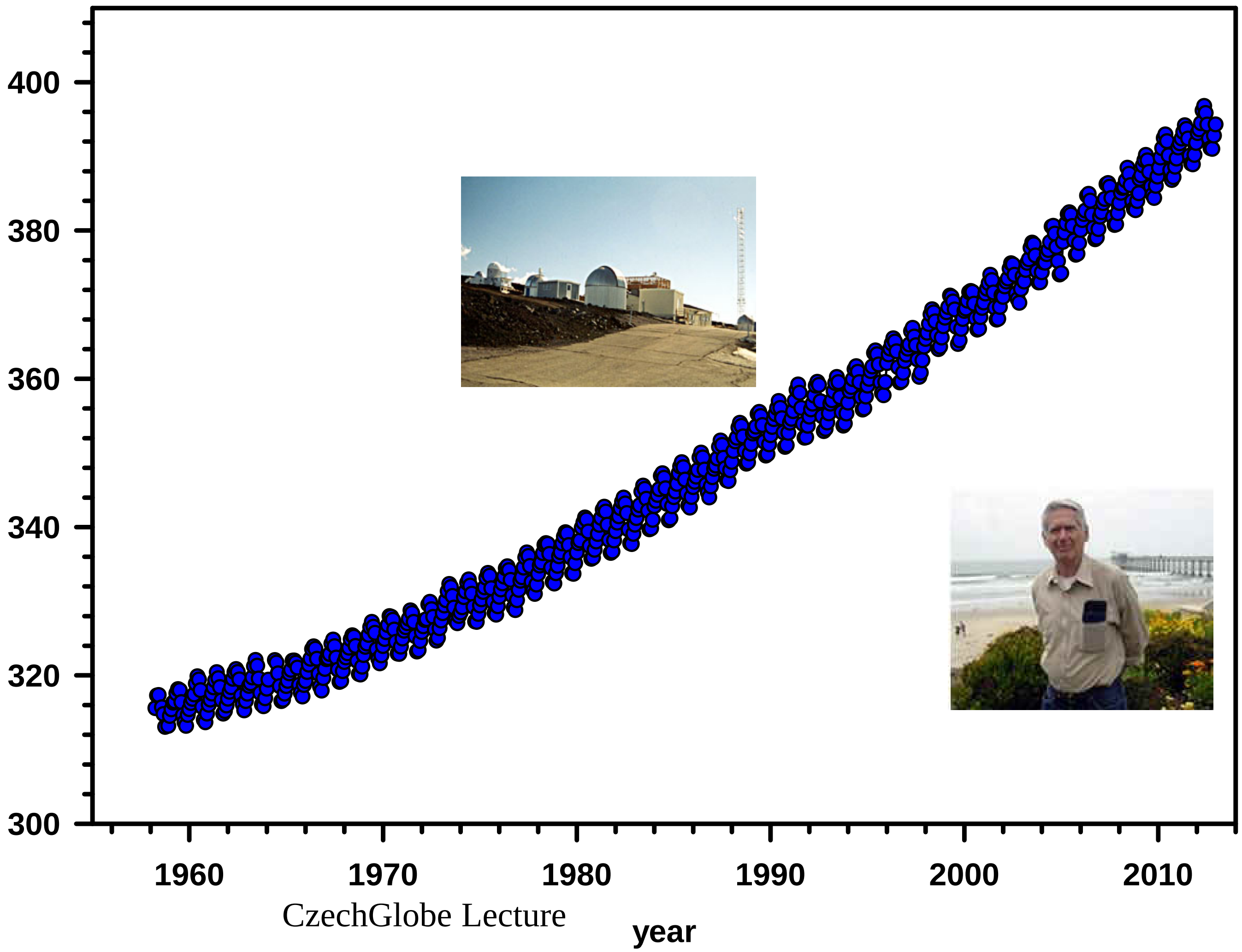
Using a Global Flux Network—FLUXNET— to Study the Breathing of the Terrestrial Biosphere

Dennis Baldocchi
ESPM/Ecosystem Science Div.
University of California, Berkeley

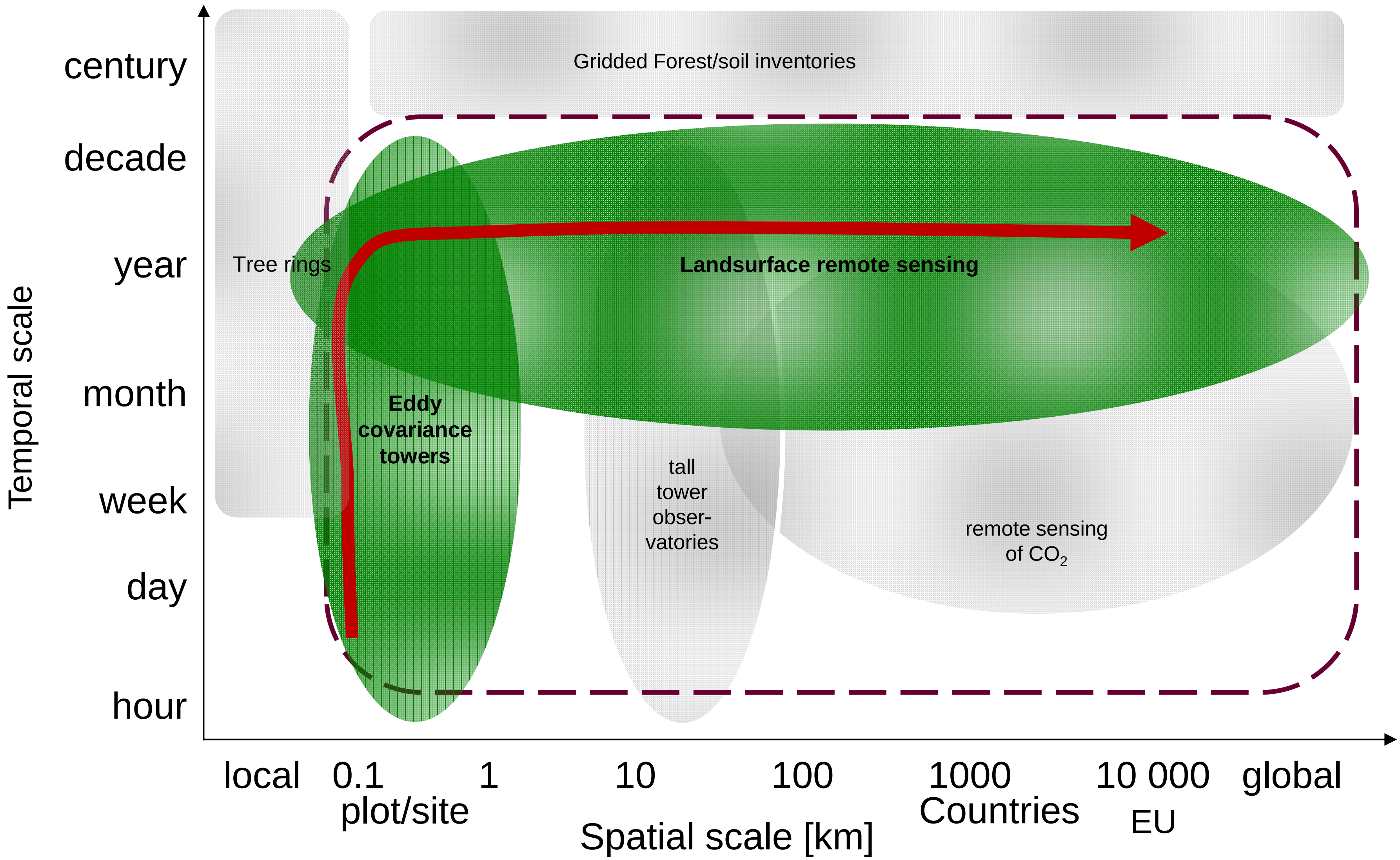
CzechGlobe Lecture

Contemporary CO_2 Record

Mauna Loa:
UC Scripps & NOAA CMDL; CDIAC



Primary Challenge:
Integrating Fluxes from Ecosystem to Global Scales

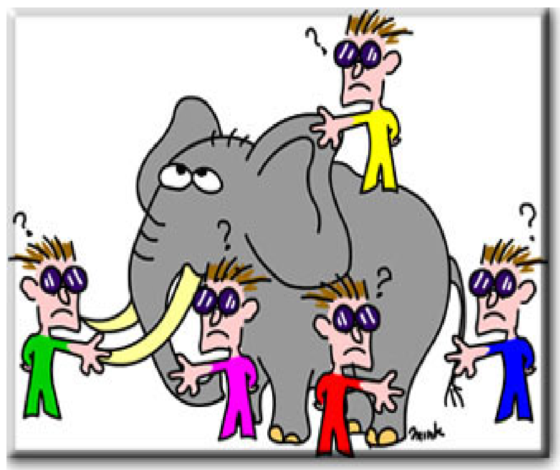


M. Reichstein MPI

Methods To Assess Terrestrial Carbon Budgets at Landscape to Continental Scales, and Across Multiple Time Scales

GCM Inversion Modeling

Remote Sensing/ MODIS



Eddy Flux Measurements/ FLUXNET

Forest/Biomass Inventories

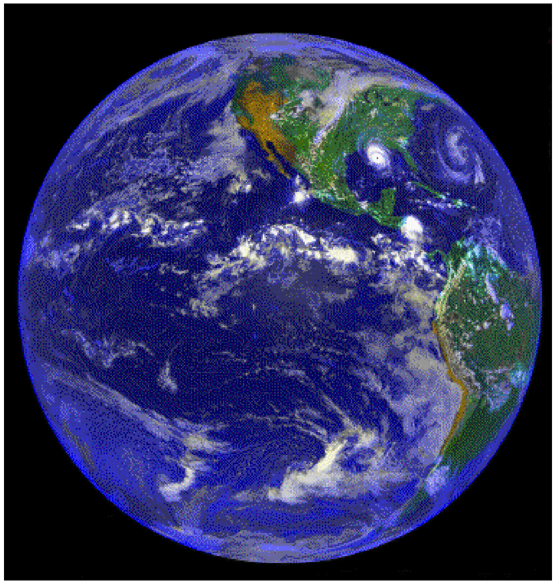
Physiological Measurements/ Manipulation Expts.

Biogeochemical/ Ecosystem Dynamics Modeling

Flask Network and Inversion models

- **Pros**
- Produces Global and Zonal C fluxes

- **Cons**
- Sparse flask network
- Biased to marine boundary layer
- Ill-posed problem
- Crude spatial resolution



Remedy

Use isotopes (^{13}C) and surface flux measurements to constrain source/sink calculations

More sites measuring C in x,y and z

Better Transport Models

Carbon Satellite, OCO

Satellites

Remedy
Satellite platforms (EOS, MODIS)
Validate Algorithms with Direct Eddy Flux Measurements

- **Pros**
- Global, Regional and Local Coverage
- Can detect Seasonal trends

- **Cons**
- Inferred estimates of GPP and LAI
- Relies on Unvalidated Algorithms
- Intermittent Coverage
- Can’t Assess NEP

Biomass and Soil Surveys

- **Pros**
- A direct measure of plant growth and soil C sequestration

- **Cons**
- High spatial variability
- Below-ground NPP is rarely measured
- No mechanistic information on C fluxes
- Takes several years to resolve significant differences
- Relies on Allometry from Few Trees

Remedy

C isotope studies

More root and below ground measurements

Micrometeorological Eddy Fluxes

Remedy

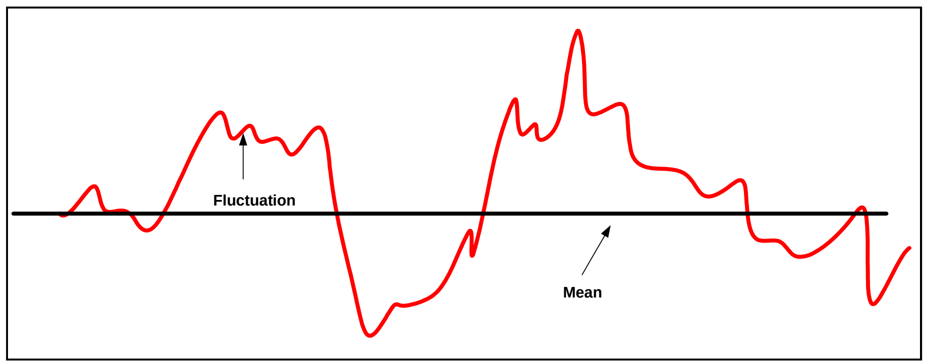
Validate with Leaf physiology and plant/soil samples, sapflow, biometry and watershed measurements

- **Pros**
- Direct measurement
- Evaluates Fluxes on diurnal, seasonal and interannual time scales
- Provides Process information

- **Cons**
- Nighttime biases
- Small footprint (< 1 km)
- Not applicable in Complex Terrain
- Network of Towers is Discrete in Space

Eddy Covariance Technique

$$F = \overline{\rho w s} \sim \overline{\rho_a} \cdot \overline{w' s'} \qquad s = \left(\frac{\rho_c}{\rho_a}\right)$$



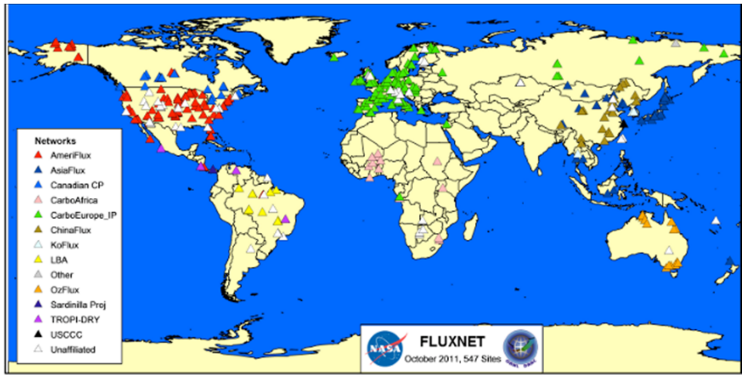
Objectives

- Network Background/History
- Time
  - Daily and Annual Integration
  - Seasonal Dynamics
  - Inter-Annual Variability
  - Disturbance/Chronosequence
- Processes
  - Photosynthesis = f(Q,T,functional type)
  - Respiration = f(T, growth, ppt, θ)
- Space
- Other Uses and Application
  - Ecosystem Modeling

Role of Flux Networks in Biogeosciences

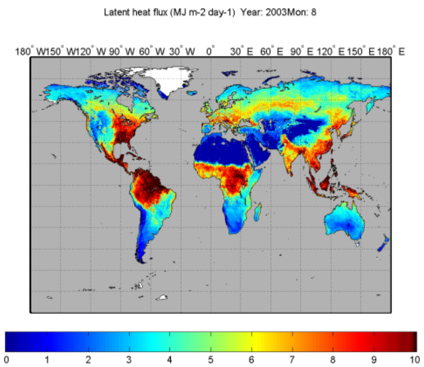
Eddy covariance flux system

Global network of flux towers



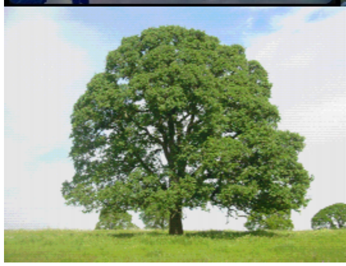
Database

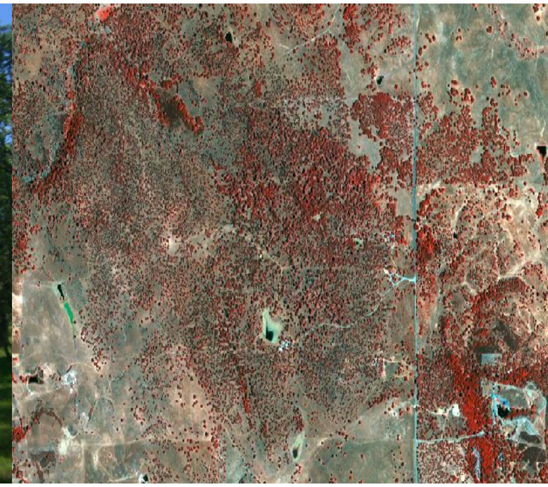
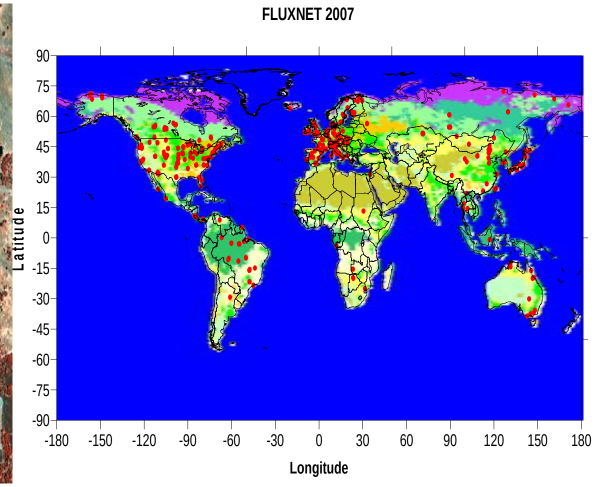
Remote sensing and Earth system science model user community



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/Traits/Land Use (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, 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.

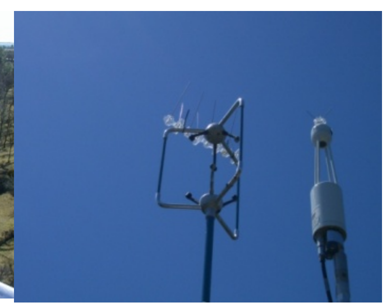



To Develop a Scientifically Defensible Virtual World
‘You Must get your boots dirty’, too

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






Guidelines for Effective Networks, 1.0

- Data are best when there are standards and protocols for instrument performance, data quality, and calibration; data gaps are minimized if redundant or replacement sensors are available; data gaps are filled with vetted methods
- Instruments don't need to be uniform, as Long as they meet standards of performance
  - We learn about instrument performance by having a diverse suite of sensors

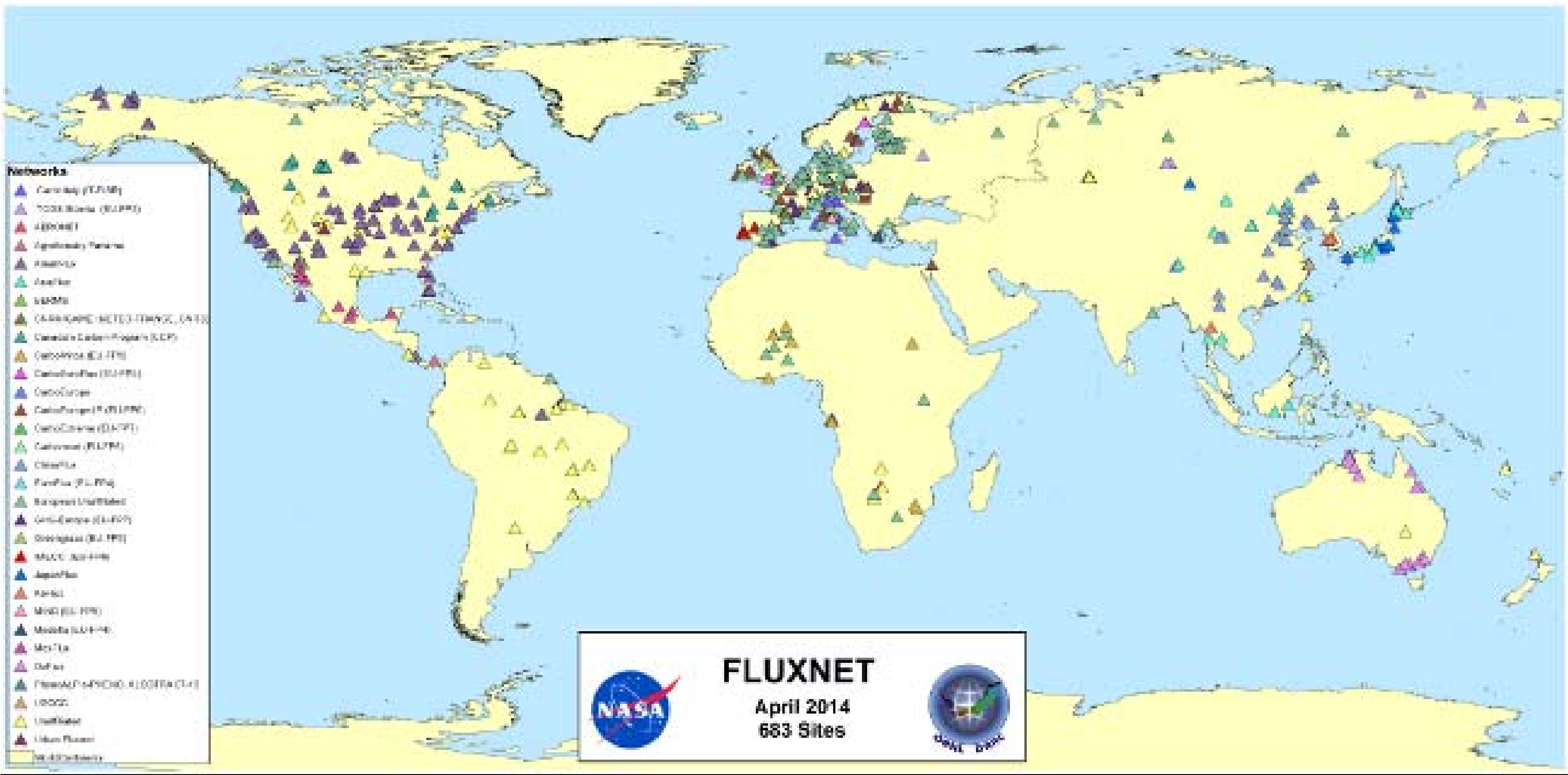
Guidelines for Effective Networks, 2.0

- Data are converted into information and knowledge when there is a shared and integrated database with which researchers can merge flux measurements with a cohort of meteorological, ecological, and soil variables.
- A centralized database can harmonize data processing and gap-filling to produce value-added products such as daily or annual sums or averages, establish version control and sharing policies, and archive data.
- Databases can be queried to pull data for specific times, locations, or variables.

Guidelines for Effective Networks, 3.0

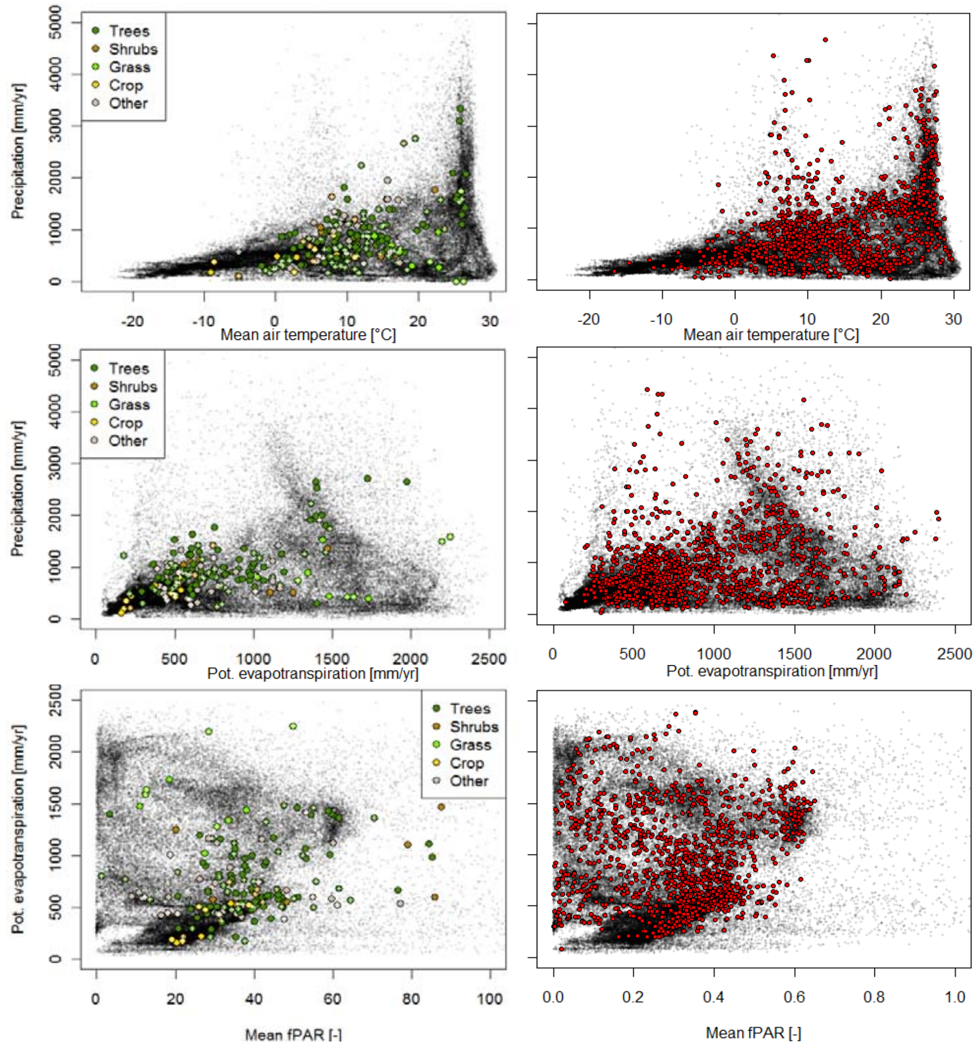
- The success of a scientific flux network relies on creating a human network, too.
- Data sharing depends upon fostering trust among colleagues, crossing cultural and political obstacles and devising a fair-_use data sharing policy.
- Shared leadership and frequent communication through workshops, internet forums, and newsletters can also help to build trust.

FLUXNET: From Sea to Shining Sea
600+ Registered Sites, *circa* 2014



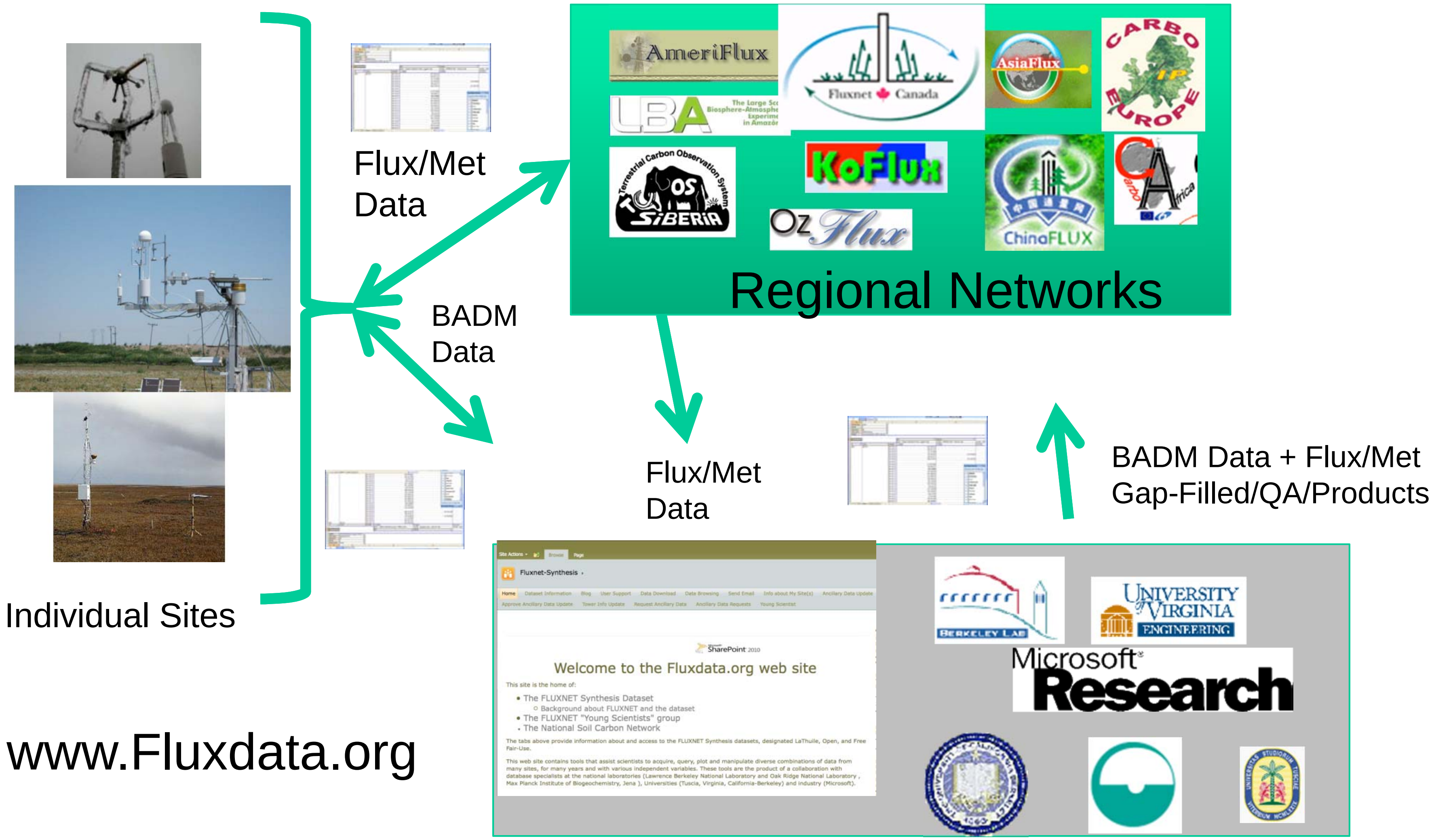
Flux Networks

Global distribution of Flux Towers Covers Climate Space Well

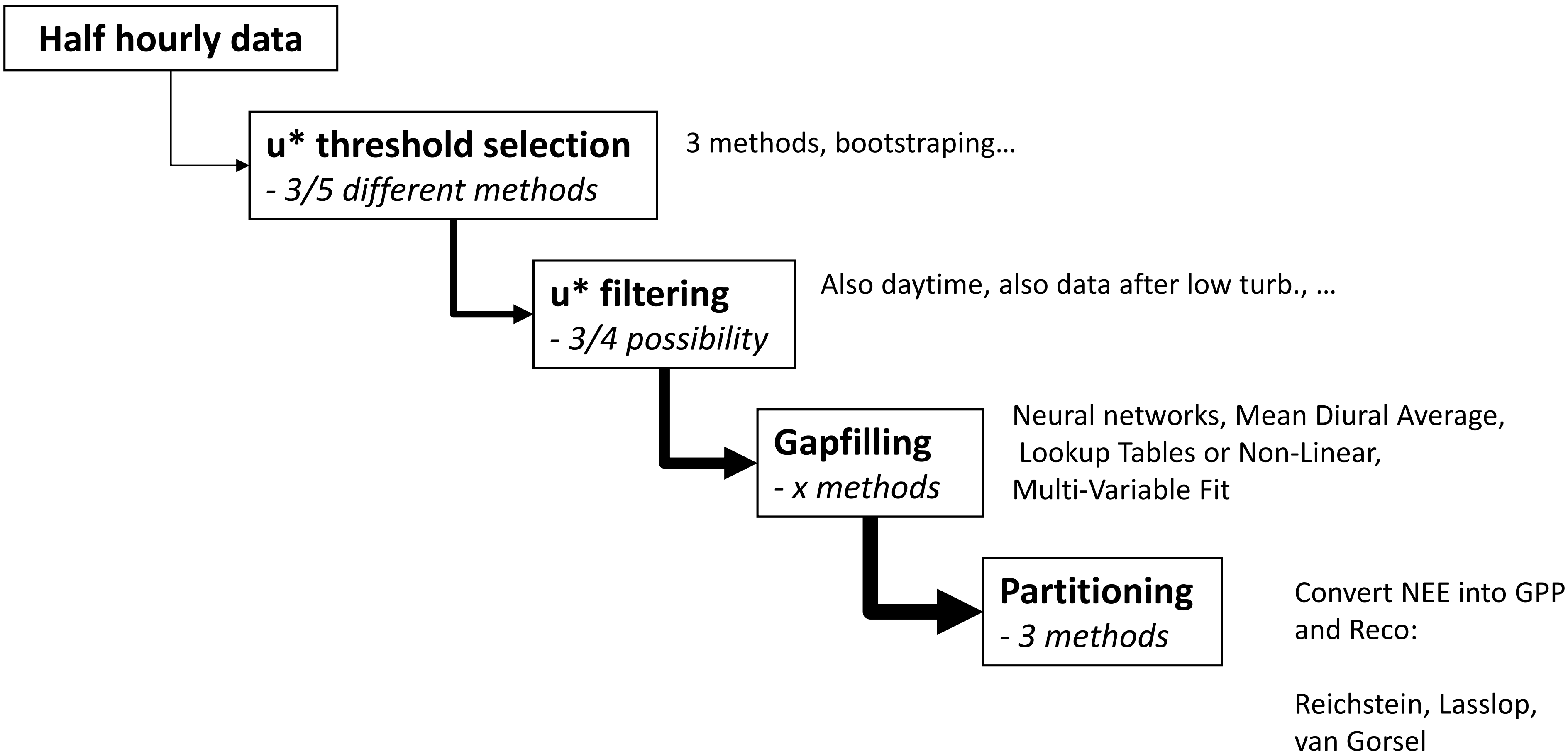


Reichstein et al. PNAS in press

Fluxdata.org – A Common, Shared Database



Data processing, Value Added Products and Uncertainty Estimation



Courtesy of Dario Papale

Time Line of Flux Data

30 hours

One Site-Year

Ten Site-Years

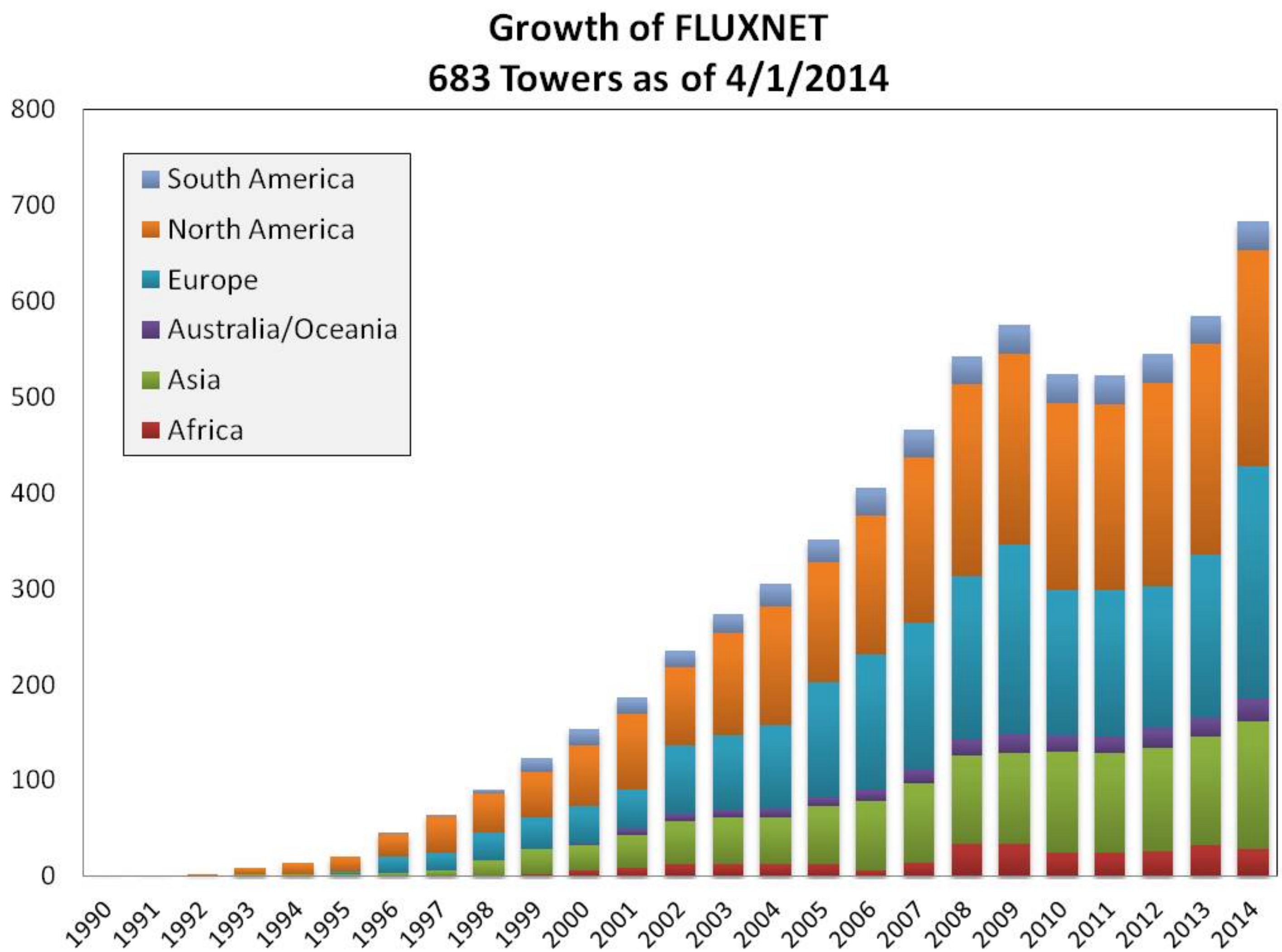
100 Site-Years

Marconi Workshop

1000 Site-Years

La Thuile II Workshop

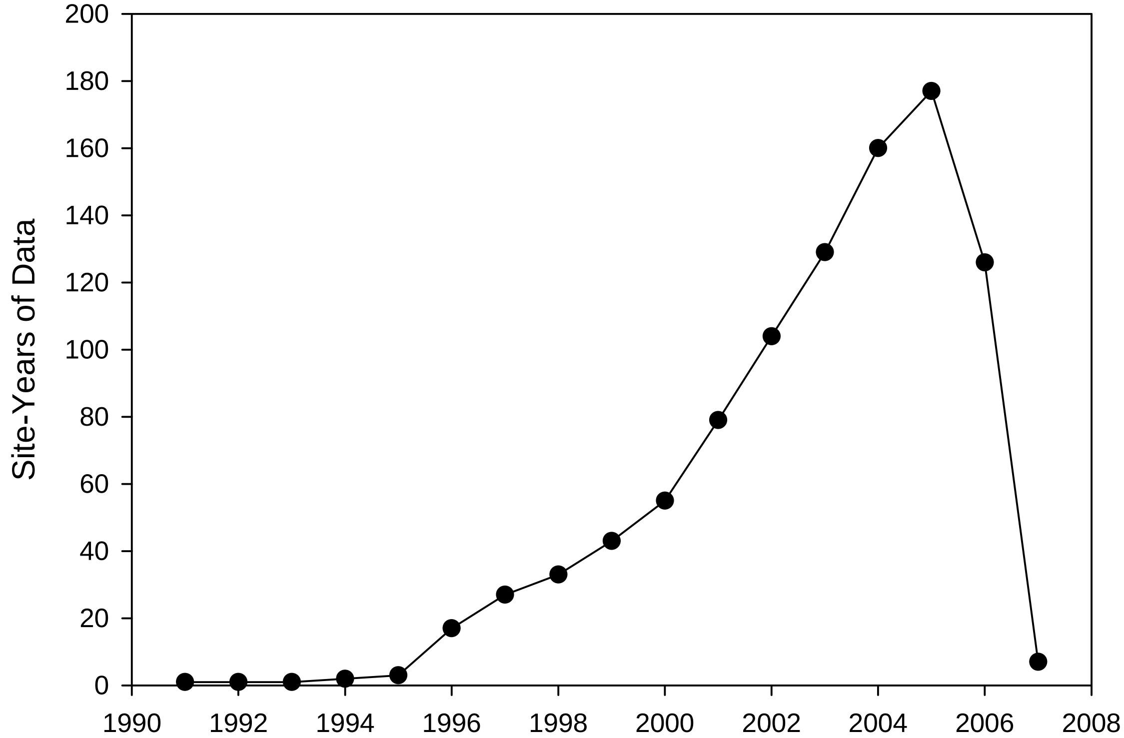
1980s **1990s** **1995s** **2000s** **2010s**

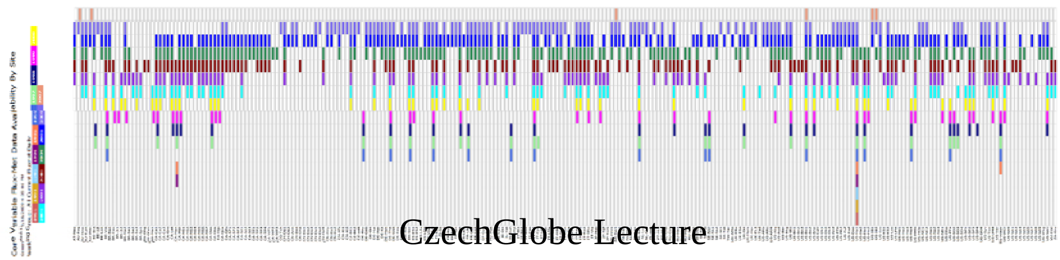


Growth in Africa, Australia and Asia,
Sustenance in Brazil and Europe
Decline in Canada and US
Voids in India and Latin America

Many Towers are Not Active, nor Submitting data, circa La Thuile dataset

FLUXNET Data Archive





LaThuile Fluxnet Workshop, Feb. 2007

- New Gap-Filled, Qa/Qc Dataset
- 250 Sites; 930 Site-years of Data
- www.fluxdata.org

Institutional Memory: Evolution of FLUXNET

- Measure Annual Cycle of NEE
  - Micromet issues of *Detrending*, *Transfer Functions*, Flux *Sampling and Measurements, Gap-filling, Error Assessment*
- Measure and Interpret Intra-annual Variation of NEE
  - Flux partitioning (GPP & R_{eco}); assessment of metadata,e.g. V_{cmax}, soil respiration, LAI, biomass inventories.
  - Quantifying Biophysical Controls on Fluxes
- Measure and Interpret Inter-annual variations of NEE
- Measure NEE over multiple Land-Use Classes
  - crops, grasslands, deciduous and evergreen broadleaf and conifer forests
  - Disturbance, logging, biodiversity and fire
- Manipulative Studies
  - Nitrogen and H_2O additions
- Measure NEE over Representative Areas
  - Scaling Flux Information of Footprint to MODIS pixel

- Workshops
  - LaThuile Italy, 1995
  - Flathead Lake MT, 1997
  - Marconi CA, 2000
  - Orvieto Italy, 2002
  - Lake Tahoe CA, 2003
  - Firenze Italy, 2004
  - LaThuile, 2007
  - Asilomar 2009
  - Berkeley 2011

FLUXNET Successes

- ‘Mountains’ of data from a spectrum of canopy roughness and stability conditions, functional types and climate spaces have been collected
- A Model for Data Sharing
  - FLUXNET Web Site, a venue for distributing Primary, Value-added and Meta-Data products
- Value-Added Products have been produced
  - Development of Gap-Filling Techniques
  - Production of Gap-Filled Daily and Annual Sums
- Many New Findings on Emergent Processes, Environmental Controls and Seasonality and Annual C fluxes
- Data for Validating and Improving SVAT models used for weather, climate, biogeochemistry and ecosystem dynamics
- Collaboration & Synthesis through Workshops and Hosting Visitors
  - Building a Collaborative, Cooperative, Multi-Disciplinary & International Community of Researchers
- Training New and Next Generation of Scientists, Postdocs, Students

‘Failures’/’Un-resolved’ Issues

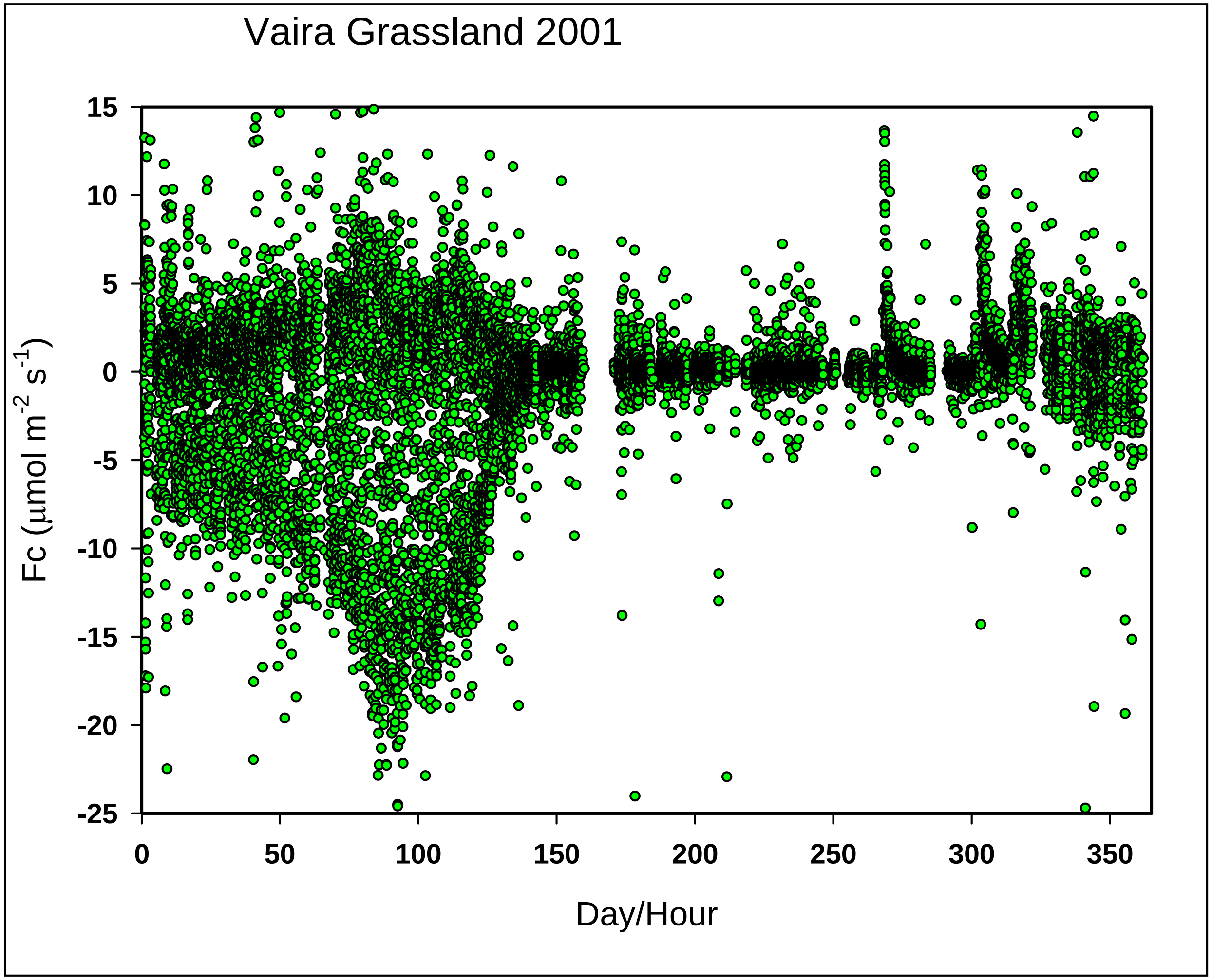
- Need to Share Data in an Open Format
- Achieve Better and Timely Data Submission from Partners
- Not Measuring Night-time Fluxes Well
  - ImPerfect U* correction
- Not Measuring Fluxes over Complex terrain and during Advection Well
- ImPerfect Flux Partitioning
  - Works Better on Longer Time Scales
- ImPerfect Energy Balance Closure
  - Could be ‘red-herring’ based limited Rn and G fetch
- Need Better Outreach and Training of New Generation of Fluxnet Scientists
  - Being Rectified with Flux Short Courses in Europe and US
  - Partly why I am here

Temporal Dynamics of C Fluxes

- Hour
- Day
- Month
- Season
- Year
- Multiple Years

- Pulses
- Lags
- Switches

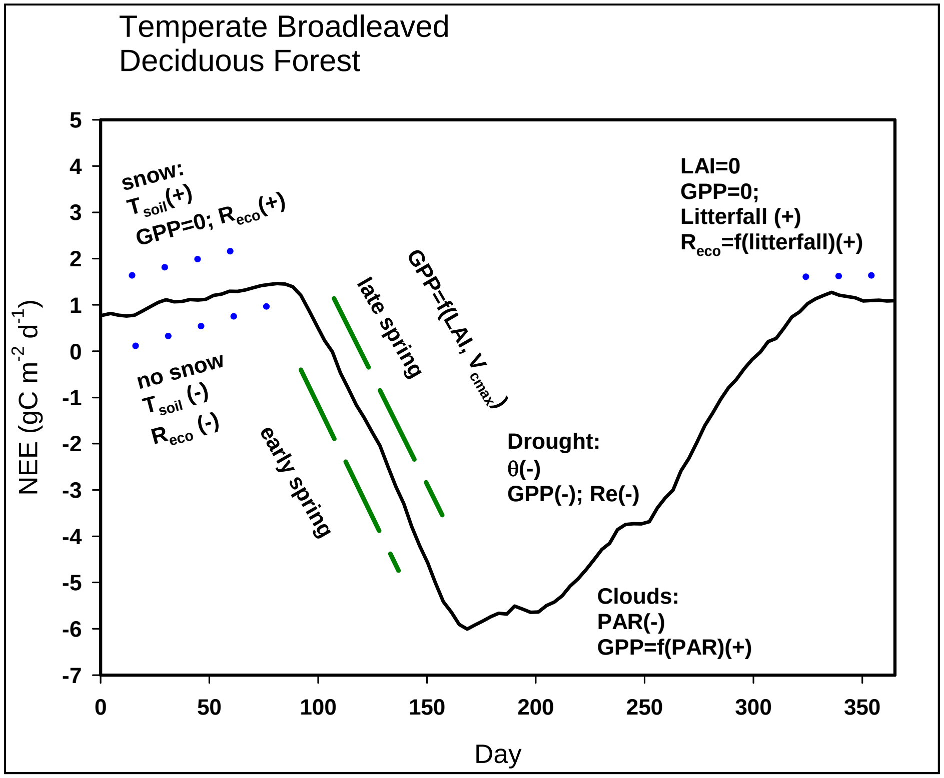
Annual Time Series of Trace Gas Exchange



Xu and Baldocchi, AgForMet, 2004

Complicating Dynamical Factors

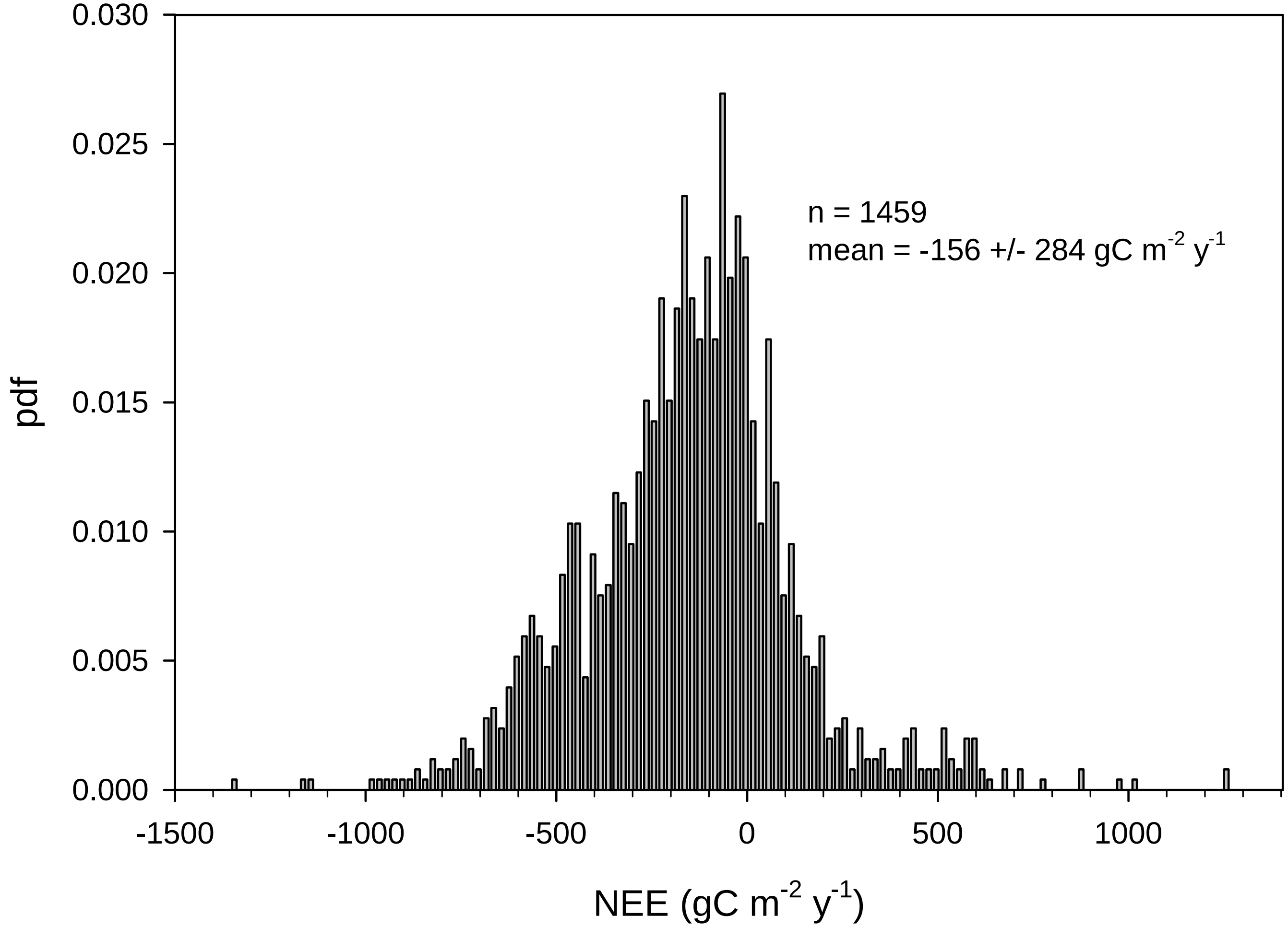
- Switches
  - Phenology
  - Drought
  - Frost/Freeze
- Pulses
  - Rain
  - Litterfall
- Emergent Processes
  - Diffuse Light/LUE
- Acclimation
- Lags
- Stand Age/Disturbance

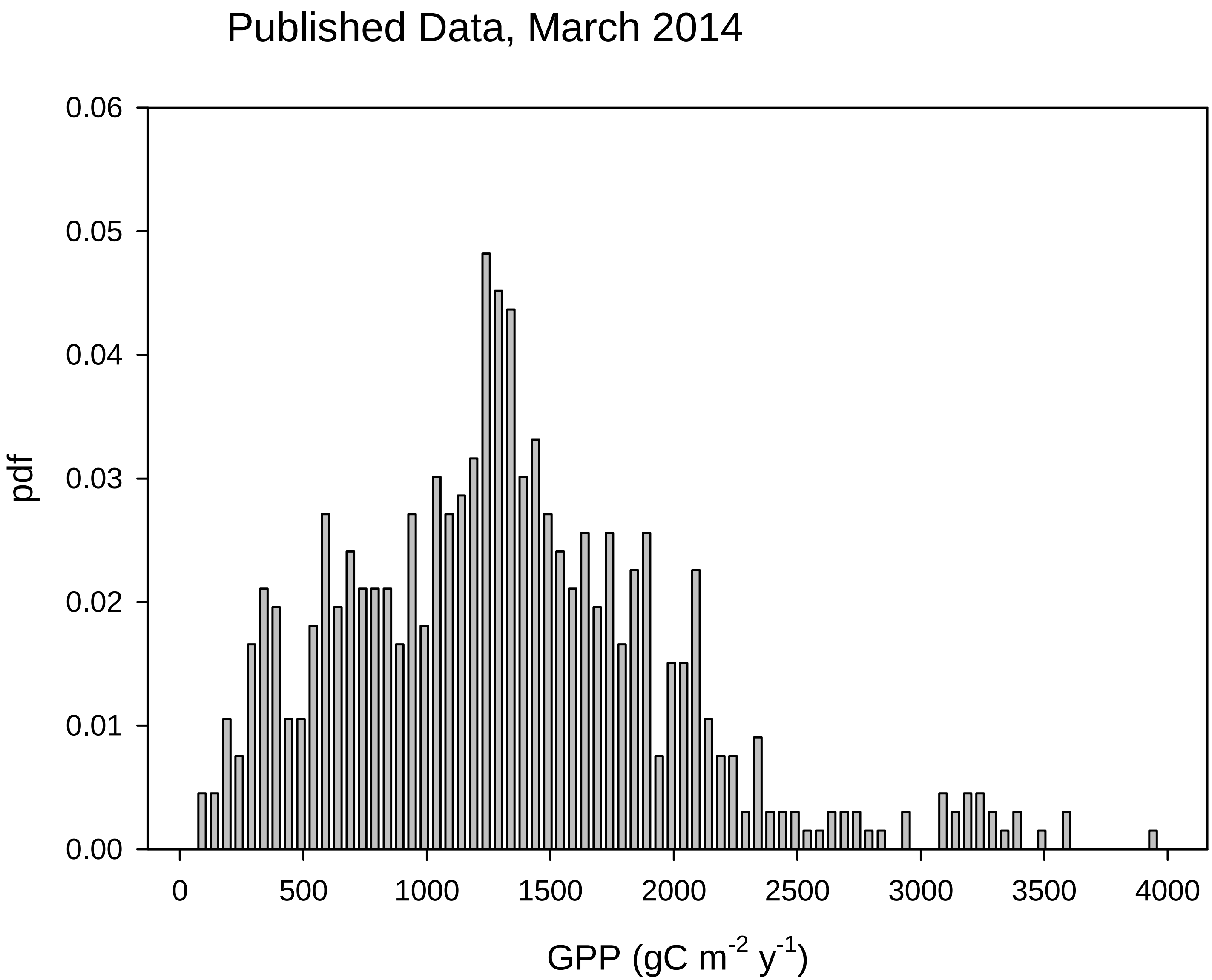


Early Questions

- What is the Annual Sum of Ecosystem Carbon Exchange, as a function of Climate Zone, Plant Functional Type, Time since Disturbance, Weather-Year and Size of the Network?

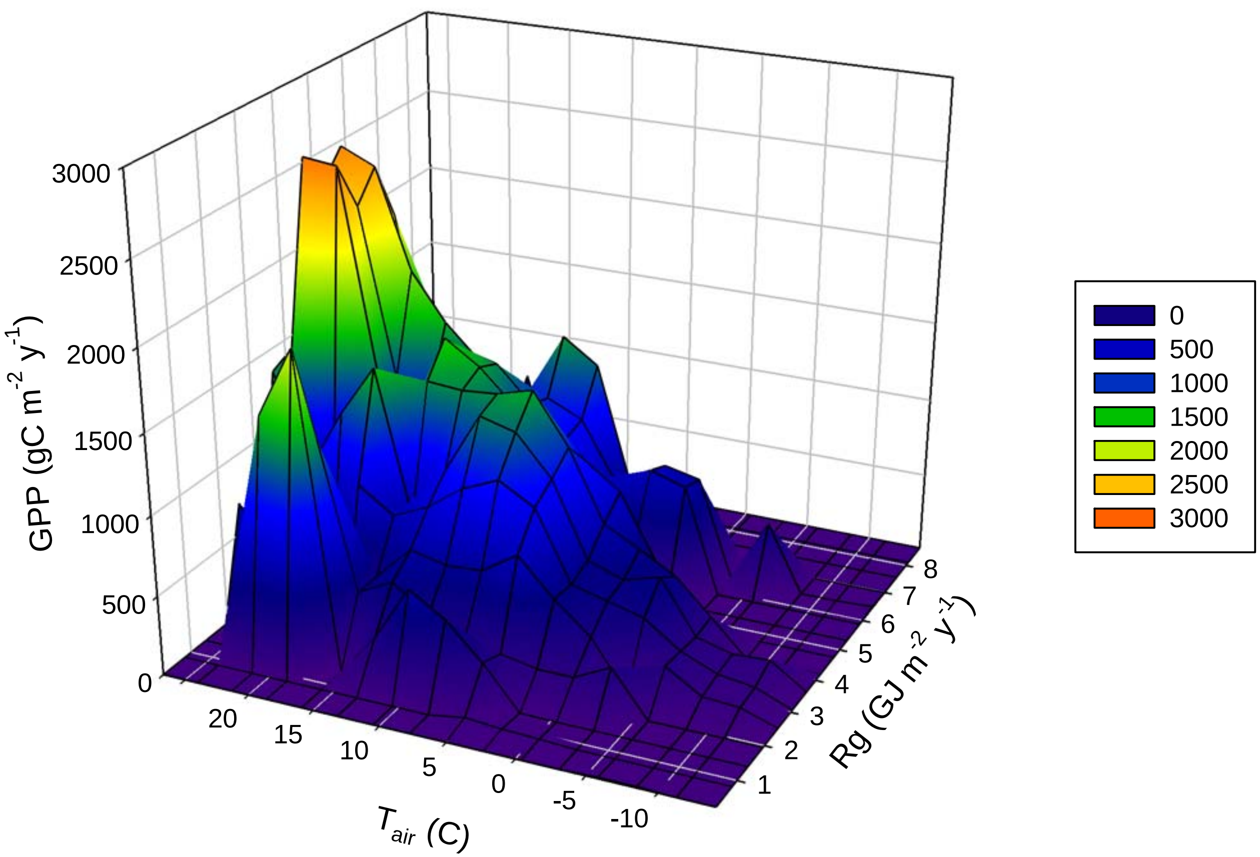
Published Data, March, 2014




Published Data, March 2014
0.06
0.05
0.04
0.03
0.02
0.01
0.00
pdf
0
500
1000
1500
2000
2500
3000
3500
4000
GPP (gC m-2 y-1)

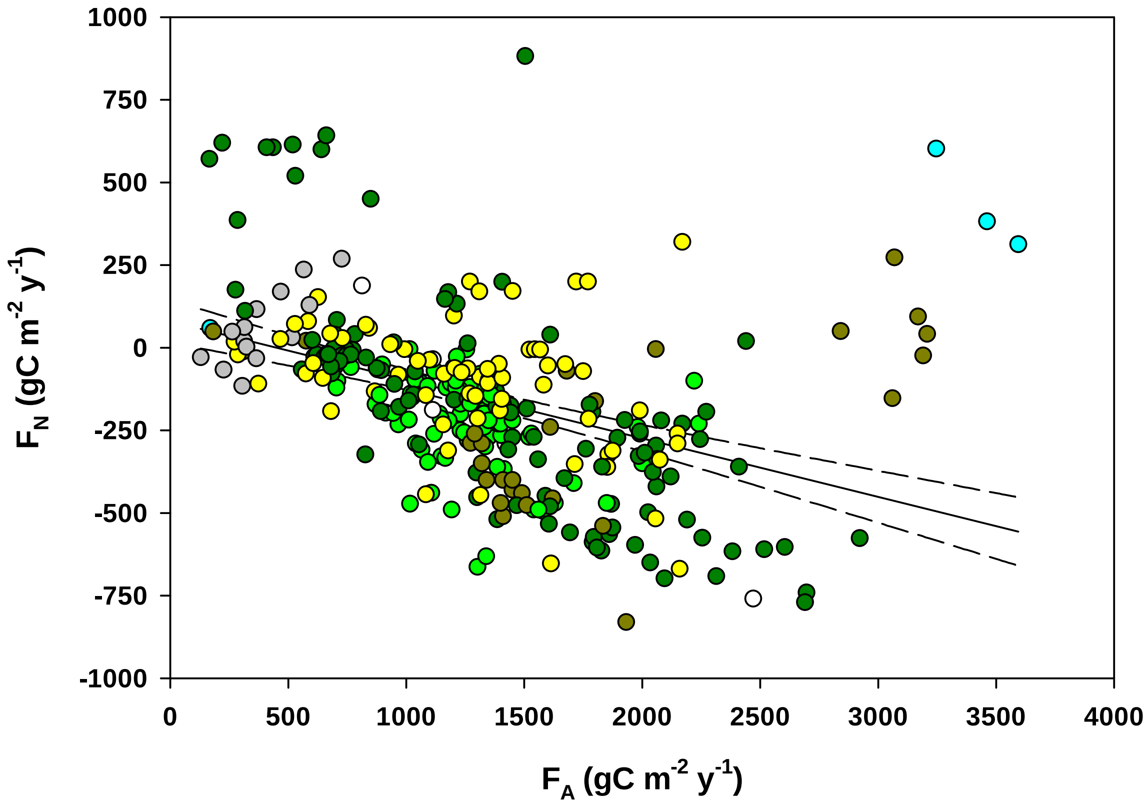
Joint pdf GPP, Solar Radiation and Temperature

FLUXNET Database



E[GPP]= 1237 gC m^{-2} y^{-1}~136 PgC/y

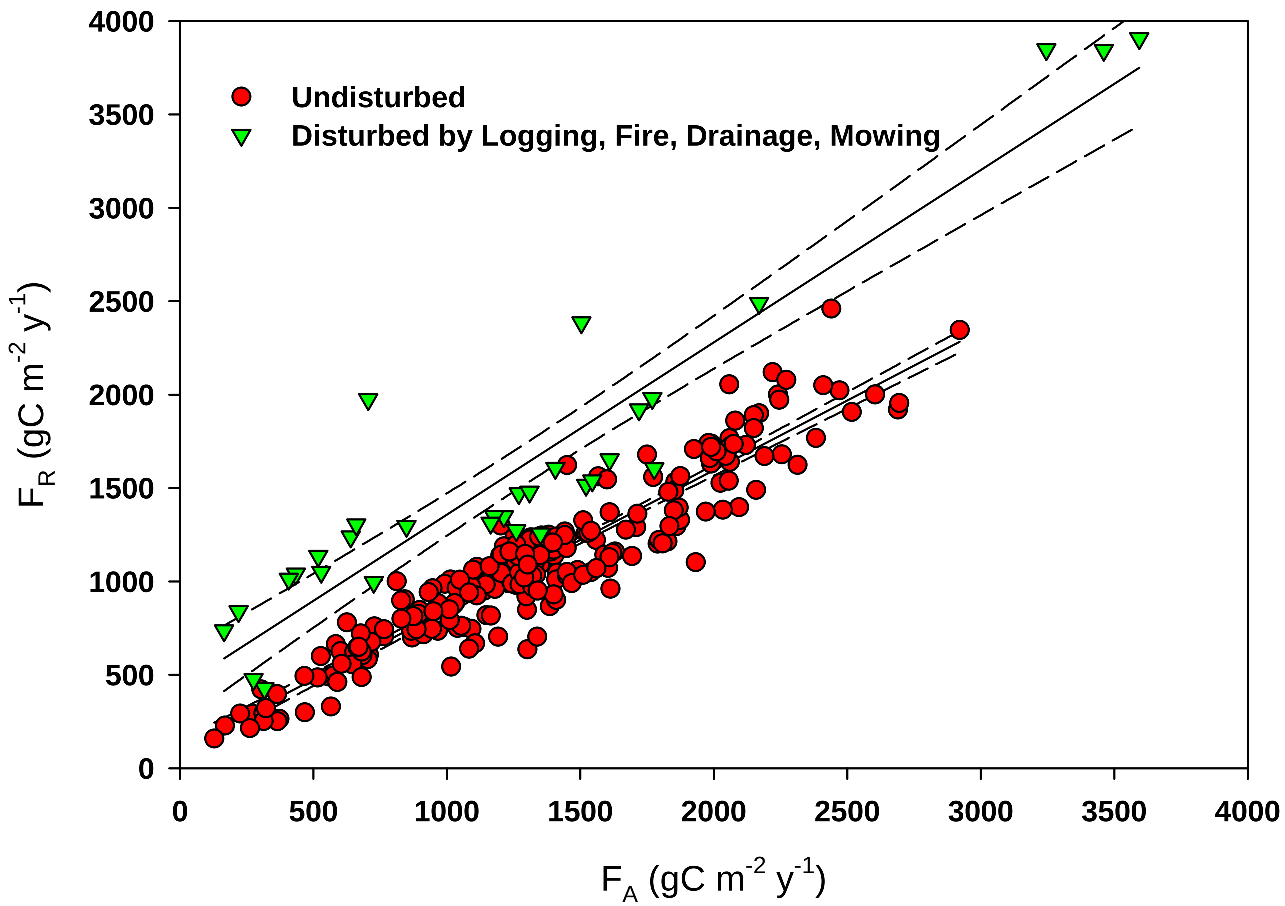
Does Net Ecosystem Carbon Exchange Scale with Photosynthesis?



Ecosystems with greatest GPP don't necessarily experience greatest NEE

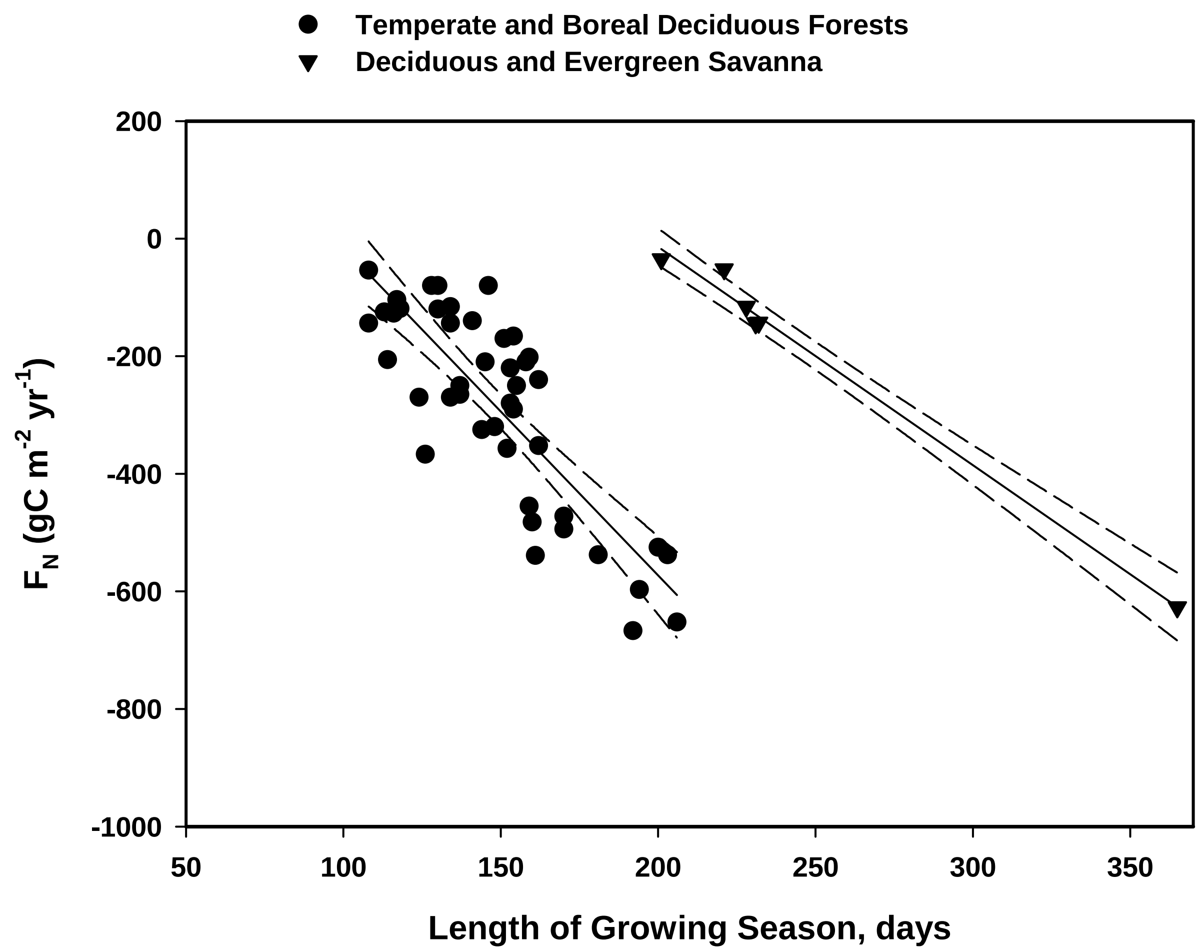
Baldocchi, Austral J Botany, 2008

Ecosystem Respiration Scales Tightly with Ecosystem Photosynthesis, But Is with Offset by Disturbance



Baldocchi, Austral J Botany 2008

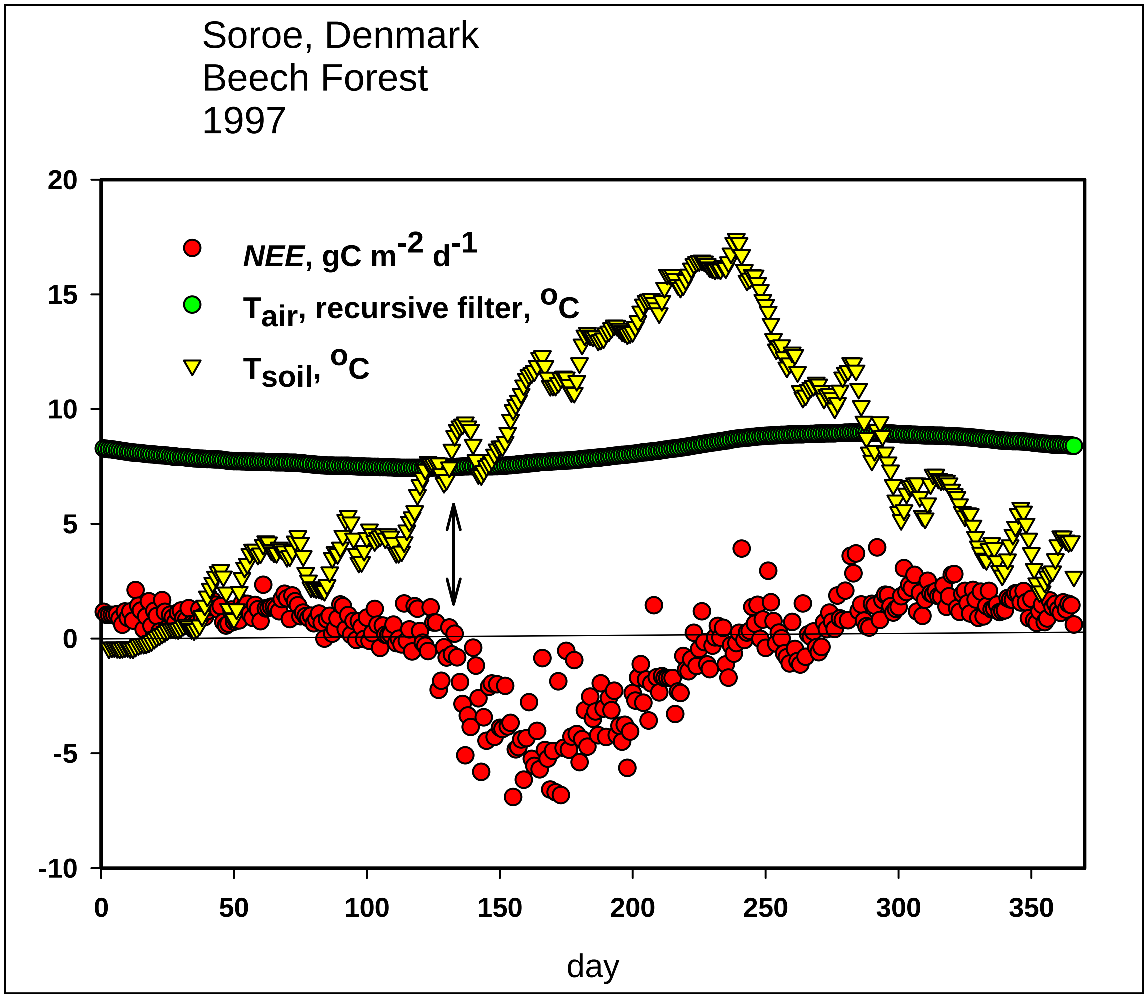
Net Ecosystem Carbon Exchange Scales with Length of Growing Season



Baldocchi, Austral J Botany, 2008

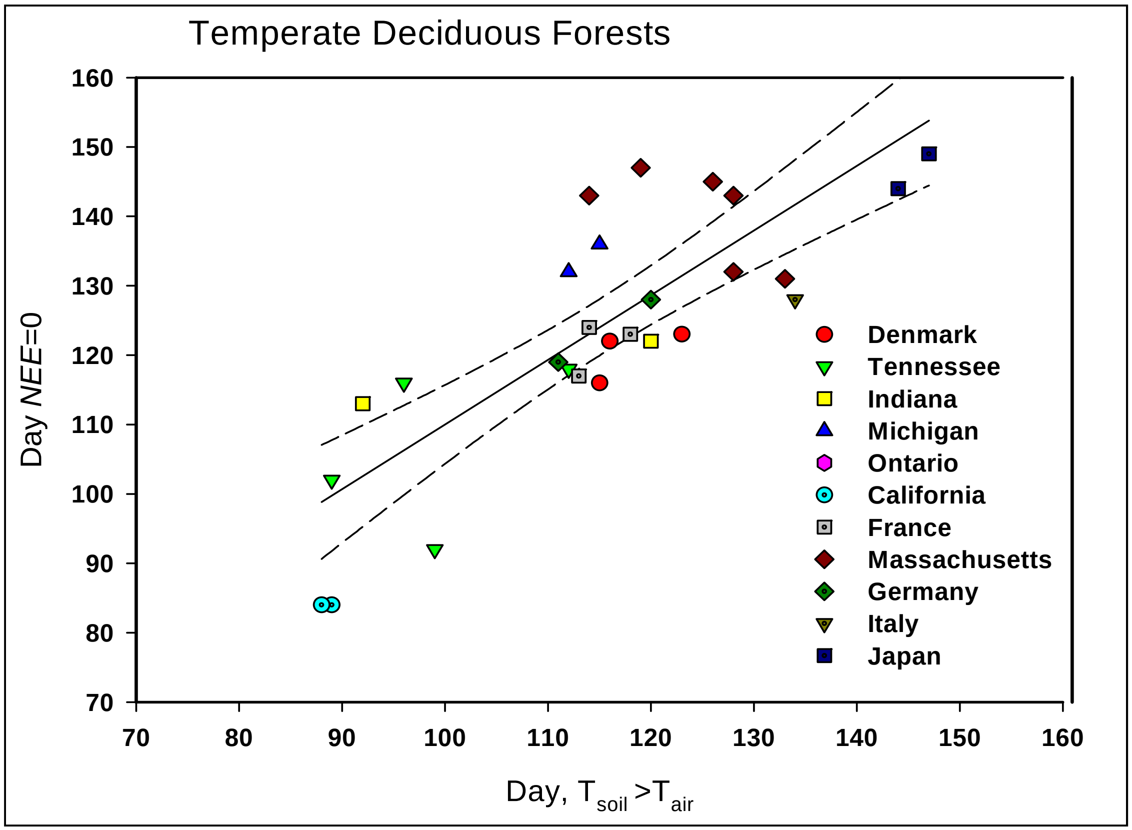
CzechGlobe Lecture

Soil Temperature: An Objective Indicator of Phenology??



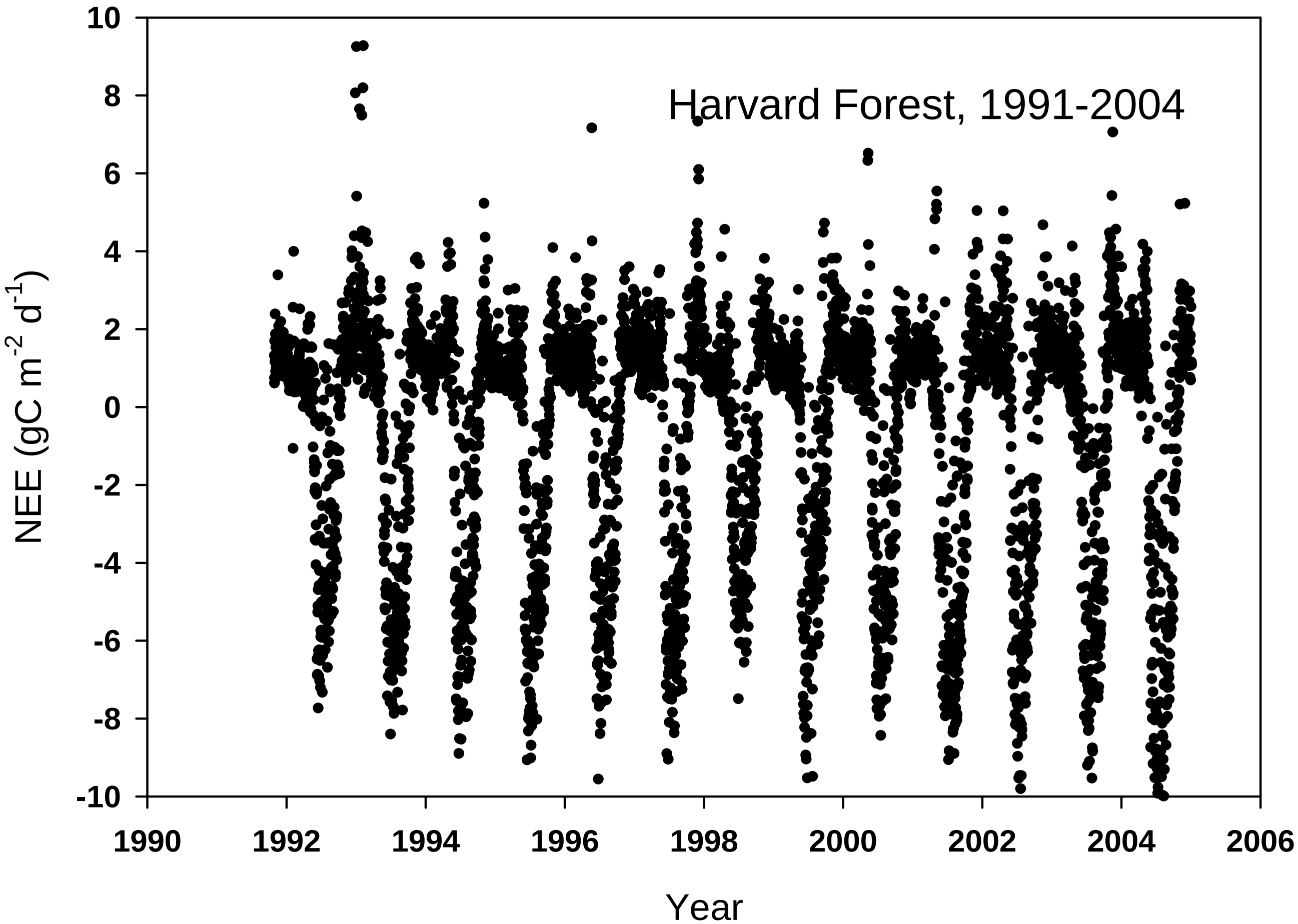
Data of Pilegaard et al.

Soil Temperature: An Objective Measure of Phenology, part 2



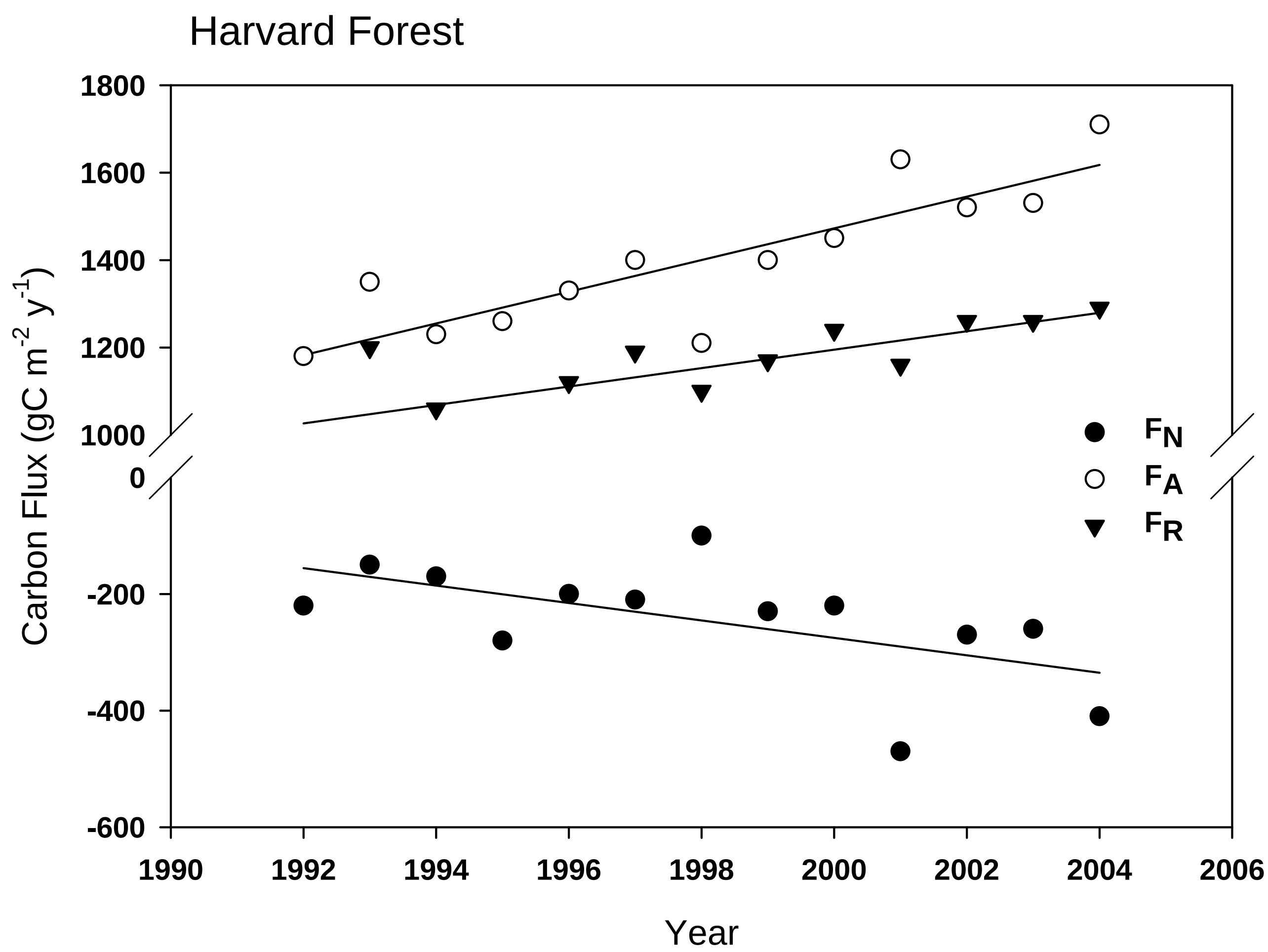
Baldocchi et al. Int J. Biomet, 2005

Decadal Plus Time Series of NEE:
Flux version of the Keeling's Mauna Loa Graph



Data of Wofsy, Munger, Goulden, et al.; Urbanski et al 2007 JGR.

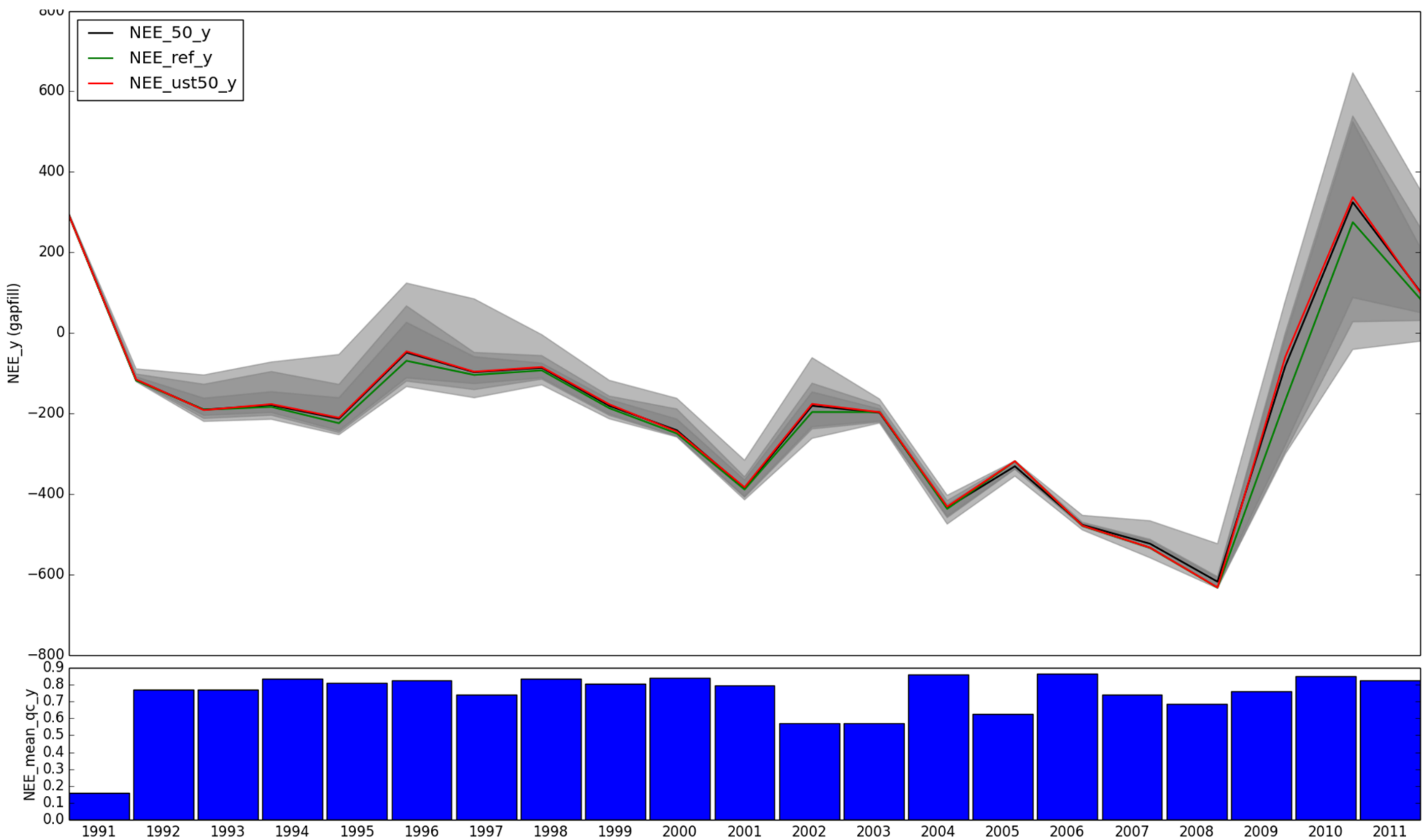
Interannual Variation and Long Term Trends
in Net Ecosystem Carbon Exchange (F_N), Photosynthesis (F_A) and Respiration (F_R)



Urbanski et al 2007 JGR

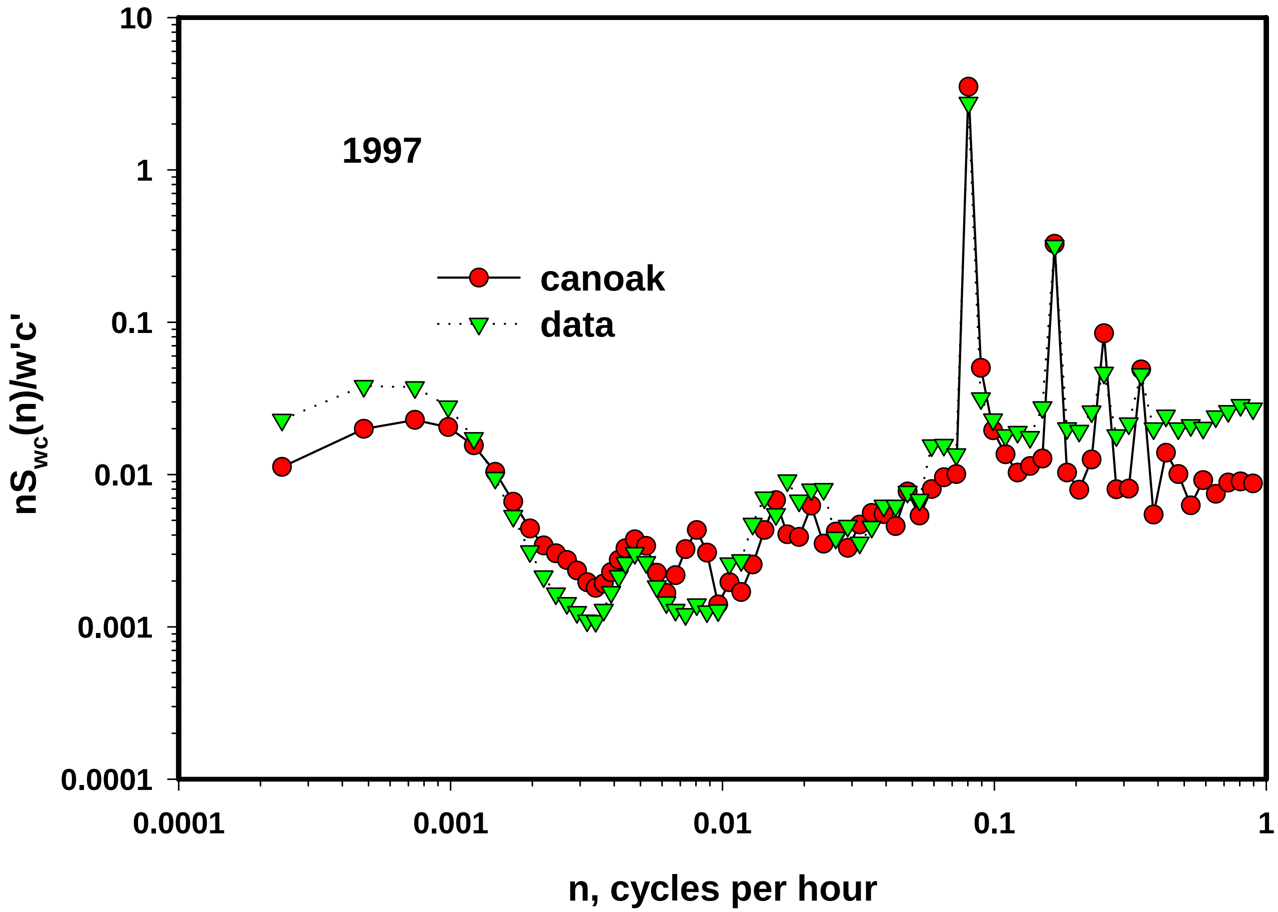
CzechGlobe Lecture

Flux Uncertainties
US-Ha1 (Harvard Forest - yearly)



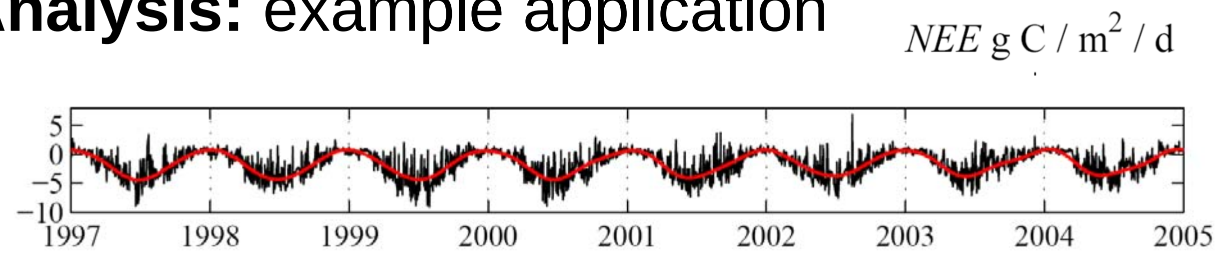
CzechGlobe Lecture

Power Spectrum of CO_2 Fluxes



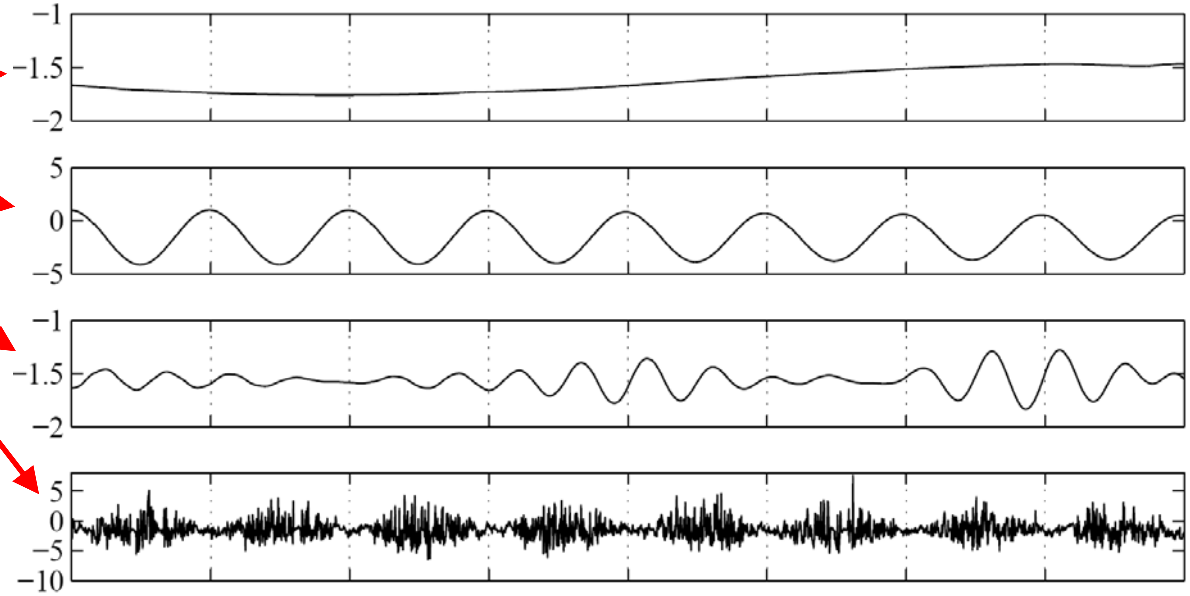
Singular System Analysis: example application

Original time series:



Decomposed time series:

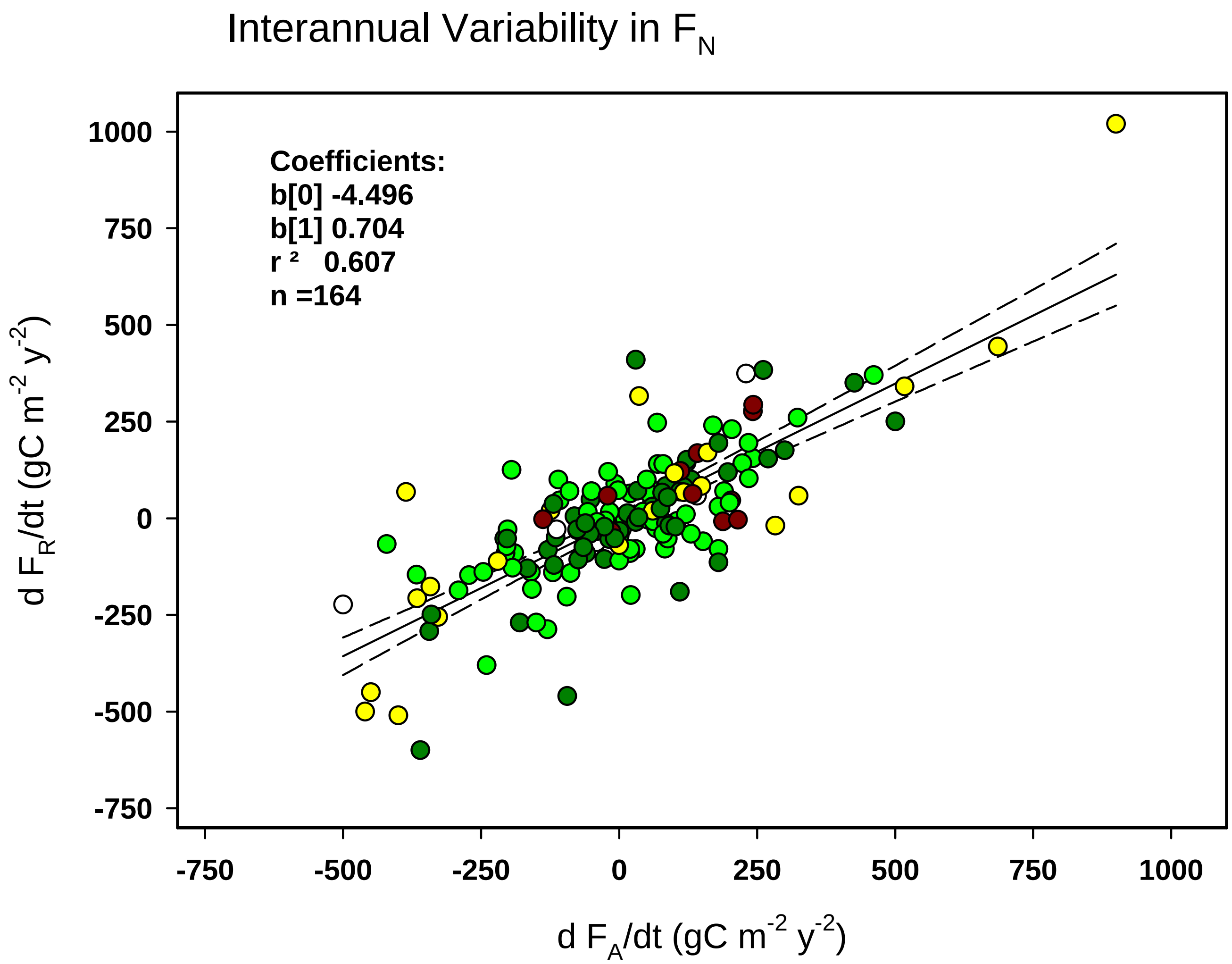
- **Nonlinear trend**
- Annual cycle
- Intra-annual cycle
- High frequency modes



New developments allow application of SSA to fragmented time series

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

Interannual Variations in Photosynthesis and Respiration are Coupled

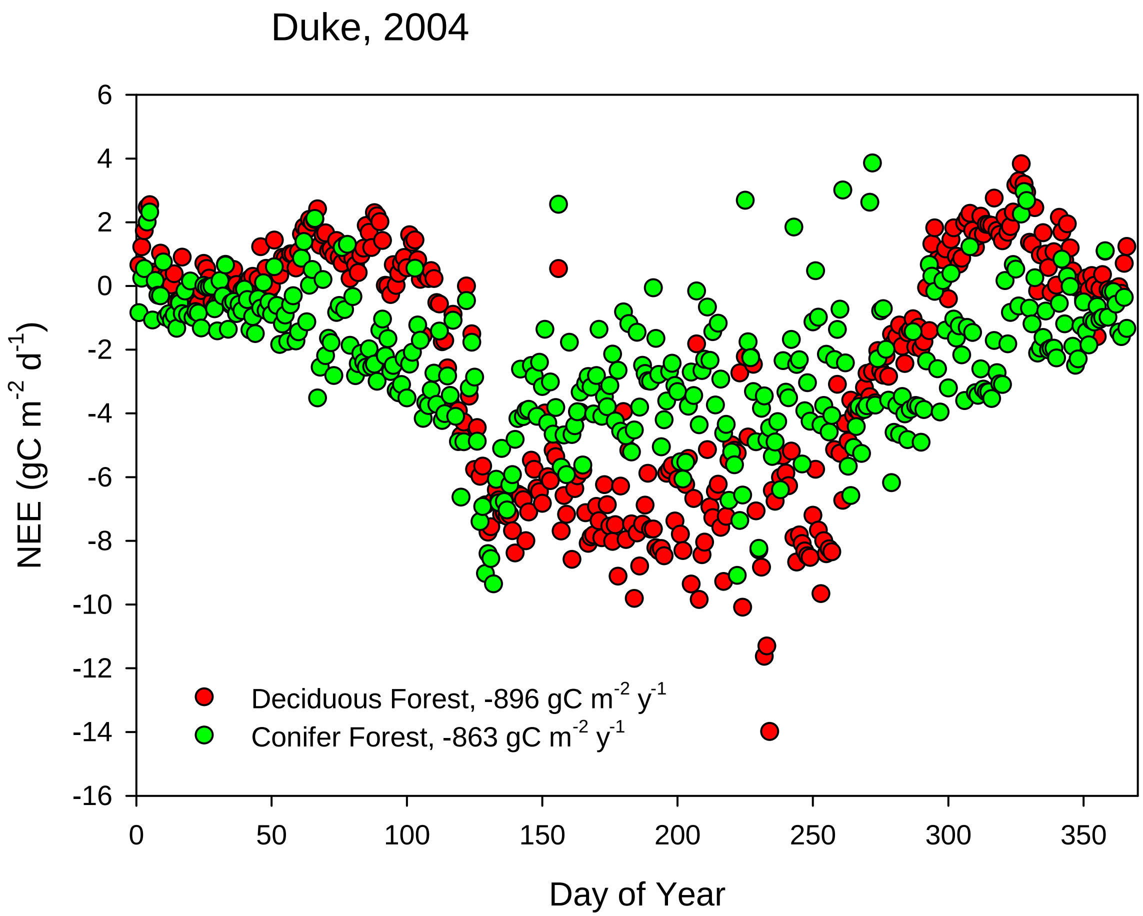


Baldocchi, Austral J Botany, 2008

Annual Fluxes by Functional Group

	Rg	Rn	albedo	H	LE	G_s	NEE
	GJ m^{-2} y^{-1}	GJ m^{-2} y^{-1}	--	GJ m^{-2} y^{-1}	GJ m^{-2} y^{-1}	mmol m^{-2} s^{-1}	gC m^{-2} y^{-1}
Crop	4.375	2.063	0.156	0.478	1.217	510	-237
Std. dev.	1.051	0.678		0.296	0.433	205	182
Grassland	4.707	1.6866	0.239	0.632	1.097	437	-156
Std.dev.	1.11	1.17		0.478	0.413	224	171
Wetland	3.427	1.3279	0.240	0.359	0.725	454	-107
Std.dev.	0.818	0.574		0.208	0.421	159	123
Evergreen needle leaved forest	4.046	2.242	0.106	0.891	0.954	432	-247
Std.dev.	0.988	0.952		0.477	0.456	173	331
Evergreen broadleaved forest	5.216	3.289	0.0825	0.893	1.888	672	-381
Std.dev	0.909	0.963		0.329	0.899	456	331
Deciduous broadleaved forest	4.086	2.310	0.204	0.651	1.081	497	-403
Std.dev	1.000	0.664		0.372	0.4659	196	289
Savanna	6.058	2.93	0.121	1.304	1.388	355	-136
Std.dev.	1.605	1.543		0.507	0.920	240	166

Effect of Plant Functional Types



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

The Advantages of Evergreeness vs Deciduousness in Mediterranean Oak

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

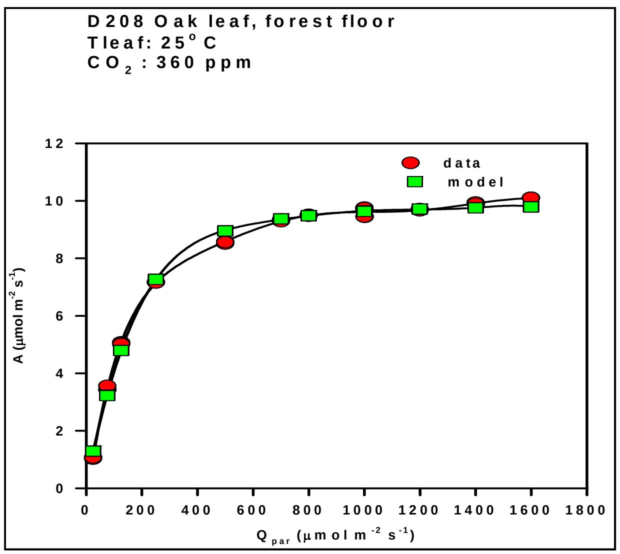
Variable	Units	Deciduous	Evergreen	LSD
GPP	$g\ C \cdot m^{-2} \cdot yr^{-1}$	1251 ± 69	1288 ± 83	152
R_{eco}	$g\ C \cdot m^{-2} \cdot yr^{-1}$	1050 ± 56	958 ± 49	137
ET	mm/yr	343 ± 37	368 ± 29	46

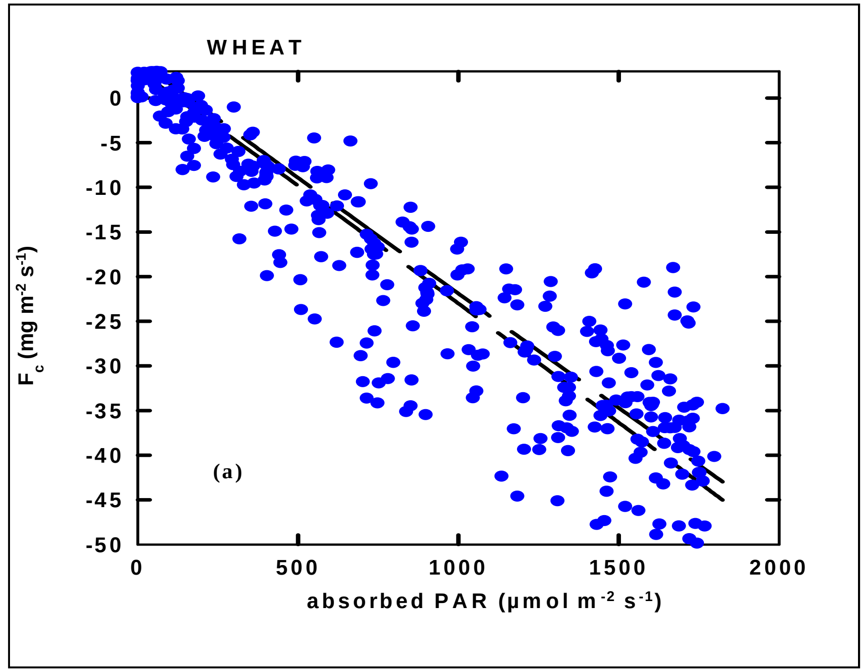
Notes: The database consists of 11 site-years for deciduous oaks and 15 site-years for evergreen oaks. For all variables and both leaf types, each flux pair was found to be identical according to Duncan's test. LSD is least significant difference at $\alpha = 0.05$.

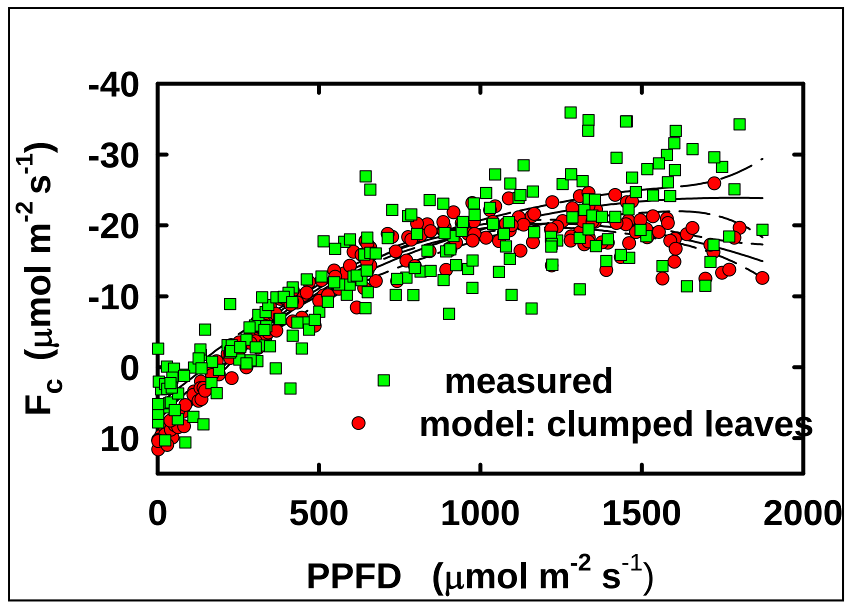
Baldocchi et al 2010. Ecol Applications

Emerging Processes

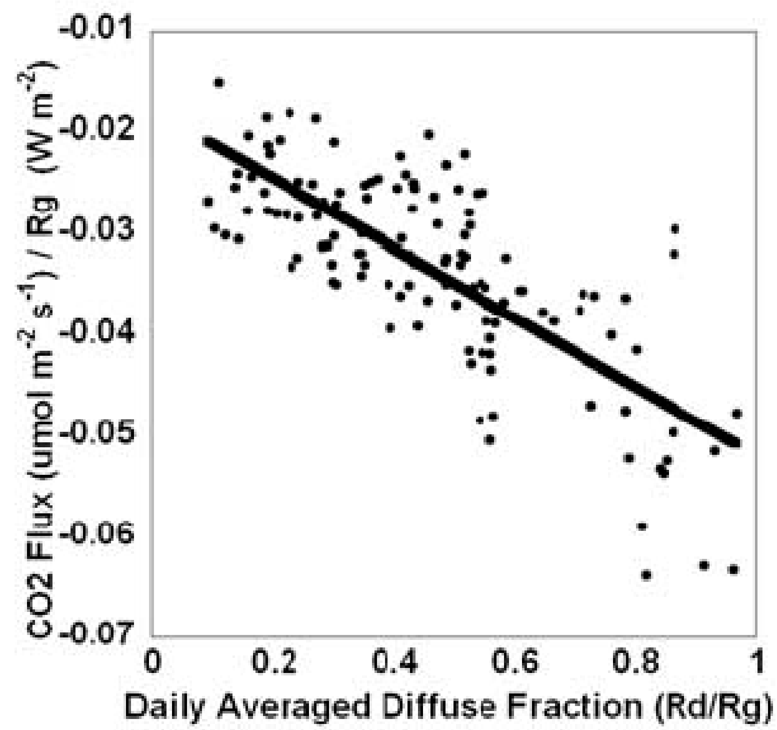
Light and Photosynthesis: Emergent Processes at Leaf and Canopy Scales







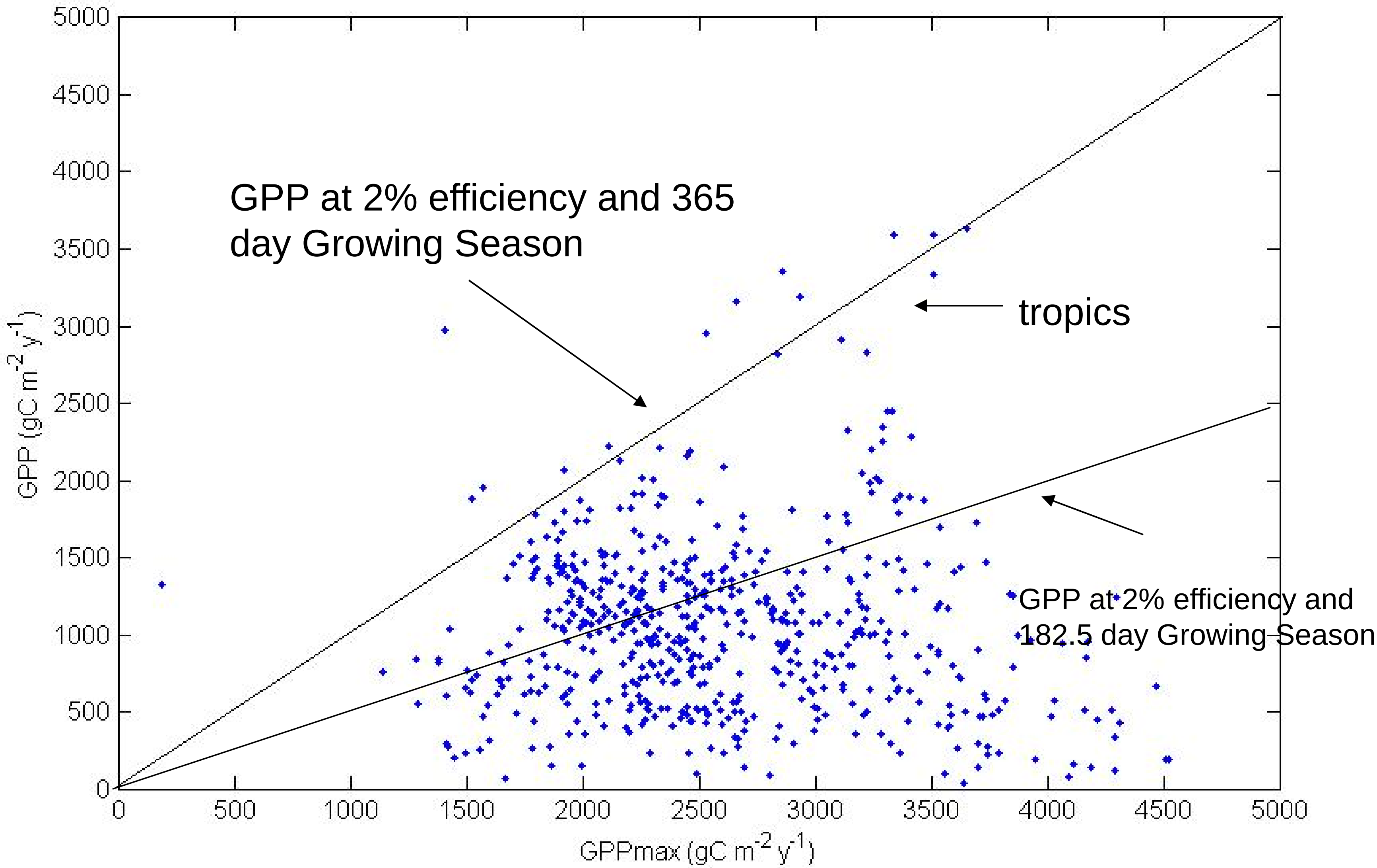
Emergent Scale Process:
CO_2 Flux and Diffuse Radiation



- We are poised to see effects of Cleaner/Dirtier Skies and Next Volcano

Niyogi et al., GRL 2004

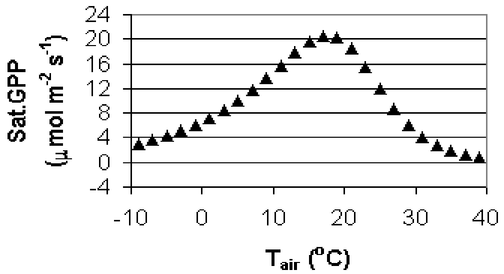
Potential and Real Rates of Gross Carbon Uptake by Vegetation: Most Locations Never Reach Upper Potential

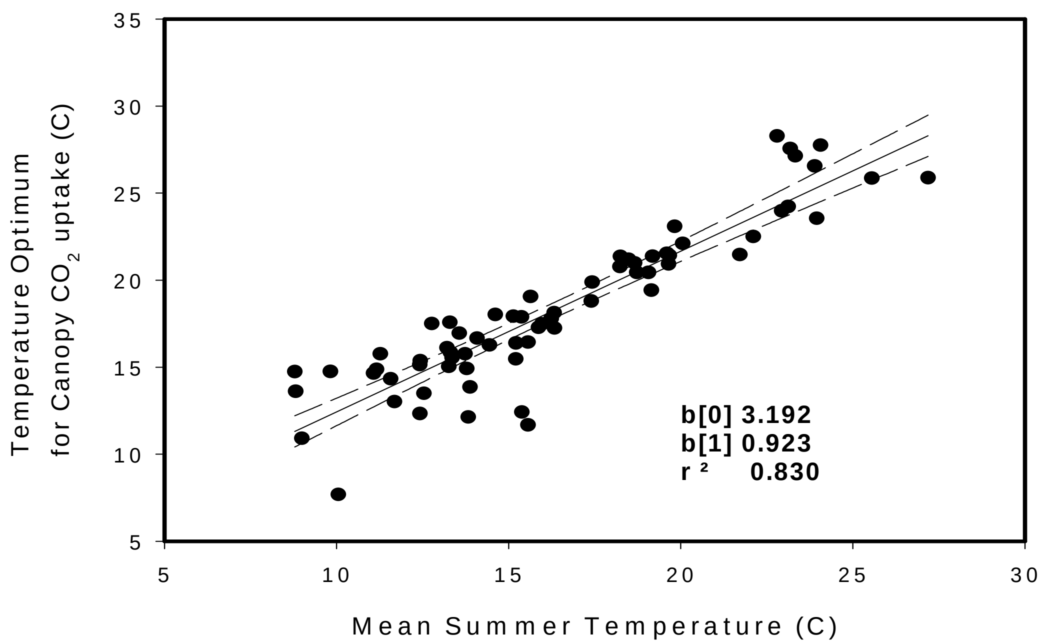


FLUXNET 2007 Database

CzechGlobe Lecture

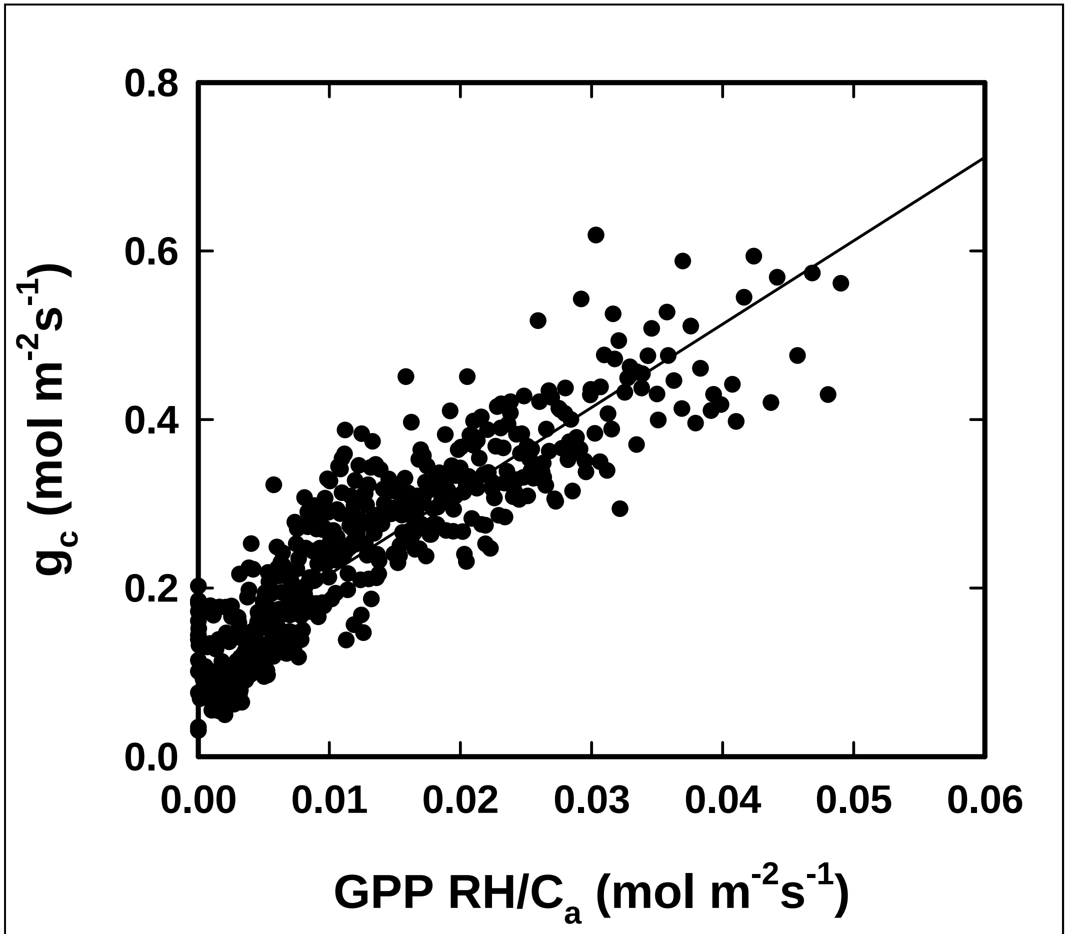
Optimal NEE: Acclimation with Temperature





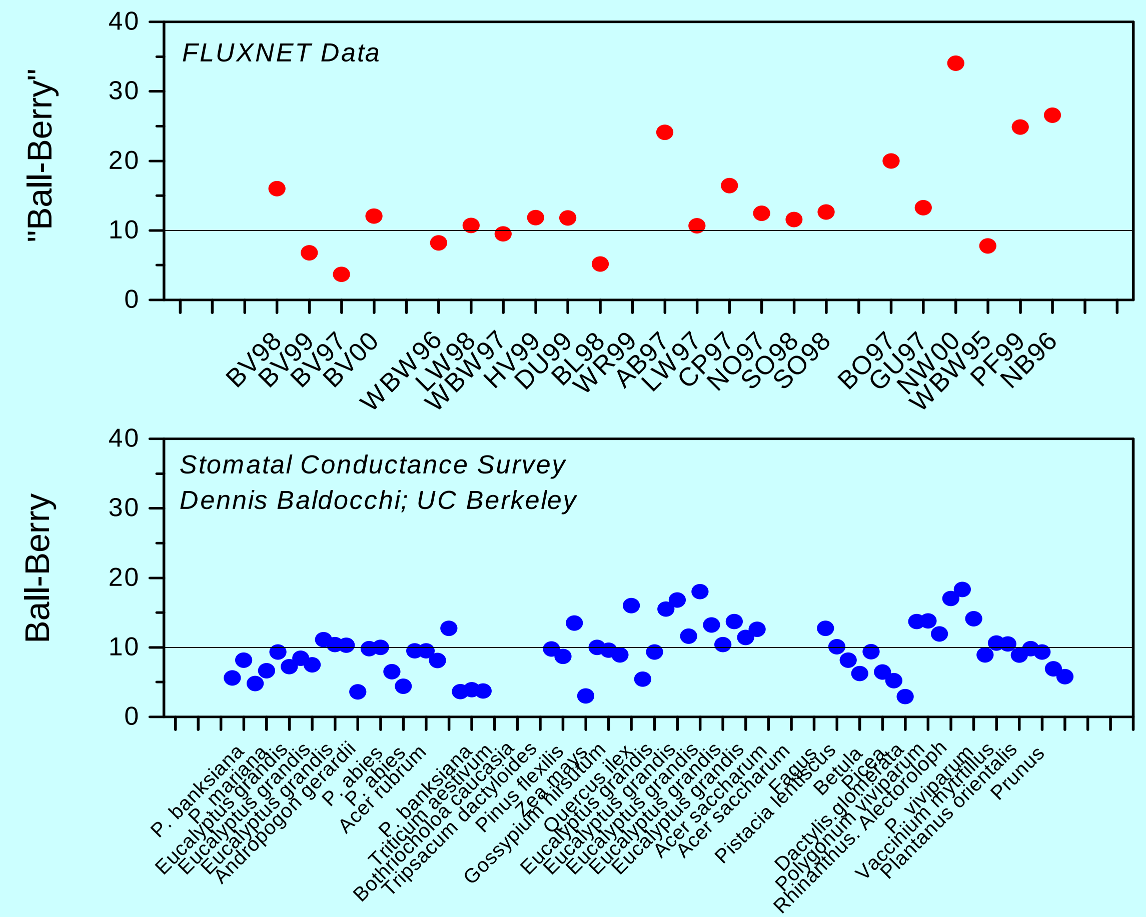
E. Falge et al 2002 AgForMet; Baldocchi et al 2001 BAMS

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



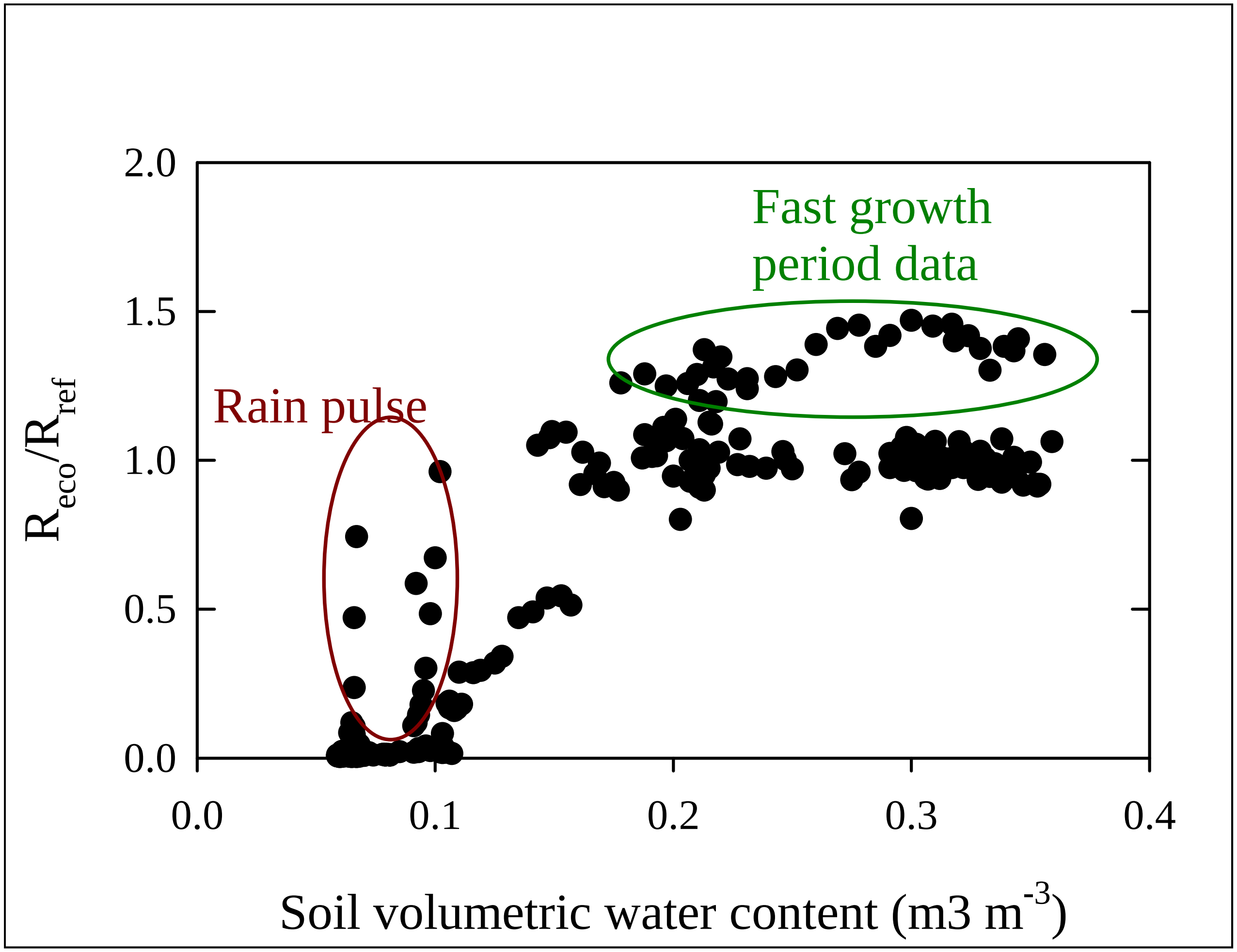
Xu + DDB, 2003 AgForMet

Gc Scale Invariance?
Task to Expand with New Database



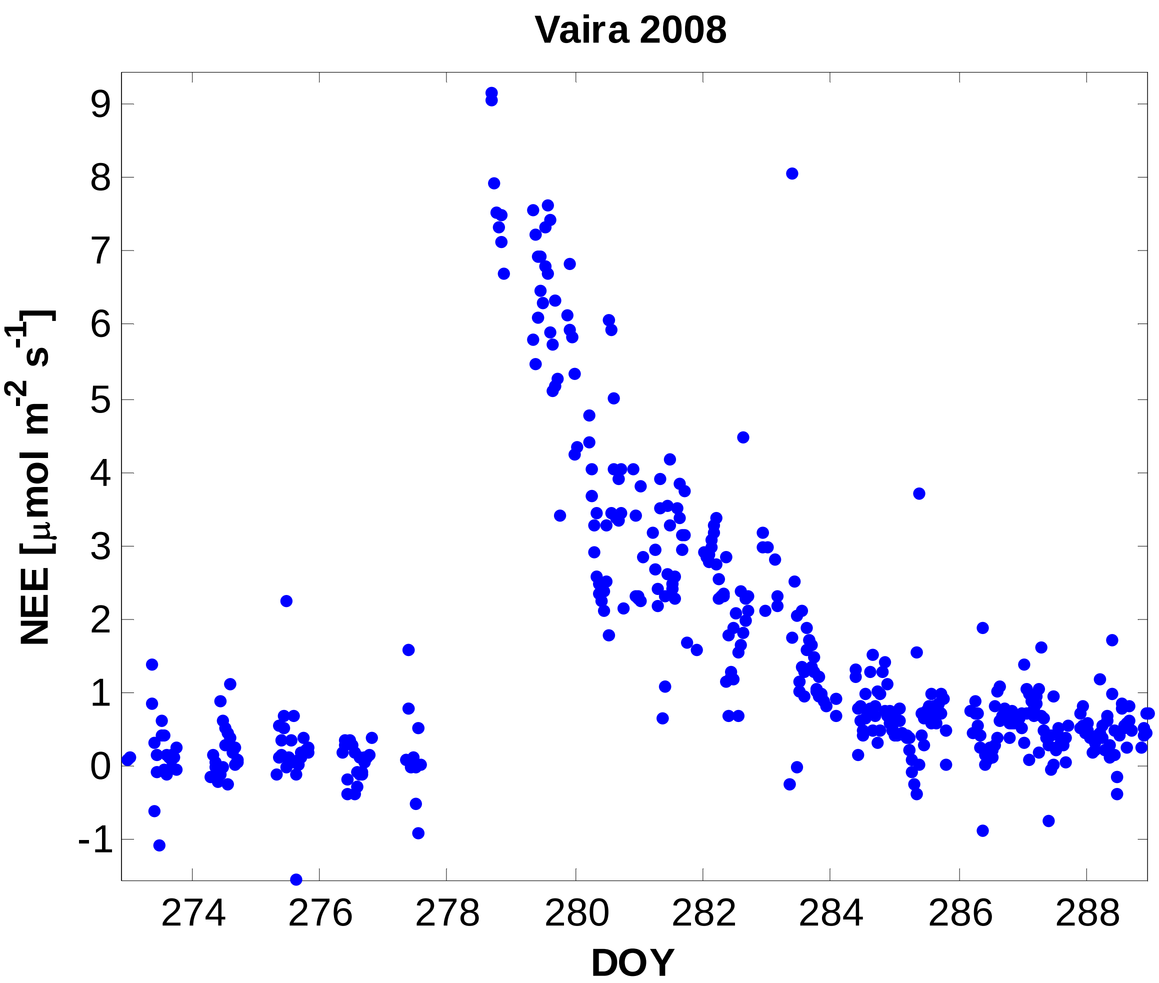
Processed by M. Falk

Environmental Controls on Respiration

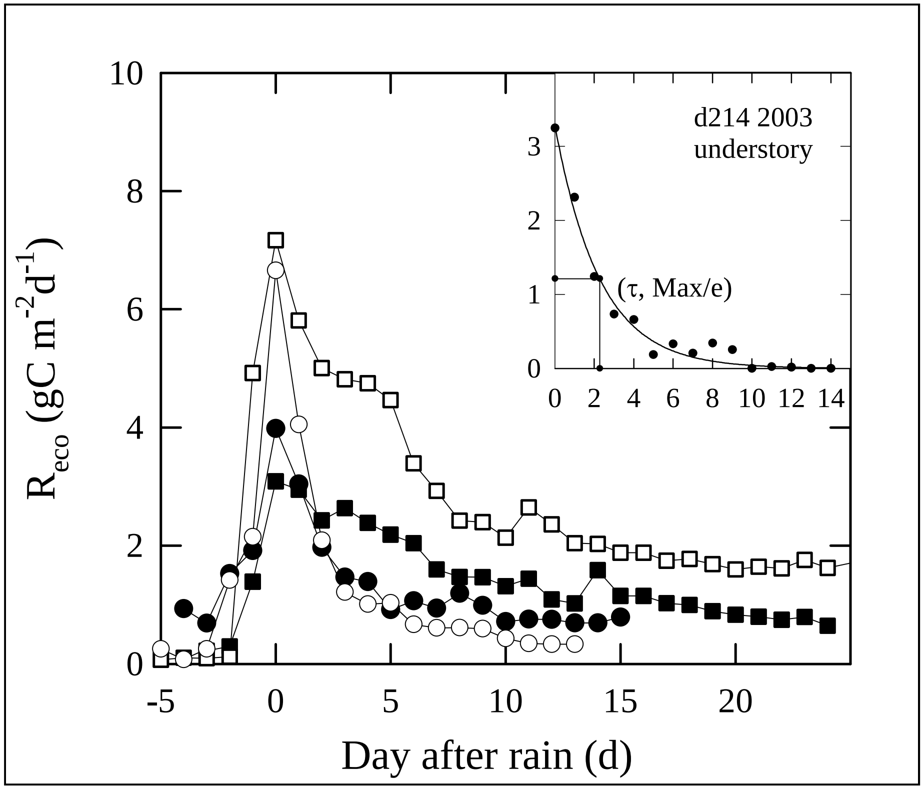


Xu + Baldocchi, AgForMet 2004

Sustained and Elevated Respiration after Fall Rain

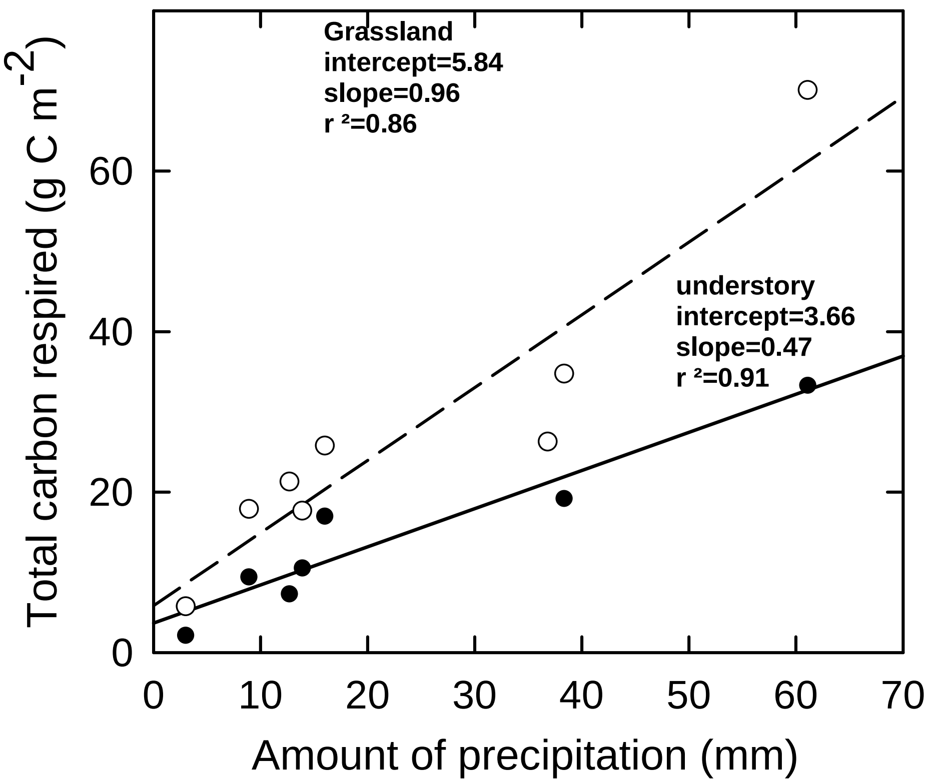


Quantifying the impact of rain pulses on respiration



Xu, Baldocchi, Tang, 2004
Global Biogeochem Cycles

Why Do Rain pulses Produce more C from Open Grassland than Understory?



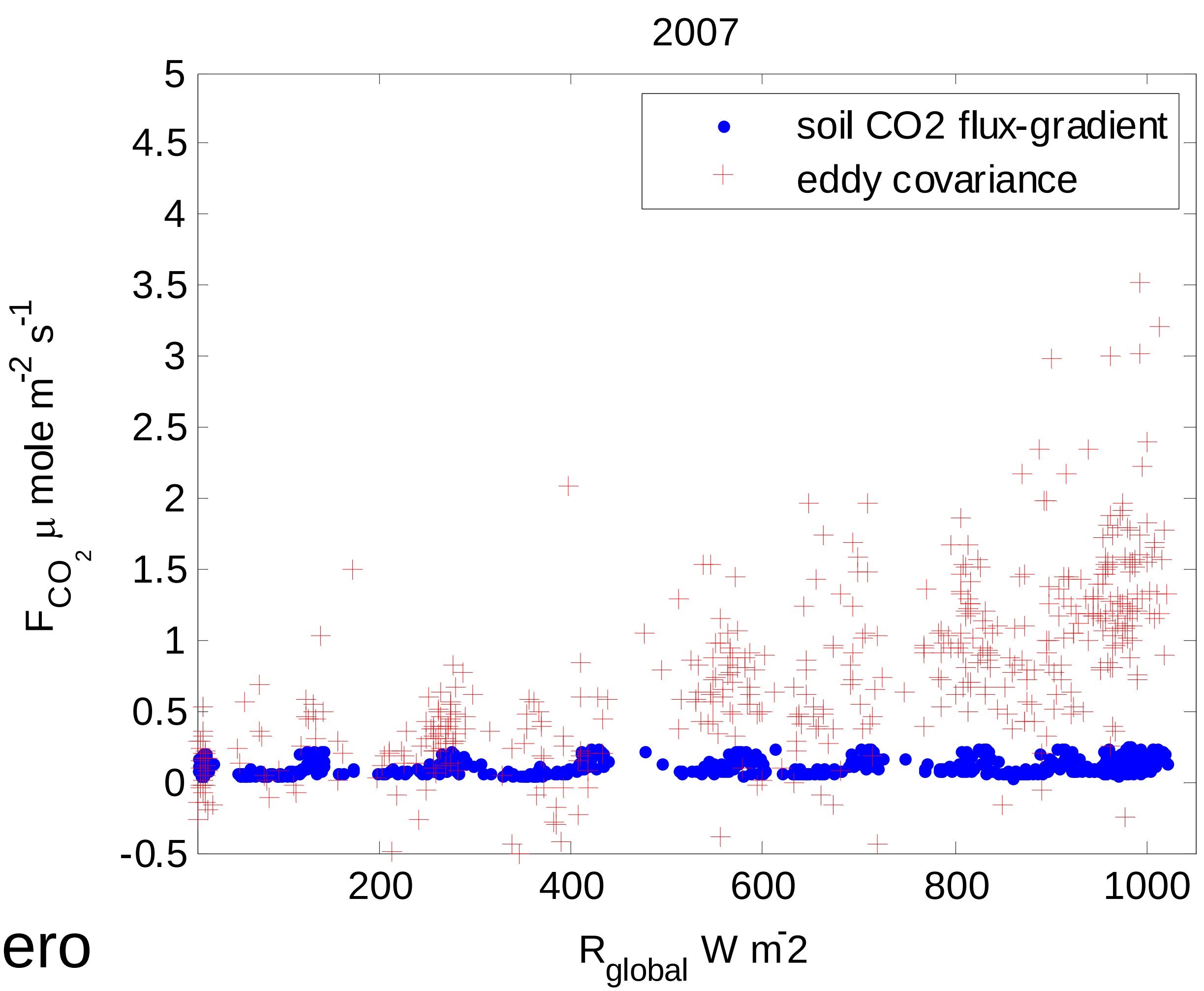
Xu et al. 2003 GBC

What Happens to the Grass?;
It is too Dry to Promote Microbial Decomposition

June

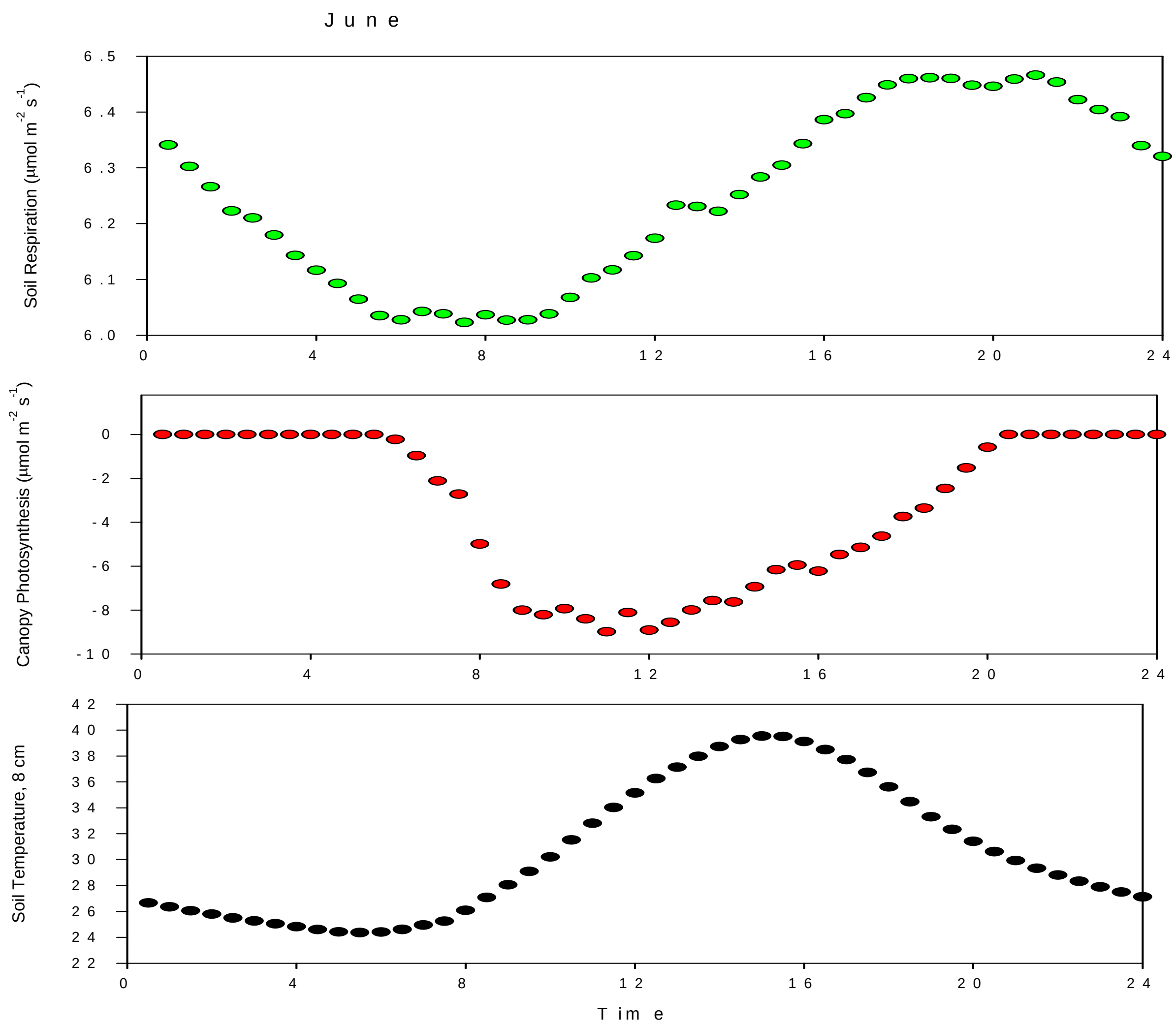
October

PhotoDegradation Can Be a Important Pathway for Carbon Loss in Semi-Arid Rangelands (~20-30 gC m^{-2} $season^{-1}$)



Note Zero
Flux at night

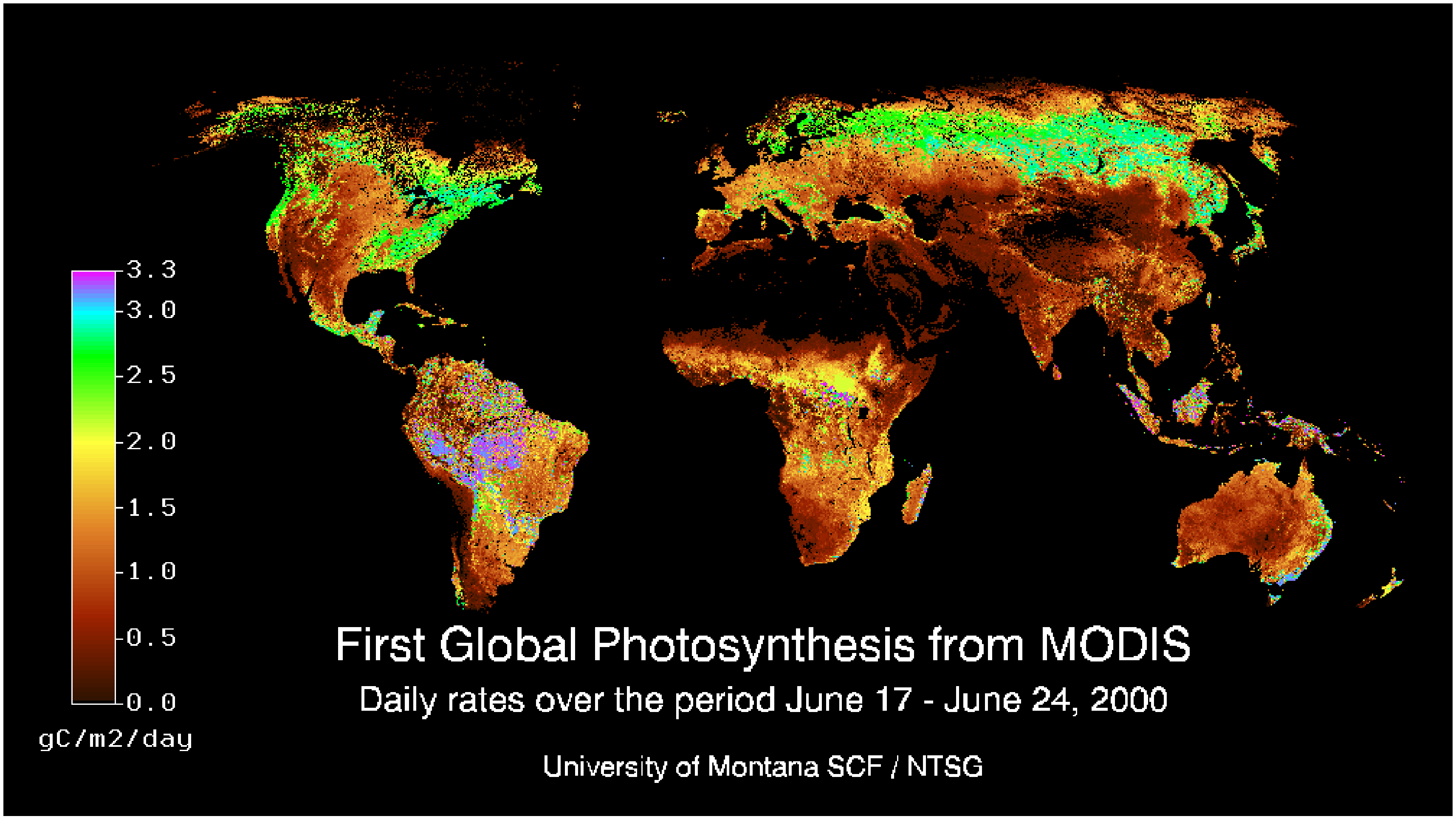
Lags and Leads in Ps, Soil Temperature and Soil Respiration



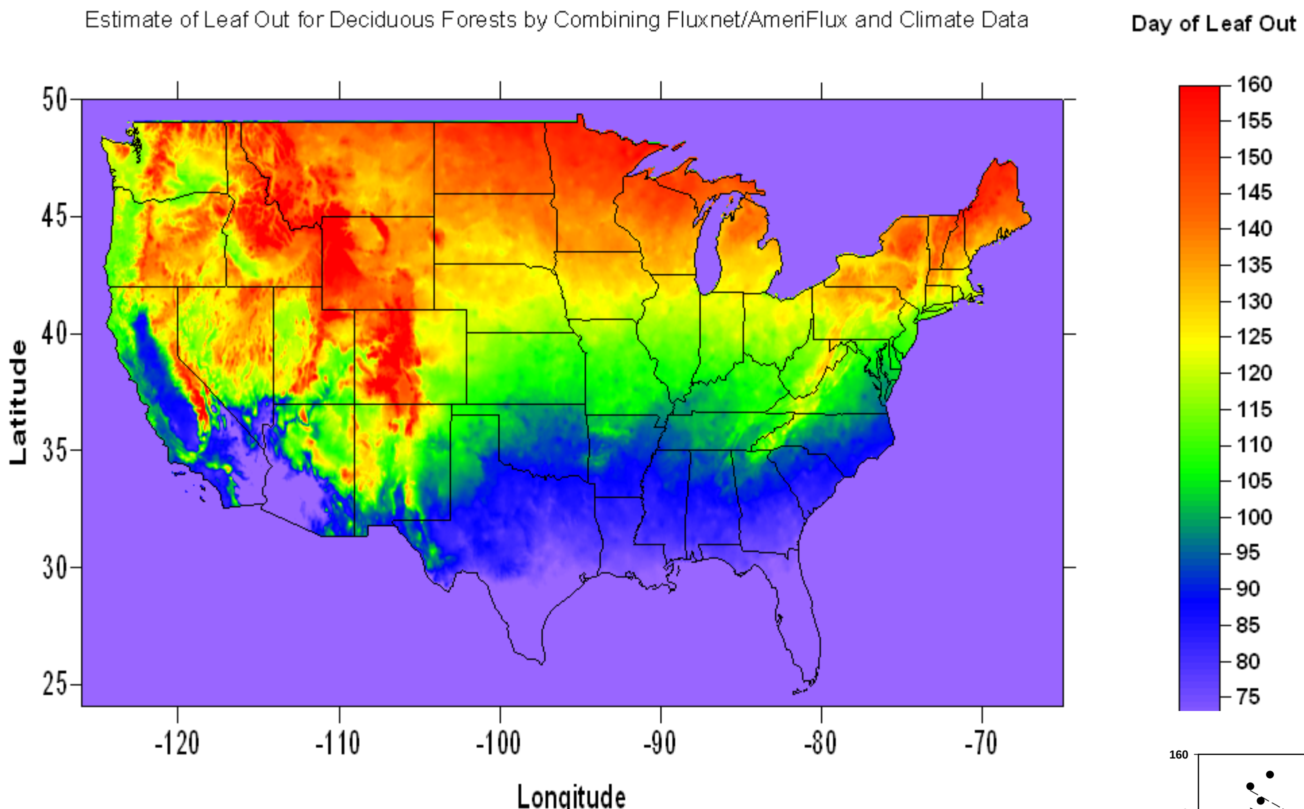
CzechGlobe Lecture

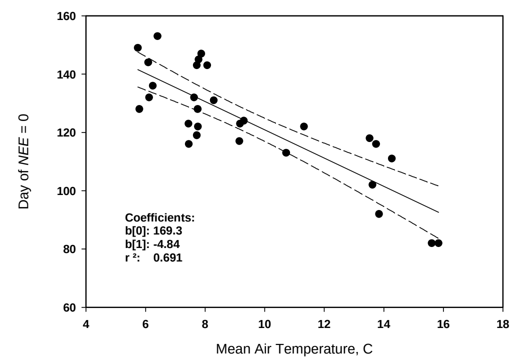
Tang et al, Global Change Biology 2005.

Spatial Variations in C Fluxes



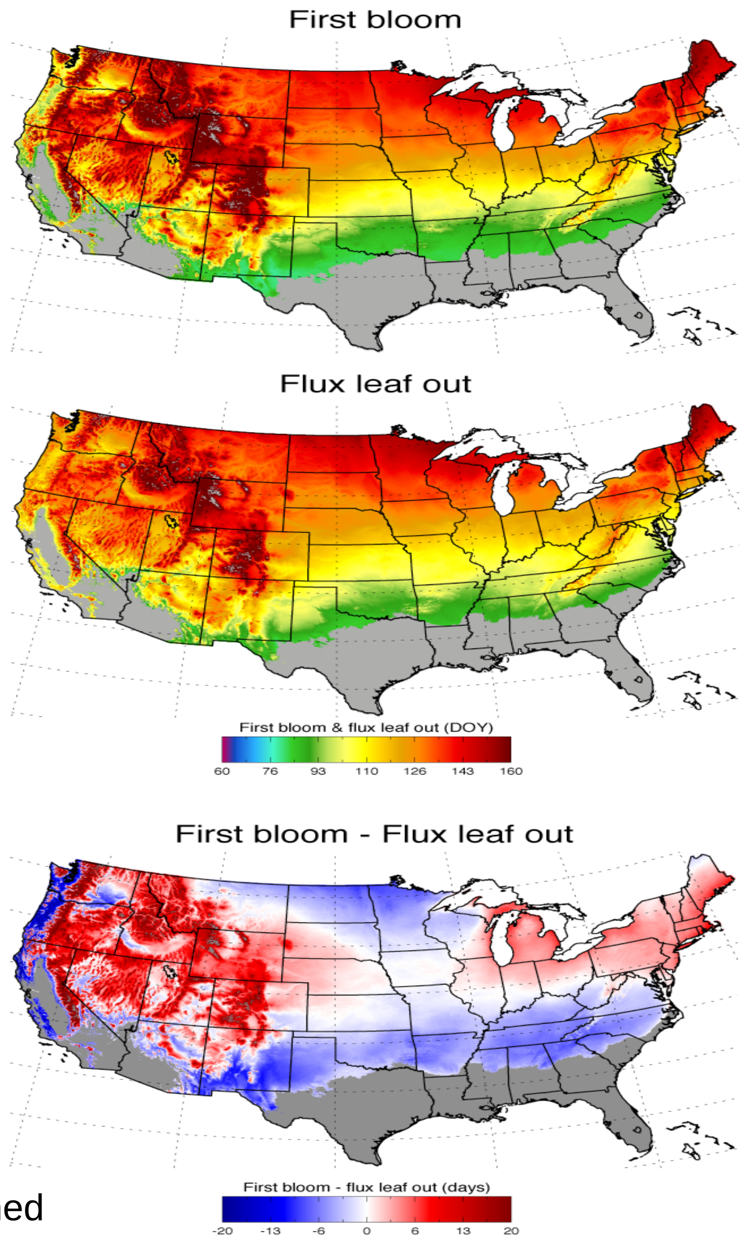
Spatialize Phenology with Transformation Using Climate Map





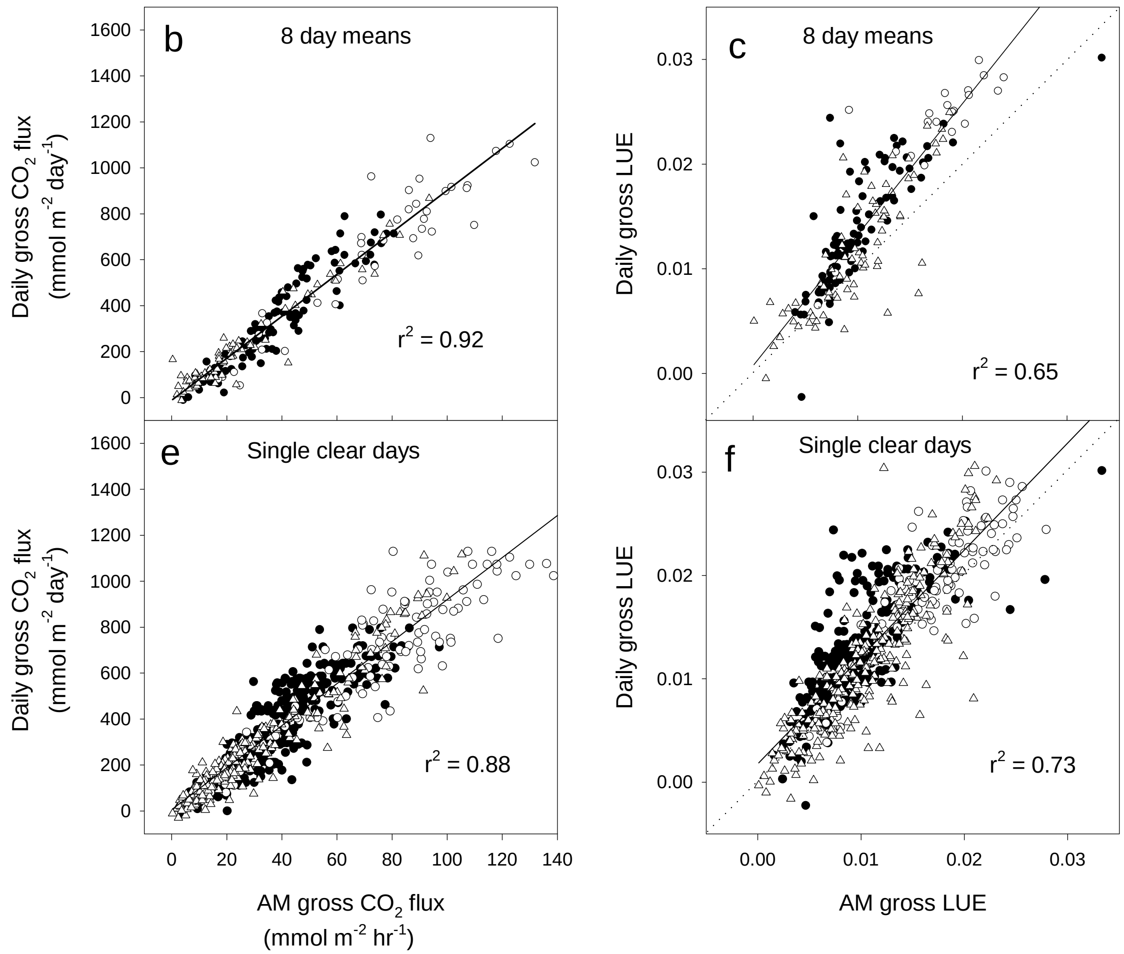
Baldocchi, unpublished

Flux Based Phenology Patterns with Match well with data from Phenology Network



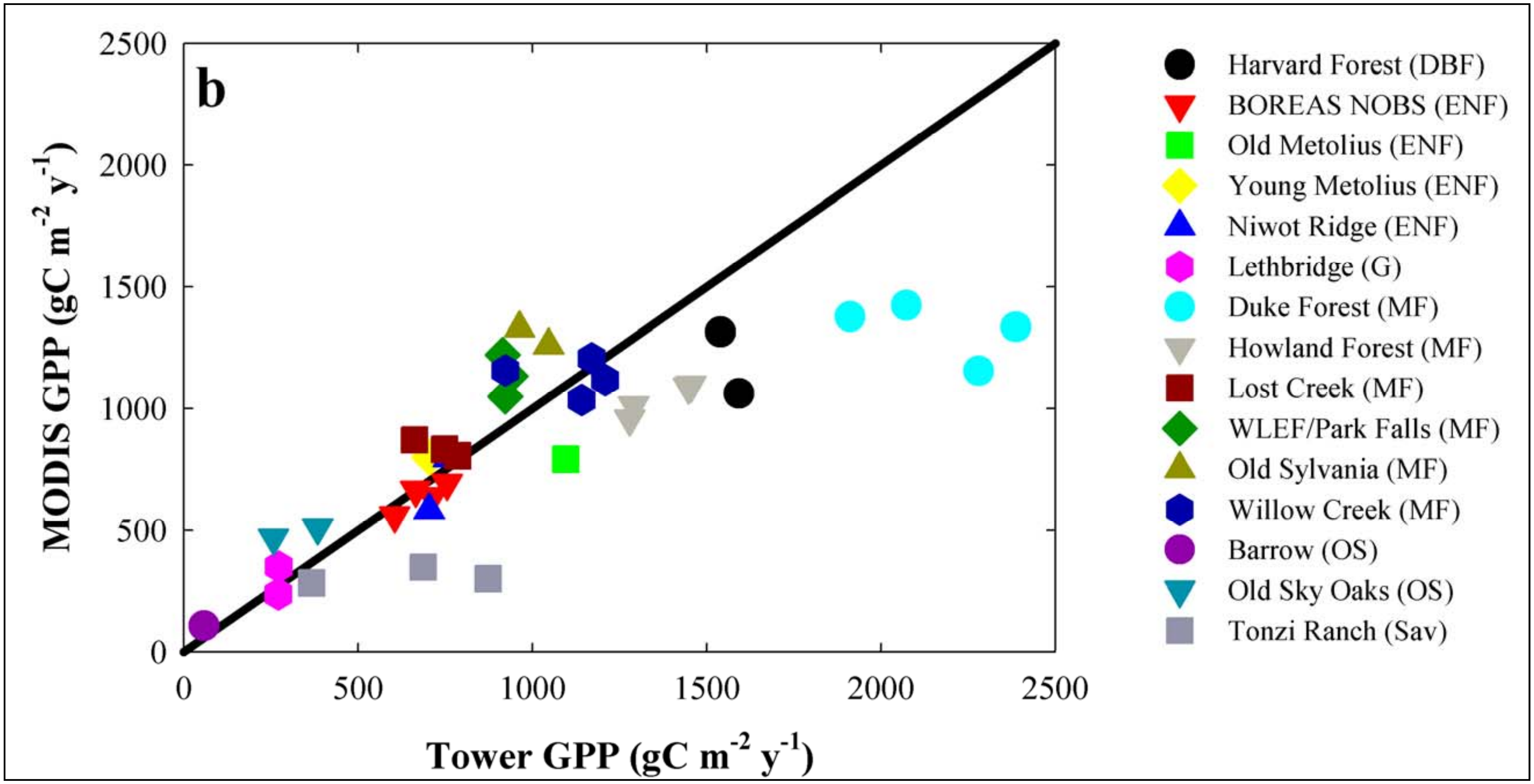
White, Baldocchi and Schwartz, unpublished

Do Snap-Shot C Fluxes, inferred from Remote Sensing, Relate to Daily C Flux Integrals?



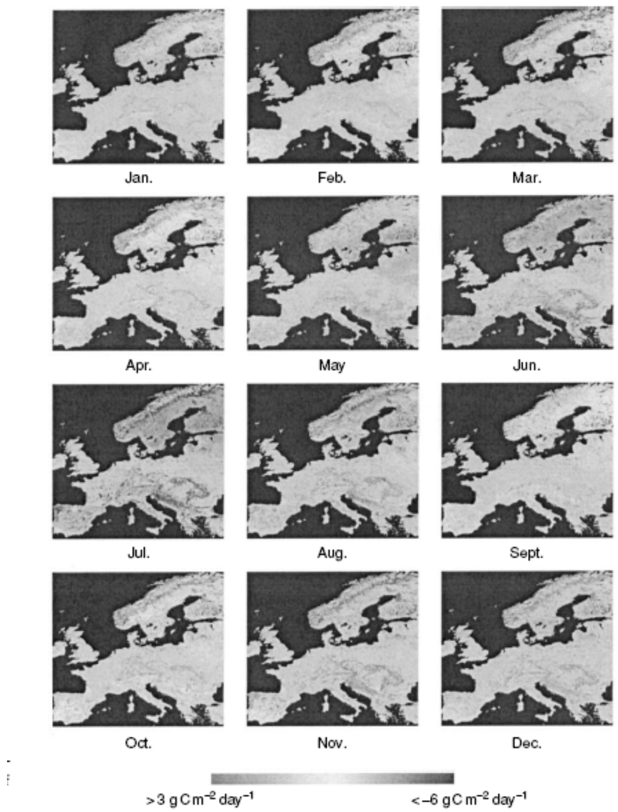
Sims et al 2005 AgForMet

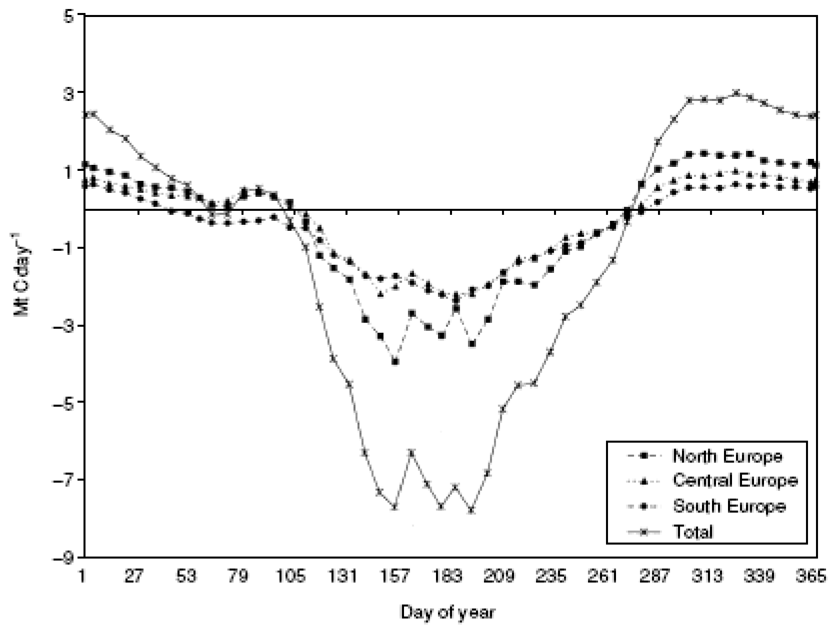
MODIS GPP Algorithm Test



Heinsch et al. 2006 RSE

Upscaling Tower Measurements with Neural Network Model and Remote Sensing





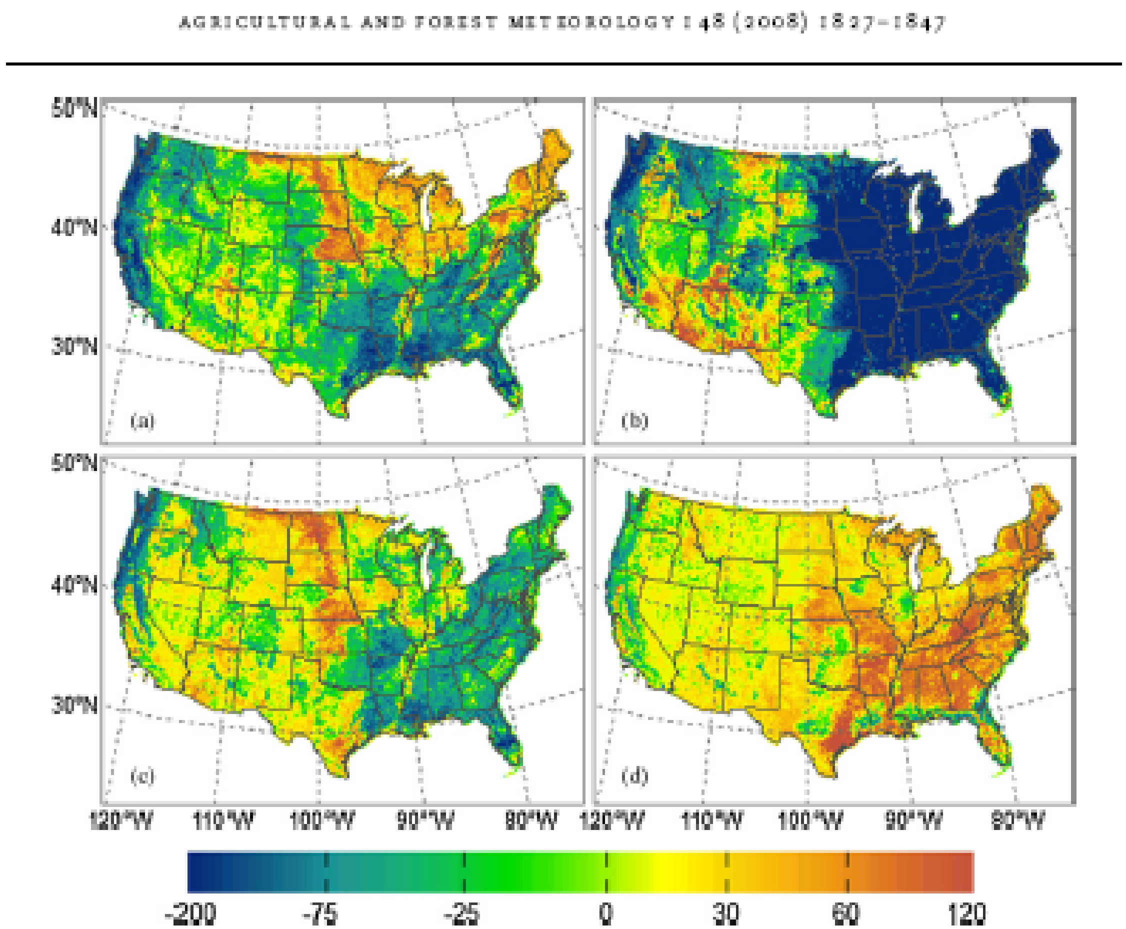
Papale and Valentini, 2003 GCB

What are Pros and Cons?

Spatial Variations in C Fluxes

spring

summer

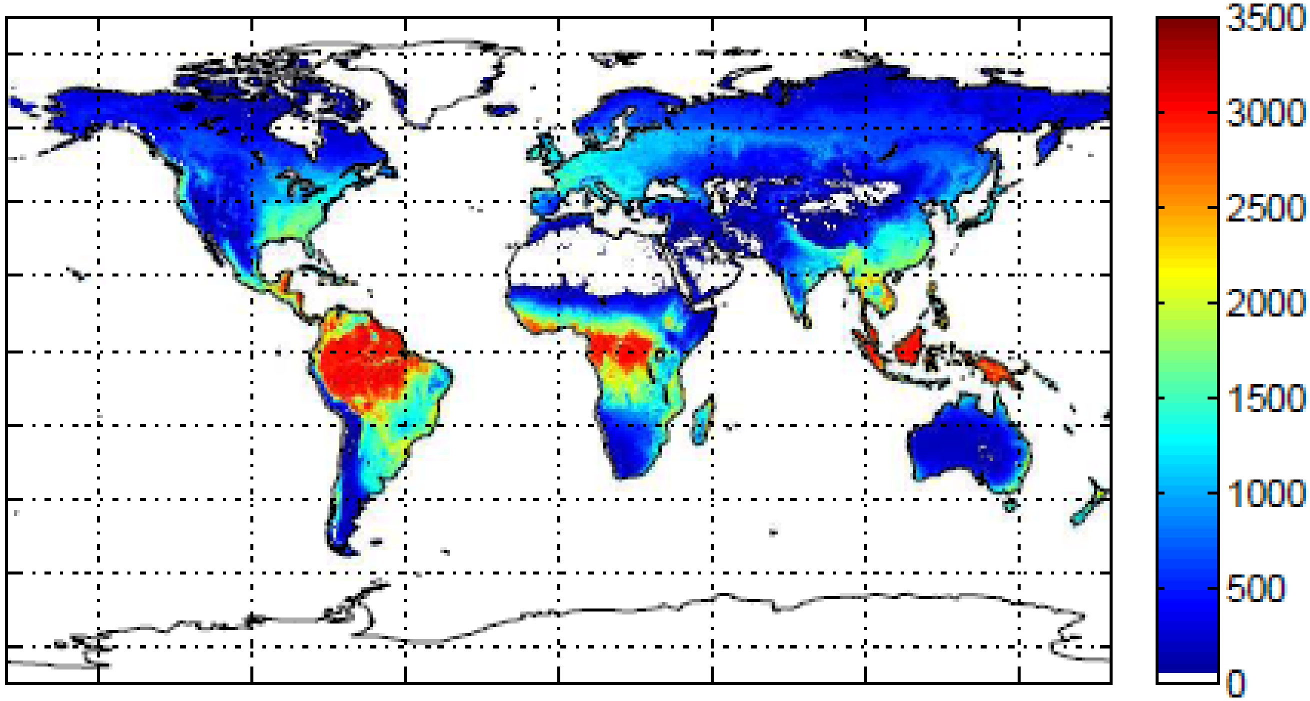


autumn

winter

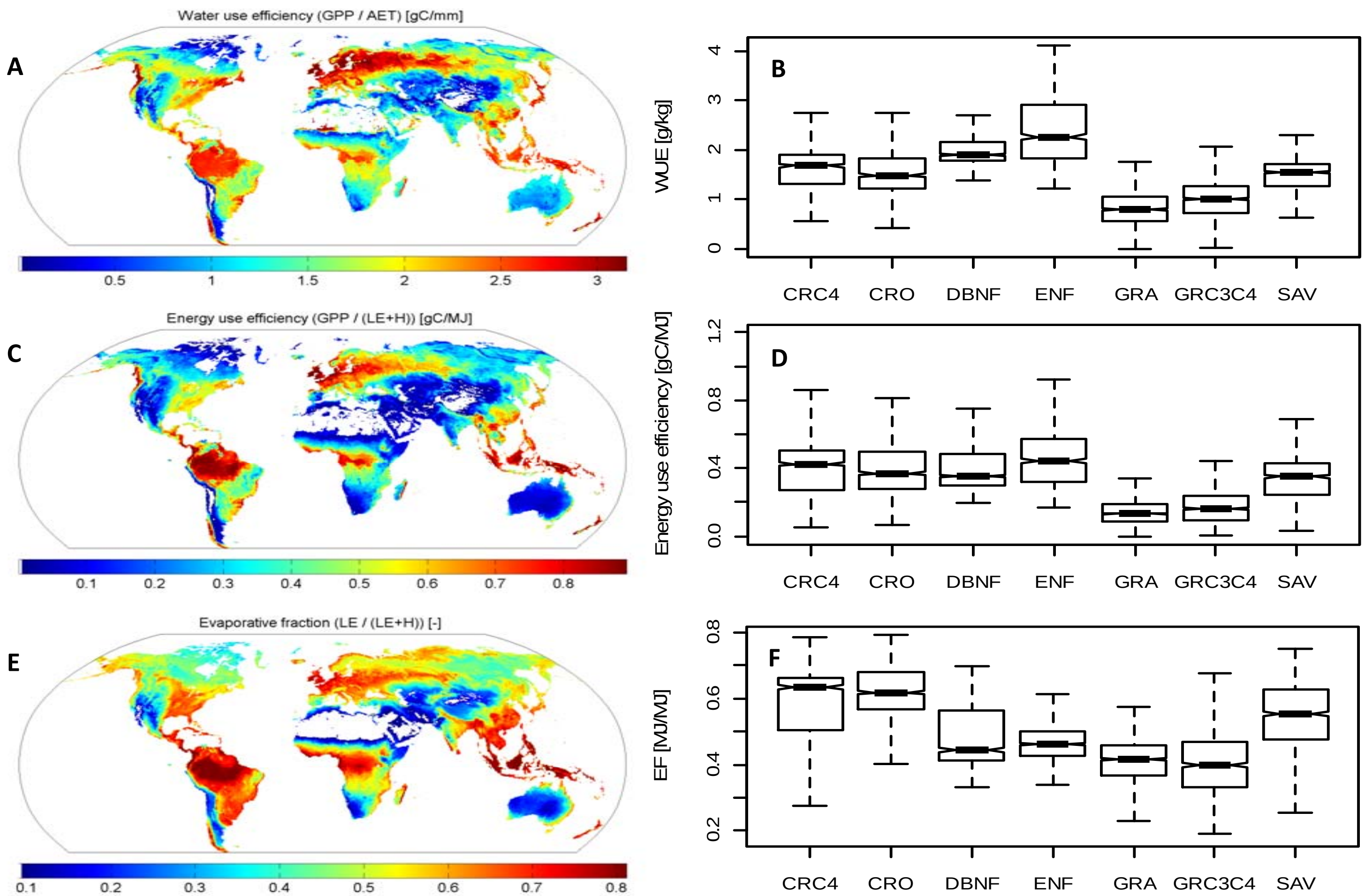
Xiao et al. 2008, AgForMet

Global Primary Productivity



GPP = 123 +/- 8 PgC y-1

Beer et al., 2010 Science



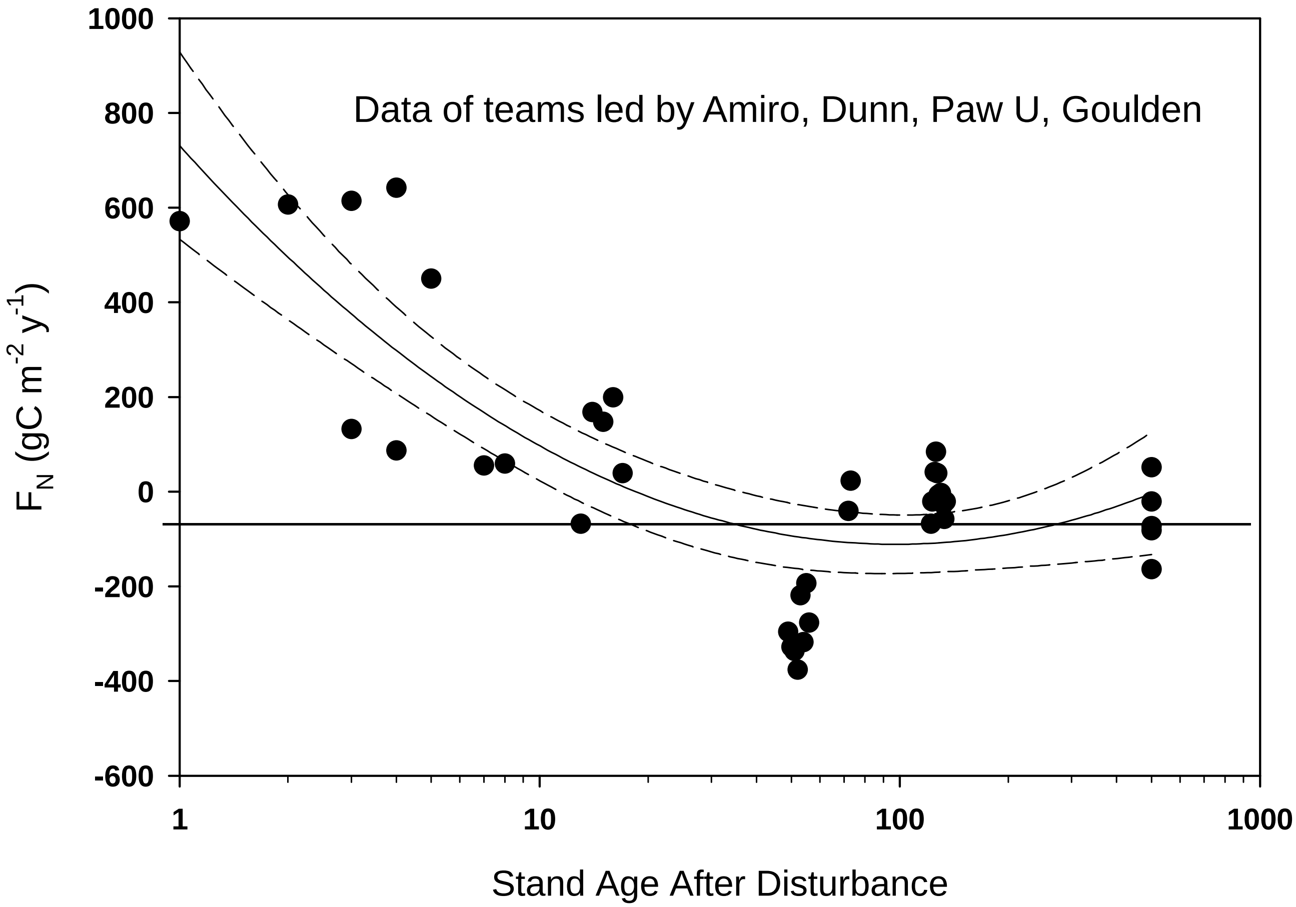
Reichstein et al. PNAS in press

Limits to Landscape Classification by Functional Type

- Stand Age/Disturbance
- Biodiversity
- Fire
- Logging
- Insects/Pathogens
- Management/Plantations
- Kyoto Forests
- Functional Traits Trump Functional Types

Time Since Disturbance Affects Net Ecosystem Carbon Exchange

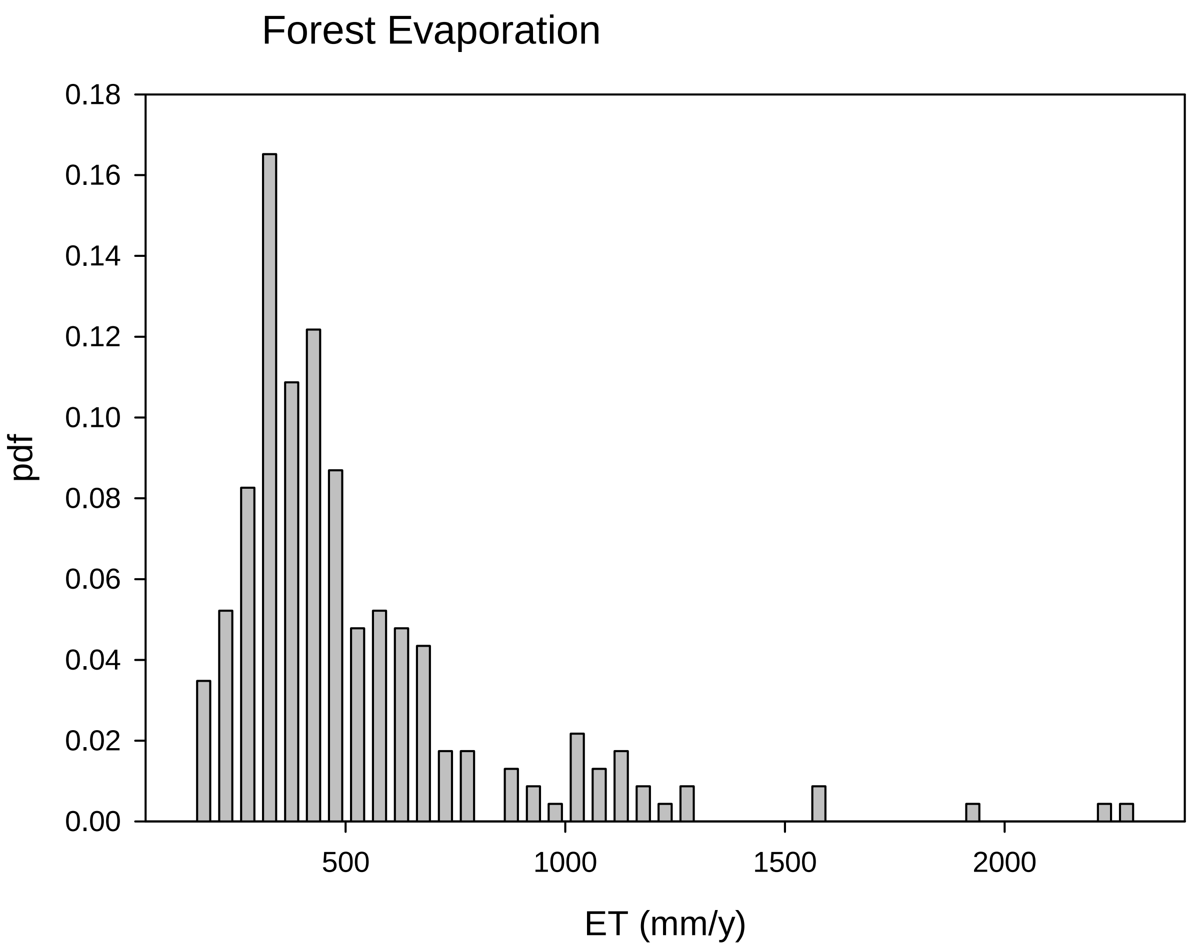
Conifer Forests, Canada and Pacific Northwest



Baldocchi, Austral J Botany, 2008

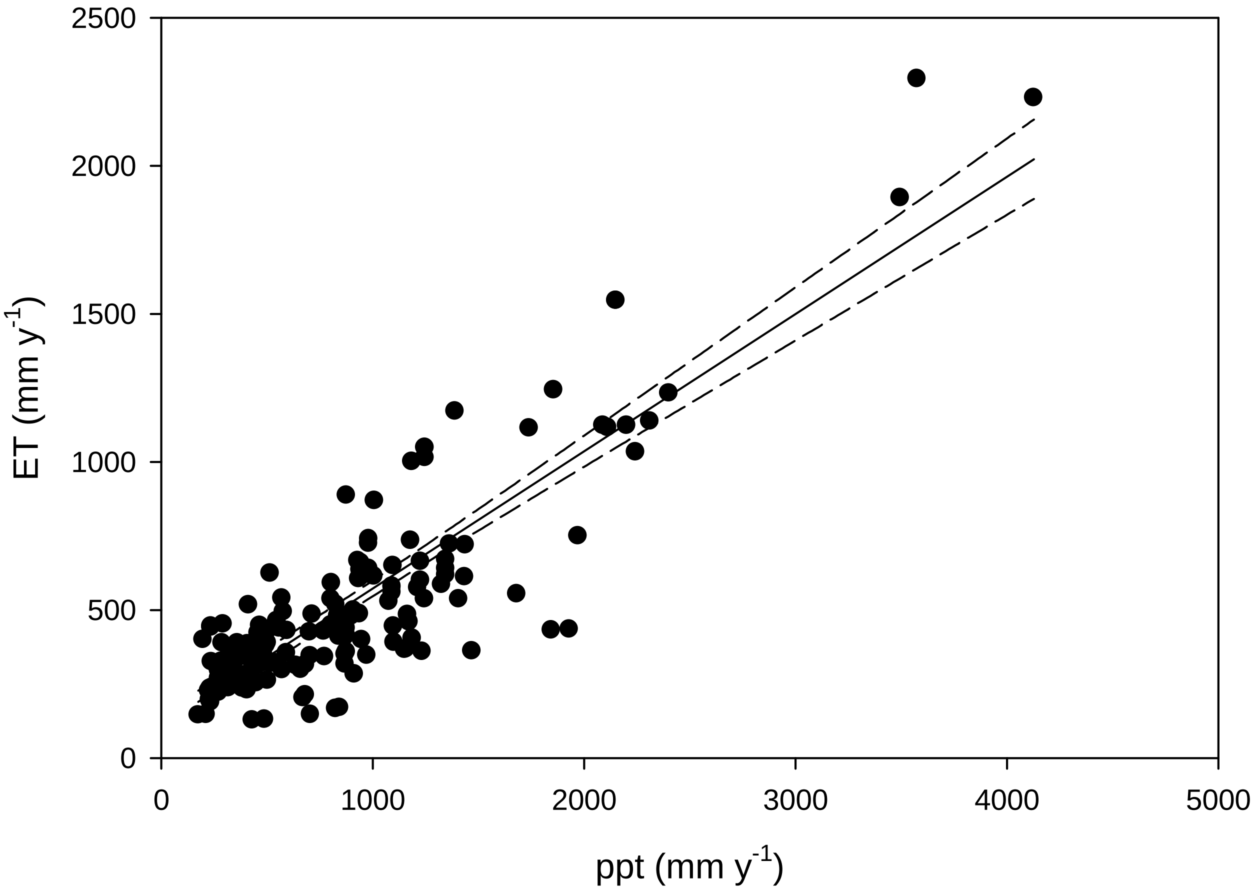
Other Activities and Uses of Fluxnet Data

- Ecosystem Modeling
- EcoHydrology
- Biodiversity
- Climate

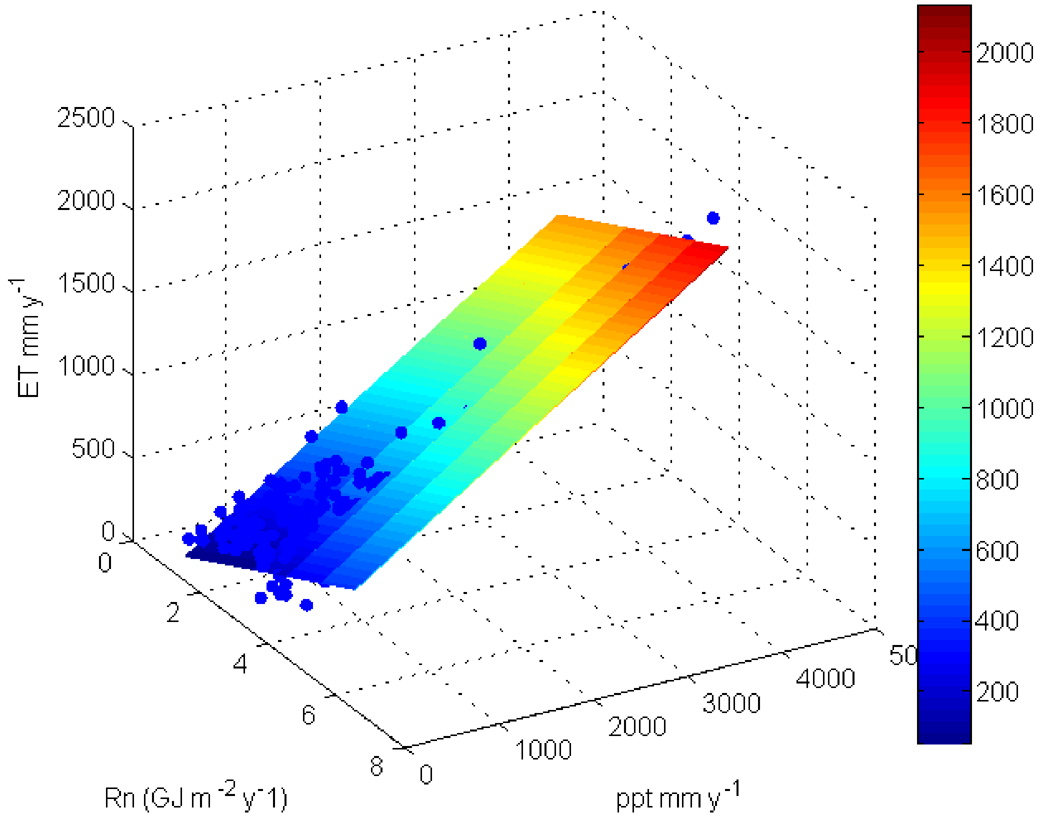


Baldocchi and Ryu, 2011
in *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*

Forests

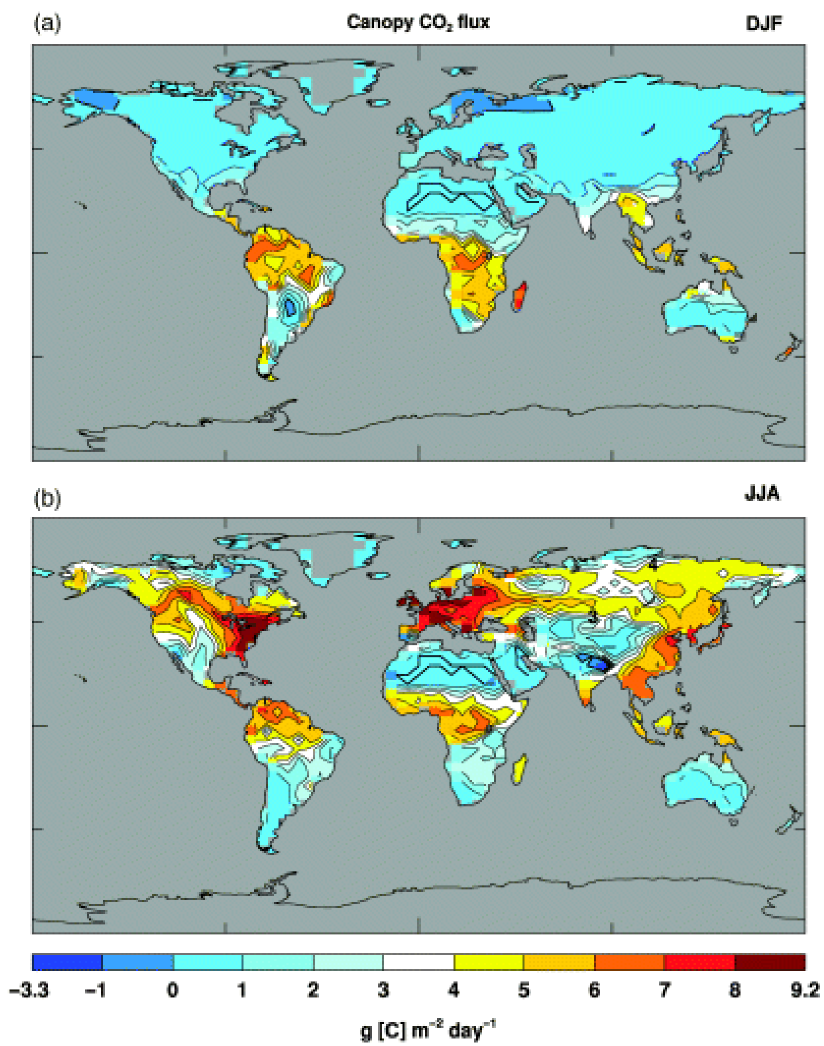


Baldocchi and Ryu, 2011
in *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*



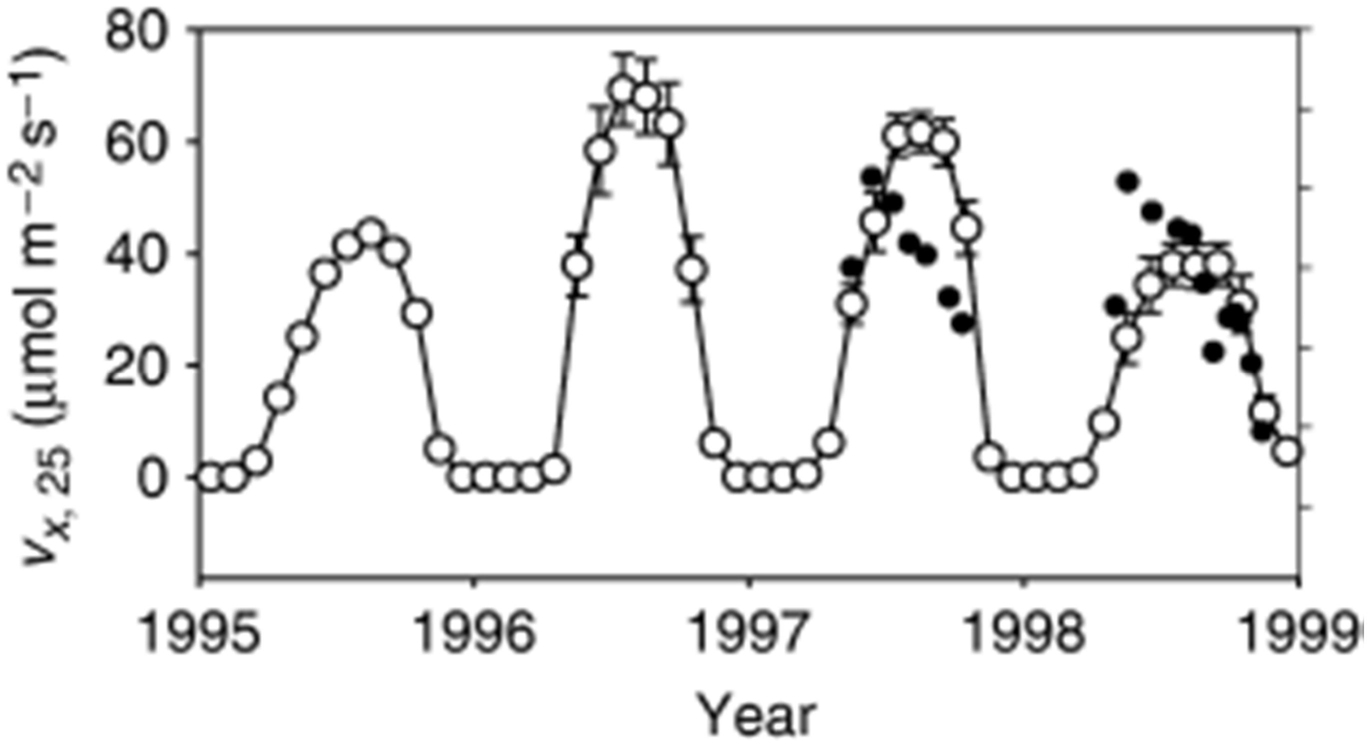
Baldocchi and Ryu, 2011
in *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*

Net ecosystem exchange of CO_2 (NEE) predicted by different terrestrial biosphere models compares favourably with FLUXNET observations at diurnal and seasonal timescales.



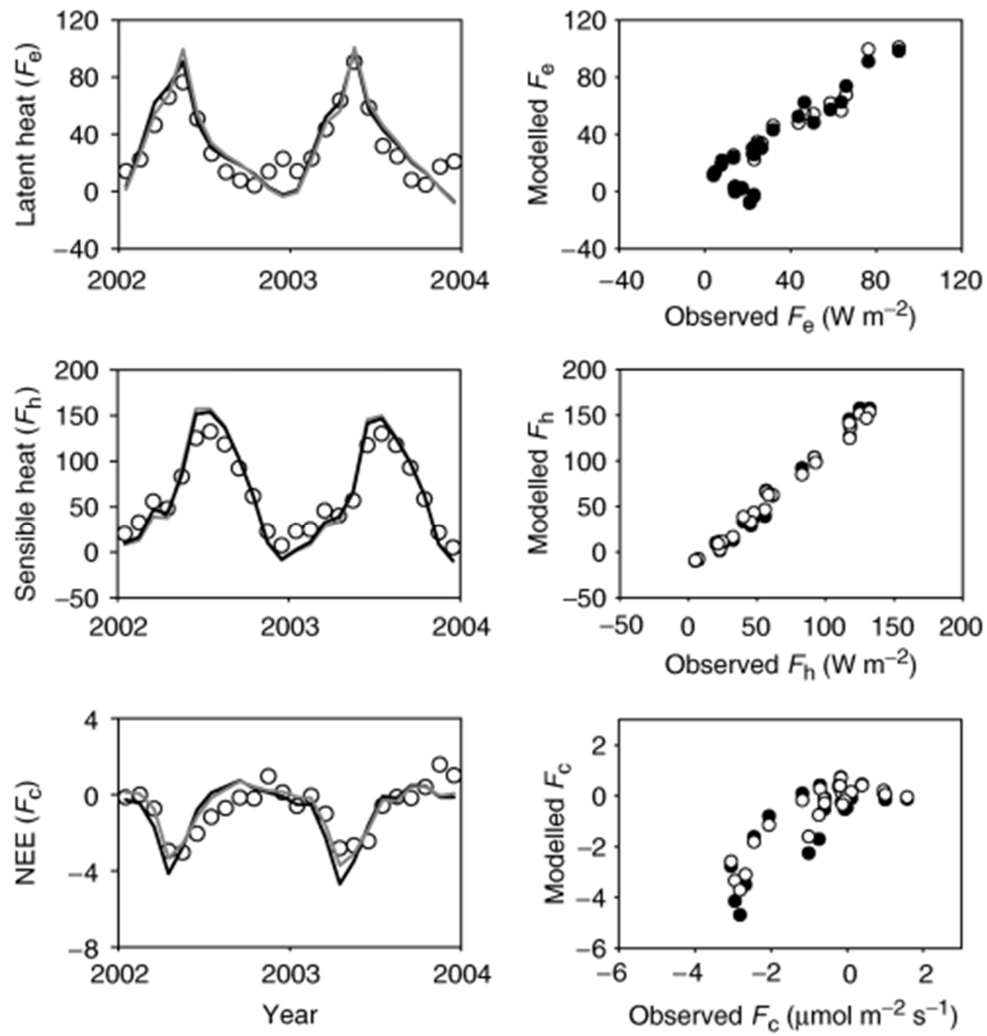
Friend et al 2007, GCB

Seasonality of Photosynthetic Capacity



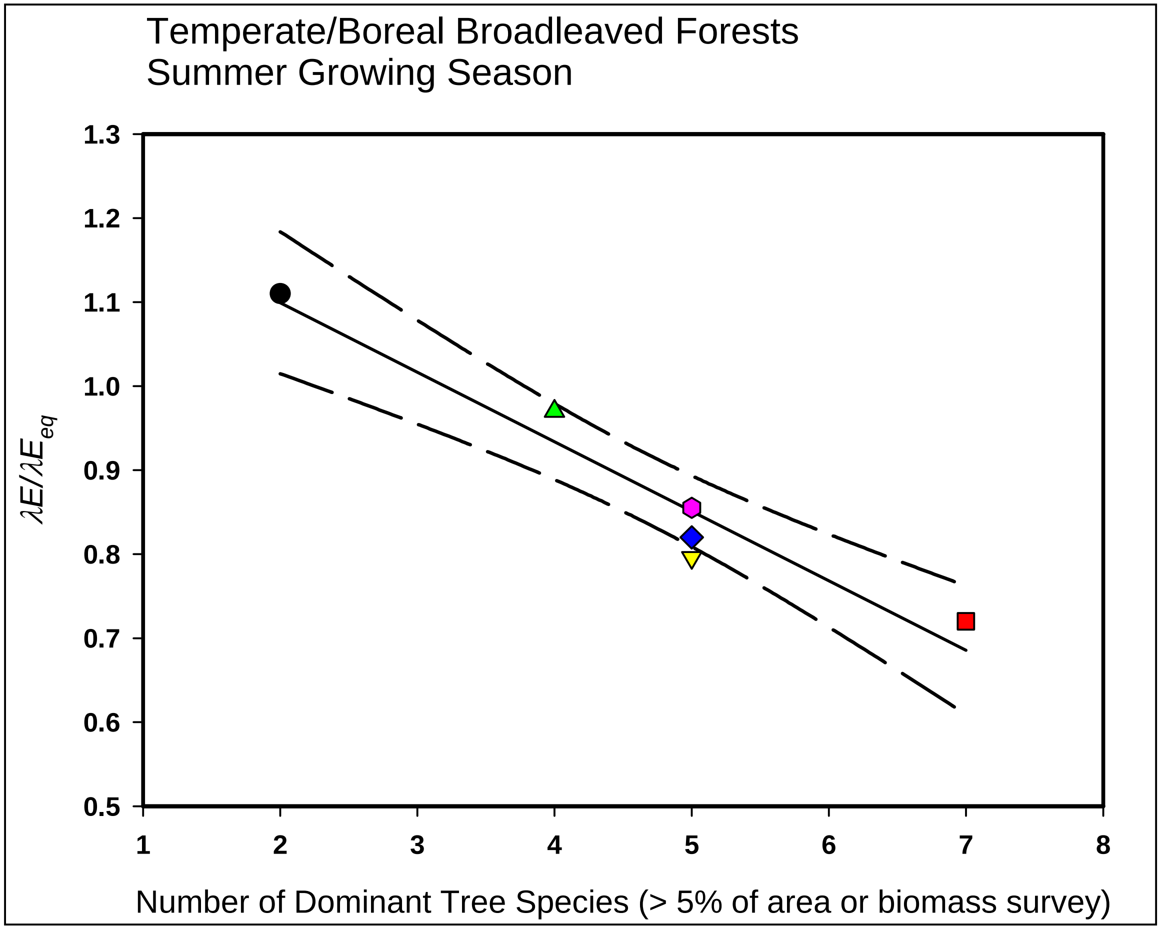
Wang et al, 2007 GCB

Optimizing Seasonality of Vcmax improves Prediction of Fluxes



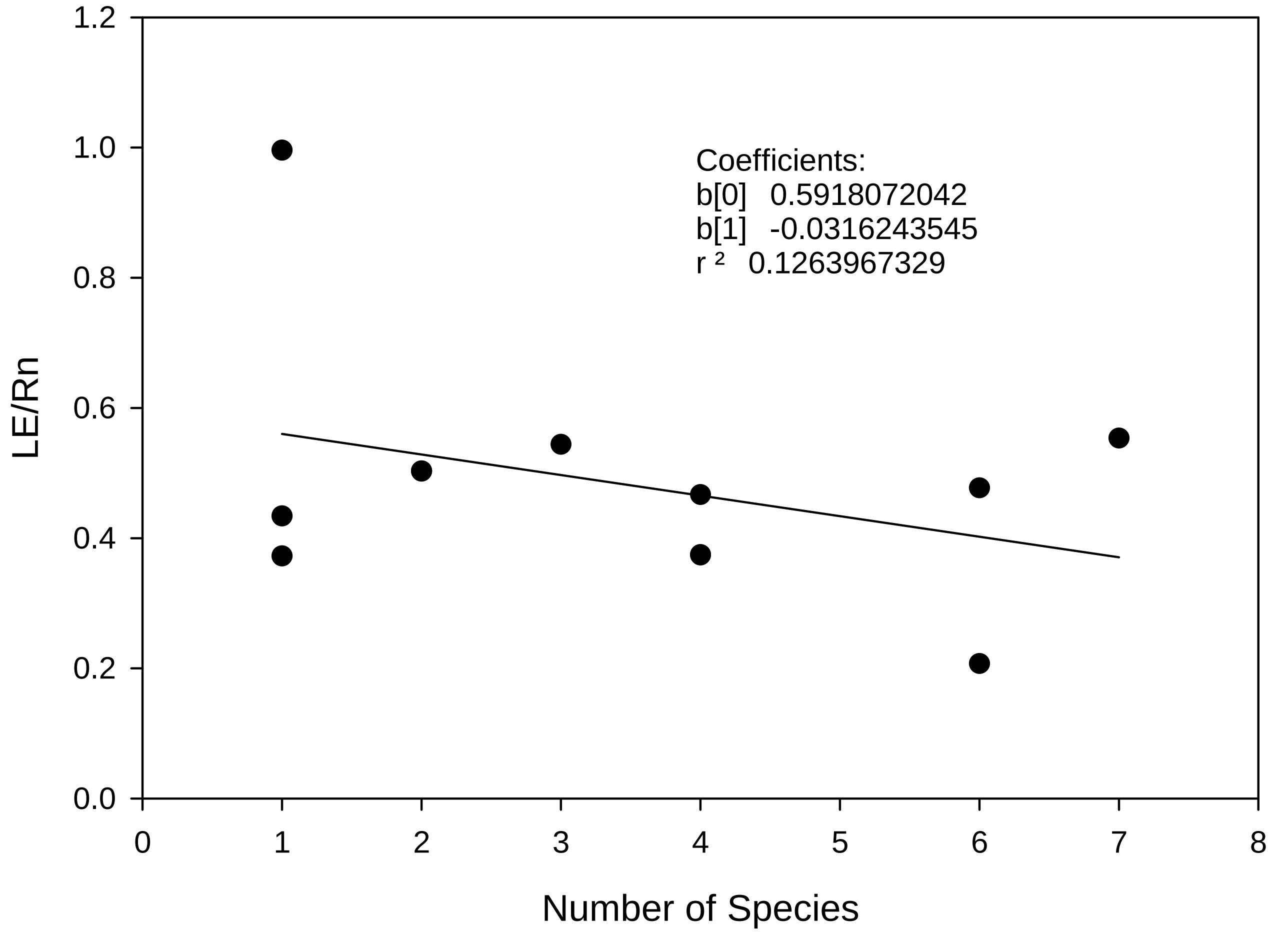
Wang et al, 2007 GCB

Biodiversity and Evaporation



Baldocchi, 2004: Data from Black, Schmid, Wofsy, Baldocchi, Fuentes

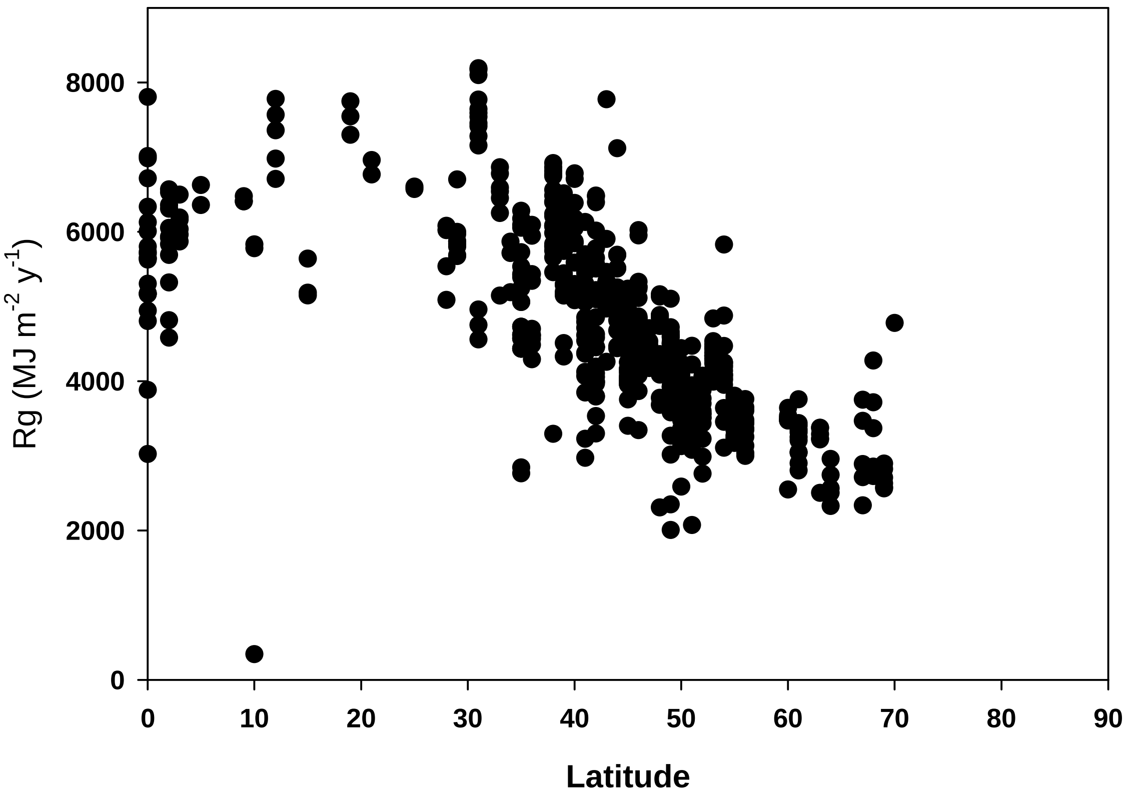
Biodiversity and Evaporation on Annual Time Scales



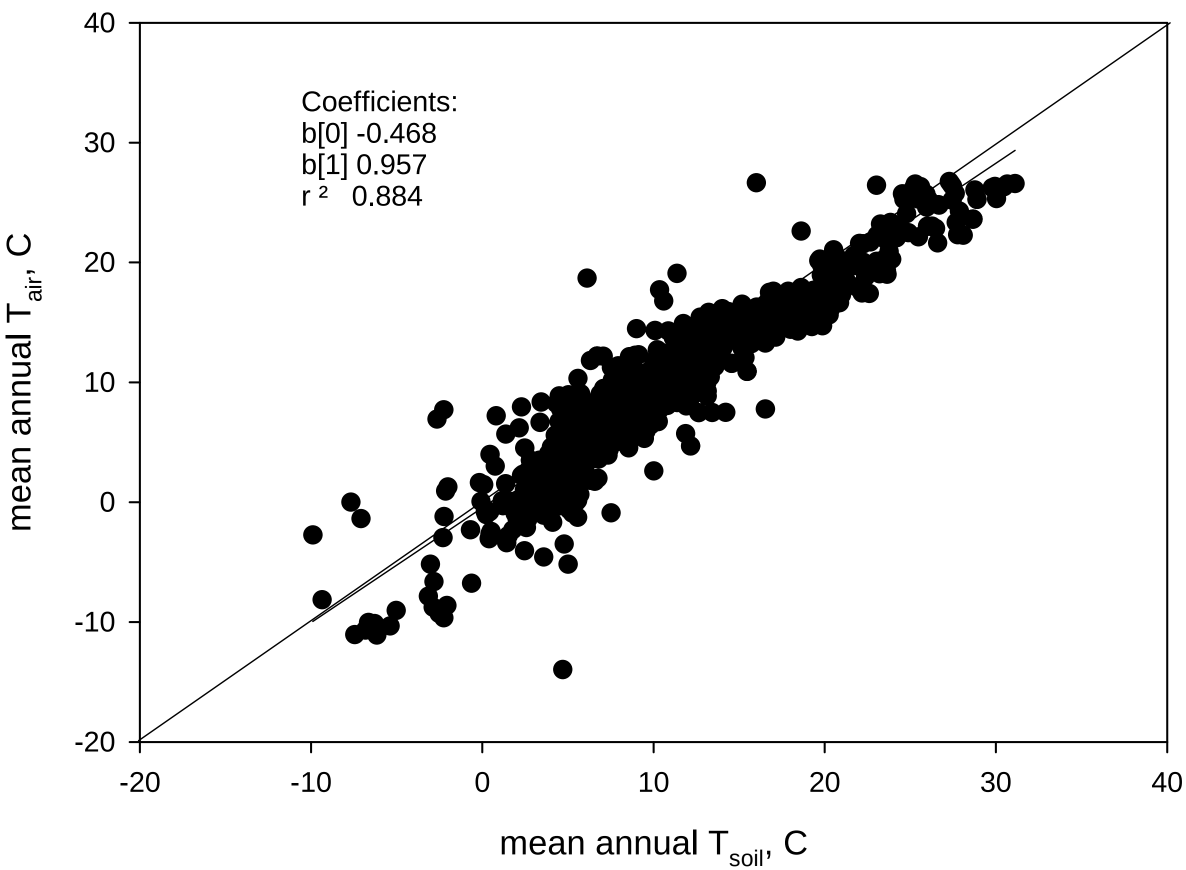
Baldocchi, unpublished

Energy Flux Biogeography

FLUXNET database



FLUXNET Database



Current and Future Scientific Directions

- NEE in Urban and Suburban, Africa, India, Latin America and High Arctic Environments
- Quantifying and Understanding the controls on Interannual Variability of C and energy Fluxes
- Monitoring the Metabolism of Ecosystems as we undergo Global Change
- Coupling CO_2, Trace Gas Deposition/Emission (O_3, voc) and Methane Fluxes
- Adopting New Technology (TDL, wireless networks) to embellish flux measurements
- Couple tower data with Real-time Data Assimilation Models.
- Boundary Layer Budgets using Fluxes and High Precision CO_2 measurements
- Spectral reflectance measurements and Digital Photos across the network for phenology and dynamics of structure and function
- Spatial-Temporal Network-Scale Analysis
- Real-time Data Assimilation
- Matching Footprints of Tower and Pixels
- Model Lags, Switches and Pulses
- Using Fluxnet data to assess problems in
    - Ecology, Ecohydrology, Biogeochemistry, Biogeography, Remote Sensing, Global Modeling, Biodiversity
    - Testing Maximum Entropy, Ecosystem Ecology, Biogeography and EcoHydrology Theories

FLUXNET 2014++
New Issues/Questions Raised

- Production of New, Expanded, Open and Shared DataBase
- Use of New Software Tools to Facilitate DataBase Navigation & Exploration
- Broader representation of vegetation types and climates on NEE, GPP and R_{eco}.
- Roles of natural and human induced disturbance on C Fluxes
- Impacts of climate and ecosystem factors on inter-annual variations of carbon, water and energy fluxes.
- Use FLUXNET data to provide ground-truth information to validate and ‘anchor’ *NPP* and *fpar* products being produced by MODIS LAND
- Perform geostatistical analyses with the FLUXNET database to examine the scales of spatial coherence of net carbon, water and energy fluxes across landscapes, regions and continents and to quantify the ‘network connectivity’ among groups of sites.
- Revisit many basic tenets of bio- & micrometeorology
  - Data are being collected from a spectrum of land surface types (short grasses and crops, through open heterogeneous canopies to tall, closed forests) on flat to moderately undulating terrain over a wide range of atmospheric stability conditions
  - Intermittent Turbulence

Acknowledgements

- Data Preparation
  - Dario Papale, Markus Reichstein, Catharine Van Ingen, Deb Agarwal, Tom Boden, Bob Cook, Susan Holliday, Bruce Wilson, +++
- Networks
  - AmeriFlux, CarboEurope, AsiaFlux, ChinaFlux, Fluxnet Canada, OzFlux, +++
- Agencies
  - NSF/RCN, ILEAPS, DOE/TCP, NASA, Microsoft, ++++

Study Sites of DDB

Crops: soybeans, alfalfa, wheat, corn, rice

Grassland and peatland pastures

Boreal Conifer Forest

Deciduous Forest

Savanna Woodland

Acquire Metadata on Leaf, Soil and Ecosystems Structure and Function, too

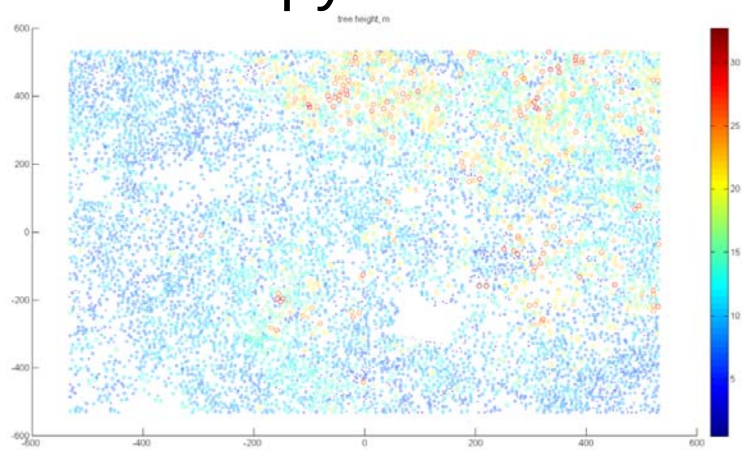
Leaf-Scale

Assess Leaf Photosynthetic Capacity and Stomatal Control

Soil System

Partition Ecosystem Fluxes according to Soil and Vegetation Components

Canopy Structure



Acquire Information on Canopy Structure with Active (LIDAR) and Passive Remote Sensing