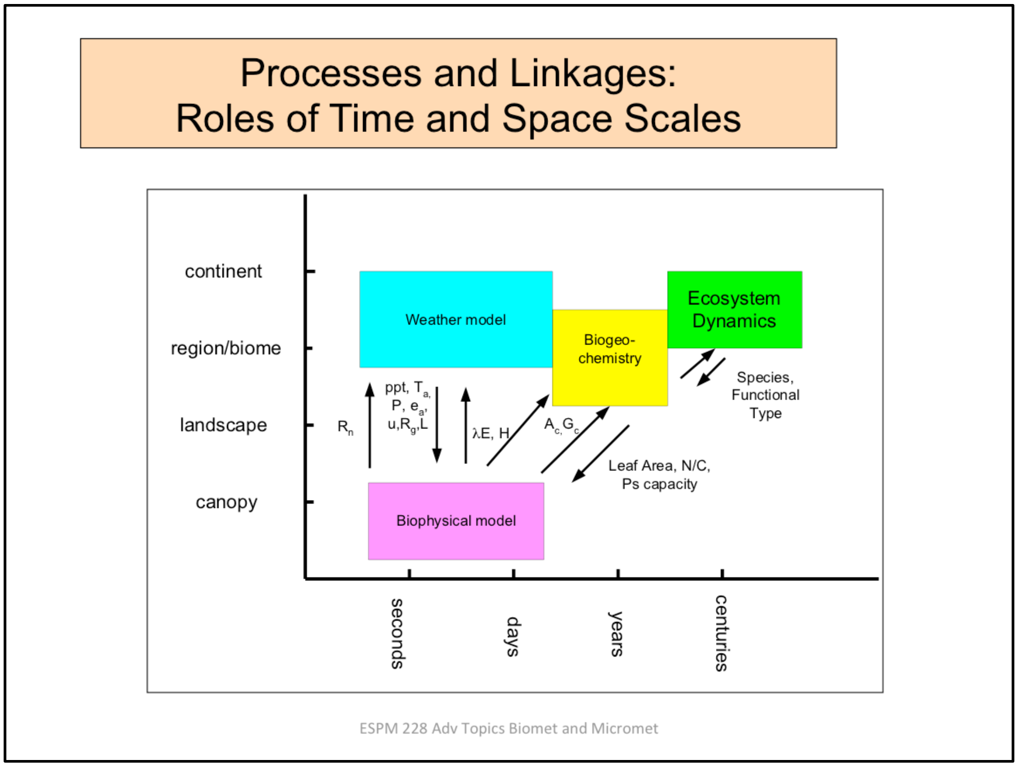


We have a great challenge because the problem we are dealing with can span 13 to 14 orders of magnitude

The Breathing of an Ecosystem is Defined by
the Sum of an Array of Coupled, Non-Linear, Biophysical
Processes that Operate across a Hierarchy/Spectrum of
Time and Space Scales

ESPM 228 Adv Topics Biomet and Micromet

We are also interested in integrating fluxes with regards to time, starting with short term, hourly averages, integreing them to days, seasons and years.



Why are these scales of interest and necessary to span? They relate to the problems we want to solve the the incorporation of additional suites of processes as we move up in scale. A key lesson is that these are complex systems and they experience scale emergent properties as we transcend scales. Biophysical models work well on short time scales given meteorological conditions and state of the vegetation, like leaf area index, albedo, roughness length. But as we go out to longer time scales we need to consider biogeochemical and ecophysiological factors that will govern phenology, photosynthetic capacity, stomatal conductance. And as we move out to climate conditions, we need information on how the dynamics of the landscape is changing.

Biophysical Modeling, Circa 1969

Cornelius T. deWit

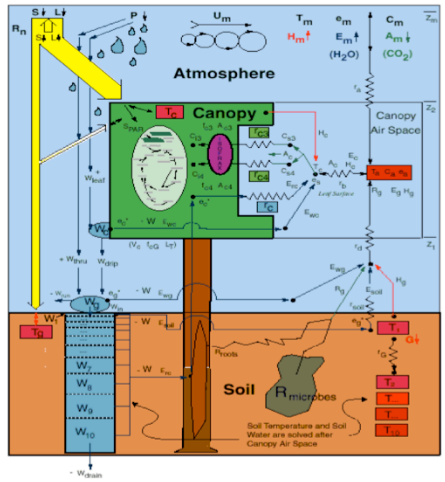
‘Seven-stage simulation models by means of which ecosystems may be explained on basis of the molecular sciences are impossible large and detailed and it is naïve to pursue their construction’

ESPM 228 Adv Topics Biomet and Micromet

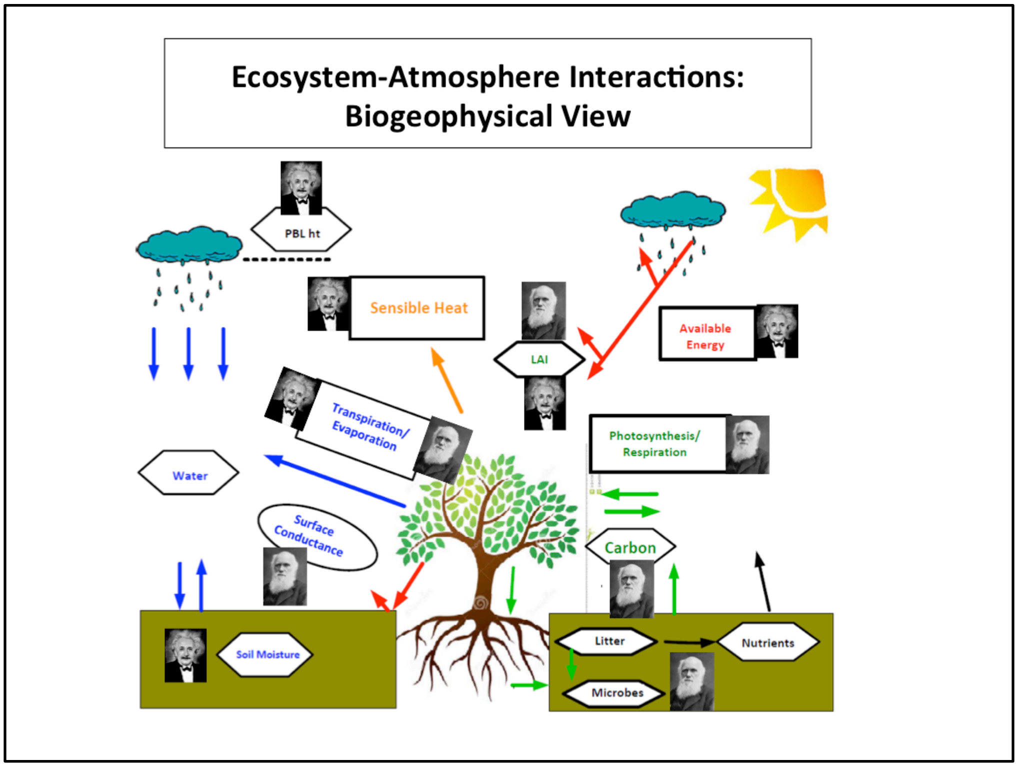
What about the skeptics who worry about garbage in and garbage out? Can we even consider these problems across scales. When deWit wrote his famous quote we did not have gridded information from satellites and weather reanalysis, so he was right. Yet over time we have been able to cross this impediment with good success, as with the advent of global ecology and development of the SIB model by Sellers and colleagues.

SIB, Simple Biosphere Model

Sellers et al, 1990s

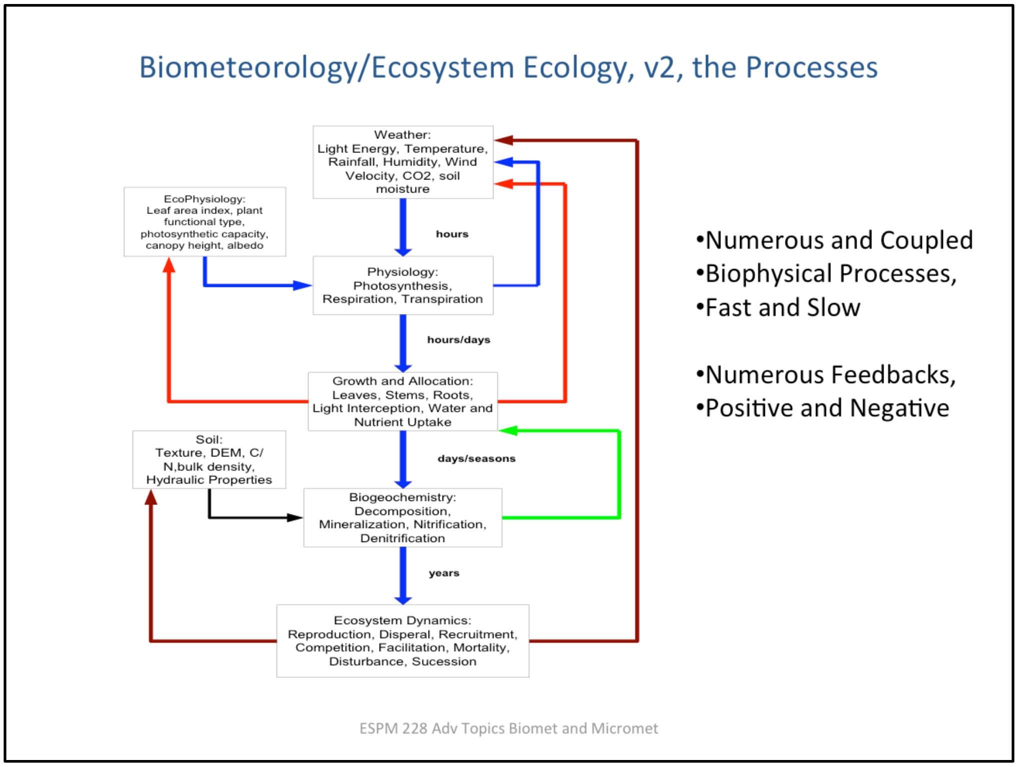


Application of bio meteorological principles to global scale fluxes of water, energy and carbon, with the SIB model, forced by satellite remote sensing inputs helped push us pass deWit's barrier.



This figure helps show why we need to couple carbon, water, energy and nitrogen to produce flux estimates across different ecosystems, land management, etc.

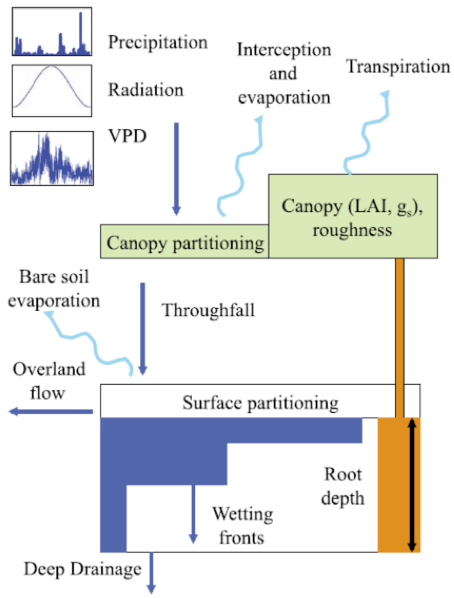
These multiple constraints help produce more defensible model computations of ecosystem scale fluxes than before with highly parameterized models, like the Jarvis siomatal conductance model



Many coupled processes; They operate across a number of time scales; involve a number of 'spheres'. Key points are feedbacks, scale emergent properties, coupling of biometeorology with ecology and biogeochemistry. This is why this course is so broad and why I challenge you, and me, to read and think broadly.

Future direction is to combine models like ED2, the ecosystem dynamics model with mesoscale models like WRF, RAMS and OLAM.

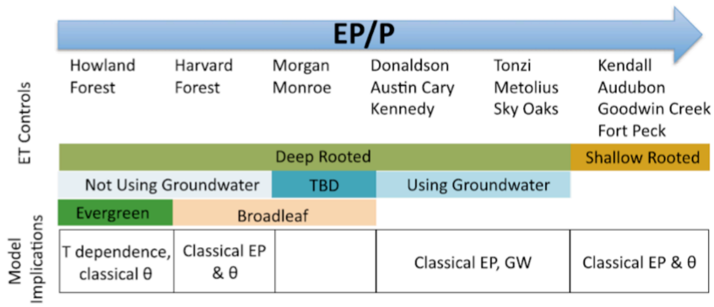
EcoHydrology Has Other Demands



Thompson et al 2011, WRR

We cant forget below ground, too, in terms of feedbacks between plants, water, roots..

Model Detail =f(ecosystem, climate)



EP: Evaporation potential; GW: Groundwater

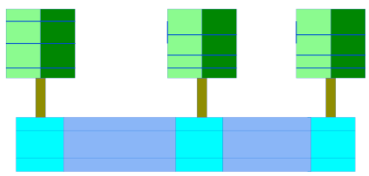
Thompson et al 2011, WRR

ESPM 228 Adv Topics Biomet and Micromet

Philosophically different levels of model detail may be needed to predict fluxes with success in different ecosystems and climate spaces.

Big-Leaf Vegetation/Bucket Soil

Multi-layer Vegetation/Soil & Sun/Shade



Hierarchy of Models:

Space:

- Big-Leaf Vegetation/Bucket Soil
- Sun/Shade Vegetation
- 2-Layer, Vegetation and Soil
- Multi-Layer 1-D
- 3-D Model

Time:

- Hour
- Day
- Month

ESPM 111 Ecosystem Ecology

How do we integrate fluxes from leaves to canopies. What are our options. Here is a hierarchy of models used by the community, trending from simple to greater detail. Some models are too simple and others are too complex to be of practical use.

All models are wrong; some models are useful

Attributed to George Box, statistician

Since all models are wrong the scientist cannot obtain a "correct" one by excessive elaboration. On the contrary following William of Occam he 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 overelaboration and overparameterization is often the mark of mediocrity. Below we describe the pros and cons of the hierarchy of models and depending on your application which one is most applicable.

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

How much model complexity is needed?

'Single layer models of evaporation from plant communities are incorrect, but useful, whereas multi-layer models are correct but useless'. (Raupach and Finnigan, 1988).

To Develop a Scientifically Defensible Virtual World
'You Must get your boots dirty', and Not Treat the Earth System Science as a Video Game

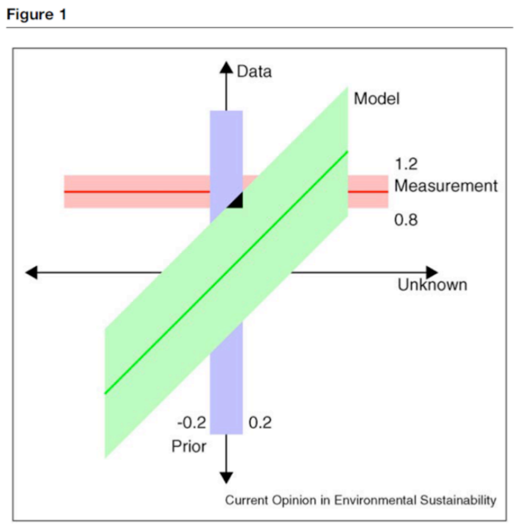
Collecting Real Data Gives you Insights on What is Important & Data/Ecological Rules to Parameterize and Validate Models

Collecting real data

Sources of Model Complexity and Uncertainty

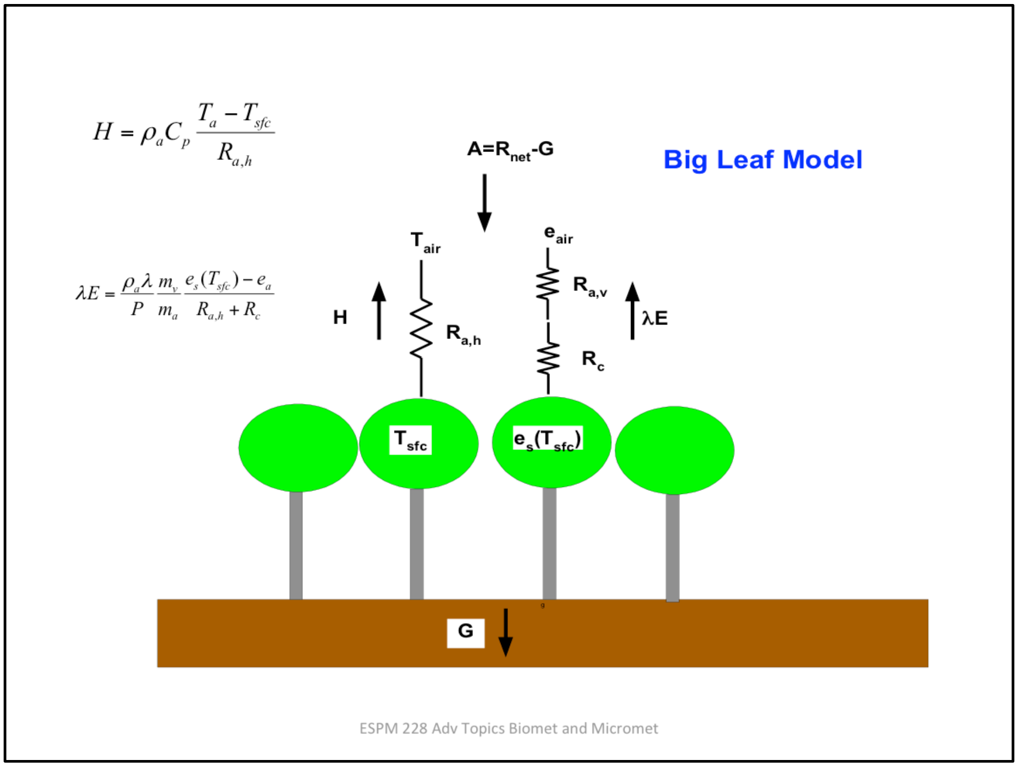
- Representation of System Complexity
  - Geometrical
  - Processes and Feedbacks
  - Non-Linearities
- Model Parameters, f(x,z,t)
- Driving, or Input, Variables and their Transformation
- Spatial and Temporal Resolution
- Accuracy/Representativeness of Test-Bed Flux Data

Model-Data Fusion

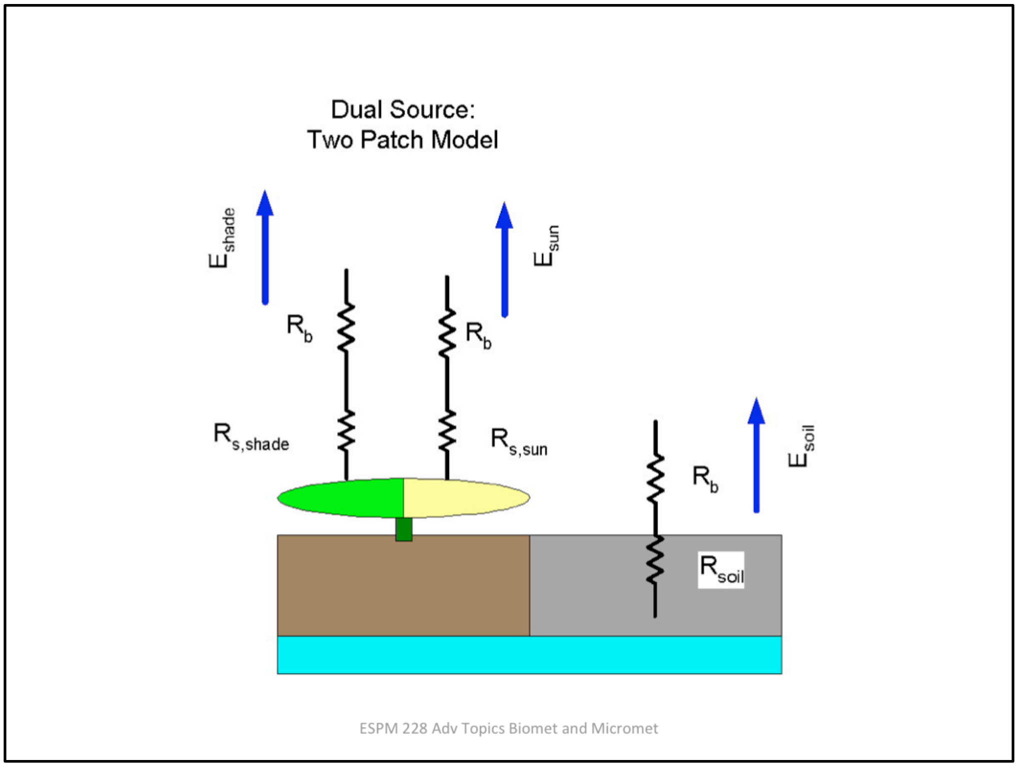


Rayner 2010 Current Opinions in Environment Sustainability

Model data fusion has made some advances in the past decade and is quite popular among certain groups. It has good utility for gap filling by integrating in time and space. Though often the model parameters may be overly tuned and not have biophysical meaning, so there should be care in using such models to project far into the future. For this reason much of this class focuses on mechanistic models that have links to biophysical processes and can be parameterized by field measurements at the leaf scale.

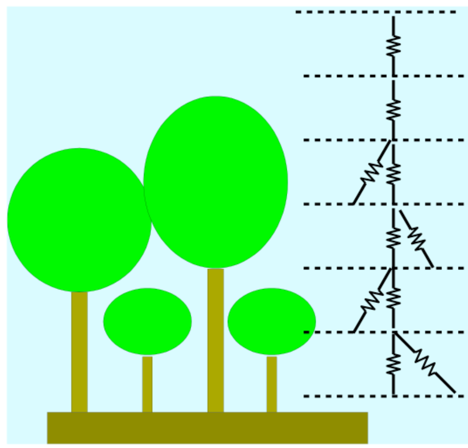


Simple big leaf model. One used by many climate, weather models, though its use is fading in terms of more complex and Better algorithms



One should use at least a dual source, dual patch model that treats fluxes for plants and soil and sun and shade fractions. We will discuss why in later slides.

Multi-Layer Models



Multi-layer models allow us to compute fluxes at multiple layers in a canopy to deal with strong gradients in light and turbulent mixing. These are among the more rigorous methods

Quantifying Sources and Sinks

$$\frac{\partial F}{\partial z} = S(C,z) = -a(z)\,\frac{(C(z) - C_i)}{r_b(z) + r_s(z)}$$

- Biology:
  - Leaf area density: a(z);
  - Internal Concentration: C_i;
  - Stomatal Resistance, r_s
- Physics:
  - Boundary Layer Resistance, r_b;
  - Atmospheric Concentration, C(z)

This equation is at the heart of multilayer models and outlines the coupled biophysical processes that must be considered. Over my career this is the equation that has guided much of my work, experiments and thinking. We need to know canopy structure and lai to assess a, wind and turbulence to assess rb and C(z), physiology and soil moisture to assess rs and biochemistry to asses Ci.

Mathematical Representation: Model Algorithms

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

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

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

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

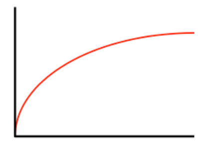
$$\frac{dc}{dt} = f(c,t)$$

Examples: Non-Linear Biophysical Processes

Photosynthesis

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

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



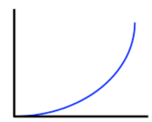
Transpiration

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

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

Respiration

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



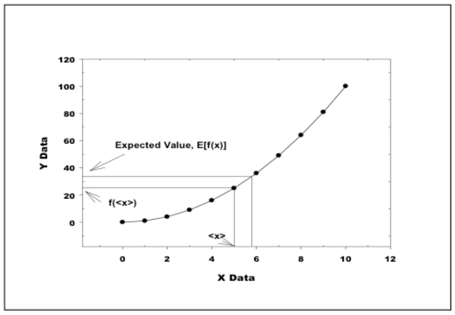
Leaf Temperature

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

Computing the Expected Value of a function

$$E[f(L)] = \int_{-\infty}^{\infty} p(x(L))f(x(L))dx$$

Why Non-linearity is Important?



Jensen's Inequality

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

Taylor's Series Expansion

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

Another Reason Why the Mean of the Function is Not Equal to the Function of the Mean

$$E[x \cdot y] = \overline{x} \cdot \overline{y} + \overline{x' y'}$$

With this simple case you see the addition of a higher order term

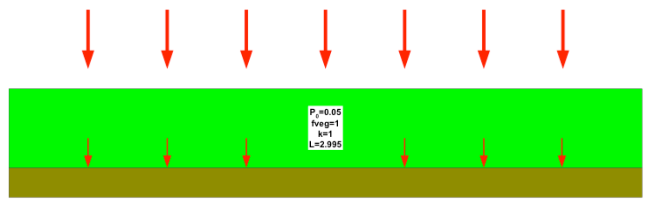
Inverting LAI from Radiation Transfer Measurements

$$P_0 = \exp(-kL)$$

$$\overline{\ln(P_0)} \neq \ln(\overline{P_0}) \qquad L = -\frac{\overline{\ln(P_0)}}{k} = -\frac{\ln(\overline{P_0})}{k}$$

L = 2.996
[P_0]=0.05
[ln(P_0)]=-2.996

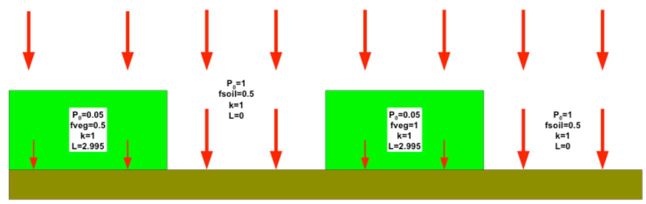
Ln[P_0]=-2.996
L*=2.996



$$L = -\frac{\overline{\ln(P_0)}}{k} \neq -\frac{\ln(\overline{P_0})}{k}$$

L = 1.497
[P_0]=0.525
[ln(P_0)]=-1.497

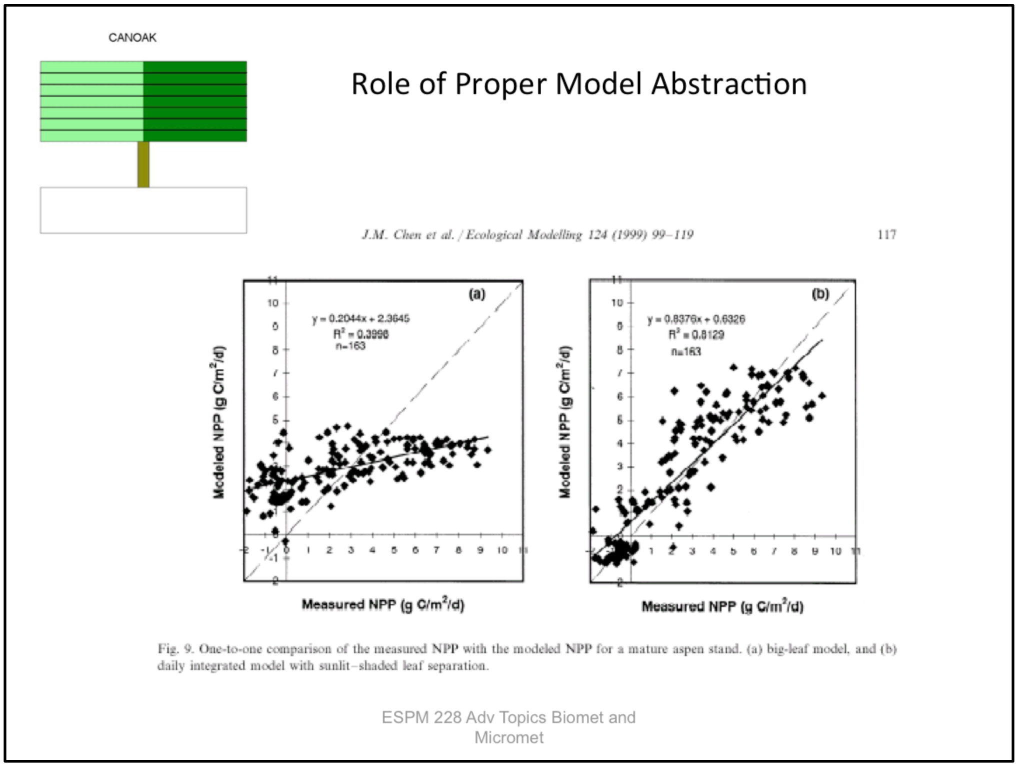
Ln[P_0]=-0.644
L*=0.644



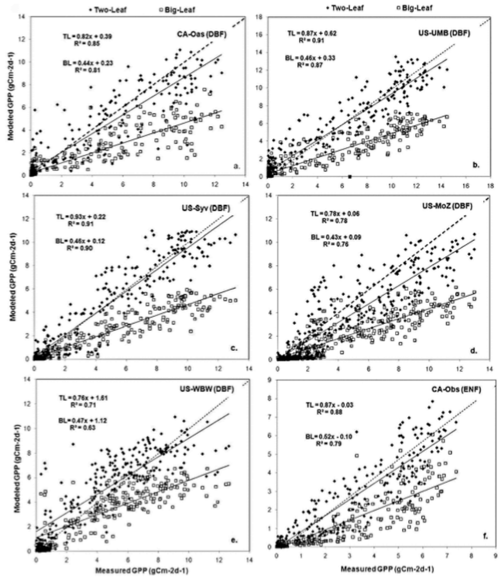
Weight Source/Sink by Fraction of Sunlit and Shaded Leaves and Their Environment

$$S(C,z) = f(I_{sun}, T_{sun}, q_{sun}, C_{sun}) \cdot p_{sun}(z) + f(I_{shade}, T_{shade}, q_{shade}, C_{shade}) \cdot p_{shade}$$

Many of the equations are very non linear so we need to apply these models by considering the sun (psun) and shade (pshade) fractions, which we will discuss below.



This paper by Chen clearly shows how wrong one may be using a big leaf model vs one that considers sun shade fractions. Clearly the sun shade model has better performance.



Sprintsin et al 2012 JGR Biogeosci

This paper is a more thorough analysis using flux data from numerous canopies

Dual Source Model: Discrete Form

Whole Canopy Surface Conductance,
Wt function of sun and shade leaf areas

$$G_{sfc} = L_{sun}G_{sun} + L_{sh}G_{sh}$$

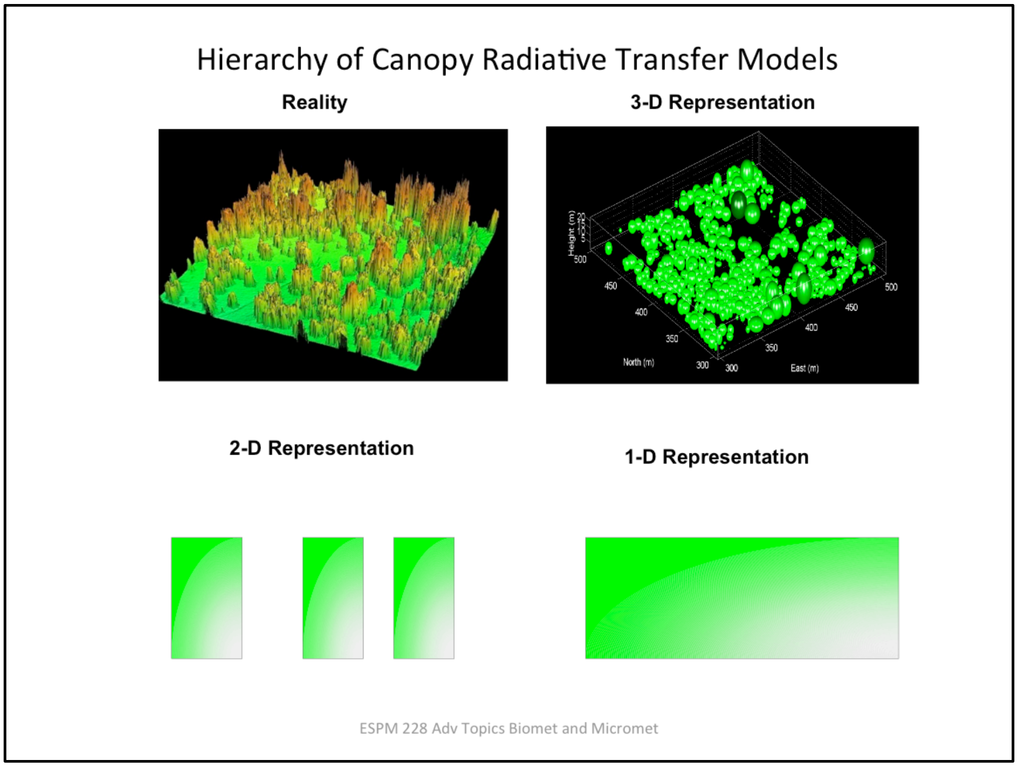
$$L_{sun} = (1 - \exp(-kL)) / k$$

Sunlit leaf area

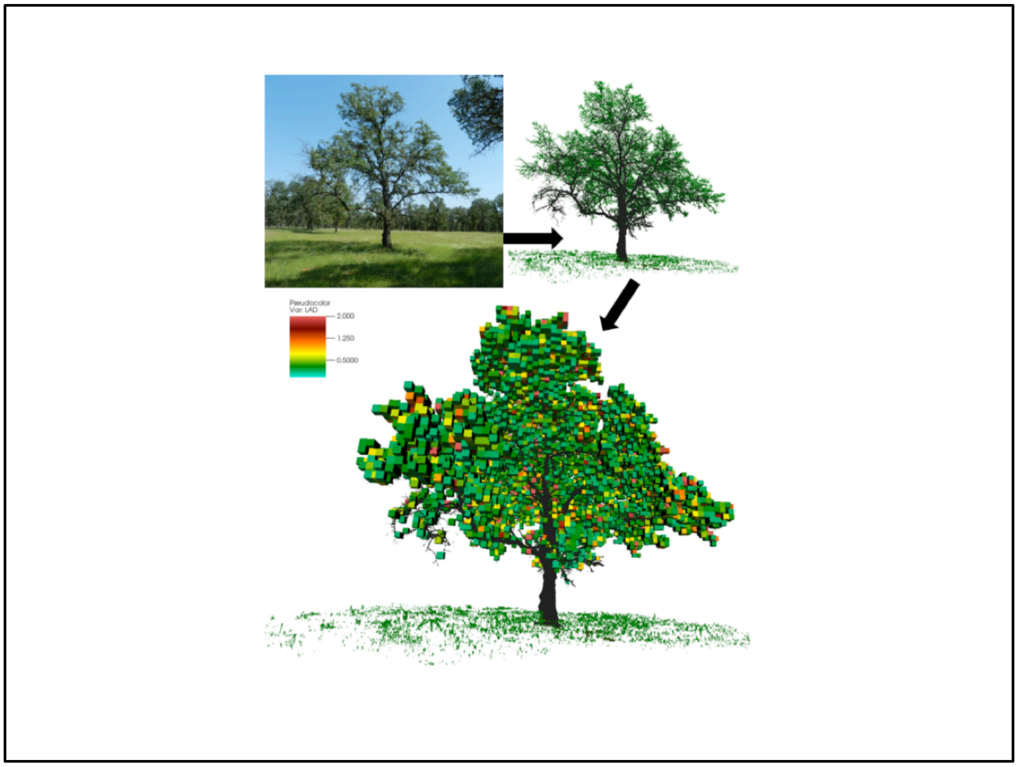
$$L_{sh} = L - L_{sun}$$

Shaded leaf area

How do we apply a sun shade model. Here is a simple case for stomatal conductane and models to compute the leaf area of the sun and shade leaves from light transfer theory. L is leaf area index and k is the extinction coefficient.

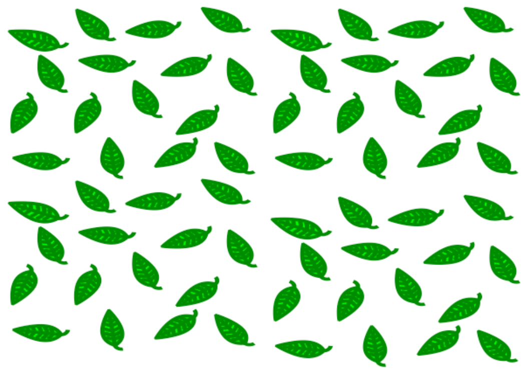


A vegetated landscape can be quite complex. What are our options for trying to model this system. We use statistical representations rather than relying on the Cartesian location of each and every leaf; though the later is becoming possible with new ground base lidar measurements of canopy structure and the application of Monte Carlo 3d ray tracing models for computing radiative transfer.



With terrestrial LIDAR we can now visualize trees in great detail and look at ray transfer through voxels.

Probability of Light Penetration, P_0, through a population of leaves, Randomly distributed in Space with a Known Distribution of Leaf Inclination angles



We use statistical theory to simulate light transfer through vegetation. It makes the endeavor tractable

Random Spatial Distribution:

Poisson Probability Distribution

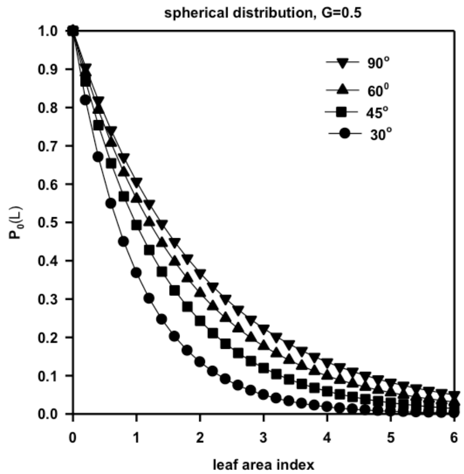
$$P_0 = \exp(-\frac{L\,G}{\sin\beta})$$

Probability of Beam Penetration, P_0

L: Leaf area Index
G: direction cosine of leaf normal vs solar zenith angle
θ: solar zenith angle
β: solar elevation angle

We start with a form of Beer's law which is used to compute the probabilty of beam penetration or the probability of zero lights, P0. It is a function of the angle of the source and the angle of the leaves

Sun Angles and the probability of beam penetration, P_0



Beer's Law

$$P_0 = \exp(-kL)$$

$$P_0 = \exp(-\frac{LG}{\cos\theta_{sun}}) = \exp(-\frac{LG}{\sin\beta_{sun}})$$

L: Leaf area Index
G: direction cosine, leaf normal vs solar zenith angle
θ: solar zenith angle
β: solar elevation angle

Here is a family of curves for different sun angles and cumulative leaf area index, L. Typical over 90% of incoming radiation is atttenuated by the time L reaches 5.

Probability of Sunlit (Beam) and Shaded Leaves

$$P_b = -\frac{\sin\beta}{G}\frac{dP_0}{dL} = \exp(-\frac{L\,G}{\sin\beta})$$

$$P_{sh} = 1 - P_b$$

L: Leaf Area Index
P_0: probability of beam penetration, or zero contacts
P_b: probability of beam
P_{sh}: probability of shade
G: cosine of the angel between the leaf normal and beam
β: solar elevation angle

Probability of Beam is a function of the derivative of P0 with respect to L, adjusted for the sun and leaf angles. It tells us what faction of leaves are sunlit. Its complement is the fraction of leaves are shaded. Ironically for randomly populations of leaves Pb and P0 are identical.

Sunlit Leaf Area

$$L_{sun} = \int_0^L P_b(l)dl$$

Sunlit leaf area index is the integration of the probability of beam with respect to leaf area index

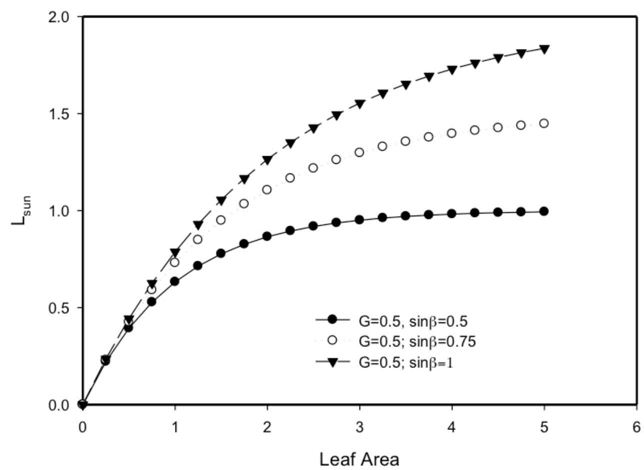
$$L_{sun} = \frac{\sin\beta}{G}(1 - \exp(-\frac{GL}{\sin\beta})$$

Analytical solution

ESPM 228 Adv Topics Biomet and Micromet

Sunit leaf area is related to the integral of P beam

Sunlit Leaf Area



Depending on the sun angle the amount of area that can be sunlit is greater than one and reaches an asymptote near 2.

Many Forests have Clumped Foliage

Clumped Vegetation: Markov Distribution

$$P_0 = \exp(-\frac{\Omega\, L\, G}{\sin\beta})$$

$$P_b = -\frac{\sin\beta}{G}\frac{dP_0}{dL} = \Omega\exp(-\frac{\Omega\, L\, G}{\sin\beta})$$

Ω: clumping factor

If leaves are clumped, we apply the clumping factor, omega. And by solving analytically for Pb, we learn in this case that Pb does not equal P0. This is important lesson in applying these ideas to models. It is important to understand the derivation and source of equations we use and not plug and chug

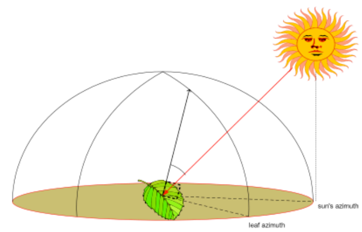
Sunlit Leaf Area, Clumped Leaves

$$L_{sun} = \int_L^0 \Omega \exp(-\frac{\Omega G L}{\sin\beta}) dL$$

$$\int a \exp(-bx) dx = -\frac{a}{b}\exp(-bx)$$

$$L_{sun} = \frac{\sin\beta}{G}(1 - \exp(-\frac{\Omega G L}{\sin\beta}))$$

G Function, the relation between leaf normals and the sun

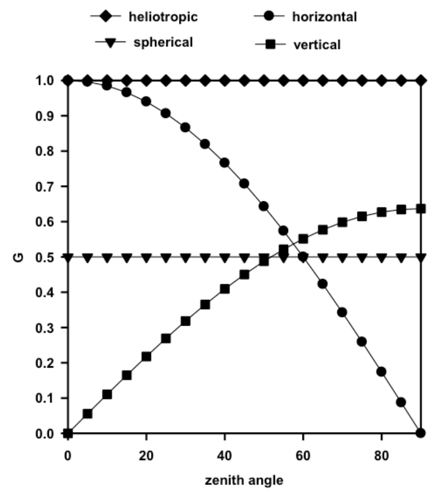


$$G(\theta,\varphi)=\frac{1}{2\pi}\int_0^{2\pi}d\varphi\int_0^{\pi/2}g(\theta_{leaf},\varphi_{leaf})\left|\cos(nn_{leaf}\right|\sin\theta_{leaf}\,d\theta_{leaf}$$

$$\cos(nn_{leaf})=\cos\theta\cdot\cos\theta_{leaf}+\sin\theta\cdot\sin\theta_{leaf}\cos(\varphi-\varphi_{leaf})$$

What is the G function. It is essentially the cosine of the angle between the beam and the leaf normal. We weight it for all the angles of the leaf distribution and integrate it across the hemisphere. We can use spherical geometry to assess cos (n nleaf)

G functions for different leaf inclination angle distributions

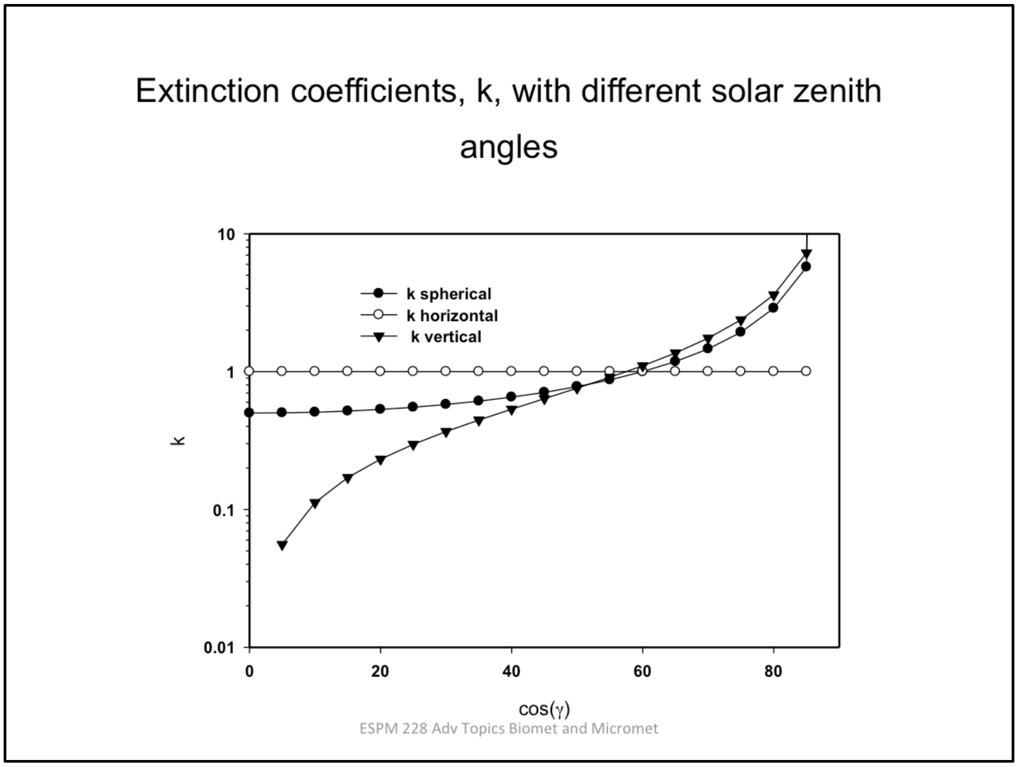


For many practical applications G is about 0.5, especially if the leaves possess a spherical distribution.

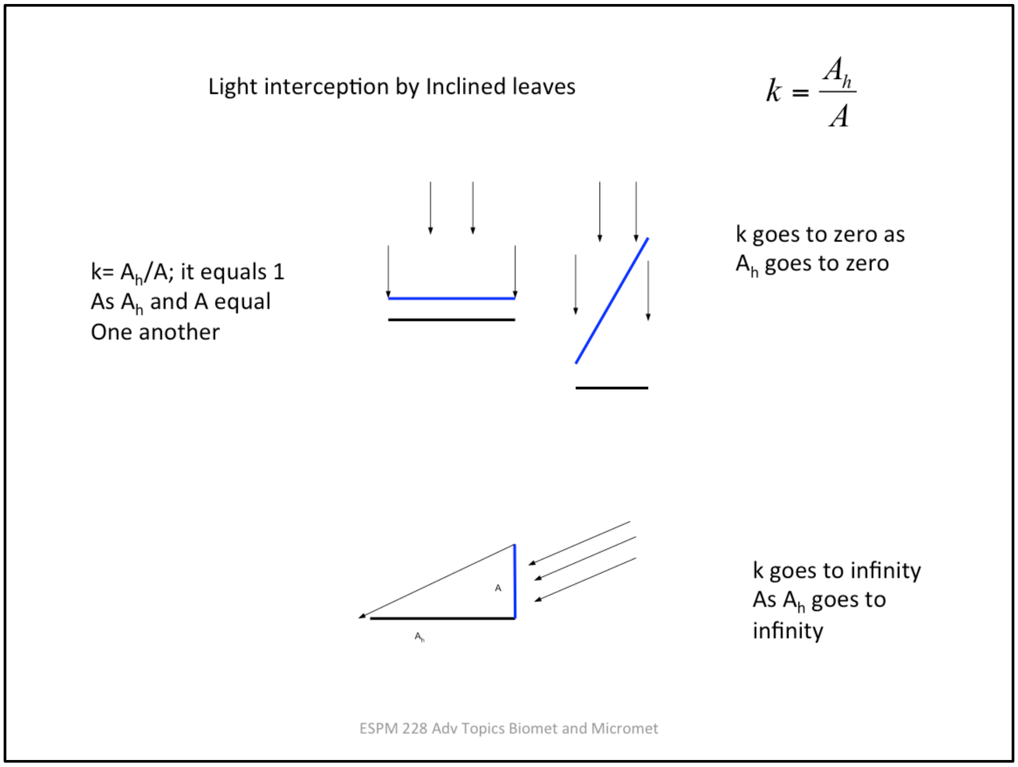
The extinction coefficient, k, equals
the fraction of hemi-surface leaf area (*A*) that is **projected onto the horizontal** (A_h), from a particular zenith angle.

$$k = \frac{A_h}{A}$$

We can better understand G by thinking about extinction coefficients, which is related to the area of leaves, A, projected on the horizontal, Ah



Extinction coefficients are another way to look at light transfer through vegetation. Here is how k varies with solar zenith angle



These are some of the key limits for k depending on angle of leaves and sun

Define K in terms of Sun and Leaf Inclination Angles

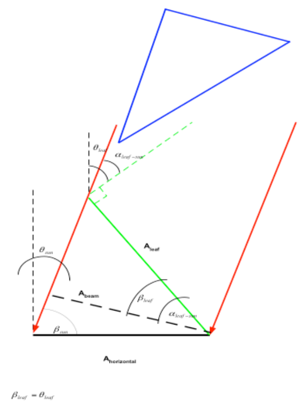
$$\frac{A_{horiz}}{A_{leaf}} = \frac{\cos\alpha}{\sin\beta_{sun}} = \kappa = \frac{G}{\sin\beta_{sun}} = \frac{G}{\cos\theta_{sun}}$$

α,angle between leaf normal
And solar zenith

β, solar elevation angle

k, extinction coefficient

G, G-function or direction cosine



ESPM 228 Adv Topics Biomet and Micromet

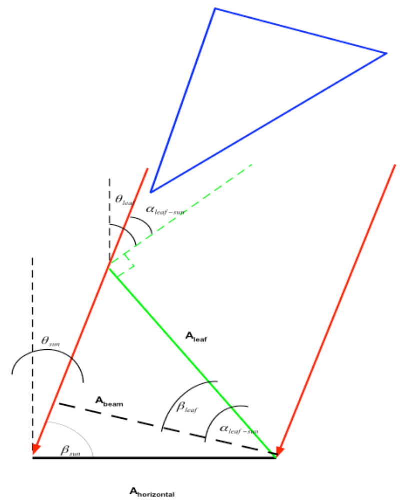
Here is a derivation relating k and G and cos (n nl)

Project the area of a leaf normal to the sun's beam (Ab) onto the horizontal (Ah).

$$\frac{A_b}{A_h} = \sin\beta = \cos\theta$$

Project the area of a leaf onto the area normal to the solar beam

$$\frac{A_{beam}}{A_{leaf}} = \cos\alpha$$

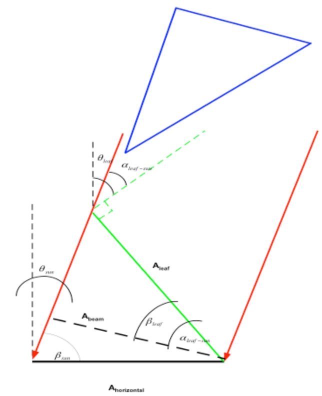


$\beta_{leaf} = \theta_{leaf}$

$$A_{beam} = A_{leaf} \cos\alpha$$

$$A_{leaf} = \frac{A_{beam}}{\cos\alpha}$$

$$\frac{A_{beam}}{A_{horiz}} = \sin\beta_{sun} = \frac{A_{leaf}\cos\alpha}{A_{horiz}} = \cos\theta_{sun}$$



$$\frac{A_{leaf}}{A_{horiz}} = \frac{\sin\beta_{sun}}{\cos\alpha} = \frac{\cos\theta_{sun}}{\cos\alpha}$$

$\beta_{leaf} = \theta_{leaf}$

Voila'

$$\kappa = \frac{G}{\sin \beta_{sun}} = \frac{G}{\cos \theta_{sun}}$$

Functions for k and G

$$\frac{A_{horiz}}{A_{leaf}} = \frac{\cos\alpha}{\sin\beta_{sun}} = \kappa = \frac{G}{\sin\beta_{sun}} = \frac{G}{\cos\theta_{sun}}$$

Leaf Angle Distribution	G, direction cosine	K, extinction coefficient
Horizontal	$\cos(\theta)$	1
Vertical	$2/\pi \sin(\theta)$	$2 \tan(\theta/\pi)$
Conical	$\cos(\theta) \cos(\theta_l)$	$\cos(\theta)$
Spherical or random	0.5	$1/(2 \cos(\theta))$
Heliotropic	1	$1/ \cos(\theta)$
Ellipsoidal	*	**

Simple algorithms for different leaf angle classes

Sunlit leaves are illuminated by direct and diffuse light

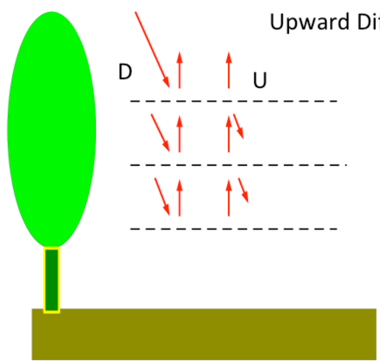
$$I_{sun} = \frac{I_{beam} \cdot G}{\sin \beta} + I_{shade}$$

Direct Light is Directional
Diffuse Light is Isotropic and Hemispherical

Radiative Transfer Scheme

Downward Diffuse $$D_i = R_l \cdot U_i + T_n D_{i+1}$$

Upward Diffuse $$U_{i+1} = R_u \cdot D_{i+1} + T_n U_i$$



$$T_n = exp(\frac{-\Delta f \cdot G \cdot \Omega}{sin\,\beta}) + (1 - exp(\frac{-\Delta f \cdot G \cdot \Omega}{sin\,\beta}))\tau$$

$$R_l = (1 - exp(\frac{-\Delta f \cdot G \cdot \Omega}{sin\,\beta}))\rho_l$$

$$R_u = (1 - exp(\frac{-\Delta f \cdot G \cdot \Omega}{sin\,\beta}))\rho_u$$

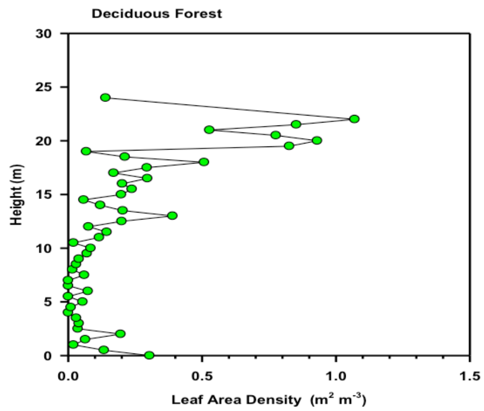
After Norman, 1979

Simple scheme for light transfer for 1D canopy, implemented by Norman. This is the scheme I use in CanVeg

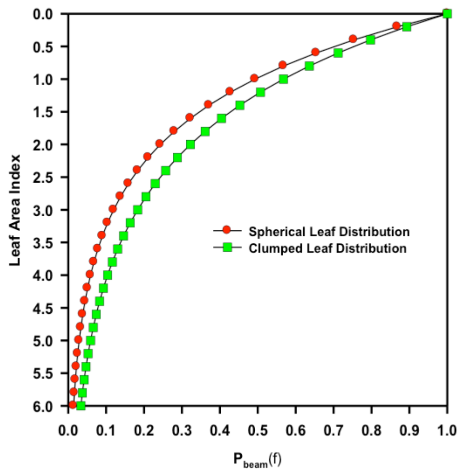
Sources of Spatial Heterogeneity

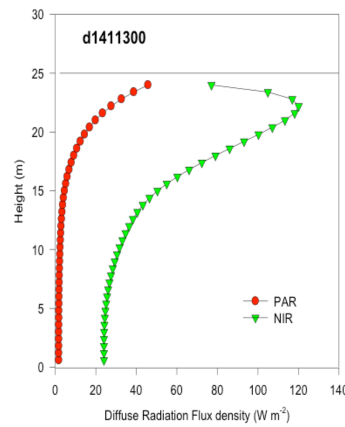
- Vertical Variations in:
  - Leaf area index
  - Leaf inclination angles
  - Leaf Clumping
  - Leaf N + photosynthetic capacity
  - Stomatal conductance
  - Light, Temperature, Wind, Humidity, CO_2

Vertical Profiles in Leaf Area



Vertical Variation in Sunlight



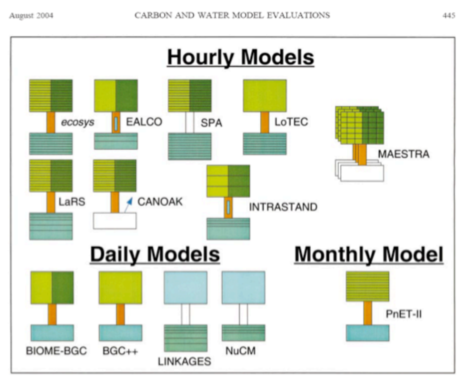


Summary

- Introduced Hierarchy of Leaf to Canopy Integration Models
- Described Why we Need to Evaluate the Expected Value of the Function
  - We need to Evaluate Biophysical Functions on Sun and Shade Fractions of Leaves
- Introduced Statistical Theories of Radiative Transfer through Vegetation

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



After Hanson et al Ecol Appl 2004

How do we integrate fluxes from leaves to canopies. What are our options. Here is a hierarchy of models used by the community, trending from simple to greater detail. Some models are too simple and others are too complex to be of practical use.

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
- Avoid Auto-Correlation, y =f(y)
- Avoid Extrapolating Empirical Regression models beyond the range of the dataset
  - Data Assimilation Best for Gap Filling in Time/Space and Diagnosis
- Use Mechanistic and Prognostic Models to predict the Future and to Upscale information
- Closure: Equal number of Equations and Unknowns is needed