"I've Looked at Plants from Both Sides Now": Ecosystem-Climate interactions

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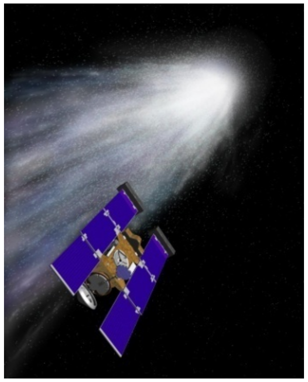
KIT Environmental Lecture, July 2014

Outline

- Big Questions and Open Problems
- Ecosystem-Atmosphere Interactions Principles
  - What are Fluxes?; Why?
  - Roles of Models and Observations
  - Non-Linear, Multi-Scaled, Coupled Feedbacks and Forcings
- Observations
  - Eddy Covariance
  - Flux Networks
- Data, Modeling and Synthesis
  - Lessons Learned, Scale Emergent Processes, Feedbacks, Roles of Land Use

Physics Wins



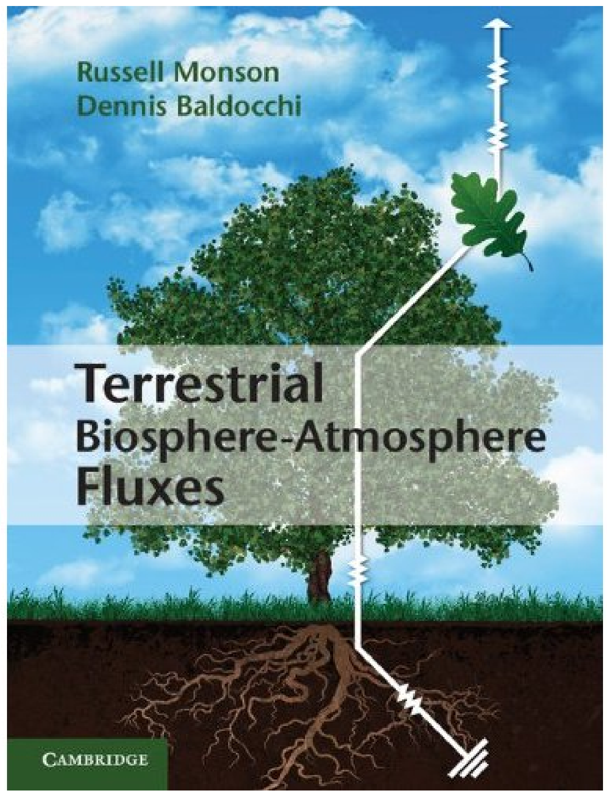
'Our bodies are stardust;
Our lives are sunlight'

Oliver Morton, 2008 Eating the Sun: How Plants Power the Planet

Ecosystem Ecology,
the Baldocchi-Biometeorology Perspective

- **Physics wins**
  - Ecosystems function by capturing solar energy
    - Only so much Solar Energy can be capture per unit are of ground
  - Plants convert solar **energy** into high energy carbon compounds for **work**
    - growth and maintenance respiration
  - Plants **transfer** nutrients and water down concentration/potential energy gradients between air, soil and plant pools to sustain their structure and function
  - Ecosystems must maintain a **Mass Balance**
    - Plants can't Use More Water or Carbon than has been acquired
- **Biology is how it's done**
  - Species differentiation (via evolution and competition) produces the structure and function of plants, invertebrates and vertebrates, which are nearly optimal for their conditions
  - In turn, structure and function provides the mechanisms for competing for and capturing light energy and transferring matter
    - Gases diffuse in and out of active ports on leaves, stomata
  - Bacteria, fungi and other micro-organisms re-cycle material by exploiting differences in redox potential; they are adept at passing electrons and extracting energy
  - Reproductive success passes genes for traits through the gene pool; less optimal plants can be excluded by natural selection

What are Fluxes?;
and, Why are they Important?



Fluxes, as a Form of Currency:
The Piggy-Bank Analogy

The Change in $$$ in a Bank Account depends on the Differences in the Fluxes of $$$ In and the Fluxes $$$ Out

Fluxes define Mass Balance of the Atmosphere and the underlying Ecosystem: The Bath Tub Analogy

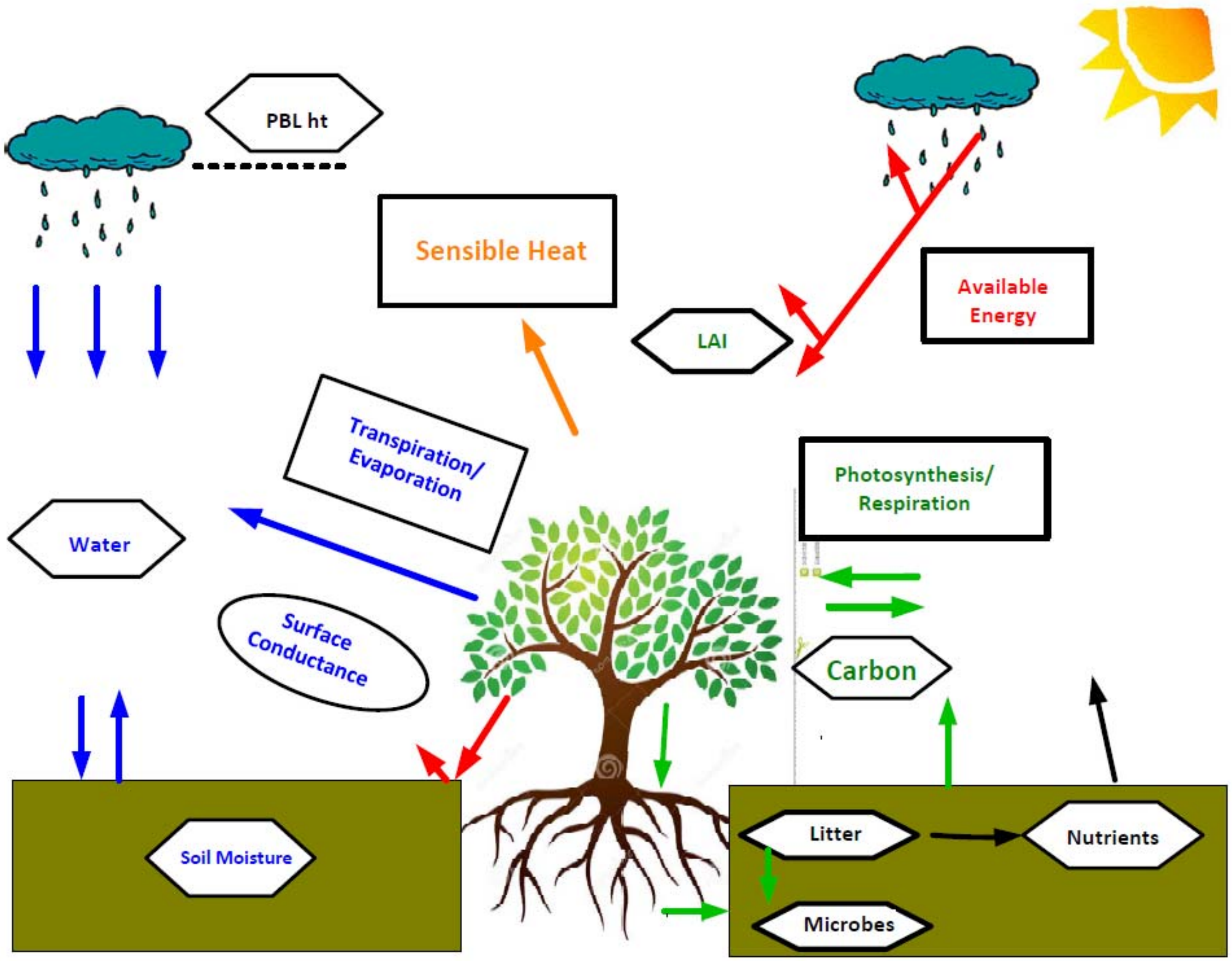
The Change in the Amount of Material in a Reservoir Depends
On the Difference between the Flux Entering and Leaving the Reservoir

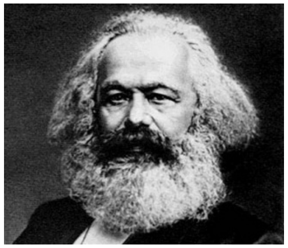
Quantify Fluxes, rather than Dose Response to Pollutants: The Analogy of Being in a Bar, and Not Drinking—You Won't get Drunk

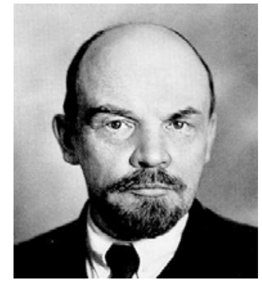
Why Study Trace Gas and Energy Exchange?

- Flux Boundary Conditions of Weather, Climate, Biogeochemical, Air Pollution and Ecological Models
  - State of the Atmosphere is determined by Fluxes across the Boundary
- Information is Needed for Ecological Assessments of Environmental Change (climate, land use, disturbance)
- Base lines for Policy and Management (Carbon and Water markets; Pollution Abatement; Forest Management, REDD)

Ecosystem-Atmosphere Interactions: Biogeophysical View



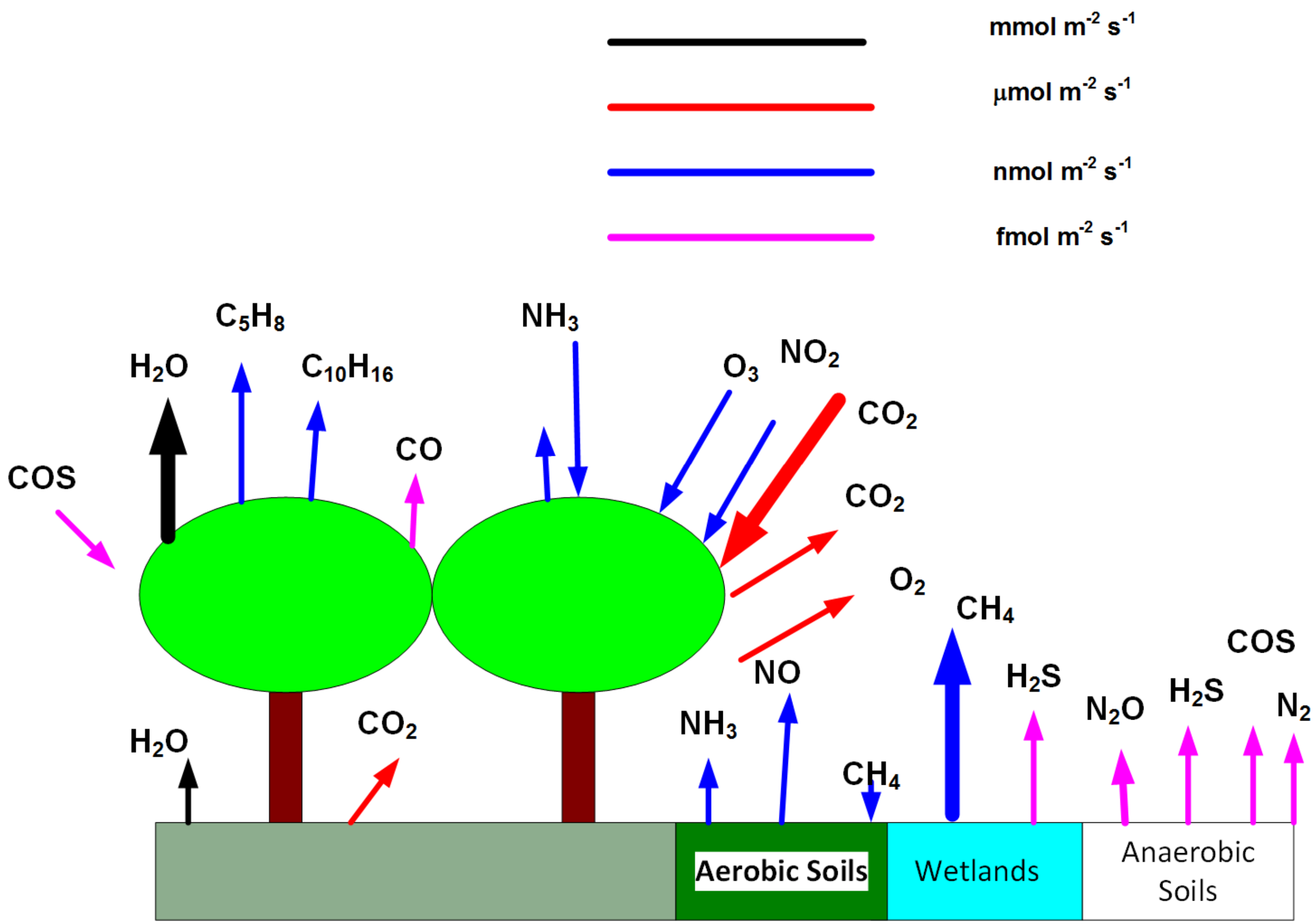




There Has Been A Revolution
in Stable, Precise, Accurate and Low Power
Fast Response Greenhouse Gas Sensors



The Composition of the Atmosphere depends on Biogenic and Biotrophic Fluxes

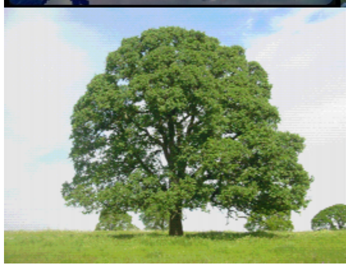


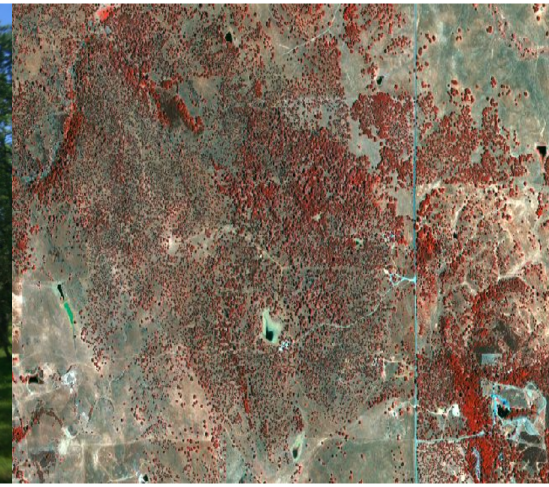
Flux-Related Questions Facing Earth System Science

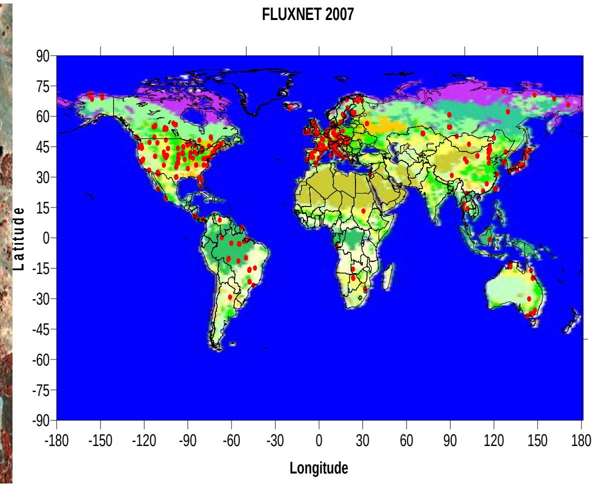
- What is the Carbon and Water Balance at Landscapes to Global Scales?
- What are the Greenhouse Gas (CH_4, N_2O, C_5H_8) and Pollution (O3, NOx, SO_2) Budgets at Landscape to Global Scales?
- How do These Balances Vary Seasonally?; Year to Year?; By Plant Functional Type/Traits?; By Climate Region?; By type of Disturbance? by Time Since Disturbance?; by Management?; by Land Use?
- Can We Scale Microbial Gas Emissions with Photosynthesis?

To Interpret Land-Atmosphere Flux Models and Measurements

We First Need to Look Under the Hood And Consider Underlying Biological, Ecological and Physiological Processes

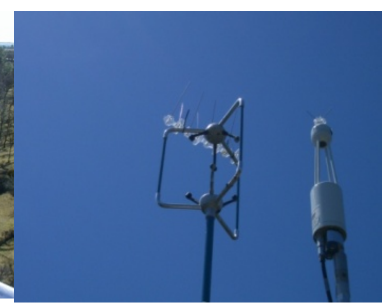




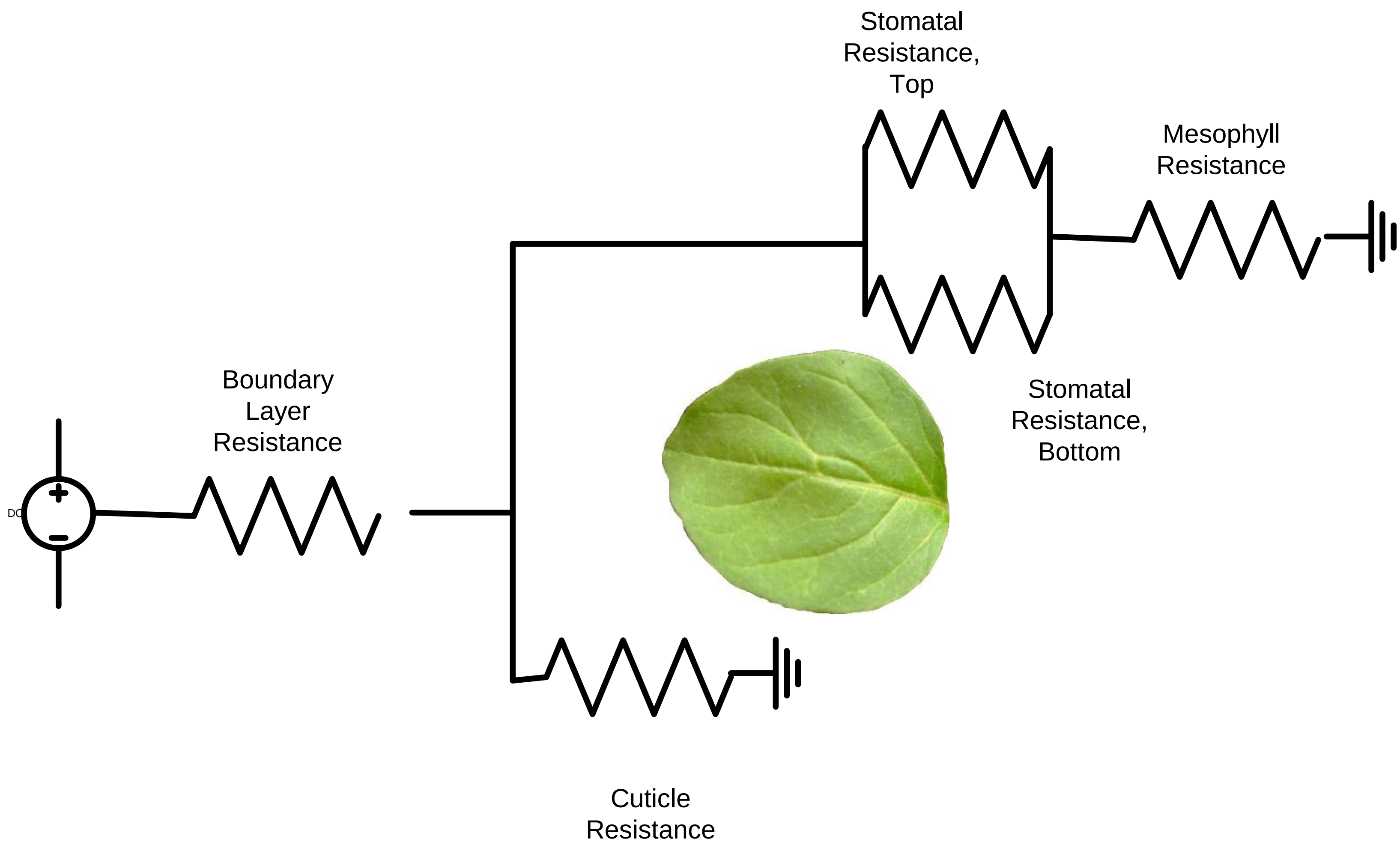


To Develop a Scientifically Defensible Virtual World 'You Must get your boots dirty', and Not Treat the Earth System Science as a Video Game

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

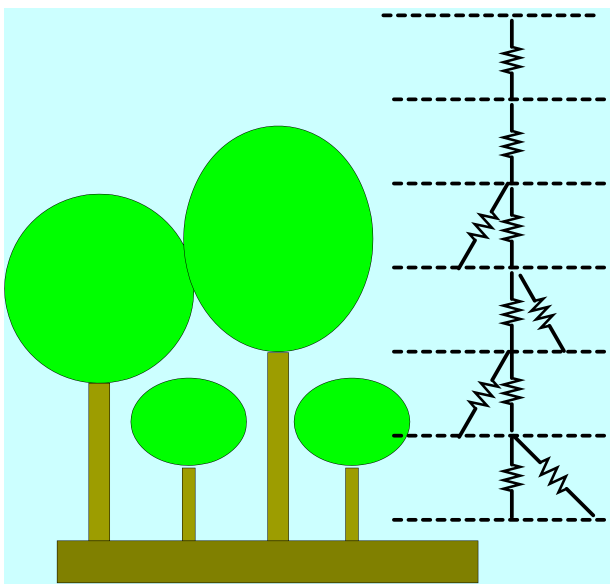


Leaf Resistance Network for Trace Gas Fluxes



Quantifying Trace Gas 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)

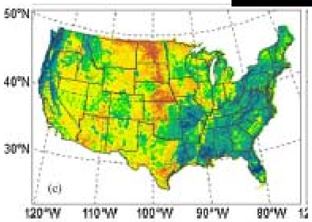
Big Picture Question Regarding Predicting and Quantifying the ‘Breathing of the Biosphere’:

- **How Do we Upscale Information from the Soil/Leaf/Plant Continuum to Canopy and Landscape scales, from hours to years?**

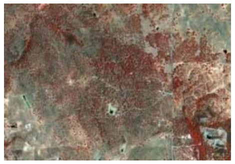
Assessing Flux-Ecosystem Atmosphere Interactions is Complex

Components Spans > 14 Orders of Magnitude in Space

Globe: 10,000 km (10^7 m)



Continent: 1000 km (10^6 m)



Landscape: 1-100 km

Canopy: 100-1000 m

Plant: 1-10 m

Leaf: 0.01-0.1 m

Stomata: 10^{-5} m

Bacteria/Chloroplast: 10^{-6} m

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 Fast to Slow Time Scales

Seconds,
Hours

Days,
Seasons

Years,
Decades

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

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

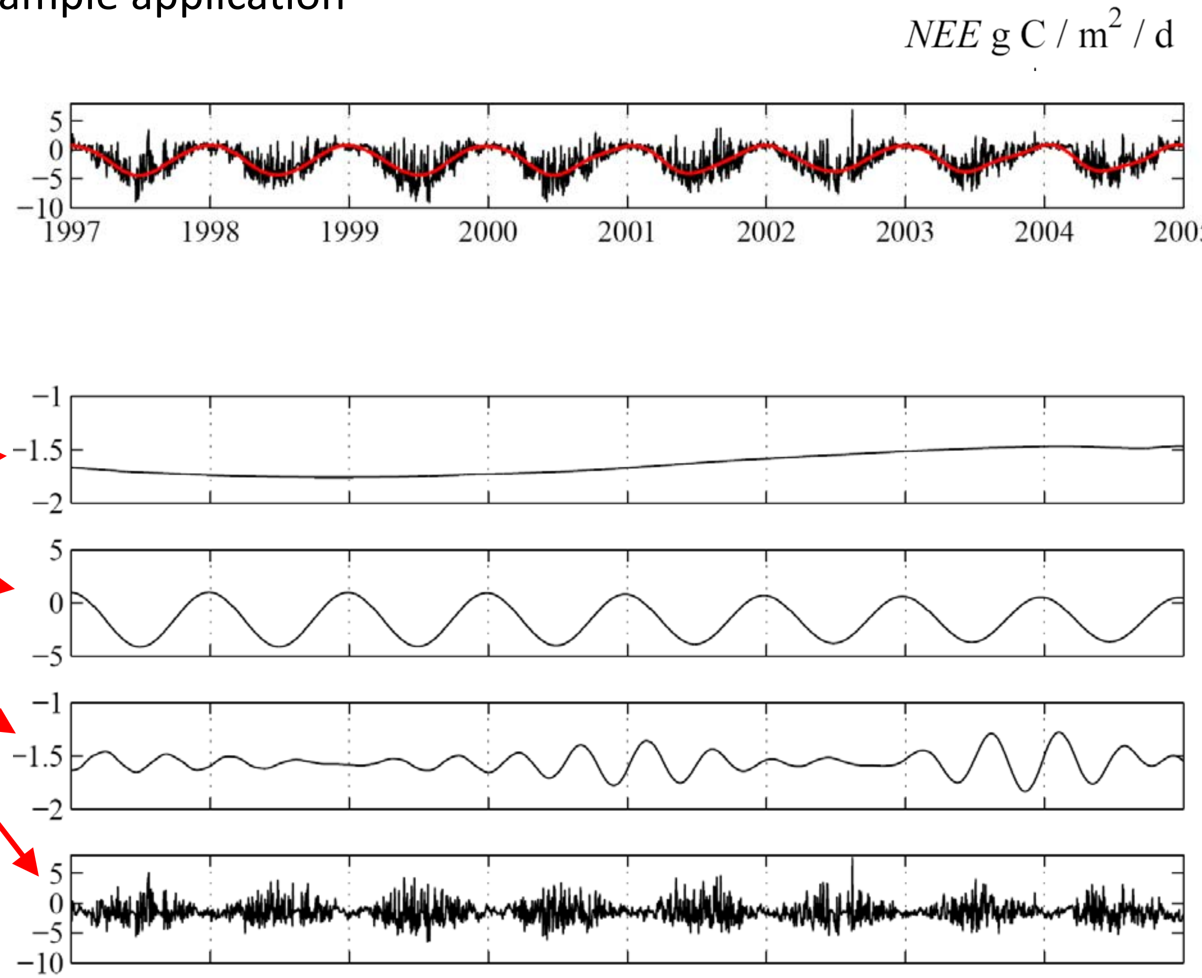
Centuries,
Millennia

Singular System Analysis: example application

Original time series:

Decomposed time series:

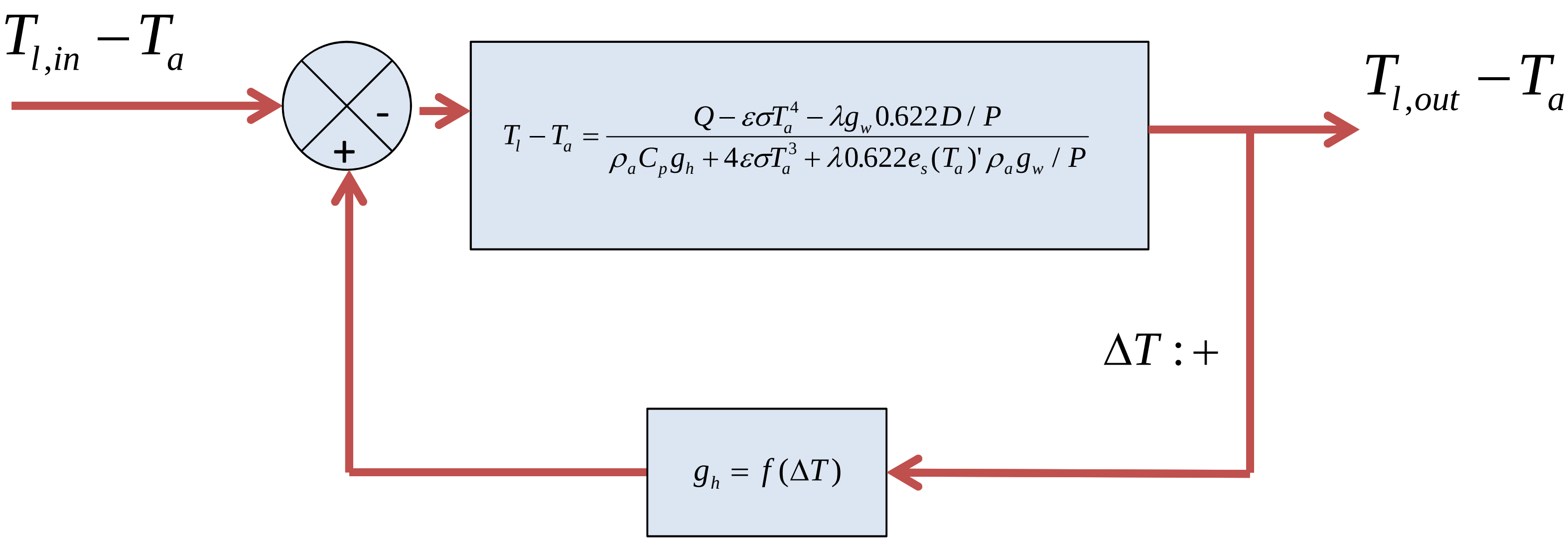
- **Nonlinear trend**
- Annual cycle
- Intra-annual cycle
- High frequency modes

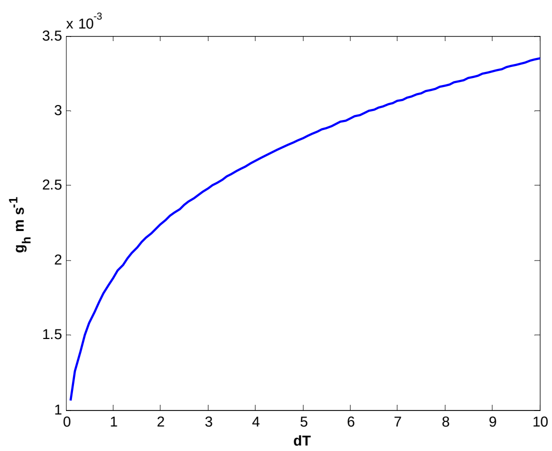


New developments allow application of SSA to fragmented time series

Mahecha et al. (2007) *Biogeosciences*, **4**, 743-758

Effects of Feedbacks on Fluxes

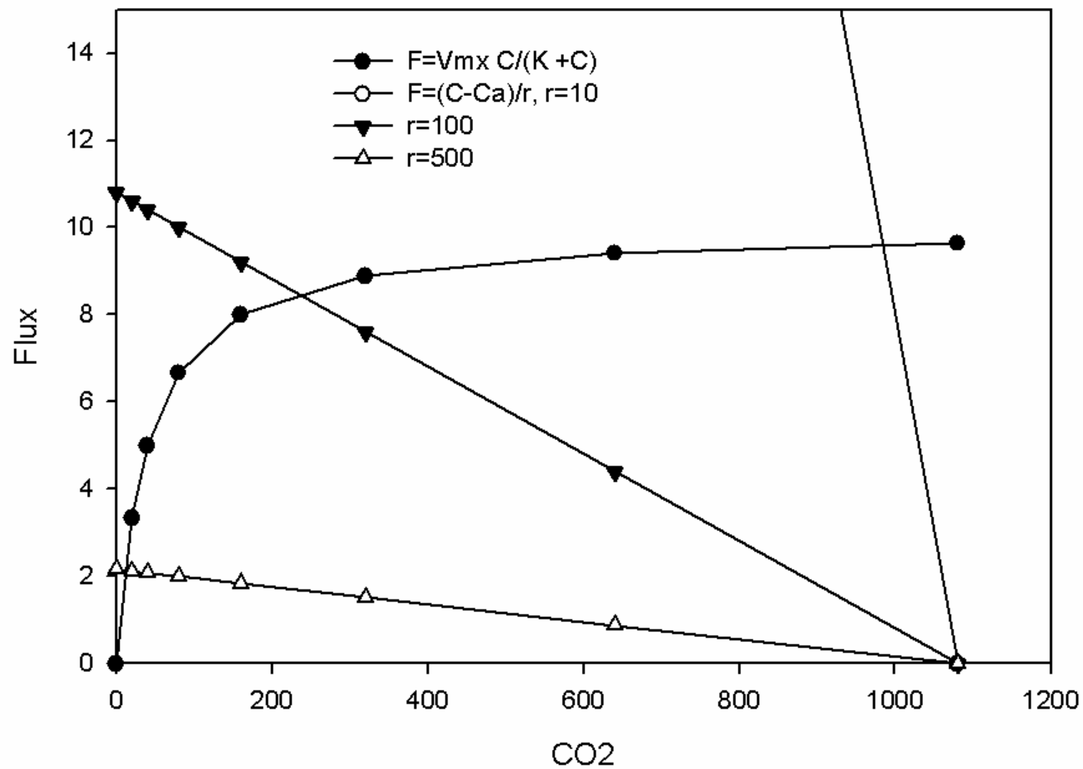




Important Ecosystem-Atmosphere Feedbacks

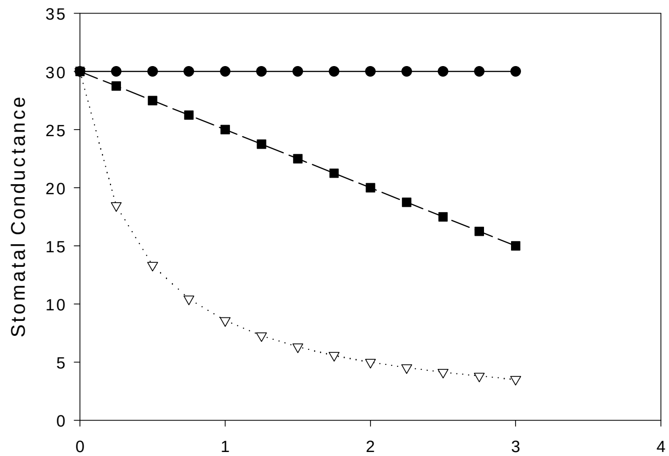
- Photosynthesis
  - As stomata close, diffusive supply does not meet demand
  - A draw-down the substrate [C] occurs and down-regulates the enzymatic flux
- Leaf Energy Balance
  - As stomata close, leaf temperature warms
  - convection is induced and radiative heat loss is increased
  - additional warming is hindered
- Leaf Transpiration
  - As stomata close, transpiration is restricted.
  - Leaf temperature increases, which increases saturation vapor pressure at the leaf and drives the leaf to air gradient, which Up Regulates Transpiration
  - The reduction in transpiration reduces the vapor pressure deficit of the surrounding air, which reduces stomatal conductance
- Soil Respiration
  - Recent photosynthesis is translocated to Rhizosphere and Up-Regulates Microbial Decomposition

Supply Demand Curves



$$F = -\frac{C_a - C}{r} = \frac{V_{mx} C}{K + C}$$

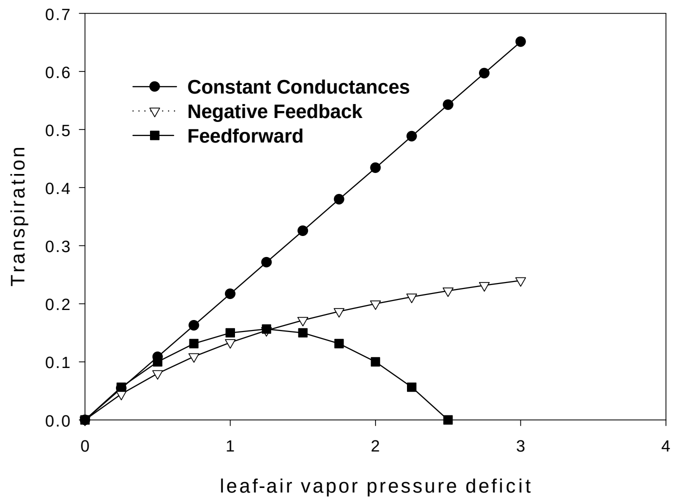
Feedbacks among Transpiration, Stomatal Conductance And Vapor Pressure Deficits



Feedforward

$$g_l = e - f\Delta e_l$$

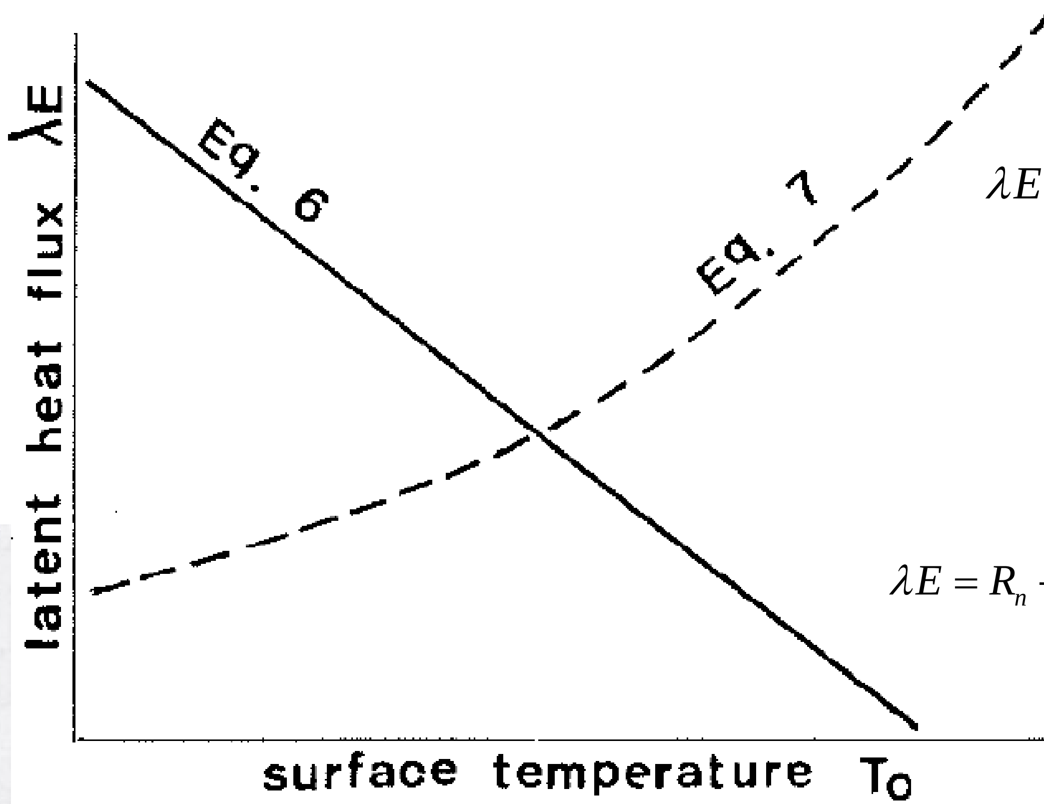
$$E = e\Delta e_l - f(\Delta e_l)^2$$



Feedback

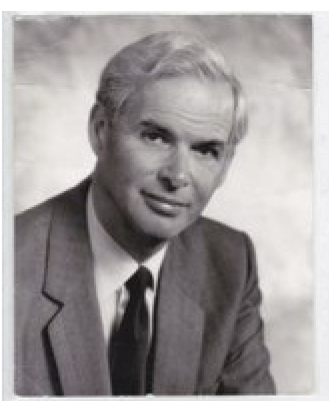
$$E = g_s(\Delta e_l)\cdot \Delta e_l$$

Conflicting Controls on Evaporation,
Supply of Water vs Demand by Available Energy



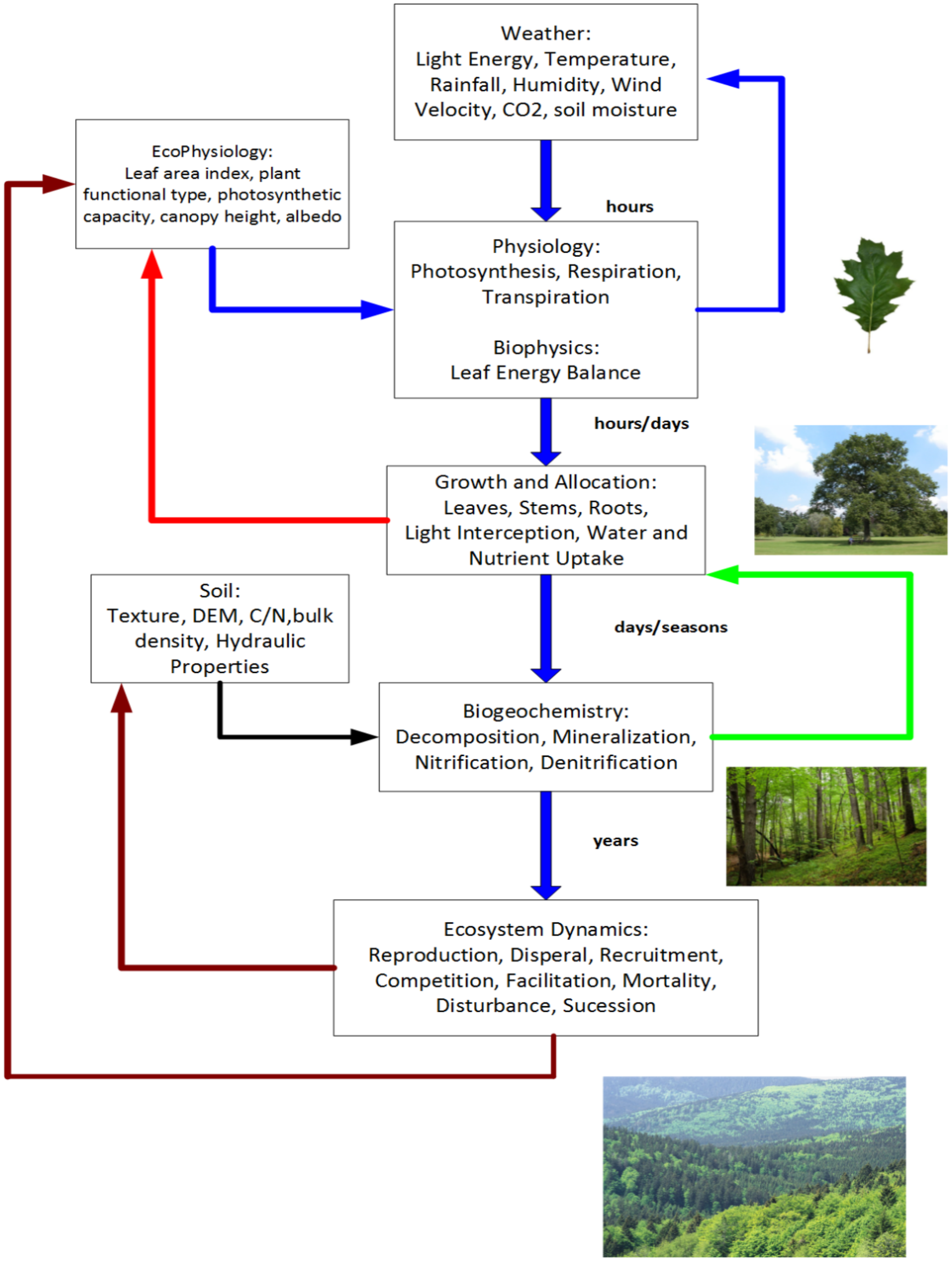
$$\lambda E = \rho \lambda \frac{q_s(T_0) - q_a}{R_w}$$

$$\lambda E = R_n - G - \rho C_p \frac{T_0 - T_a}{R_H}$$



Monteith, 1981 QJRMS

Biometeorological View of Ecosystem Ecology



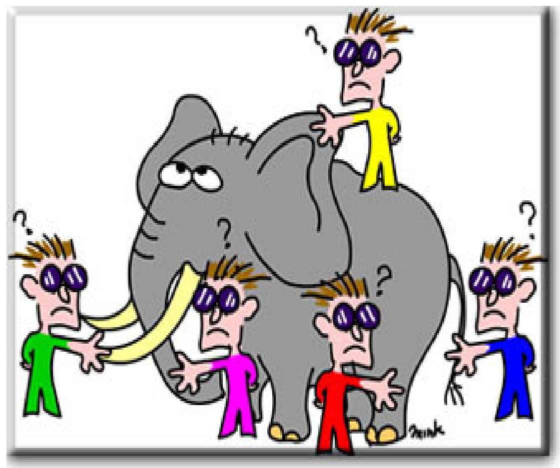
- •Numerous and Coupled
- •Biophysical Processes,
- •Fast and Slow

- •Numerous Feedbacks,
- •Positive and Negative

Multiple Methods To Assess Terrestrial Trace Gas Budgets with Different Pros and Cons Across Multiple Time and Space Scales

GCM Inversion Modeling

Remote Sensing/ MODIS



Eddy Flux Measurements/ Flux Networks, e.g. FLUXNET

Forest/Biomass /Soil Inventories

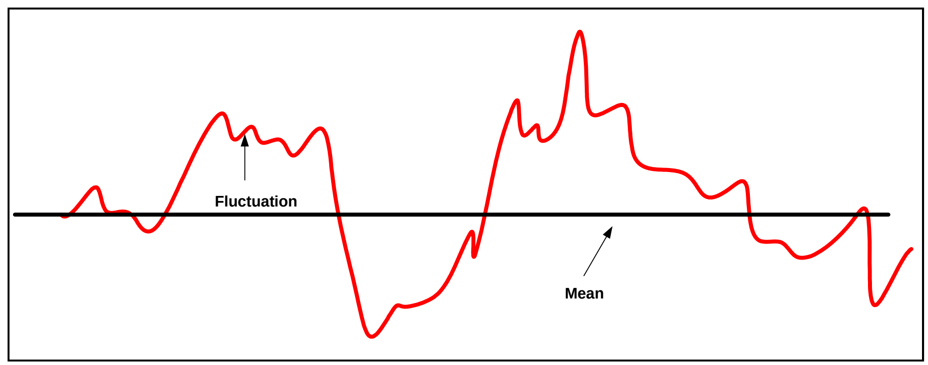
Physiological Measurements/ Manipulation Expts.

Biogeochemical/ Ecosystem Dynamics Modeling

Eddy Covariance Technique

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

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

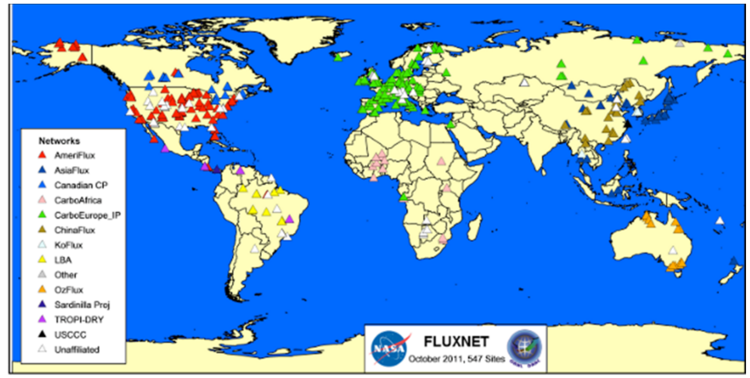


- Direct
- *In situ*
- Quasi-Continuous

Role of Flux Networks in Biogeosciences

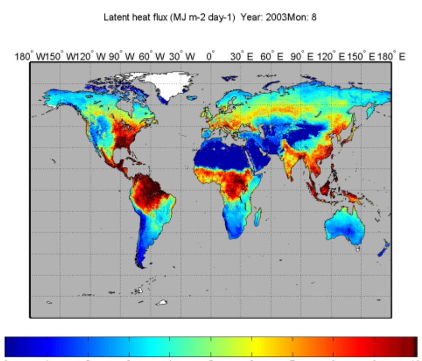
Eddy covariance flux system

Global network of flux towers



Database

Remote sensing and Earth system science model user community



What Information Do Networks of Flux Towers Produce?

- Groups of towers at the landscape, regional, continental, and global scales allow scientists to study a greater range of climate and ecosystem conditions
  - Dominant plant functional type (Evergreen/Deciduous Forests, Grasslands, Crops, Savanna, Conifer/Broadleaved, Tundra)
  - Biophysical attributes (C3/C4 Photosynthesis; Aerodynamic Roughness; Albedo; Bowen Ratio)
  - Biodiversity
  - Time since the last disturbance from fire, logging, wind throw, flooding, or insect infestation
  - The effect of management practices such as fertilization, irrigation, or cultivation or air pollution
- A global flux network has the potential to observe how ecosystems are affected by, and recover from, low-probability but high-intensity disturbances associated with rare weather events.

Lessons Learned from Flux Studies

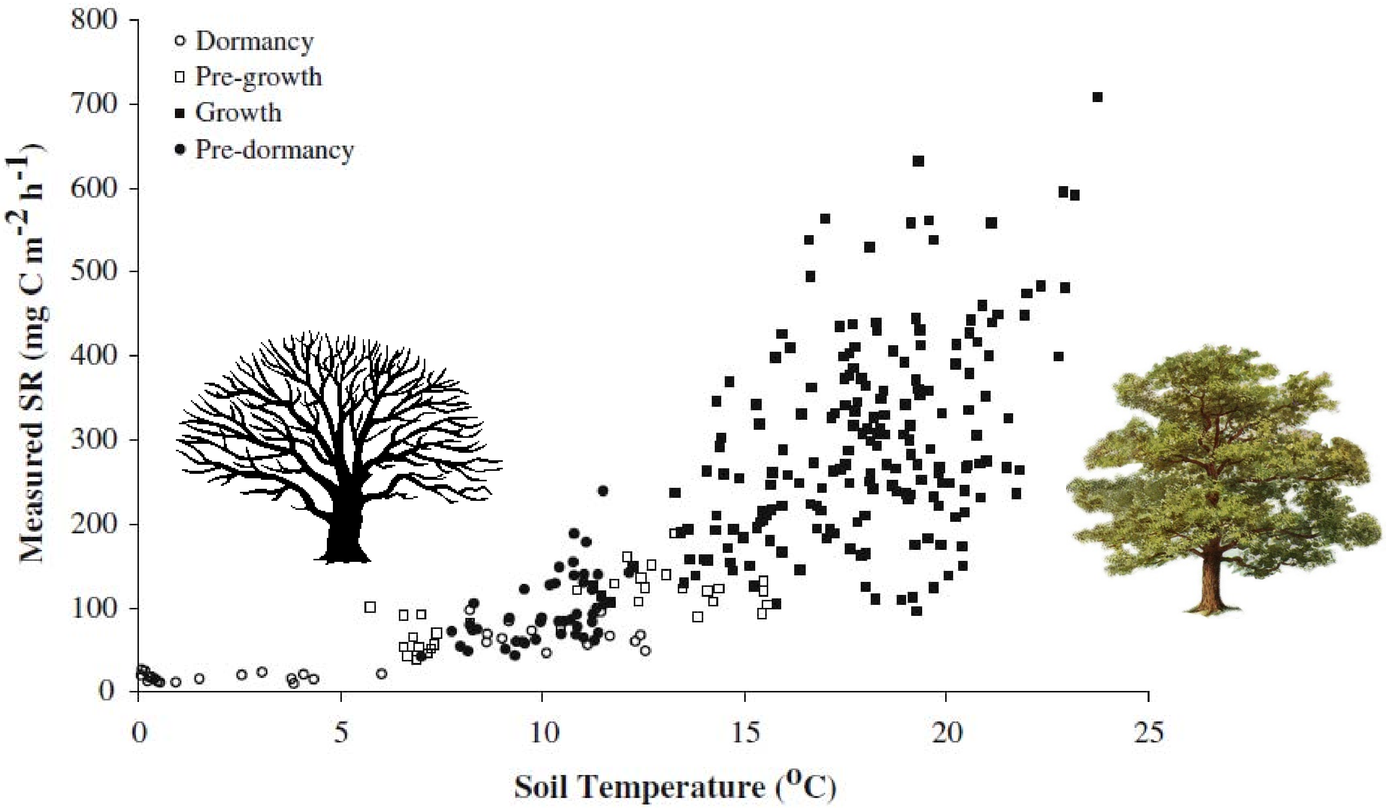
Iron House School in 1896

Emergent Scale Properties

- Leads, Lags and Pulses
  - Photosynthesis Drives Microbial Activity
  - Rain Induces Pulses in Soil Respiration
- Up Regulation
  - Light response curves, diffuse light
  - Photosynthesis Drives Microbial Activity
  - Acclimation of Photosynthetic Response to Temperature
- Feedbacks
  - Soil Temperature Drives Phenology, Phenology Drives Net Carbon Flux
  - Water Use Efficiency, Stomatal Conductance and Vapor Pressure Deficits
  - Land Use (Grass/Forest; Evergreen/Deciduous) on Surface Temperature and Mass and Energy Exchange
- Upscaling
  - Footprints Define VOC Fluxes in Mixed Forest and for Microbially-Mediated Fluxes (e.g. methane)

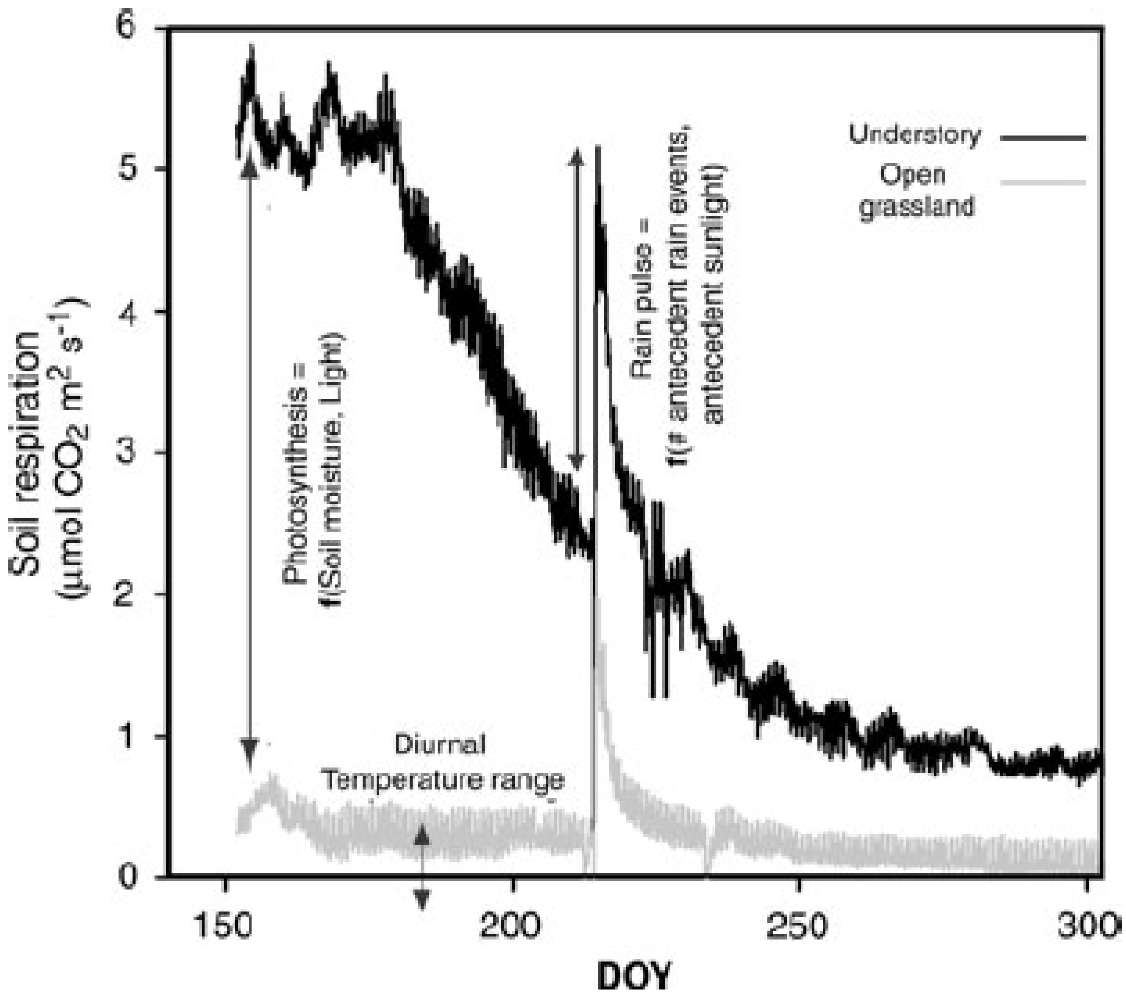
Effects of Meteorology on Fluxes

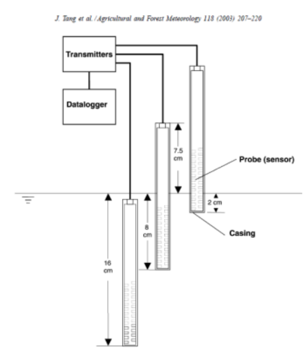
Classical View of Soil Respiration, F = f(T)
Does Photosynthesis drive Microbial activity?



deForest et al 2006 Int J Biomet

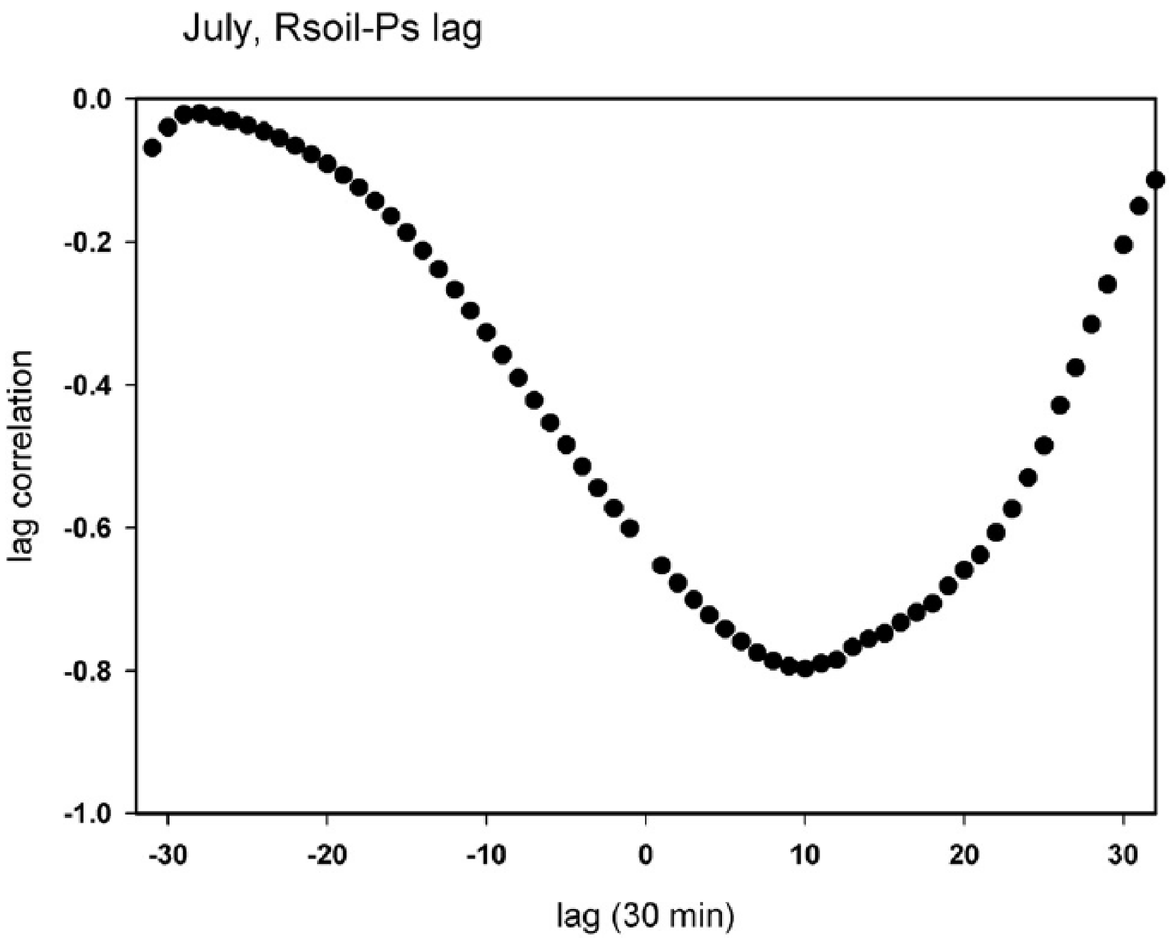
Photosynthesis Enhances Soil Respiration





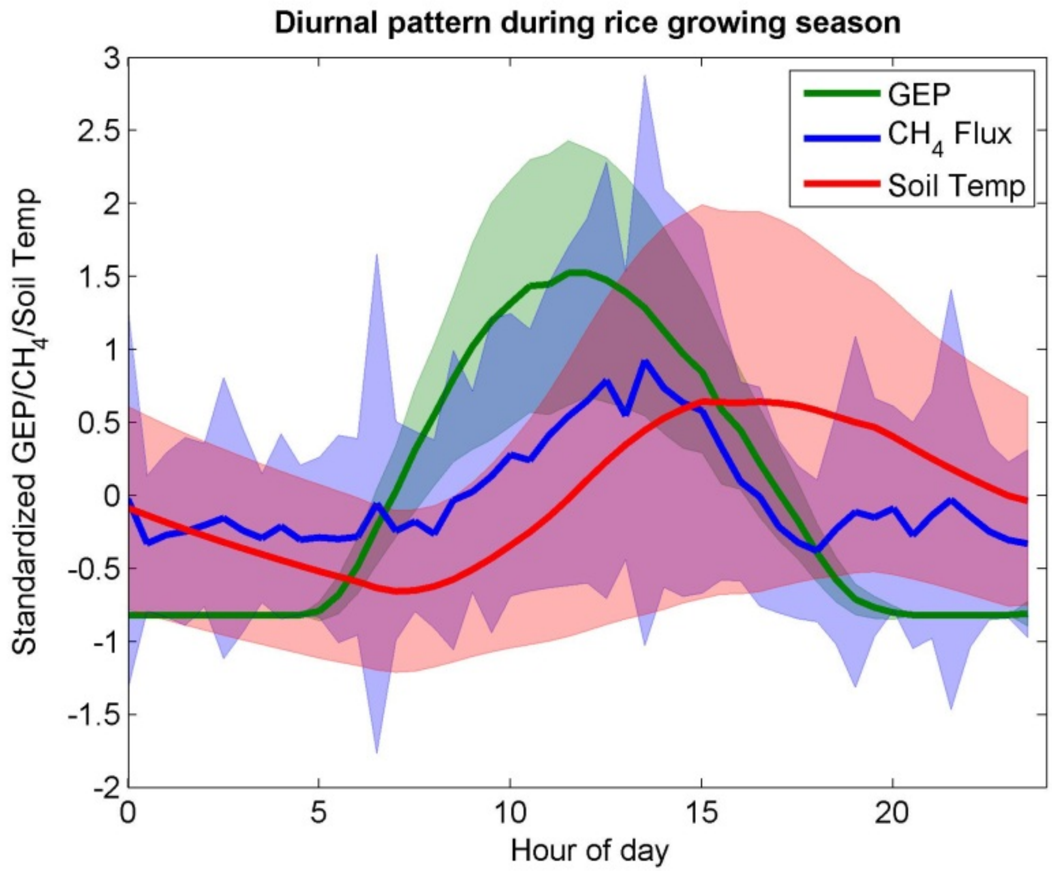
Baldocchi et al. JGR Biogeoscience, 2006

Translocation of C to the Rhizosphere Causes a 5 hour Lag in the Enhancement in Respiration



Baldocchi et al. JGR Biogeoscience, 2006

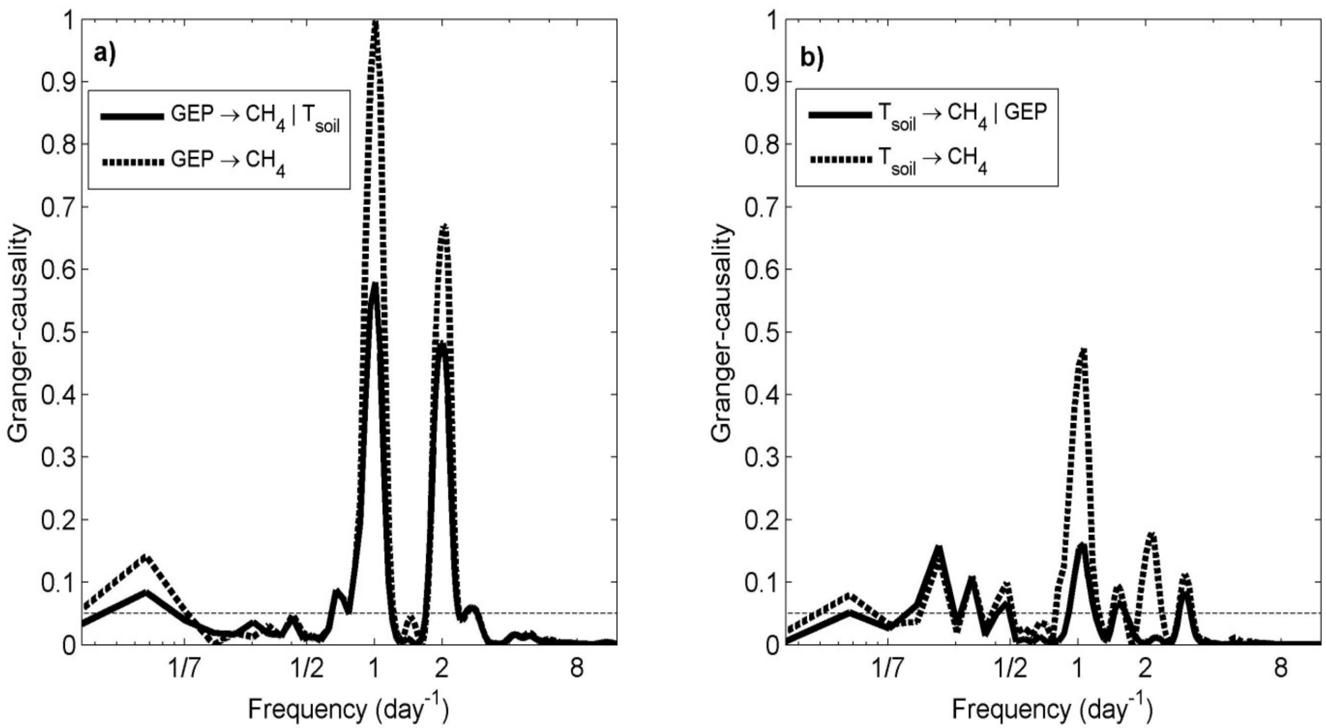
Photosynthesis leads Methane Fluxes, which lead Temperature
Recently Fixed and More Labile C feeds Microbes



Hatala et al, GRL 2012

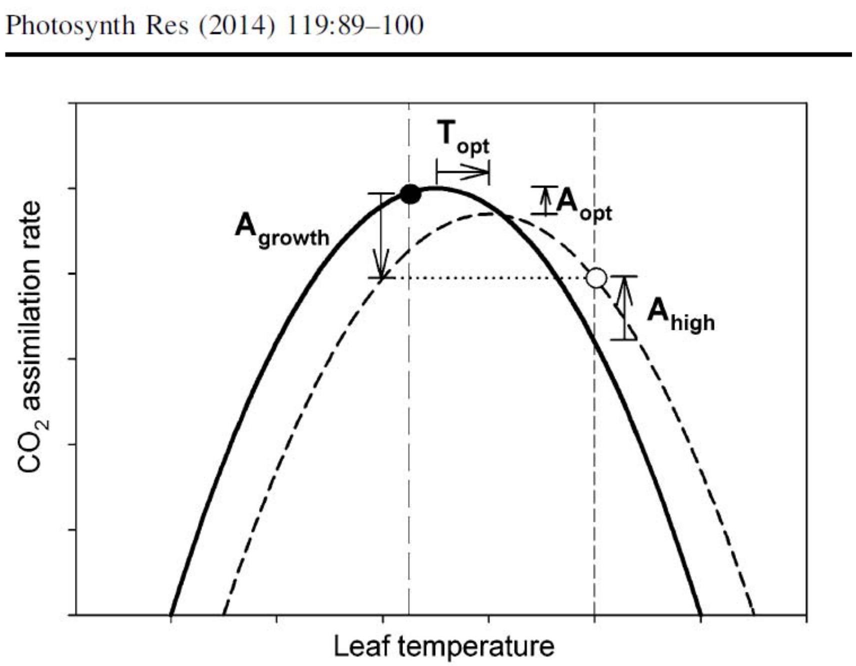
Let's Avoid Hand-waving Arguments

Granger Causality, an Auto Regressive Tool for Quantifying Cause and Effect

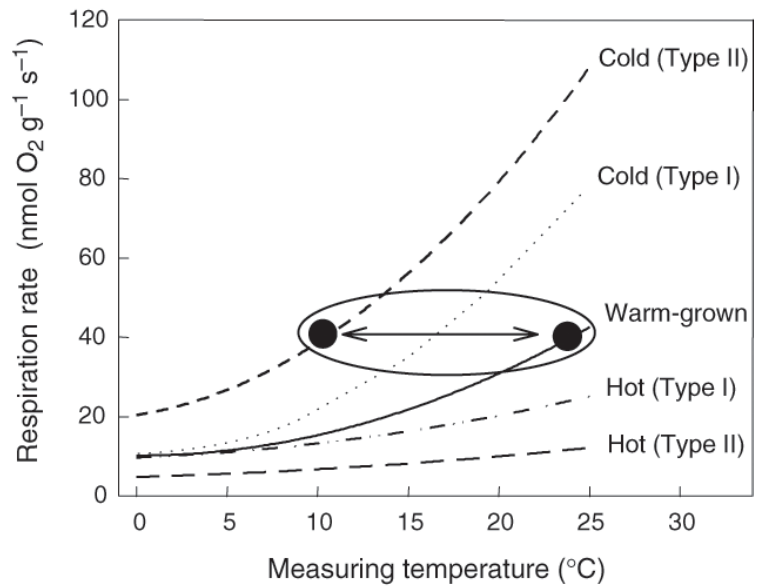


Hatala et al, GRL 2012

Acclimation

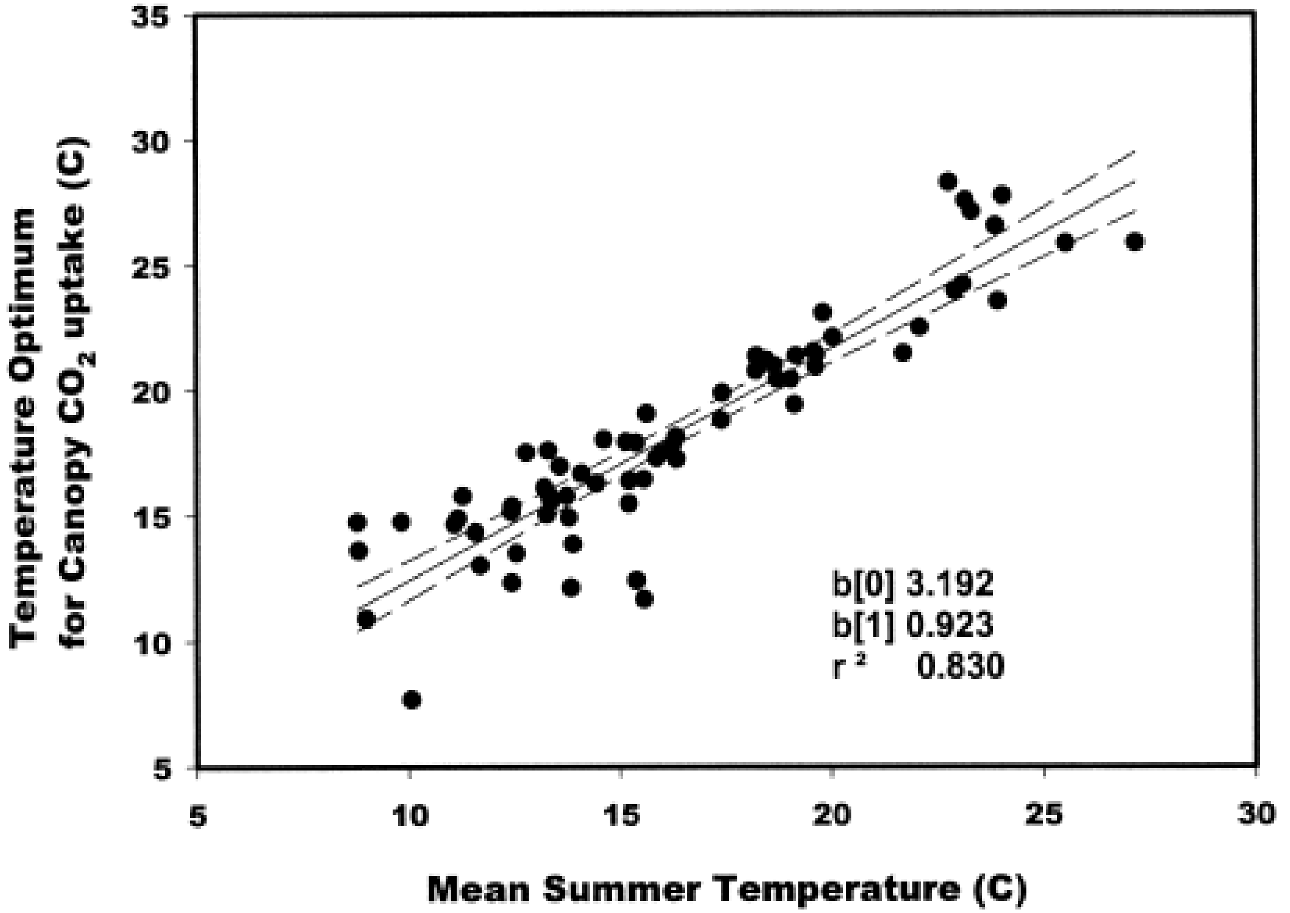


Way and Yamori 2014



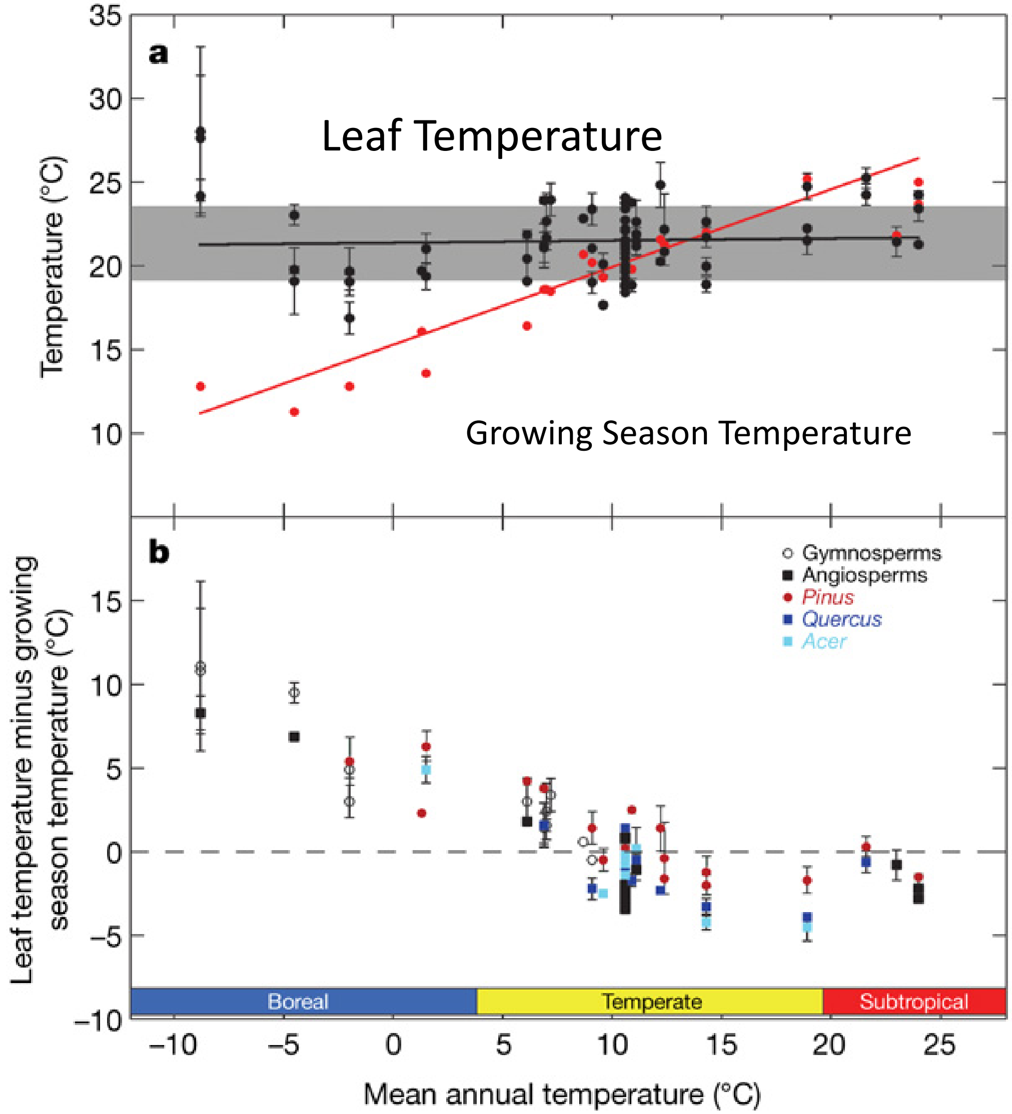
Atkin 2005 Func Plant Biol

Optimum Temperature for Canopy Photosynthesis Acclimates with Summer Growing Season Temperature



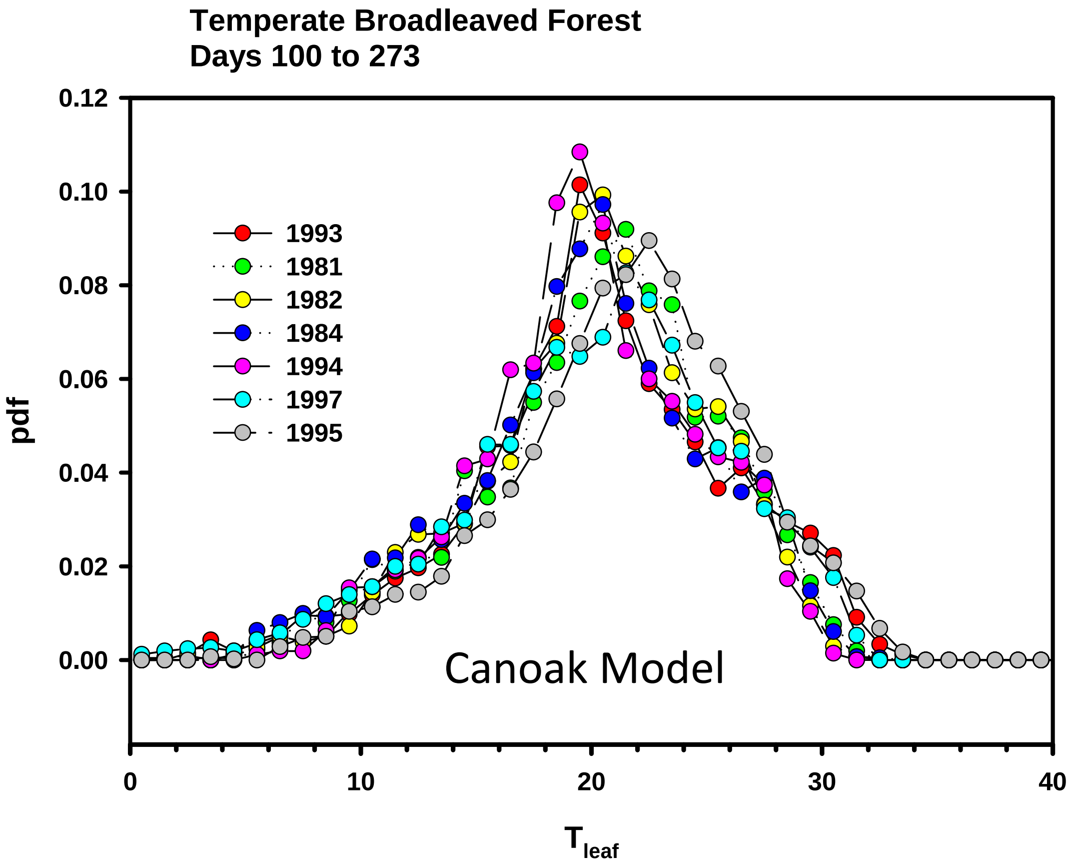
Baldocchi et al. 2001 BAMS

Isotopes Infer Leaf Temperatures of Tree Leaves are Constrained, ~ 21 C



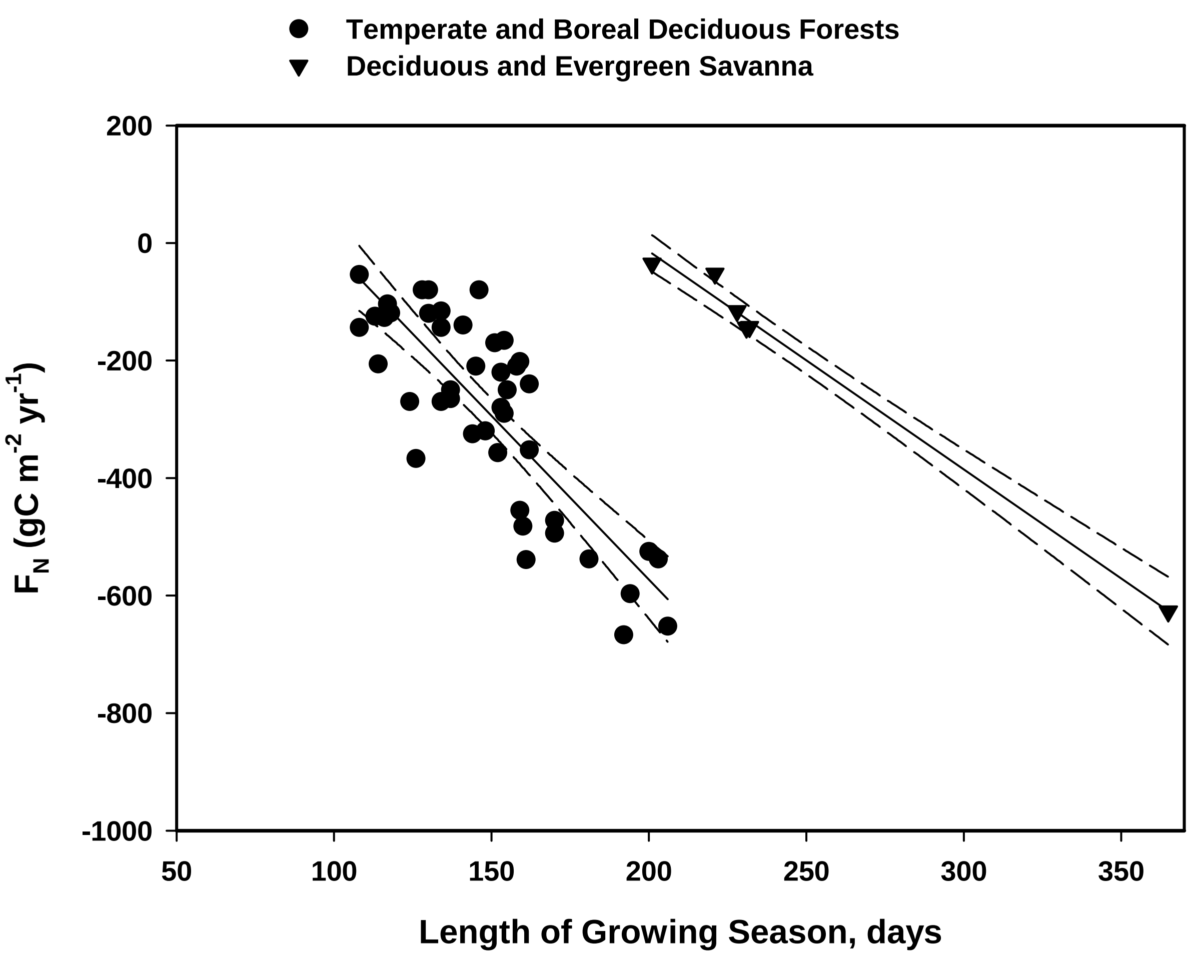
Helliker and Richter 2008 Nature

Leaf Temperature, Modeled with CANOAK, as a Central Tendency near 20 C



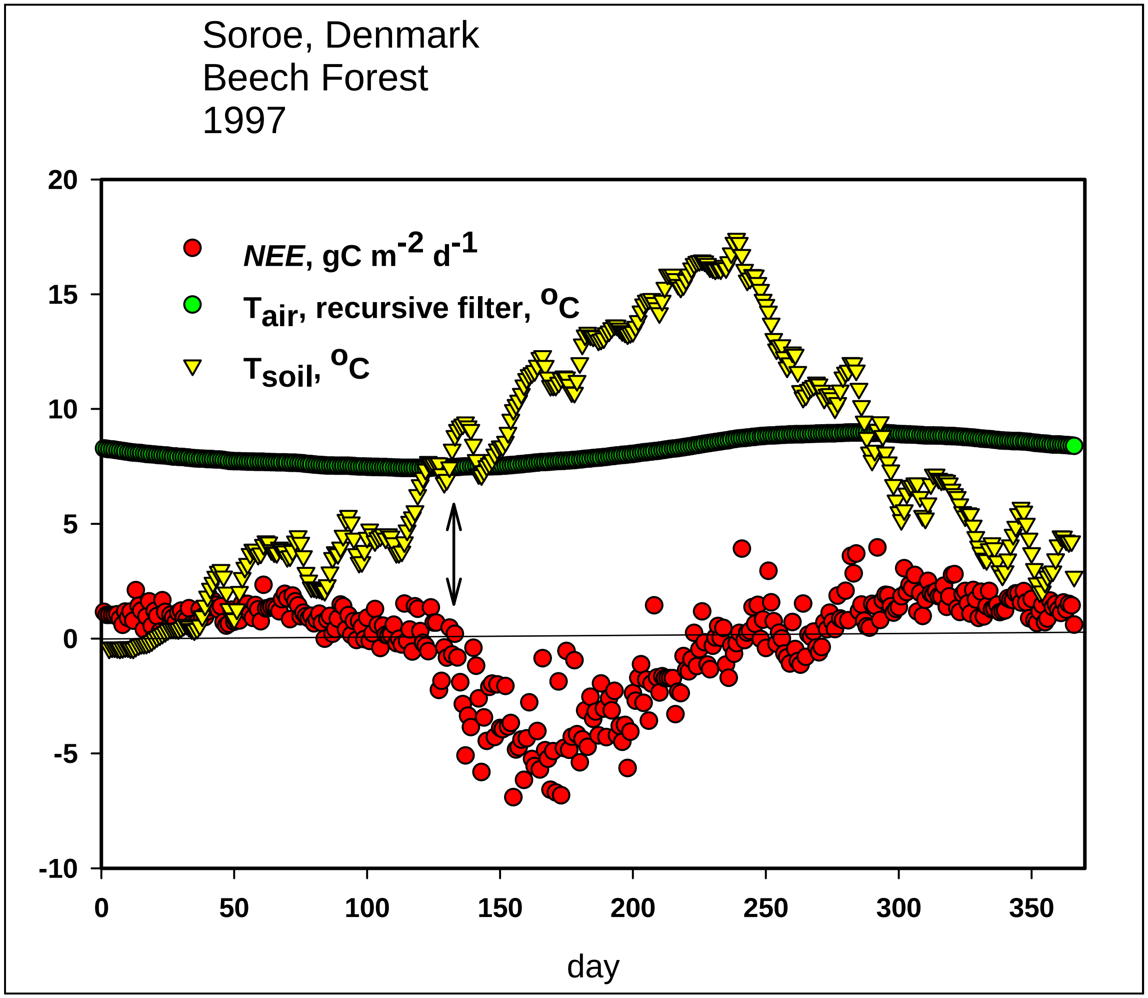
? Plants Adjust Leaf Energy Balance to Operate near Optimal Temperature?

Net Ecosystem Carbon Exchange Scales with Length of Growing Season



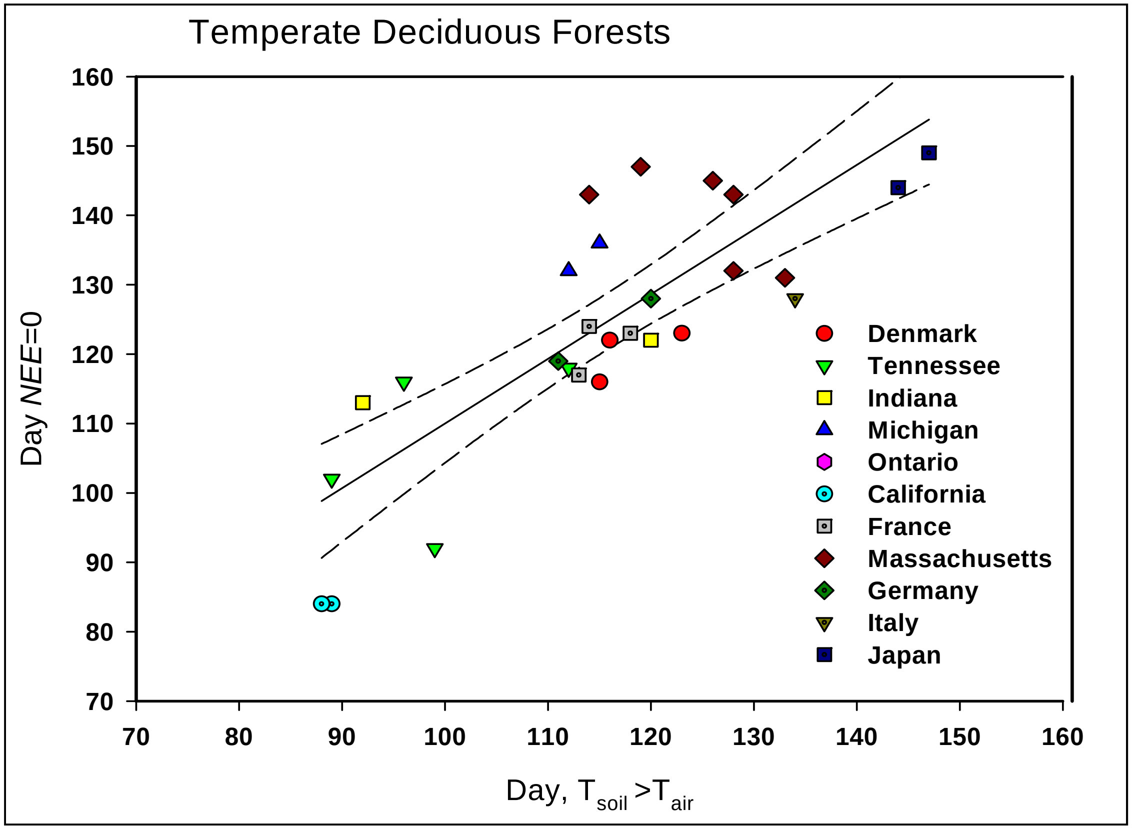
Baldocchi, Austral J Botany, 2008

Soil Temperature:
An Objective Indicator of Phenology??



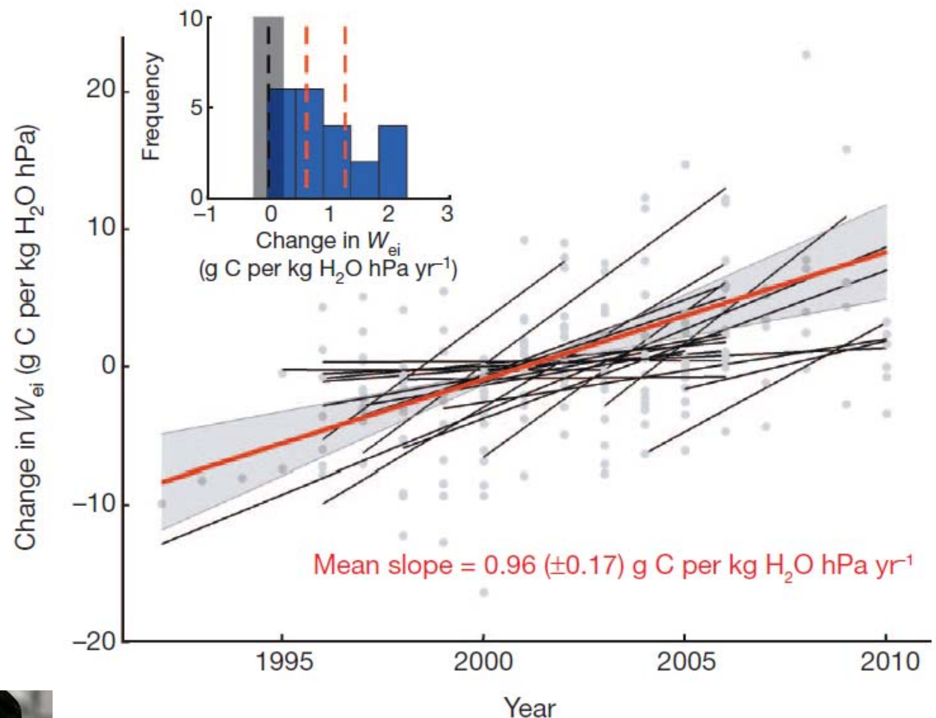
Data of Pilegaard et al.

Soil Temperature:
An Objective Measure of Phenology, part 2

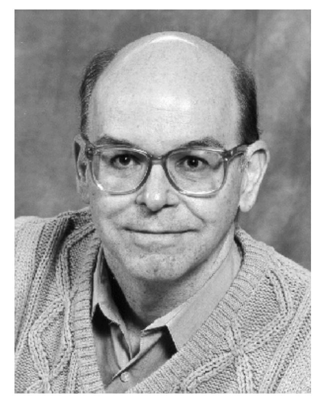


Baldocchi et al. Int J. Biomet, 2005

Is Water Use Efficiency Trending with CO2?
Conceptually, Stomatal Conductance Decreases with CO2, Thereby Increasing WUE
Has CO2 Increased Enough to Affect WUE?



Keenan et al. 2013 Nature

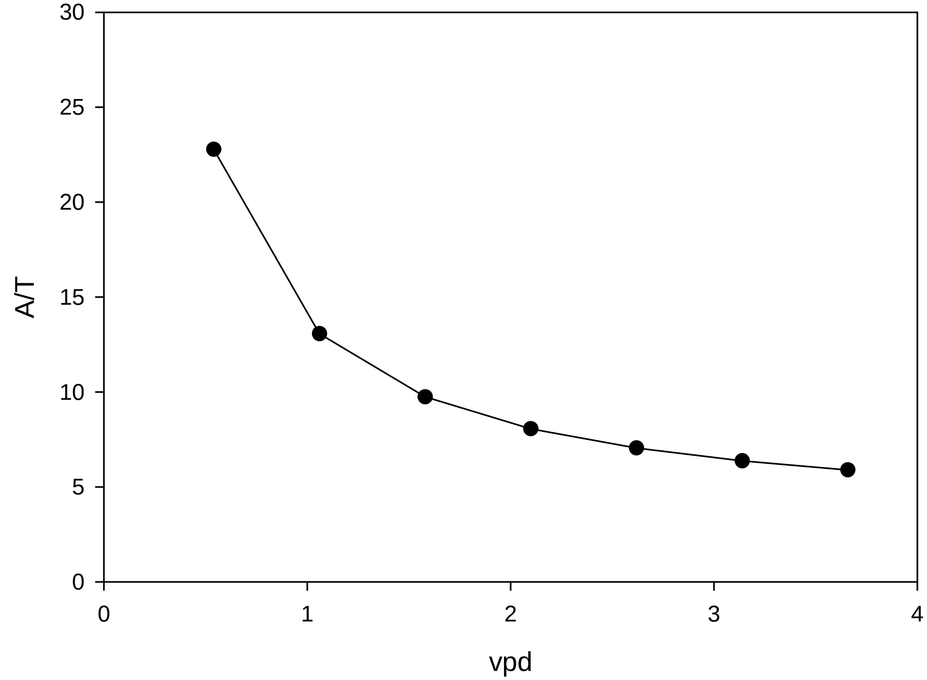


John Norman
'Watch for Confounding Factors'

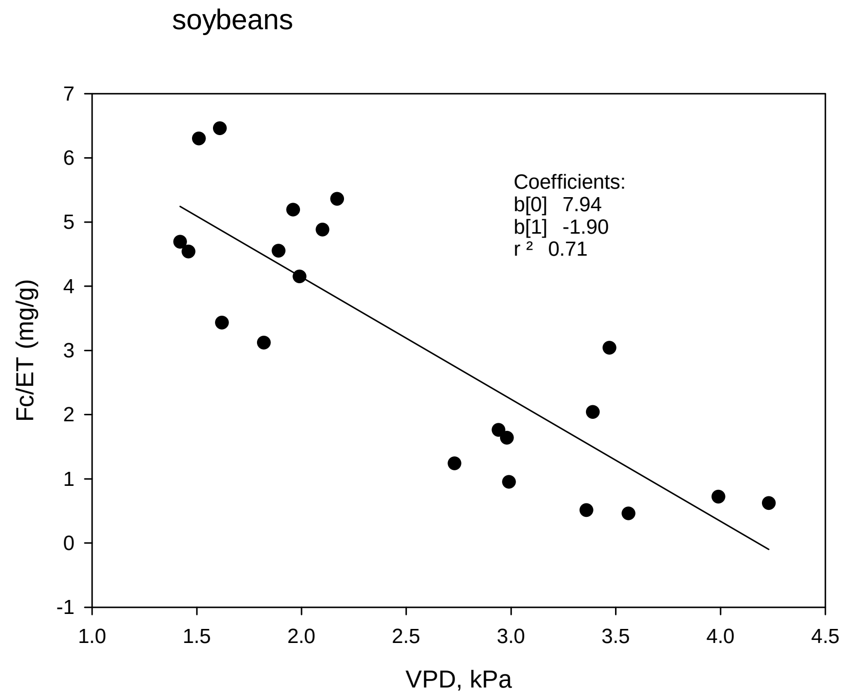
Water Use Efficiency, A/T, Decreases with Increasing Vapor Pressure Deficits: Theoretically and Experimentally

Ralph Slatyer

$$\frac{A}{T} \approx \frac{k}{vpd}$$

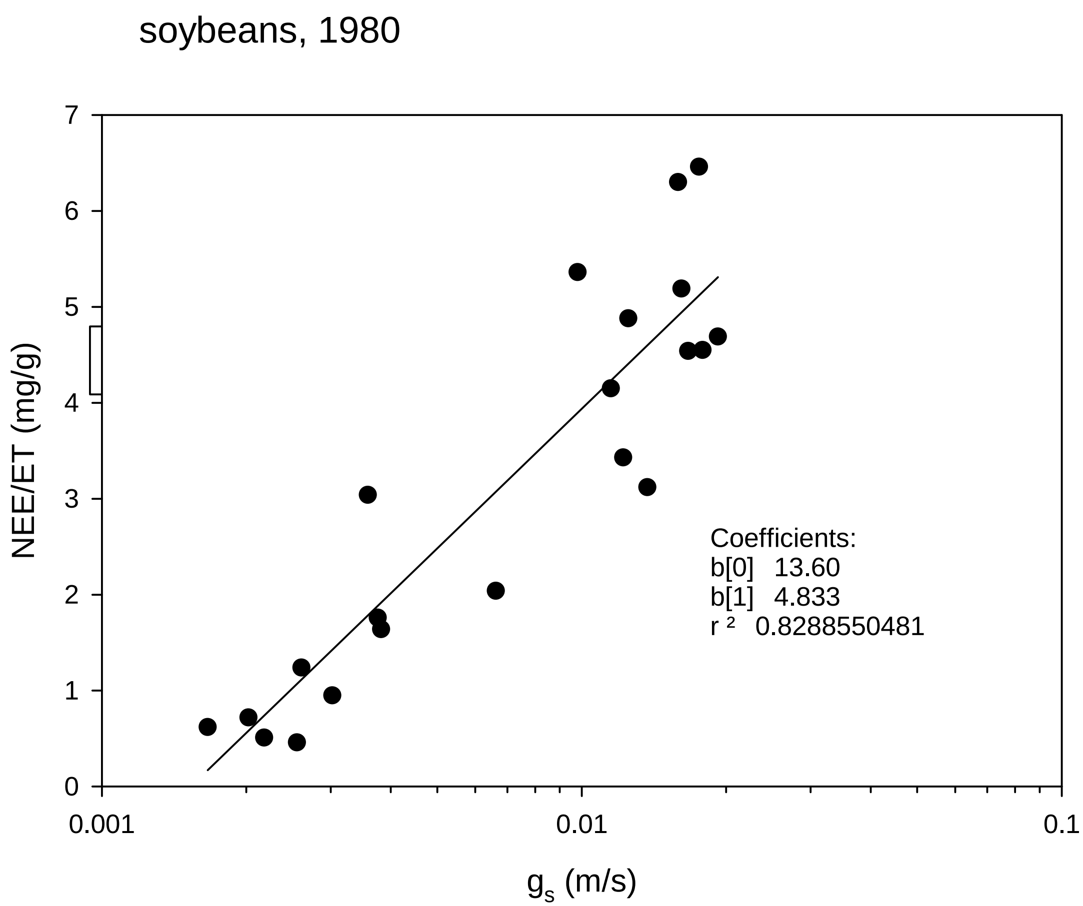


Canoak
Baldocchi and Harley, 1995, PCE



Baldocchi et al. 1984 AgForMet

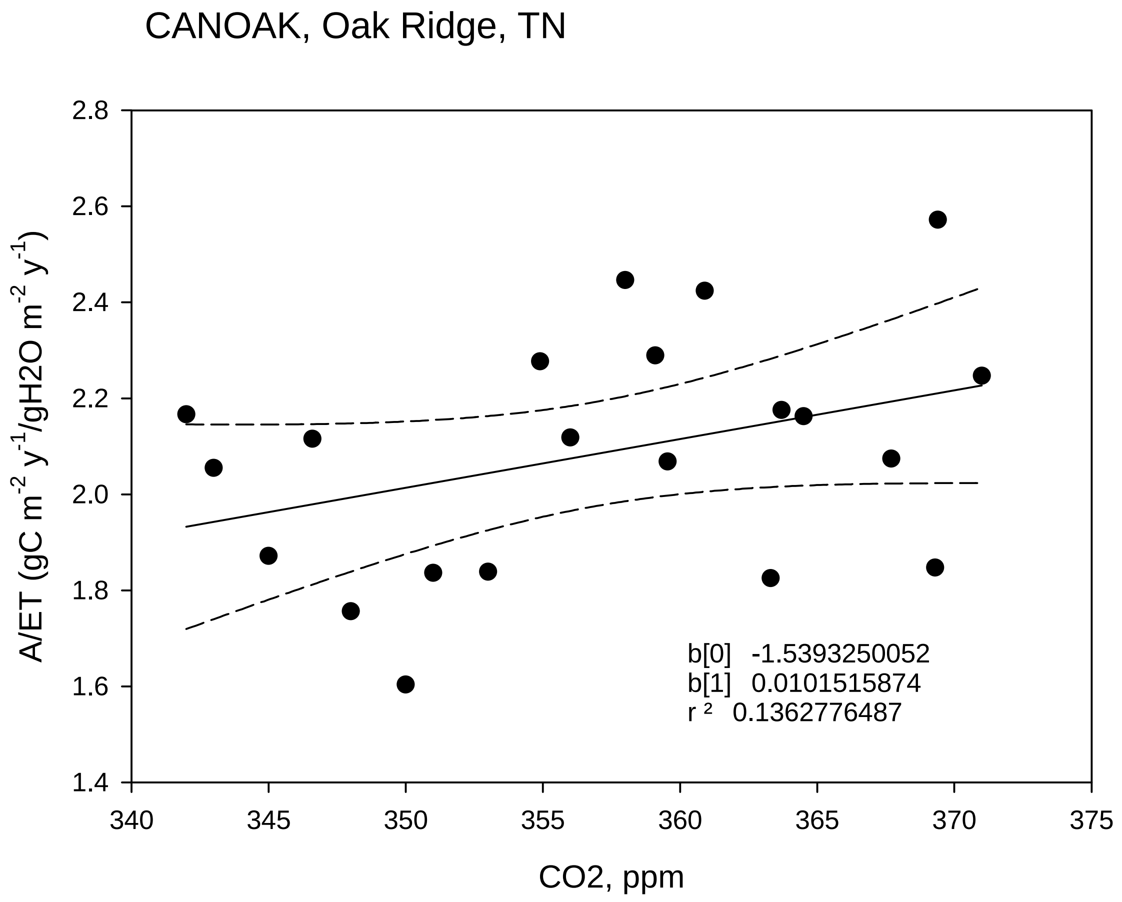
With Drought, a Reduction in Stomatal Conductance Reduces ET and WUE; Reduced ET produces an Increase in VPD



Baldocchi et al 1984, AgForMet

What Happens over 20 years across a Wider Range of CO_2?

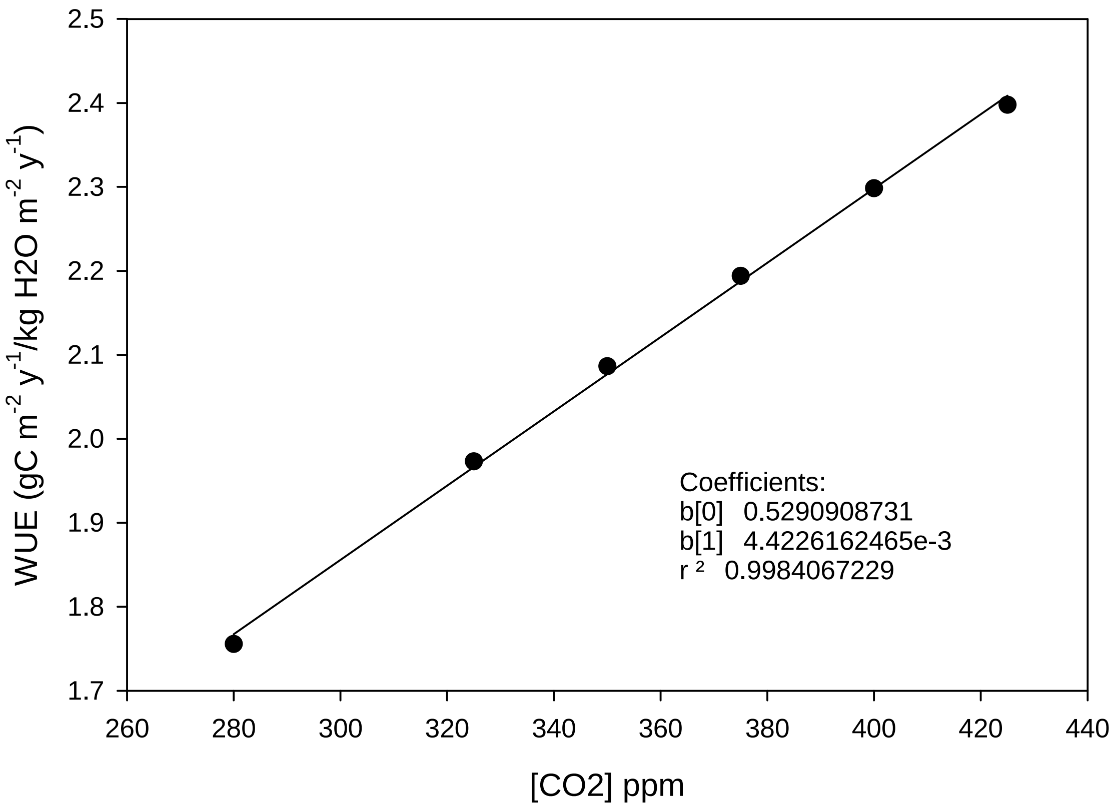
WUE (A/ET) and CO_2, CANOAK



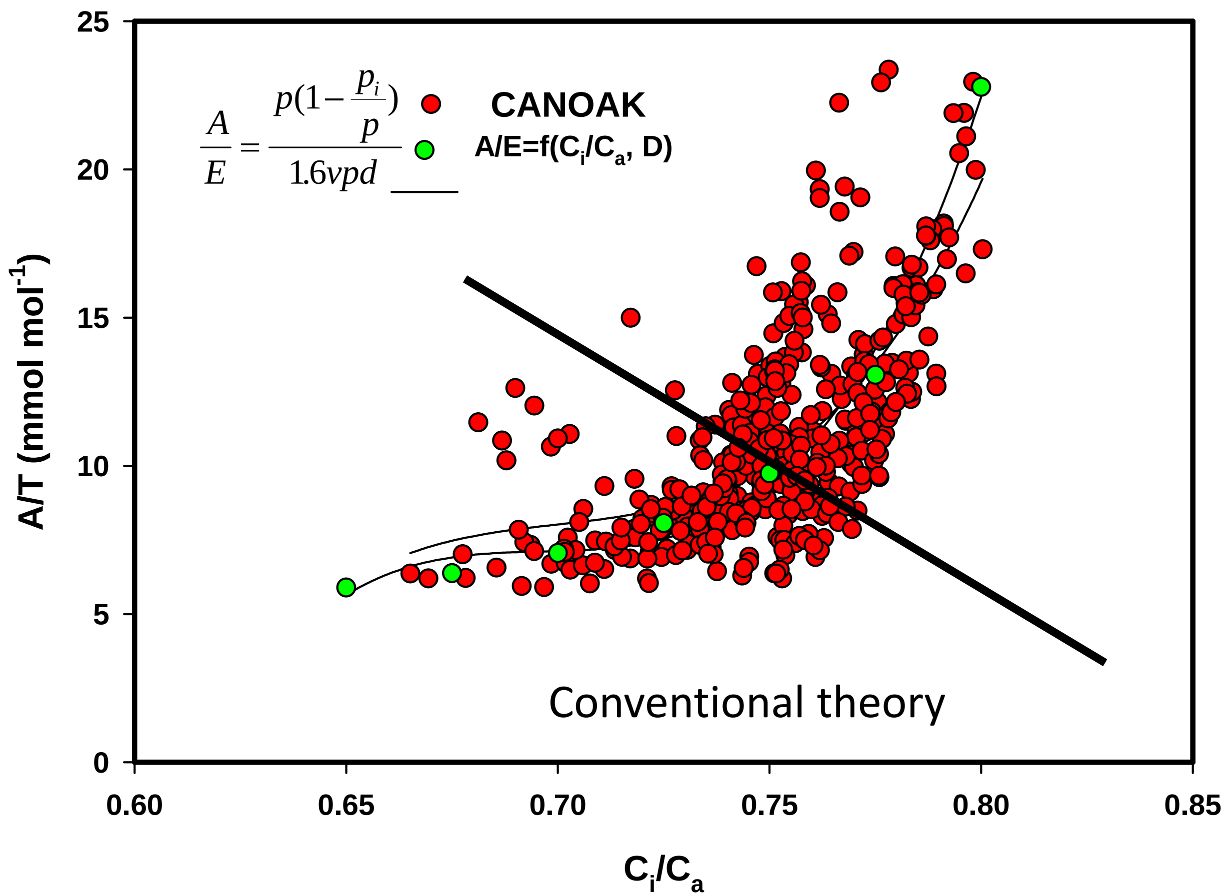
Computations using Meteorological Data, 1981-2001

Using Model to Isolate CO2 Forcing from Meteorology, Physiological Stress and Growth

CANOAK, 1982 Meteorology, Oak Ridge, TN



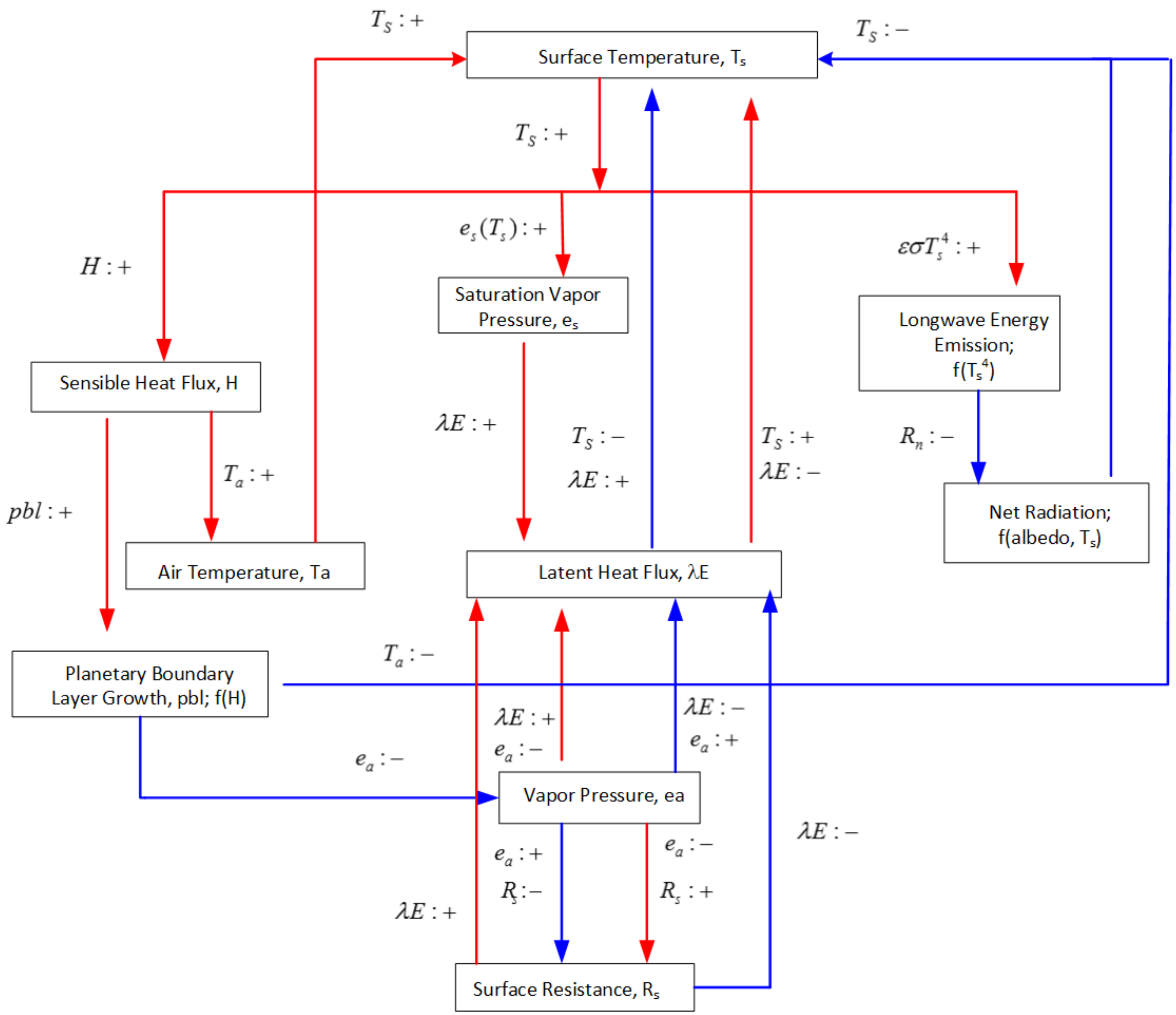
Re-Interpreting WUE from Stable Isotopes: with Drought both VPD and Ci/Ca change



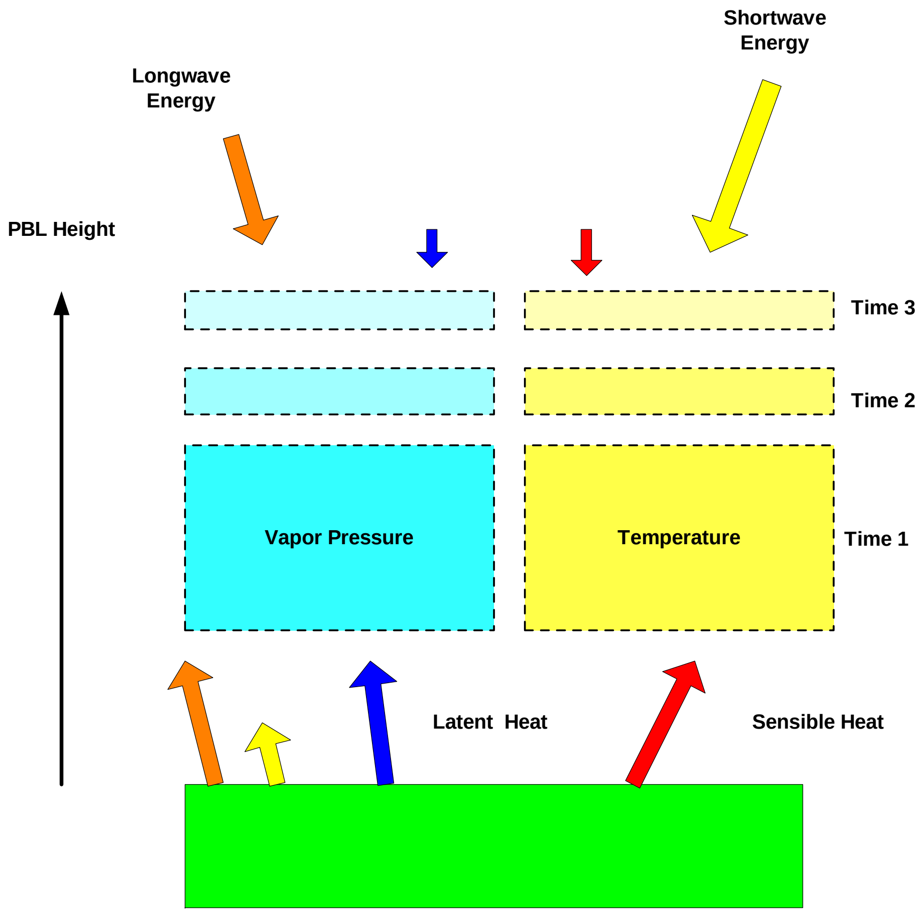
Effects of Surface Layer-Boundary Layer Interactions

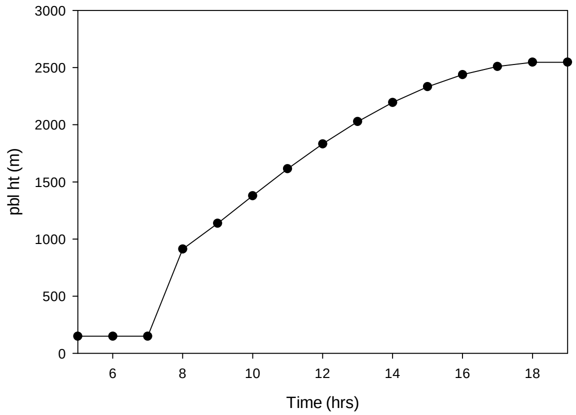
CzechGlobe 250 m ICOS tower

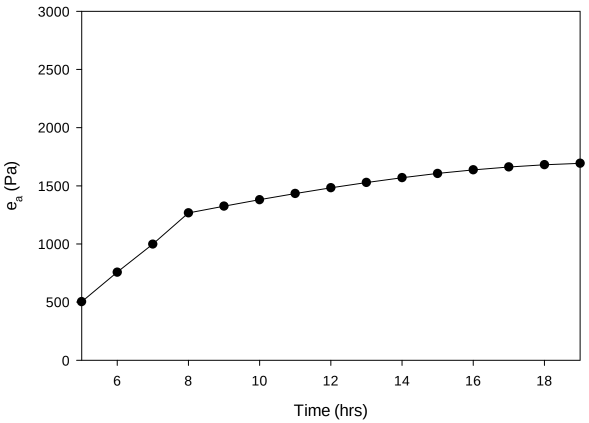
What Happens when you Warm the Surface?



To Understand Land-Atmosphere Interactions, We CANNOT forget PBL Feedbacks

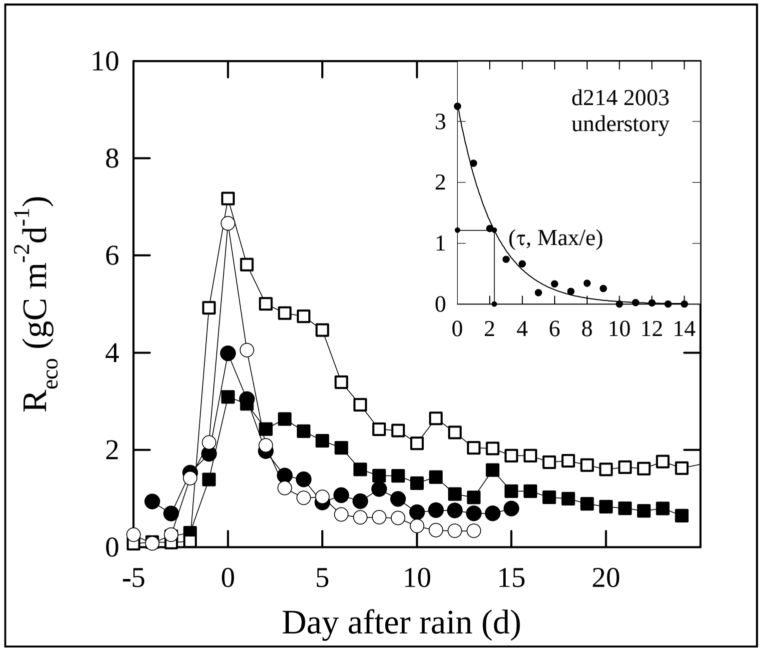




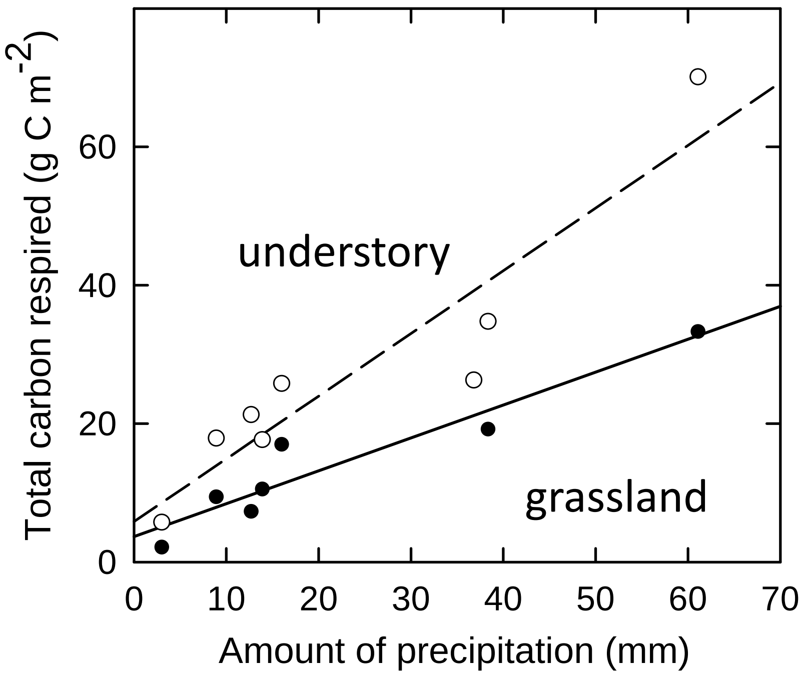


Rain Induces of Pulses in Soil Respiration

Role of Subsequent Pulses and Labile C



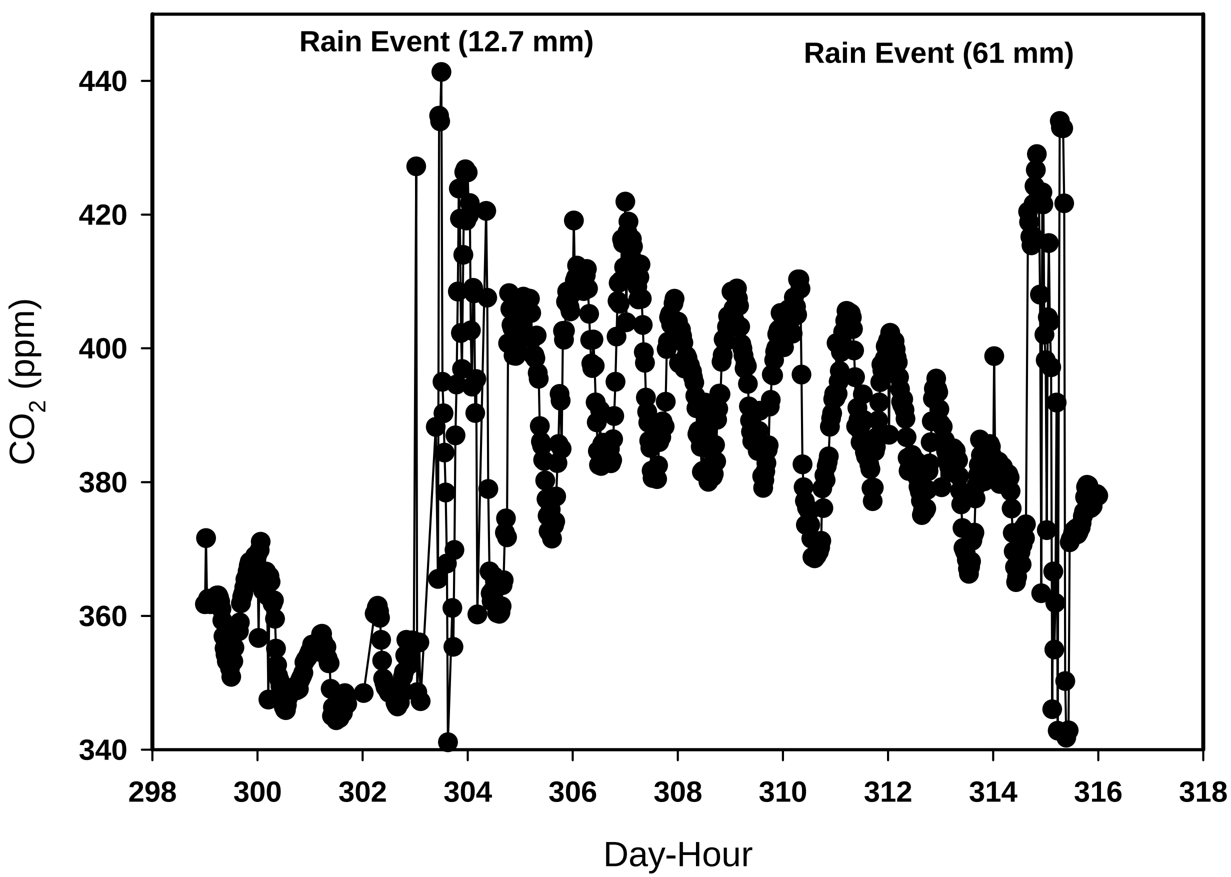
Role of Photodegradation



Xu, Baldocchi, Tang, 2004
Global Biogeochem Cycles

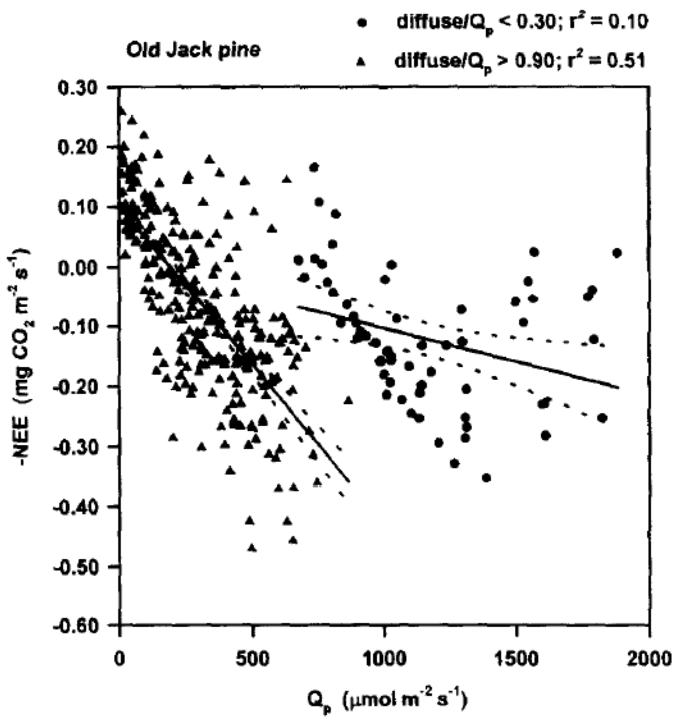
Rise In [CO2] in PBL Following Rain-Induced Respiration Pulse

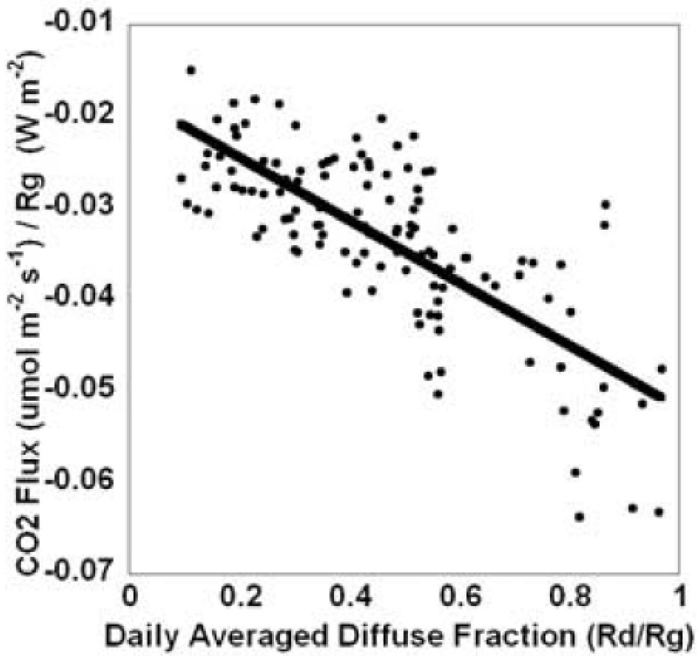
2001



How Sky Conditions Affect Net Carbon Uptake?

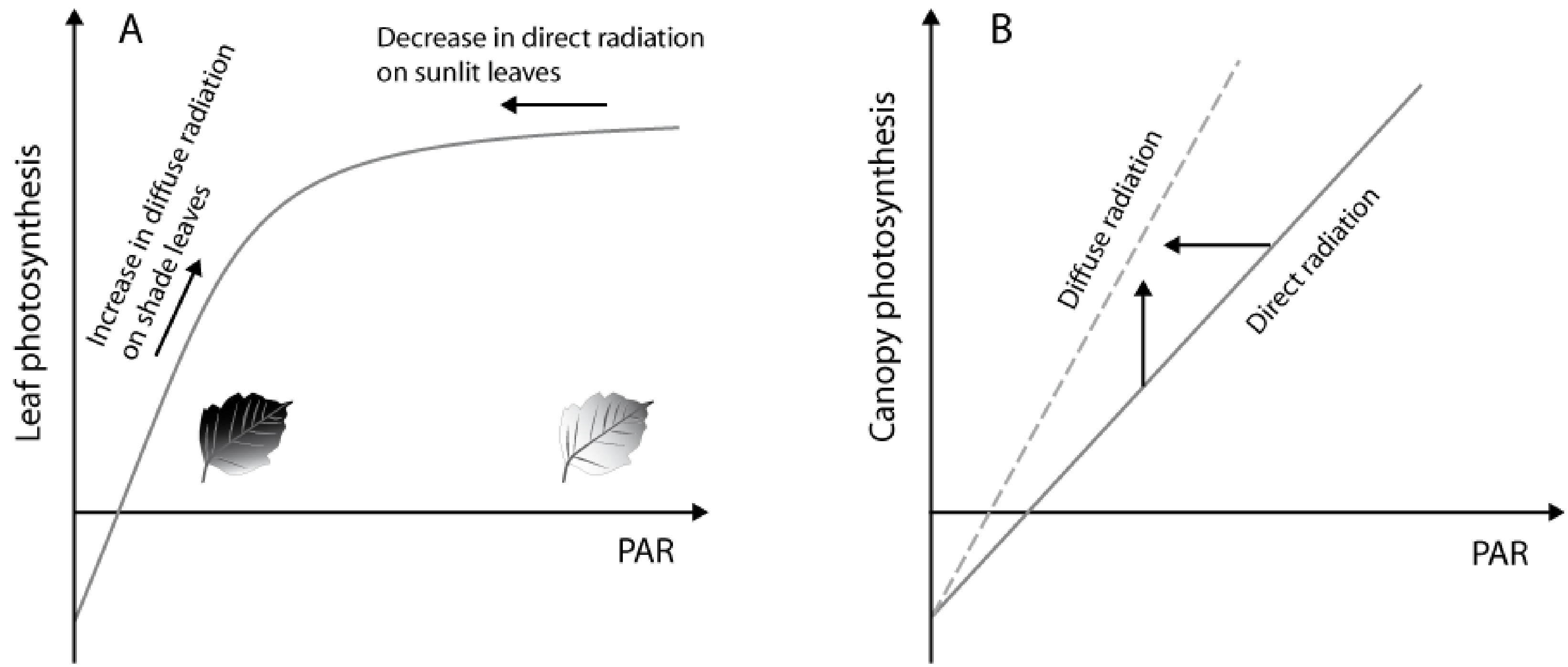
D.D. Baldocchi et al. / Agricultural and Forest Meteorology 83 (1997) 147–170



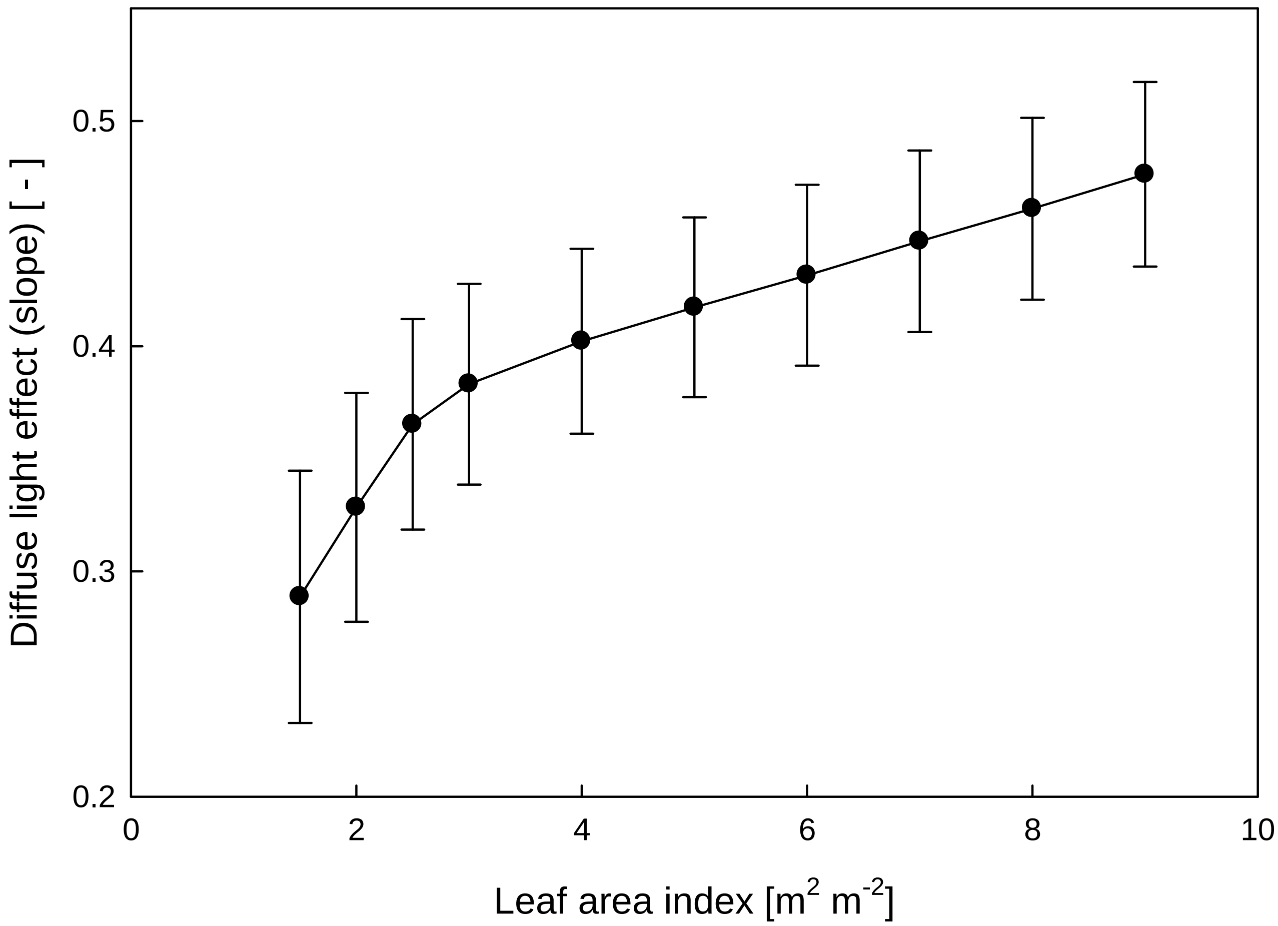


Niyogi et al. 2004 GRL

The Functioning of the Canopy is Different from that of Leaves



Diffuse Enhancement of Photosynthesis is function of LAI



Knohl and Baldocchi, 2008 JGR Biogeosci

Effects of Land Use on Fluxes

On the Differential Advantages of Evergreenness and Deciduousness in Mediterranean Oak Woodlands: A Flux Perspective

Pros and Cons of Being Evergreen

- Advantages
  – Longer Photosynthesis period
  – Lower Amortization Cost for Leaf Construction
  – Has ecological advantage on nutrient poor soils
  – Lower hydraulic conductance
- Disadvantages
  – Must withstand herbivory by producing leaves with defense compounds
  – Must withstand occasional frosts and freezing
- Adaptive Mechanisms
  – Leaves are constructed with less nitrogen, with a cost of lower photosynthetic rates and lower rates of nitrogen losses
  – Xylem architecture withstands low water potentials and avoids embolisms

Pros and Cons of being Deciduous

- Advantages
  - Avoids winter stress periods when it is cold and photosynthetic potential is low
- Disadvantages
  - Shorter photosynthetic period

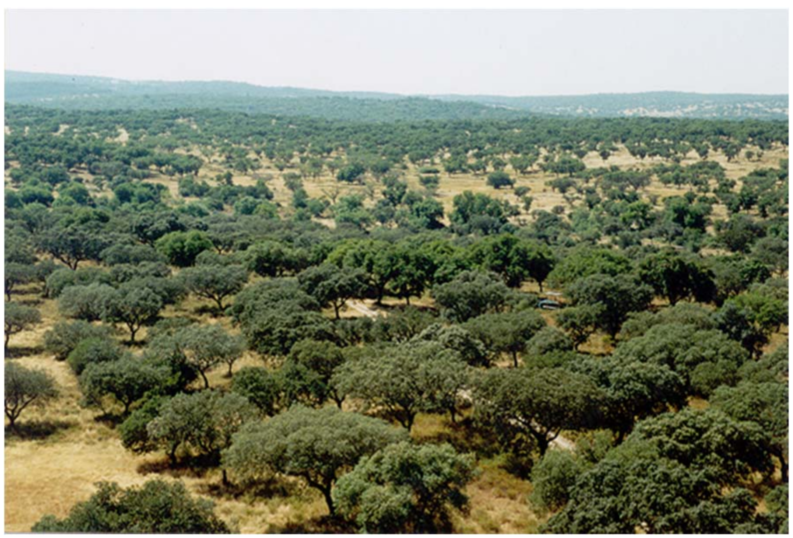
- Adaptive Mechanisms
  - Produce leaves with more N and higher rates of photosynthesis

Evergreen Sites

Deciduous Sites

Puechabon, FR

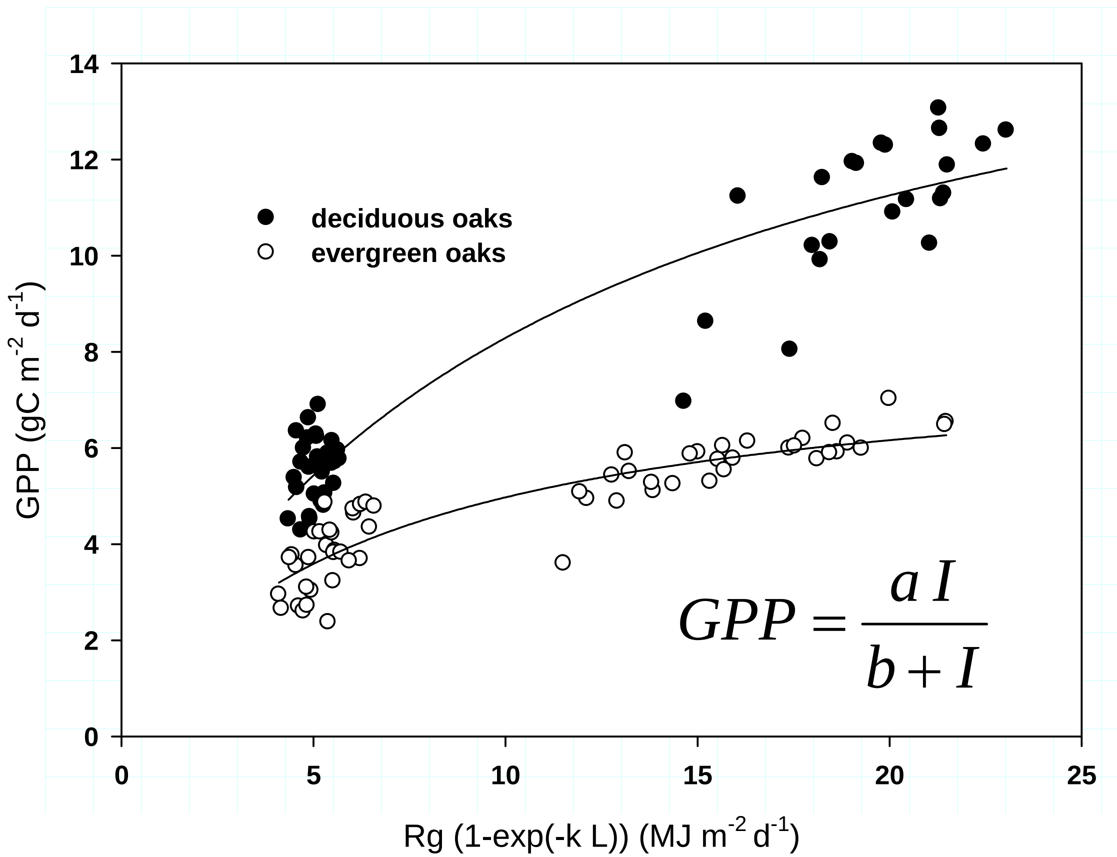
Roccaraspampani, IT



Evora, PT

Ione, CA

Light Use Efficiency is Greater over Deciduous Oaks, Regardless of Differences in Leaf Area Index



Light Use Efficiency: deciduous: 17.5 +/- 0.85 gC MJ^{-1} ; evergreen: 8.09 +/- 0.35 gC MJ^{-1}

On Annual Time Scales Evergreen and Deciduous Oaks do the Same Thing, Differently

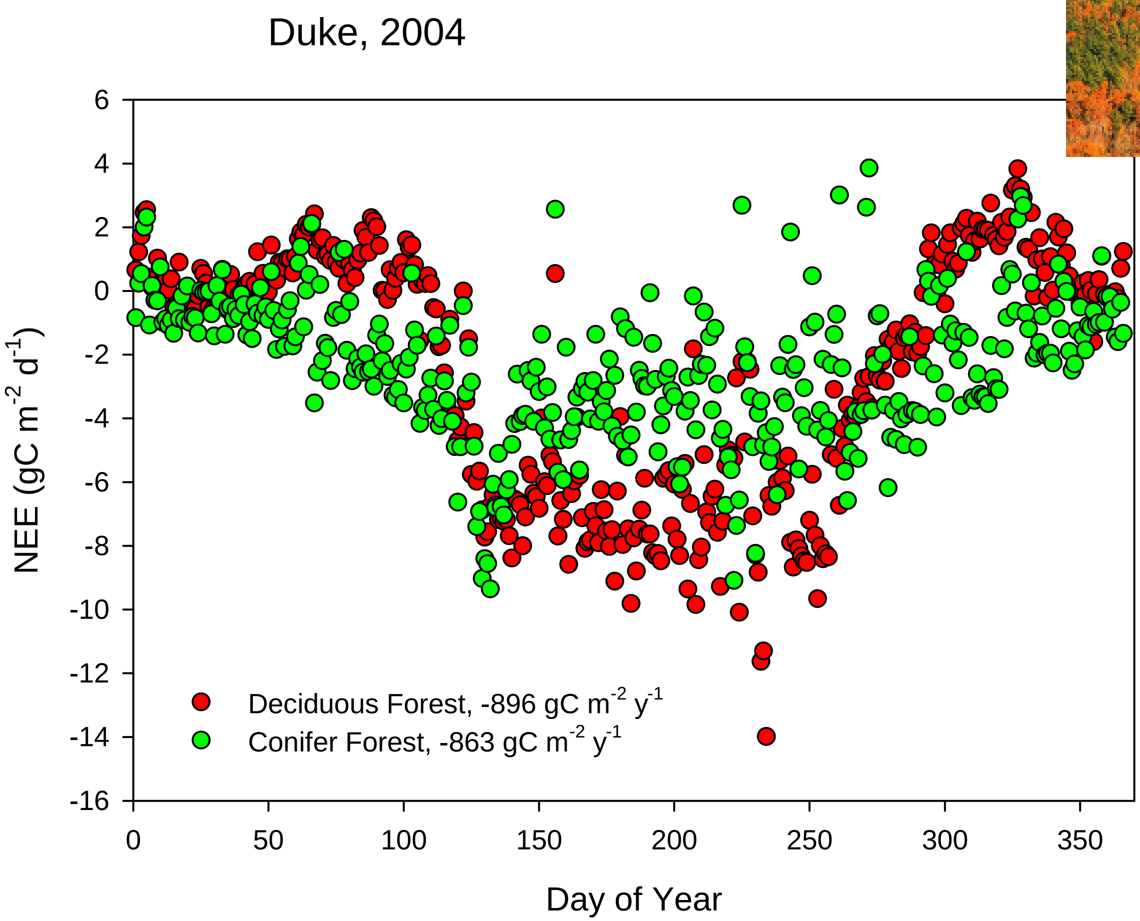
TABLE 2. Analysis of deciduous vs. evergreen leaves (mean ± SE) for annual total gross primary productivity (GPP), ecosystem respiration (R_{eco}), and evapotranspiration (ET).

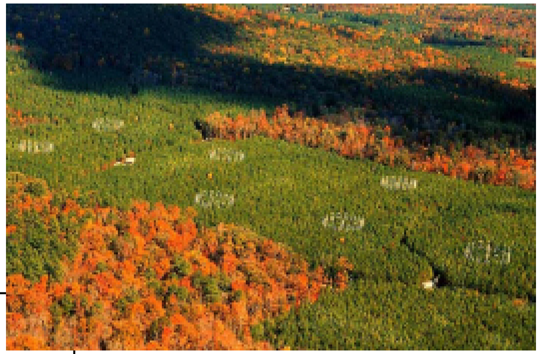
Variable	Units	Deciduous	Evergreen	LSD
GPP	$g\ C \cdot m^{-2} \cdot yr^{-1}$	1251 ± 69	1288 ± 83	152
R_{eco}	$g\ C \cdot m^{-2} \cdot yr^{-1}$	1050 ± 56	958 ± 49	137
ET	mm/yr	343 ± 37	368 ± 29	46

Notes: The database consists of 11 site-years for deciduous oaks and 15 site-years for evergreen oaks. For all variables and both leaf types, each flux pair was found to be identical according to Duncan's test. LSD is least significant difference at $\alpha = 0.05$.

Baldocchi et al. 2010 Ecological Applications

Evergreen Conifer vs Deciduous Broadleaved Forests





Deciduous: Higher Capacity, shorter Growing Season
Conifer: Lower Capacity, longer Growing Season
Net Difference in NEE is small; similar finding for oaks

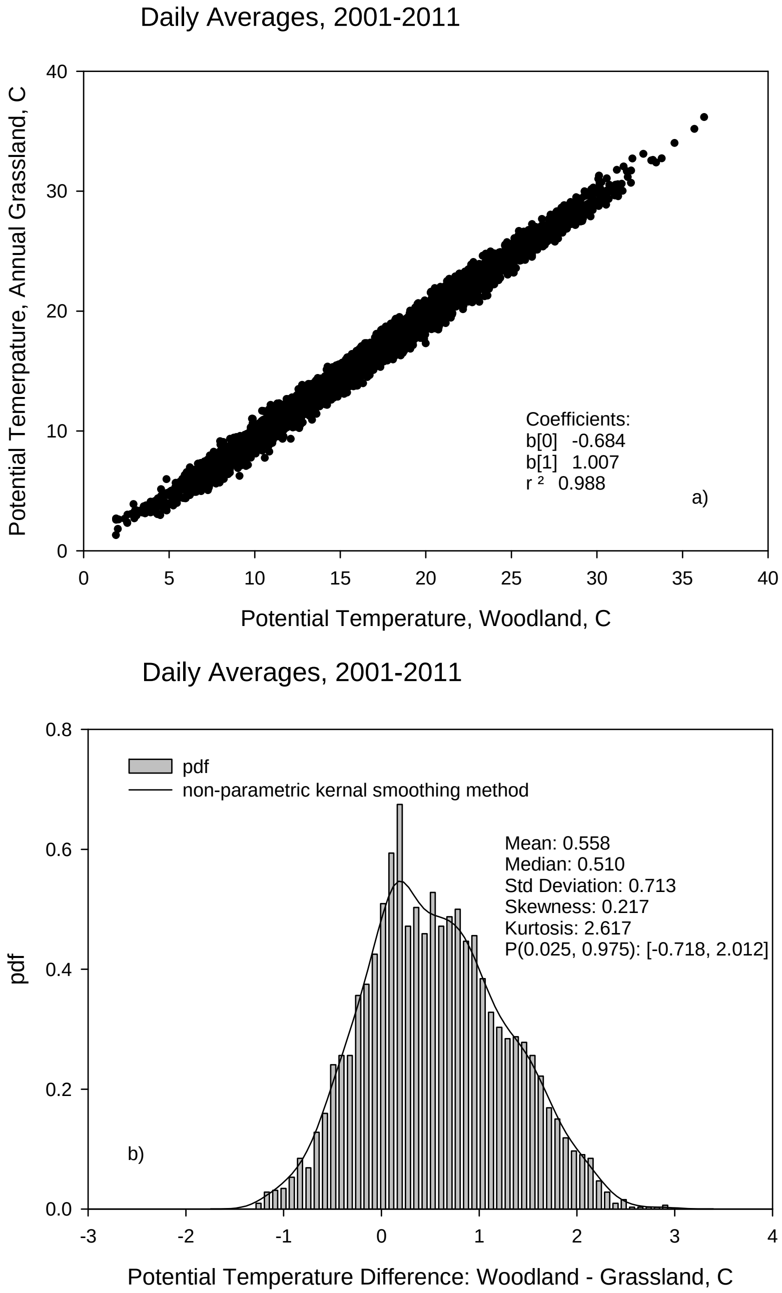
Katul data

Roles of Land Use on Temperature

Case Study
Oak Savanna and Annual Grassland

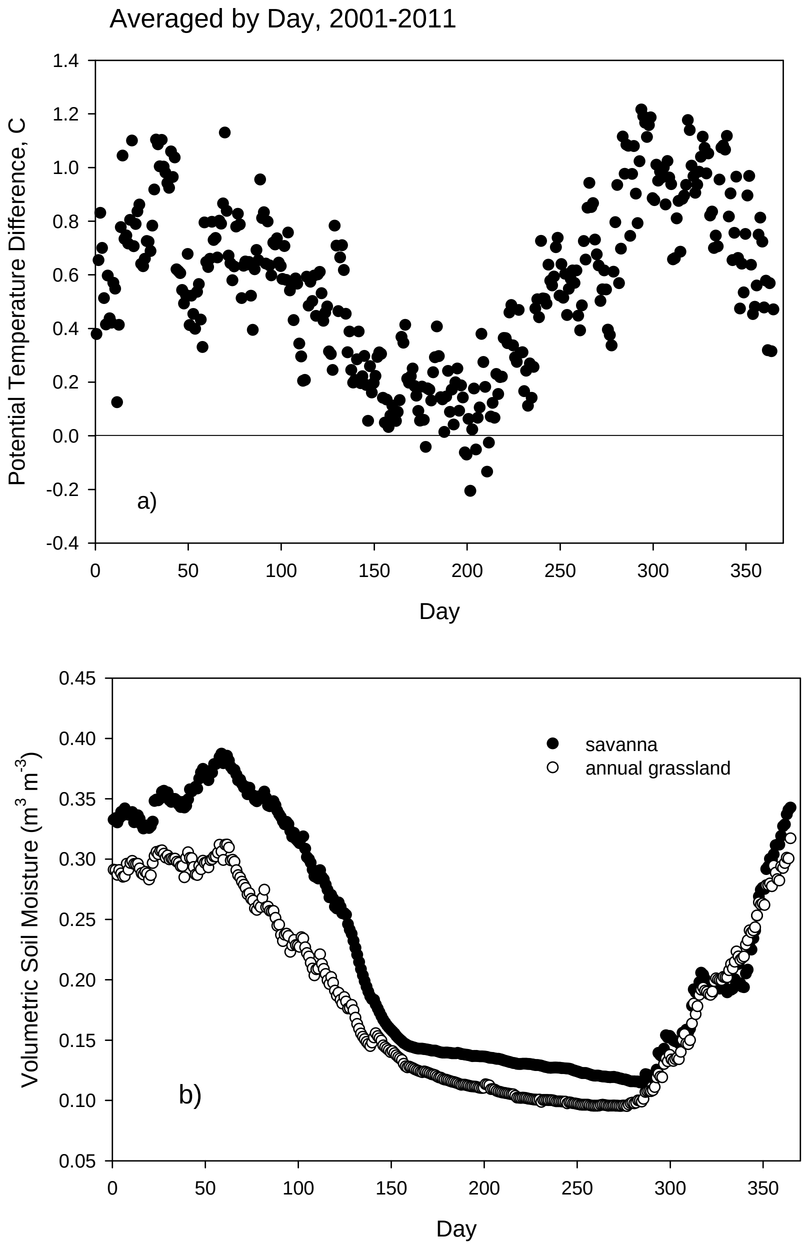
Working Hypotheses

- H1: Forests have a negative feedback on Global Warming
  - Forests are effective and long-term Carbon Sinks
  - Landuse change (more forests) can help offset greenhouse gas emissions and mitigate global warming
- H2: Forests have a positive feedback on Global Warming
  - Forests are optically dark and Absorb more Energy
  - Forests have a relatively large Bowen ratio (H/LE) and convect more sensible heat into the atmosphere
  - Landuse change (more forests) can help promote global warming



On Average, mean Daily Averaged Potential Temperature over savanna is warmer than over grassland, Δ = 0.558 C

Baldocchi and Ma, 2013 Tellus



Baldocchi and Ma, 2013 Tellus

Air above the oak woodland is Warmer because it:

- is darker, so it absorbs more radiation.
- is aerodynamically rougher, so it is able to inject more sensible heat into the atmosphere.

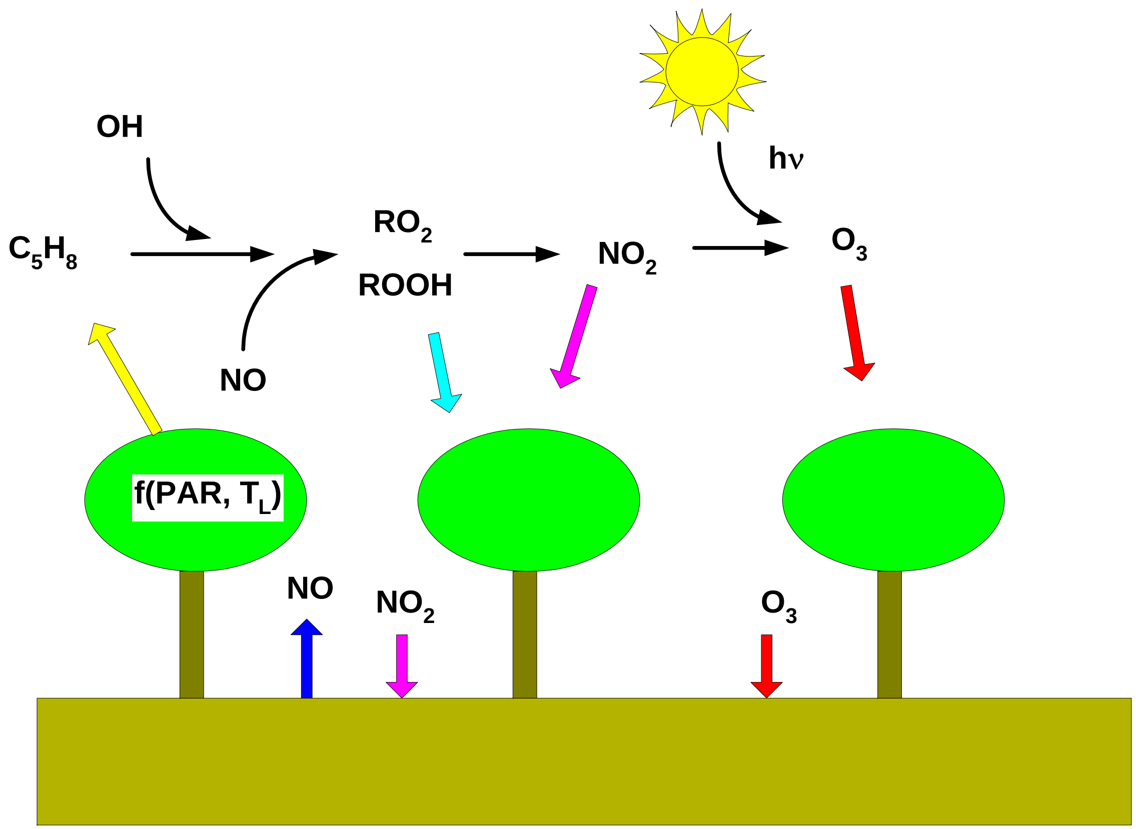
The magnitude of the temperature differences were conditional on time of year, phenology, biophysical conditions of the surface and the depth of the planetary boundary layer.

Future Directions

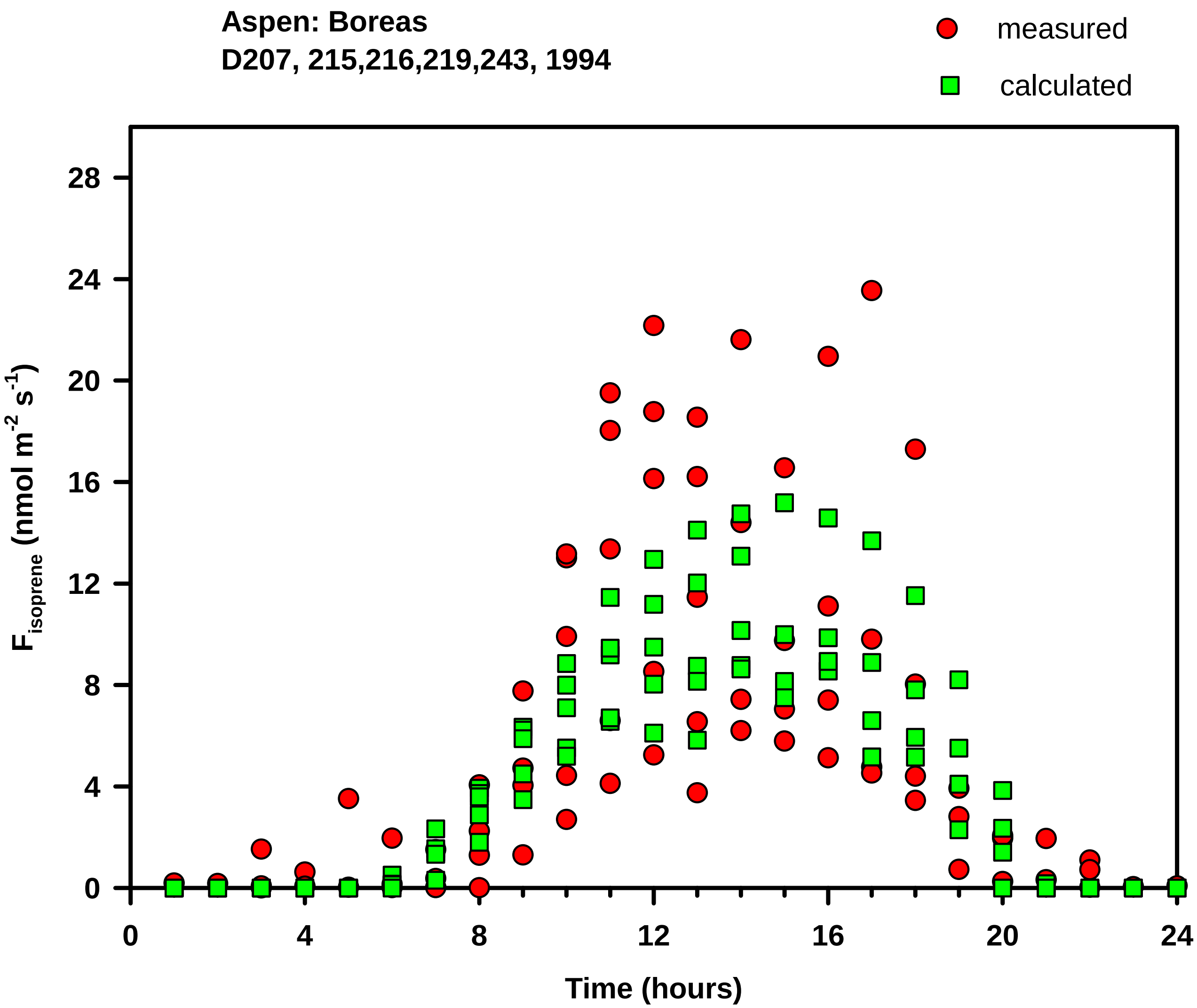
- Fluxes over Non-Ideal Landscapes with Spatially Varying Sources and Sinks
- Roles of Flux Footprint Models and Satellite Remote Sensing

Measuring and Modeling Biogenic Hydrocarbon Fluxes

Roles of Appropriate Environmental Drivers,
Species Diversity, and Flux Footprints



Isoprene from Mono-Specific Aspen Forest

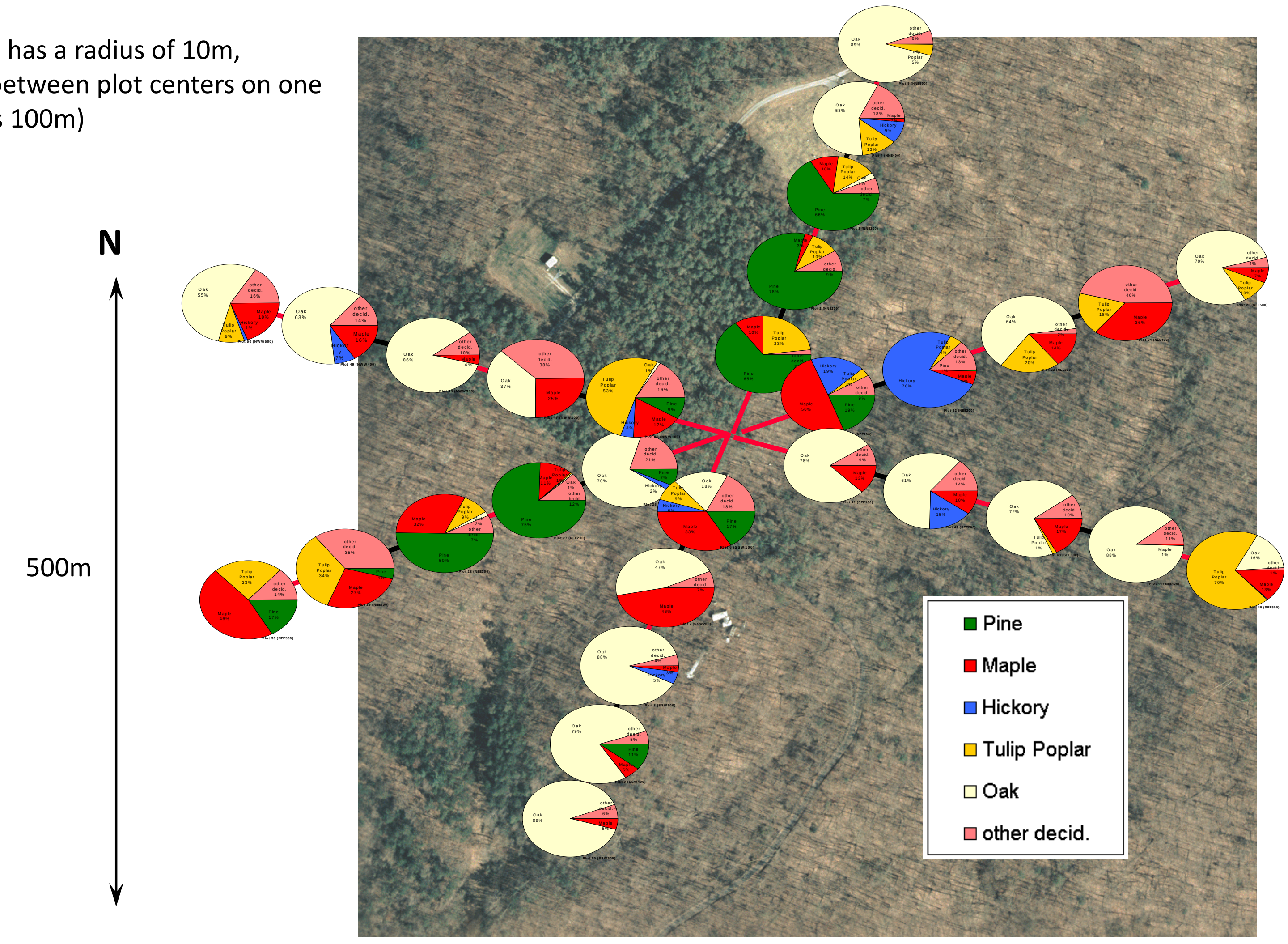


Baldocchi et al 1999 JAM

Walker Branch 1999
Species Composition

Mixed Forests Contain Isoprene Emitters and non Emitters

(each plot has a radius of 10m, distance between plot centers on one transect is 100m)

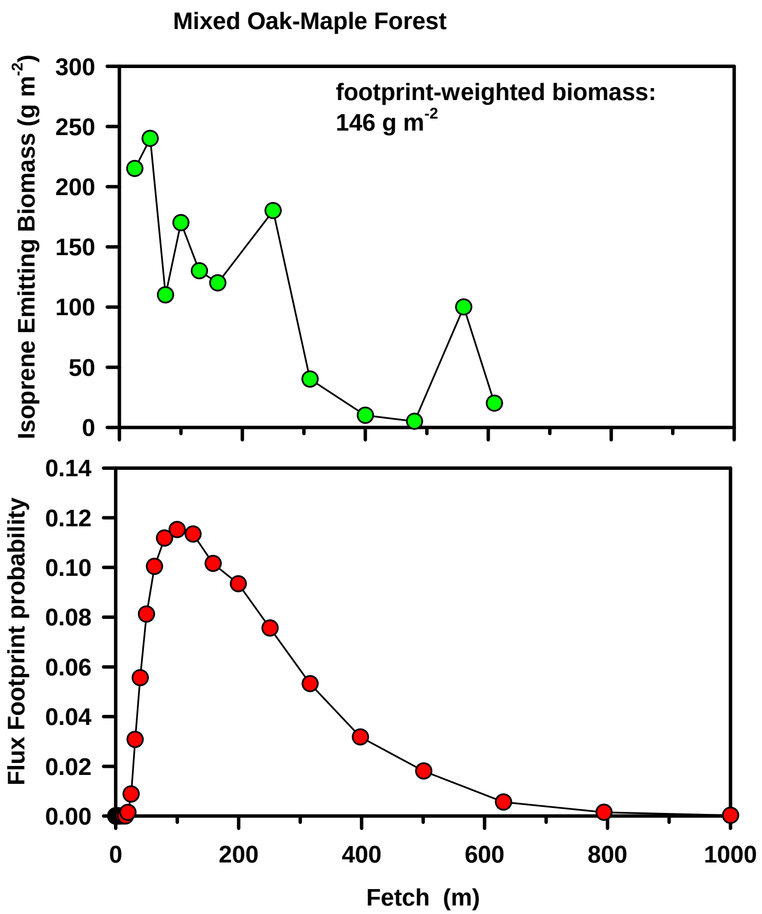


Data of Eva Falge

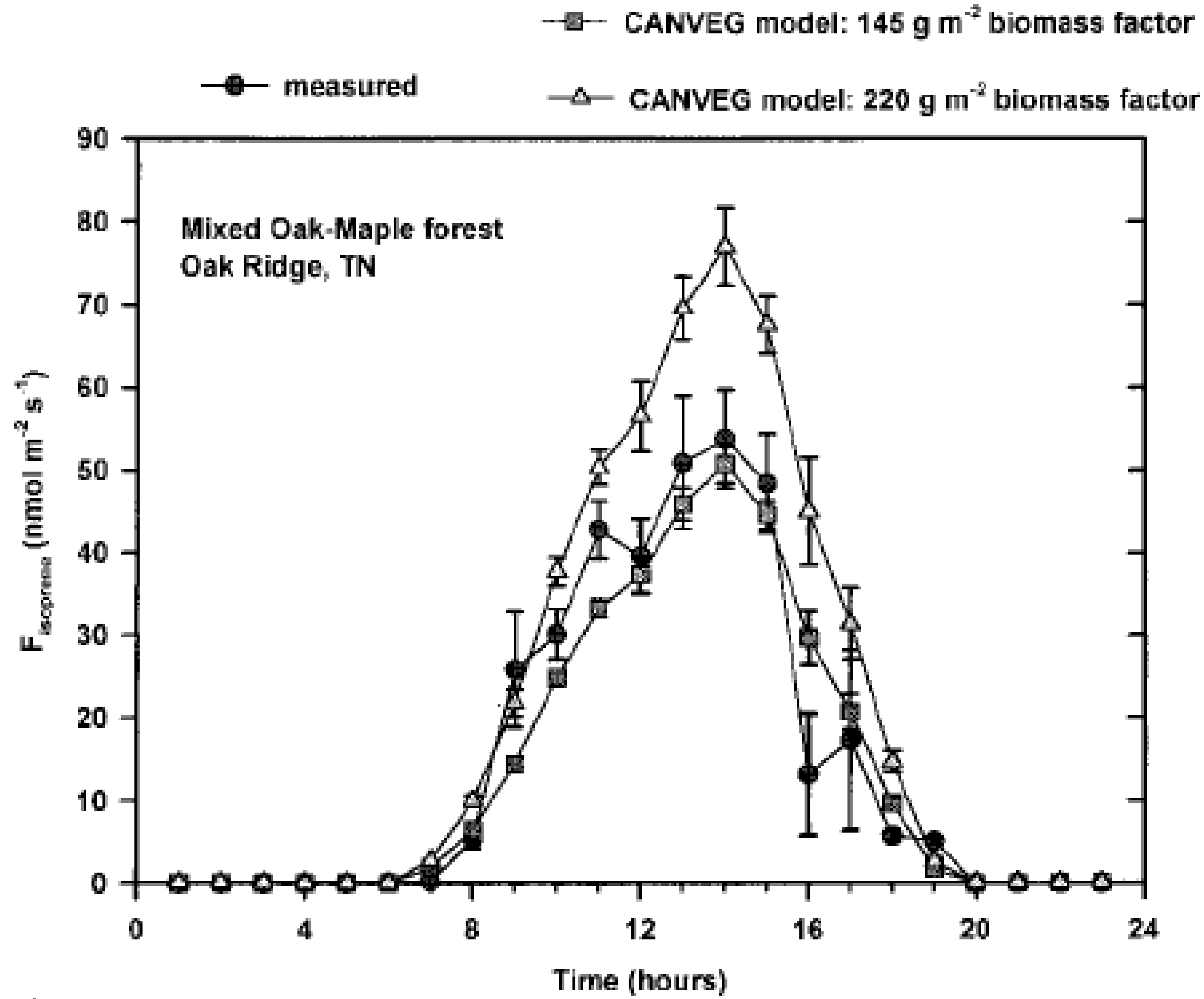
Footprint Weighted Biomass

$$b_I = \int_0^\infty b_I(x)p(x)dx$$

isoprene emitting biomass (b_I), sensed by a micrometeorological flux measurement system, along the wind-blown axis (x) is a function of the flux footprint, defined by the probability distribution p(x)



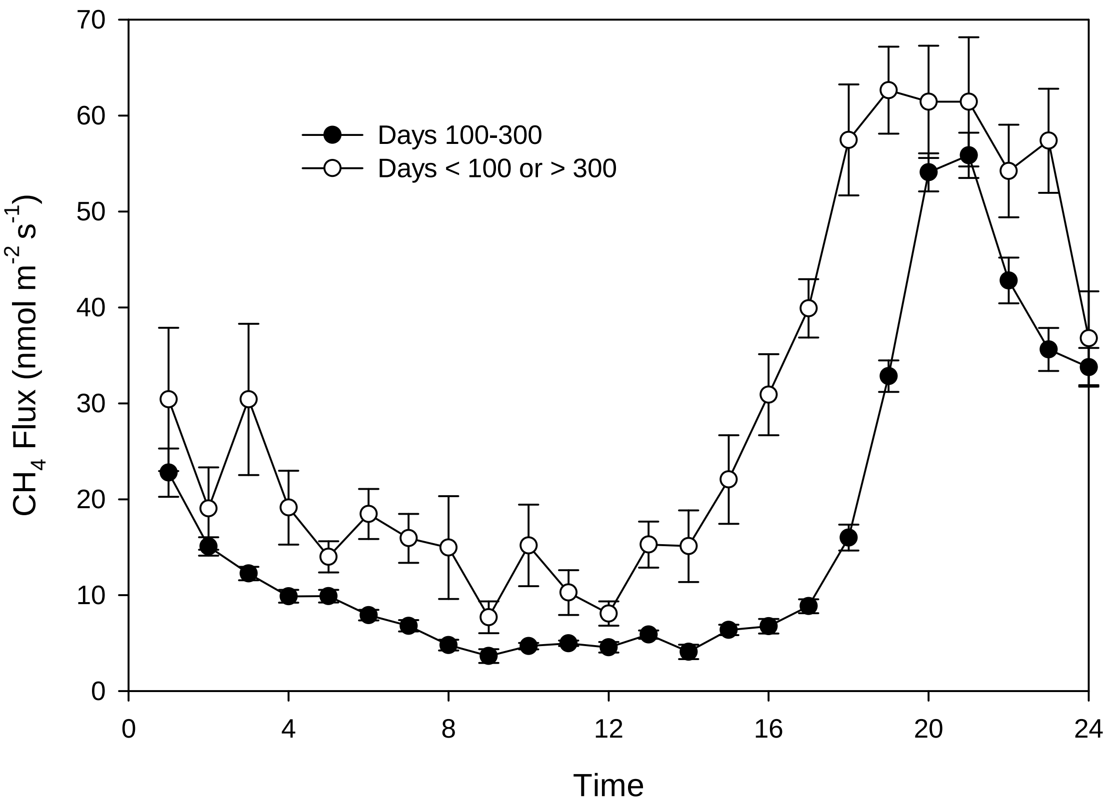
Model in Mixed Forest with and without Flux Footprint



Baldocchi et al 1999 JAM

Emerging Mystery:

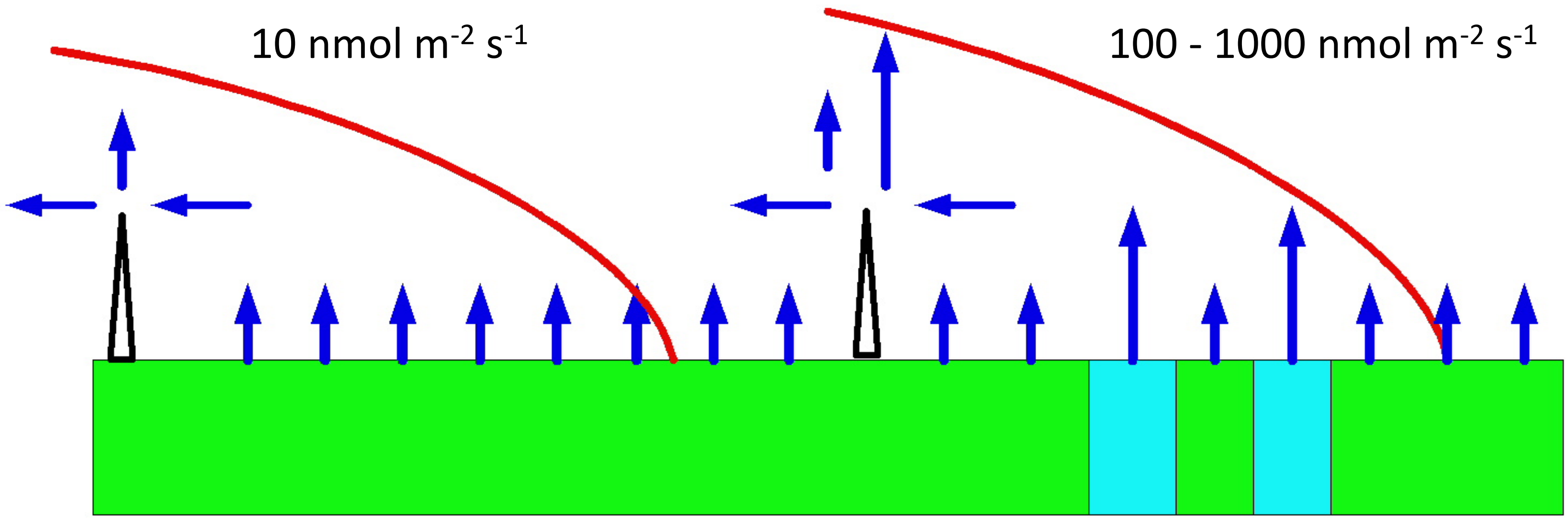
Strong, Unexpected Diurnal Pattern in Methane Efflux with a Nocturnal Efflux Maximum…



Baldocchi et al AgForMet, 2012

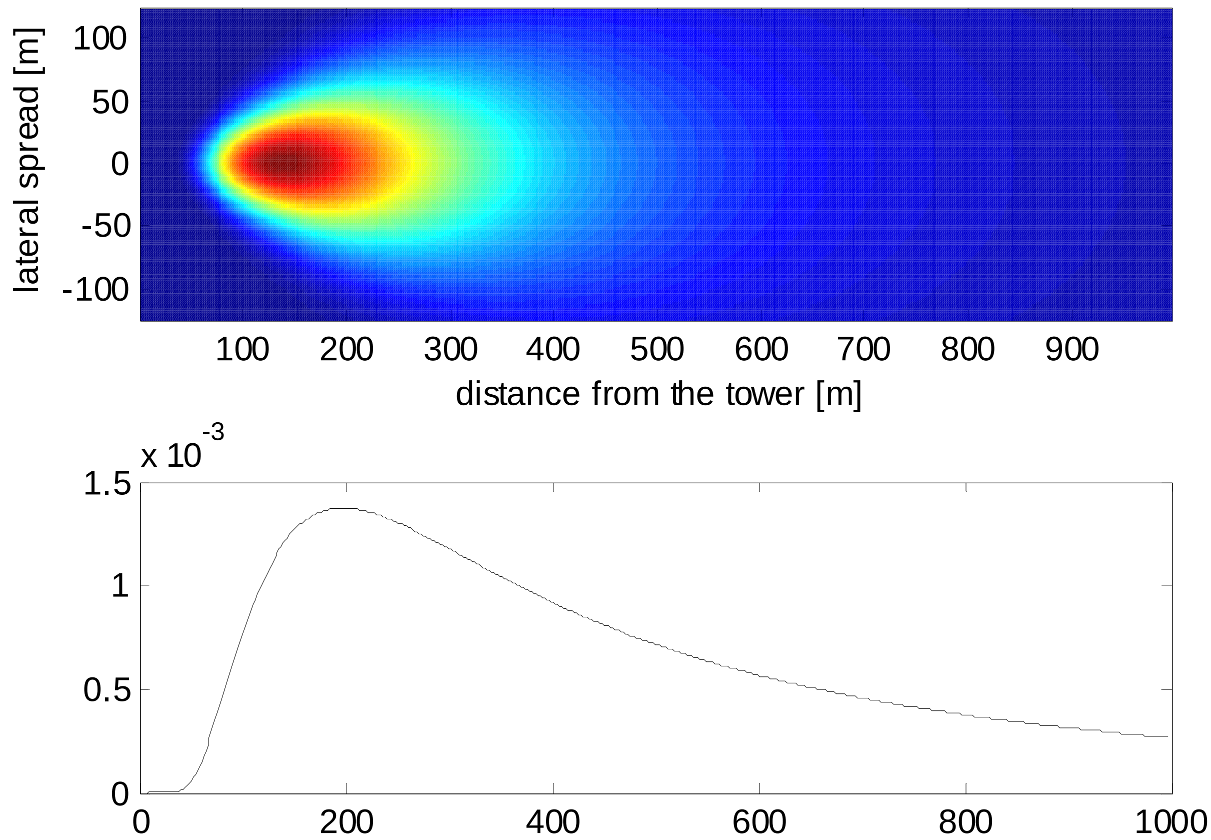
Even Over Perfect Flat Sites with Extensive Fetch
Advection can/does Occur with Methane:

Source Strength of Hot spots and Cold Spots can Differ by 1 to 2 orders of Magnitude (10x to 100x)

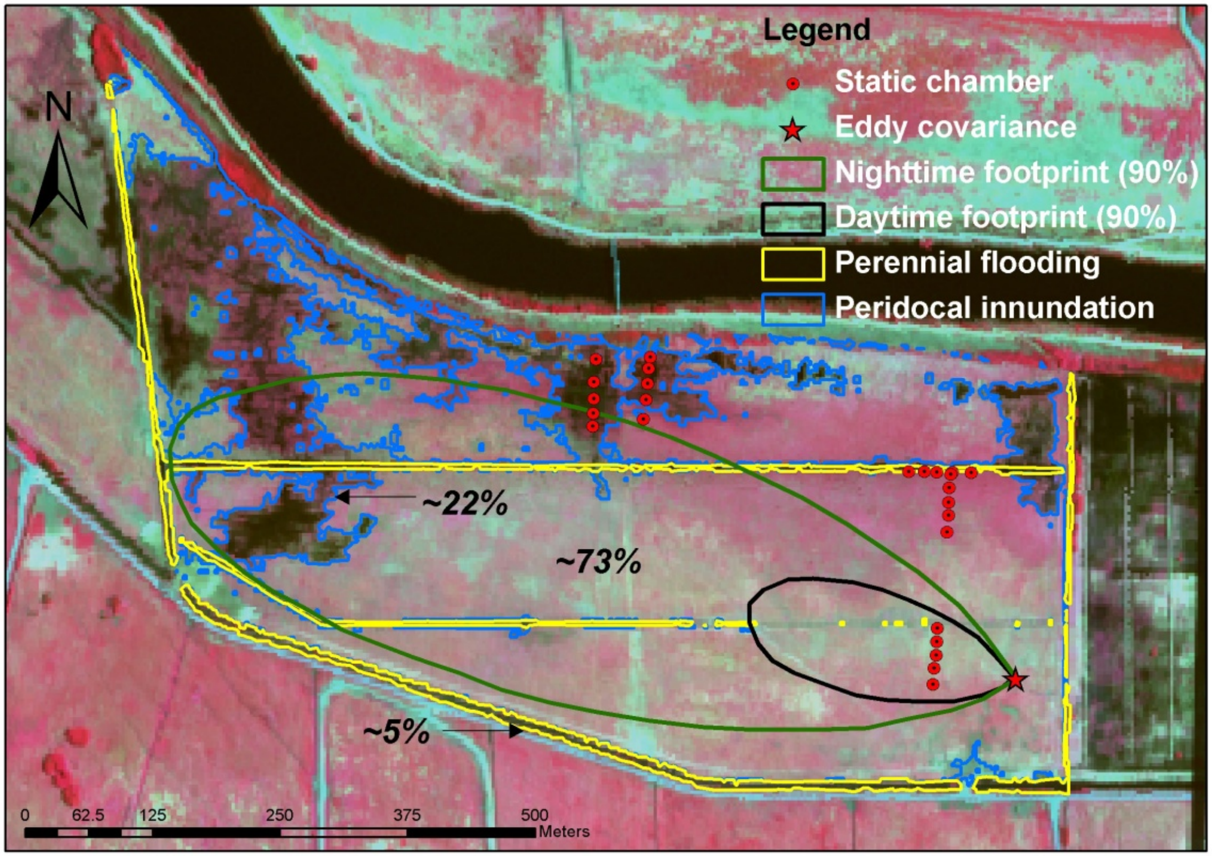


Such Advection is Less Pronounced for Water Vapor and CO_2 Fluxes Because Flux Differences Emanating from the Different Land Forms are Smaller

2D-Footprint Model of Detto-Hsieh



Daytime Footprint, drained ditches and paddock
Night Footprint, wetter fields and ditches



Night-time Flux Footprint Does Not Extend to the Wetlands

Concluding Remarks

- Flux Networks remain fundamental tool for enriching our ability to study the breathing of the biosphere with satellite remote sensing, new orbital CO_2 sensors, and coupled climate-ecosystem models
- Plants are Coupled to the Atmosphere, and Vice Versa
- Soil Microbes are Coupled to Plants, and Vice Versa
- Physics Wins, Biology is How it is Done