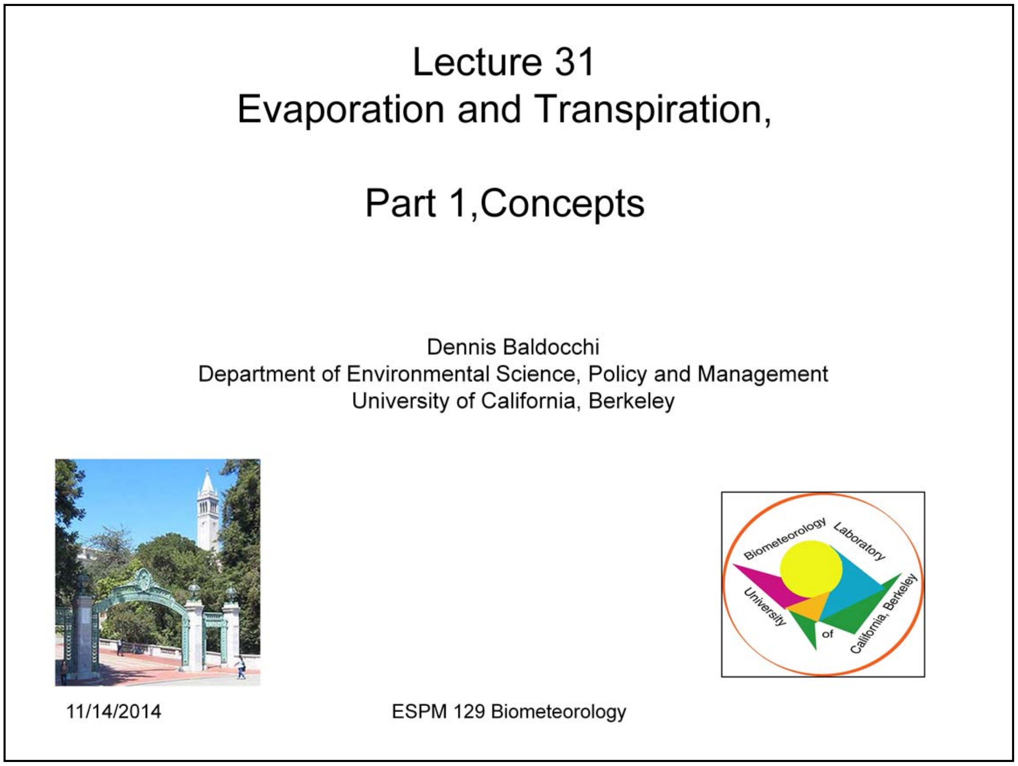


Much of the material in this class has built up to assess evaporation of landscapes. Here we discuss concepts and data. The field of evaporation has grown and advanced a lot over the past few decades

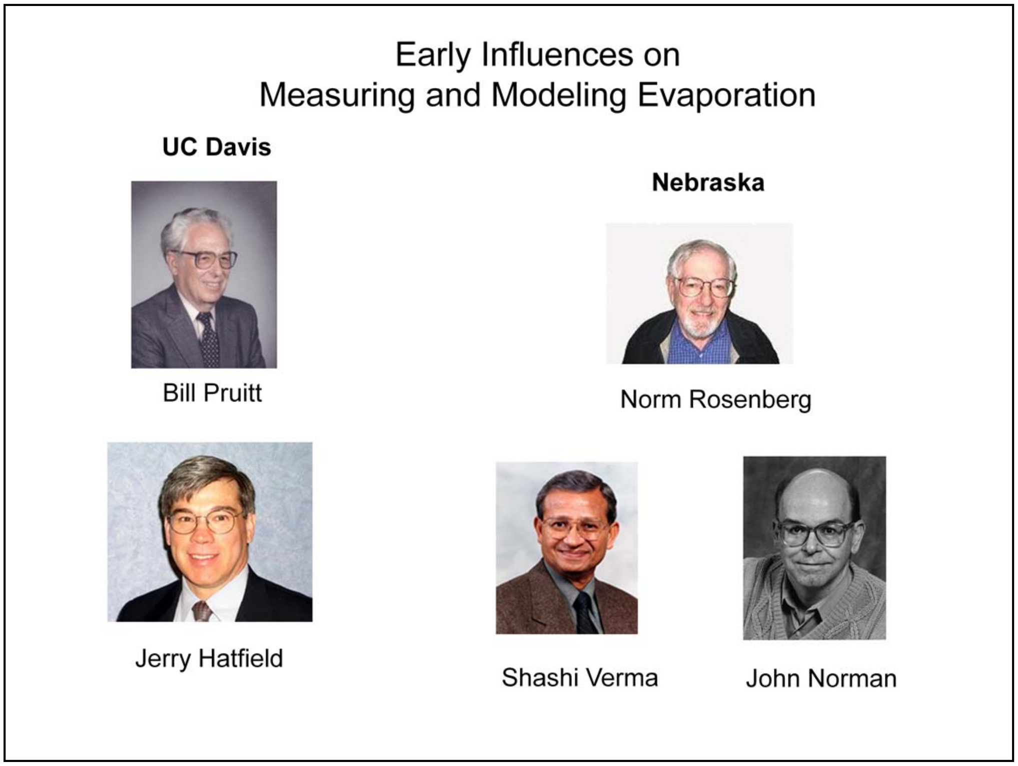
Outline

- Processes, Supply vs Demand, Short and Long Time scales
  - Short
    - Energy
    - Meteorology
  - Long
    - Leaf area index
    - Nutrition
    - Plant Functional type
  - Short to Long
    - Surface Conductance
    - Soil Moisture
- Time
  - Day/Night
  - Seasonal
  - Interannual
- Space
  - Land Use
  - PBL/Landscape
  - Globe

Long Interest in Evaporation

Circa 1960

My early training was in agricultural meteorology with a need to measure evaporation of crops to better schedule irrigation and conserve water. Here I am irrigating our walnut orchard.



I was lucky to be trained by some of the leading scientists of their time measuring and modeling ET at UC Davis and Nebraska. Bill Pruitt wrote the FAO manual on evaporation; Hatfield taught me biometeorology; Rosenberg was a pioneer measuring ET with lysimeters and Bowen ratio; Verma was a pioneer applying eddy covariance to measure ET; Norman was a pioneer coupling leaf-canopy models to simulate evaporation with a mechanistic approach.

Big Picture Question Regarding Predicting and Quantifying Global Evaporation:

- **How can We Evaluate Water Fluxes 'Everywhere All the Time?'**

Teaching this course has helped me evolve scientifically. Our big goal is towards applying biometeorology and ecological theory to estimate evaporation everywhere, all the time

Wedding at Cana, Veronese, the Louvre, Paris

Other Over Arching Questions

- What is Annual ET of Natural Ecosystems, as measured directly by Eddy Covariance?
- How does Annual ET respond to Precipitation, Available Energy, & Drought?
- What is Annual ET at Regional and Global Scales, using New Generation of Eco-hydrological Information, Flux Networks and Satellite-based Remote Sensing?

Motivation, Part 1

- Most Annual Water Budgets are Indirect, Inferred from Water Budgets (ET ~ Precipitation – Runoff)

- Global Network of Direct, Continuous and Multi-year Carbon and Water Eddy Covariance Flux Measurements Exists that has been Under-Utilized with regards to the Annual Water Budget of Terrestrial Ecosystems

We can now measure evaporation year round with eddy covariance and do so directly. This has the potential to improve water balances determined as residuals from rain and runoff.

Evaporation

- Evaporation is the "physical process by which a liquid or solid is converted to a gaseous state" (Glossary of Meteorology).
- Plant canopies introduce water vapor into the atmosphere via **transpiration** and the **evaporation** of water from the soil and free water on the leaves and stems.

ESPM 129 Biometeorology

Definition of evaporation

Potential Evaporation

- “the evaporation from an extended surface of a short grass that is supplied with water and the canopy covers the ground completely.”

ESPM 129 Biometeorology

Reference evaporation is defined by potential evaporation

Can Potential ET > Pan ET?

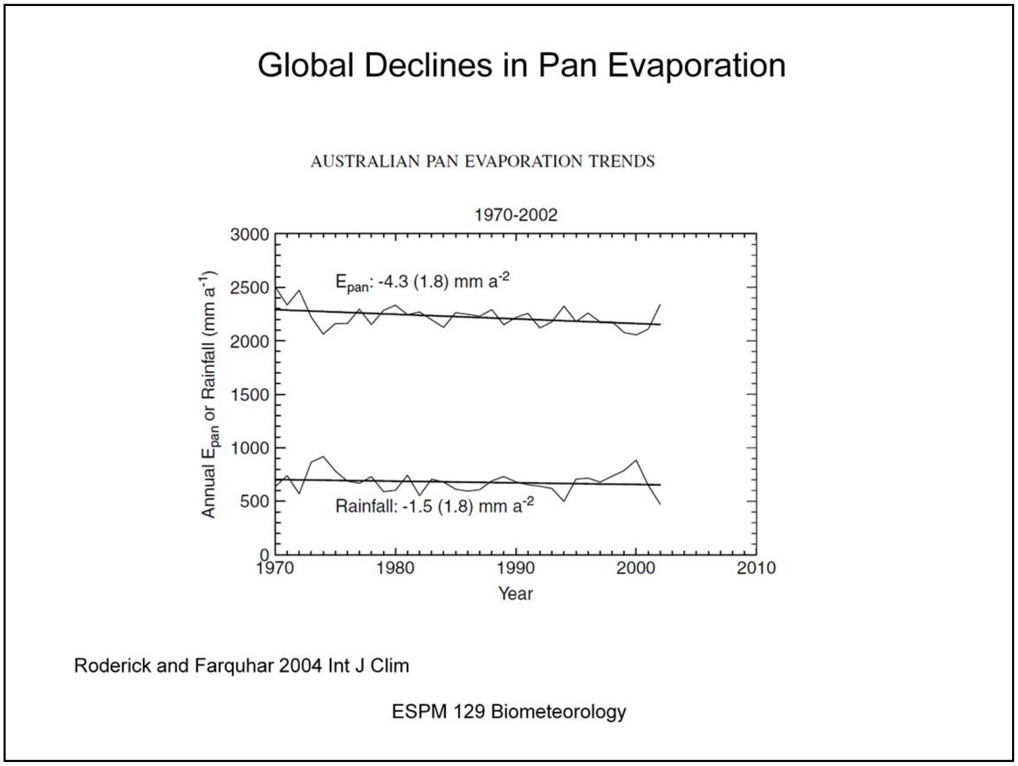
ESPM 129 Biometeorology

Early and simple estimates of evaporation were developed using evaporation pans.
Are these good proxies for studying crop or forest evaporation?

Yes!

- The surface area of transpiring leaf area exceeds the surface area of a water body, as an evaporation pan.
- Water is partially transparent to sunlight and stores heat energy.
  - the energy available to evaporate water will be different than that used to evaporate water from vegetation
- Evaporation pans are also subject to error due to the **oasis effect** and from animals drinking from it.

Pans are biased and have resulted in a pan paradox in terms of trends in evaporation; pan evaporation has declined world wide in spite of a warming world and a stronger evaporation potential



Pans are simple and have been used for over 50 years in experiment stations across the globe. In numerous analyzes scientists are finding and reporting downward trends in pan evaporation. What does this mean? Should we not expect higher evaporation rates in a warming world

Pan Paradox

- Reduction in Pan Evaporation Does not mean Actual Evaporation is decreasing; the opposite can be occurring, instead
  - Brutsaert and Parlange
- Cause of the Trend in Pan Evaporation
  - Stilling of the Winds
  - Dimming of the Sun
    - Roderick Farquhar

We are experiencing a pan paradox. Brutsaert and Parlange examine this problem in terms of Buchet's complimentary theory and a decrease in pan evaporation can correspond with an increase in actual evaporation; pan et only measures atmospheric demand. Actual evaporation is the balance between supply and demand. More supply in a water limited land can humidify the atmosphere and reduce pan et, while leading to an increase in actual evaporation. Roderick and Farquhar have modeled pan evaporation and claim the trends follow a global reduction in wind (stilling) and a decline in solar radiation (due to pollution) (dimming)

Potential Evaporation:

Priestley-Taylor Equation

$$\lambda E_{pot} \approx 1.26 \frac{s}{s+\gamma}(R_n - S)$$

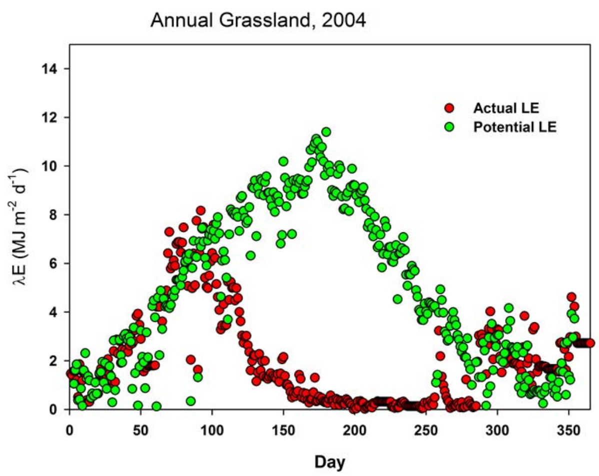
s, slope of saturation vapor pressure-Temperature curve
γ, psychrometric constant
Rn, net radiation (W m^{-2})
S, Soil heat flux (W m^{-2})

$$\gamma = \frac{C_p \cdot P \cdot m_a}{\lambda \cdot m_v}$$

ESPM 129 Biometeorology

Potential evaporation is a good reference and one can compute an upper limit in terms of the Priestley Taylor equation, which is a function of available energy. Potential evaporation is a good measure of evaporation if water supply to the plant is ample.

Seasonal and Annual Time Scales



Potential and Actual Evaporation are Decoupled in Semi-Arid System

ESPM 129 Biometeorology

Here is a nice comparison of evaporation measured and potential. During the wet period, ET is radiation limited so measured and potential are nearly identical. As the soil dries actual evaporation drops and potential follows the seasonal course of available energy

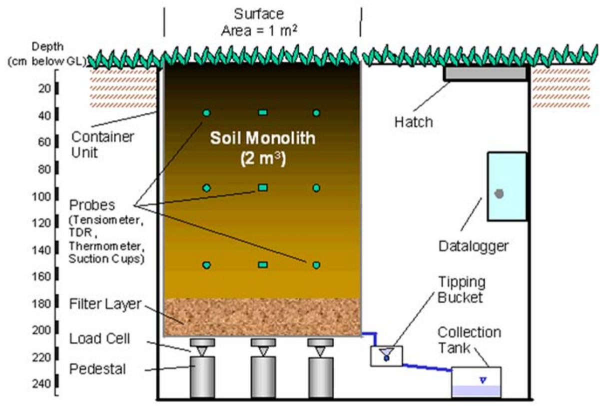
Actual Evaporation

- Lysimeter
- Aerodynamic Approach
- Energy Balance (Bowen Ratio) Approach
- Eddy Covariance
- Evaporation Pan
- Soil Water Budget
- Combination Method
  - Penman Equation
  - Penman-Monteith Equation
  - Modified Priestly-Taylor Method
- Climatological Methods
  - Thornthwaite Equation

ESPM 129 Biometeorology

Actual evaporation is hard to evaluate if the world is water limited. There are many ways to measure of model evaporation

Lysimeter



ESPM 129 Biometeorology

Lysimeters weigh the change of mass on a soil monolith. It is a direct measure but is poorly replicated and can yield a bias in how the plants grow on the lysimeter vs around it

Lysimeter at UC Davis

ESPM 129 Biometeorology

This is the famous UC Davis lyimeter, 10 m in diameter! But shallow.

Aerodynamic Method

E is f() of humidity Deficits and Turbulent Mixing

$$E = (e_s - e) f(u)$$

$$E = \rho_a \varepsilon \frac{\frac{e_s}{(p - e_s)} - \frac{e}{(p - e)}}{R_w} = \rho_a \varepsilon \frac{(c_{ws} - c_w)}{R_w}$$

ESPM 129 Biometeorology

Ways to measure ET. Aerodynamic method using gradients in humidity and some estimate of a resistance or eddy diffusivity

Evaluate E by Measuring Vertical Gradients of vapor pressure (e) and Wind Speed (u)

$$E \approx K_w \frac{\Delta e}{\Delta z}$$

Eddy Exchange of Kwater ~ K momentum

$K_w \sim K_m$

$$K_m \approx k^2 (z-d)^2 \frac{\Delta \bar{u}}{\Delta z}$$

ESPM 129 Biometeorology

K theory version to measure ET. I used this approach with my dissertation

Energy Balance Method

$$R_n = \lambda E + H + S$$

λE, latent heat flux density
H, sensible heat flux density
S, soil heat flux density
Rn, net Radiation flux density

$$\lambda E = R_n - H - S$$

$$1 + \frac{H}{\lambda E} = 1 + \beta = \frac{R_n - S}{\lambda E}$$

ESPM 129 Biometeorology

Bowen ratio method uses the energy balance

Bowen Ratio Method,
measured with temperature and humidity gradients

$$\beta = \frac{H}{\lambda E} \qquad \beta = \frac{C_p (T_2 - T_1)}{\lambda \frac{M_v / M_a}{P} (e_2 - e_1)} = \gamma \frac{(T_2 - T_1)}{(e_2 - e_1)}$$

$$\lambda E = \frac{R_n - S}{1 + \beta}$$

ESPM 129 Biometeorology

We can estimate K by the ratio of temperature to humidity gradients. This takes a very precise and accurate psychrometer system to meaure small differences in well mixed conditions. A technical challenge and one even greater over forests. In fact this technical issue led to a delay in active measurement of ET over forests.

Eddy Covariance,
Flux Density: mol m^{-2} s^{-1} or J m^{-2} s^{-1}

$$F = \overline{\rho_a w s} \sim \overline{\rho_a} \cdot \overline{w' s'}$$

$$s = (\frac{\rho_c}{\rho_a})$$

ESPM 129 Biometeorology

Game changer. Direct measurement method, but needed to co evolution of computers,computer storage, 3d sonic anemomers and hygrometers (lyman alpha or infrared spectrometers).

Thornthwaite Equ

$$E = 1.6 \frac{L}{12} \frac{N}{30} (10 \frac{T}{I})^a$$

L is daylength in hours
N is number of days in a month
T is mean monthly air temperature
I is a heat index,
computed as a function of the sum of 12 monthly temperature indices, *i*

ESPM 129 Biometeorology

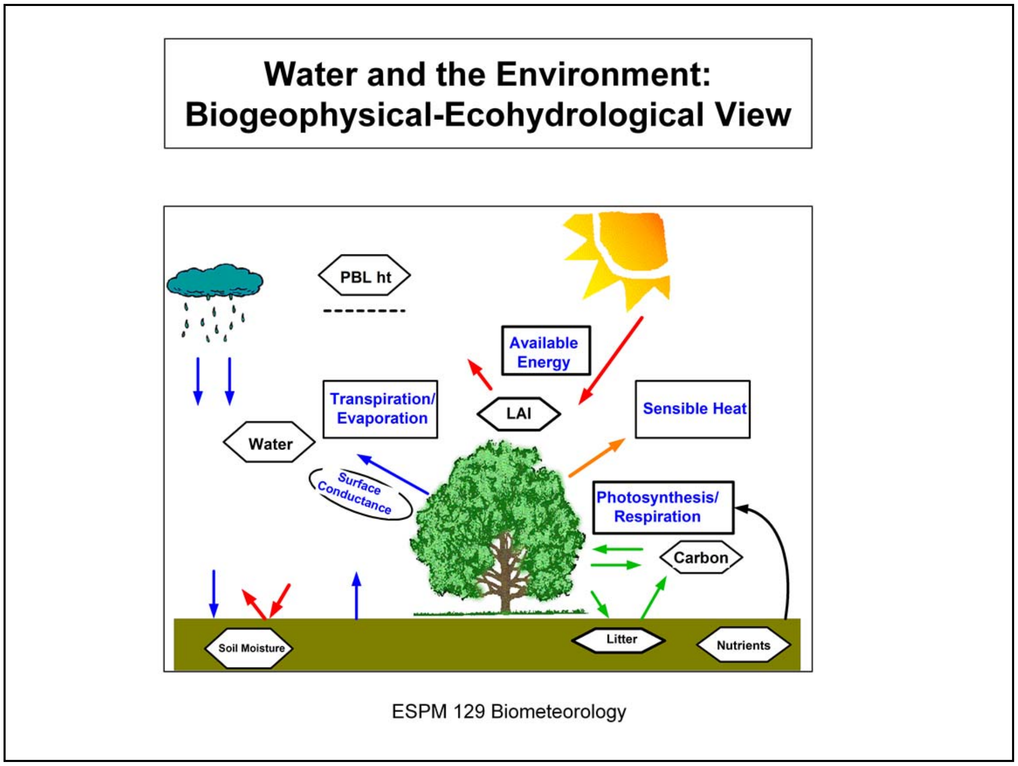
Classic model used by geographers and ecologists. Popular because a function of climate variables so evaporation could be mapped.

Why the Thornthwaite Equation Should Not Be Used

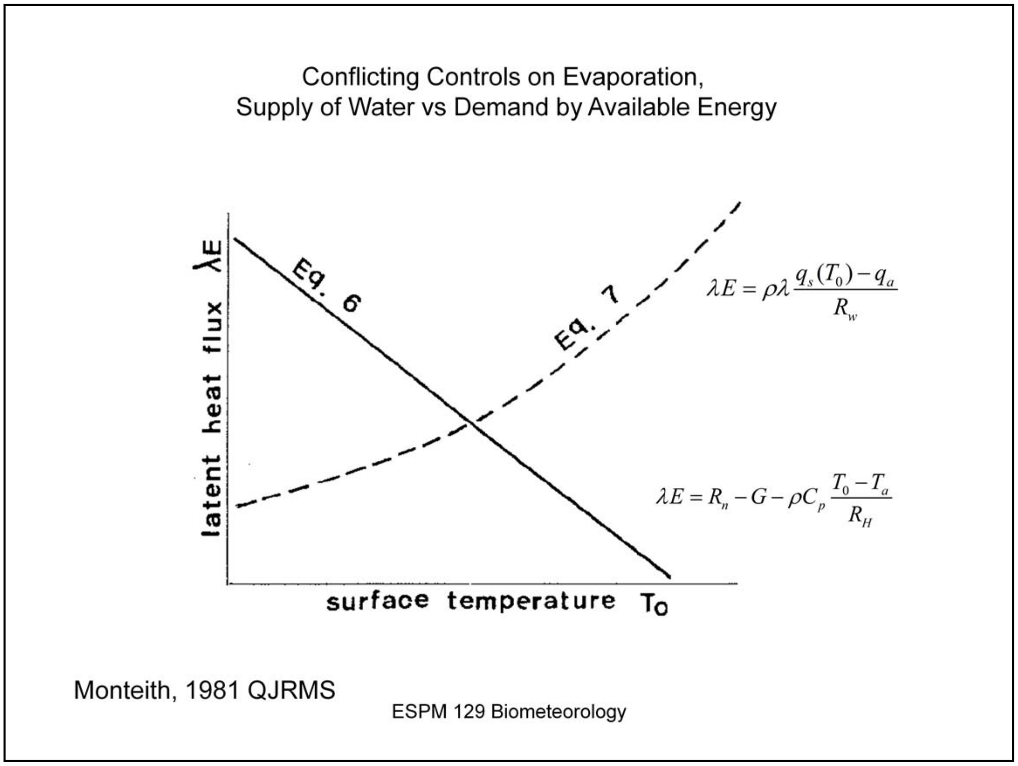
- Evaporation and temperature are out of phase with one another
- It has no physiological feedback between supply and demand
- Can not be applied to short term studies
- temperature is not a suitable proxy for radiation on short time scales.

ESPM 129 Biometeorology

Recent paper by Roderick et al go as far as stating we should stop using the Thornthwaite equation. I agree heartedly.



Towards assessing actual evaporation. We must consider coupling between radiation, state of the atmosphere, depth of the boundary layer and status of the vegetation, in terms of leaf area index, photosynthetic capacity, soil moisture.



Biometeorology is invoked to understand the intersection between demand and supply. From the supply perspective a warmer surface would promote greater evaporation as the humidity at the leaf surface increases. But the demand says, using the energy balance that a warmer surface would reduce available energy and reduce evaporation. In practice there is an intersection. This yields actual evaporation for a set of conditions.

Penman Monteith Equation

John L Monteith, FRS
(1929-2012)

$$\lambda E = \frac{s(R_n - S) + \rho \cdot C_p \cdot G_H \cdot D}{s + \gamma + \gamma \frac{G_H}{G_s}}$$

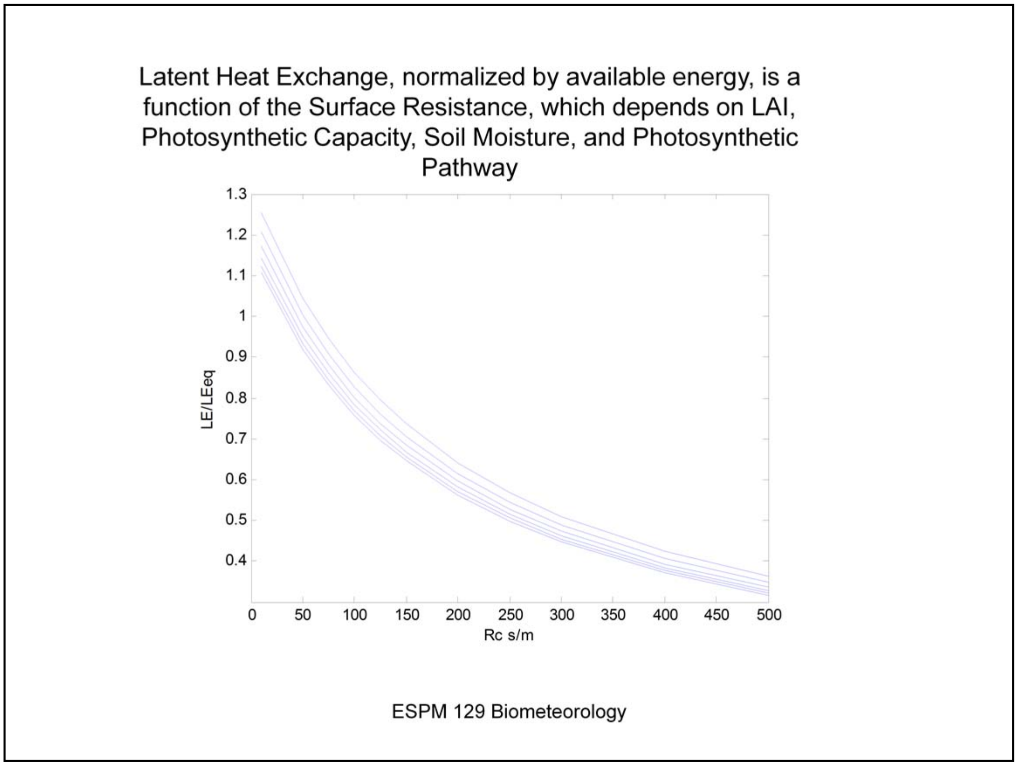
Function of:

- •Available Energy (Rn-S)
- •Vapor Pressure Deficit (D)
- •Aerodynamic Conductance (Gh)
- •Surface Conductance (Gs)

ESPM 129 Biometeorology

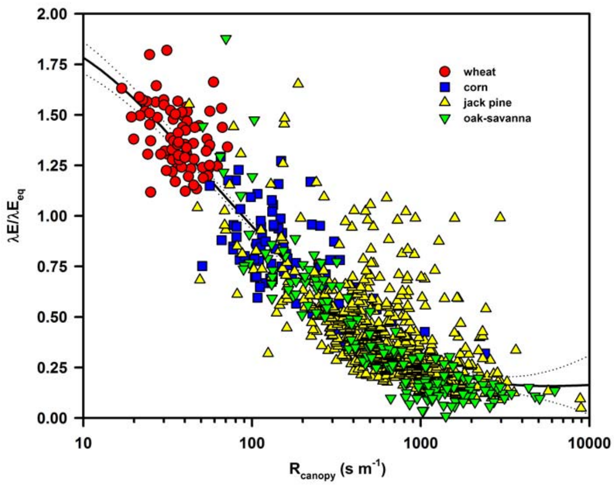
John Monteith was the first to unify the plant vs meteorological approaches and produce the famous Penman Monteith equation

Monteith, J. L. 1965. Evaporation and Environment. Pages 205-234 Symposium Society of Experimental Biology XIX.



Normalizing latent heat by equilibrium evaporation we can see how changes in canopy resistance affect ET. At low resistances we approach the value of the Priestley Taylor equation (1.26) with some variability do to wind and turbulence

Effects of Functional Types and R_{sfc} on Normalized Evaporation



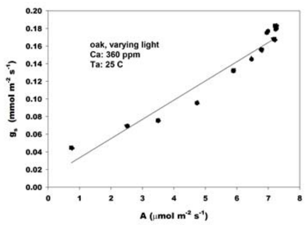
R_c is a f(LAI, N, soil moisture, Ps Pathway)

ESPM 129 Biometeorology

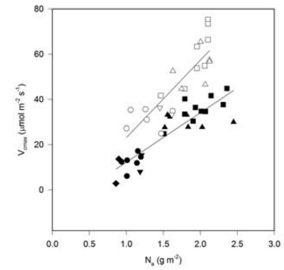
This allows us to see how different vegetation types play a role on controlling supply of water to the atmosphere. In essence these vary with lai, nitrogen, soil moisture, ps pathway and hydraulic conductance

Stomatal Conductance Scales with N, via Photosynthesis

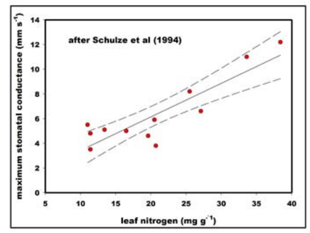
Stomatal Conductance Scales with Photosynthesis



Photosynthetic Capacity Scales with Nitrogen

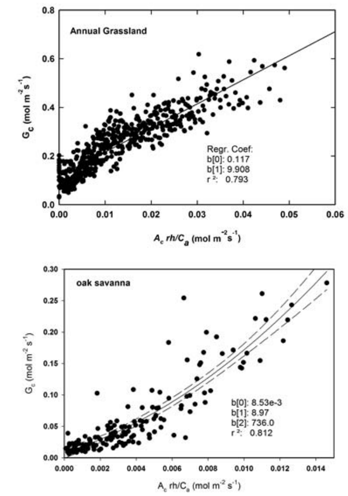


Stomatal Conductance scales with Nitrogen



Wilson et al. 2001, Tree Physiology
Schulze et al 1994. Annual Rev Ecology

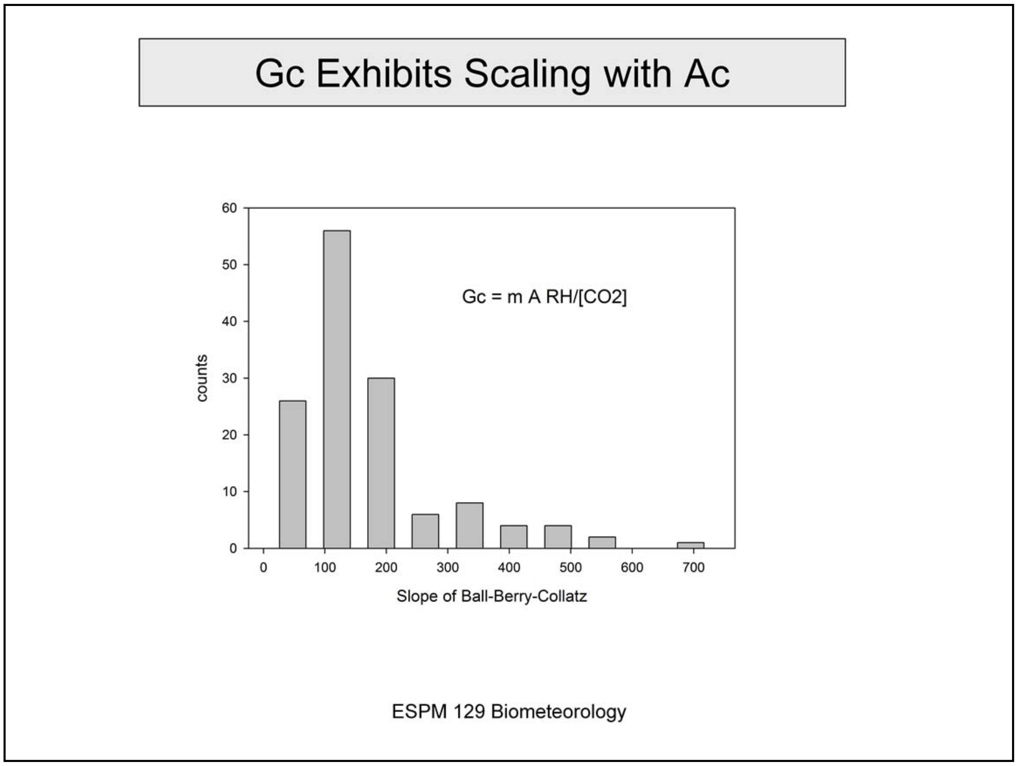
Linking Water and Carbon: Potential to assess G_c with Remote Sensing



Xu + DDB, 2003 AgForMet

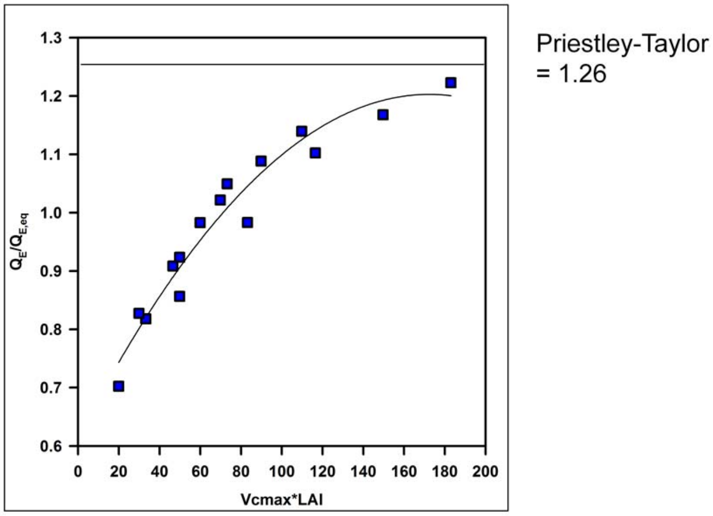
ESPM 129 Biometeorology

We can adopt the Ball-Berry approach to ecosystem evaporation and find that Gc scales with photosynthesis times relative humidity divided by CO2



Looking at data from over 220 site-years across the Fluxnet universe we obtain this distribution

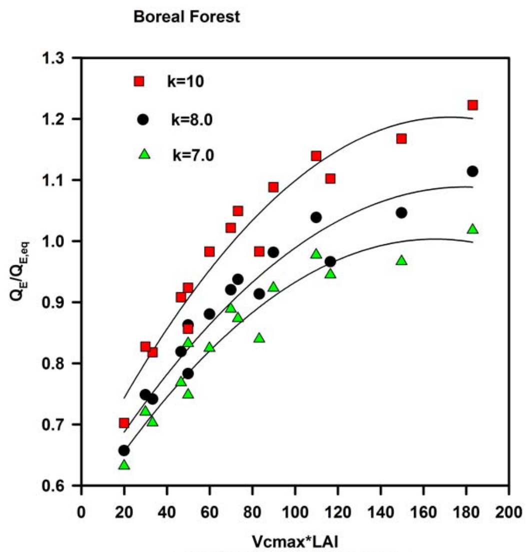
Effects of Leaf Area and Photosynthetic Capacity on Normalized Evaporation: Well-Watered Conditions



Canveg Model, Baldocchi and Meyers, 1998 AgForMet

Coupled leaf-canopy models can also be instructive on how evaporation scales with ecophysiological variables. We see that latent heat exchange, normalized by equilibrium evaporation reaches the Priestley-Taylor value for canopies with high LAI and high Ps capacity

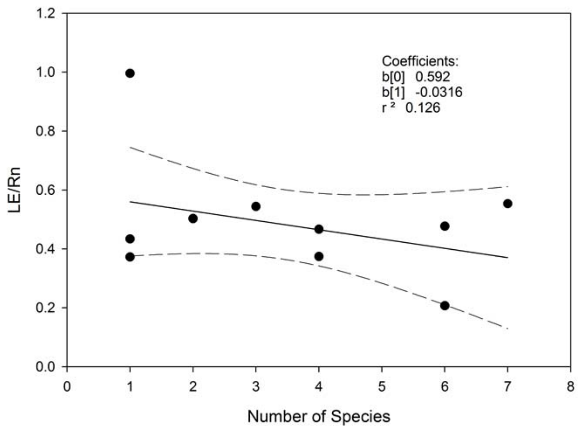
Effects of Leaf Area and Photosynthetic Capacity on Normalized Evaporation: Watered-Deficits



ESPM 129 Biometeorology

Evaporation and Biodiversity?

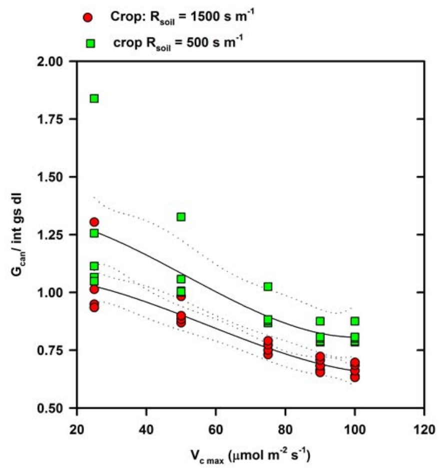
Biodiversity and Evaporation on Annual Time Scales



ESPM 129 Biometeorology

Does Biodiversity affect evaporation. Using long term data from the Fluxnet Project we find the answer is very little. This is consistent with the fact that energy drives much evaporation and scaling theory shows that energetics is scale invariant. Yet, there can be some role in the case that different species may have different hydraulic conductances and stomatal capacity.

Canopy Surface Conductance Does Not equal the Canopy Stomatal Conductance

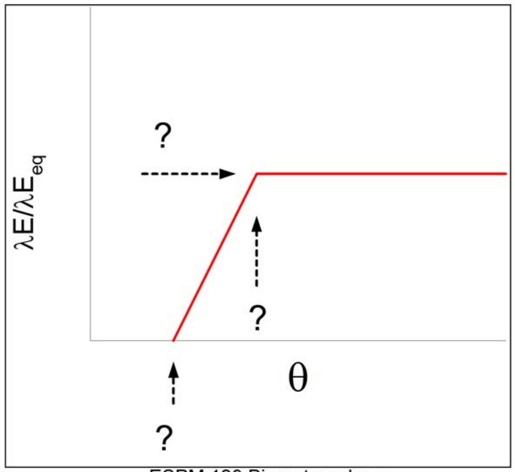


Be Careful about using G_{can} to compute isotopic discrimination

ESPM 129 Biometeorology

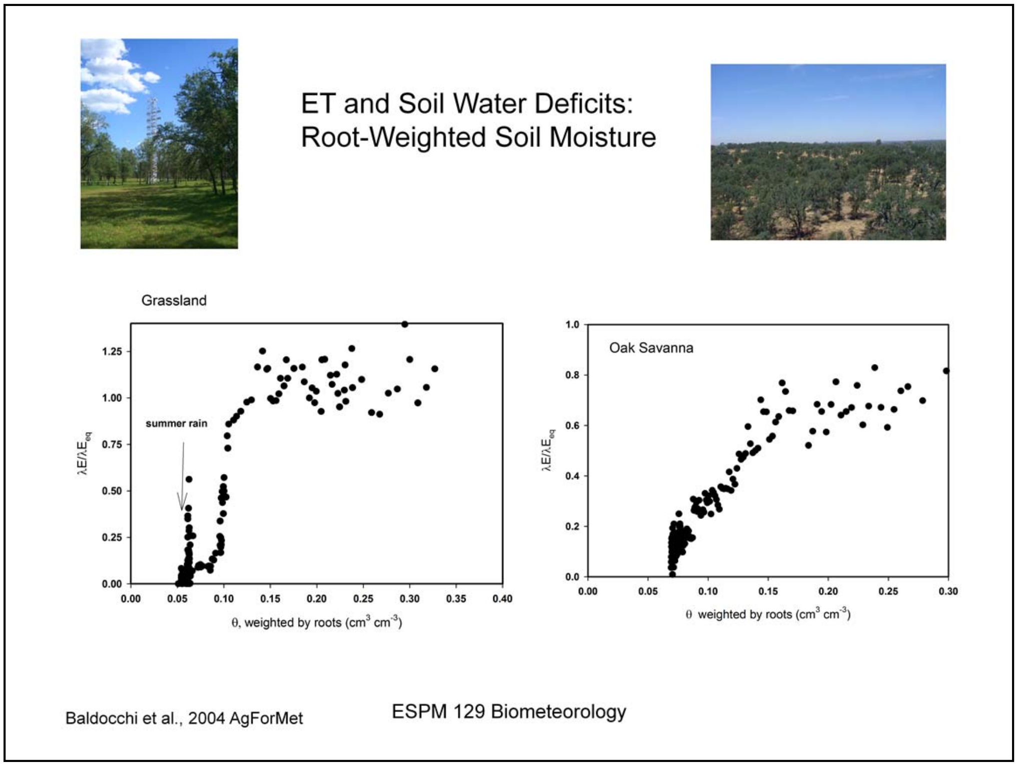
We have to be careful assuming that Gc is leaf conductances times LAI.. It may be but often is not. This assumption depends on the intent.

Eco-hydrology:
ET, Functional Type, Physiological Capacity and Drought

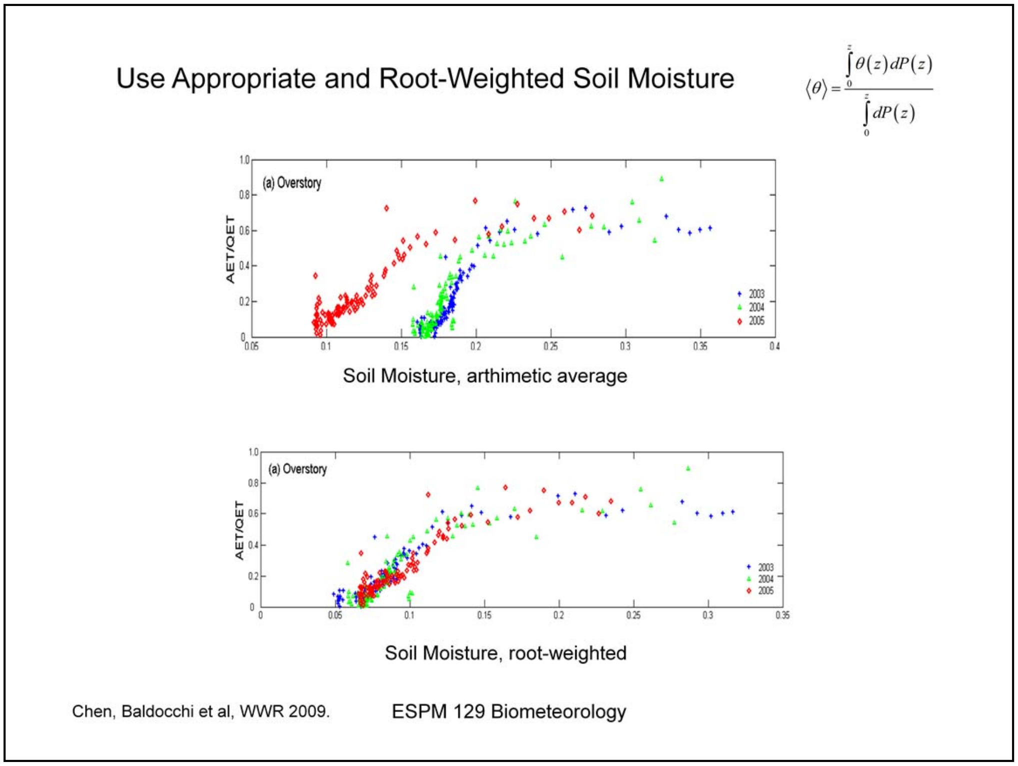


ESPM 129 Biometeorology

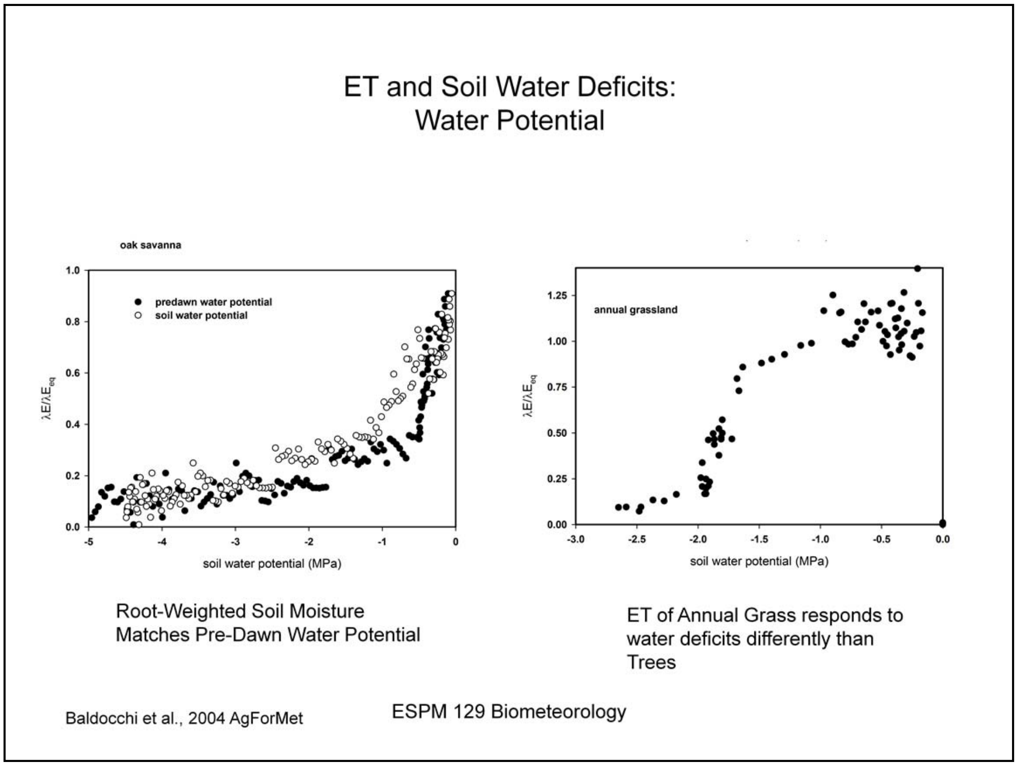
Evaoporation scales with soil moisture



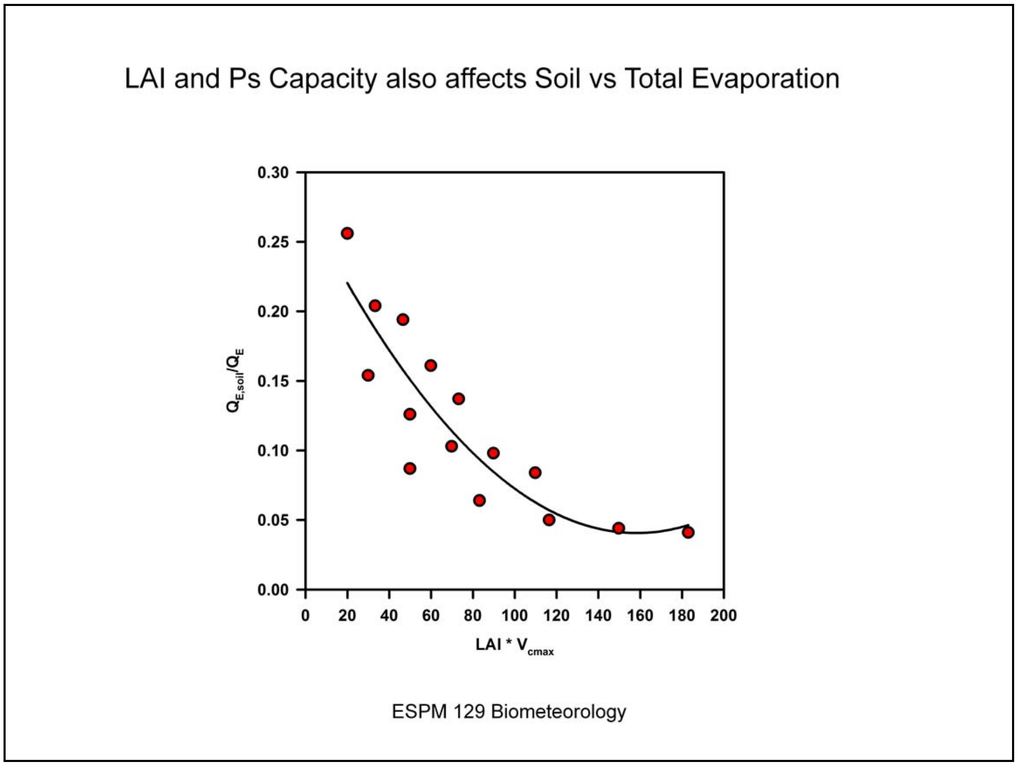
Data from our savanna and grassland



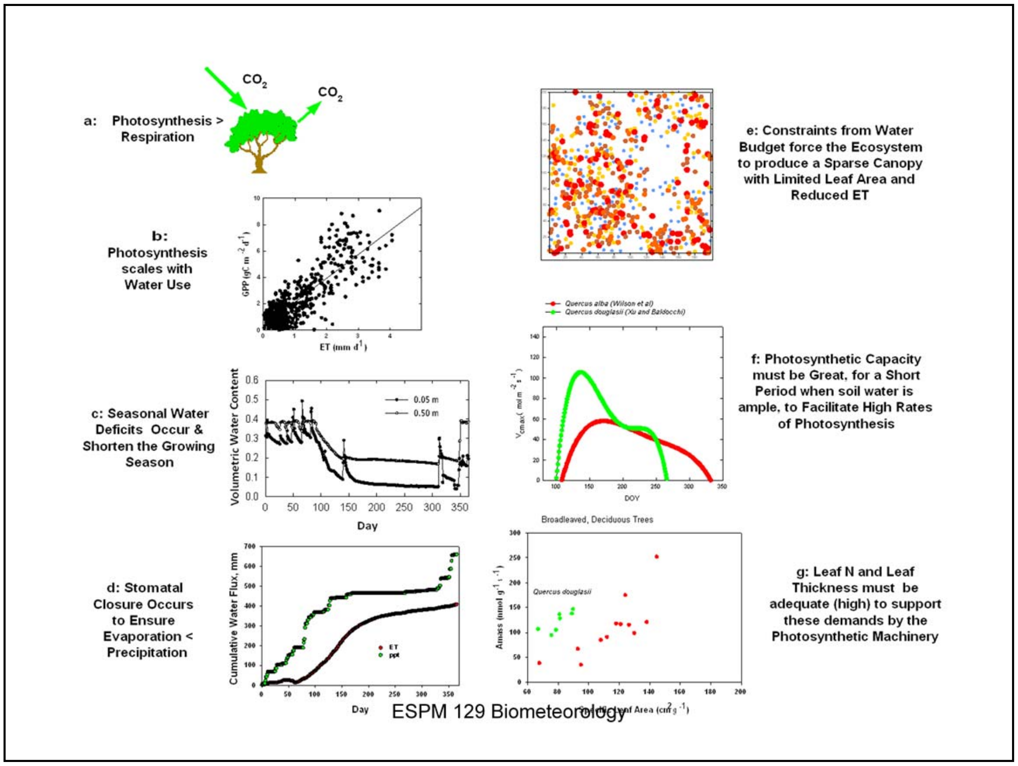
Demonstrates the importance of root weighted soil moisture. Get the independent variable to represent the conditions sensed by the plant!!! So important



Pre dawn water potential is even better.



Partitioning soil vs veg is another important aspect



Life of an oak.. A lesson for the intricate interactions between soil moisture, leaf area index, phenology, photosynthetic capacity and evaporation.