Physics Wins, Biology is How it’s Done: Biometeorology@Berkeley

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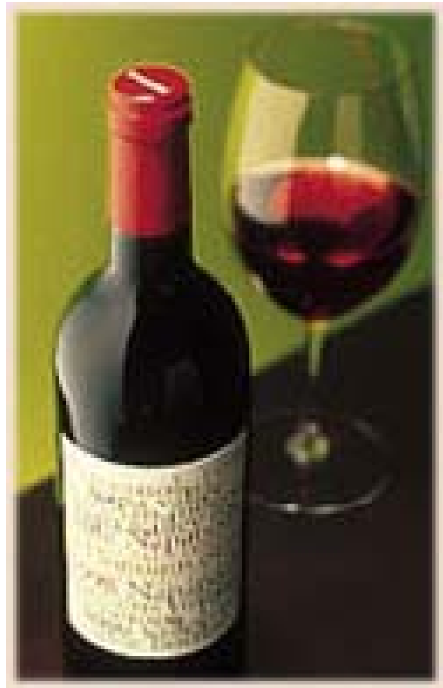
B.S., LAWR, Atmos. Sci, 1977

What Is Biometeorology?

- It is a science that deals with the relationship between living things and atmospheric phenomena.

Has Applications to Biogeochemistry, Ecosystem Ecology, Agriculture, Weather and Climate Prediction, etc

Biometeorology in a Bottle



Wine, the Perfect Integrator of Climate, Terroir and Biology

Goals of Biomet Research @ UCB

'Breathing of the Biosphere'

Study the physical, biological, and chemical process that control trace gas fluxes between the biosphere and atmosphere

Physics Wins—Biology is How it's Done

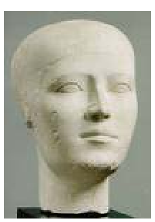
- Physics wins
  - Ecosystems function by capturing solar energy
    - Only so much Solar Energy can be captured per unit are of ground
  - Plants convert solar energy into high energy carbon compounds for work
    - growth and maintenance respiration
  - Ecosystems must maintain a Mass Balance
    - Plants can't Use More Water or Carbon than has been acquired
  - Plants transfer nutrients and water between air, soil and plant pools to sustain their structure and function.
- Biology is how it's done
  - Species differentiation (via evolution and competition) produces the structure and function of plants, invertebrates and vertebrates
  - In turn, structure and function provides the mechanisms for competing for and capturing light energy and transferring matter
    - Stomata open and close to regulate gas exchange through leaves
  - Bacteria, fungi and other micro-organisms re-cycle material by exploiting differences in redox, passing electrons and extracting energy
  - Reproductive success passes genes through the gene pool.

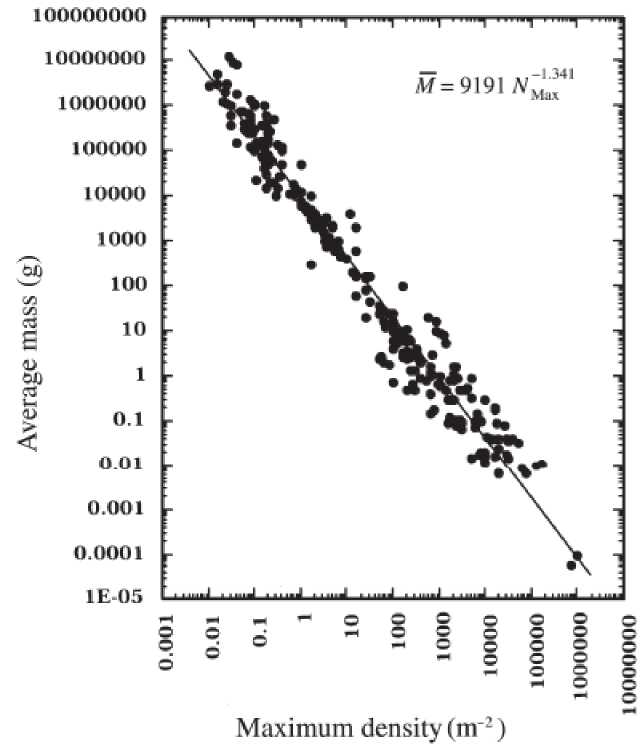
Size vs Density transcends 9-12 orders of magnitude

Physics Wins:
You can only be so big and sustain
so many individuals
with the resources available

Corollary 1: You can only grow so fast; an Ecological lesson
for the stock market and the Federal Reserve.

Corollary 2: Don't Eat anything
Bigger than your Head





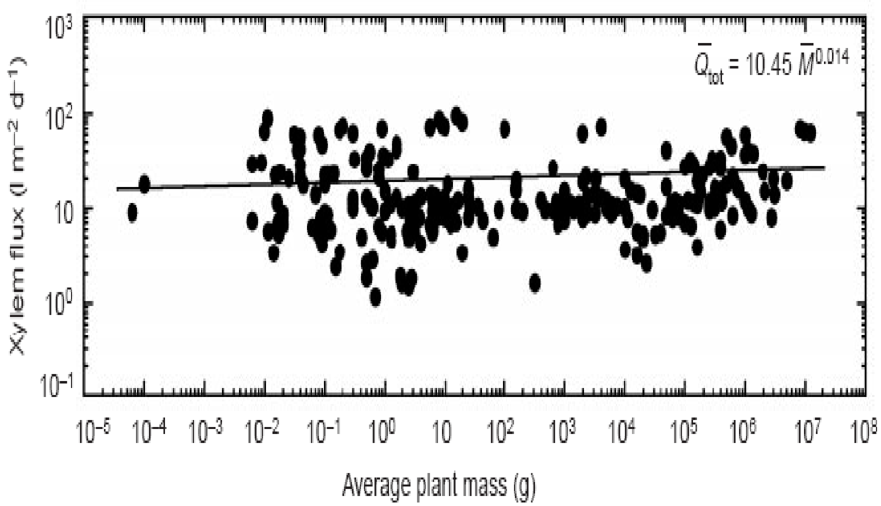
Enquist et al. 1998. Nature, 395

Metabolic Scaling of Populations of Organisms

Energy flux of a population per unit area (B_t) is invariant with mass of the system (M):

$$B_T = N_i B_i \propto M_i^{-3/4} M_i^{3/4} = M^0$$

Allen et al. (2002)

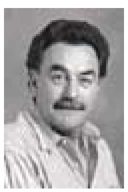


Enquist et al 1998 Nature

Biometeorology: Represents Multidisciplinary Integration of Atmospheric Science, Plant Physiology and Ecosystems

Intellectual Influences
Davis, 1973-1977

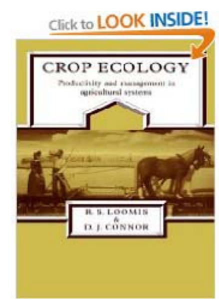
Ted Hsiao:
Plant Water Relations



John Carroll:
Atmospheric Science

Bill Pruitt:
Evapotranspiration

Jerry Hatfield:
Biometeorology



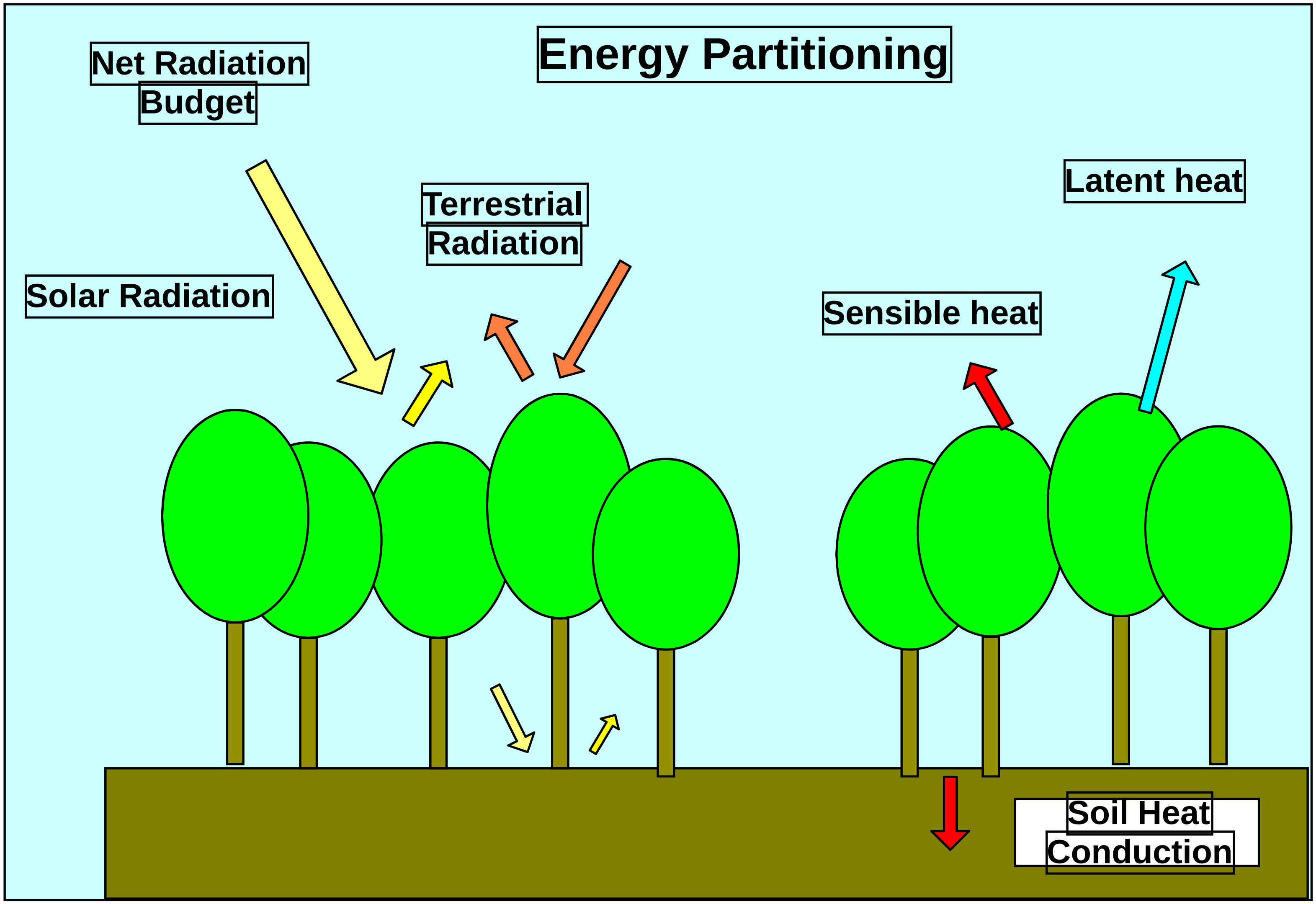
Bob Loomis:
Crop Ecology

Leonard Myrup:
Micrometeorology

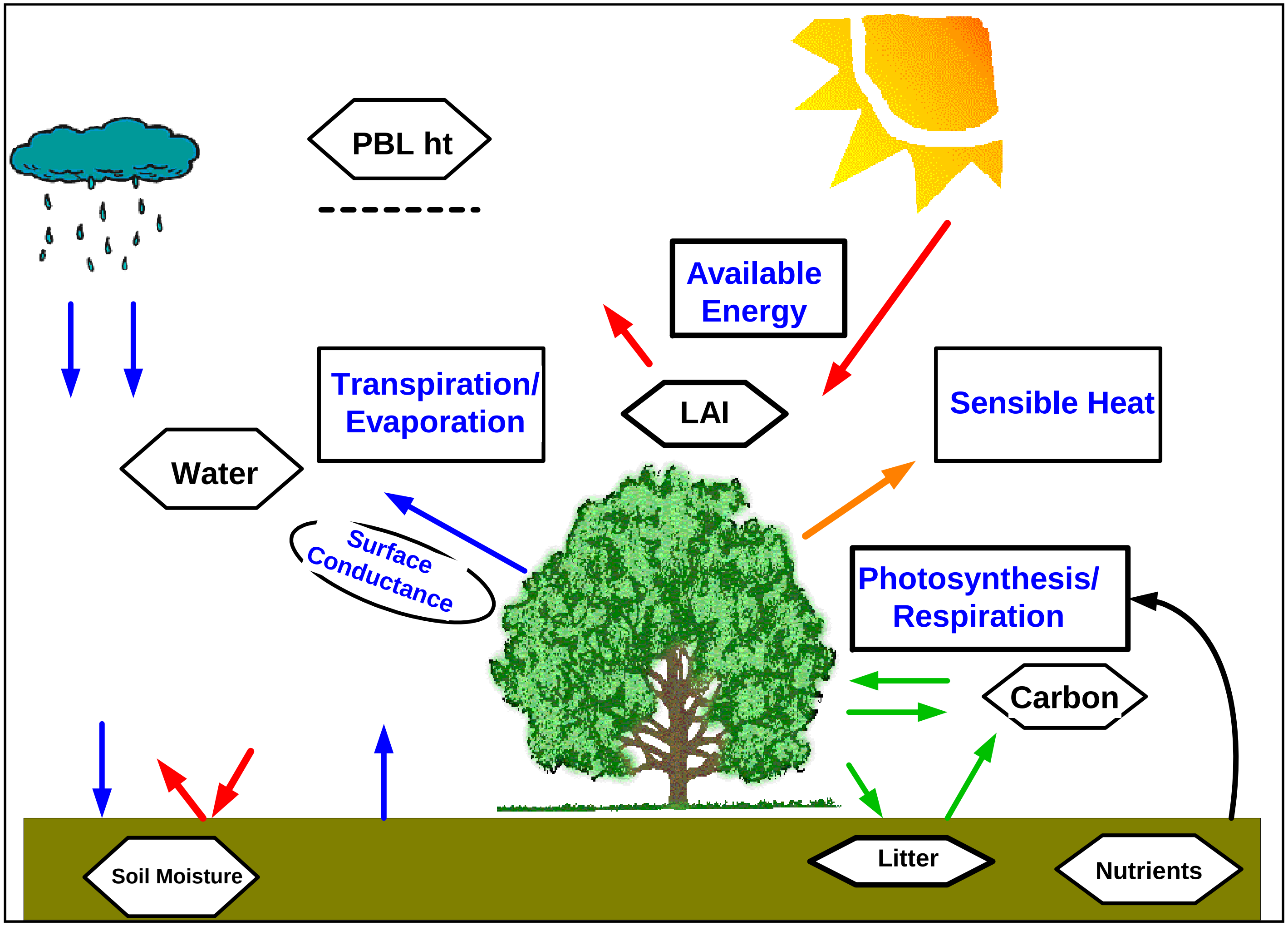
Outline

- Water and Energy
- Carbon Dioxide
- Policy Implications:
  - Pros/Cons of Afforestation to Remedy Global Warming

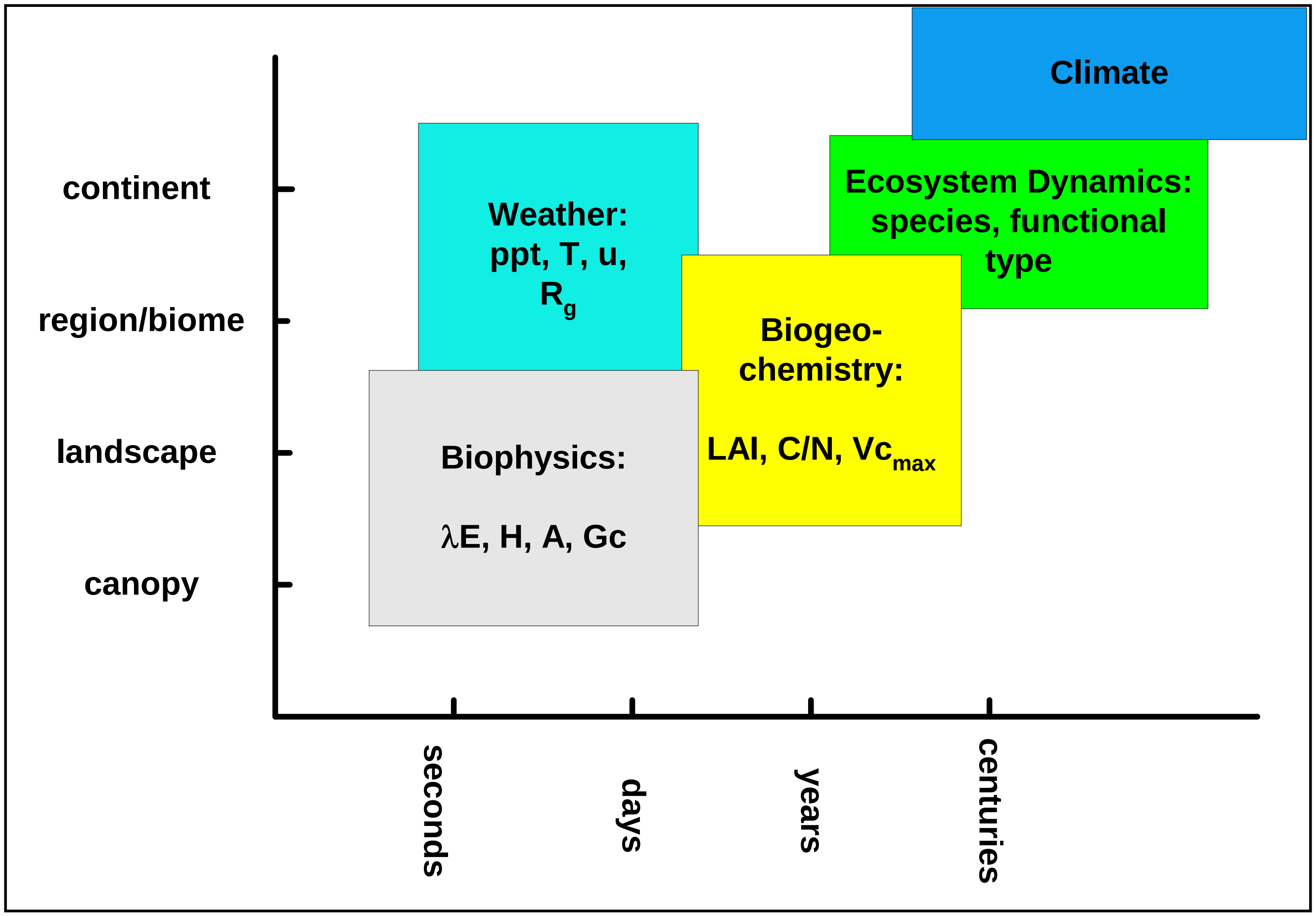
Energy Exchange: Classical View



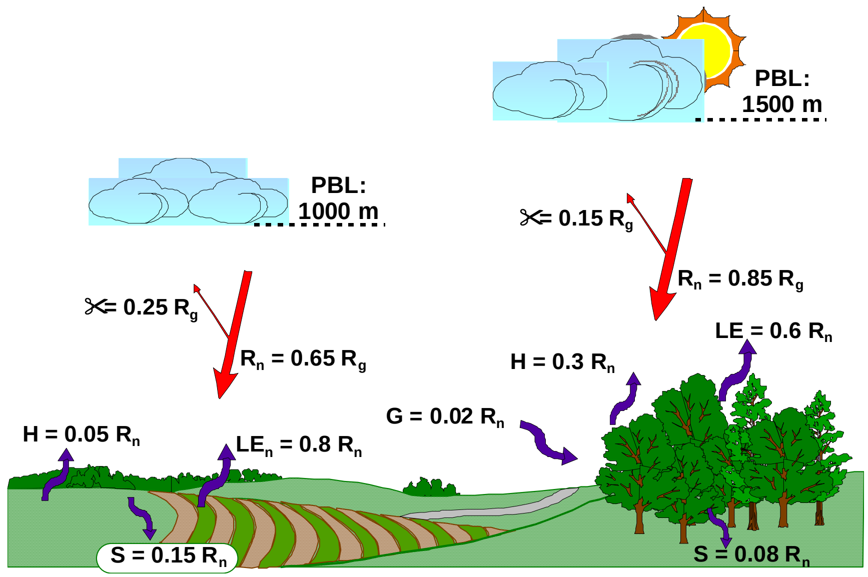
Biogeophysical-Ecohydrological View



Controlling Processes and Linkages: Roles of Time and Space Scales



Energy Exchange

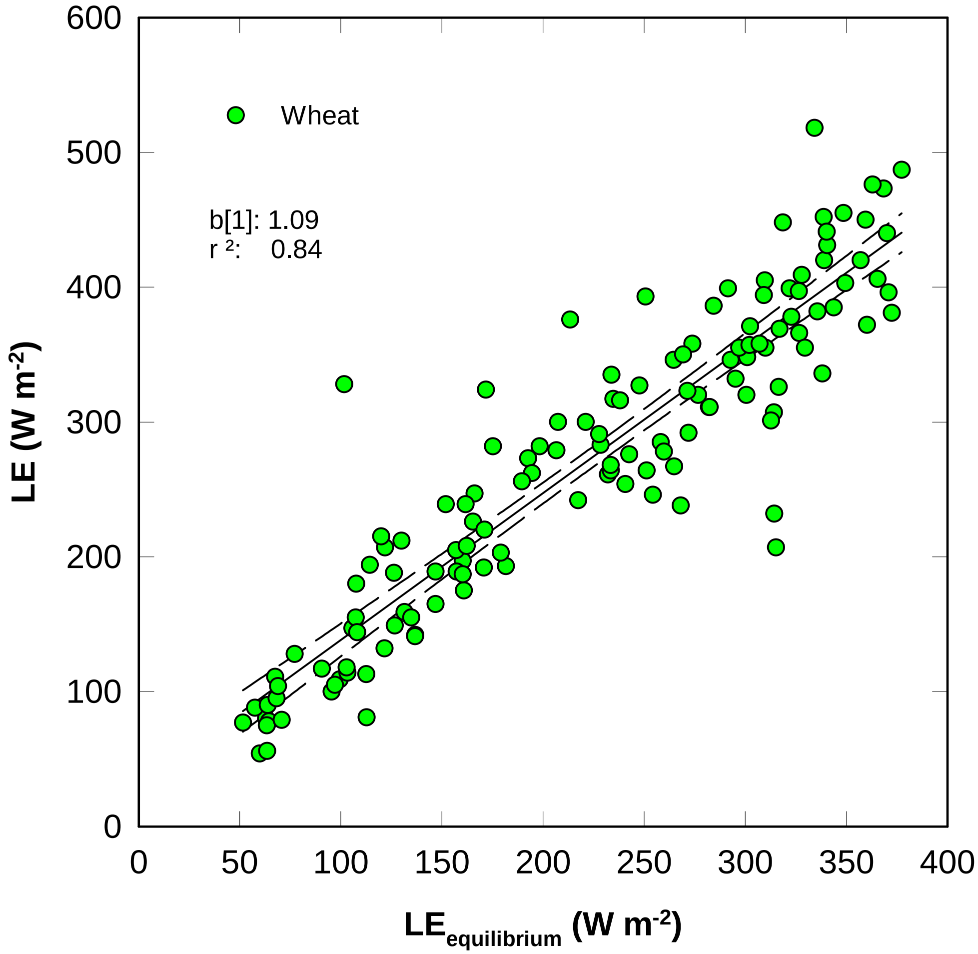


- How does Evaporation vary with Climate and Ecosystem?

- How much Solar Energy is Available?
    - Pros/Cons of biofuels vs solar cells

- How does Land Use Change affect Climate, Weather and Water Availability?
    - Tropical Deforestation
    - Large-scale Biofuels Plantations
    - Re-Forestation

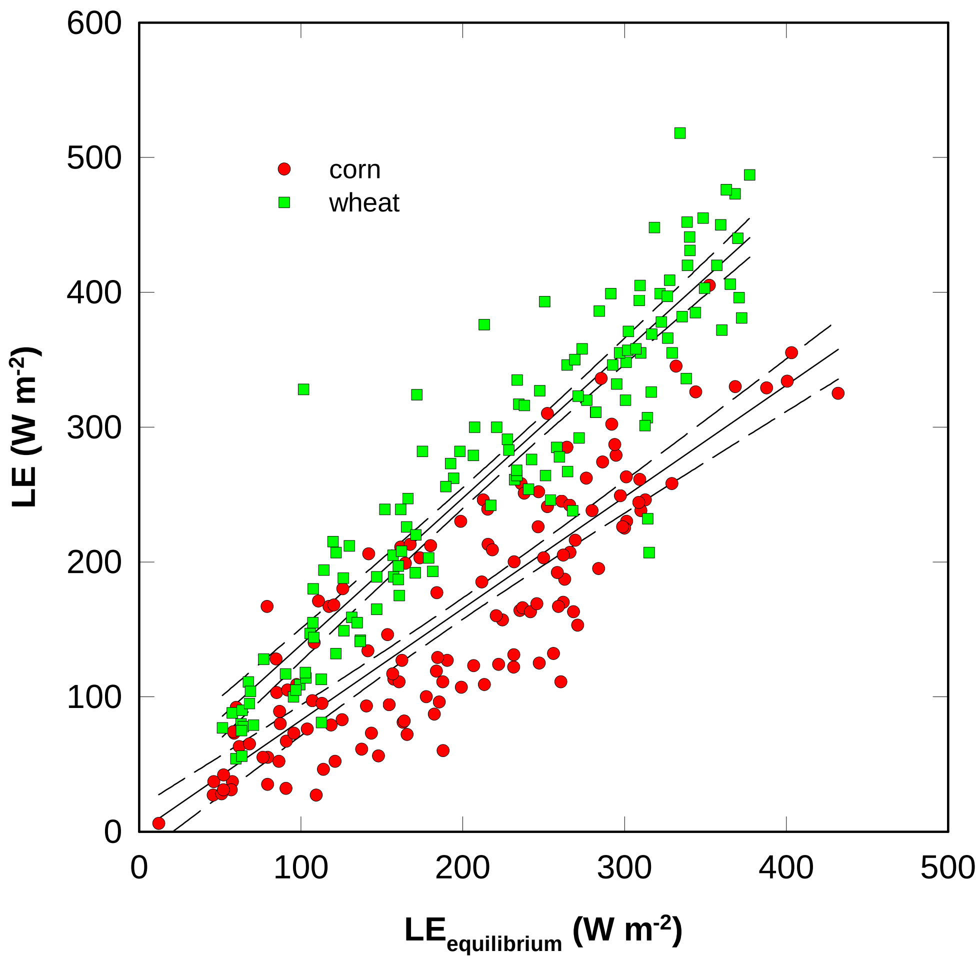
Crop Evaporation is Strongly Coupled to Solar Radiation



$$\lambda E_{eq} = \frac{s}{s+\gamma}(R_n - G)$$

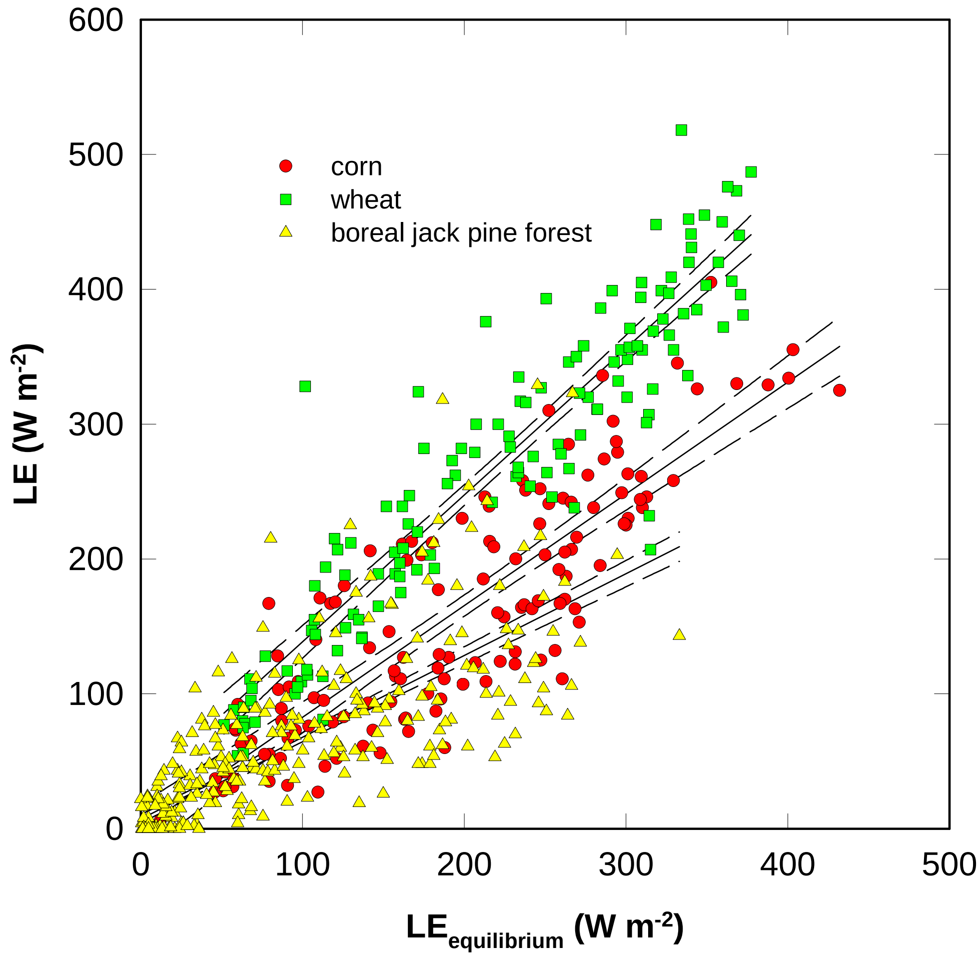
Baldocchi, 1994, AgForMet
Boardman, OR; 1991

But Corn (C_4) Doesn't Evaporate like Wheat (C_3)!

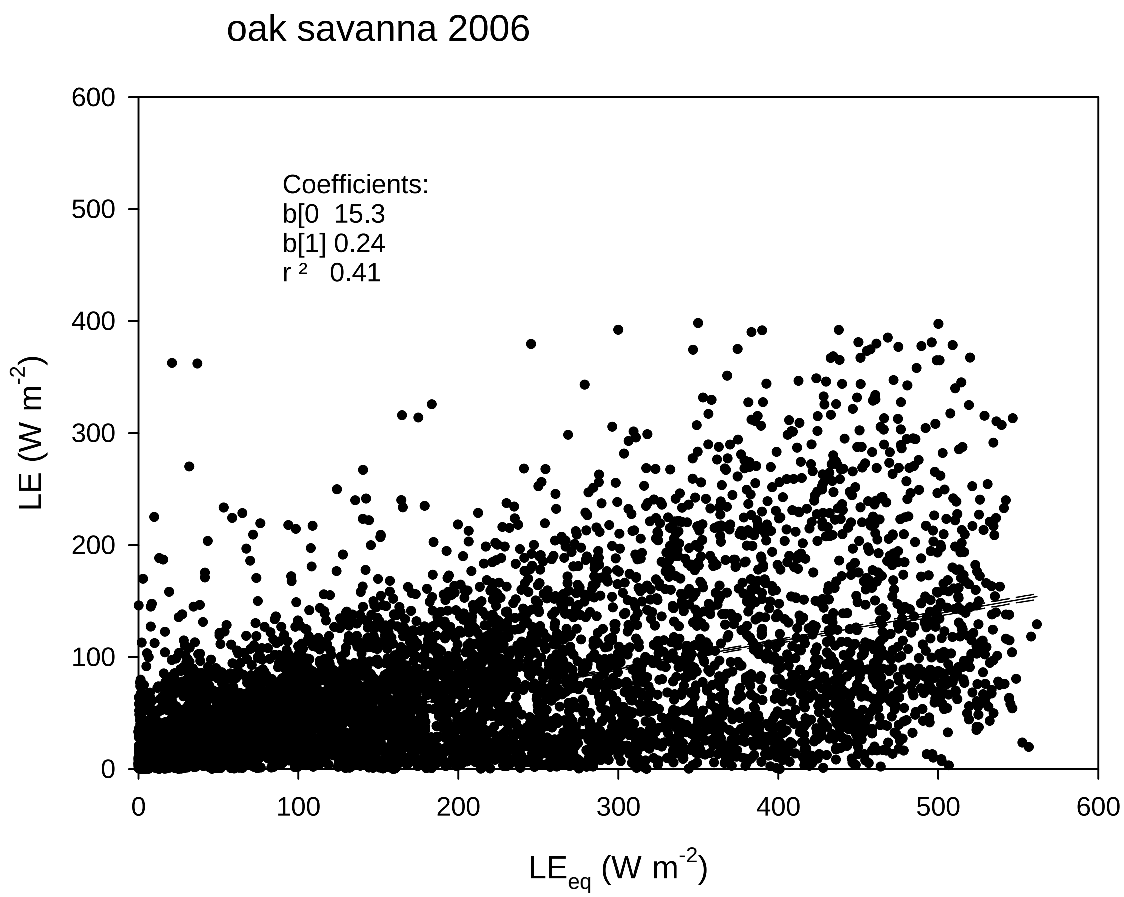


Baldocchi, 1994, AgForMet
Boardman, OR; 1991

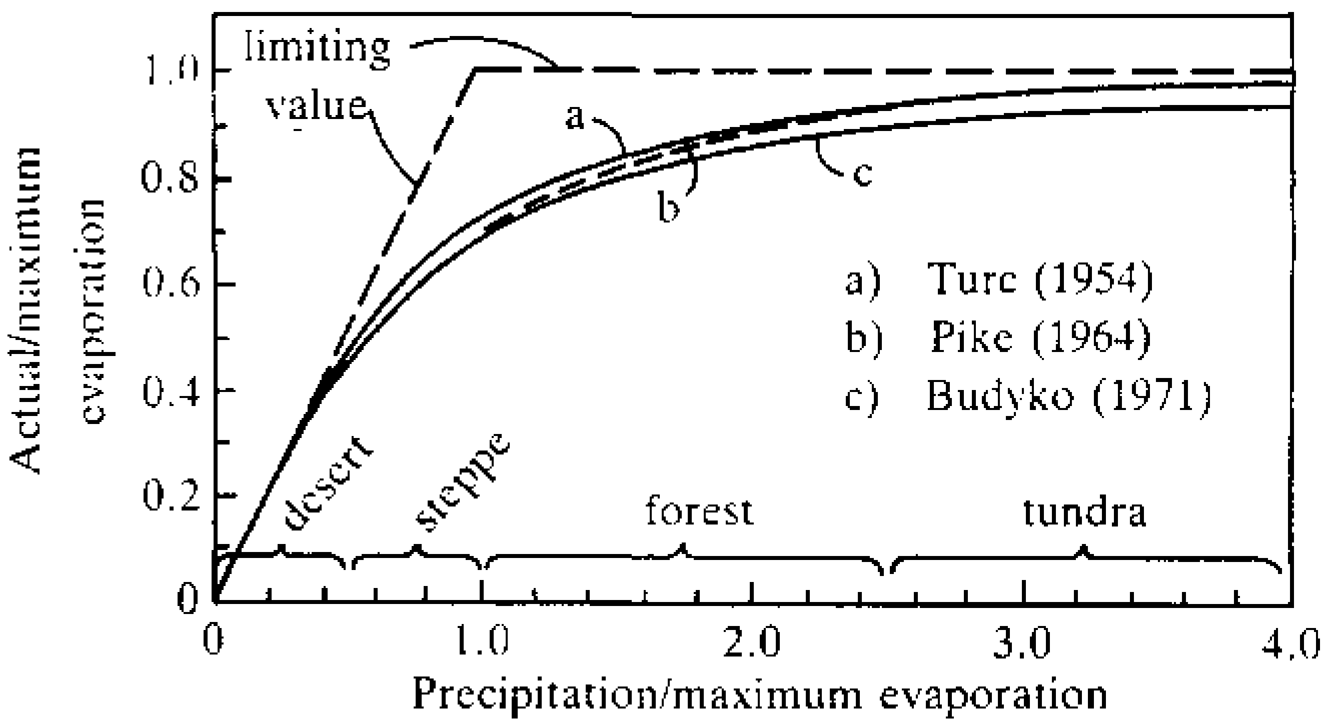
Plus Forests Do not Evaporate Like Crops



And Evaporation of a California Oak Savanna is weakly related to Available Energy



Classic View Meteorological View to Evaporation:
Budyko Evaporation Index



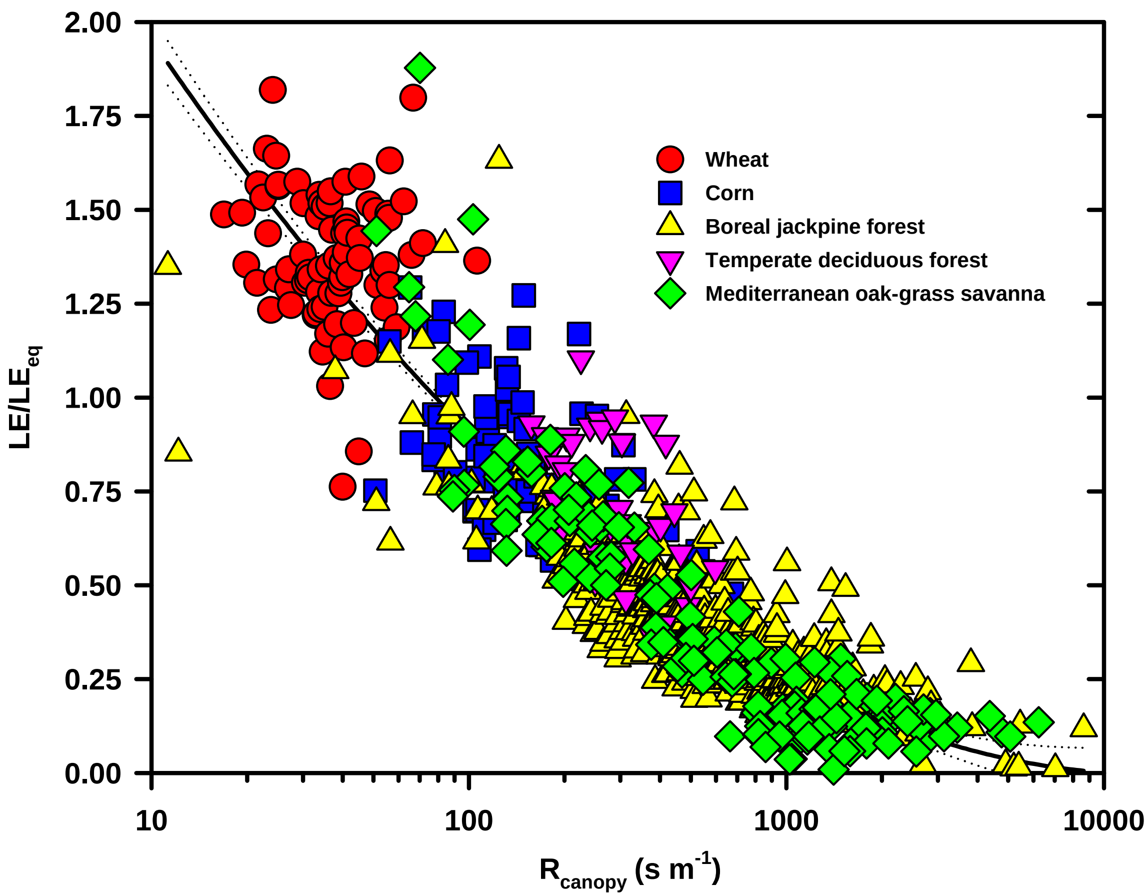
Biometeorological View to Evaporation
Penman Monteith Equation

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

Function of:

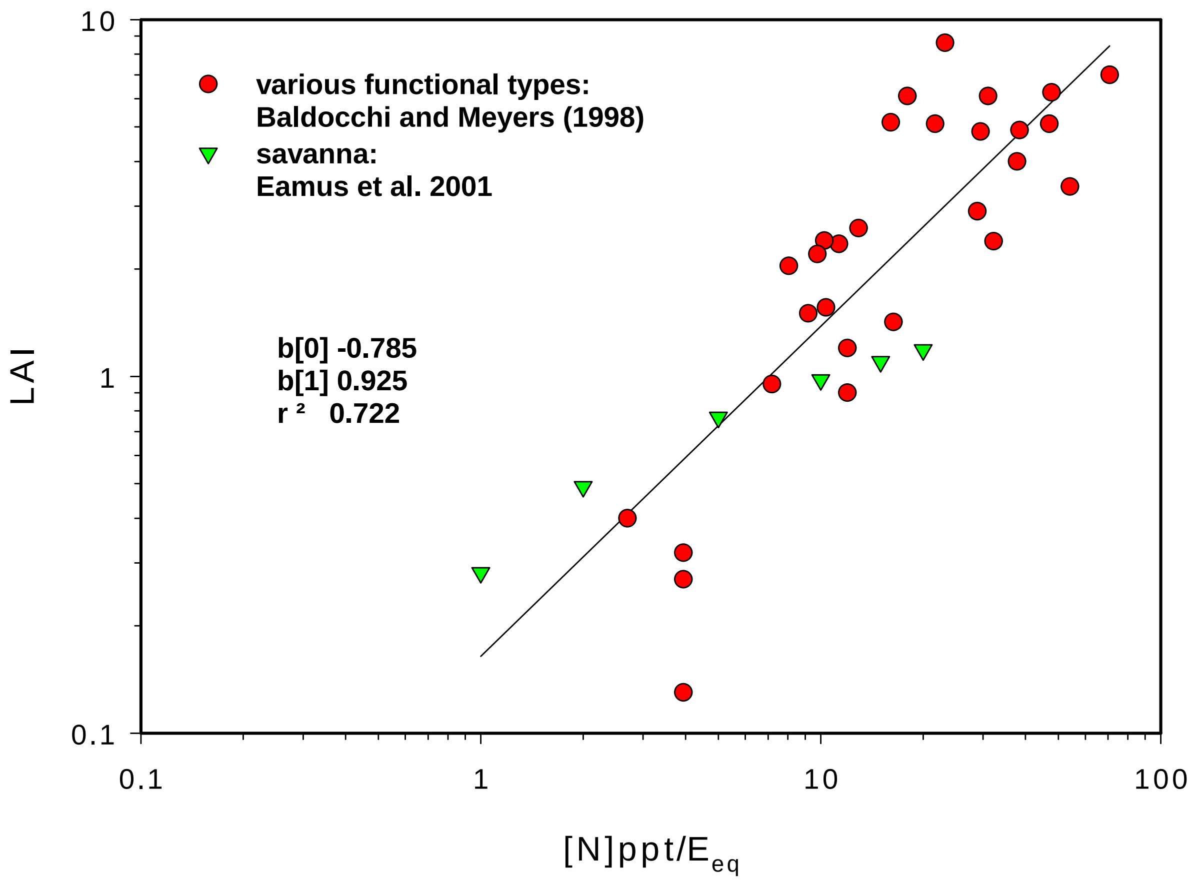
- Available Energy (Rn-S)
- Vapor Pressure Deficit (D)
- Aerodynamic Conductance (Gh)
- Surface Conductance (Gs)

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



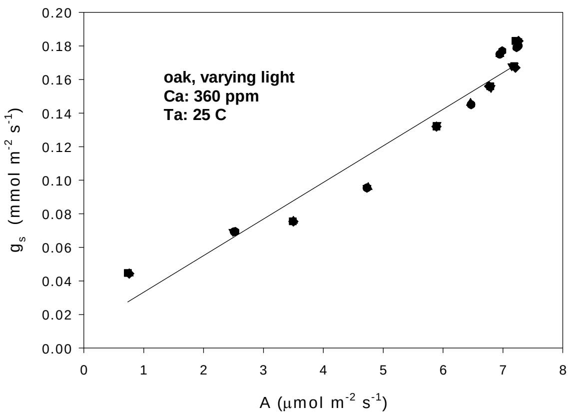
R_c is a f(LAI, N, soil moisture, Ps Pathway)

You Need Water to Grow Trees, Maintain high LAI and Achieve a Low Surface Resistance!

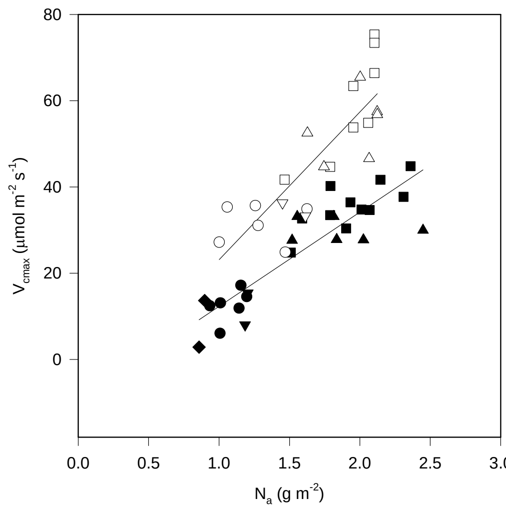


Stomatal Conductance Scales with N, via Photosynthesis

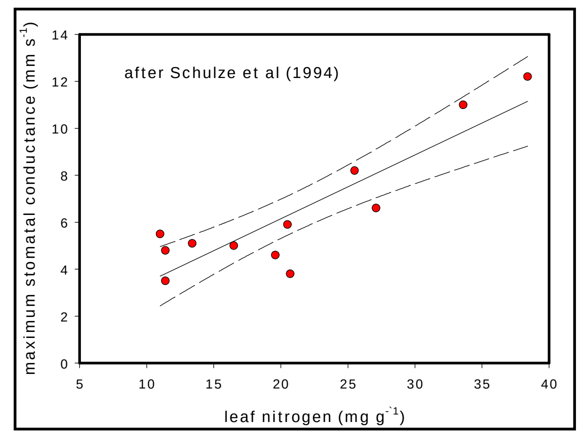
Stomatal Conductance Scales with Photosynthesis



Photosynthetic Capacity Scales with Nitrogen and Ps Pathway

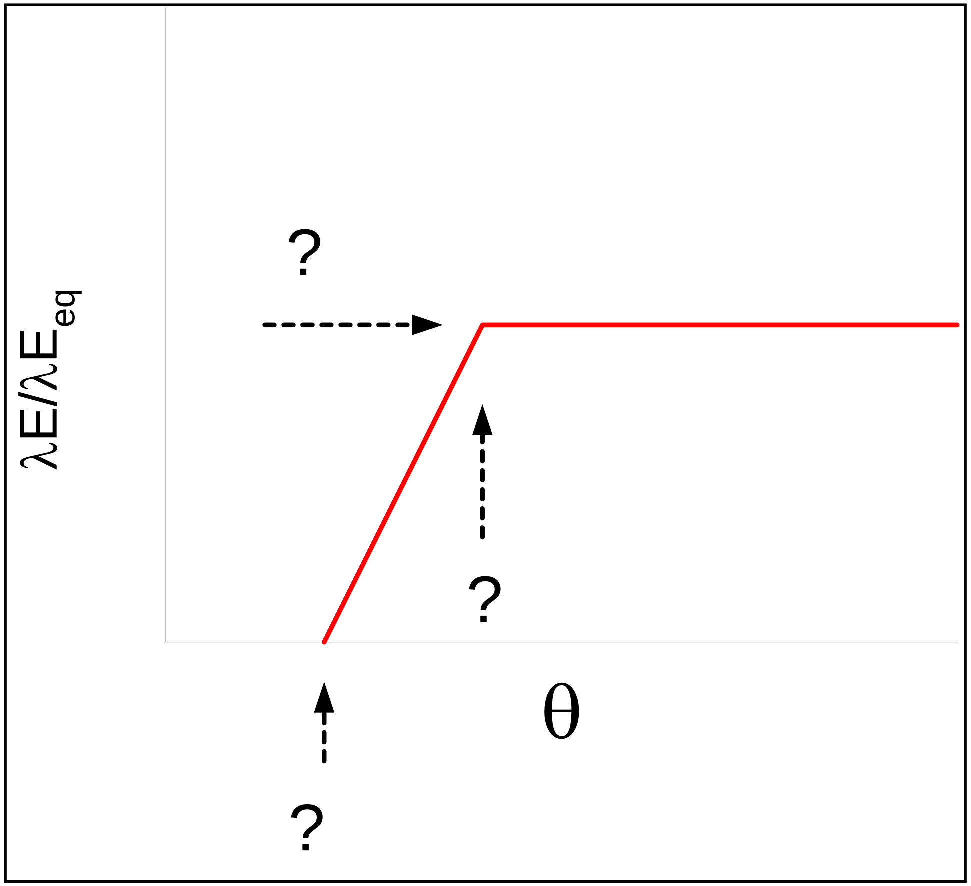


Stomatal Conductance scales with Nitrogen

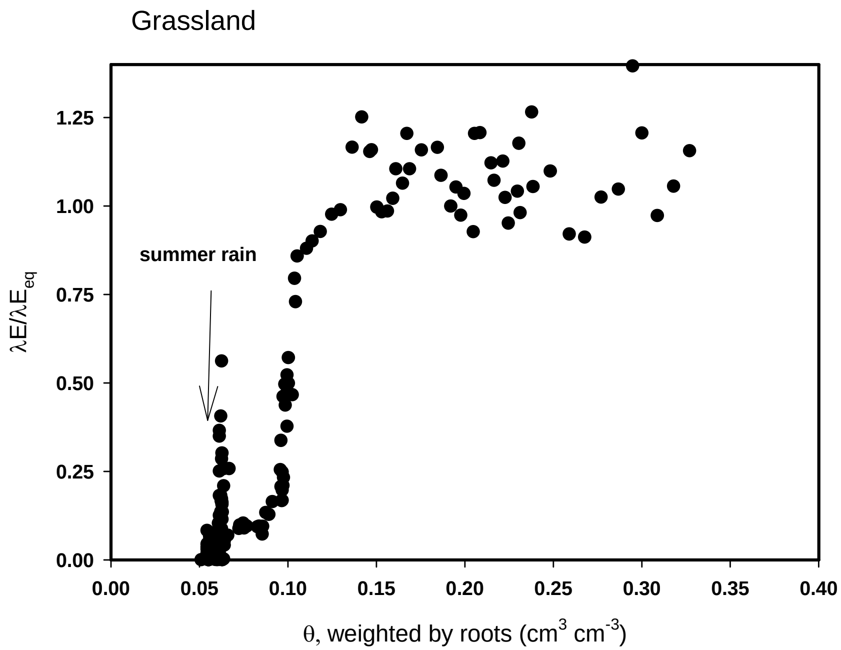


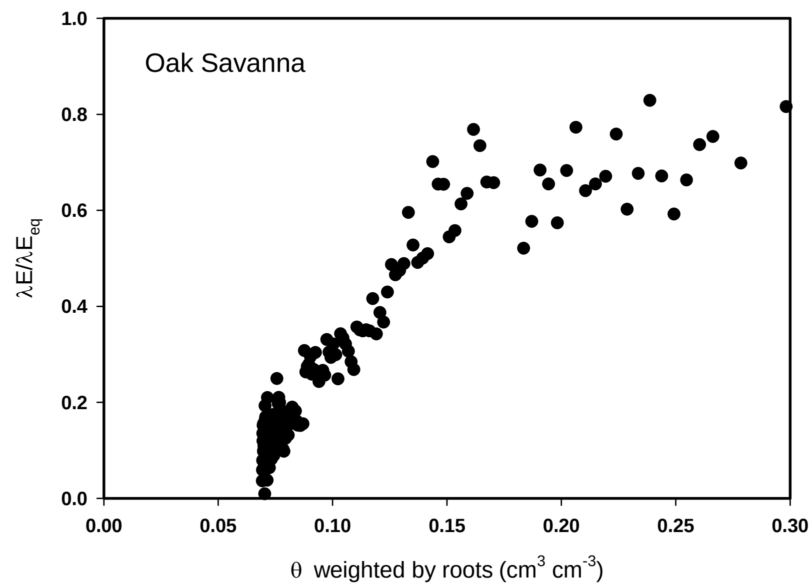
Wilson et al. 2001, Tree Physiology
Schulze et al 1994. Annual Rev Ecology

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



ET and Soil Water Deficits: Root-Weighted Soil Moisture

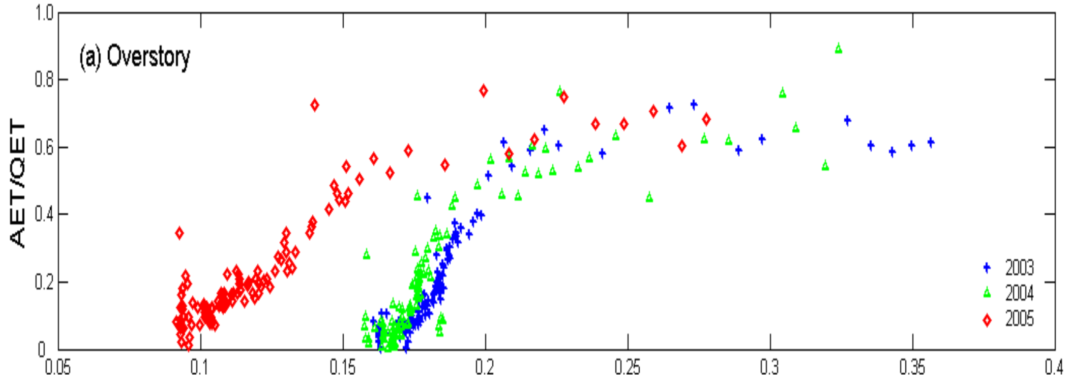




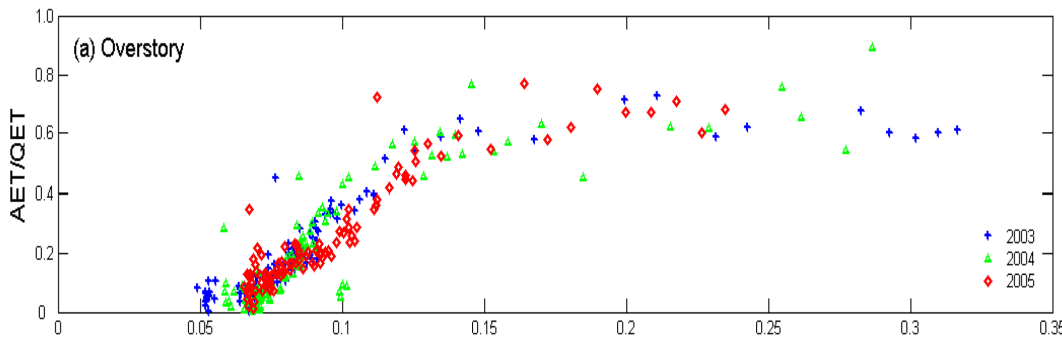
Baldocchi et al., 2004 AgForMet

Use Appropriate and Root-Weighted Soil Moisture

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



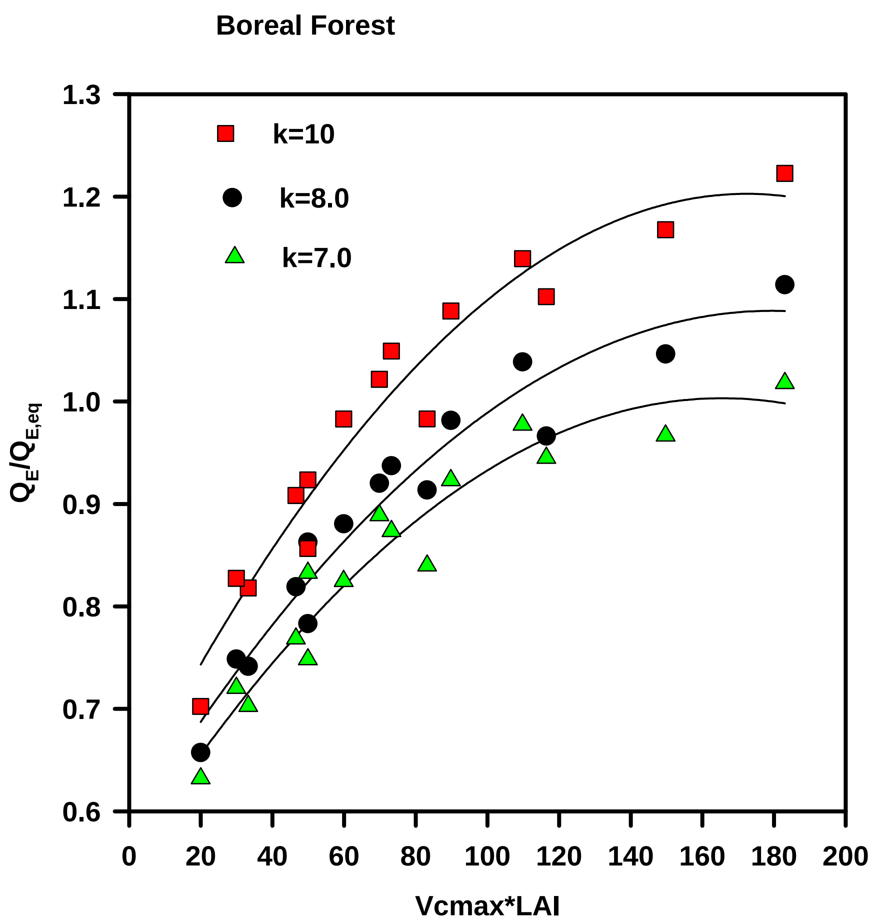
Soil Moisture, arthimetic average



Soil Moisture, root-weighted

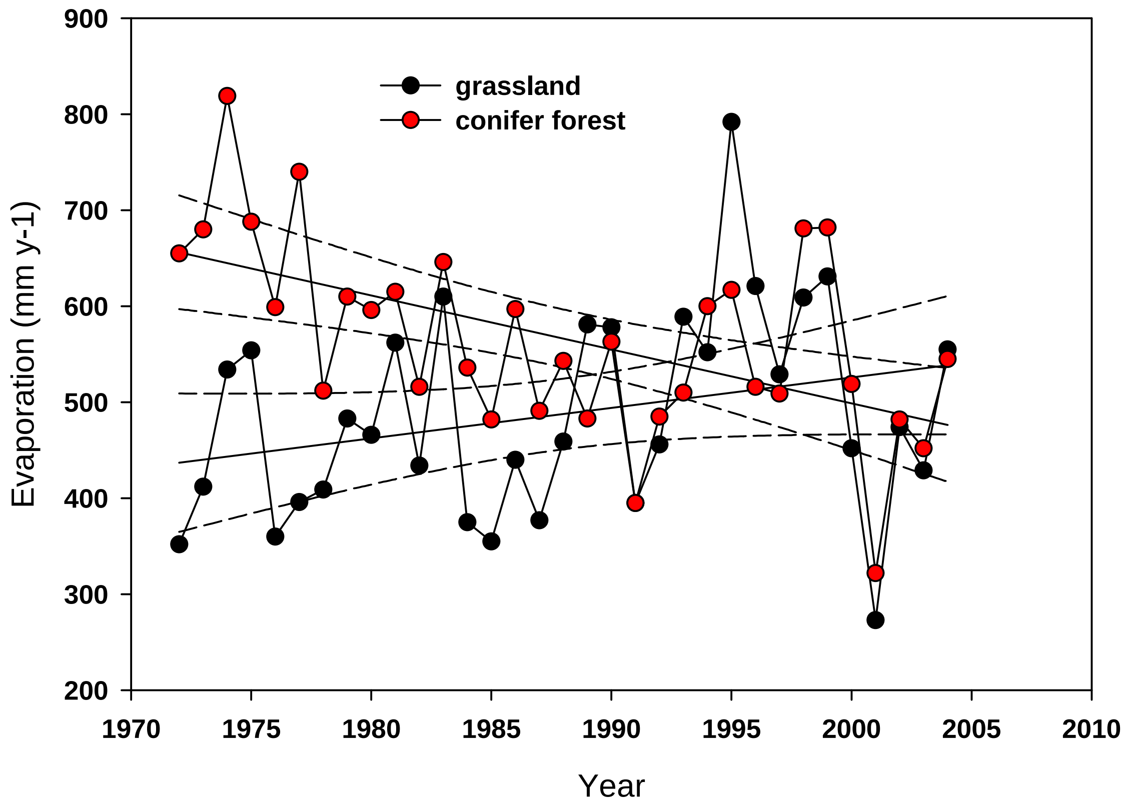
Chen et al, 2008 WRR

$$G_c \sim f(LAI, G_{s\max}, N, \theta_v)$$



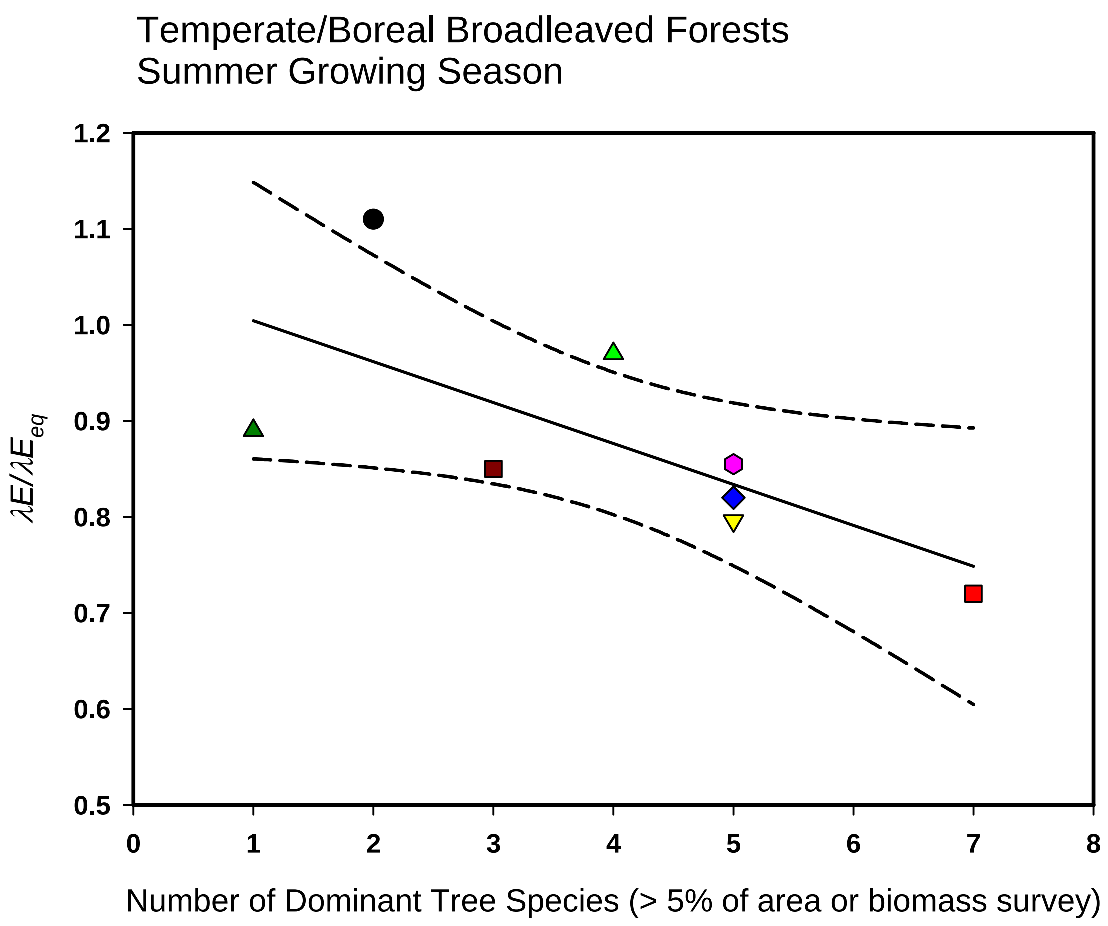
Stand Age also affects differences between ET of forest vs grassland

Plynlimon, Wales



Marc and Robinson, 2007 HESS

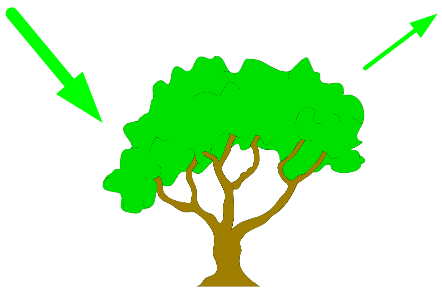
Forest Biodiversity is Negatively Correlated with Normalized Evaporation

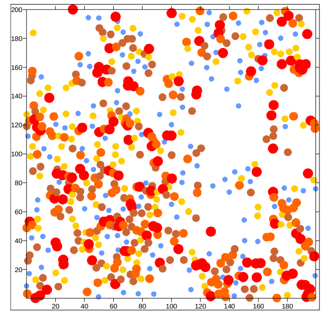


Baldocchi, 2005 In: Forest Diversity and Function: Temperate and Boreal Systems.

Photosynthesis > Respiration

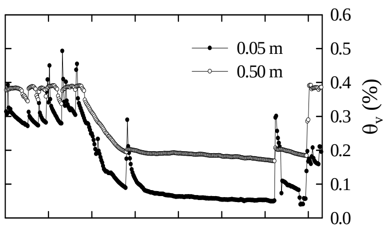
CO_2

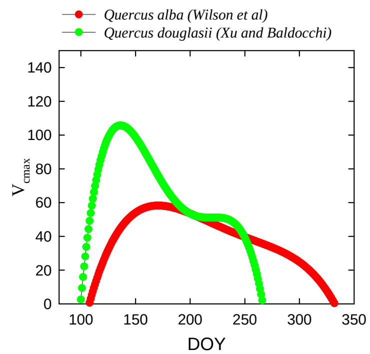




Limited Lear Area and Sparse Canopy Reduce ET, too

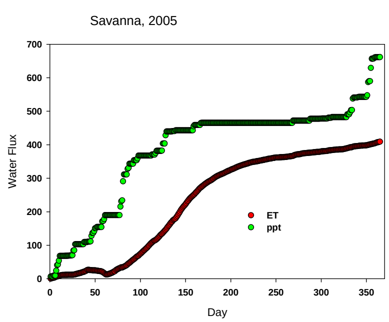
Short growing season with available moisture

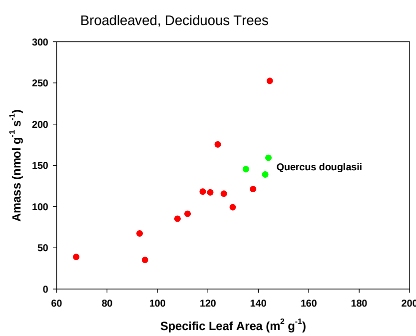




Ps Capacity must be Great, For Short Period

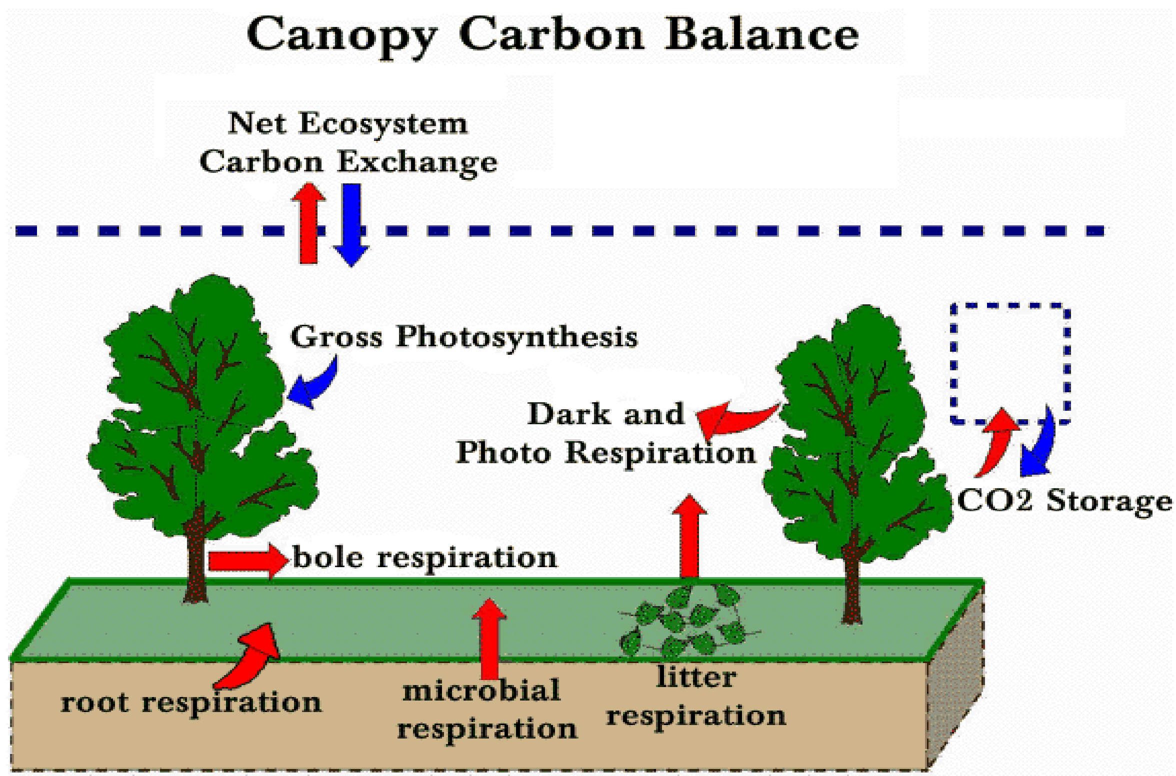
Stomatal Closure so Evaporation > Precipitation





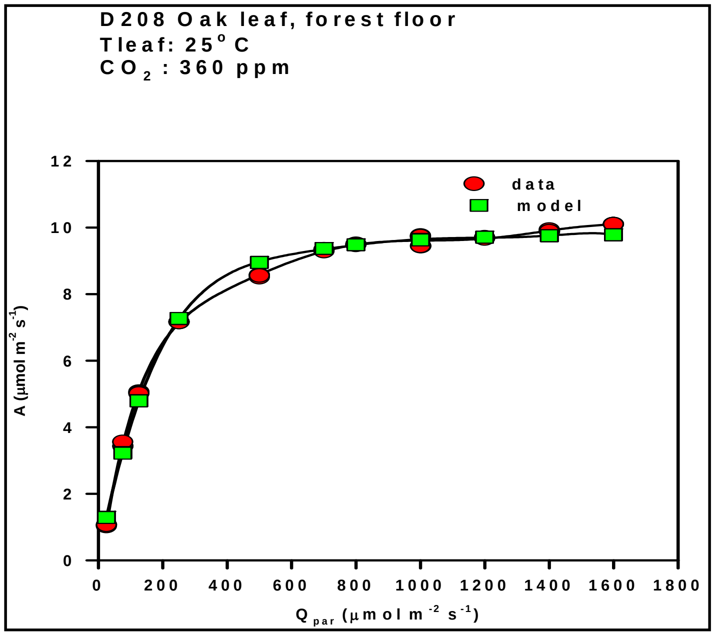
data of Reich et al and Xu and Baldocchi

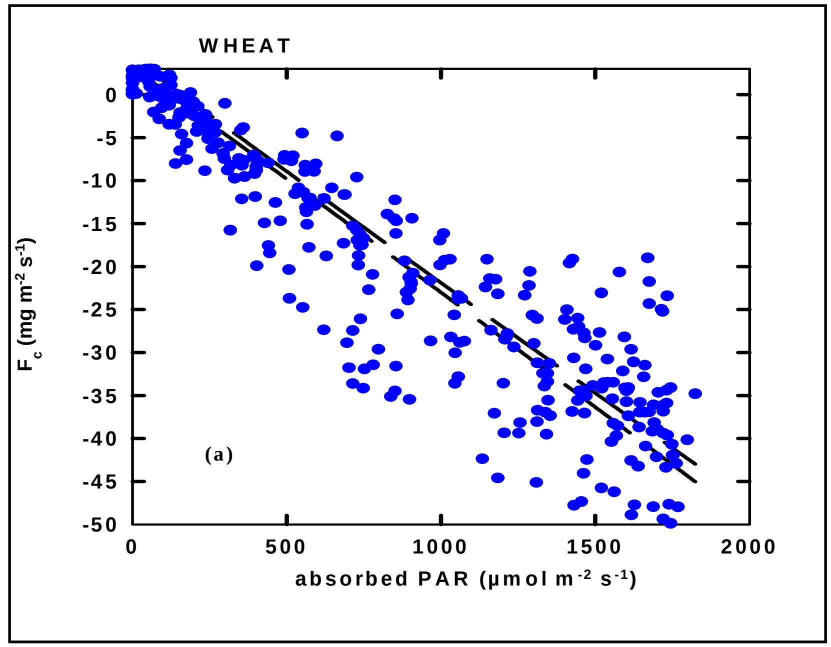
Leaf N and Leaf Thickness must support Ps Machinery



- What types of landscapes are better or worse sinks for Carbon?
- How does Carbon Assimilation and Respiration respond to Environmental stresses, like drought, heatspells, pollution?
- Are Forests Effective Mitigators for stalling Global Warming?

Carbon Uptake of Crops is a Linear Function of Sunlight: An Emergent Property of the EcoSystem



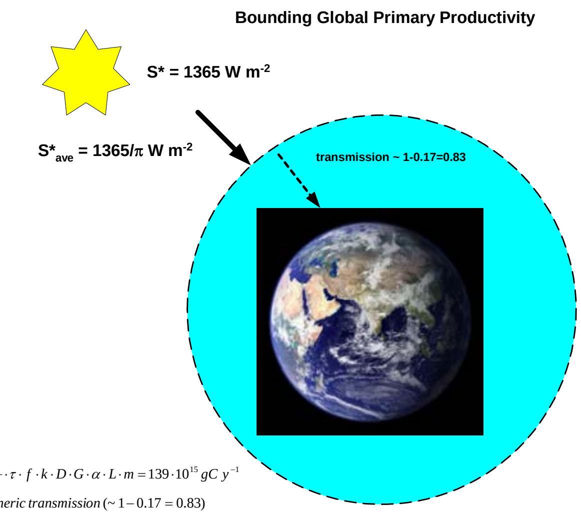


What is the Upper Bound of GPP?

Bottom-Up:
Counting Productivity on leaves, plant by plant, species by species

Global GPP is ~ 120 * 10^{15} gC y^{-1}

Top-Down:
Energy Transfer



$$GPP = \frac{S^*}{\pi} \cdot \tau \cdot f \cdot k \cdot D \cdot G \cdot \alpha \cdot L \cdot m = 139 \cdot 10^{15}\, gC\, y^{-1}$$

t : atmospheric transmission ($\sim 1 - 0.17 = 0.83$)

k : conversion factor, shortwave energy to moles visible quanta ($0.5 \cdot 4.6 \cdot 10^{-6}$)

f : fraction of absorbed quanta by canopy (0.9)

D : daylength (12hr x 3600 s / hr)

G : growing season (180days)

a : light use efficiency

L : Land area ($100 \cdot 10^{12}\ m^2$)

m : 12gC mole

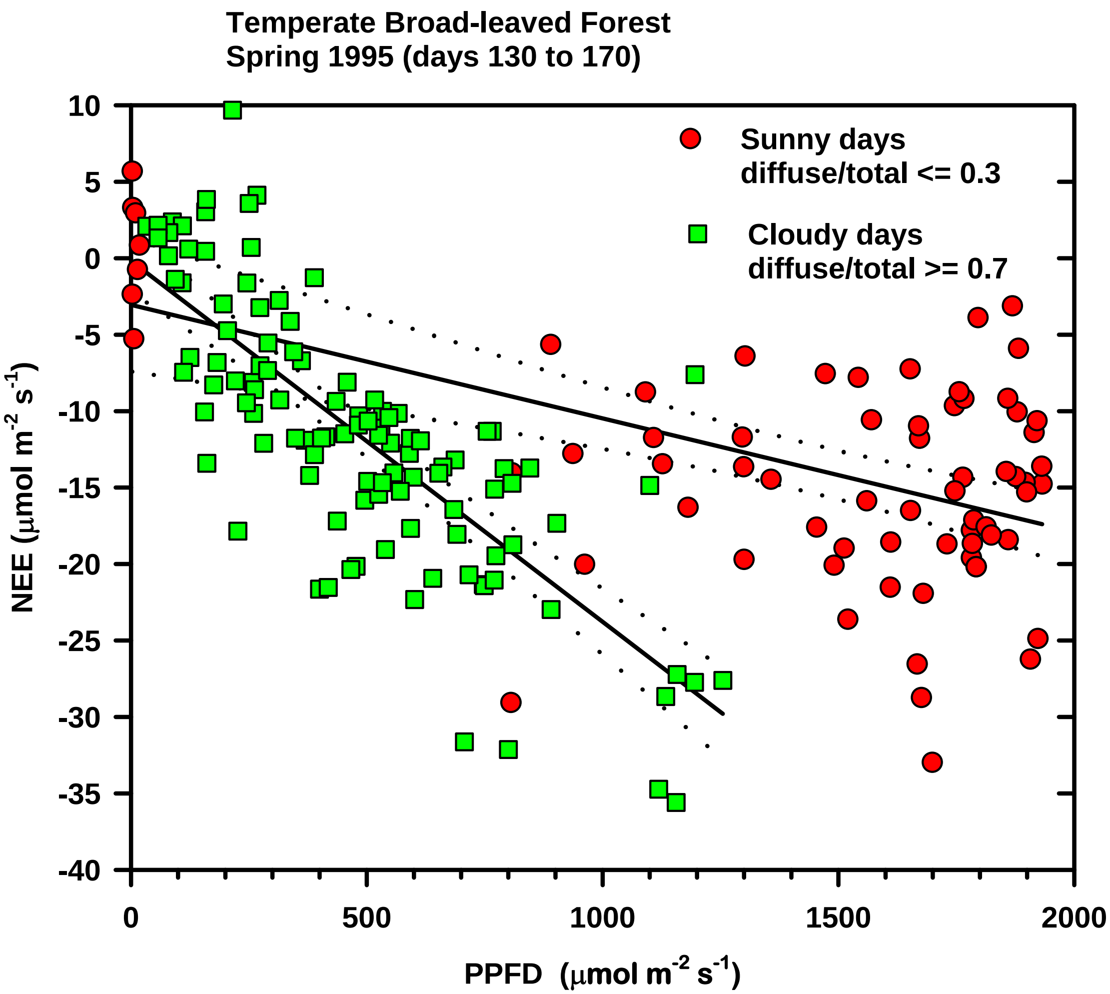
Upper-Bound on Global Gross Primary Productivity

- Global GPP is ~ 120 * 10^{15} gC y^{-1}

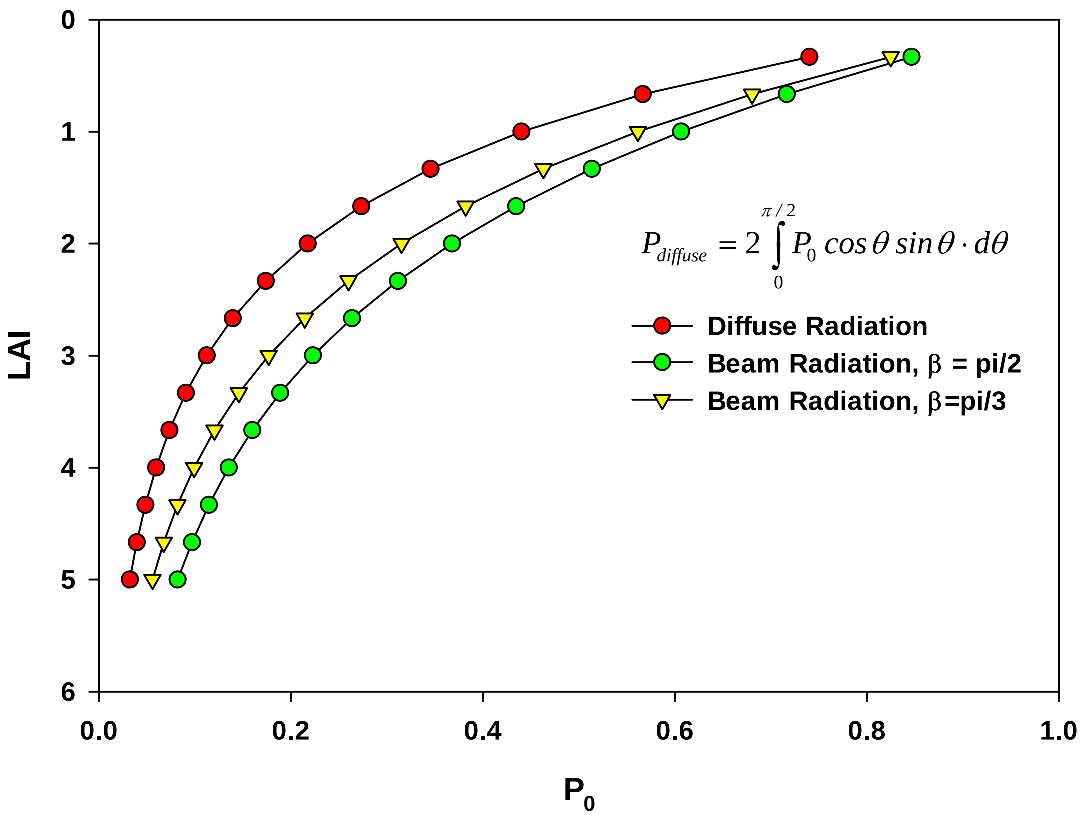
- Solar Constant, S* (1366 W m^{-2})
  - Ave across disk of Earth S*/4
- Transmission of sunlight through the atmosphere (1-0.17=0.83)
- Conversion of shortwave to visible sunlight (0.5)
- Conversion of visible light from energy to photon flux density in moles of quanta (4.6/10^6)
  - Mean photosynthetic photon flux density, Q_p
- Fraction of absorbed Q_p (1-0.1=0.9)
- Photosynthetic efficiency, a (0.015)
- Arable Land area (~ 133 * 10^{12} m^2)
- Length of daylight (12 hours * 60 minutes * 60 seconds = 43200 s/day)
- Length of growing season (188 days)
- Gram of carbon per mole (12)

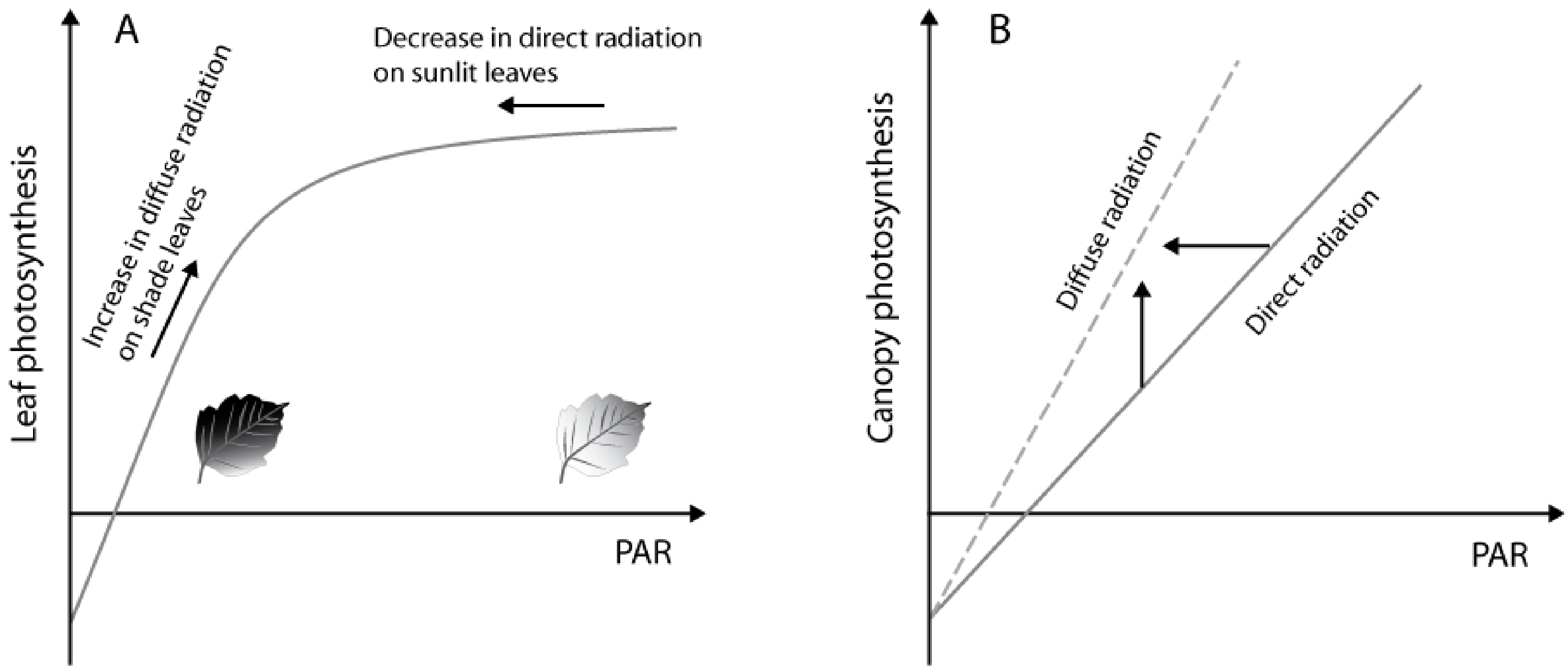
GPP = 1366*0.83*0.5*4.6*0.9*0.015*133 10^{12}*43200*188*12/(4* 10^6)=114* 10^{15} gC y^{-1}

Canopy Light Response Curves: Effect of Diffuse Light



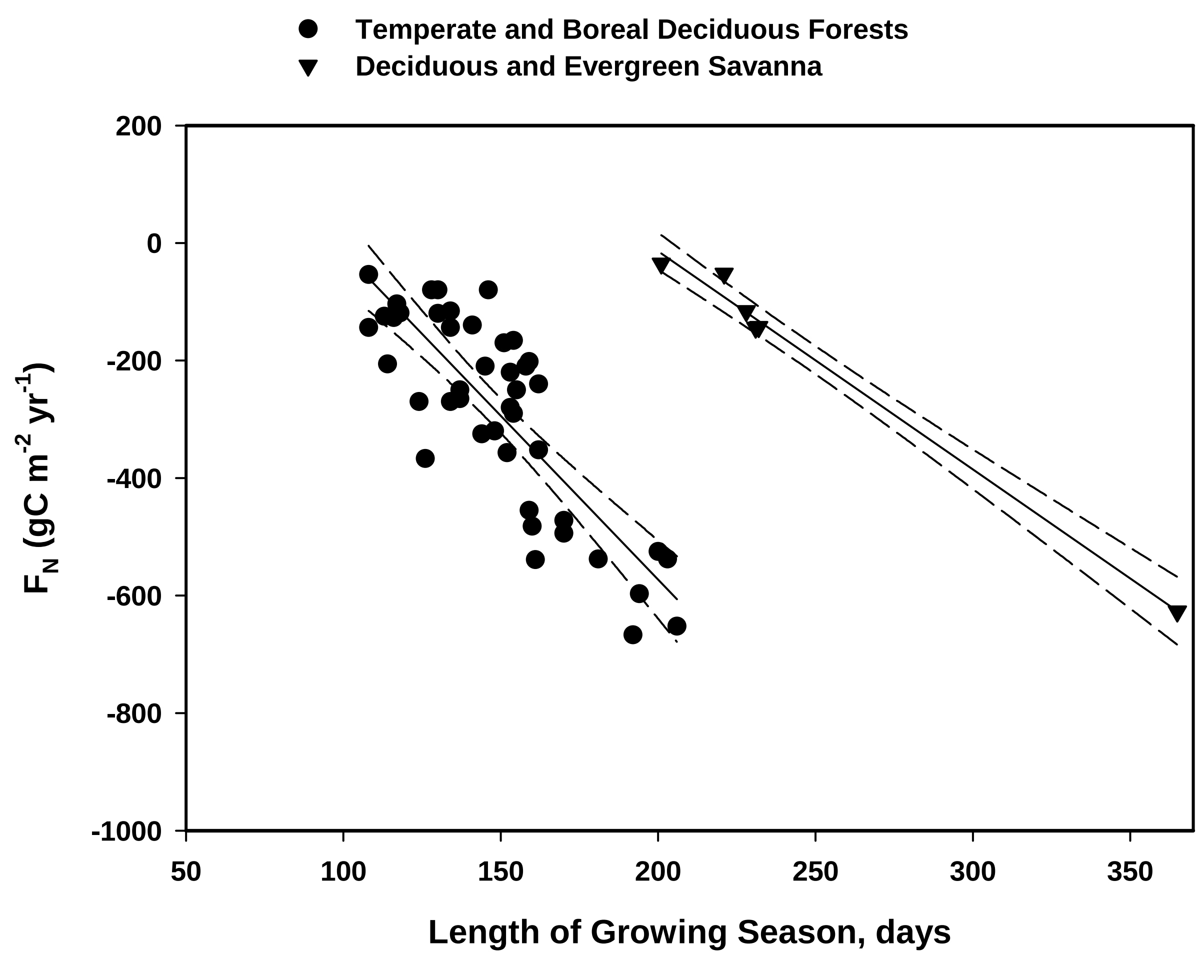
More Diffuse Light is Intercepted that Direct Radiation, at High Solar Elevation Angles





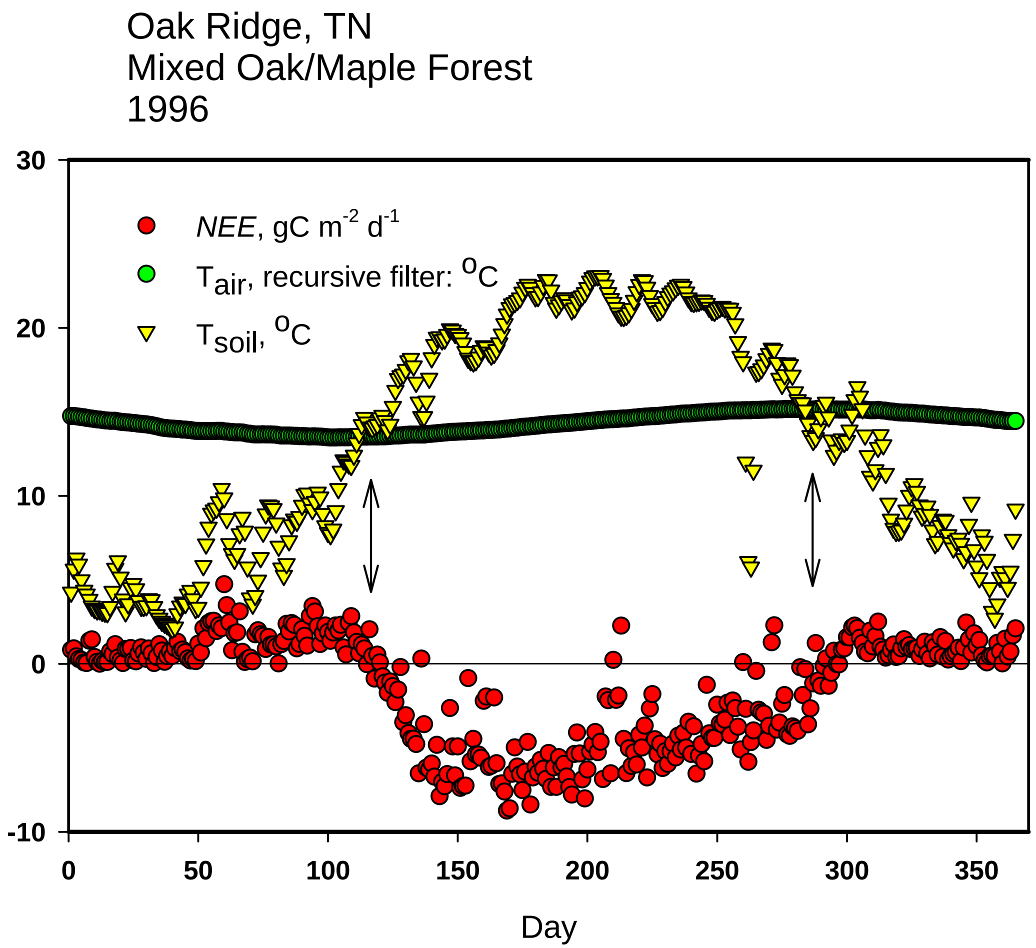
Knohl and Baldocchi, 2008 JGR Biogeosciences

Net Ecosystem Carbon Exchange Scales with Length of Growing Season

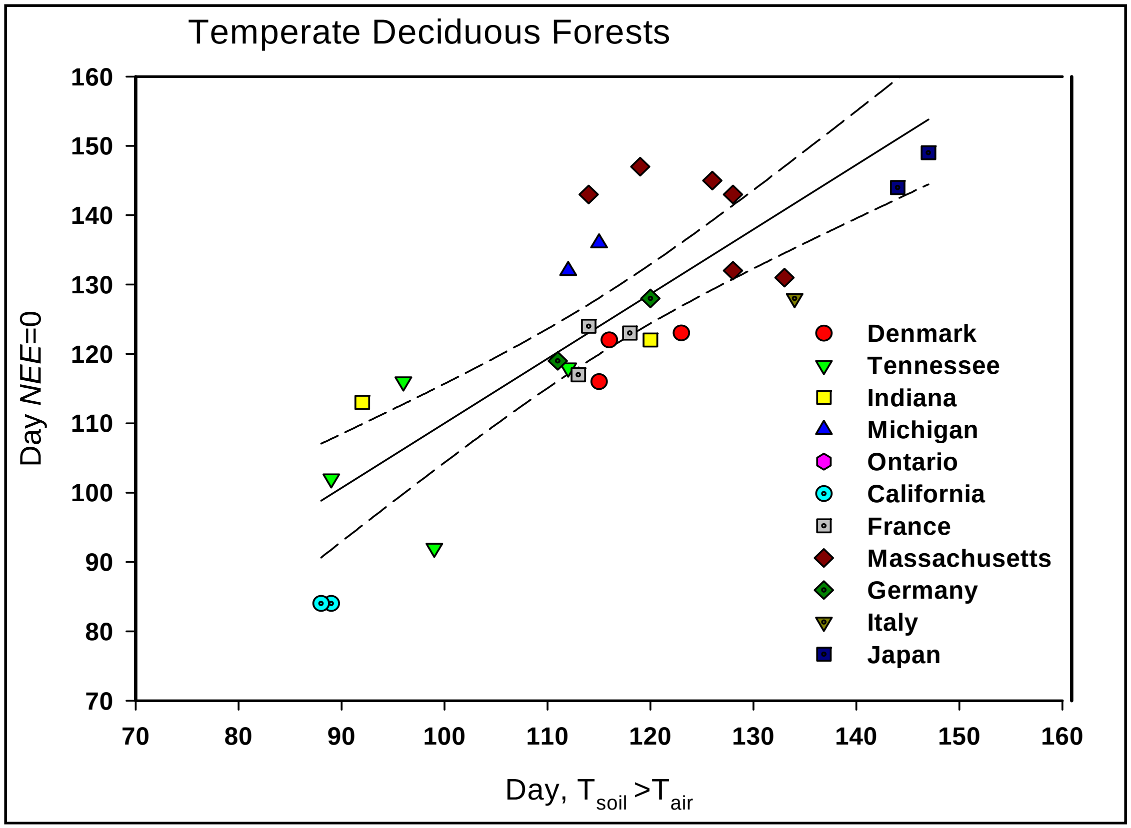


Baldocchi, Austral J Botany, 2008

Length of Growing Season, in Temperate Ecosystems, is associated with the timing between soil temperature and mean annual air temperature



Soil Temperature:
An Objective Measure of Phenology, part 2



Baldocchi et al. Int J. Biomet, 2005

If Papal Indulgences Saved Them from burning in Hell: Can Carbon Indulgences save us from Global Warming?

Alexander VI

Sixtus IV

Innocent VIII

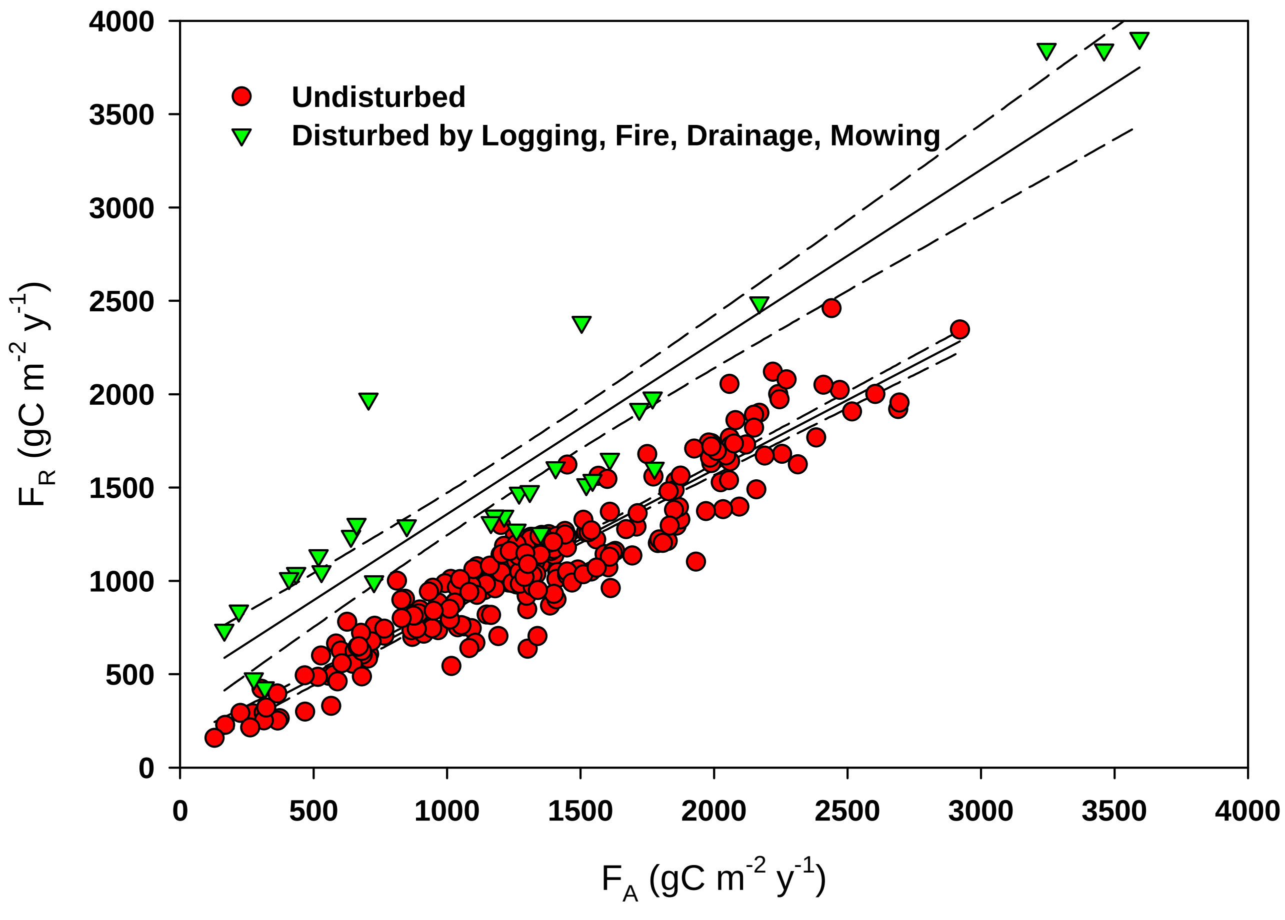
Julius II

Leo X

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

Ecosystem Respiration Scales Tightly with Ecosystem Photosynthesis, And Is with Offset Positively by Disturbance



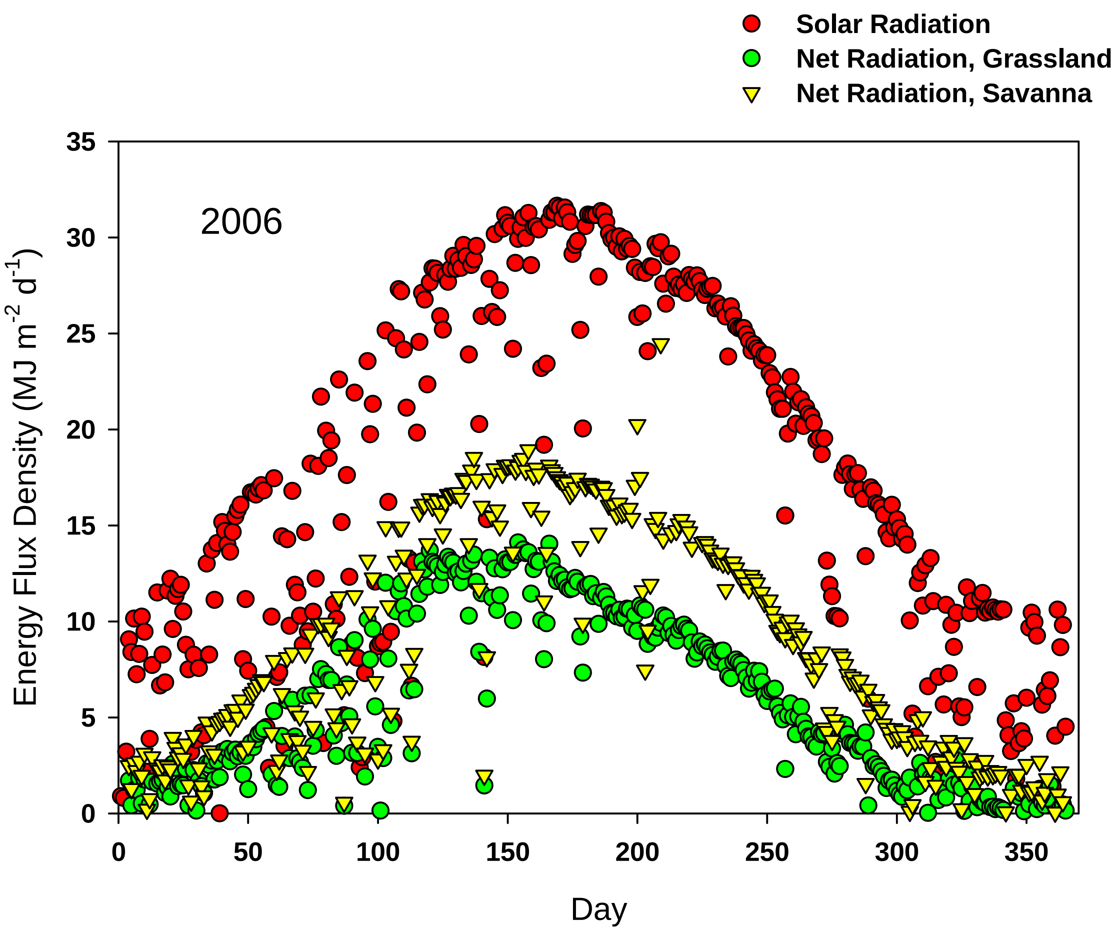
Baldocchi, Austral J Botany, 2008

Case Study:

Energetics of a Grassland and Oak Savanna

Measurements and Model

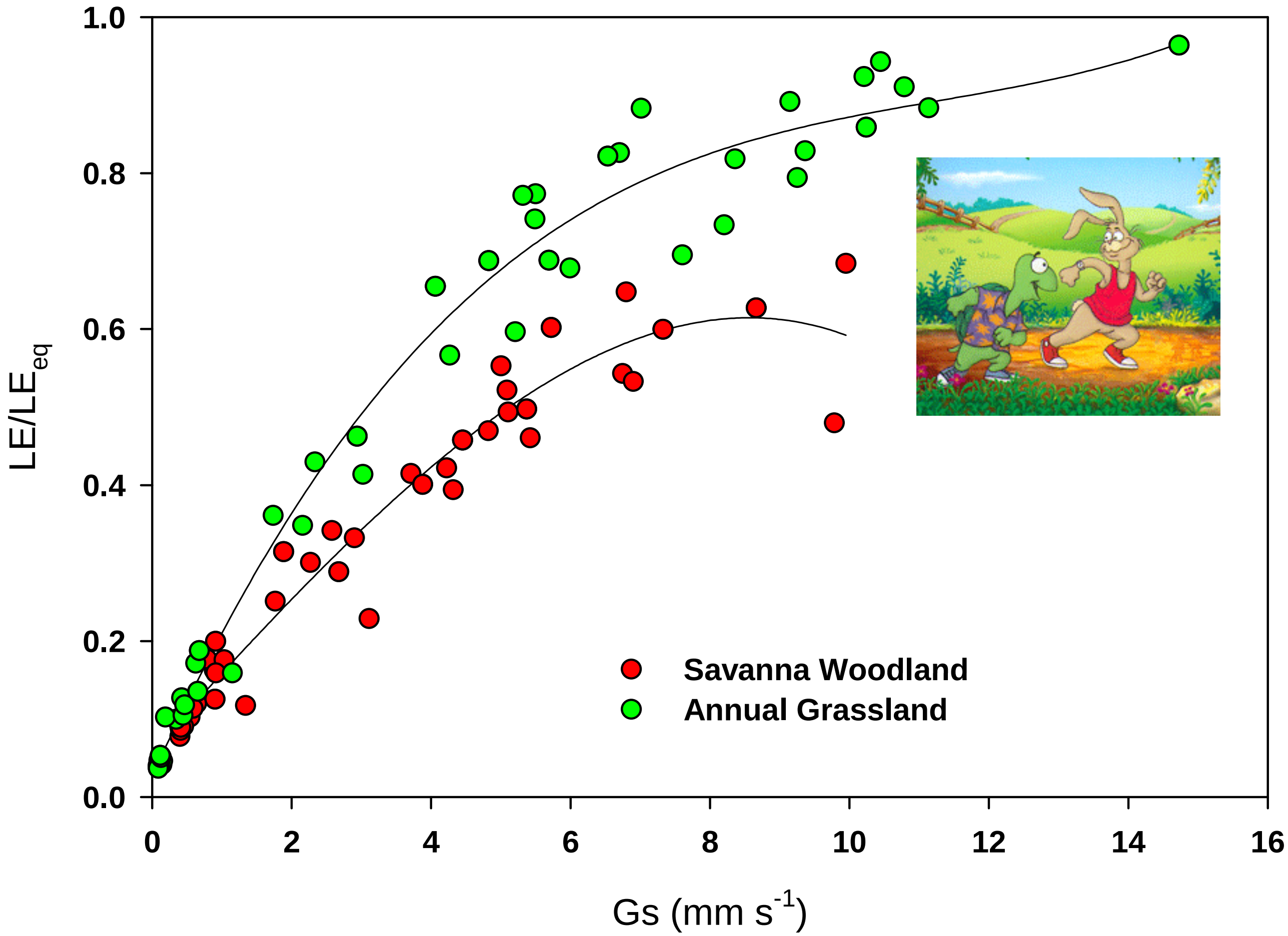
Case Study:
Savanna Woodland adjacent to Grassland



1. Savanna absorbs much more Radiation (3.18 GJ m^{-2} y^{-1}) than the Grassland (2.28 GJ m^{-2} y^{-1}) ; ΔRn: 28.4 W m^{-2}

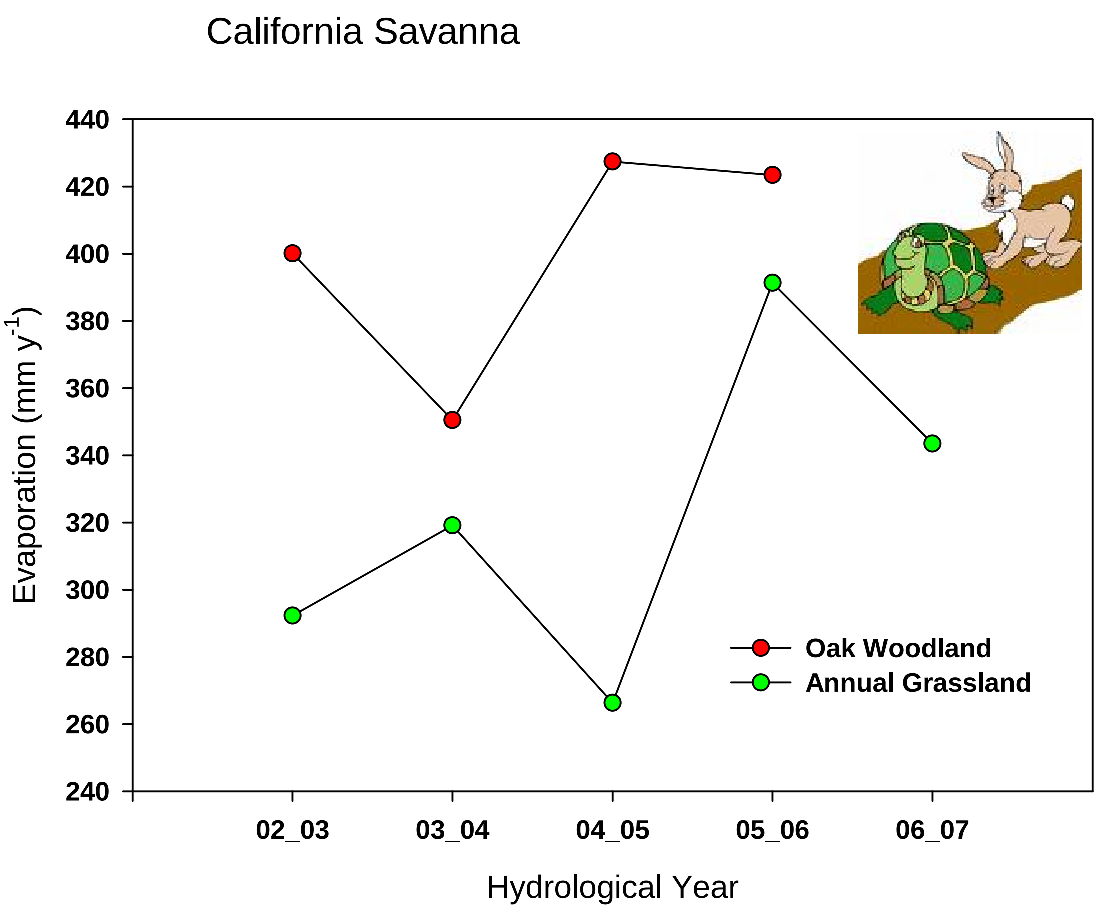
Landscape Differences
On Short Time Scales, Grass ET > Forest ET

Monthly Averages



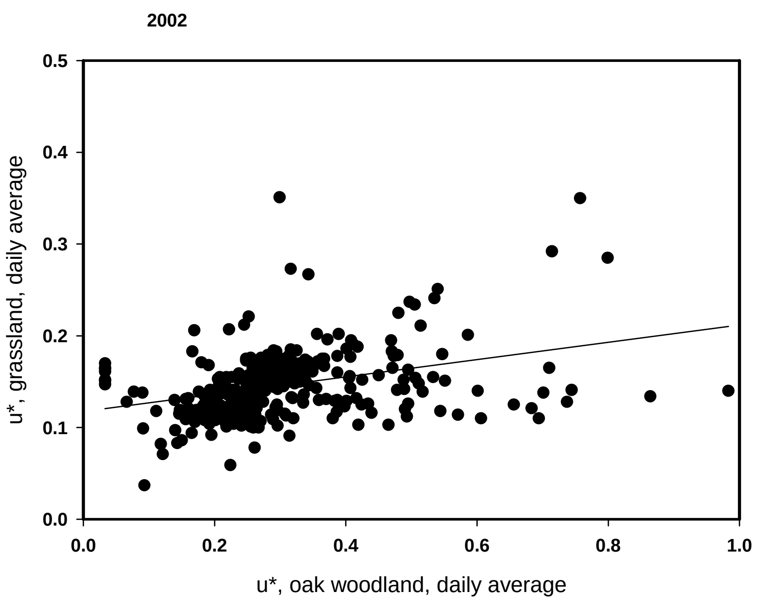
Ryu, Baldocchi, Ma and Hehn, JGR-Atmos, 2008

Role of Land Use on ET:
On Annual Time Scale, Forest ET > Grass ET

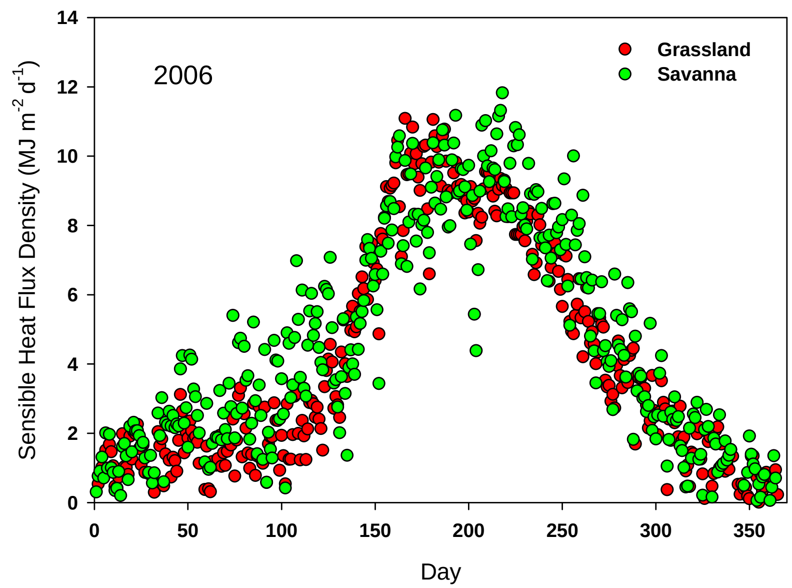


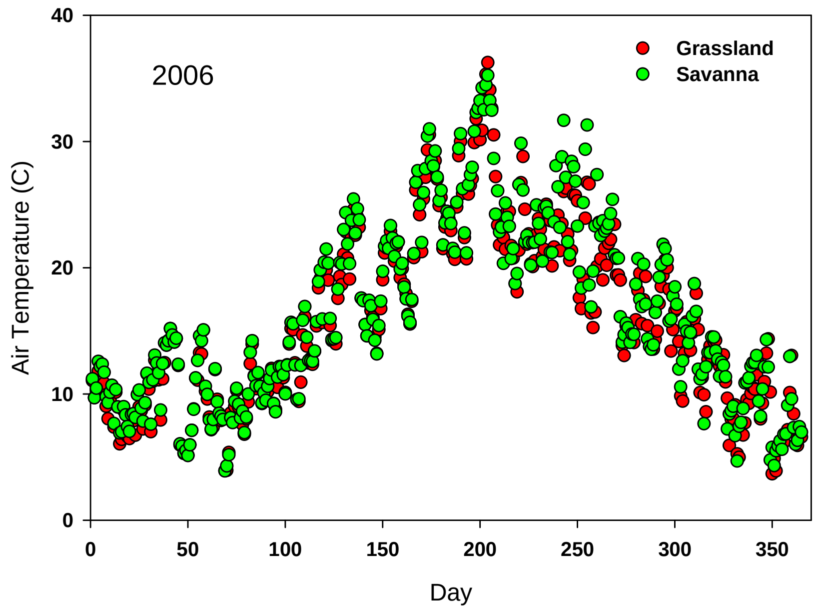
Ryu, Baldocchi, Ma and Hehn, JGR-Atmos, 2008

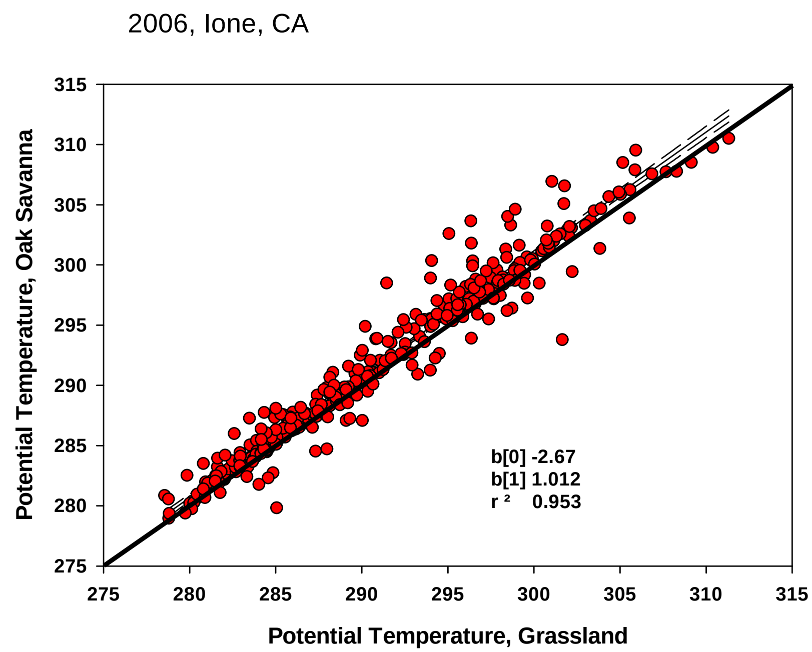
4a. U* of tall, rough Savanna > short, smooth Grassland



4b. Savanna injects more **Sensible Heat** into the atmosphere because it has more **Available Energy** and it is **Aerodynamically Rougher**



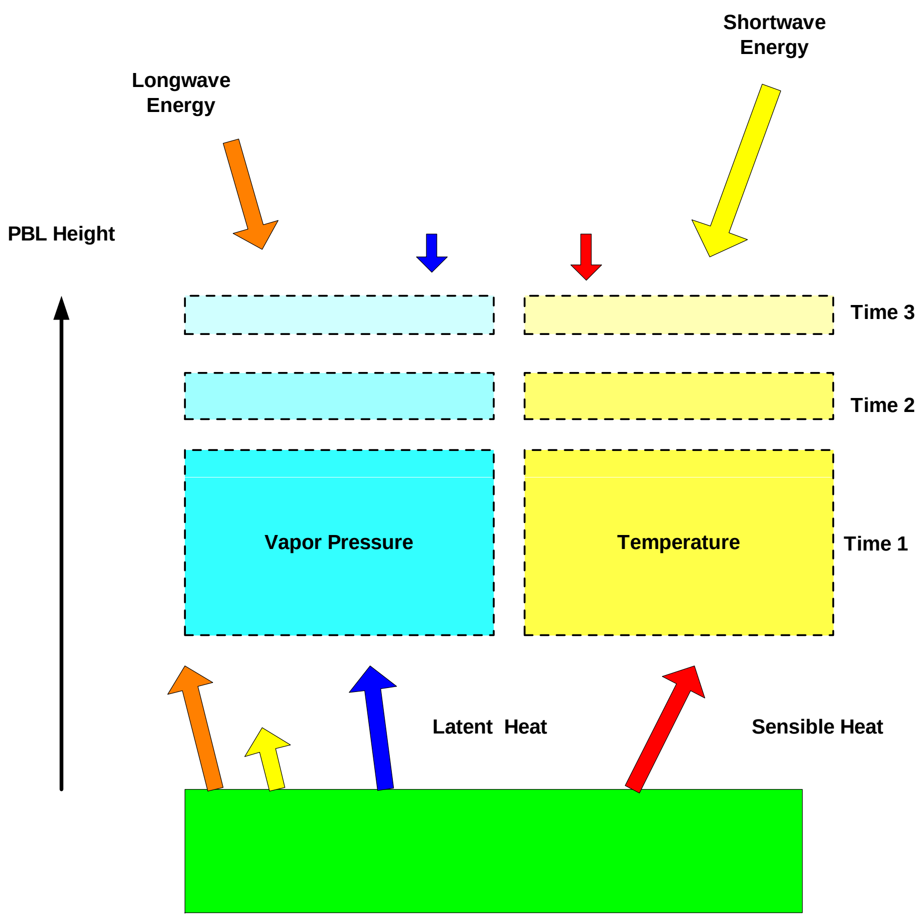


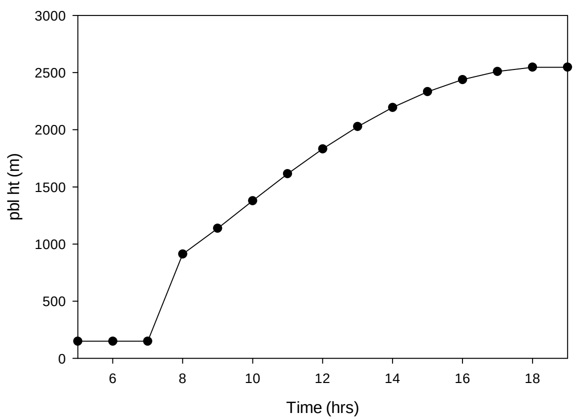


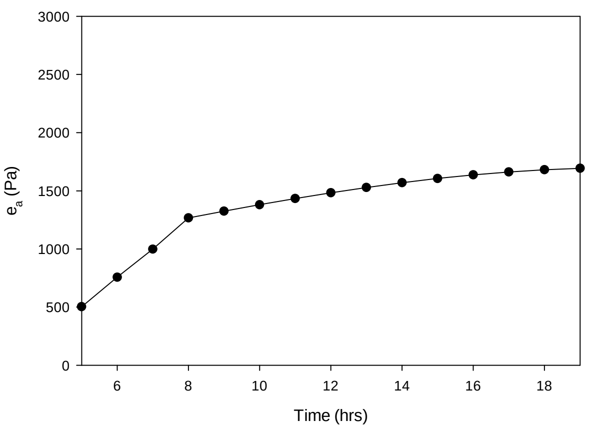
5. Mean **Potential Temperature** differences are relatively small (0.84 C; grass: 290.72 vs savanna: 291.56 K); despite large differences in Energy Fluxes--albeit the **Darker** vegetation is **Warmer**

Compare to Greenhouse Sensitivity ~2-4 K/(4 W m^{-2})

Conceptual Diagram of PBL Interactions







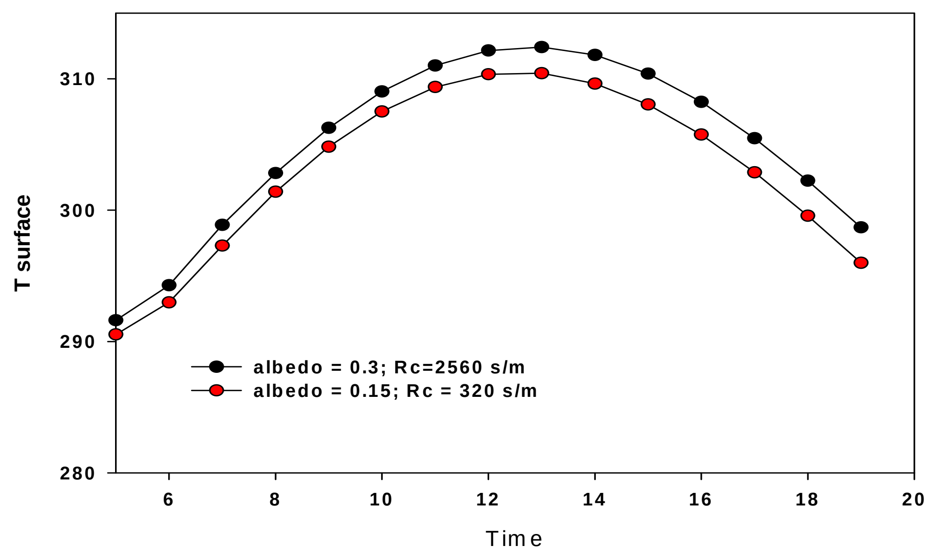
H and LE: Analytical/Quadratic version of Penman-Monteith Equation

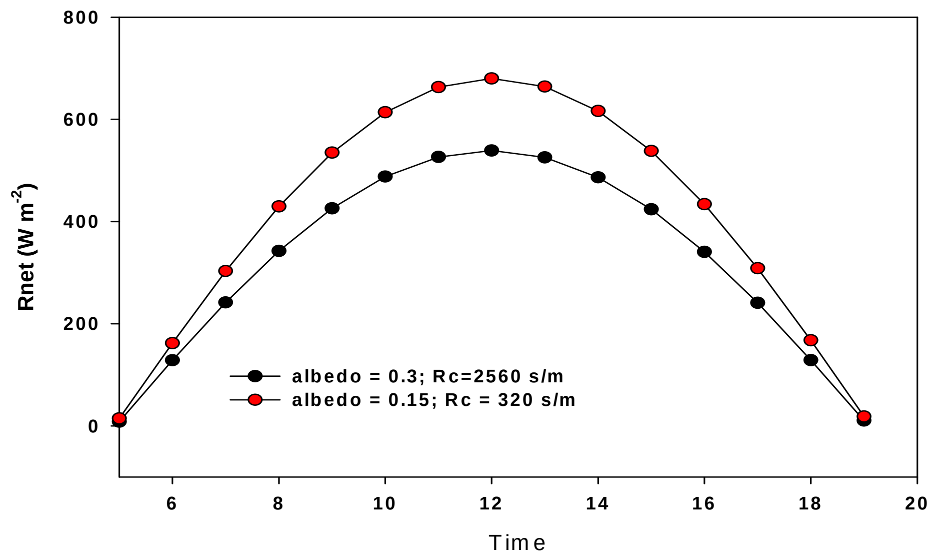
- The Energetics of afforestation/deforestation is complicated

- Forests have a low albedo, are darker and absorb more energy

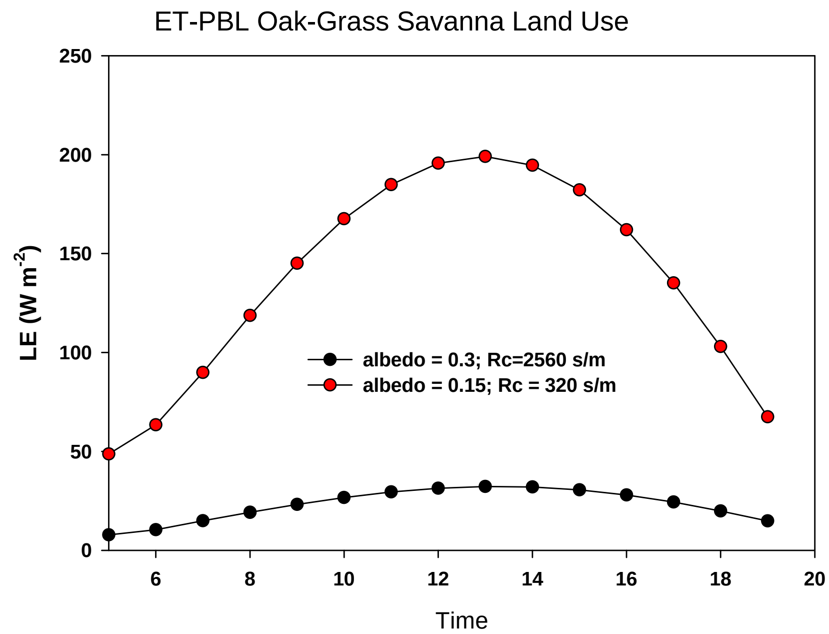
- But, Ironically the **darker** forest maybe **cooler** (T_{sfc}) than a bright grassland due to evaporative cooling

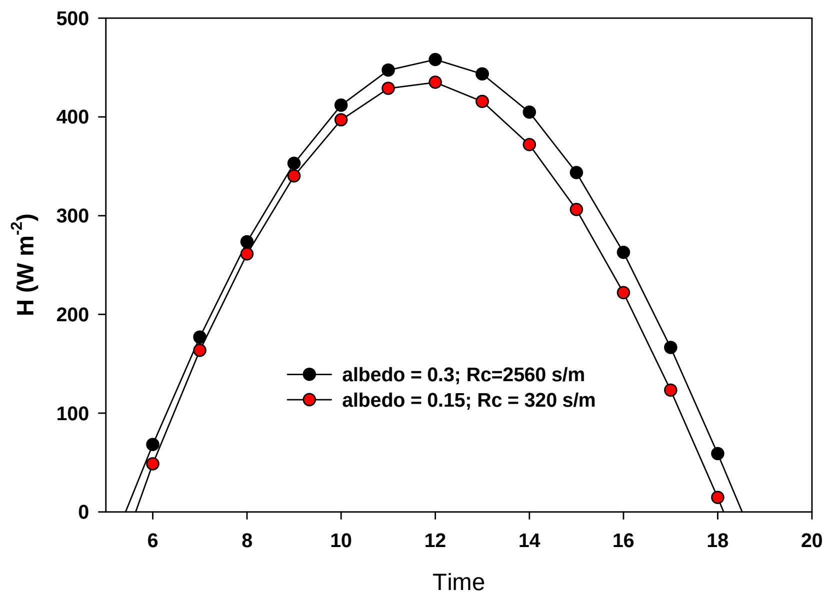
ET-PBL Oak-Grass Savanna Land Use



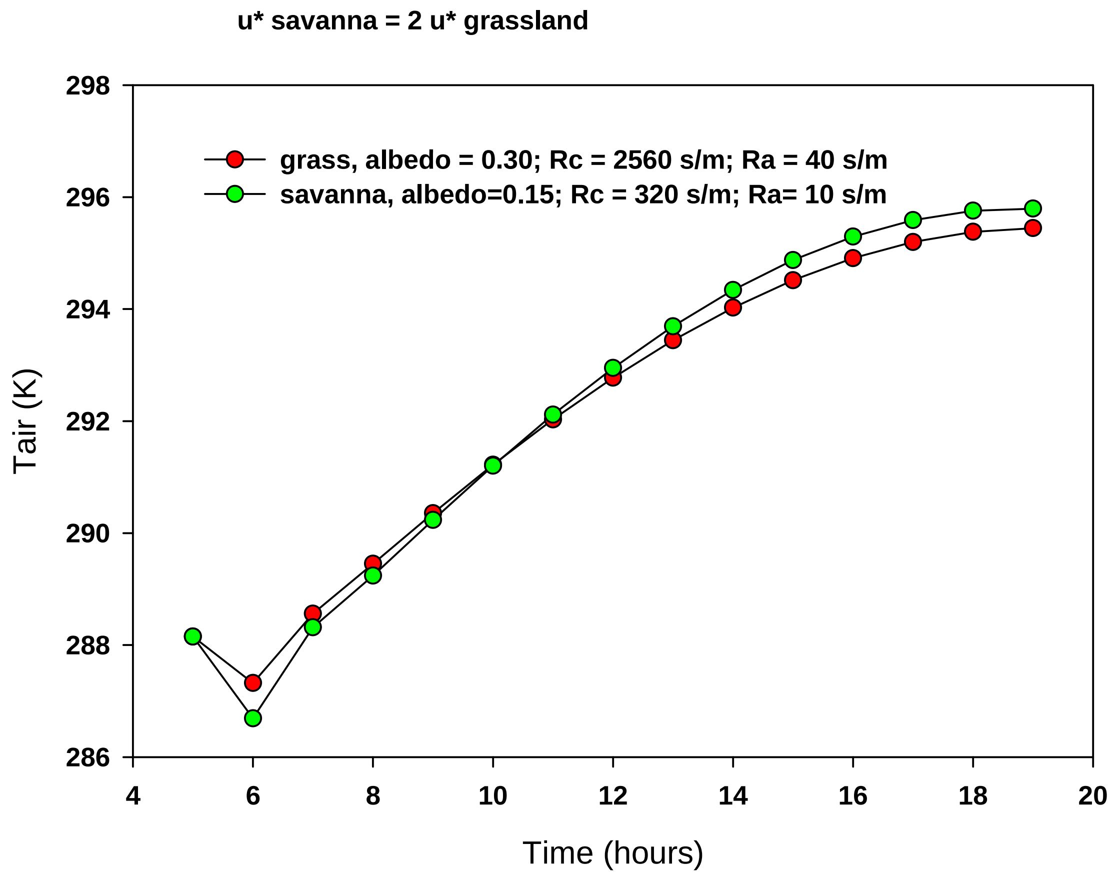


• Forests Transpire effectively, causing evaporative cooling, which in humid regions may form clouds and reduce planetary albedo





Small, but Positive, Temperature Differences Stem from interactions among PBL, R_a and albedo….!!

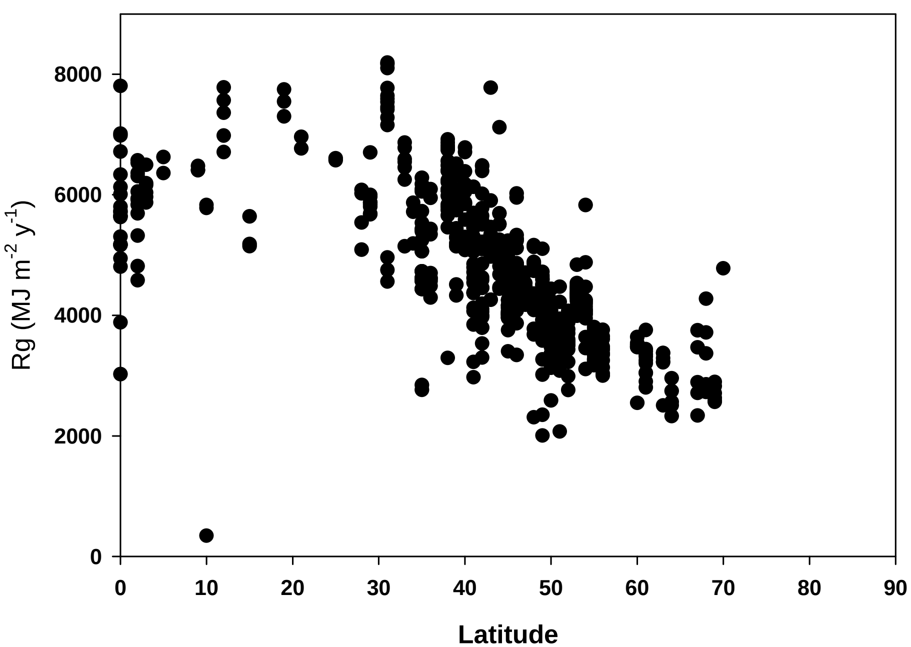


Summer Conditions

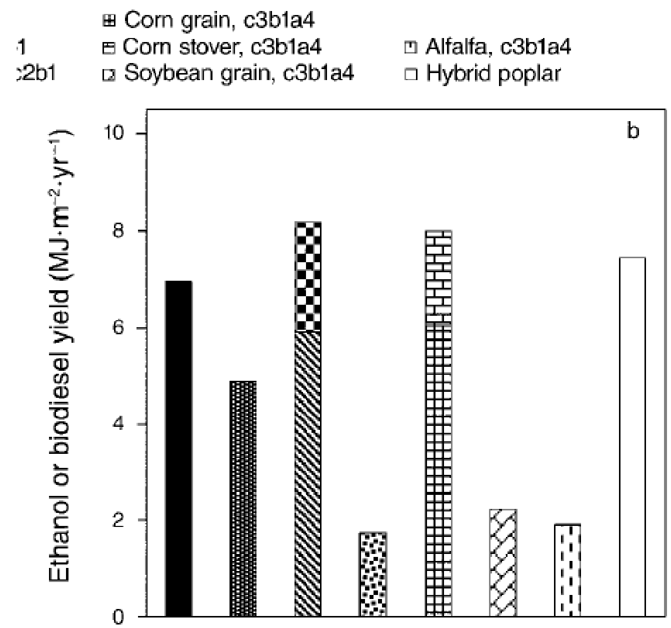
What about Forests and other Vegetation as a source Biofuels?

Energy Drives Metabolism:
How Much Energy is Available and Where

FLUXNET database



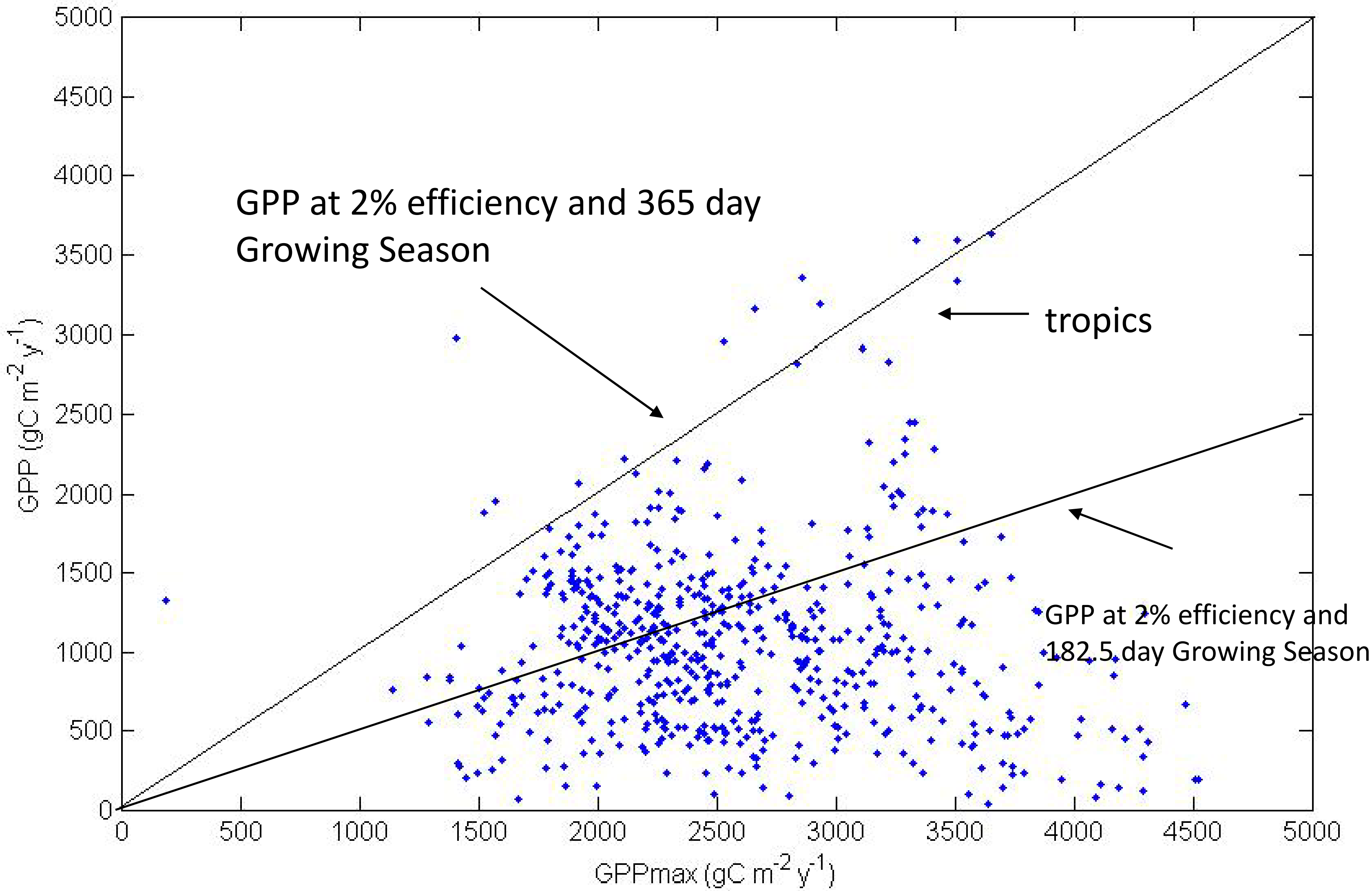
Only a small fraction of Solar Energy is converted to Biofuels



Adler et al 2007 Ecol Appl

Plant systems are Low Efficiency Solar Cells that Operate only Part of the Year!

Potential and Real Rates of Gross Carbon Uptake by Vegetation: Most Locations Never Reach Upper Potential



FLUXNET 2007 Database

How Does Energy Availability Compare with Energy Use?

- US Energy Use: 105 EJ/year
  - 10^{18}J per EJ
  - US Population: 300 10^{6}
  - 3.5 10^{11} J/capita/year
- US Land Area: 9.8 10^{6} km^2=9.8 10^{12} m^2 = 9.8 10^{8} ha
- Energy Use per unit area: 1.07 10^{7} J m^{-2}
- Potential, Incident Solar Energy: 6.47 10^{9} J m^{-2}
  - Ione, CA
- Assuming 20% efficient solar system
  - 8.11 10^{10} m^2 of Land Area Needed (8.11 10^{5} km^2, the size of South Carolina)

Concluding Issues to Consider

- Vegetation operates less than ½ of the year and is a solar collector with less than 2% efficiency
  - Solar panels work 365 days per year and have an efficiency of 20%+
- Ecological Scaling Laws are associated with Planting Trees
  - Mass scales with the -4/3 power of tree density
- Available Land and Water
  - Best Land is Vegetated and New Land needs to take up More Carbon than current land
  - You need more than 500 mm of rain per year to grow Trees
- The ability of Forests to sequester Carbon declines with stand age
- There are Energetics and Environmental Costs to soil, water, air and land use change
  - Changes in Albedo and surface energy fluxes
  - Emission of volatile organic carbon compounds, ozone precursors
  - Changes in Watershed Runoff and Soil Erosion
- Societal/Ethical Costs and Issues
  - Food for Carbon and Energy
  - Energy is needed to produce, transport and transform biomass into energy
  - Role of forests for habitat and resources
  - Fostering natural Carbon Sinks may be a Band-Aid compared to ‘natural’ growth attributed to population and economy

How much is C in the Air?

- Mass of Atmosphere
  - F=Pressure x Area=g x Mass
  - Surface Area of the Globe = $4\pi R^2$
  - M_{atmos} = 101325 Pa 4π (6378 10^3 m)^2/9.8 m^2 s^{-1}=
  - 5.3 10^{21} g air
- Compute C in Atmosphere @ 380 ppm

$$M_{atmos} = \frac{P \cdot 4\pi R^2}{g}$$

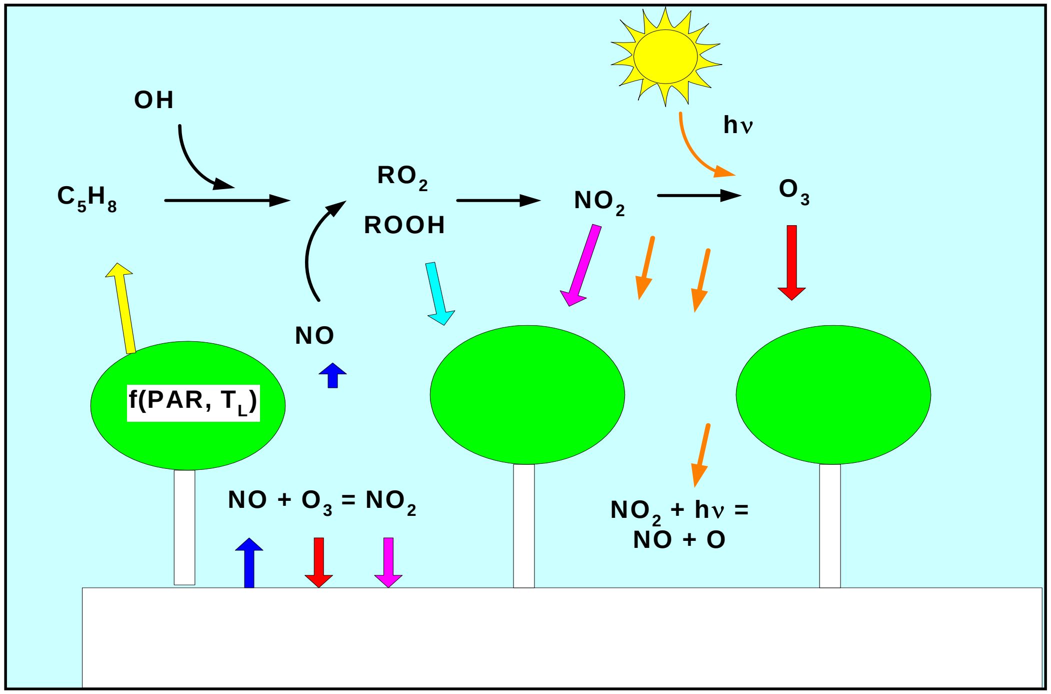
$$M_c = M_{atmos} \frac{p_c}{P} \frac{m_{co2}}{m_a} \frac{m_c}{m_{co2}} = 833 \cdot 10^{15}\, gC$$

$$M_c / (\frac{p_c}{P}) = 2.19$$

CO_2 in 50/100 years Business as Usual?

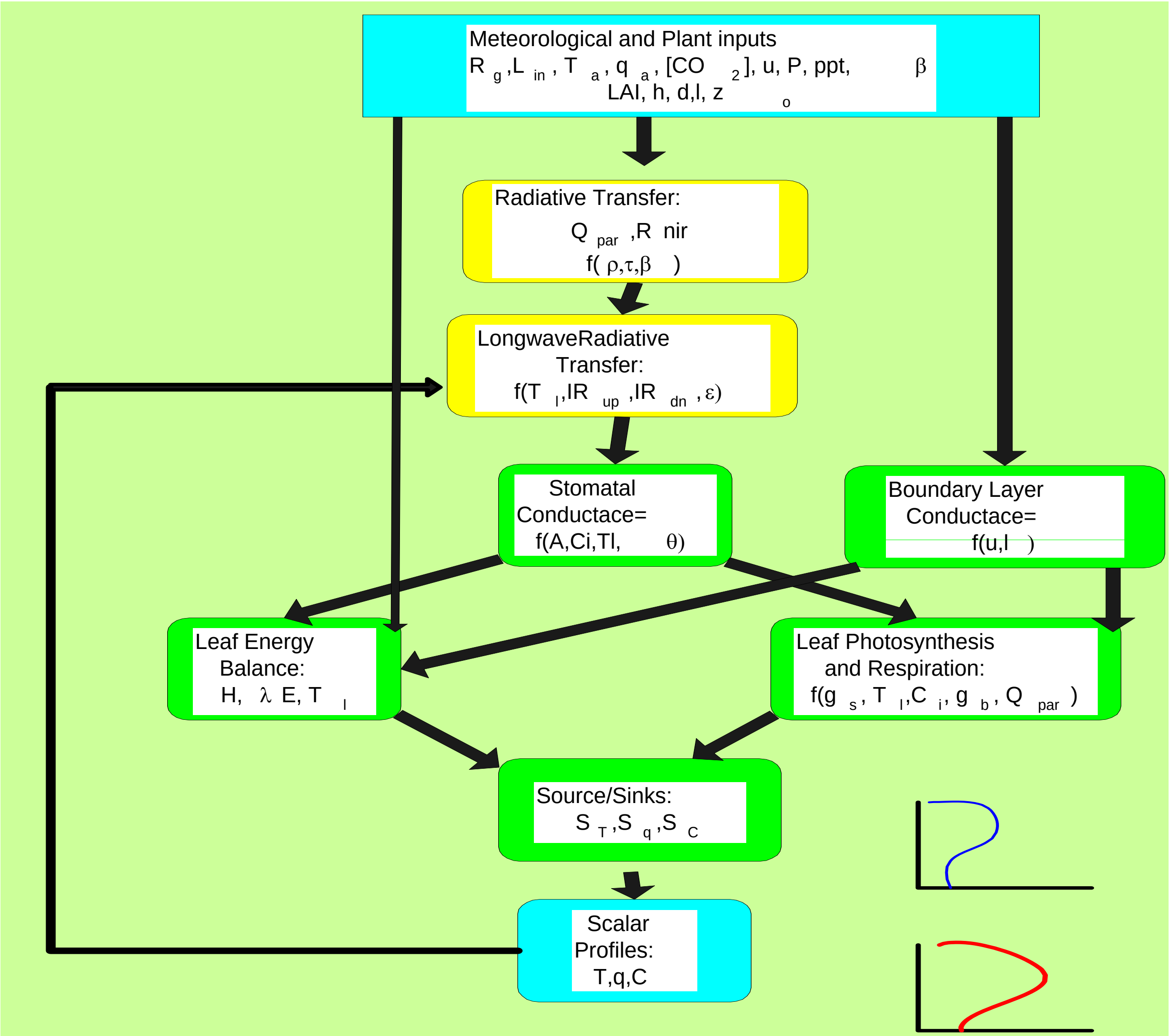
- Current Anthropogenic C Emissions
  - 7 GtC/yr, (1 GtC = 10^{15} g=1Pg)
  - 45% retention in Atmosphere
- Net Atmospheric Efflux over 50 years
  - 7 * 50 * 0.45 = 157 GtC
- Atmospheric Burden over 50 years
  - 833 (@380 ppm) + 157 = 990 GtC,
- Conversion back to mixing ratio
  - 451 ppm (2.19 Pg/ppm) or 1.6 x pre-industrial level of 280 ppm
- To keep atmospheric CO2 below 450 ppm the world must add less than157 GtC into the atmosphere over the next 100 to 200 years.

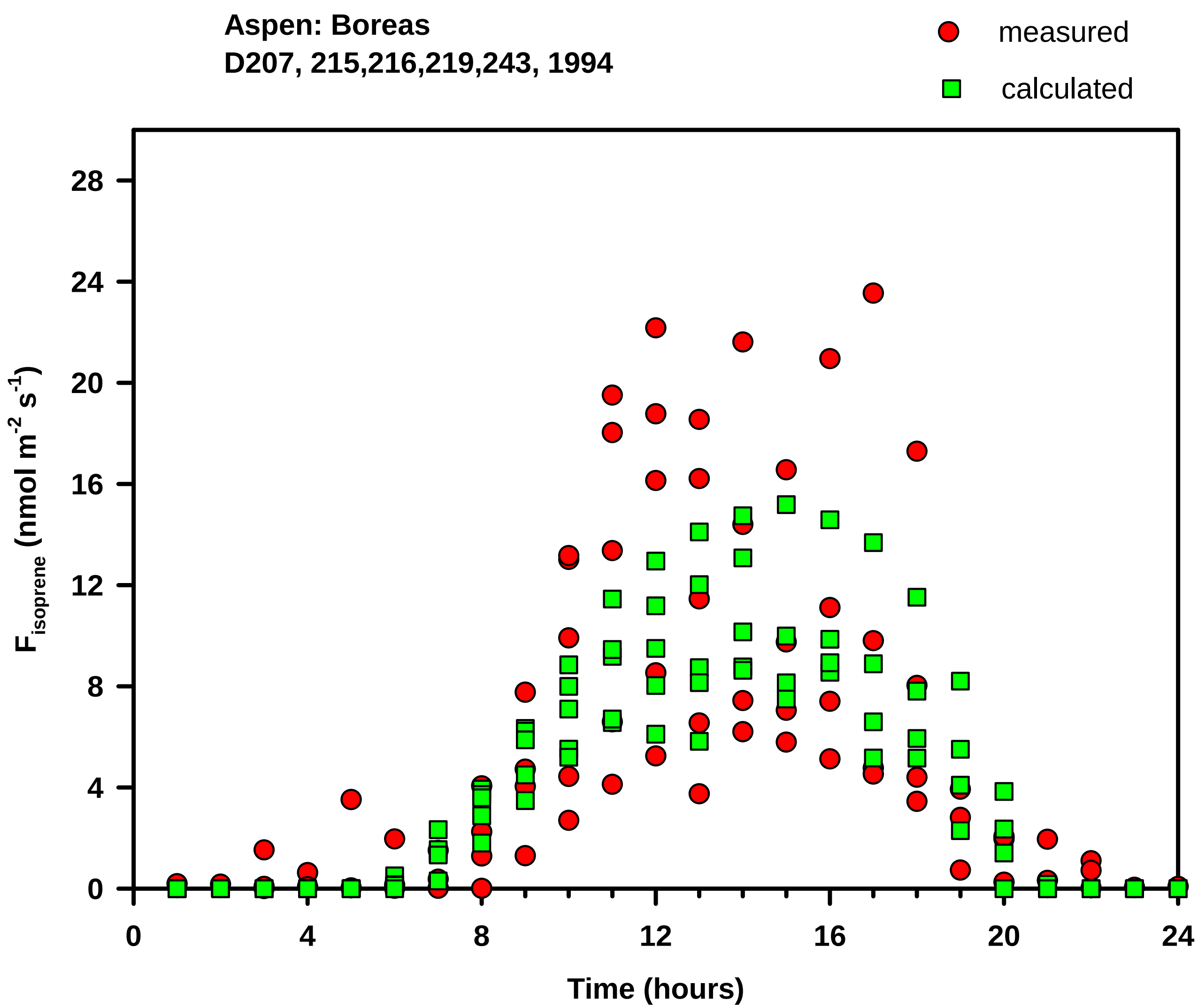
Atmospheric Chemistry



- How effective is Vegetation as a sink for Pollution?
- To what extent are forests sources of precursors for pollution?
- What is the Feedback between aerosols and LUE?
- How do the sources and sinks vary with weather and climate?

CANVEG Schematic



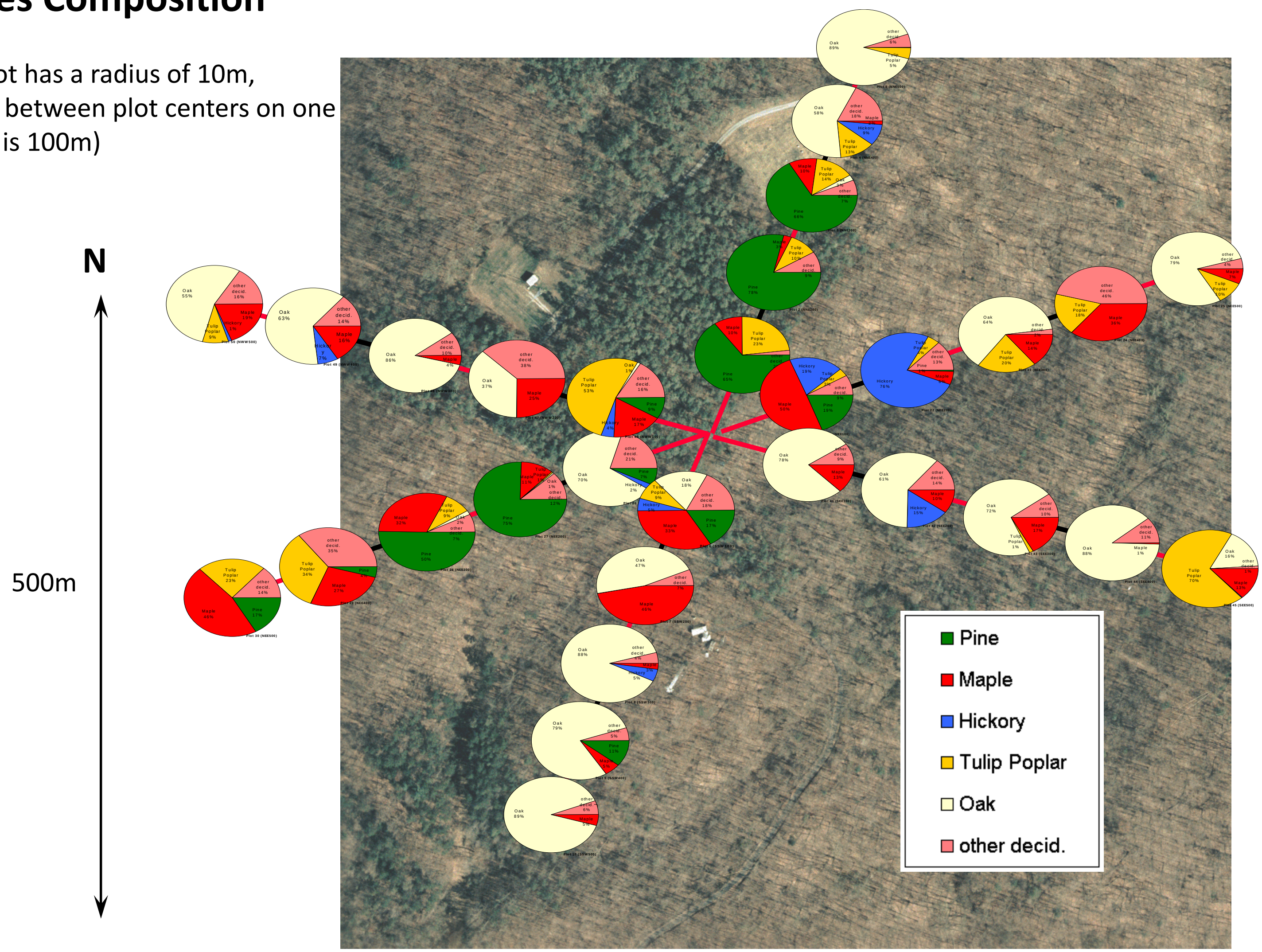


Baldocchi et al 1999 JAM

Mixed Forests Contain Isoprene Emitters and non Emitters

Walker Branch 1999
Species Composition

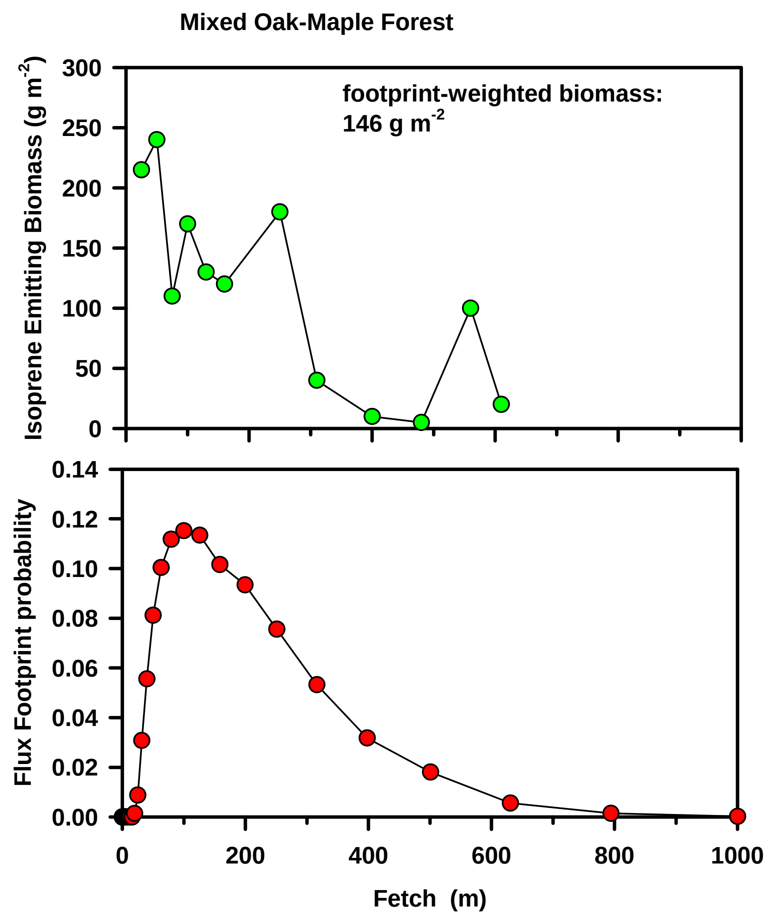
(each plot has a radius of 10m, distance between plot centers on one transect is 100m)



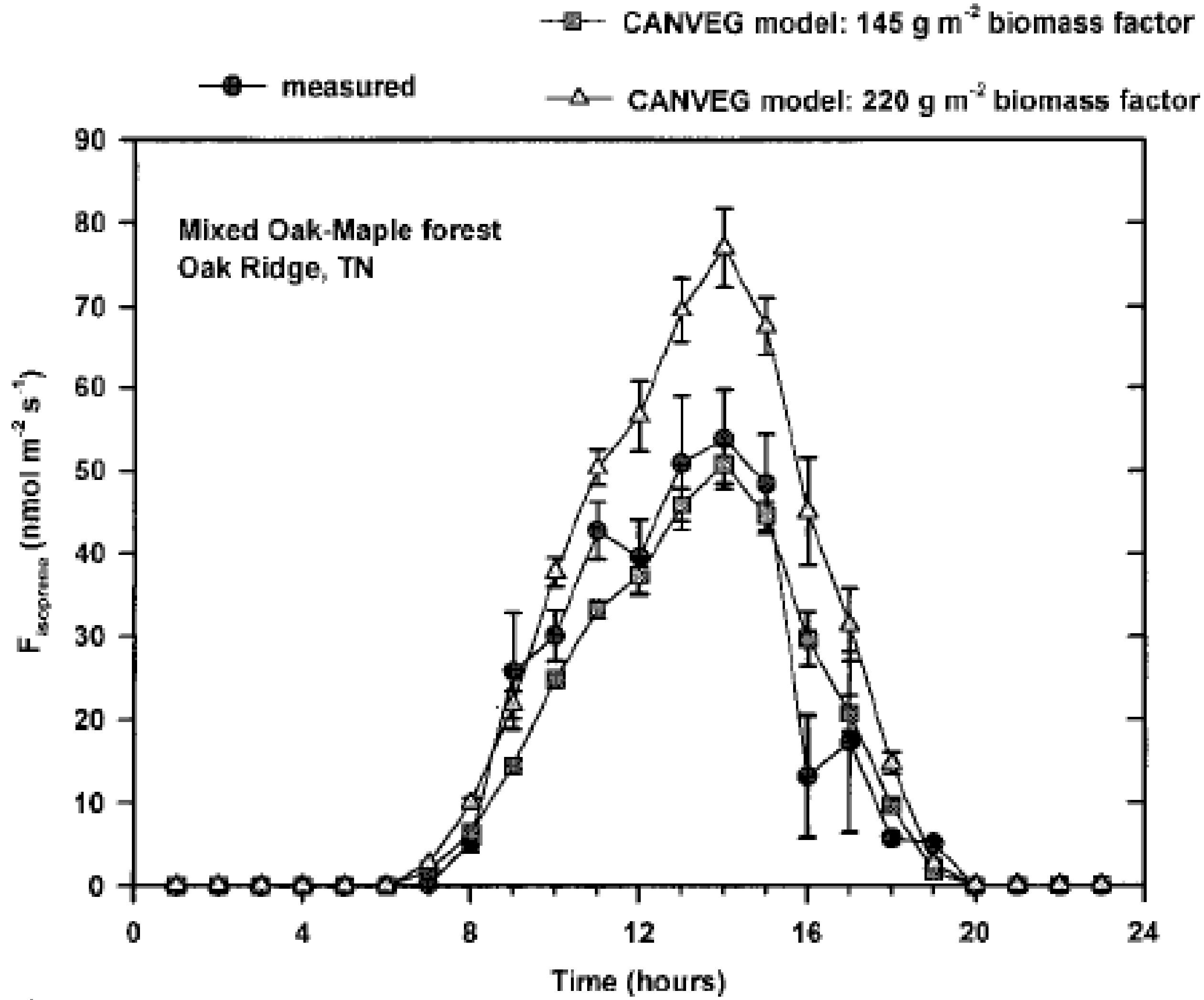
Data of Eva Falge

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

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:
For Atmospheric Chemistry Species Composition MATTERS as well as the biophysics



Baldocchi et al 1999 JAM