Why Ecologists Need Soil Physics, and *Vice Versa*

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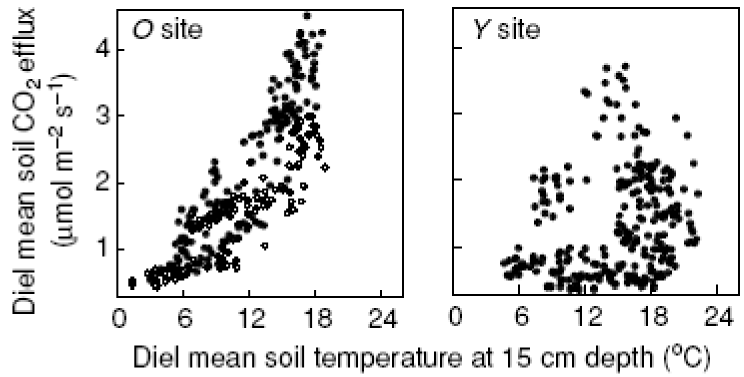
The Big Picture

- Soil Physics Drives Many of the Biological Processes in the soil that are of interest to Ecologists
  - Soil Temperature, Moisture, Trace Gas Diffusion
- Ecologists Have Many interesting Questions that relate to Mass and Energy Transfer and Require Collaboration with Soil Physicists
  - Soil Respiration, Evaporation, Decomposition, Trace Gas (N_2O, CH_4, CO_2) Production

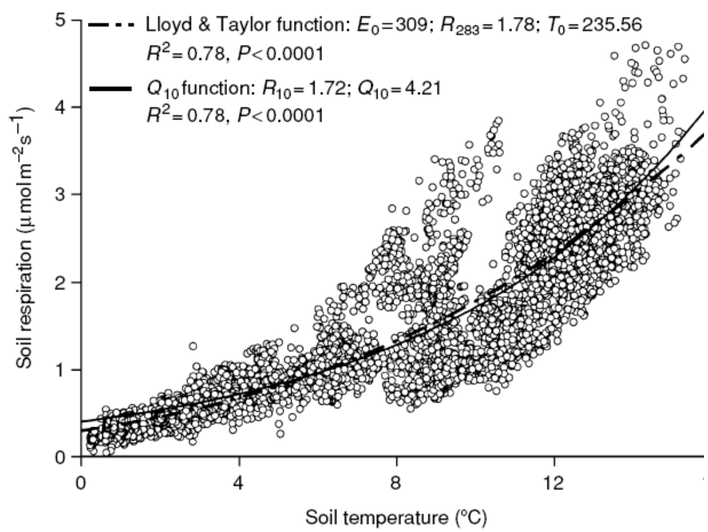
Outline

- Temperature and Soil Respiration
- Photosynthesis vs Soil Respiration
- Soil Evaporation Measurements and Modeling
- How Moisture Regulates Soil Respiration & Evaporation
- Alternative/'novel' Measurement Methods
  - Better Experimental Design
  - Eddy Covariance, an alternative to Chambers
  - Soil CO_2 probes & Fickian Diffusion
  - Improved Incubation Measurement Protocols
  - Improved Sapflow Sampling Protocols

Soil Respiration vs Soil Temperature, at one depth, yields complicated functional responses, hysteresis and scatter

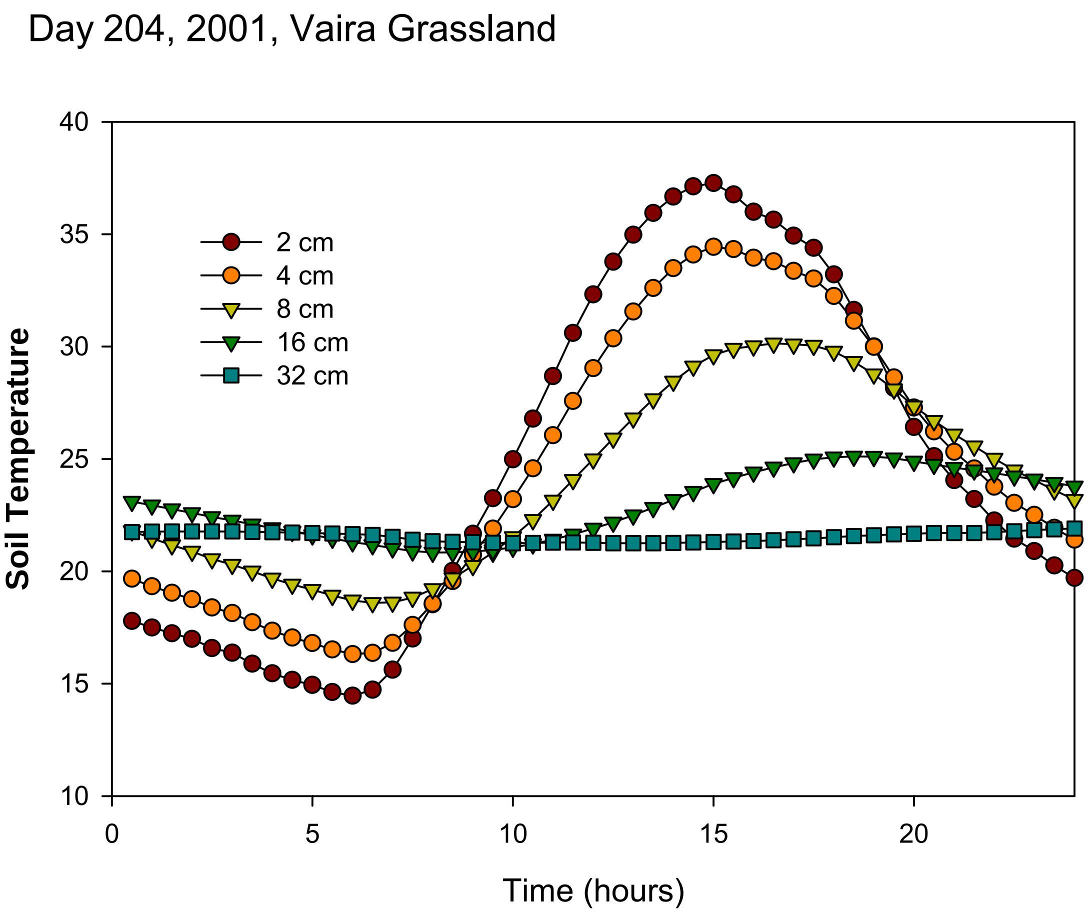


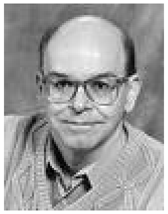
Irvine and Law, GCB 2002



Janssens and Pilegaard, 2003 GCB

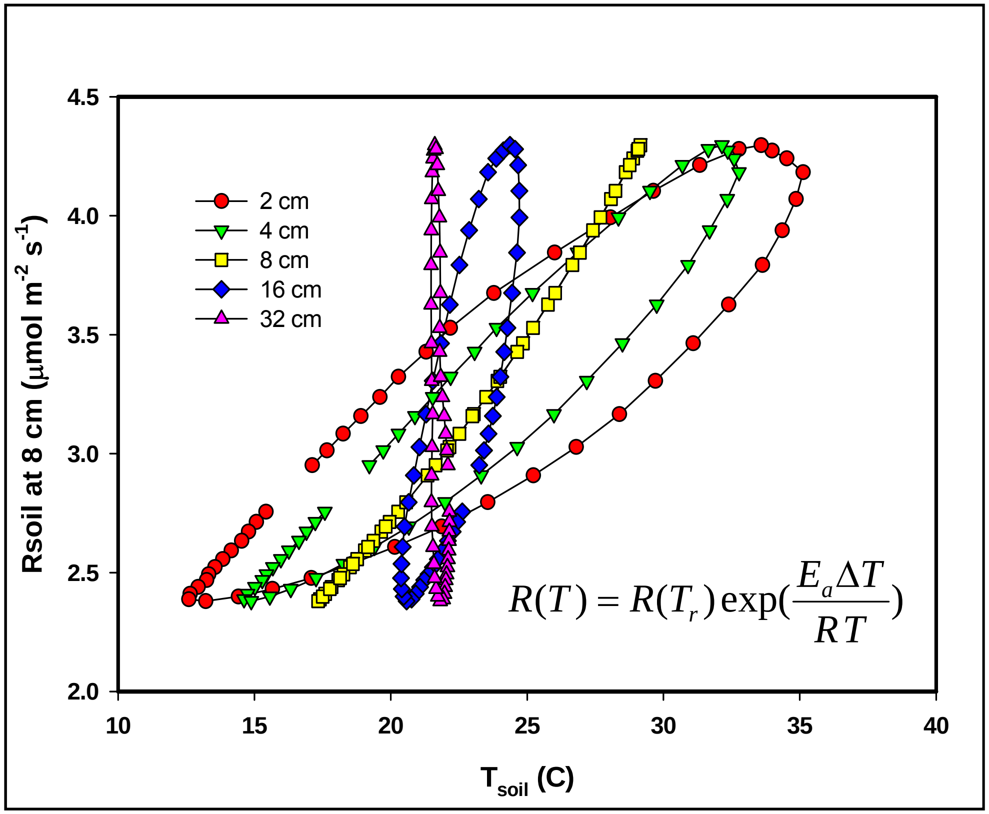
Soil Temperature Amplitude and Phase Angle Varies with Depth





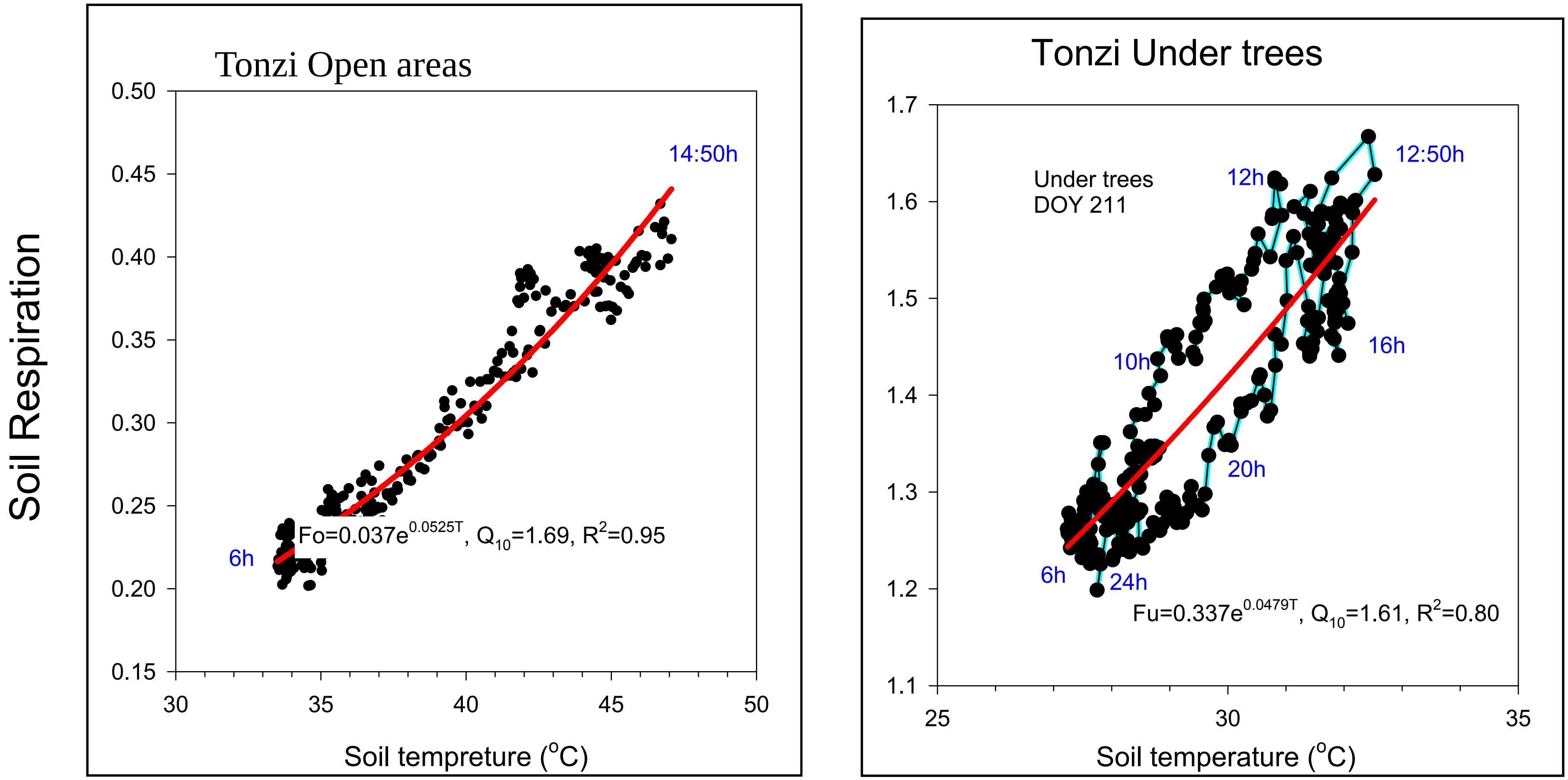
It is critical to measure Soil Temperature
at Multiple Depths and with Logarithmic Spacing

Measure Soil Temperature at the Location of the Source



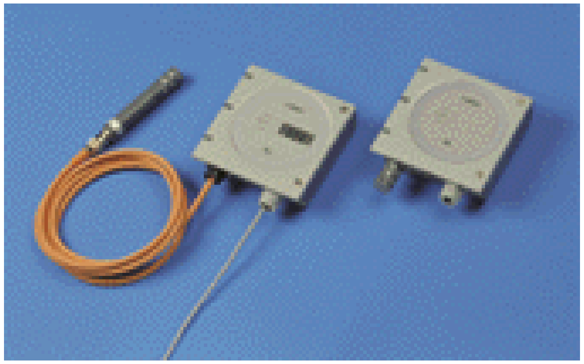
Otherwise Artificial Hysteresis or Poor Correlations may be Observed

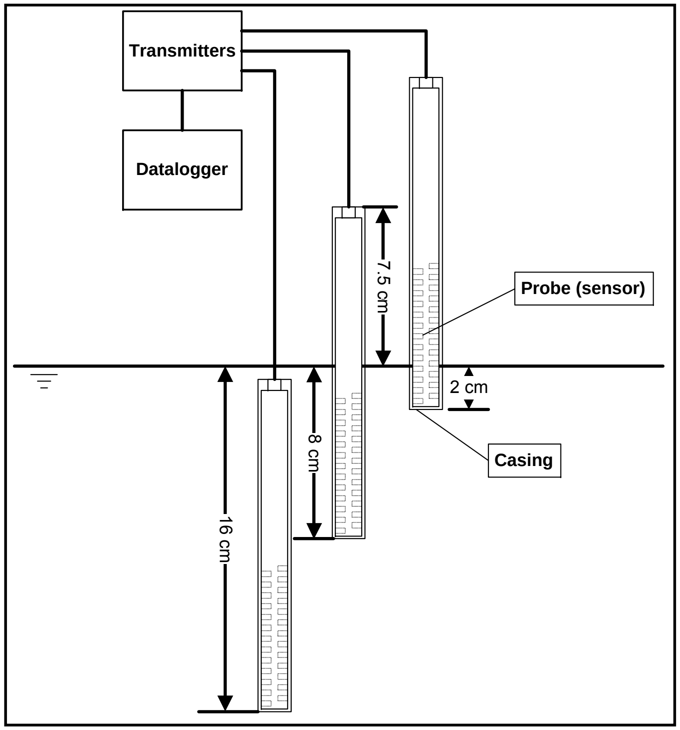
But Sometimes Hysteresis between Soil Respiration and Temperature is Real:
The Role of Photosynthesis and Phloem Transport



Tang, Baldocchi, Xu, GCB, 2005

Continuous Soil Respiration with soil CO_2 Sensors





Theory/Equations

$$F = -D_s \frac{dC}{dz}$$

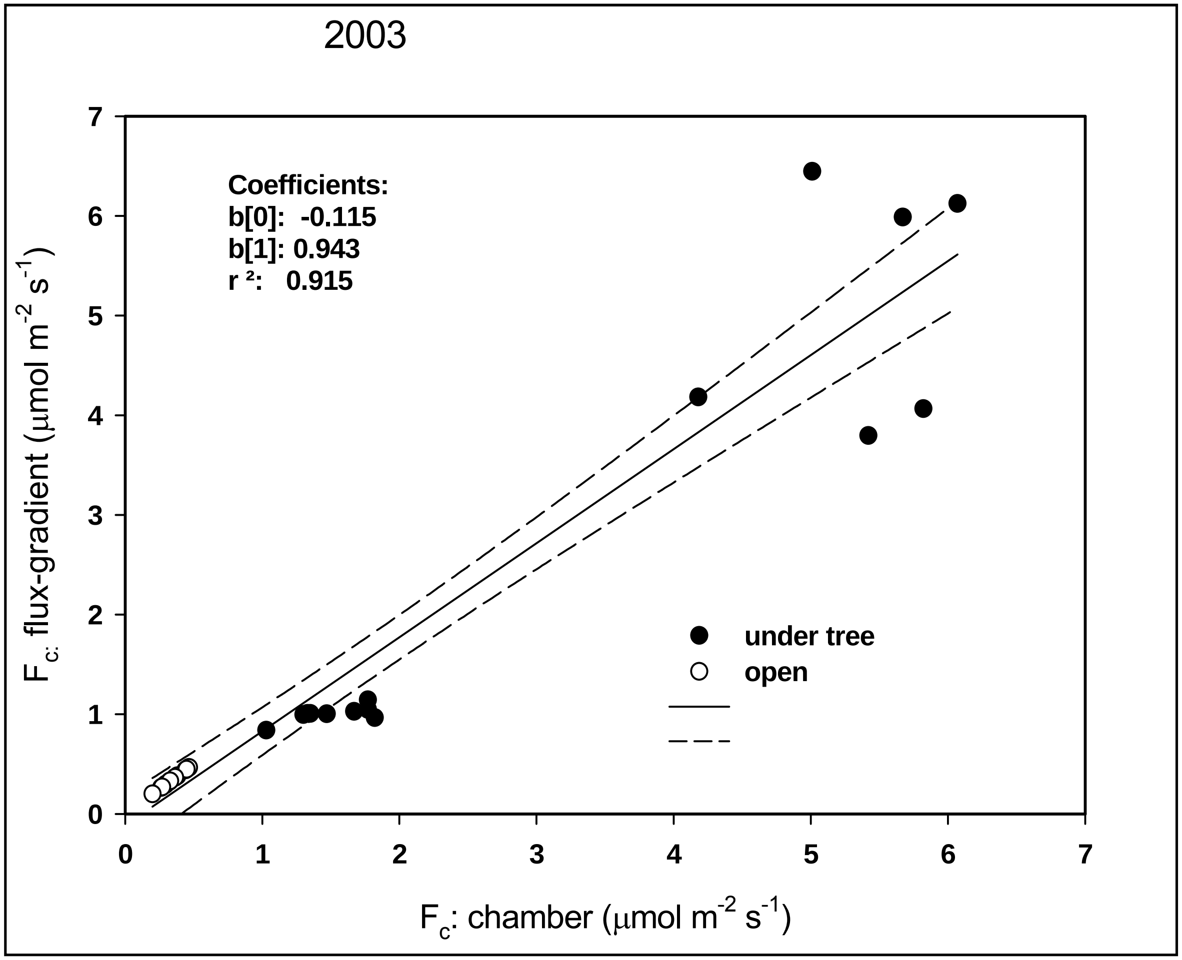
$$D_a = D_{a0}(T / 293.15)^{1.75}(P / 101.3)$$

Moldrup et al. 1999

$$\frac{D_s}{D_a} = \phi^2 \left(\frac{\varepsilon}{\phi}\right)^{\beta \cdot Fcp}$$

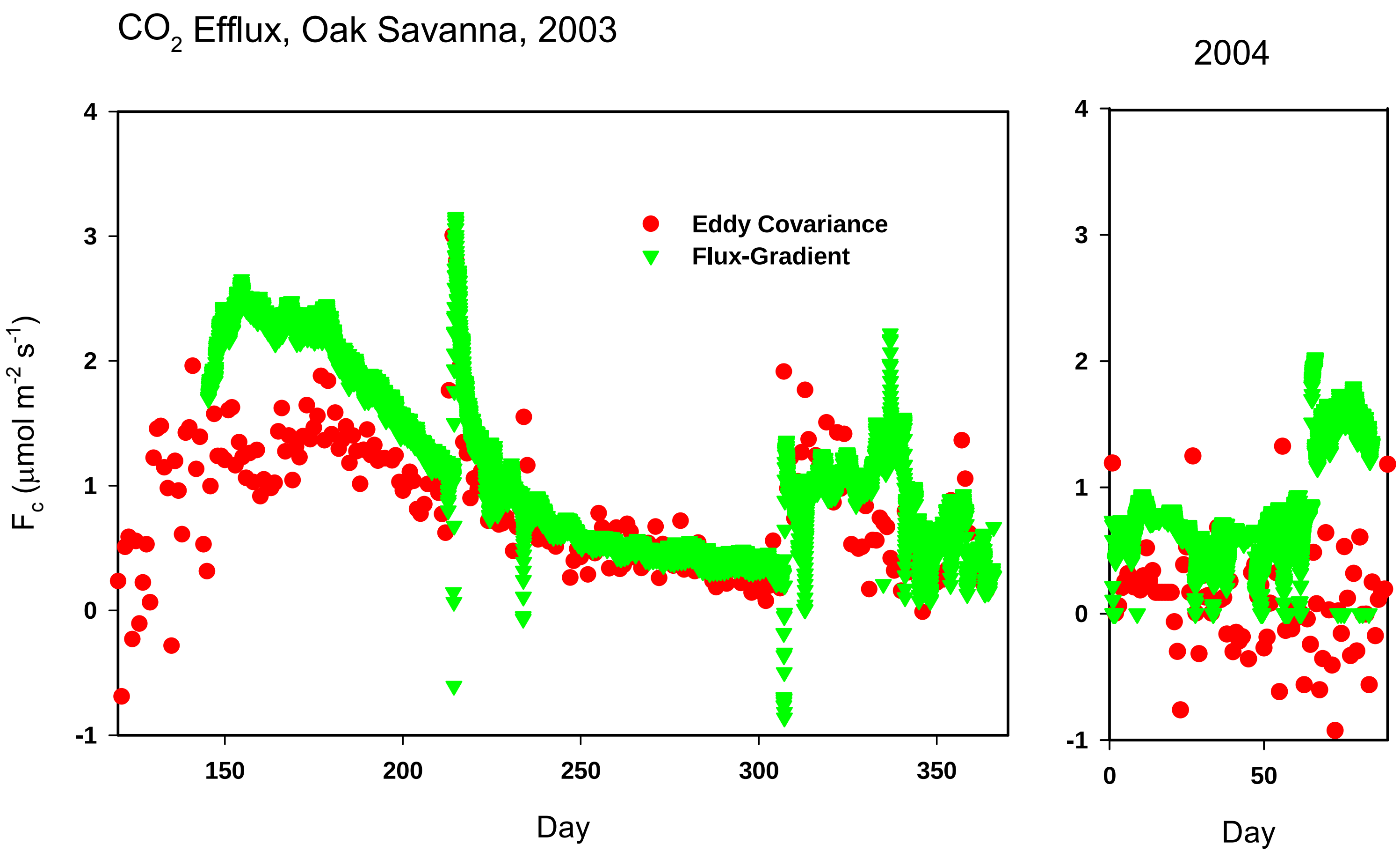
F_{cp}: fraction silt and sand; β: constant; ϕ:porosity; ε: air-filled pore space

Validation with Chambers



Tang et al, 2005, Global Change Biology

Validation with Eddy Covariance



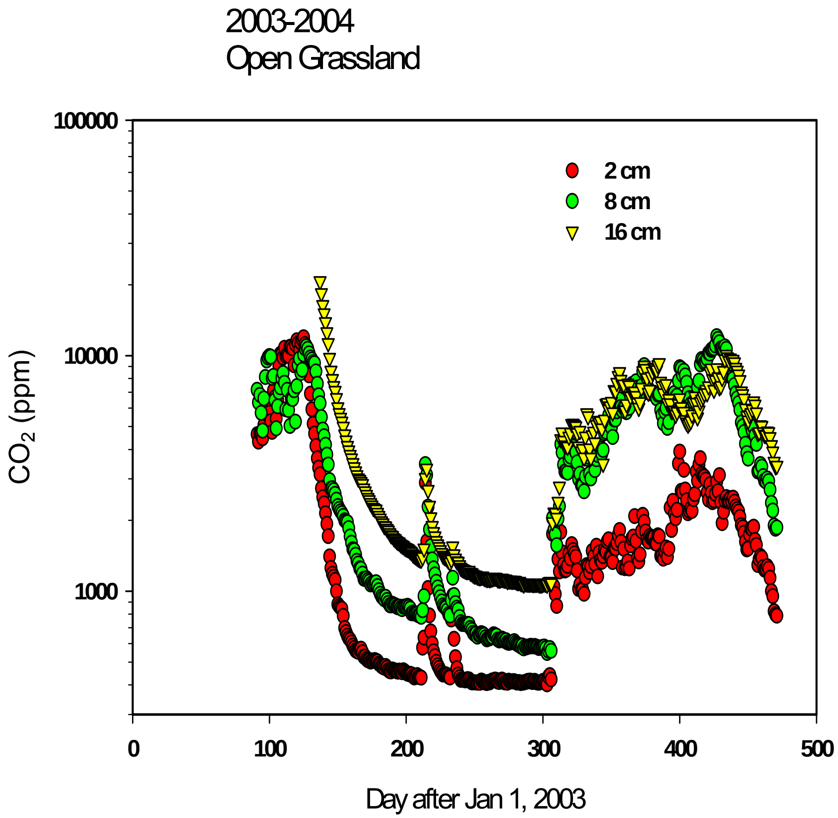
Baldocchi et al, 2006, JGR Biogeosciences

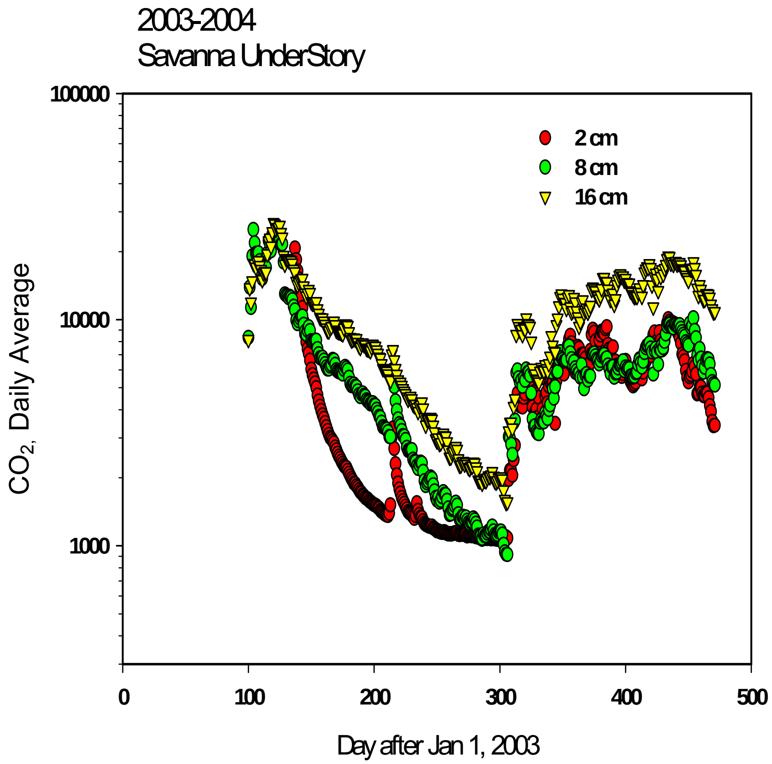
Savanna: Ideal Model to Separate Contributions from Roots and Microbes

Under a Tree:
$\sim R_a + R_h$

Open Grassland:
$\sim R_h$ (summer)

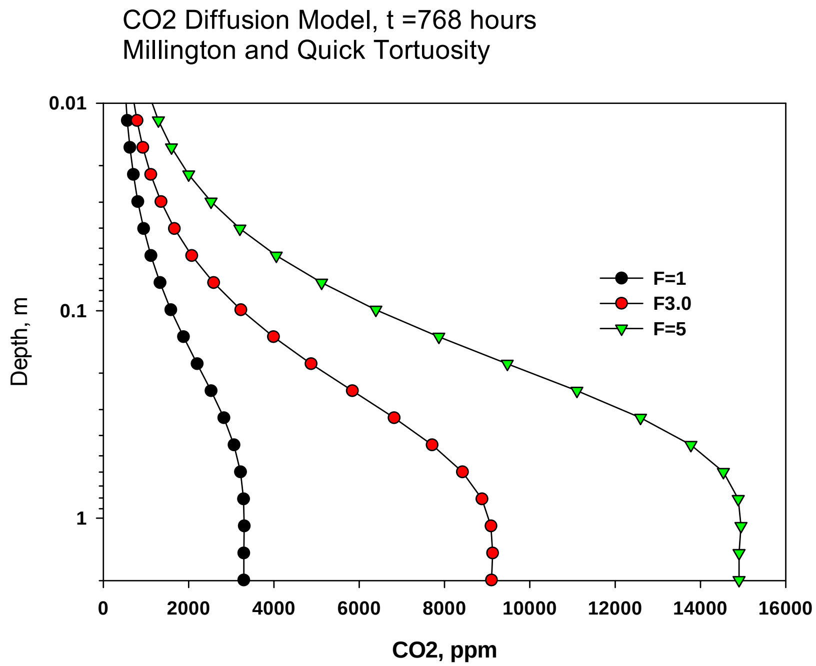
Soil CO_2 is Greater Under Trees

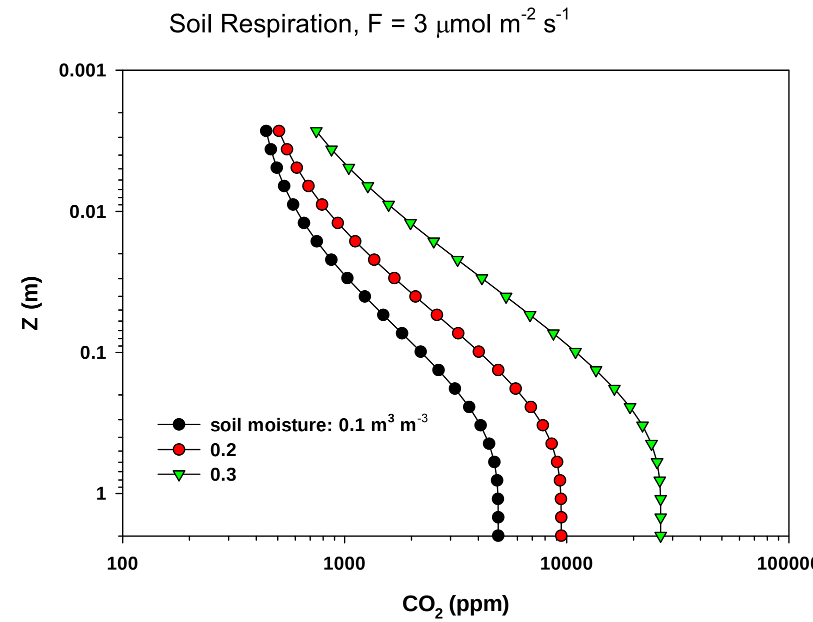




Baldocchi et al, 2006, JGR Biogeosciences

Interpreting Data by Modeling CO_2 in Soil



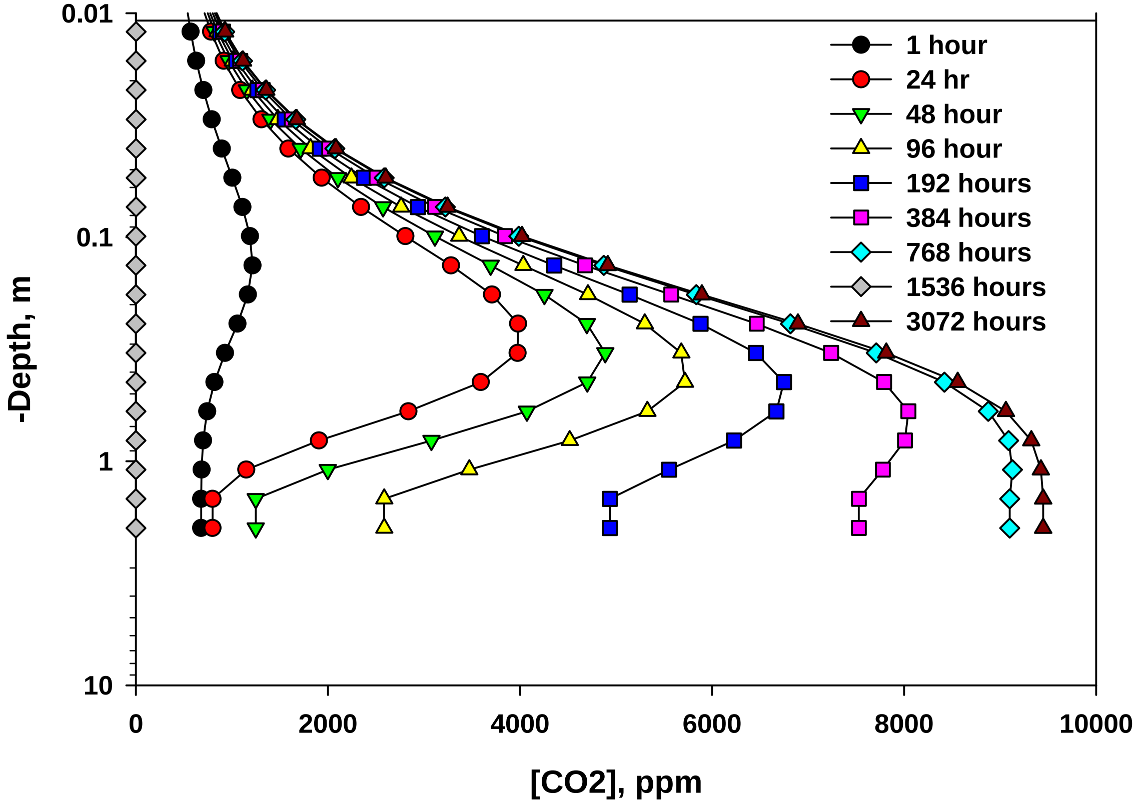


Soil CO2 Diffusion Model

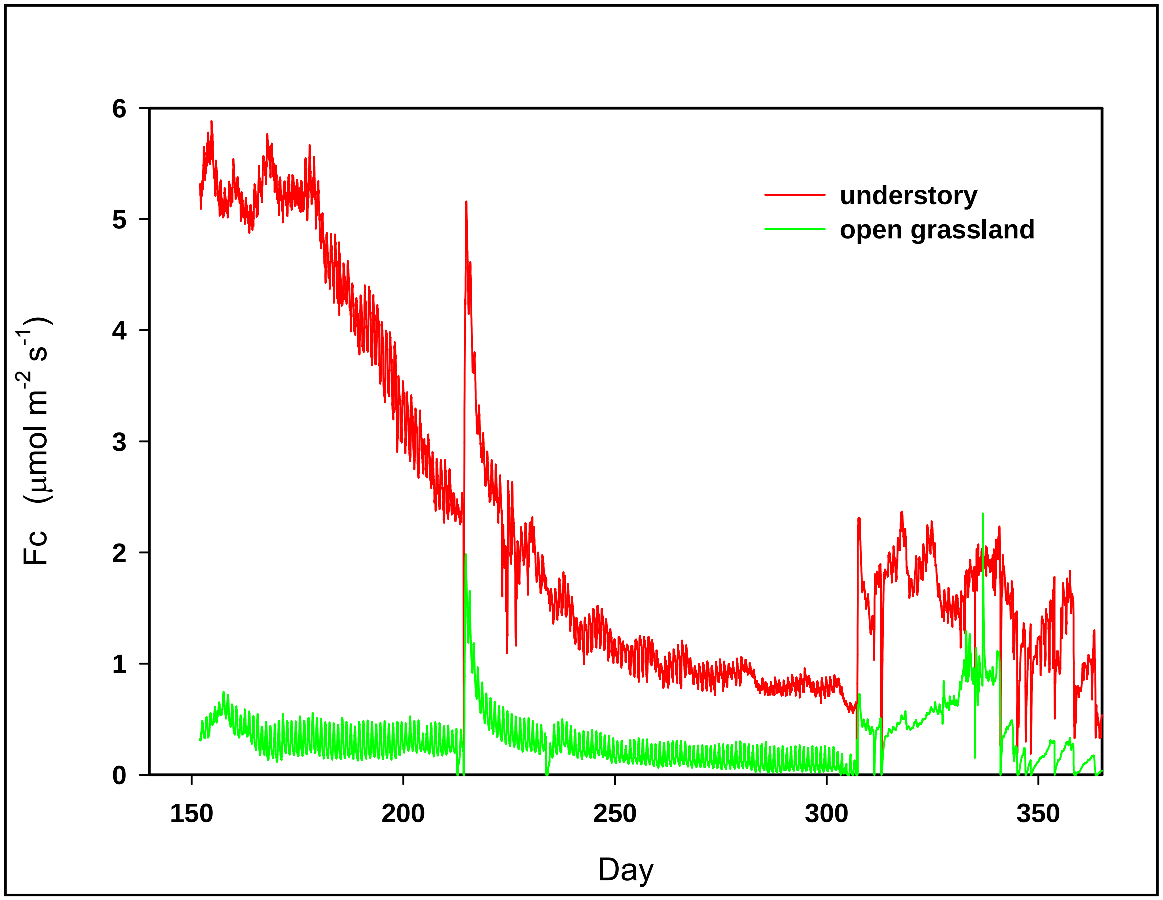
Source flux: 3 μmol m^{-2} s^{-1}

lower boundary condition, dc/dz=0

soil moisture: 0.20

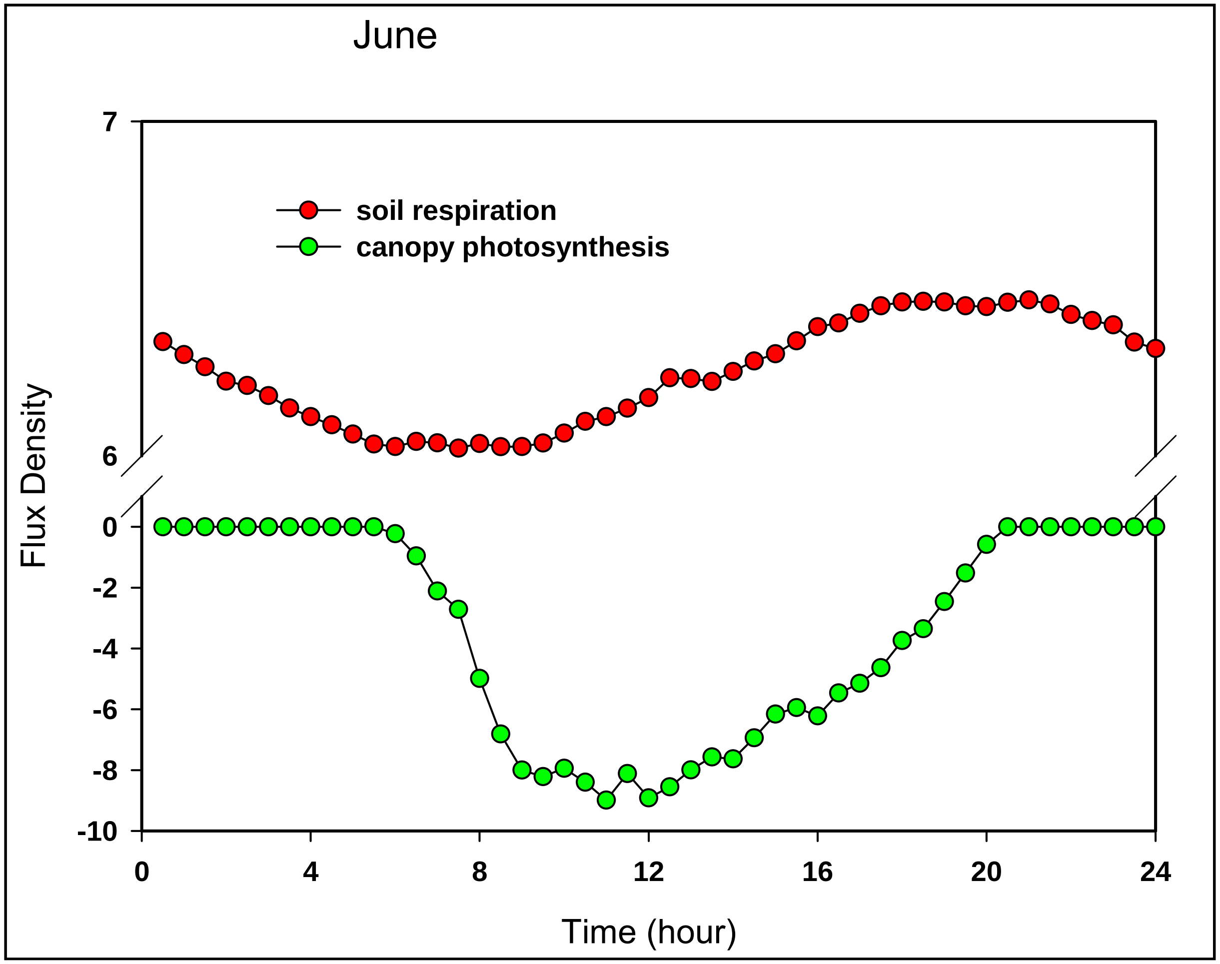


Impact of Rain Pulse and Metabolism on Ecosystem respiration:
Fast and Slow Responses



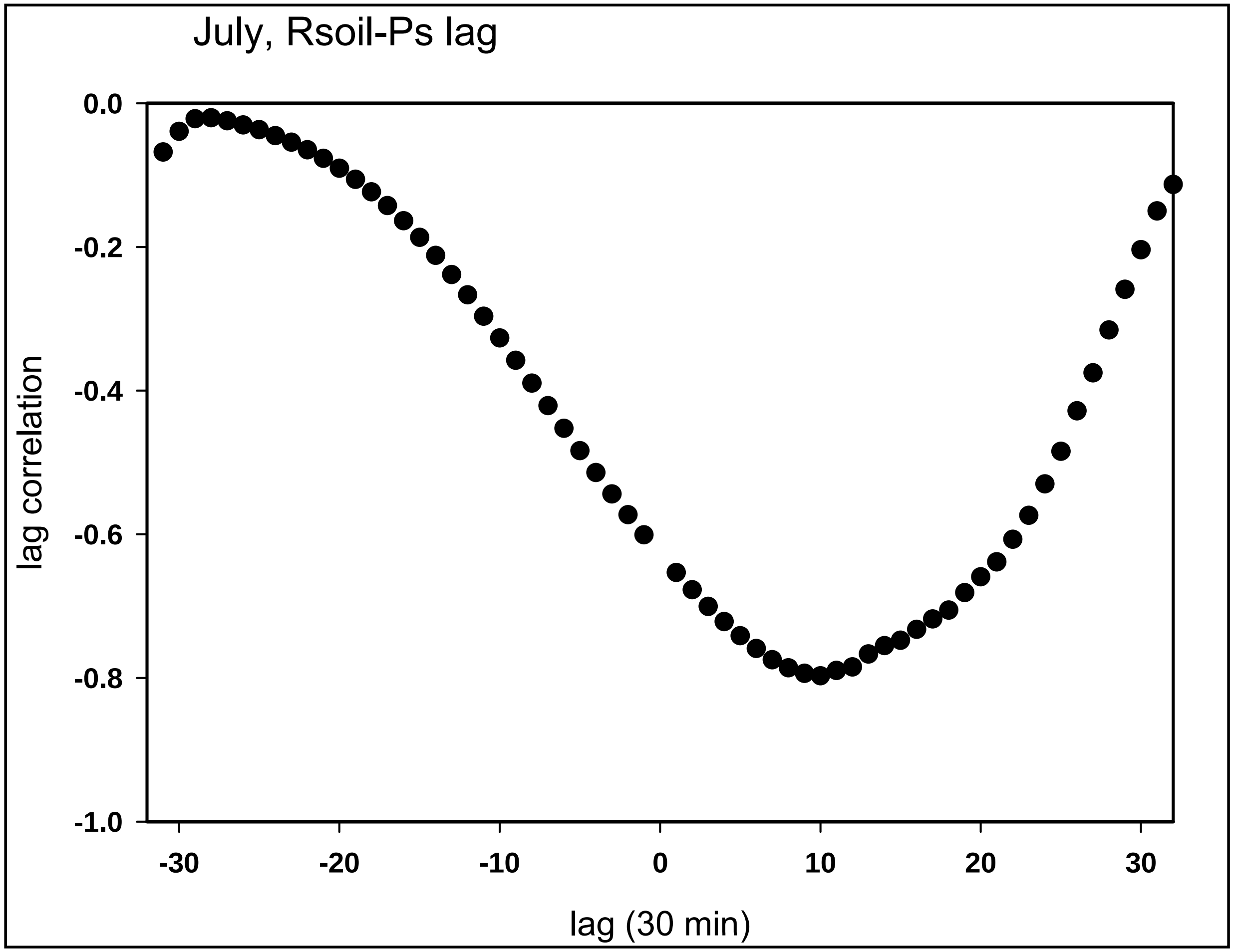
Baldocchi et al, 2006, JGR Biogeosciences

Lags and Leads in Ps and Resp: Diurnal



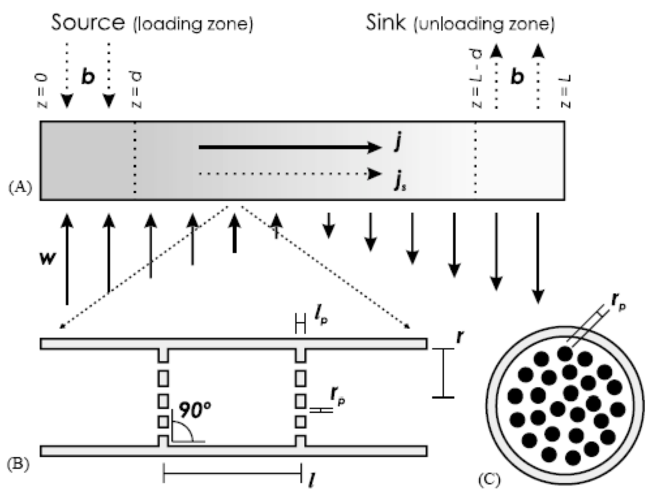
Tang et al, Global Change Biology 2005.

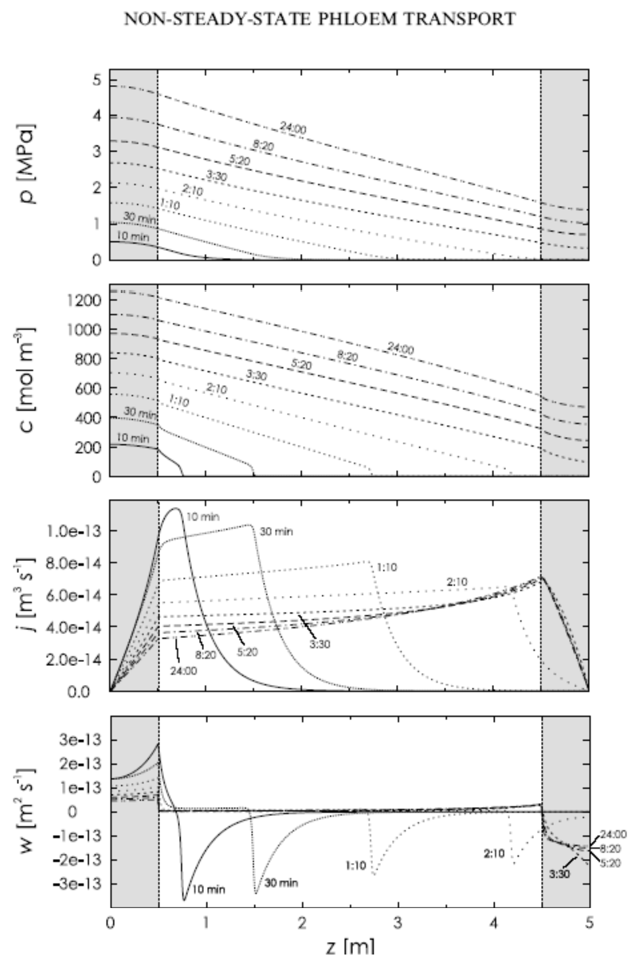
Continuous Measurements Enable Use of Inverse Fourier Transforms to Quantify Lag Times



Tang et al, Global Change Biology 2005.

Phoelem Transport Model shows that sucrose fronts travel at ~ 2 m/hour;
blue oak trees are 13 m tall…~6 hour lag





Thompson and Holbrook 2003 J Theor Biol

Other Evidence that Soil Respiration Scales with GPP

Understory Eddy Flux

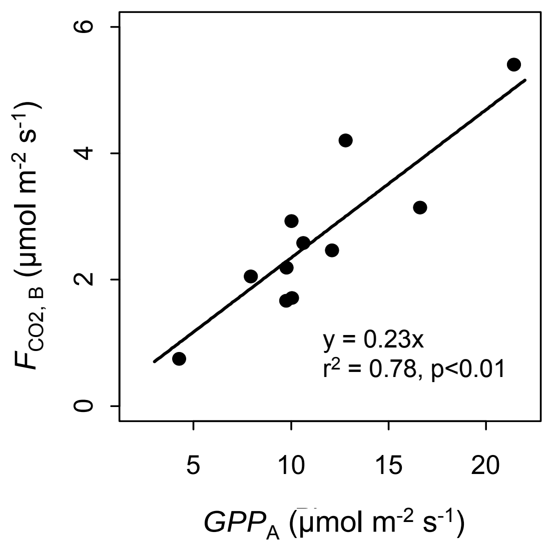
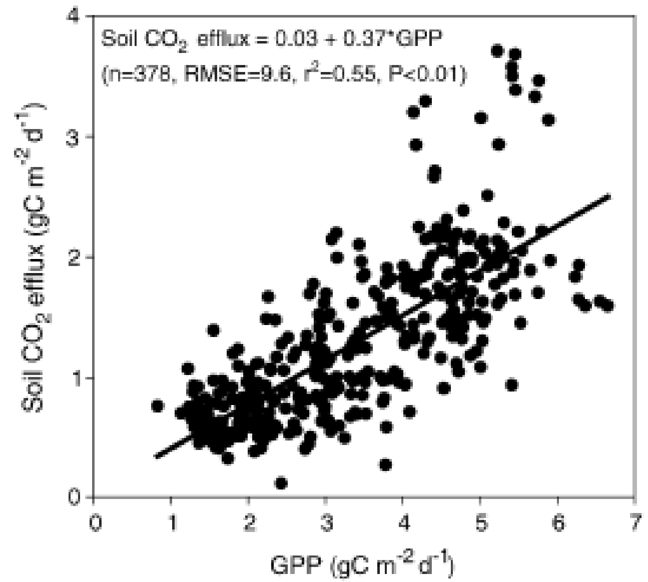


Figure 10. Nighttime understory CO_2 flux below the main canopy as a function of whole canopy GPP

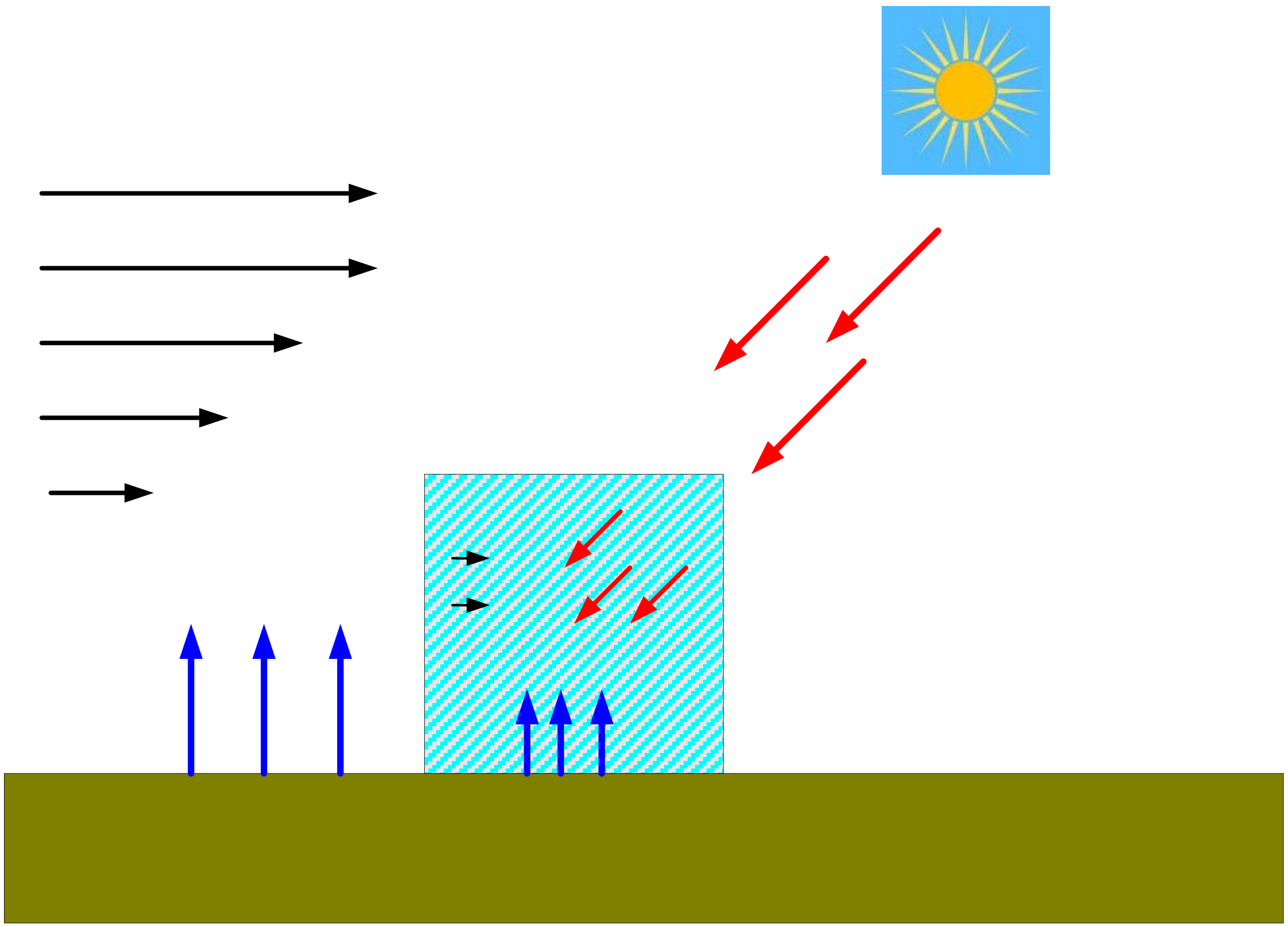
Misson et al. AgForMet. 2007

Auto Chambers



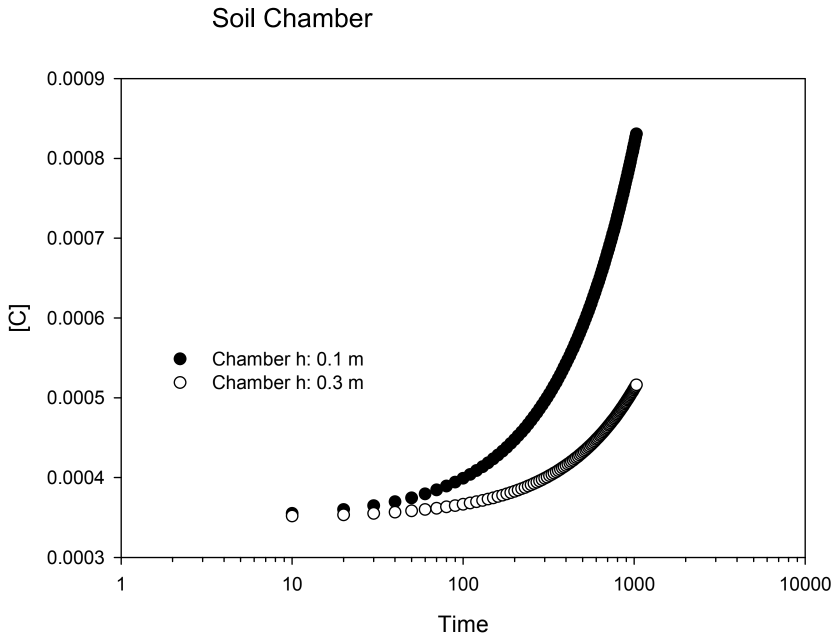
Irvine et al 2005 Biogeochemistry

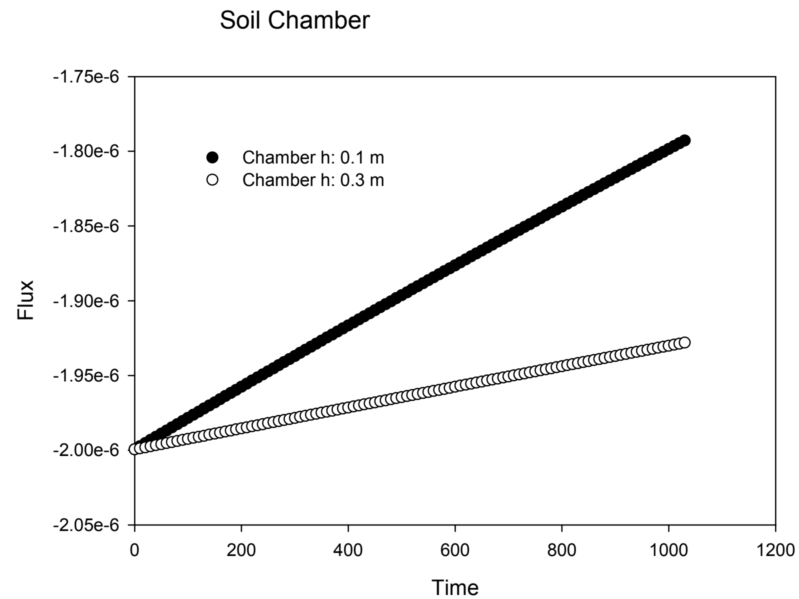
Soil Evaporation:
Chambers Perturb Solar Energy Input & Wind and Turbulence, Humidity and Temperature Fields



Scalar Fluxes Diminish with Time, using Static Chambers, due to C build-up and its negative Feedback on F

$$\frac{\Delta c}{\Delta t} = \frac{\Delta F}{\Delta z} = \frac{F(c)}{h}$$

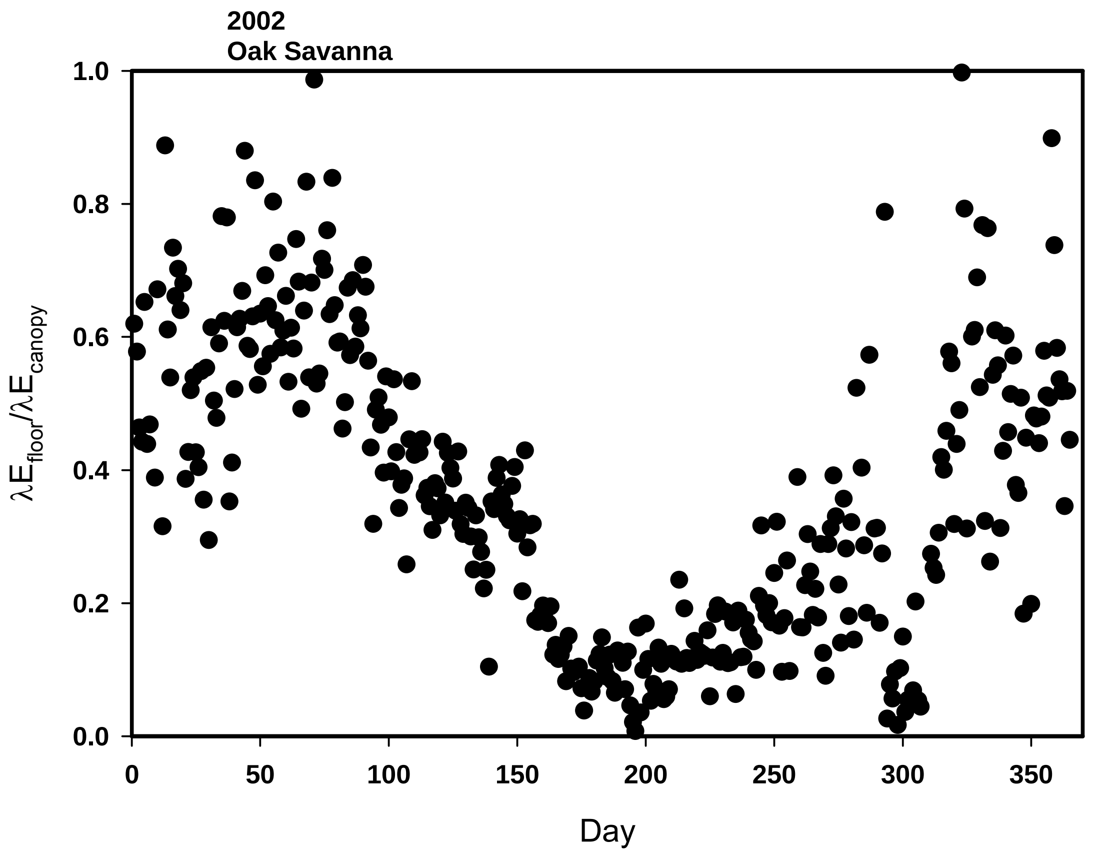




Ability to measure dC/dt well is a function of chamber size and F

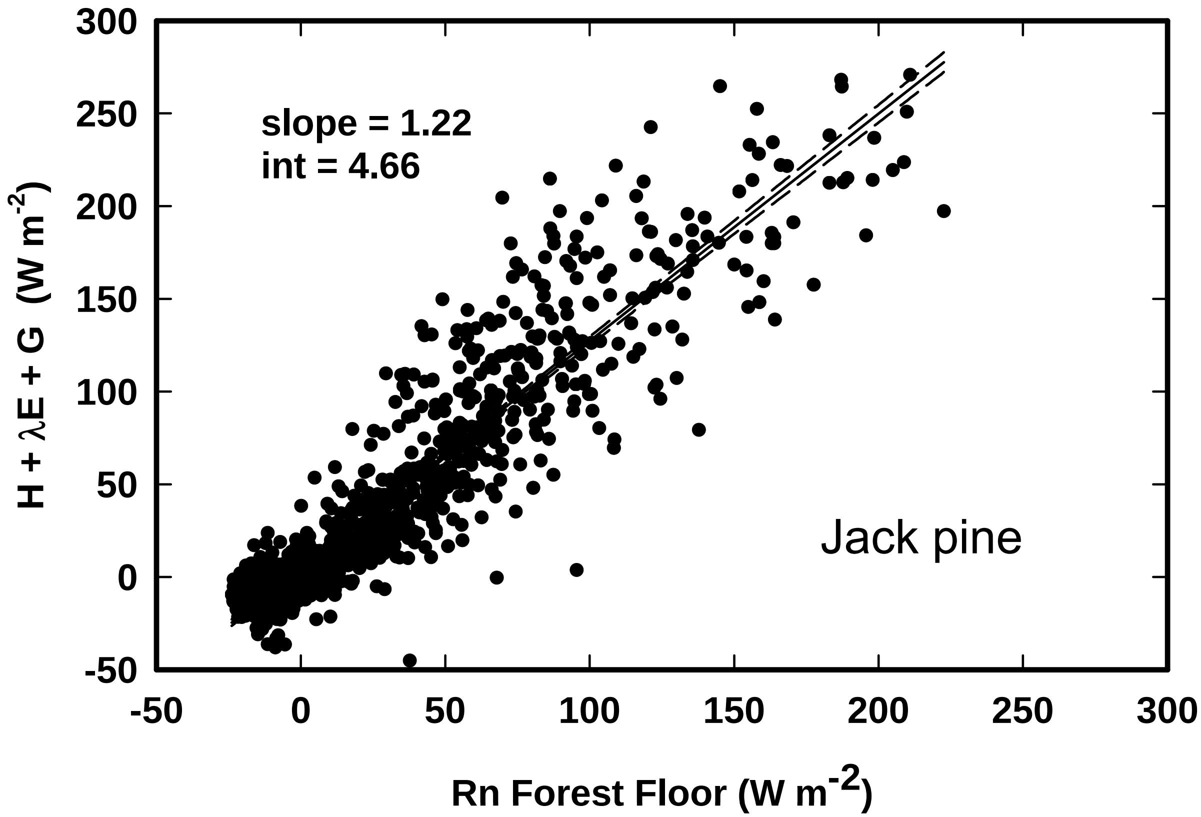
Understory Eddy Flux Measurement System:
An Alternative Means of Measuring Soil Energy Fluxes: LE and H

Understory Latent Heat Exchange Can be a Large Fraction of Total Evaporation:



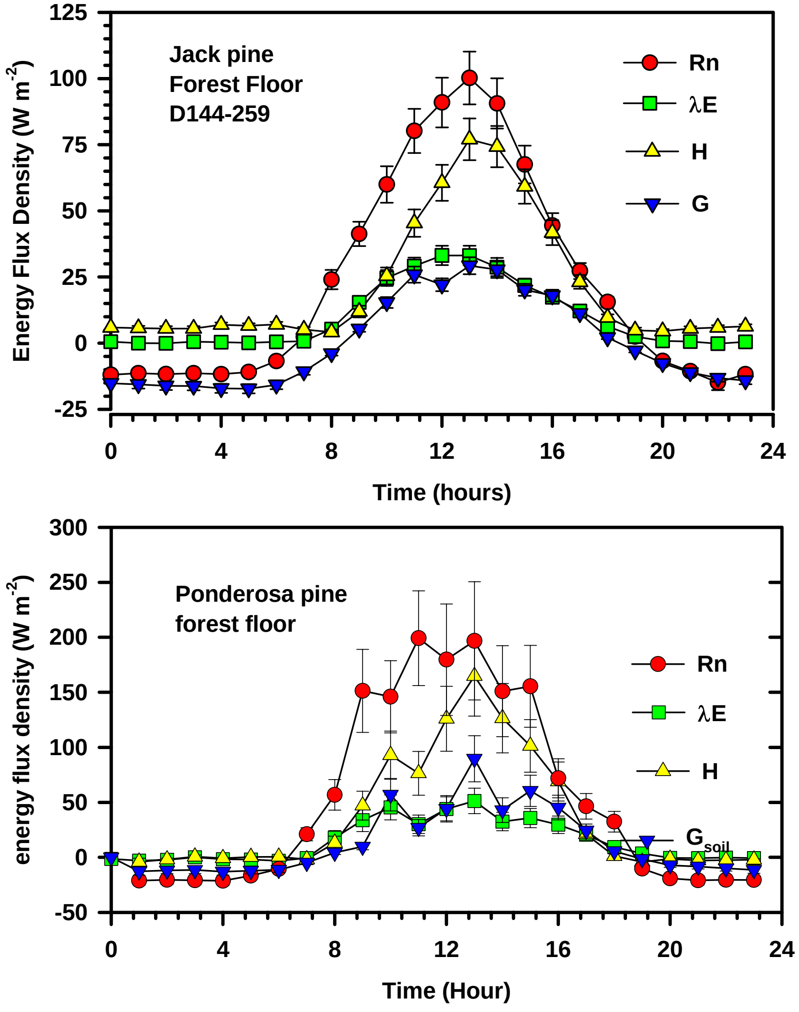
Baldocchi et al. 2004 AgForMet

Reasonable Energy Balance Closure can be Achieved



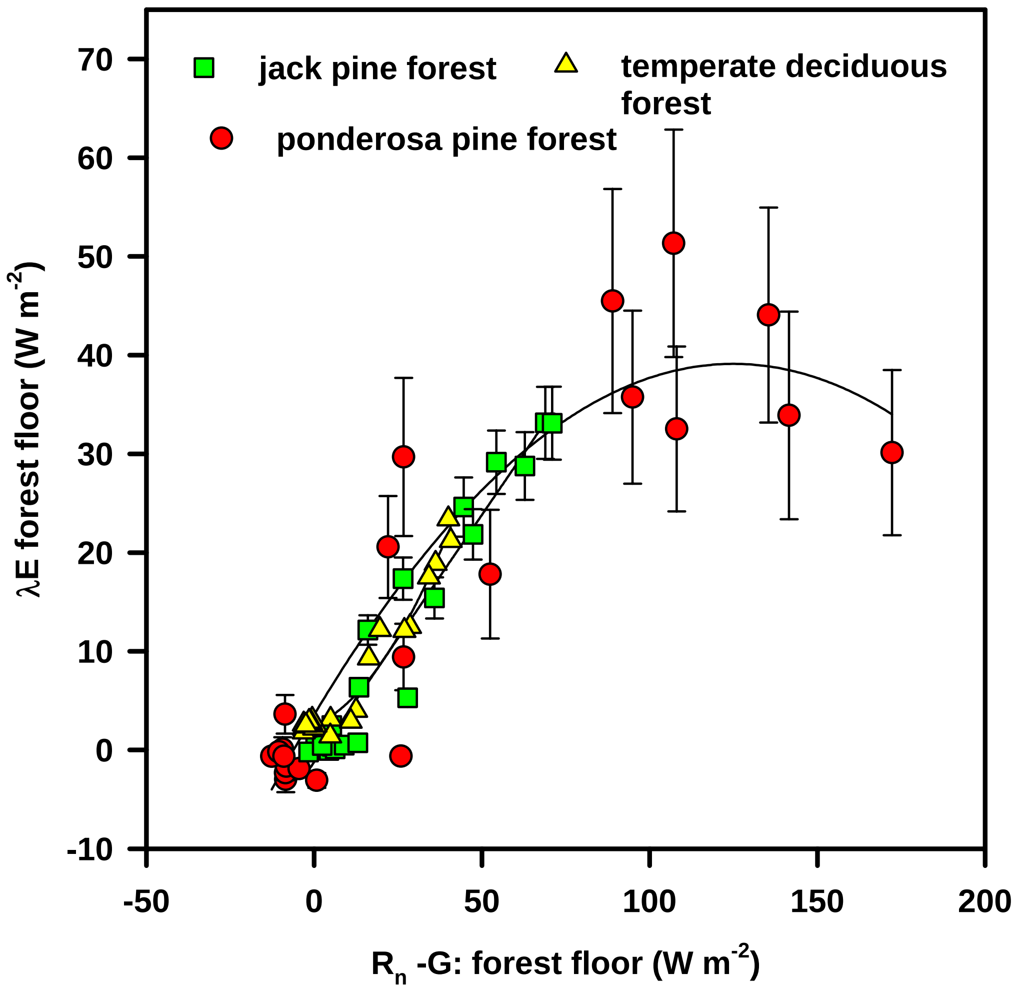
Baldocchi et al. 2000 AgForMet

Overstorey Latent Heat Exchange Partitioning: Closed Oak Forest and Patchy Mature Pine Forest



Baldocchi et al. 2000 AgForMet

LE is a Non-Linear Function of Available Energy

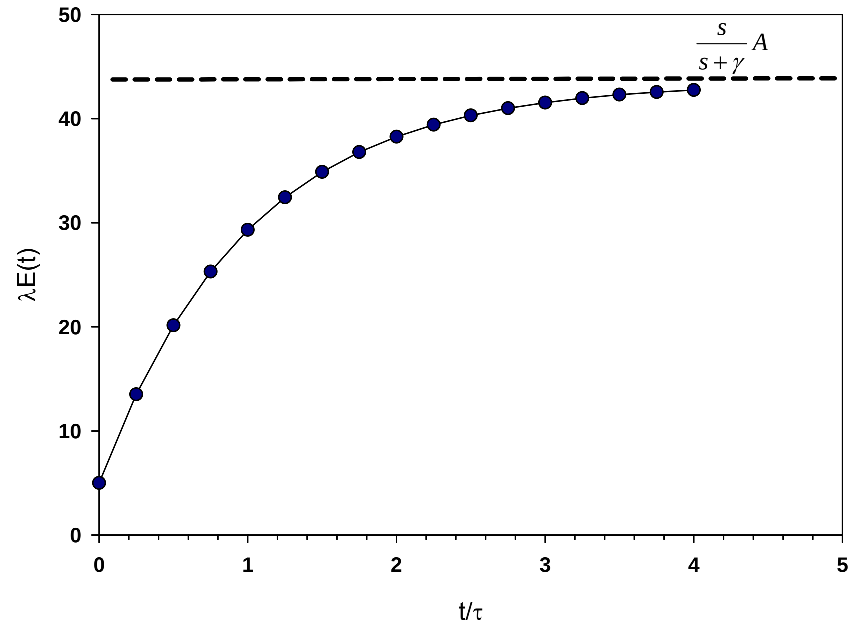


Baldocchi et al. 2000 AgForMet

Why Does Understory LE Max out at about 20-30 W m^{-2} in closed canopies?

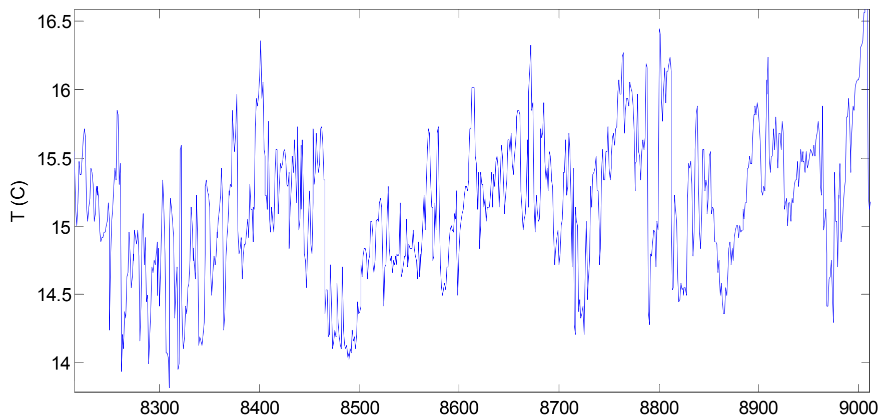
Consider Evaporation into the Canopy Volume and feedbacks with vapor pressure deficit, D

$$\lambda \frac{dE}{dt} = \lambda \frac{dE(t)}{dD} \frac{dD}{dt}$$

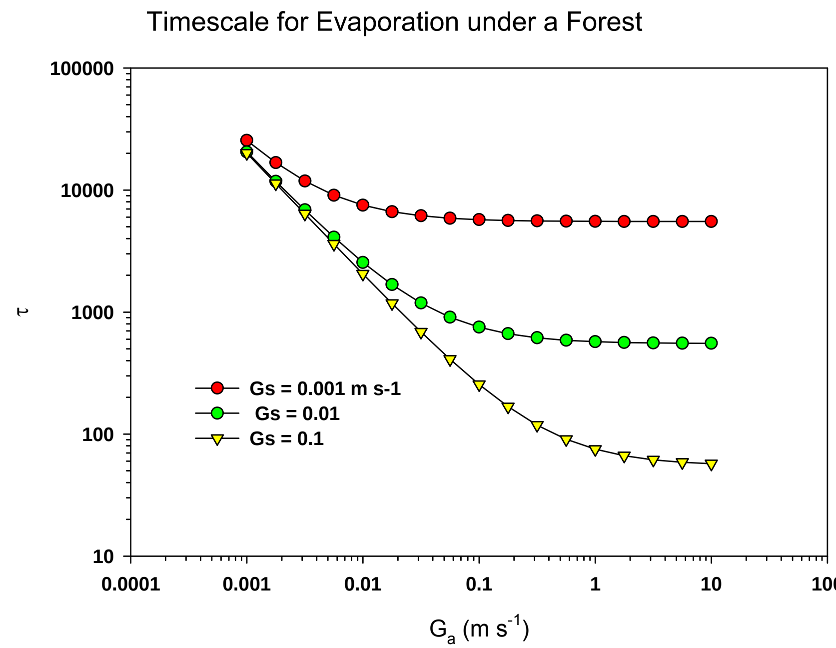


$$\lambda E(t) = \frac{s}{s+\gamma} A + \exp(-\frac{t}{\tau})[\lambda E(0) - \frac{s}{s+\gamma} A]$$

Periodic and Coherent Eddies Sweep through the Canopy Frequently, and Prevent Equilibrium Conditions from Being Reached



t, 10 Hz

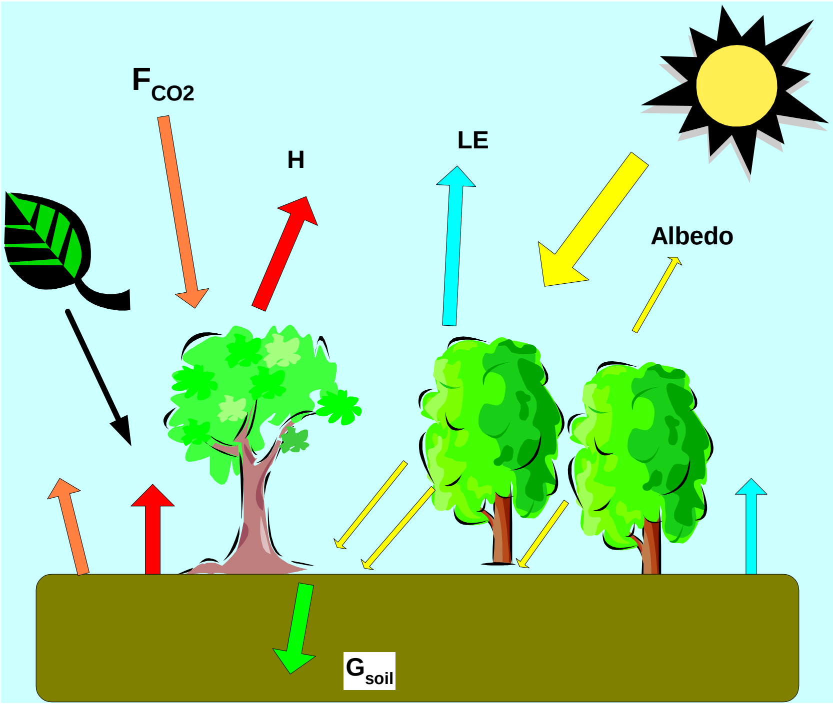


$$\tau = \frac{h(s + \gamma + \gamma(G_{av} / G_s))}{G_{av}(s + \gamma)}$$

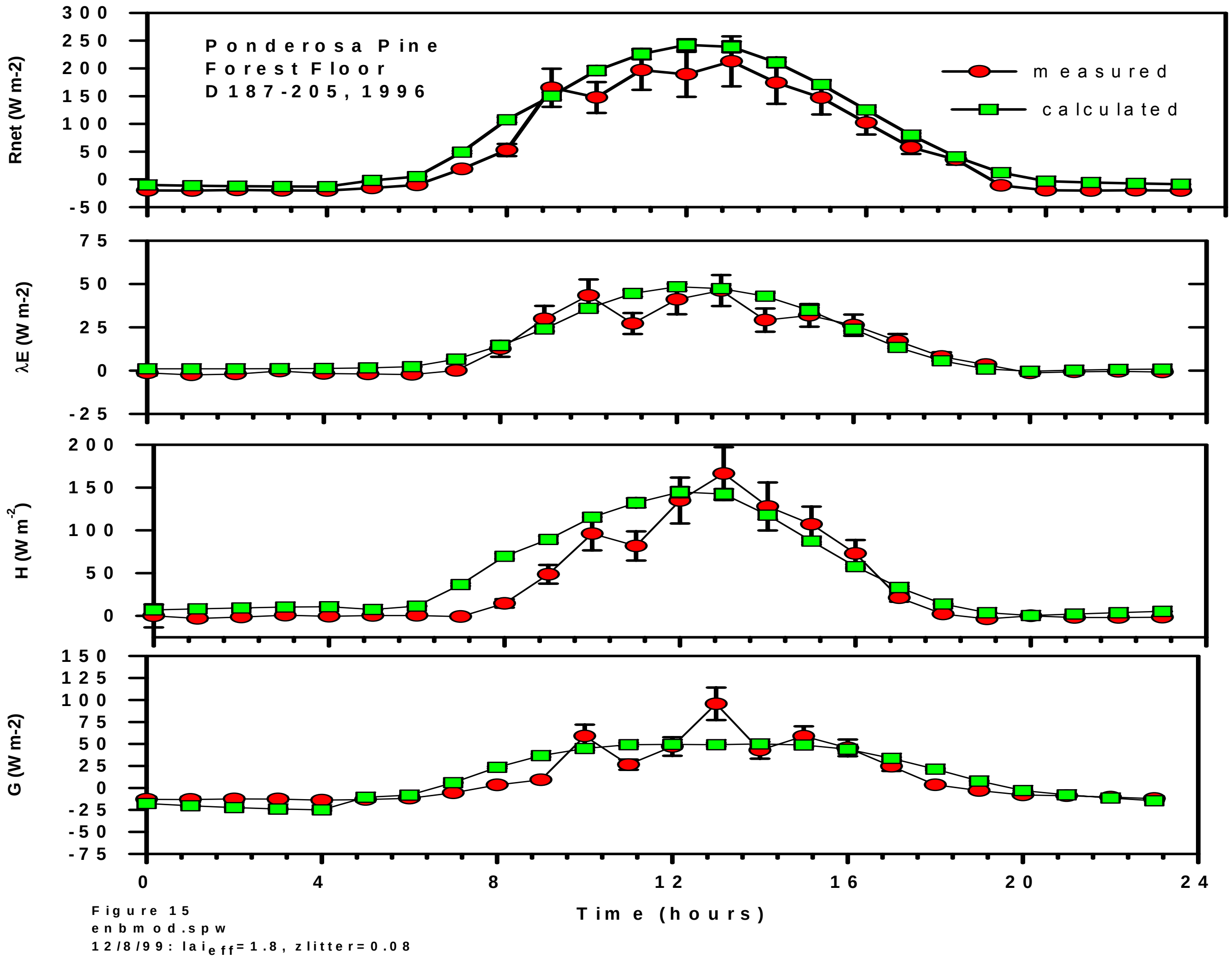
Timescale for Equilibrium Evaporation (~1000s) >> Turbulence Timescales (~200s)

Modeling Soil Evaporation

$$R_n = (1-\alpha)R_g + \varepsilon L^{\downarrow} - \sigma\varepsilon T_s^4 = \lambda E + H + G$$



Below Canopy Energy Fluxes enable Us to Test Model Calculations of Soil Energy Exchange



Baldocchi et al. 2000 AgForMet

Lessons Learned:
1. Convective/Buoyant Transport Has a Major Impact on Understory Aerodynamic Resistances

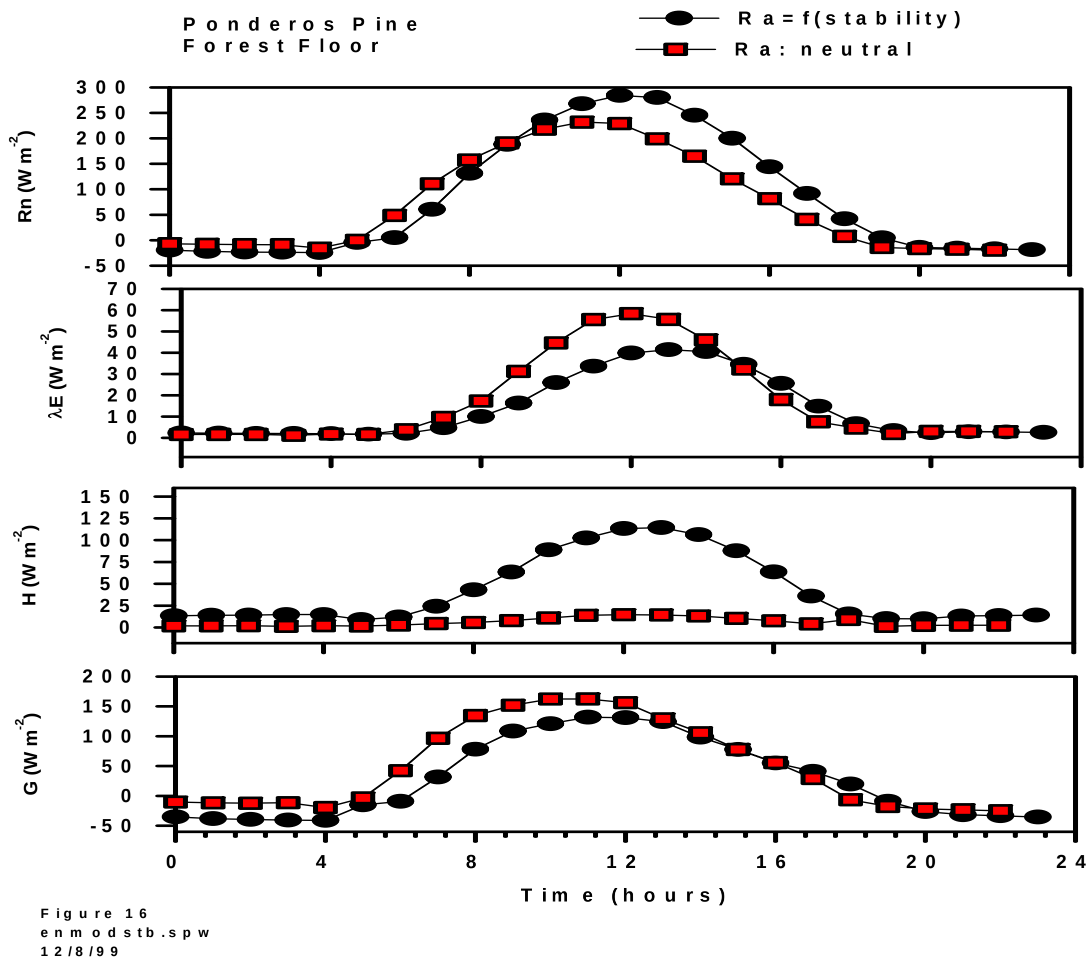
$$H = \rho_a C_p \frac{T_a - T_{sfc}}{R_a}$$

$$R_a = \frac{(\ln(\frac{z}{z_0}))^2}{k^2 u}(1+\delta)^{\varepsilon}$$

$$\delta = \frac{5gz(T_s - T_a)}{T_a u^2}$$

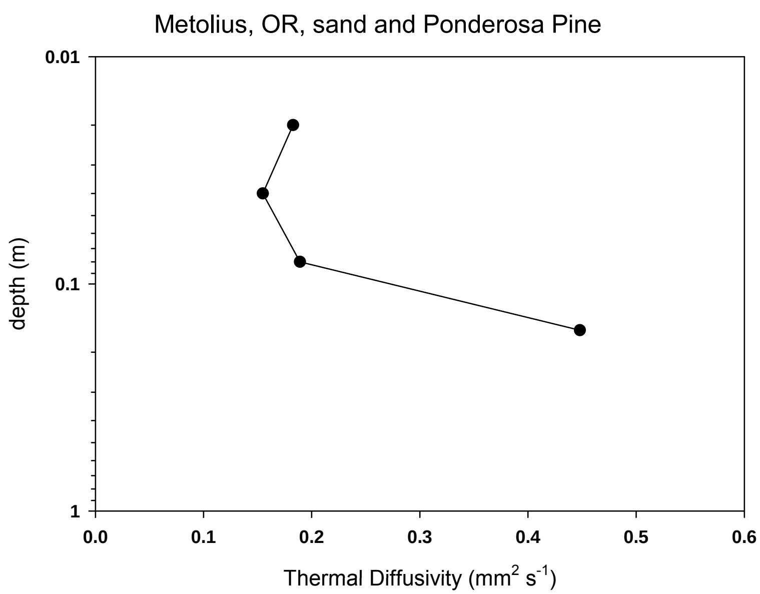
Daamen and Simmons Model (1996)

Ignoring Impact of Thermal Stratification Produces Errors in H AND *Rn, LE, & G*



Baldocchi et al. 2000 AgForMet

Sandy Soils Contain More Organic Content than May be Visible



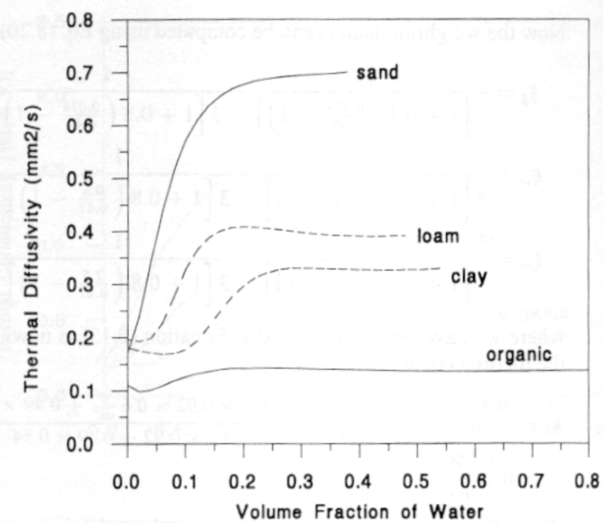
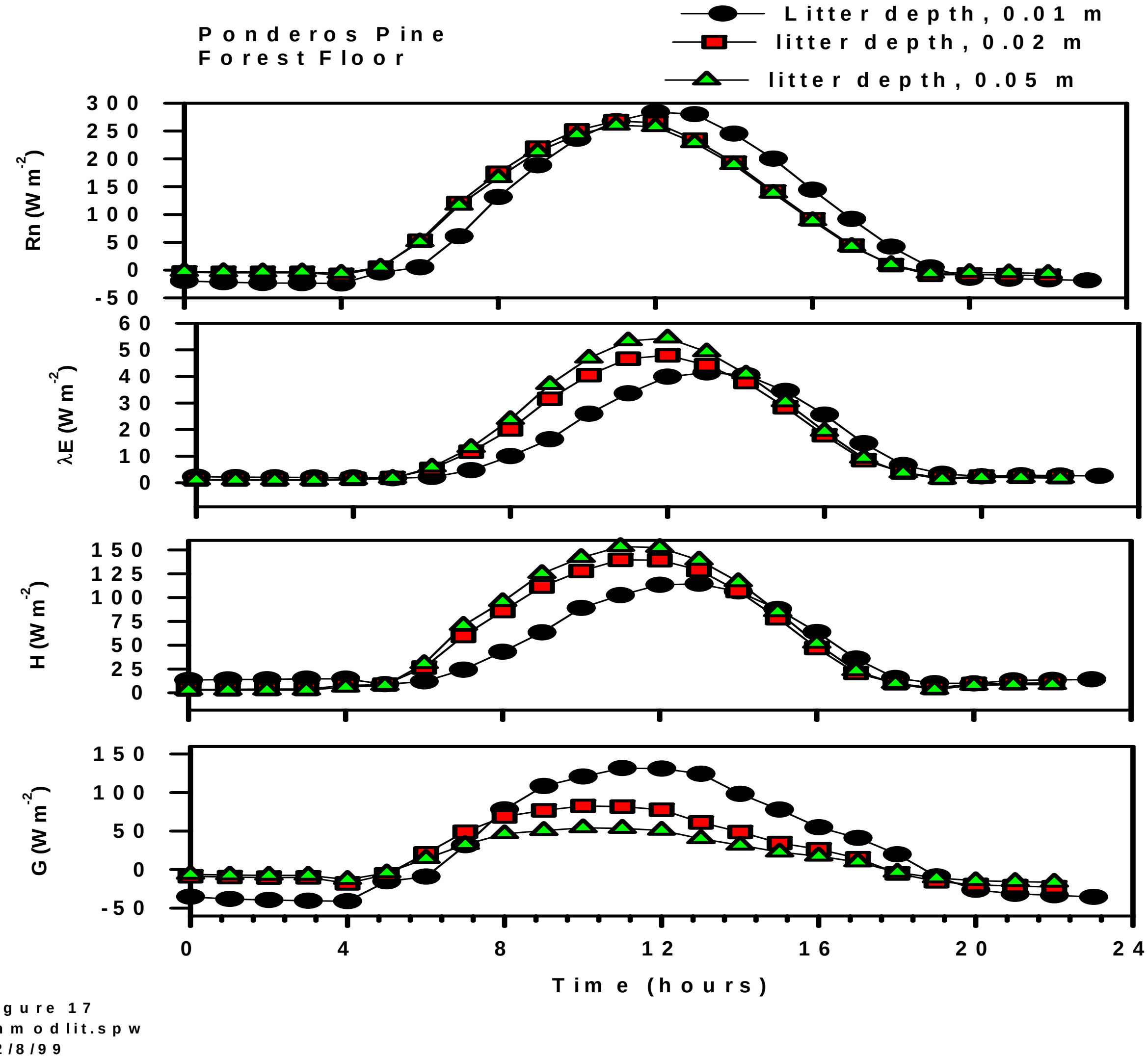


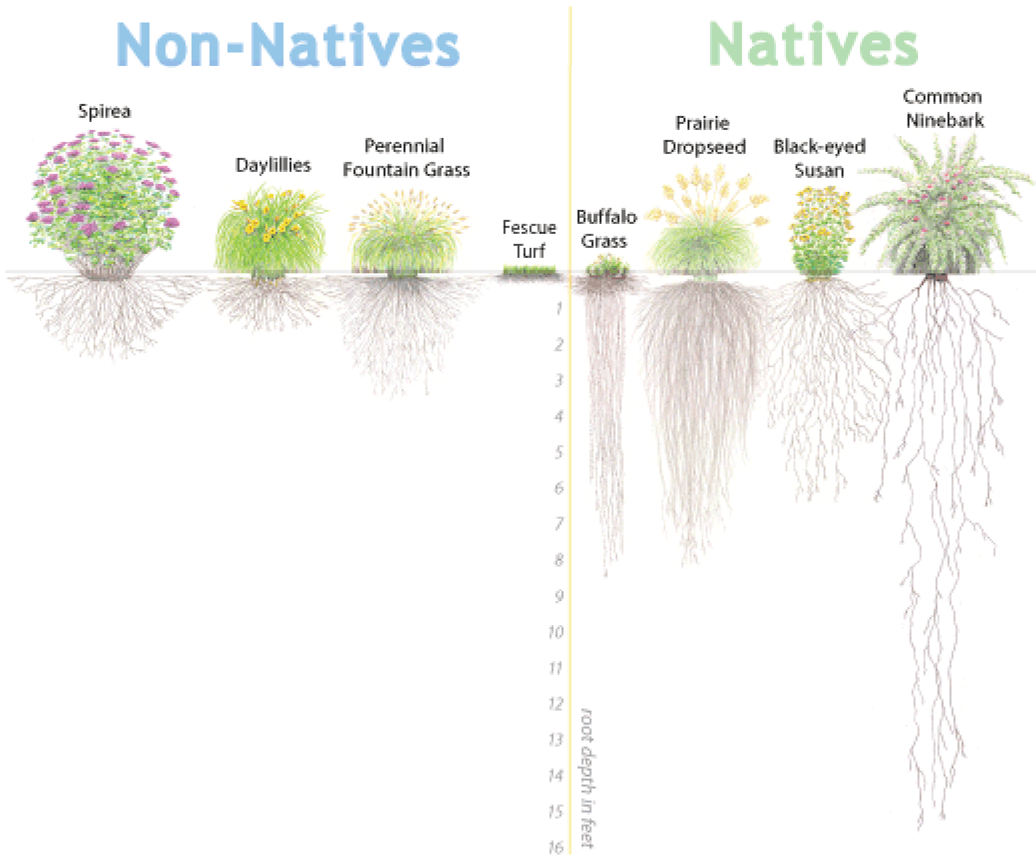
FIGURE 8.4. Thermal diffusivities of soils from Figs. 8.2 and 8.3.

Litter Depth affects Thermal Diffusivity and Energy Fluxes

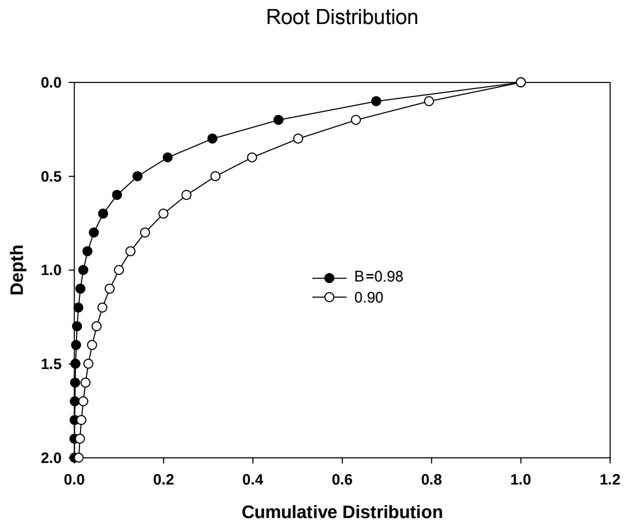


Baldocchi et al. 2000 AgForMet

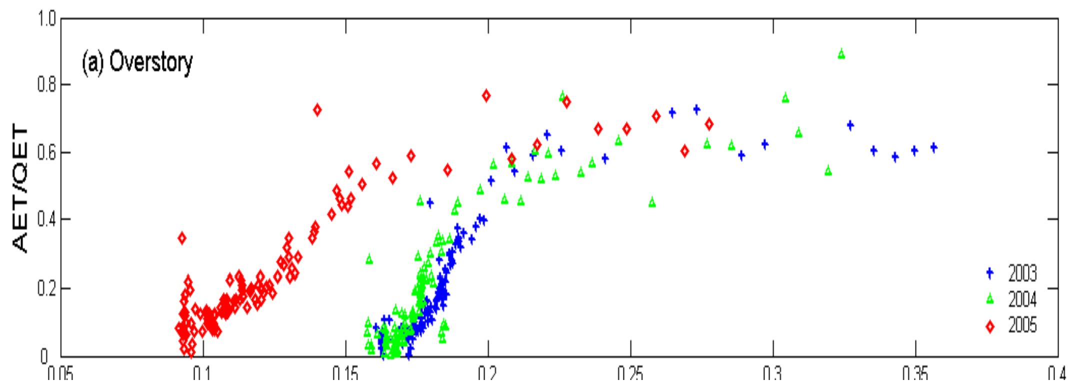
Use Appropriate and Root-Weighted Soil Moisture, Not Arithmetic Average



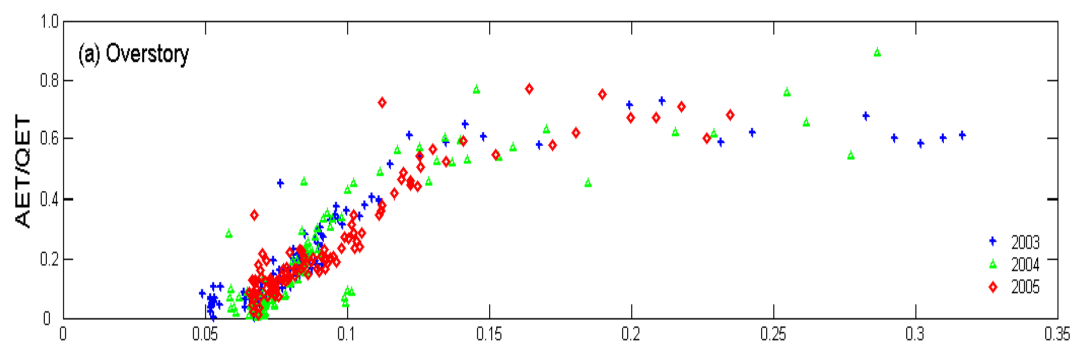
$$\langle \theta \rangle = \frac{\int_0^z \theta(z)\, dP(z)}{\int_0^z dP(z)}$$



Use of Root-Weighted Soil Moisture Enables a 'Universal' relationship between normalized Evaporation and Soil Moisture to be Observed



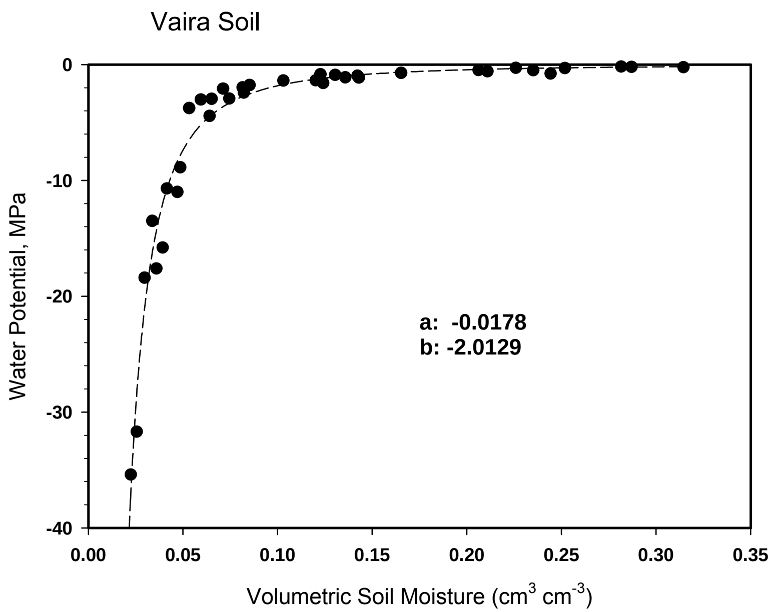
Soil Moisture, arithmetic average

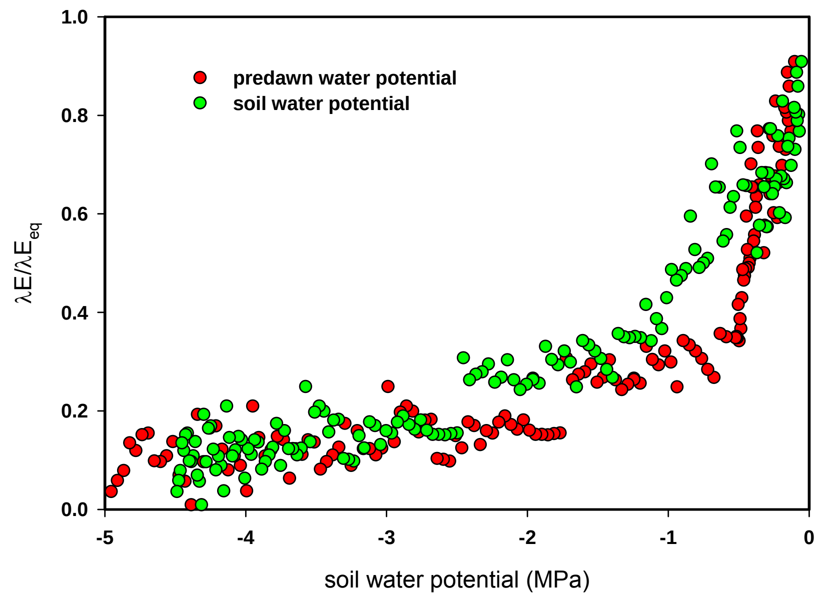


Soil Moisture, root-weighted

Chen et al, WRR in press.

Combining Root-Weighted Soil Moisture and Water Retention Produces a Functional Relation between λE and Water Potential



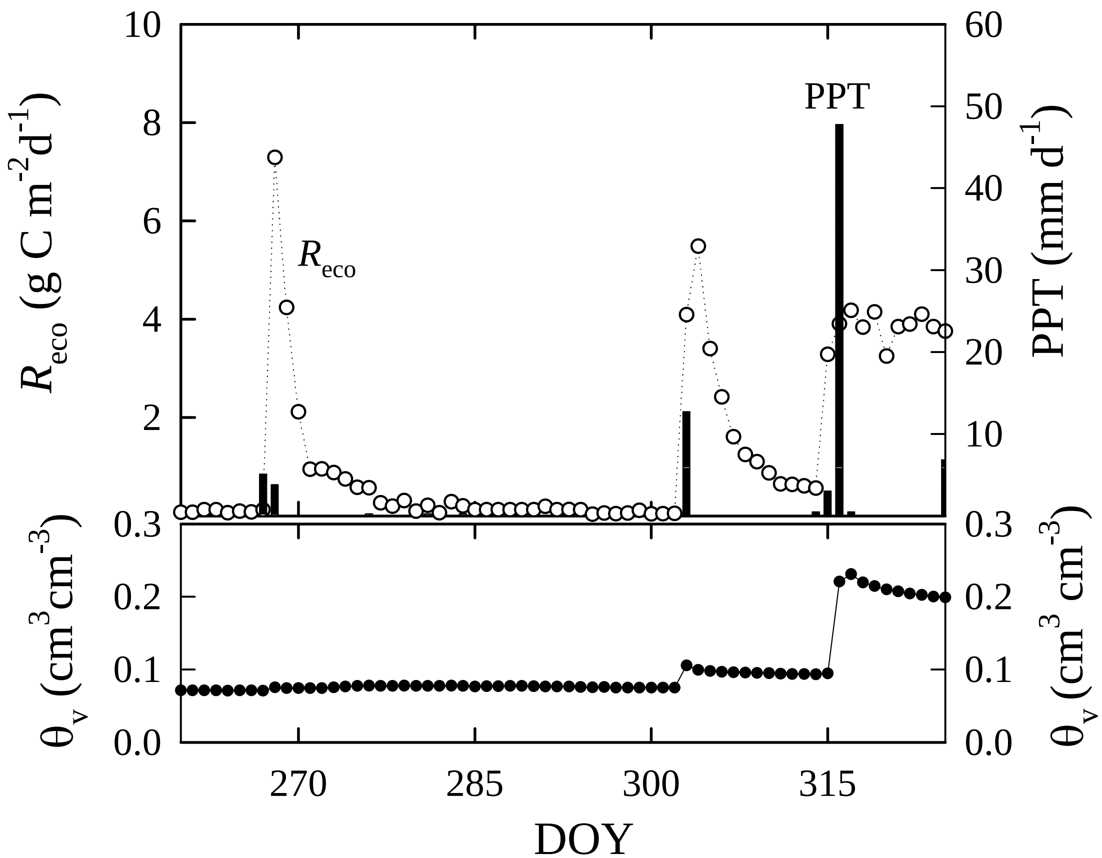


Water Retention Curve Provides a Good Transfer Function with Pre-Dawn Water Potential

Baldocchi et al. 2004 AgForMet

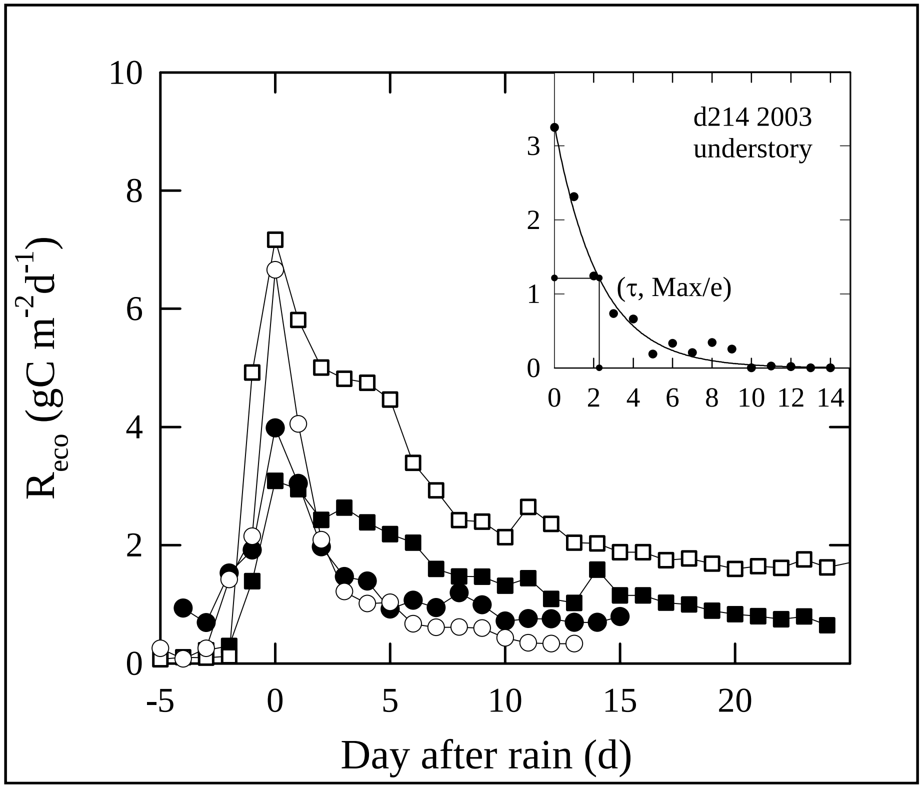
Impact of Rain Pulses on Soil Respiration:

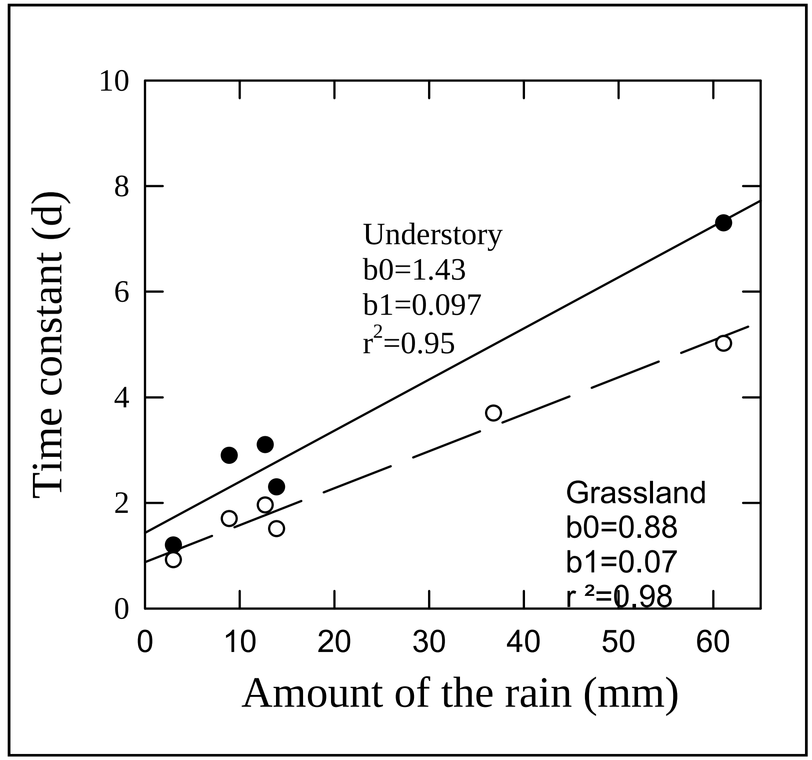
Rains Pulse do not have Equal Impacts



Xu, Baldocchi *Agri For Meteorol* , 2004

Quantifying the impact of rain pulses on respiration: Assessing the Decay Time constant via soil evaporation



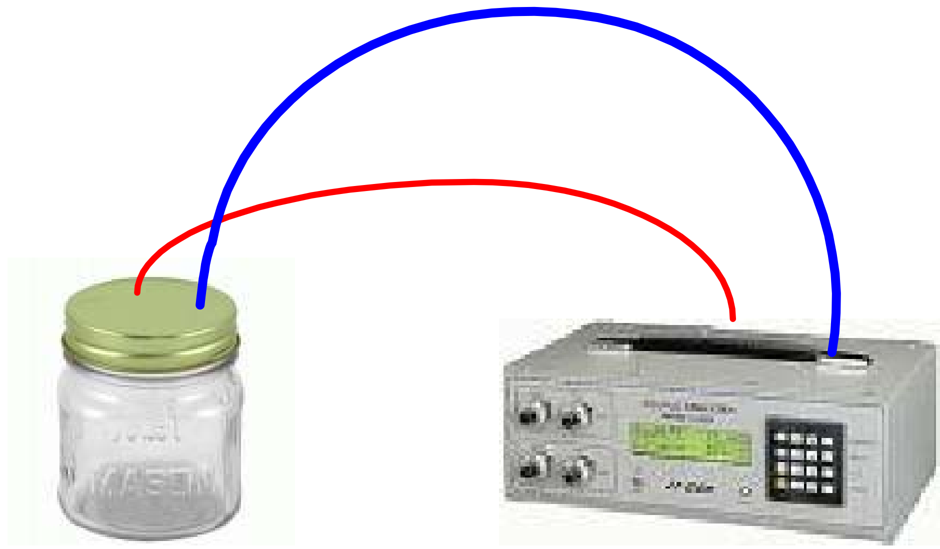


Xu, Baldocchi, Tang, 2004
Global Biogeochem Cycles

$$R_{eco} = b_0 + b_1 \exp(\frac{-t}{\tau})$$

Forming a Bridge between Soil Physics and Ecology:
Refining Sampling and Analytical Measurements Protocols

Continuous Flow Incubation System

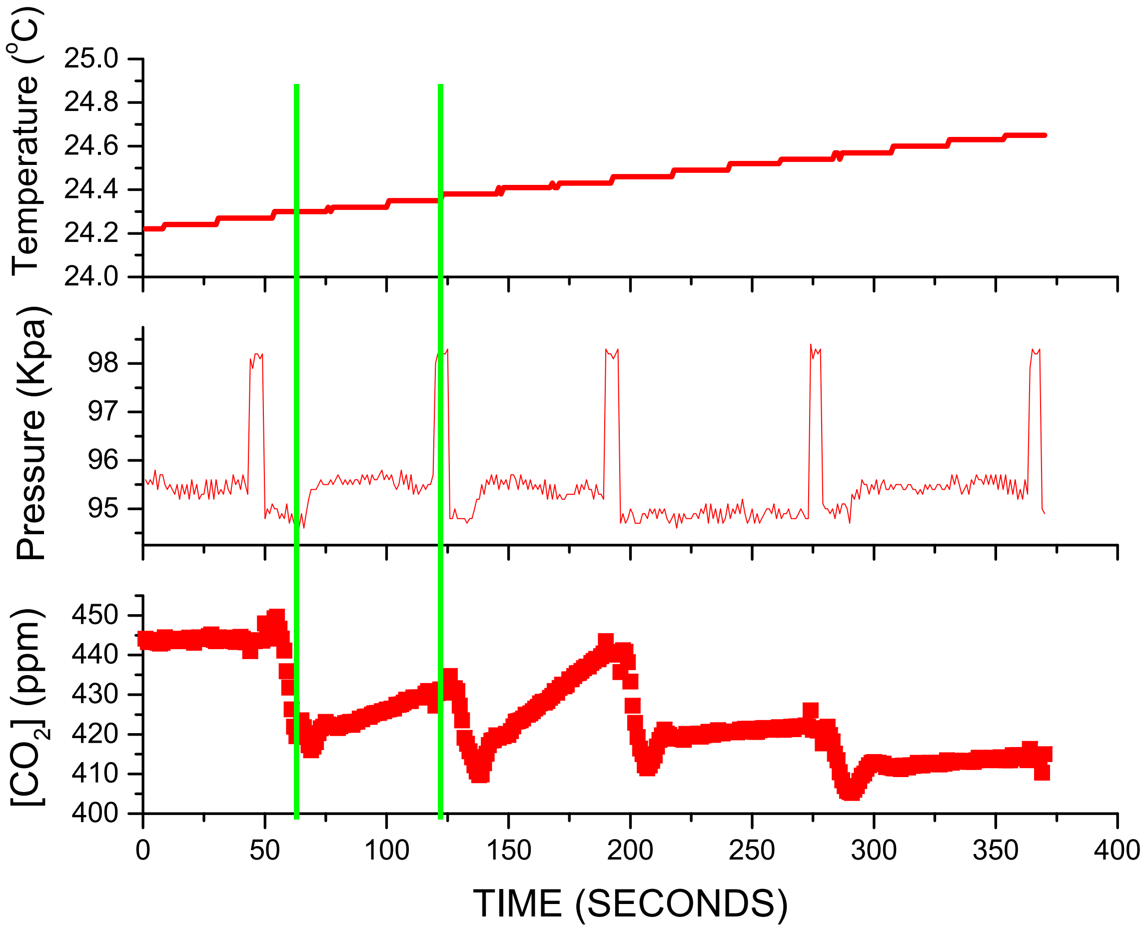


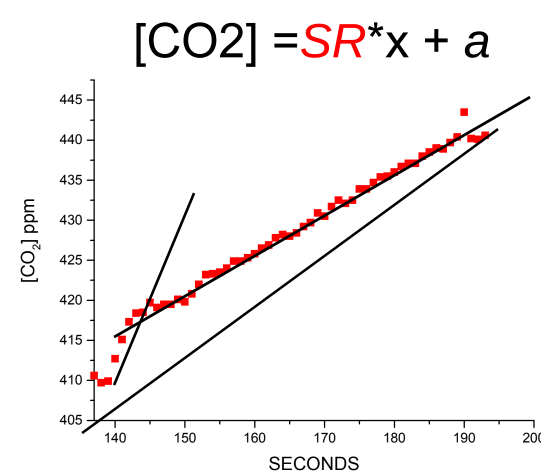
Intact soil core of known volume and density to assess water potential

Re-Designing Incubation Studies

- Use Closed path IRGA
  - Data log CO_2 continuously with precise time stamp to better compute flux from dC/dt at time 'zero'.
  - Avoid/ exclude P and C perturbation when closing lid
- Use soil samples with constrained volume
  - If you know bulk density and gravimetric water content, you can compute soil water potential from water release curve
- Expose treatment to Temperature range at each time treatment, *a la* Fang and Moncreif.
  - Reduces artifact of incubating soils at different temperatures and thereby burning off different amounts of the soil pool
  - Remember F = [C]/t
  - Because T will be transient sense temperature at several places in the soil core.

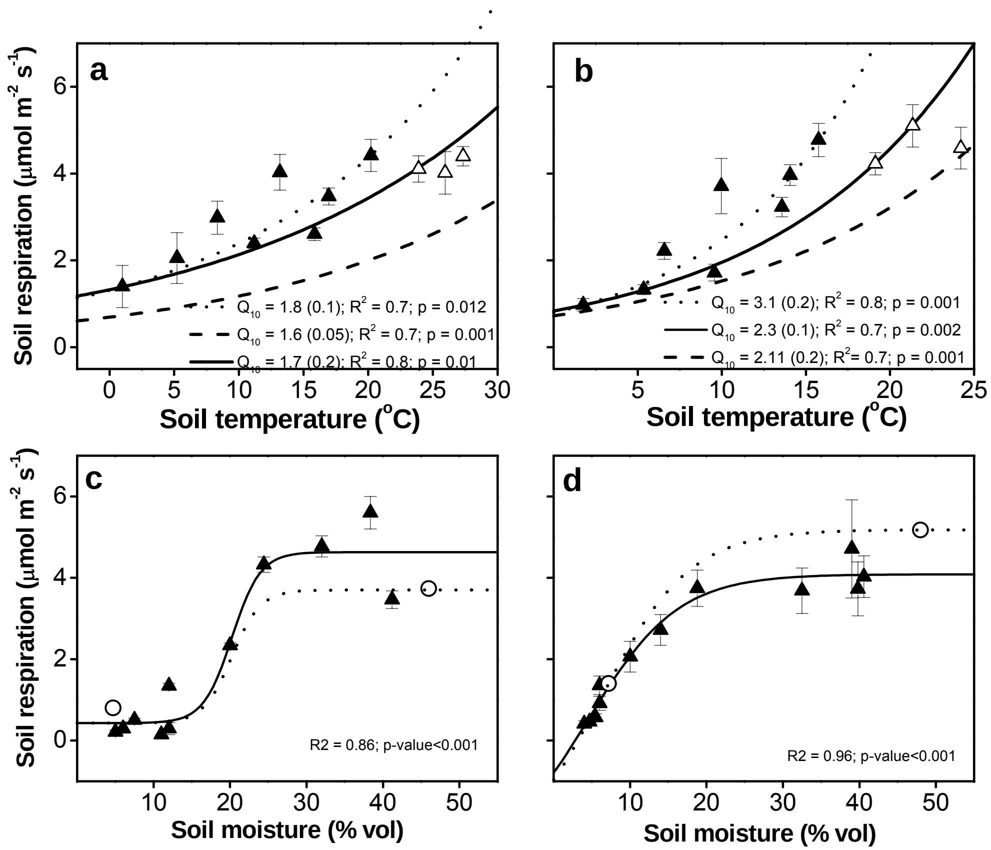
Experimental Data



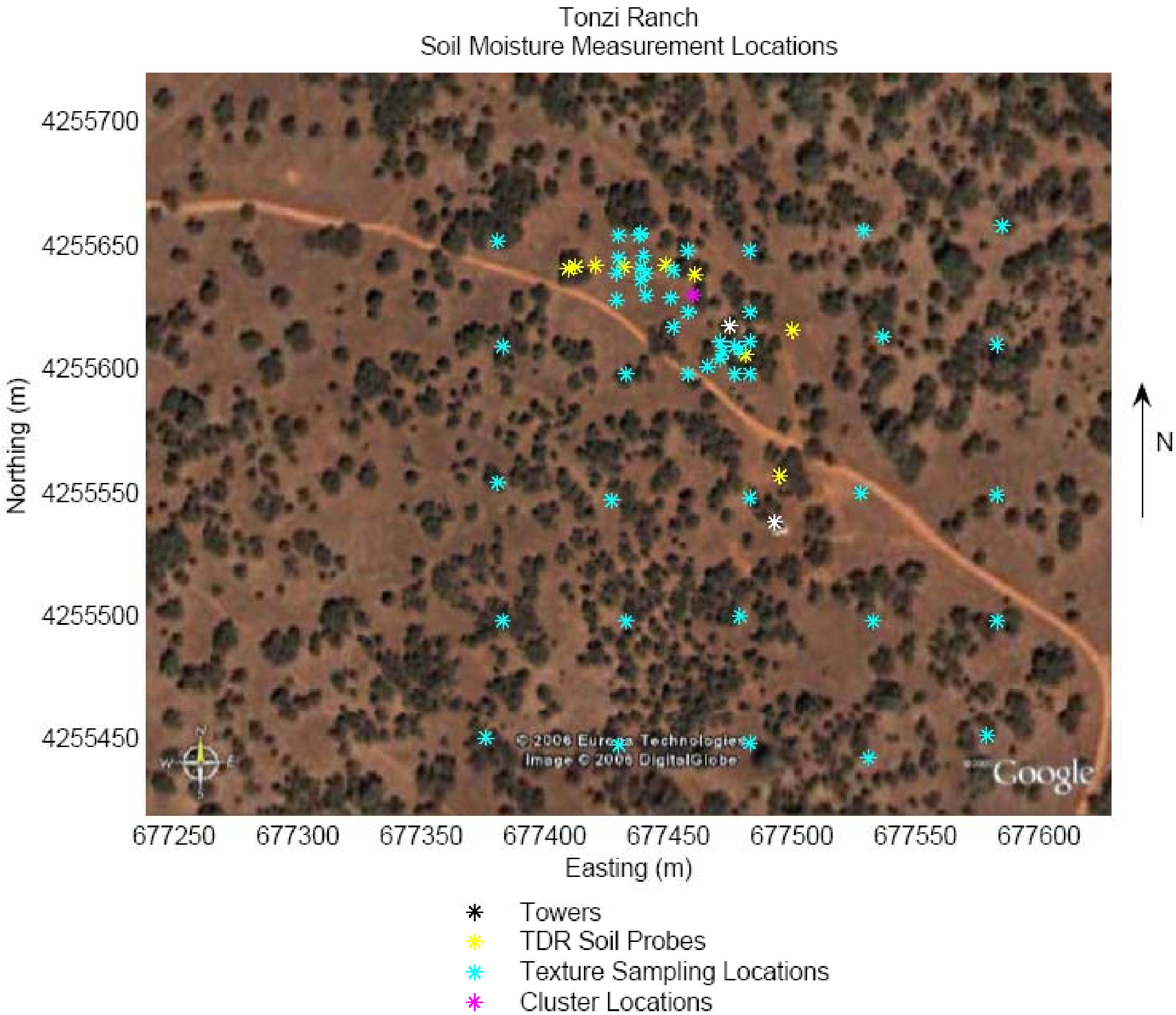


Curiel et al. 2008 GCB

Sample of Results from Curiel-Yuste et al, 2008 GCB

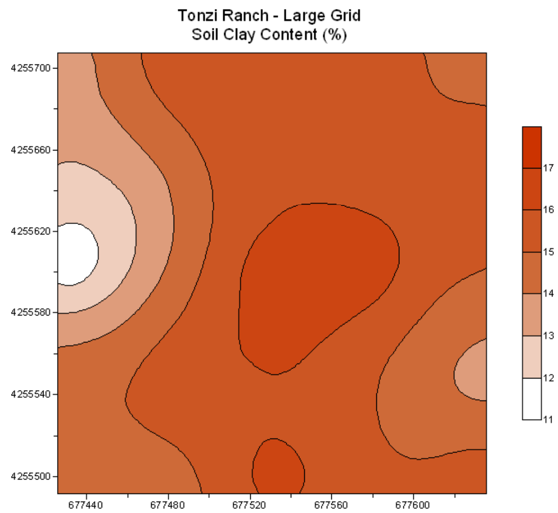


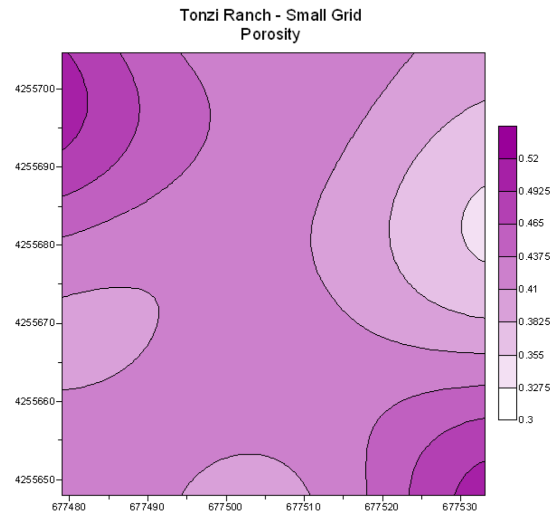
Use Distributed Soil Measurements and Tree Information to 'Site' Representative Sapflow Stations

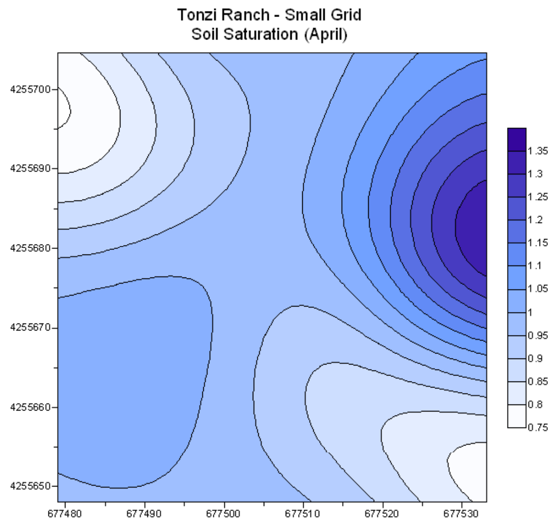


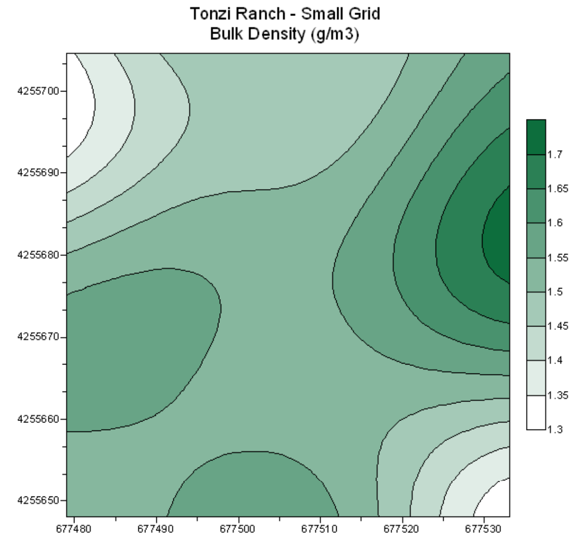
Data of Gretchen Miller and Xingyuan Chen

Soil Maps









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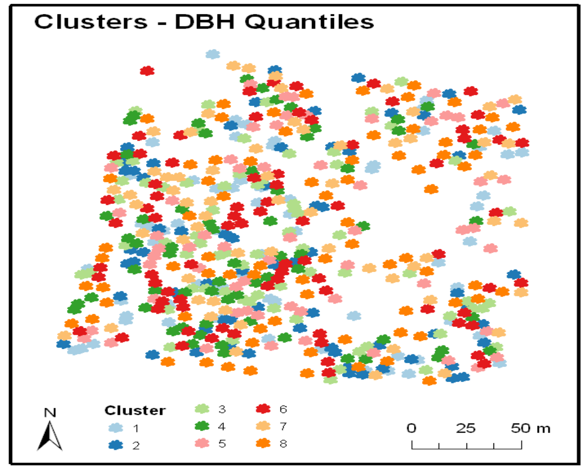
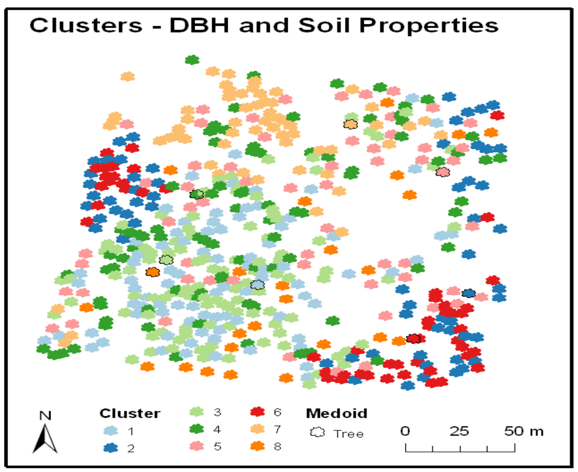
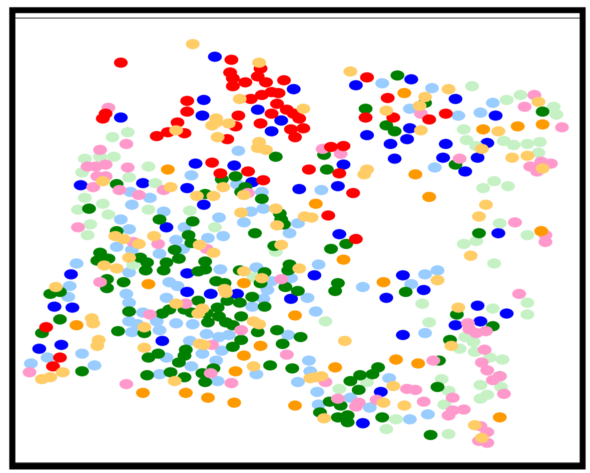
Use Cluster Analysis to Determine where to Sample Sap Flow







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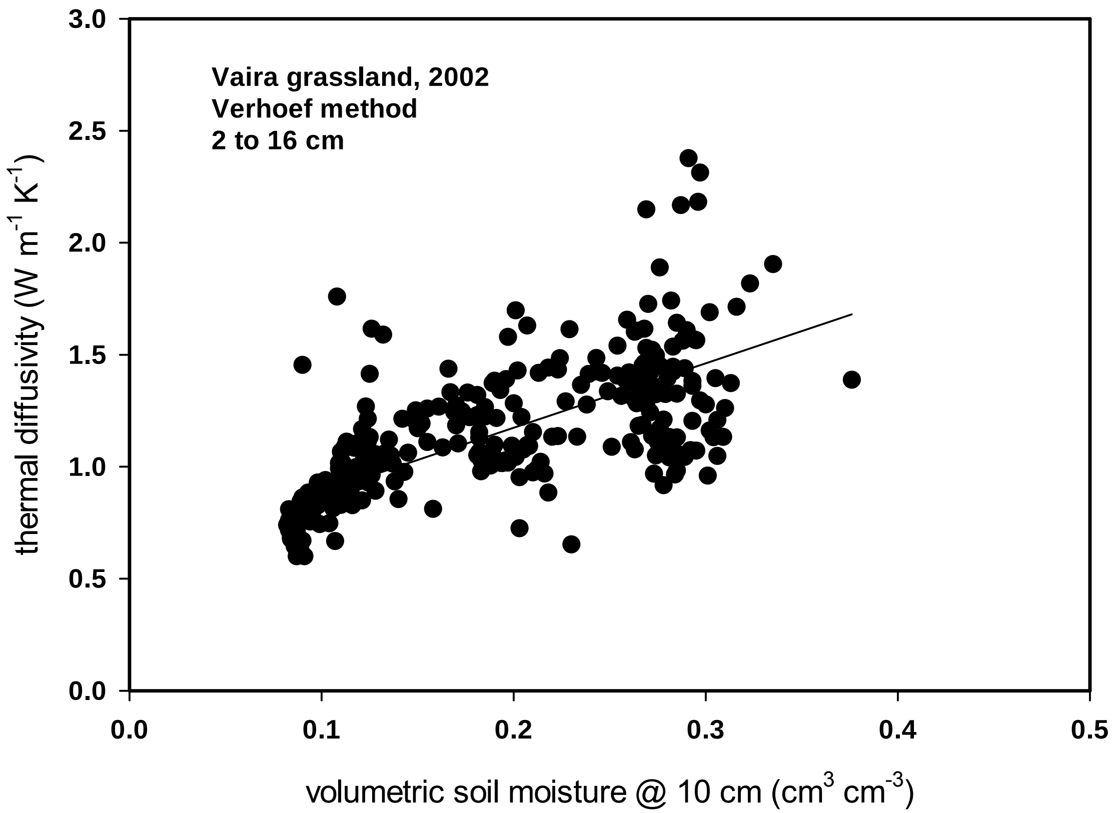
Results of Clustering Analysis (DBH and Simulated Soil Properties Method)										
Cluster Number	Number of Trees	Diameter (cm)		Elevation (m)		Slope (%)		Sand (%)	
1	117	33	●	168.54	●	1.43	○	47.32	○
2	50	45	●	168.11	○	2.27	●	47.88	●
3	52	29	●	169.06	●	2.47	●	49.63	●
4	151	20	○	168.79	●	1.6	○	47.75	○
5	21	16	○	168.57	●	2.05	●	47.12	○
6	59	26	○	166.85	○	2.66	●	48.65	●
7	79	11	○	168.29	●	1.61	○	47.65	○
8	9	66	●	168.86	●	1.9	●	47.44	○

● = above average, ○ = below average

Data of Gretchen Miller and Xingyuan Chen

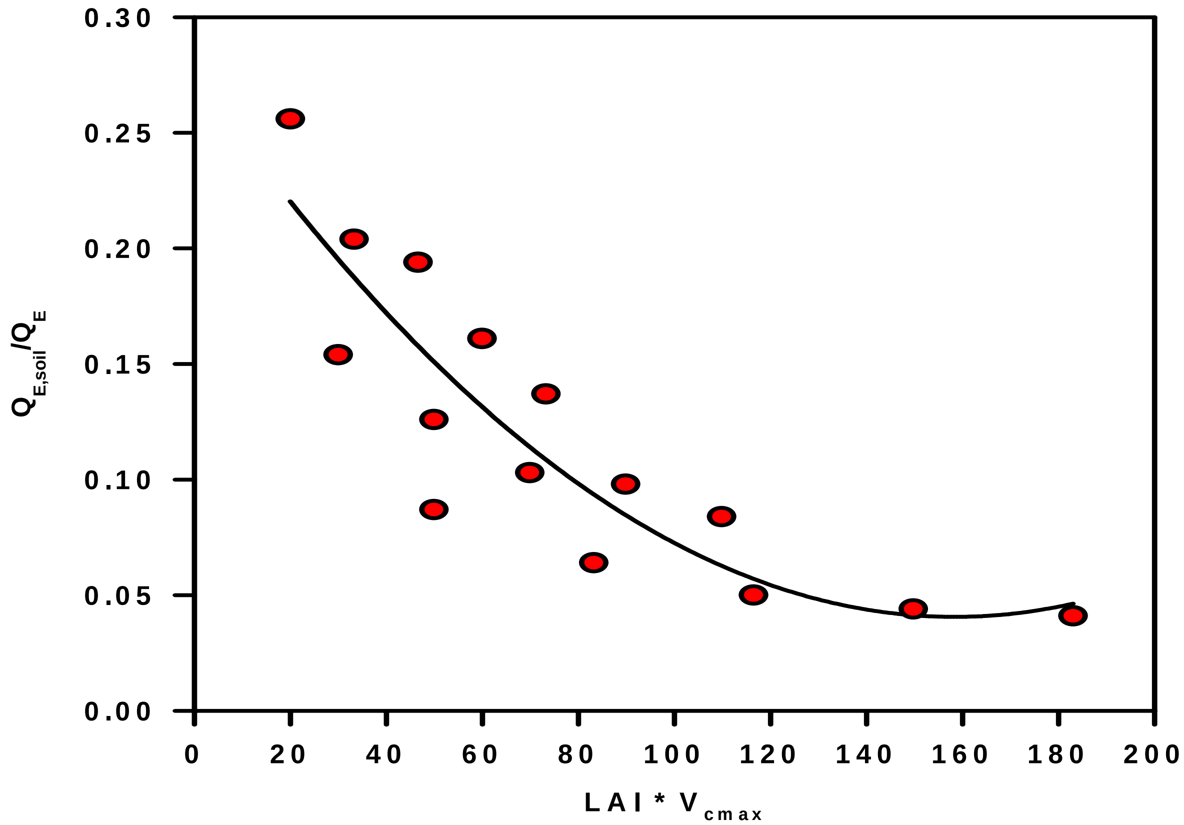
Summary

- Temperature and Soil Respiration
  - Vertical Gradients, Lags and Phase Shift
  - Hysteresis, a need to match depth of production with temperature
- Photosynthesis and Soil Respiration
  - Photosynthesis Controls Soil Respiration
  - But, Lags occur between Soil Respiration and Photosynthesis
- Soil Evaporation & Moisture
  - Turbulence Sweeps and Ejections Regulate Soil ET
  - Modeling Soil Energy Exchange requires information on Convection
  - Spatial scaling of Soil Moisture
    - Pre-dawn water potential and root weighted soil moisture
  - Soil Moisture and ET
- Soil Respiration & Rain
  - Stimulation of Respiration by Rain
- Alternative/'novel' Measurement Methods
  - Better Experimental Design for Soil Respiration
  - Understory Eddy Covariance, an alternative to Chambers
  - Soil CO_2 probes & Fickian Diffusion
  - Improved Incubation Protocols
  - Improved Sapflow Sampling Protocols

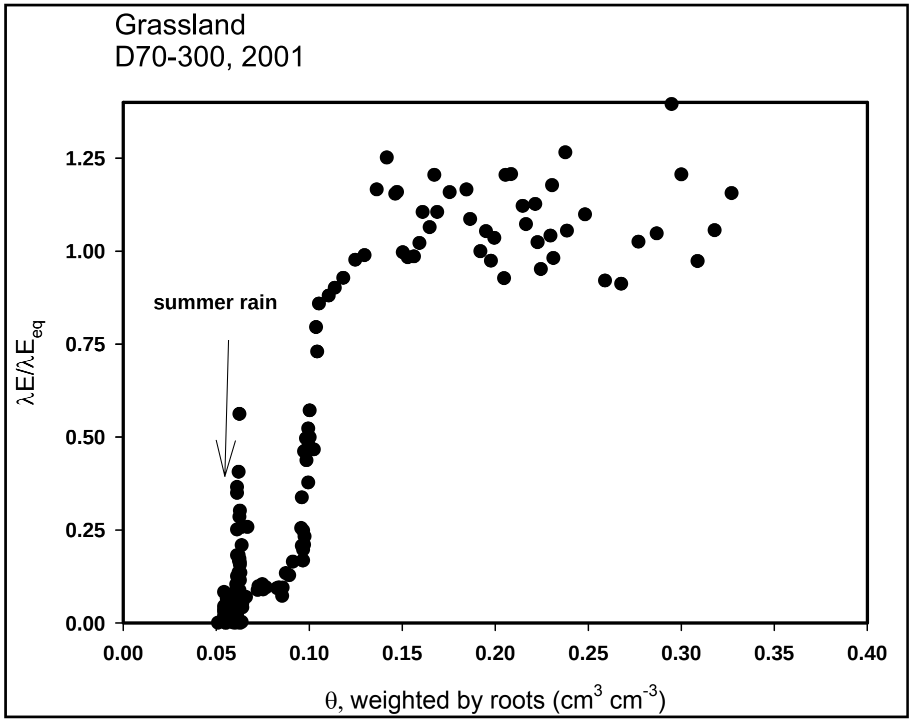


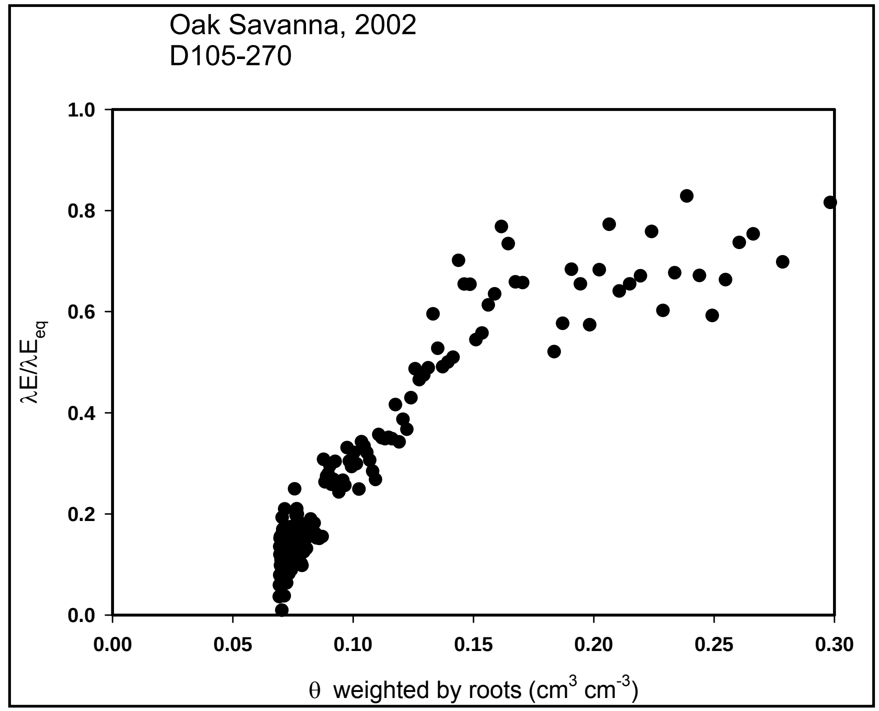
$$\kappa = \frac{\omega}{2}\left[\frac{z_2 - z_1}{\ln(A_1 / A_2)}\right]^2$$

Below Canopy Fluxes and Canopy Structure and Function



Evaporation and Soil Moisture Deficits





Baldocchi et al, 2004
AgForMet