Biosphere-Atmosphere Interactions: Issues, Observations and Technology

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UC Berkeley
Land Atmosphere Observation Facility Workshop
Boulder, CO, June, 2012

Outline

- Big Questions and Open Problems
- Biosphere-Atmosphere Interactions Principles
  - Roles of Models and Observations
  - Non-Linear, Coupled Feedbacks and Forcings
  - Multi-Scaled
- Designing Experiments
- Observations
  - Flux Networks
- Modeling and Satellites

Why Study Trace Gas and Energy Exchange?

- Flux Boundary Conditions of Weather, Climate, Biogeochemical and Ecological Models
  - State of the Biosphere is determined by Fluxes
- 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)

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?; By Climate Region?; By Disturbance and Time Since Disturbance?

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

- **How can We Compute Biosphere-Atmosphere Trace Fluxes 'Everywhere, All of the Time?'**

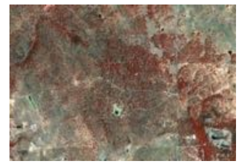
Designing Earth System Flux Experiments and Measurements

We First Need to Look Under the Hood

The Biosphere Spans > 14 Orders of Magnitude in Space

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

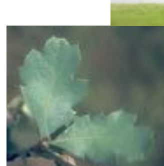
Continent: 1000 km (10^6 m)



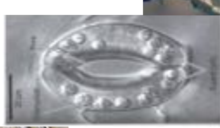
Landscape: 1-100 km

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

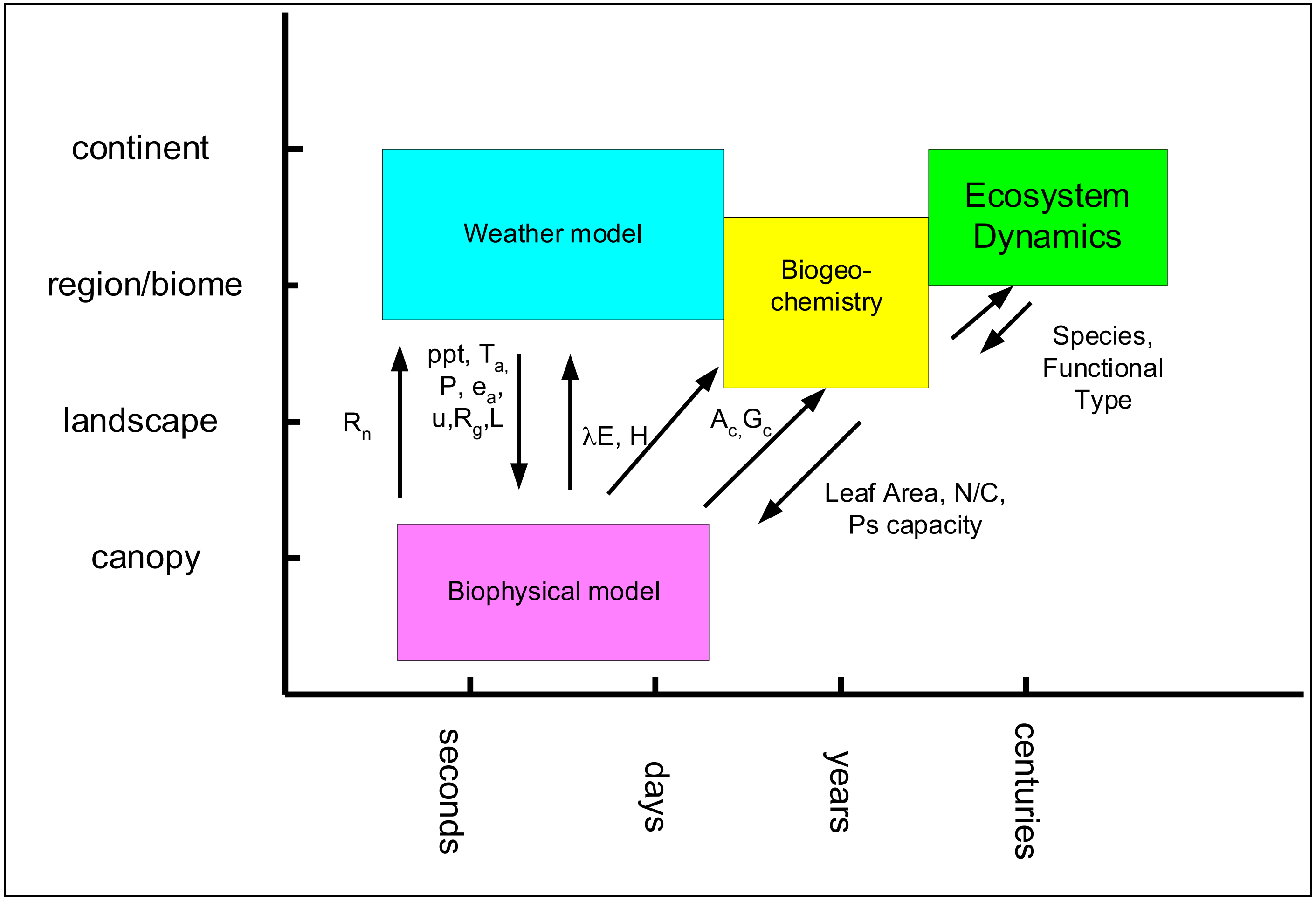
Years,
Decades

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

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

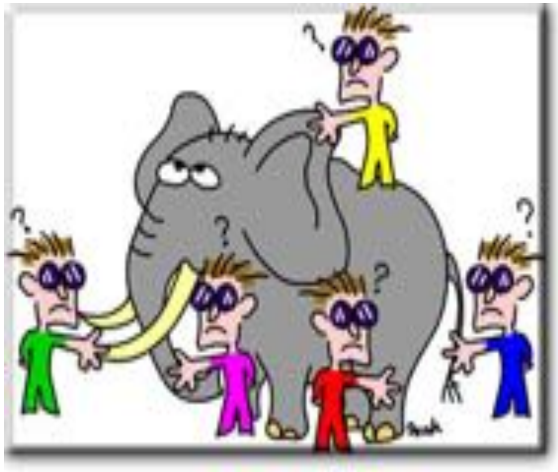
Centuries,
Millennia

Biophysical Processes and their Linkages in Time and Space



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

GCM Inversion Modeling



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

Remote Sensing/ MODIS

Forest/Biomass /Soil Inventories

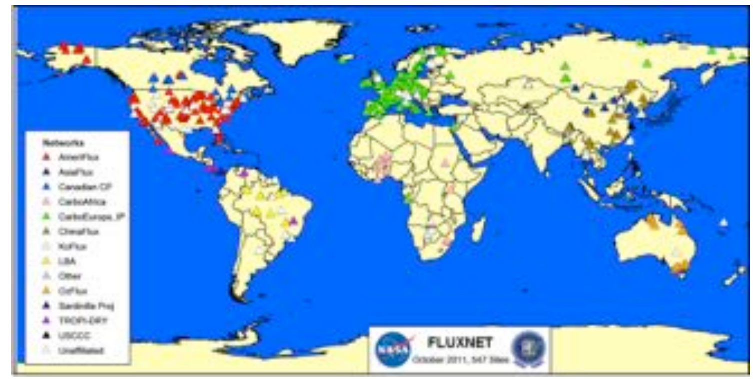
Physiological Measurements/ Manipulation Expts.

Biogeochemical/ Ecosystem Dynamics Modeling

Role of Flux Networks in Biogeosciences

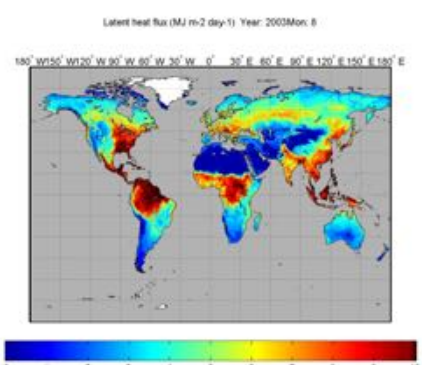
Eddy covariance flux system

Global network of flux towers



Database

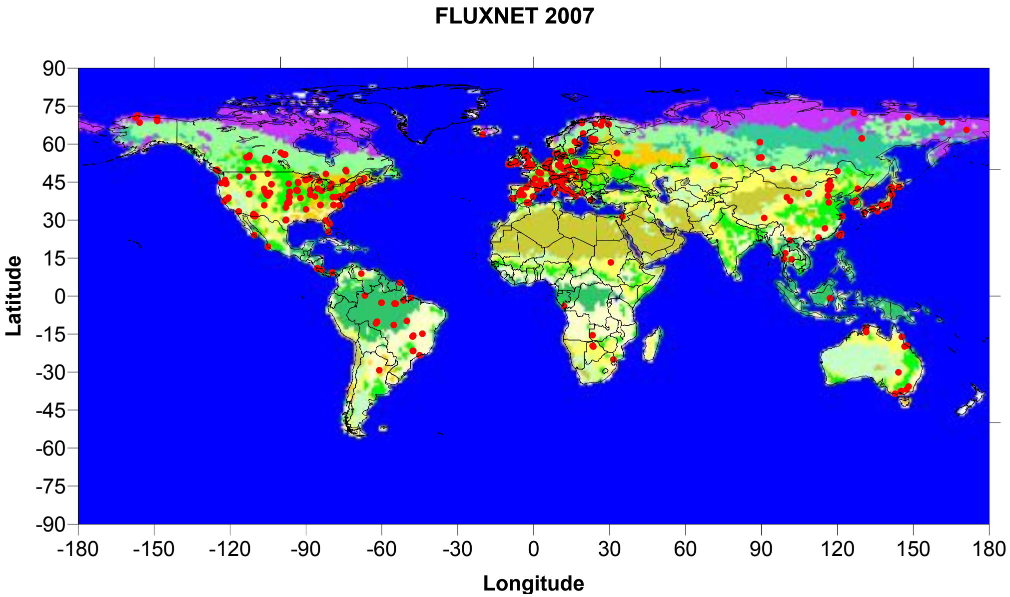
Remote sensing and Earth system science model user community



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 (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.

Global Flux Networks—FLUXNET—Offer opportunities to Parameterize, Test and Validate Models across a Spectrum of Climates and Biomes

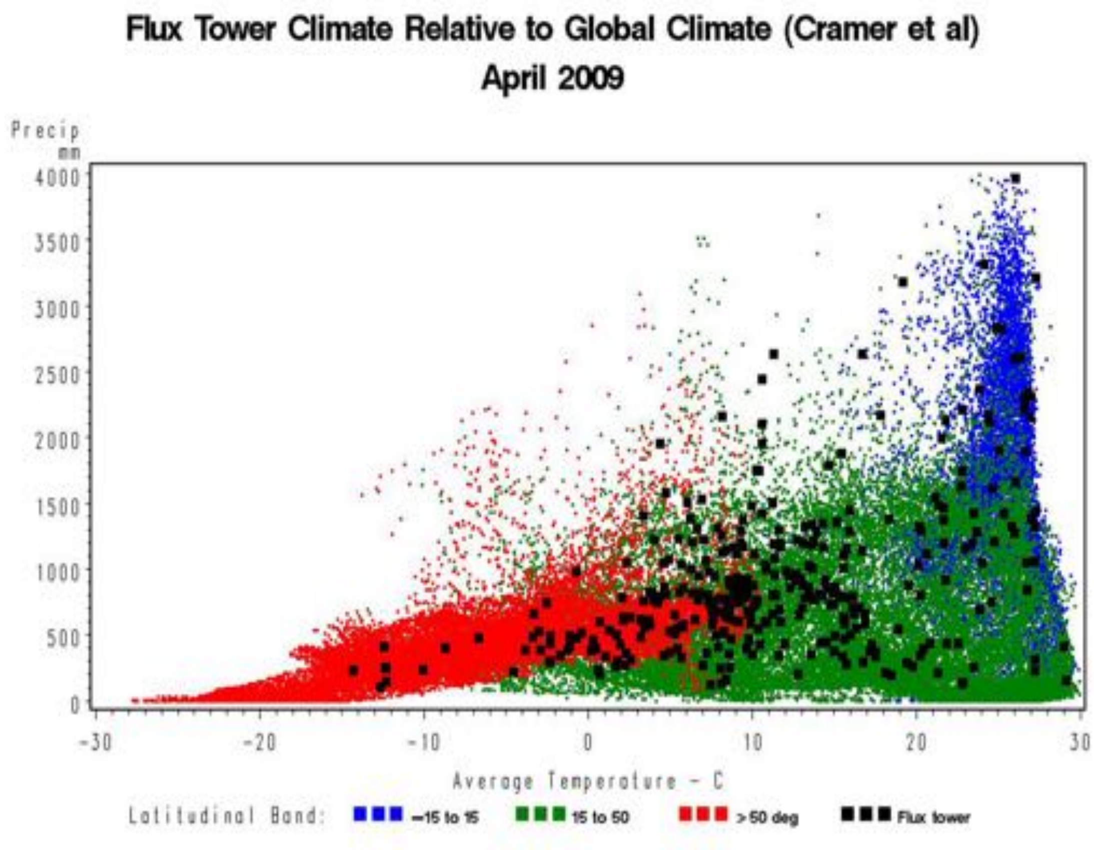


www.fluxdata.org

Questions Regarding Networks

- How Many Stations Are Enough?
- Where Should there be Flux Measurements Stations?
- How long Should we Continue to Measure Fluxes?

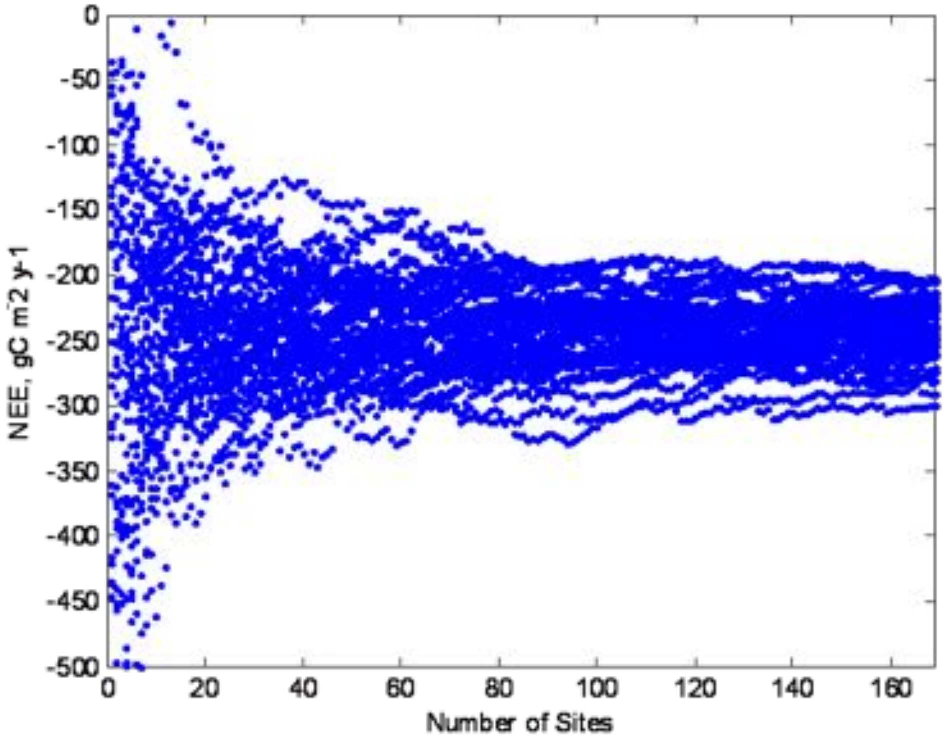
Global distribution of Flux Towers Covers Climate Space Well



Can we Integrate Fluxes across Climate Space,
Rather than Cartesian Space?

How many Towers are needed to estimate mean NEE, GPP and assess Interannual Variability, at the Global Scale?

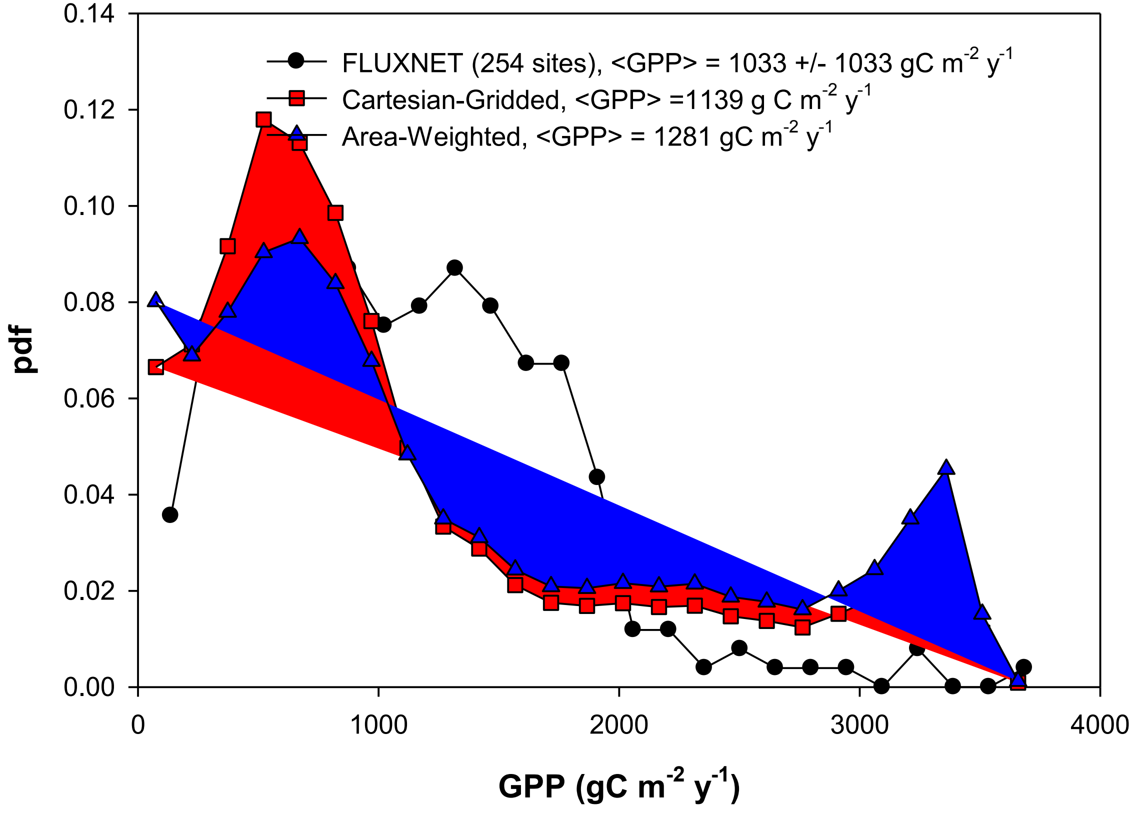
Green Plants Abhor a Vacuum, Most Use C3 Photosynthesis, so we May Not need to be Everywhere, All of the Time



We Need about 75 towers to produce Robust and Invariant Statistics

We Need to be in the Right Places
Bias in Sampling Pdf from Network vs Globe

FLUXNET Database



FLUXNET is Undersampling Tropics, Tundra and Semi-Arid Regions
It is Oversampling Temperate Zones

How Long Should We Measure?
Time Line of Existing Flux Data

1000 Site-Years

La Thuile II Workshop

100 Site-Years

Marconi Workshop

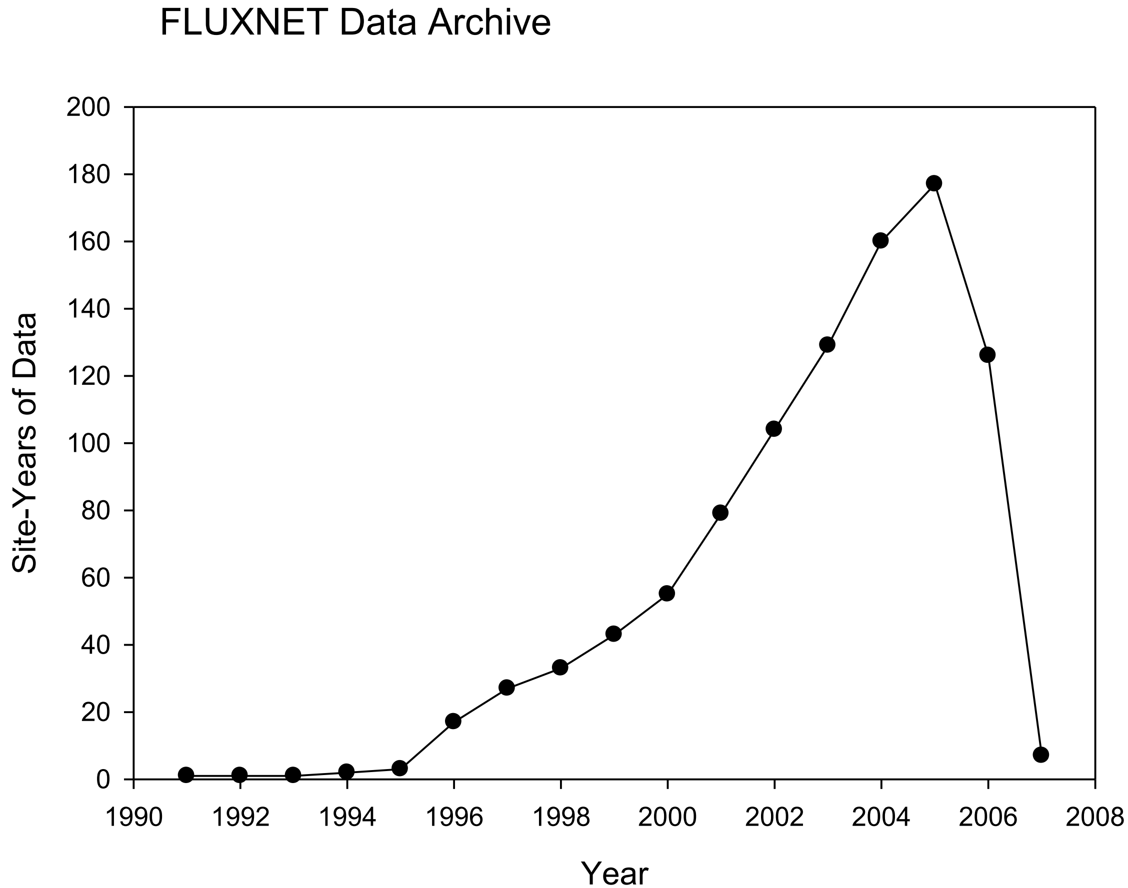
Ten Site-Years

One Site-Year

30 hours

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

Few Locations with Long Records
Many with 2 to 3 Year Long Records
Delays in Data Submission and Network Processing



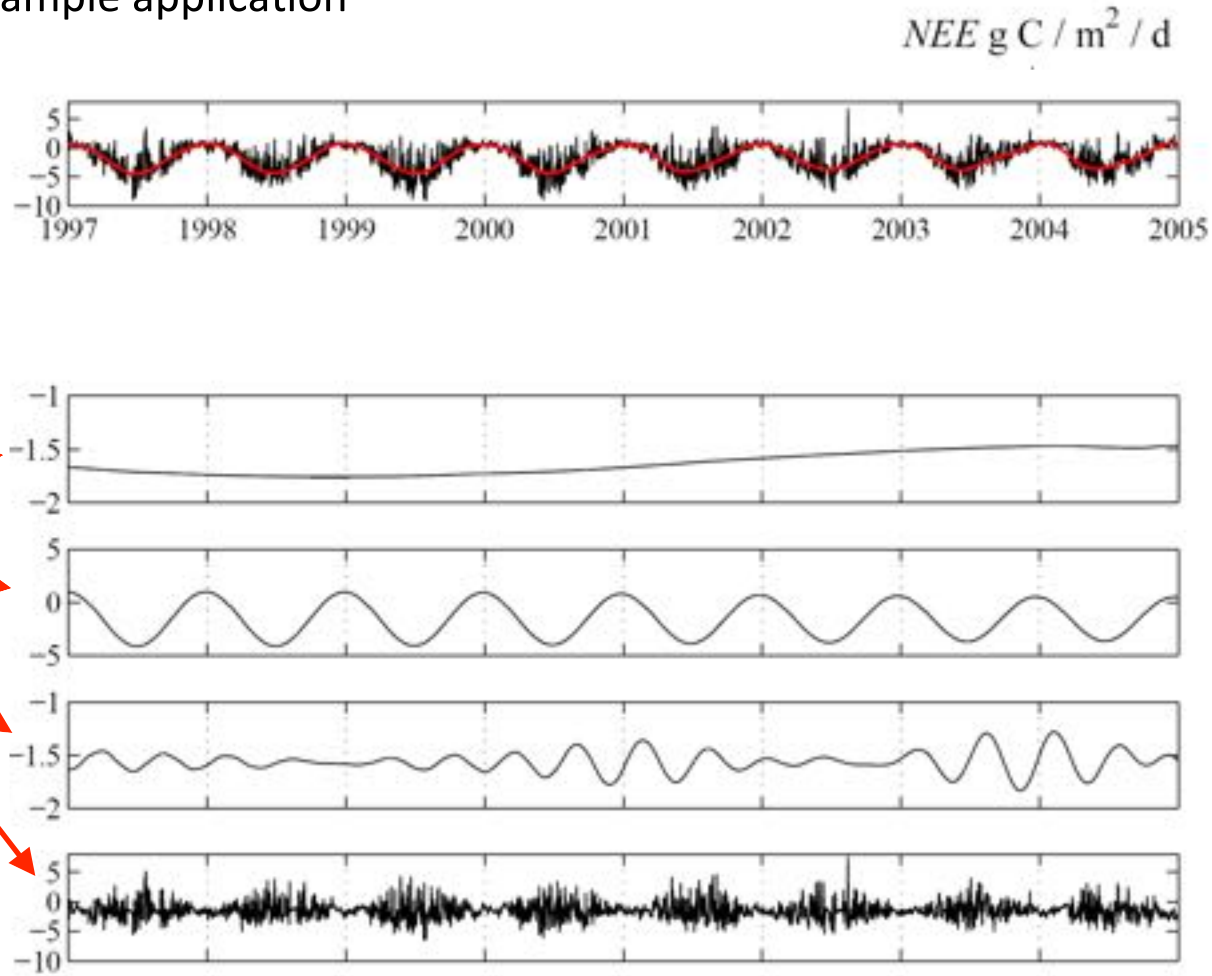
Some Towers are Not Active, nor Submitting data, circa La Thuile dataset

Singular System Analysis: example application

Original time series:

Decomposed time series:

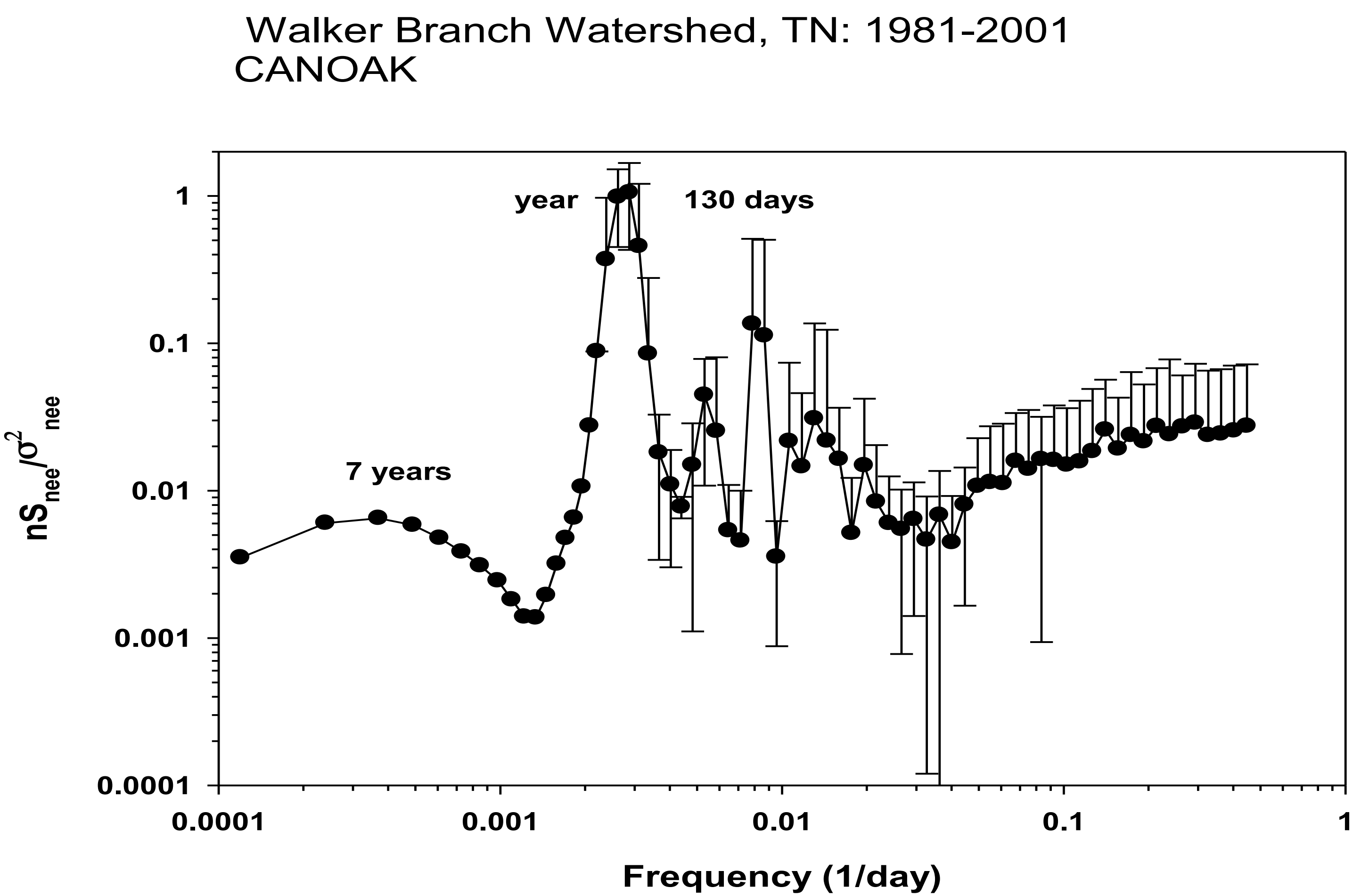
- **Nonlinear trend**
- Annual cycle
- Intra-annual cycle
- High frequency modes



New developments allow application of SSA to fragmented time series

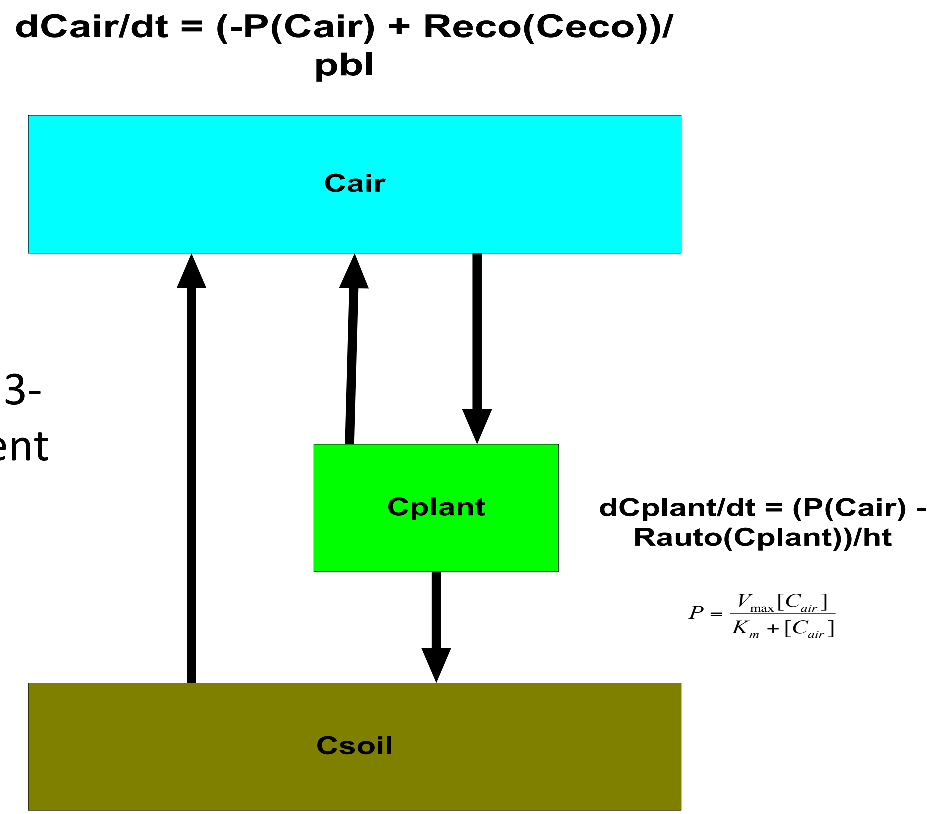
Mahecha et al. (2007) *Biogeosciences*, **4**, 743-758

Decadal Scales of Variability, Information exists at Long time scales



Coupled Exchange Across Big and Small Pools with Short and Long Time Scales

Dynamics of a Coupled 3-Pool Model with different Turnover Times

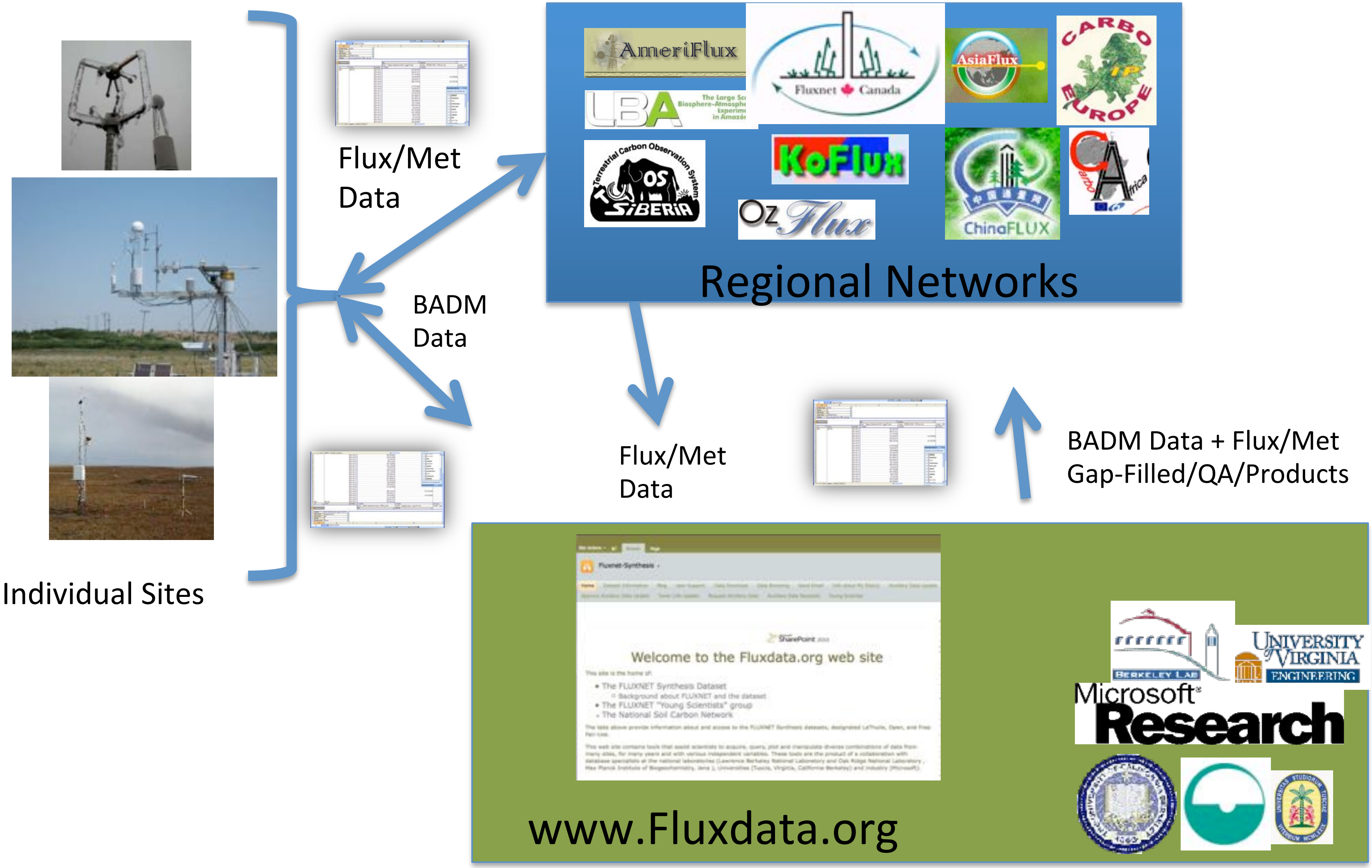


$$P = \frac{V_{\max}[C_{air}]}{K_m + [C_{air}]}$$

Csoil/dt = +dCplant/dt - Rhetero(Csoil)/zsoil

$$R_{heteor} = \frac{C_{soil}}{\tau_{soil}} \qquad R_{auto} = \frac{C_{plant}}{\tau_{plant}}$$

Fluxdata.org – A Common, Shared Database



Guidelines for Effective Networks, 1.0

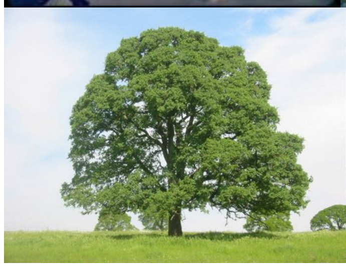
- Data are best when there are standards and protocols for instrument performance, data quality, and calibration; data gaps are minimized if redundant or replacement sensors are available; data gaps are filled with vetted methods

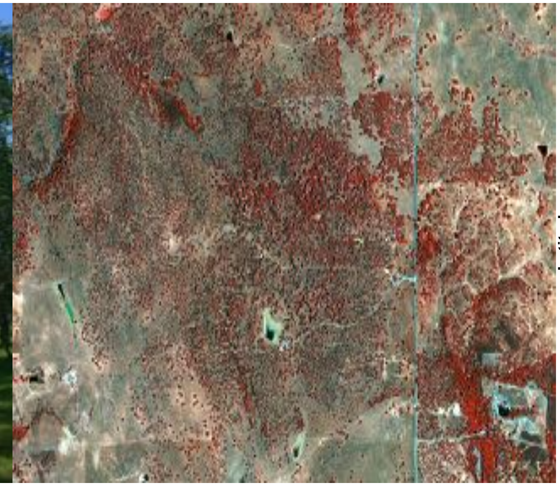
Guidelines for Effective Networks, 2.0

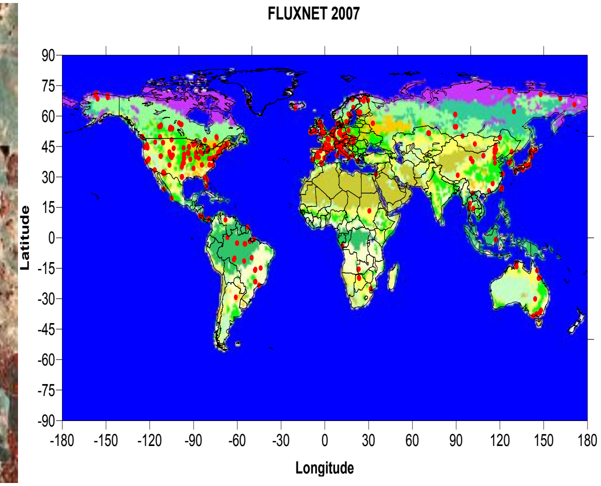
- Data are converted into information and knowledge when there is a shared and integrated database with which researchers can merge flux measurements with a cohort of meteorological, ecological, and soil variables.
- A centralized database can harmonize data processing and gap-filling to produce value-added 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.







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

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

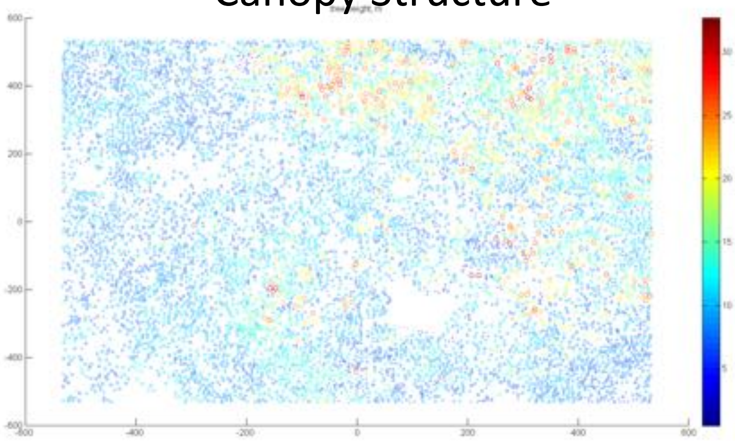
Leaf-Scale

Assess Leaf Photosynthetic Capacity
and Stomatal Control

Soil System

Partition Ecosystem Fluxes
according to Soil and Vegetation
Components

Canopy Structure



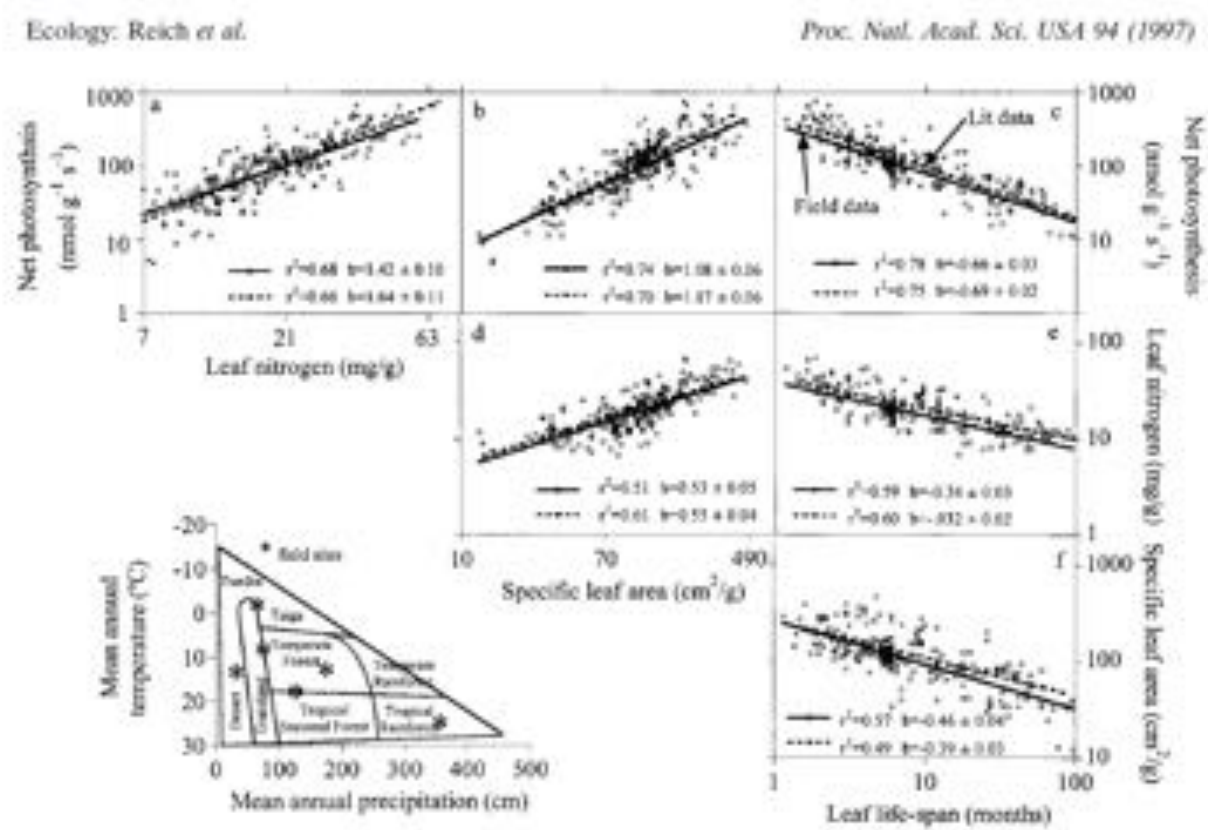
Acquire Information on Canopy Structure with Active (LIDAR) and Passive Remote Sensing

The New Millennium: Optimism and Opportunity

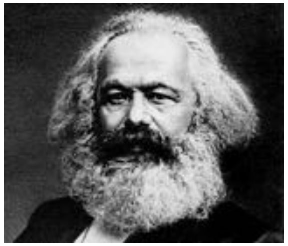
Data Sets are Getting Longer and Longer
Plethora of New Data (Satellite, Flux, Ecological) and Scaling Rules

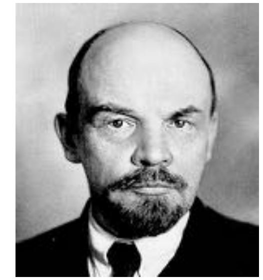
Plethora of EcoPhysiological Scaling Rules:

Metabolism vs Life Span, Specific Leaf Area and Nitrogen



http://www.try-db.org





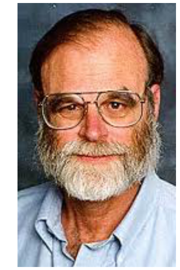
There Has Been A Revolution in Fast Response Greenhouse Gas Sensors




New Technology

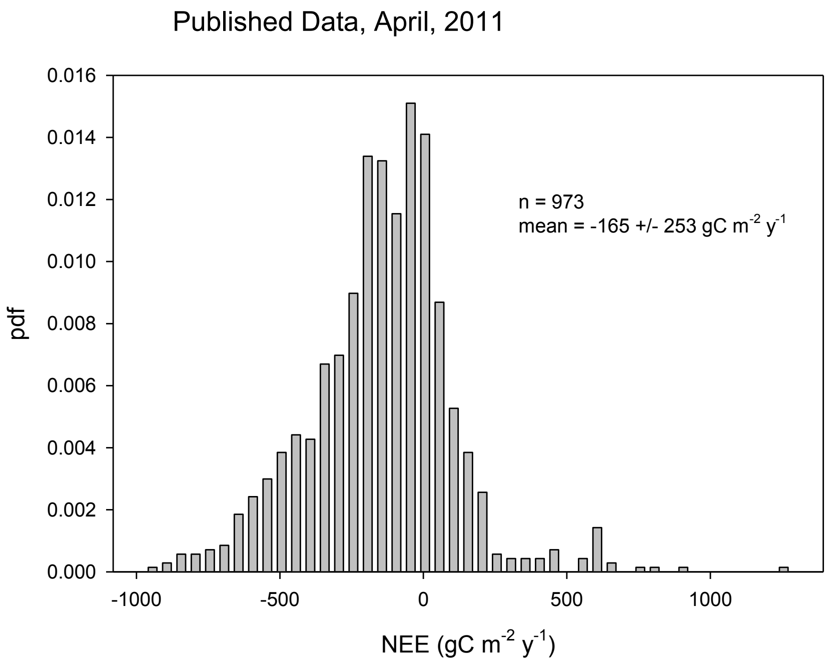
- Tunable Diode Laser Spectrometers
  - CH_4, N_2O, ^{13}C, COS, ^{18}O
- Proton Transfer Reaction Mass Spectrometers
  - Hydrocarbons, Terpenes, Sequeterpenes
- Wireless Networks
- Ground Penetrating Radar, LIDAR
- Electromagnetic Induction (EMI)
- Satellite Remote Sensing
- Flux Footprint Modeling
- Digital Cameras for Phenology and Leaf Area

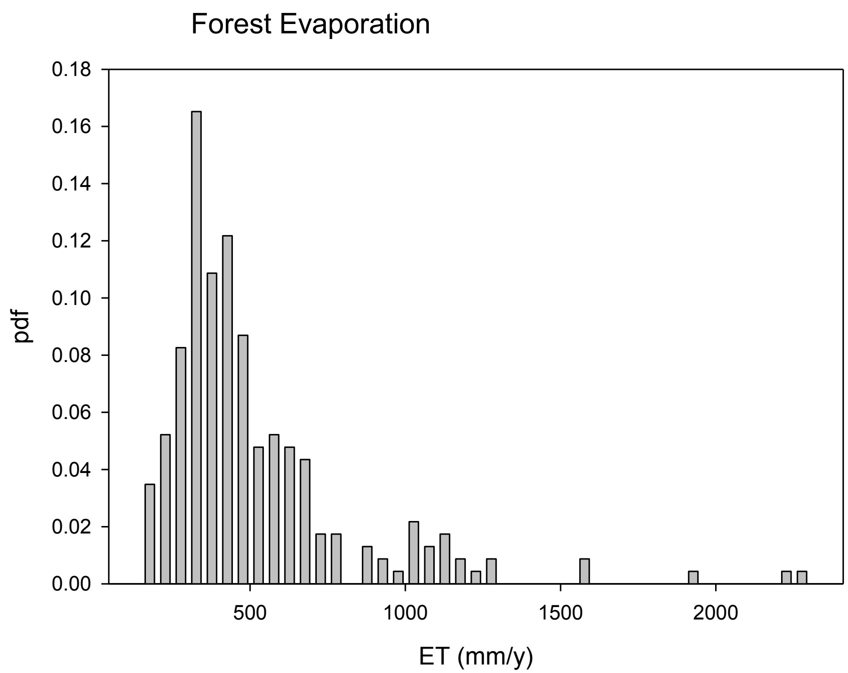
4^{th} Paradigm



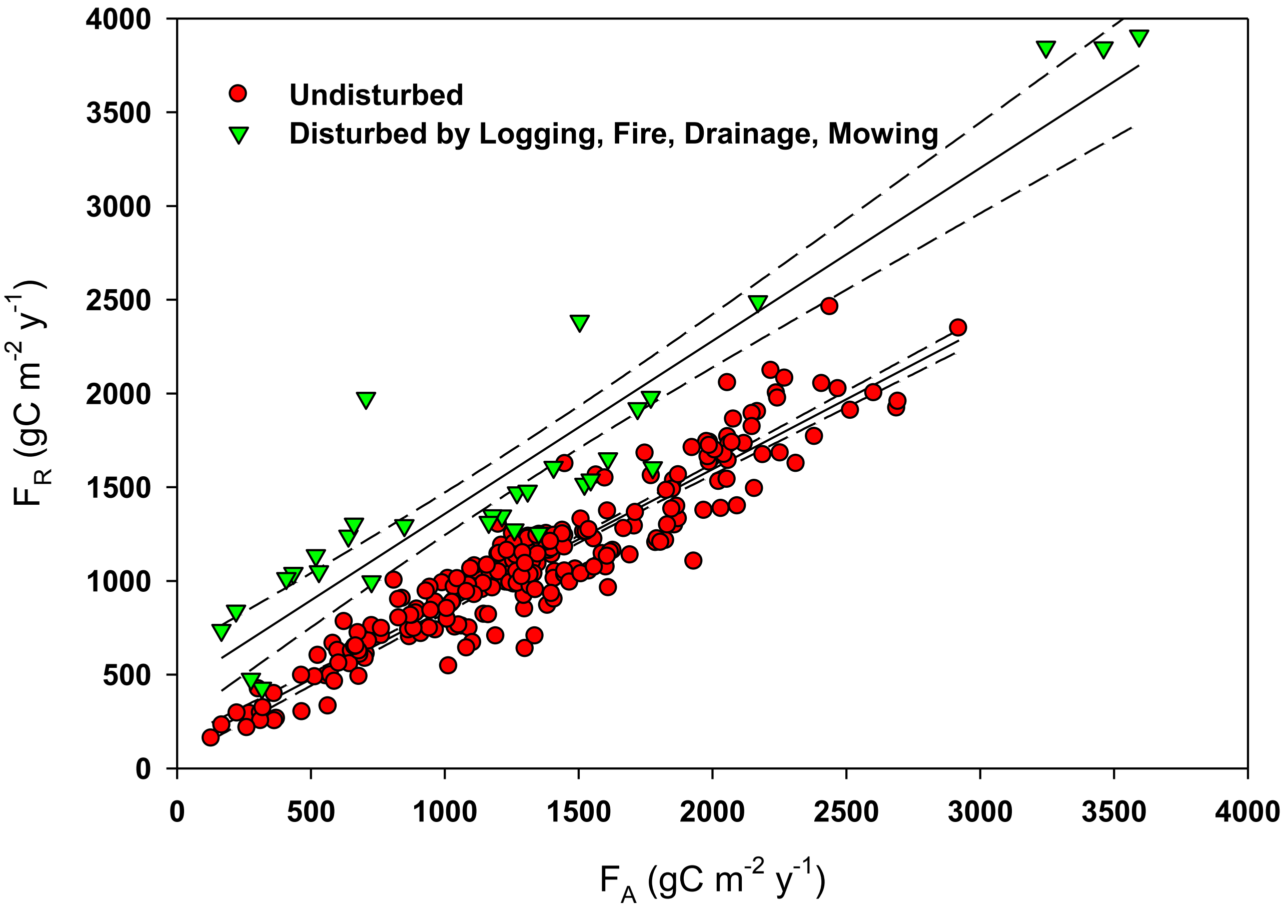
- What to Do with This Mass Quantity of Data?
  - – Plot Histograms and Time Series
  - – Plot Spectral Transforms
    - Fourier or Wavelet Transforms
  - – Plot X vs Y
    - Look for Non-Linearities, Lags, Hysteresis, Conditional Switches and Pulses; Test Granger Causality
  - – Plot Y in Multi-Variate Space
    - Look for Covariance and Confounding Effects
  - – Data-Model Fusion

Histograms of Annual Integrated Carbon and Water Fluxes



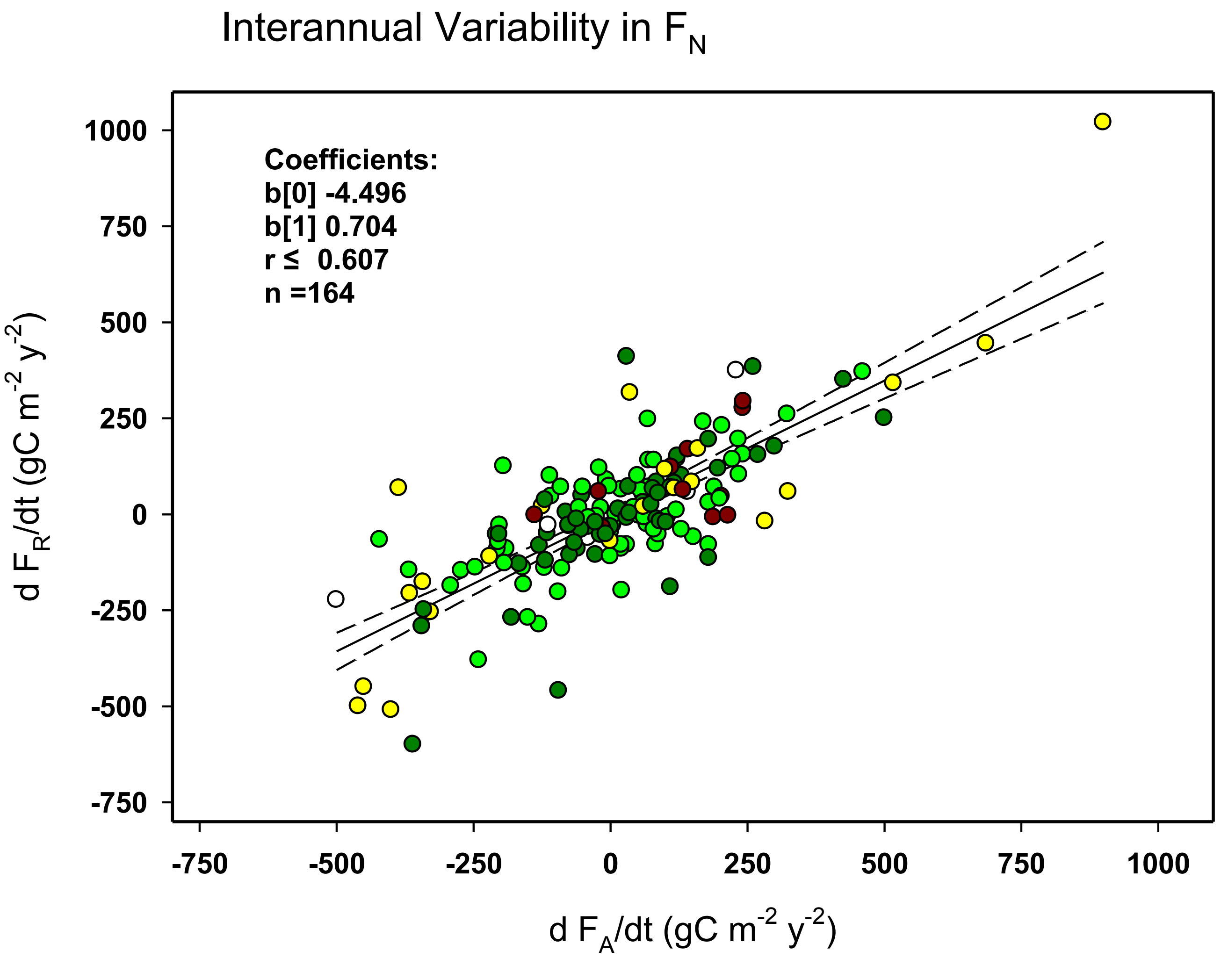


Ecosystem Respiration Scales Tightly with Ecosystem Photosynthesis, But Is with Offset by Disturbance



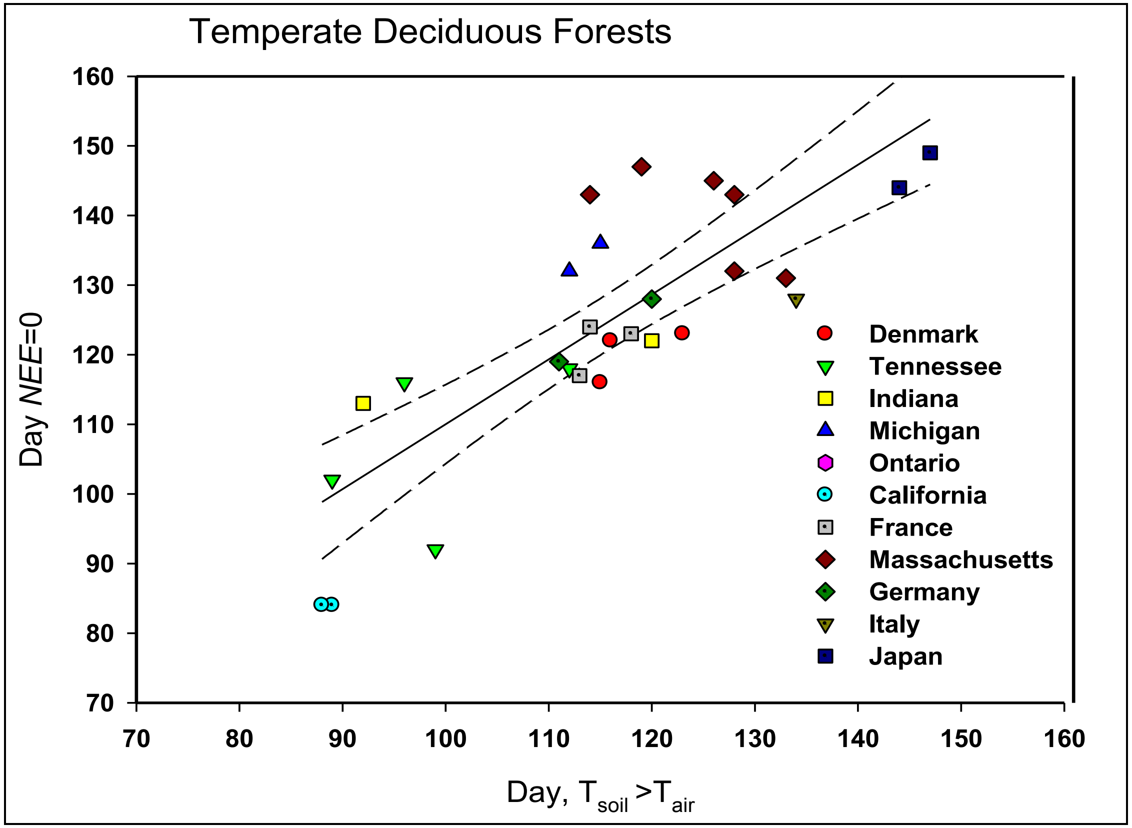
Baldocchi, Austral J Botany 2008

Interannual Variations in Photosynthesis and Respiration are Coupled



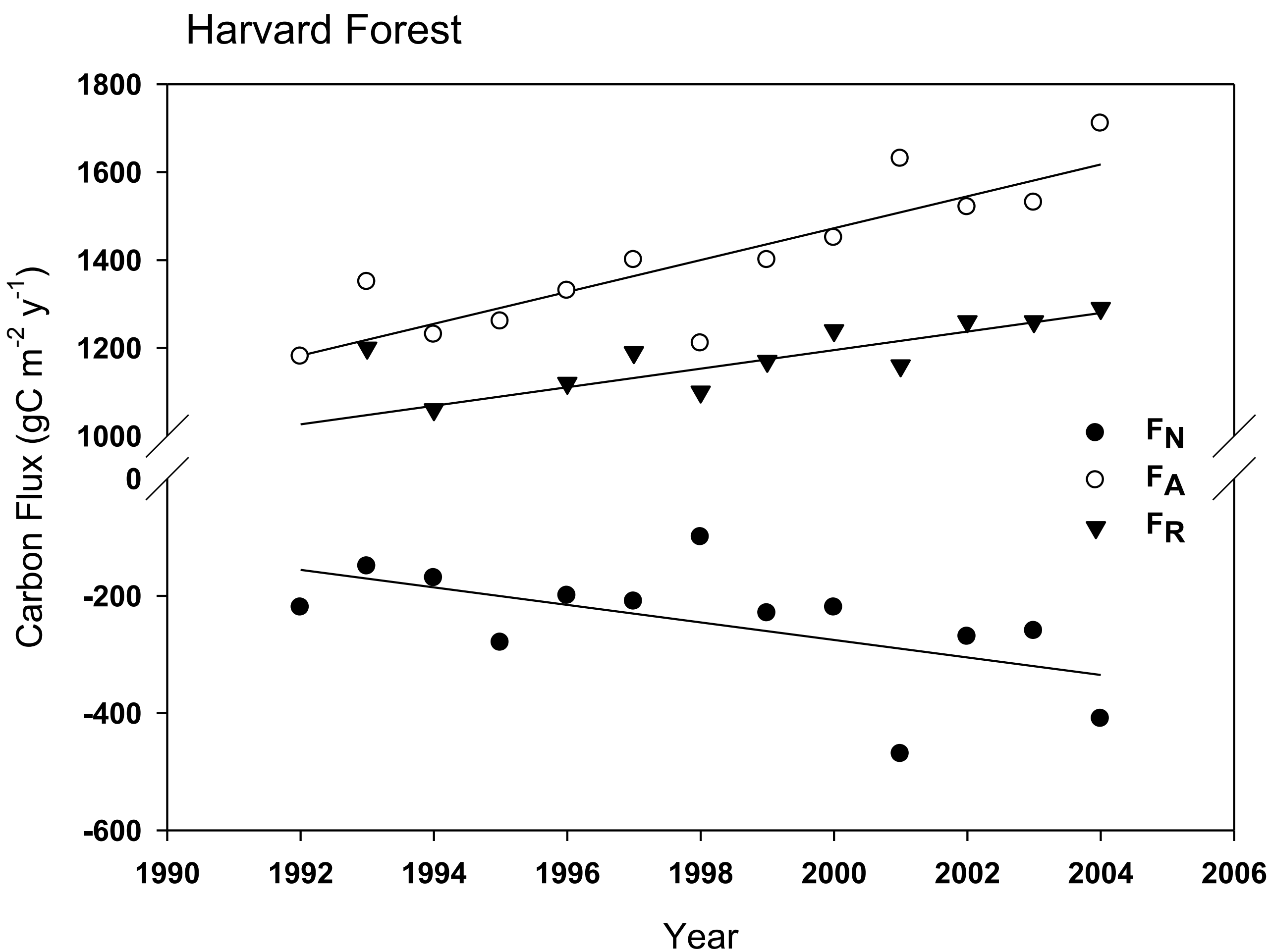
Baldocchi, Austral J Botany, 2008

Soil Temperature:
An Objective Measure of Phenology, part 2



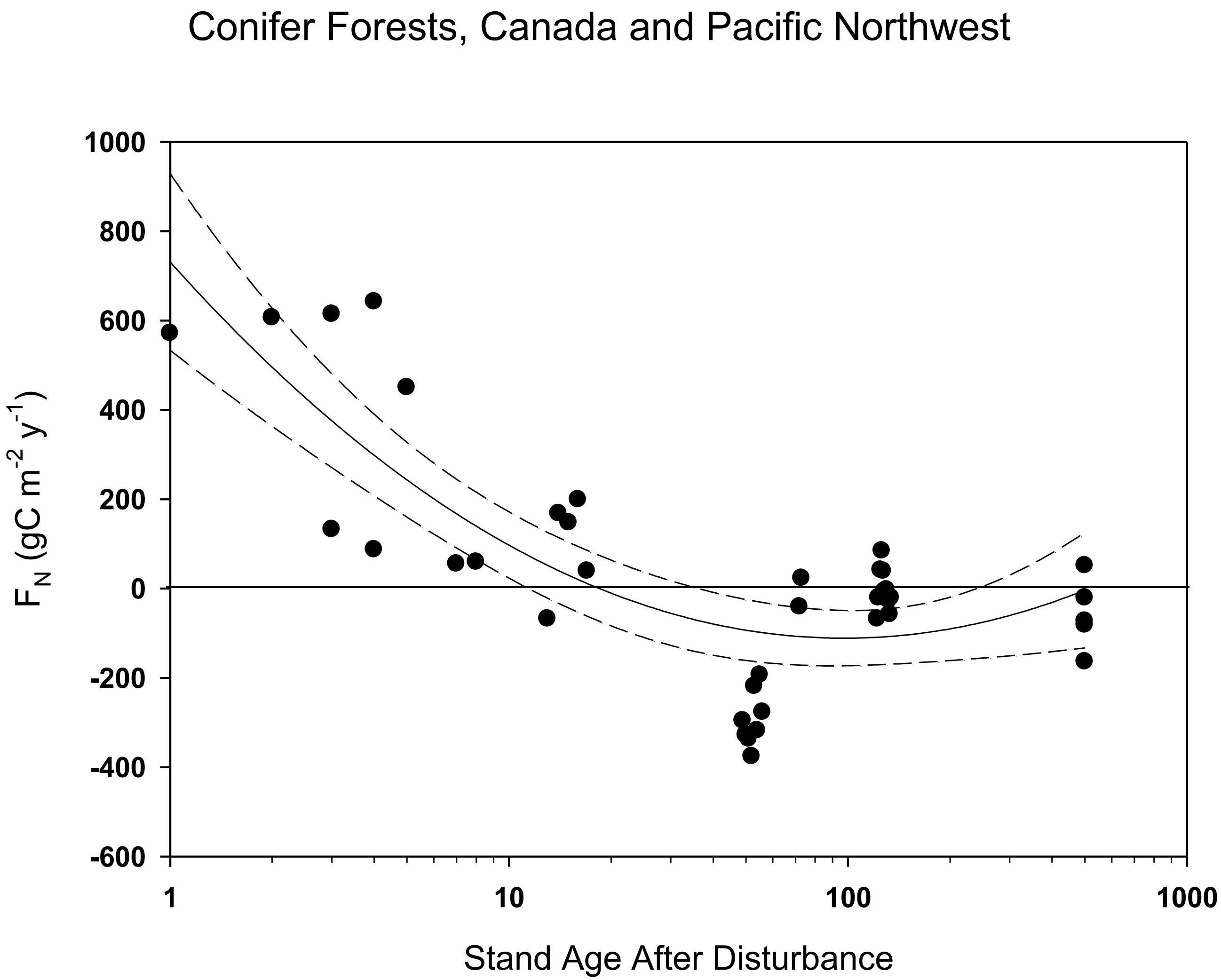
Baldocchi et al. Int J. Biomet, 2005

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

Time Since Disturbance Affects Net Ecosystem Carbon Exchange



Baldocchi, Austral J Botany, 2008

Data of teams lead by Amiro, Dunn, Paw U, Goulden

Challenge for Landscape to Global Upscaling

Converting Virtual 'Cubism' back to Virtual 'Reality'

Realistic Spatialization of Flux Data
Requires the Merging Numerous Data Layers with varying Time Stamps (hourly, daily, weekly), Spatial Resolution (1 km to 0.5 degree) and Data Sources (Satellites, Flux Networks, Climate Stations)

Biophysical Modeling, Circa 1969: A Pessimistic Legacy

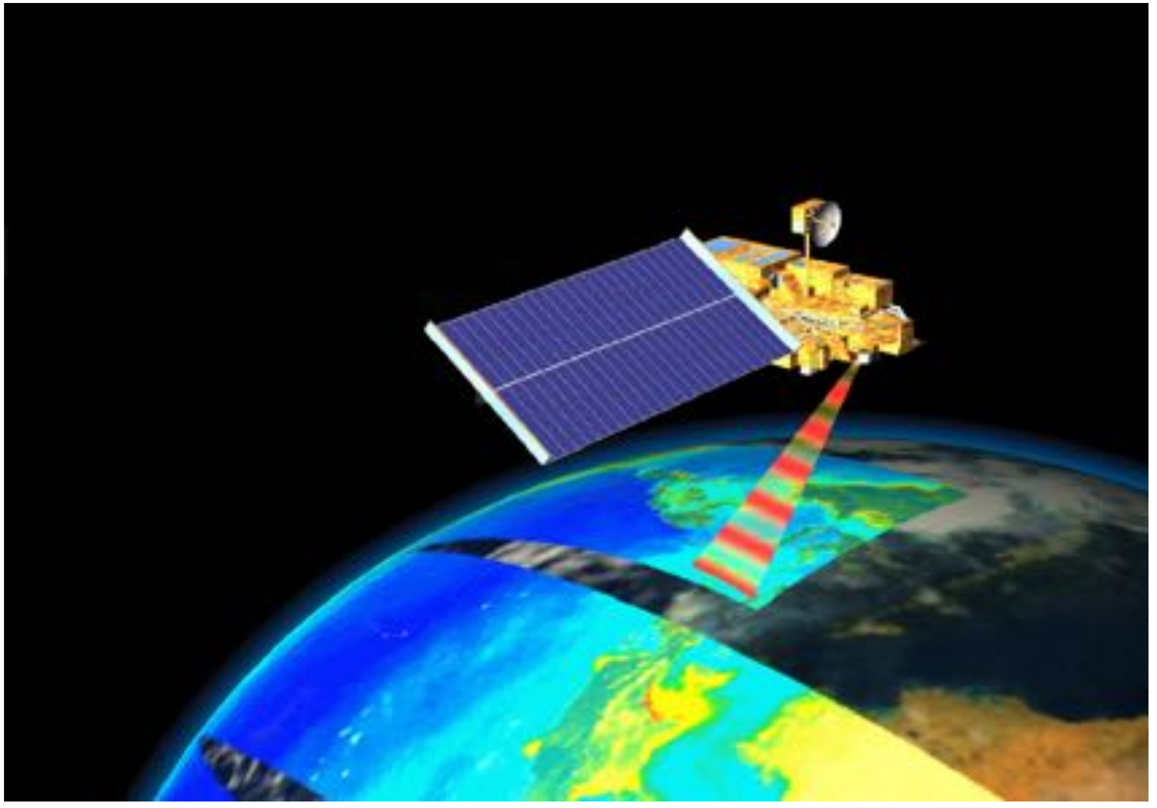
Cornelius T. deWit

‘Seven-stage simulation models by means of which ecosystems may be explained on basis of the molecular sciences are impossible large and detailed and it is naïve to pursue their construction’

Sources of Model Complexity and Uncertainty

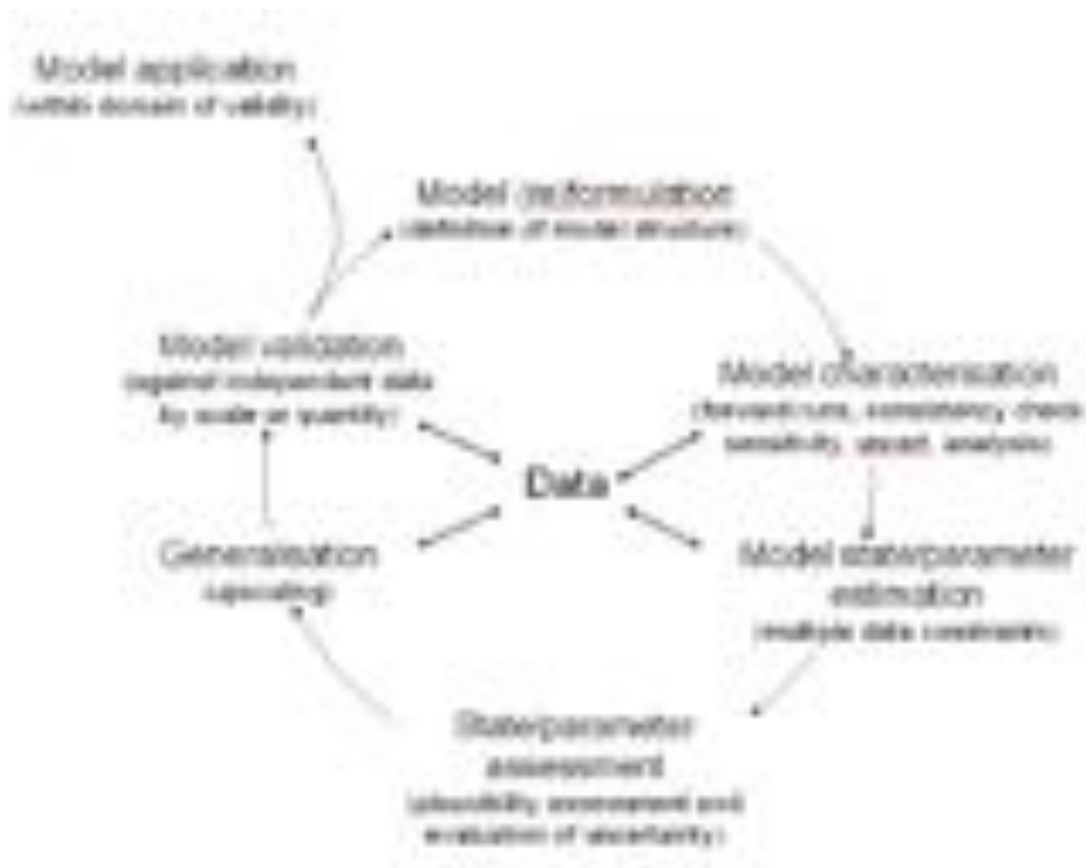
- Representation of System Complexity
  - Geometrical
  - Processes
  - Non-Linearities
- Model Parameters
- Driving, or Input, Variables and their Transformation
- Spatial and Temporal Resolution
- Duration of the Record
- Accuracy of Test-Bed Flux Data

Satellite Remote Sensing Gives Us the Ability to Stitch this Information Together



MODIS on Terra and Aqua

Model Data Fusion Using Flux Networks and Satellite Data



Williams et al 2009 Biogeosciences

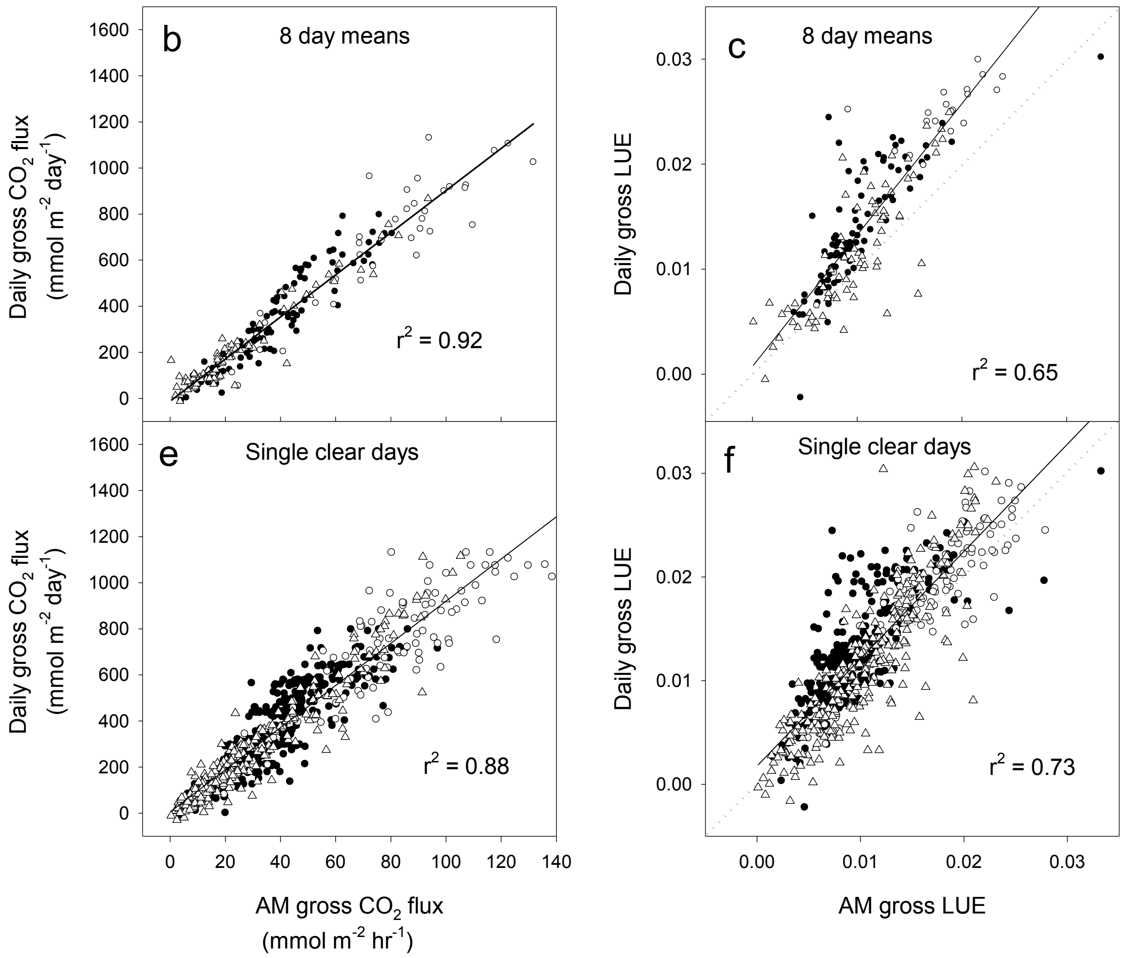
Key Questions

- How Complex or Simple Should the Structure of the Model be?
- Should Model Parameters be Held Constant or Vary with Season and Plant Functional Type?
- How Best to Couple Fast Biophysical Algorithms, with Slower Biogeochemical Algorithms and Slow Dynamic Vegetation/ Ecological Algorithms?

Other Questions

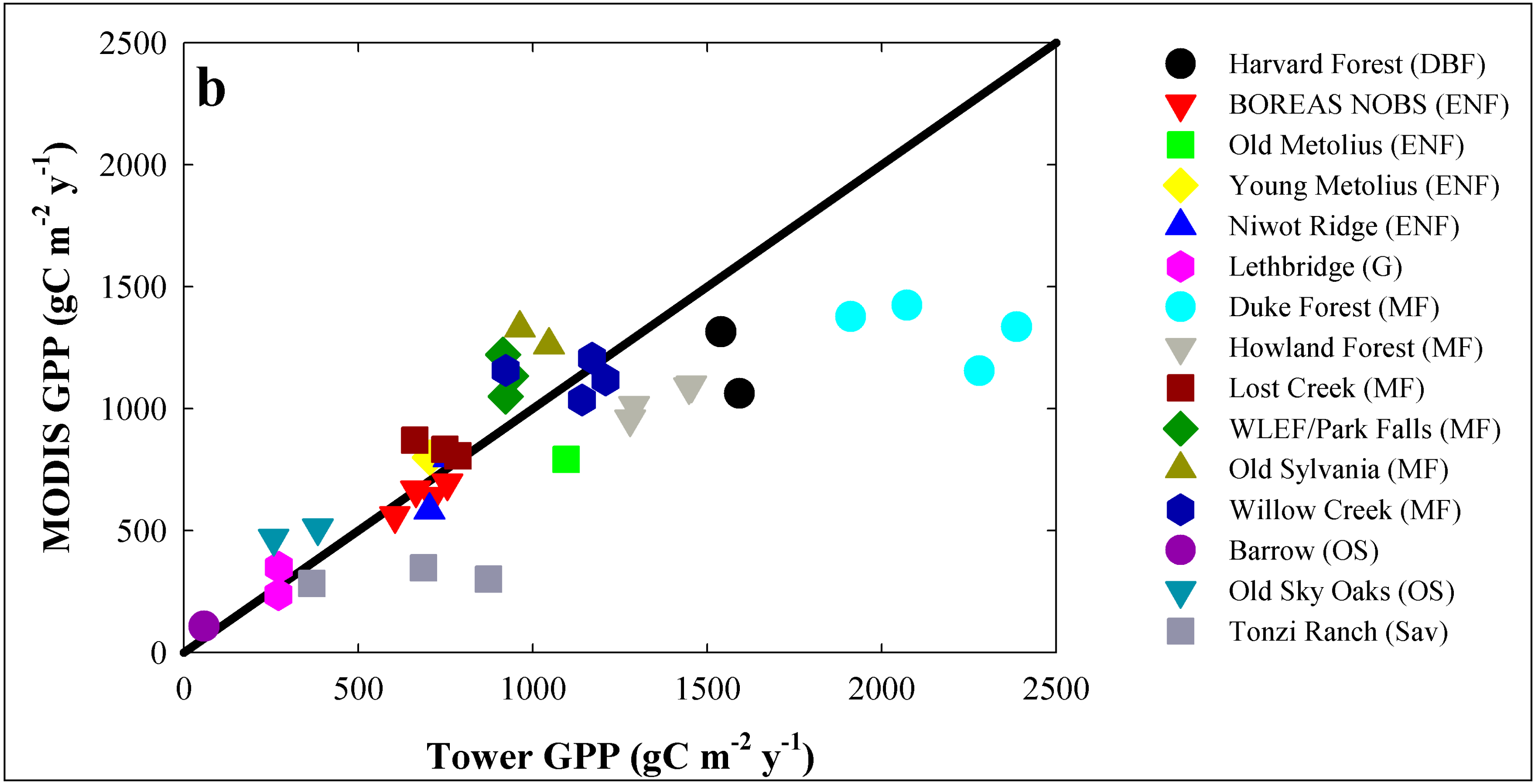
- How Can We Upscale and Integrate Satellite Remote Sensing Products in Time that
- May only Sample the Surface Once a Day?
- Whose Vision of the Surface May be Obscured by Clouds?
- With Sensors that Measure Reflected Light, which are Proxies, and Infer Fluxes?

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



Sims et al 2005 AgForMet

MODIS GPP Algorithm Test: How Good is Good Enough?



Heinsch et al. 2006 RSE

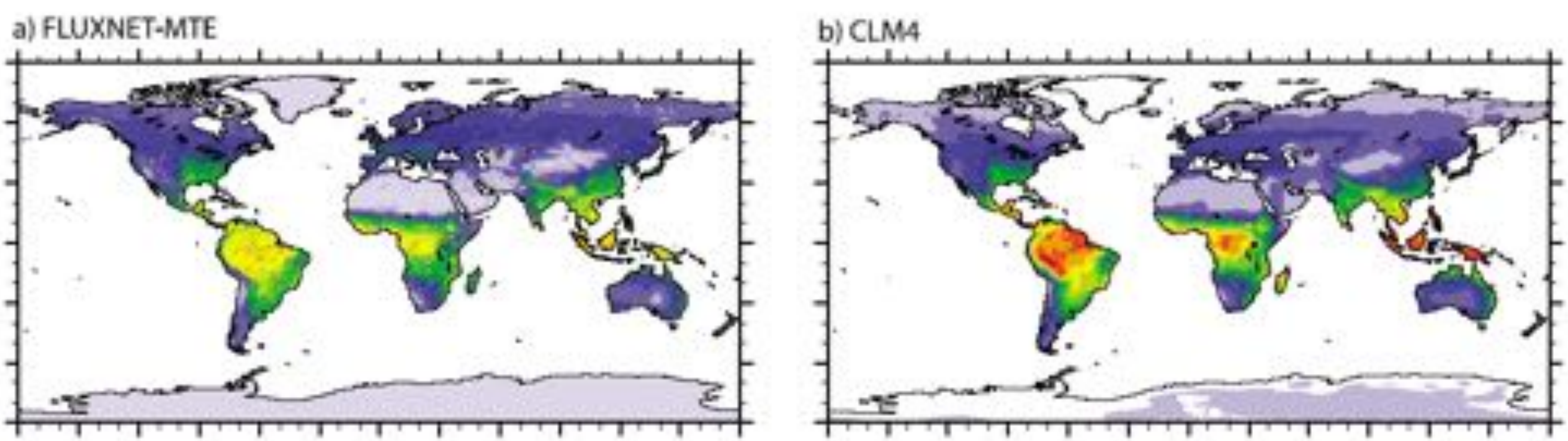
Deriving and Using Model Parameters in Land Surface Models

Table 3
Model parameters with 95% confidence intervals derived for groups of site years (n) within seven vegetation classes. $v_{cm,25}$ and $J_{m,25}$ in $\mu mol\ m^{-2}\ s^{-1}$, α and λ in $mol\ mol^{-1}$.

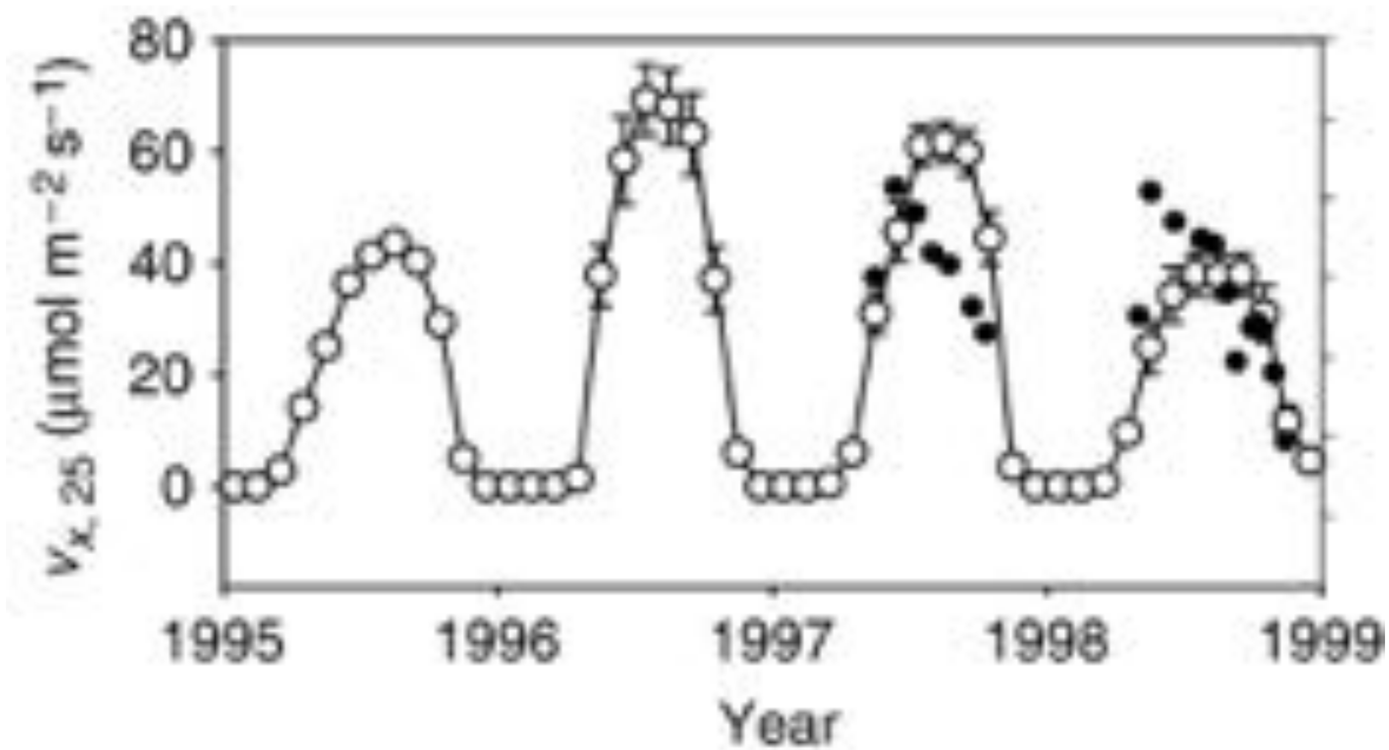
	n	$v_{cm,25}$	$J_{m,25}$	α	λ
Cropland	12	48.6 ± 29.9	136.9 ± 33.2	0.27 ± 0.09	150.60 ± 124.8
Savanna	22	18.0 ± 9.7	68.4 ± 35.5	0.11 ± 0.02	593.34 ± 273.0
Deciduous broadleaf forest	63	30.9 ± 8.1	154.9 ± 29.9	0.16 ± 0.02	128.56 ± 33.2
Evergreen broadleaf forest	22	34.3 ± 4.6	114.1 ± 31.3	0.22 ± 0.05	190.77 ± 41.8
Evergreen needleleaf forest	150	27.7 ± 5.2	121.6 ± 13.6	0.16 ± 0.02	209.63 ± 36.1
Grassland	55	43.3 ± 5.0	238.9 ± 31.0	0.10 ± 0.02	276.46 ± 75.4
Mixed forest	25	36.4 ± 11.0	136.2 ± 51.8	0.25 ± 0.05	149.80 ± 131.0

Groenendijk et al. 2011 AgForMet

G02014 BONAN ET AL.: COMMUNITY LAND MODEL CANOPY PROCESSES G02014

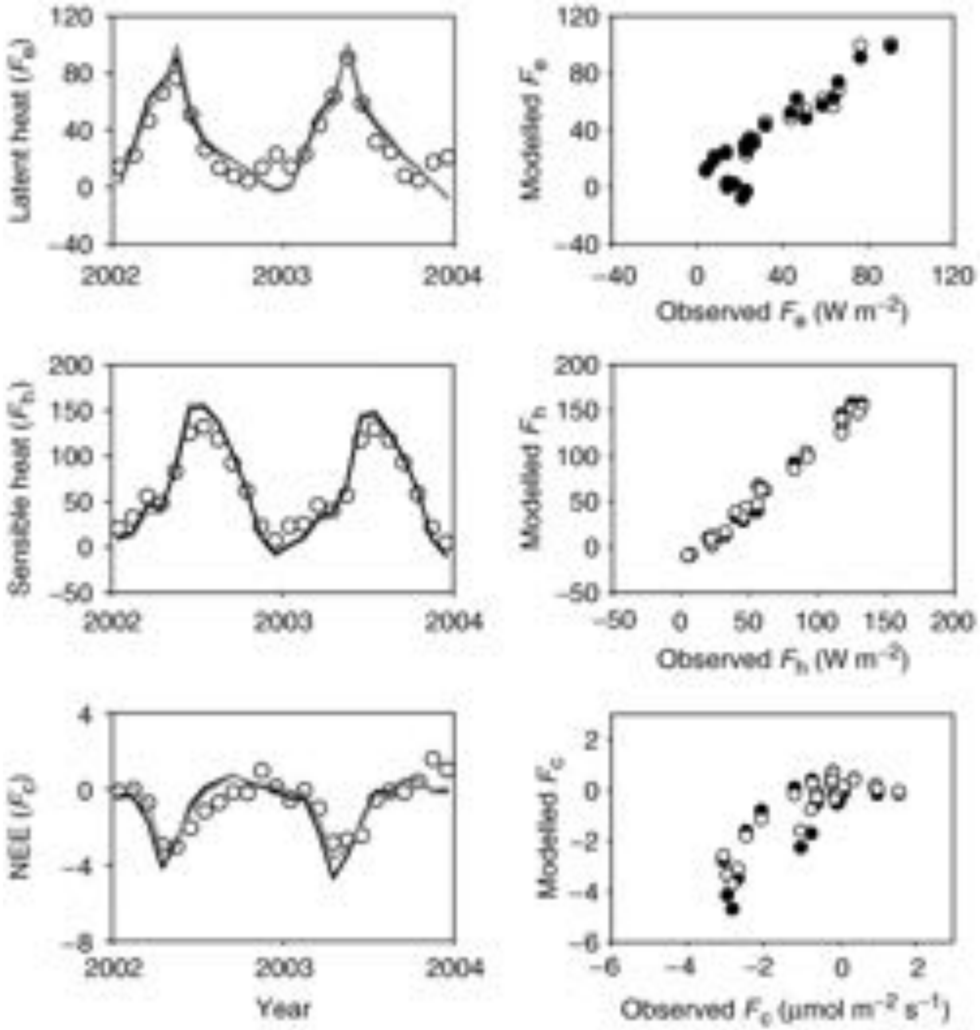


Seasonality of Photosynthetic Capacity



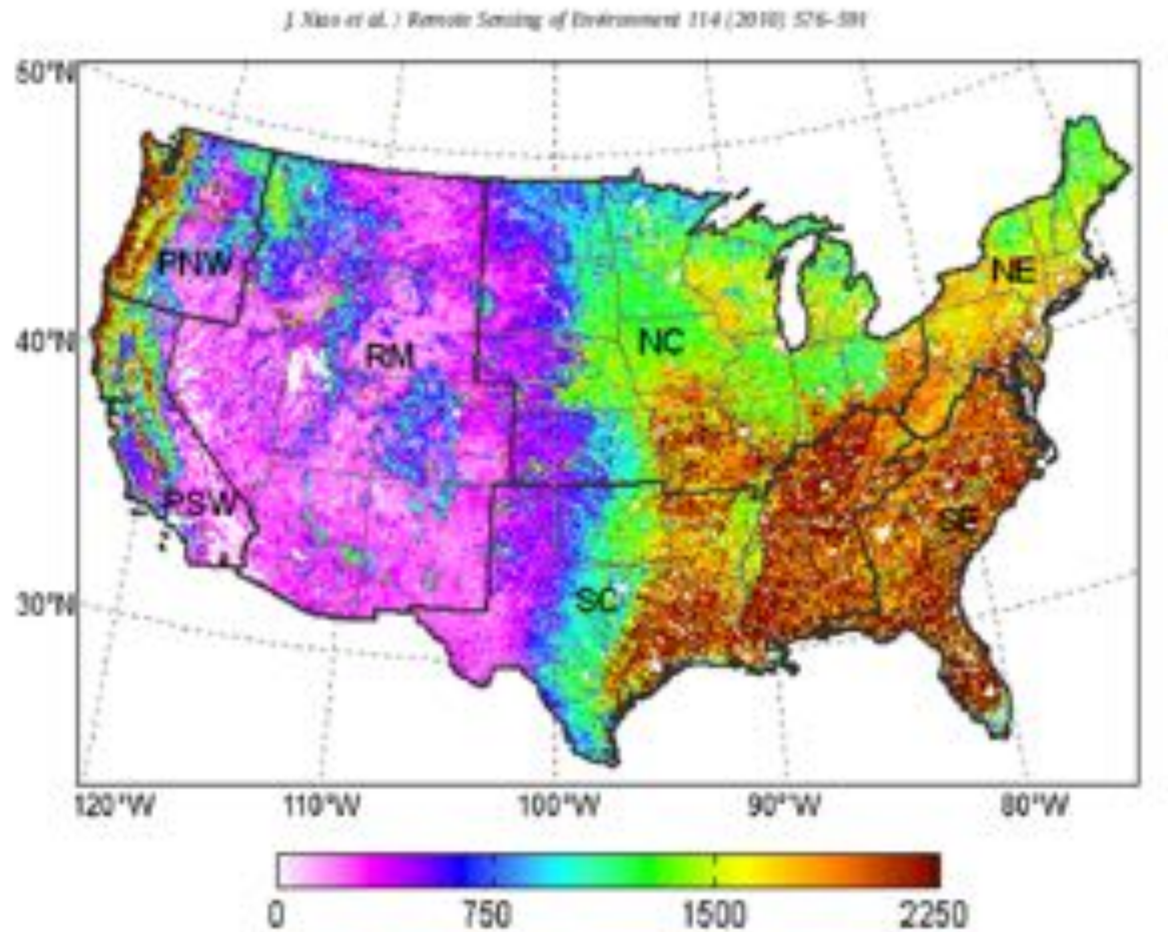
Wang et al, 2007 GCB

Optimizing Seasonality of Vcmax improves Prediction of Fluxes

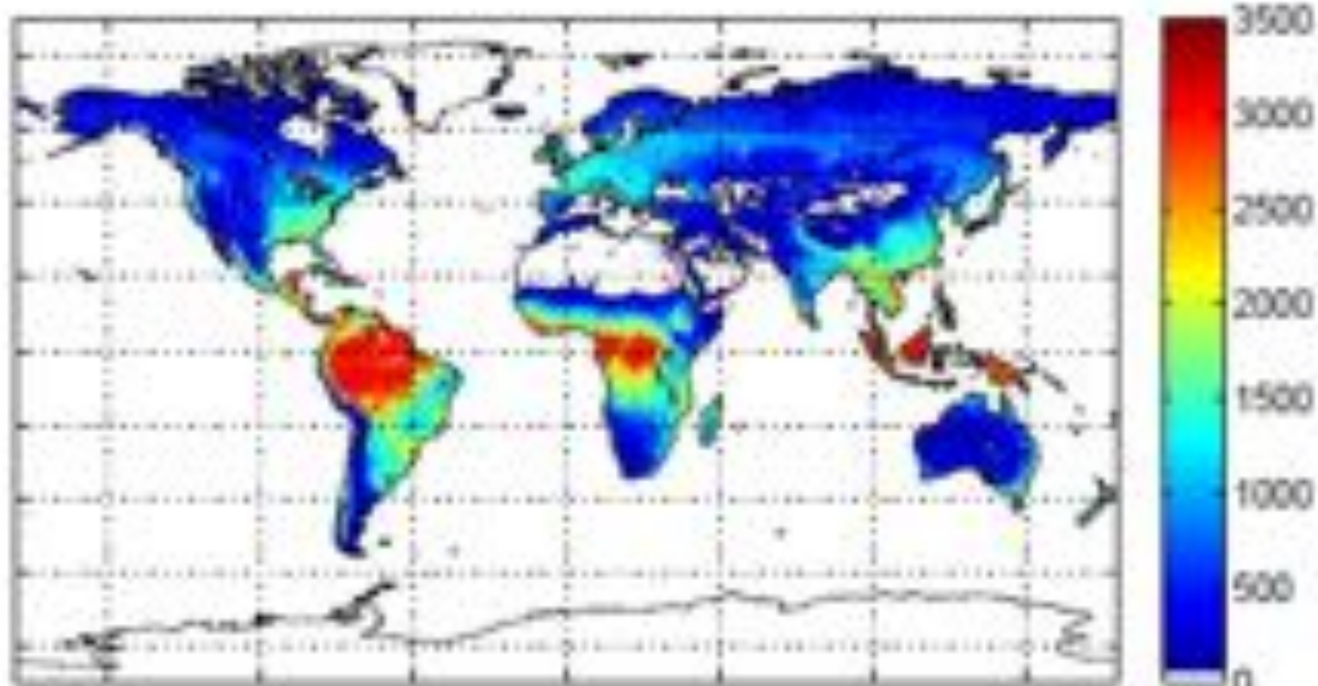


Wang et al, 2007 GCB

Spatial Upscaling of Carbon Fluxes with Flux Networks, Remote Sensing and Machine Learning Models



Global Primary Productivity

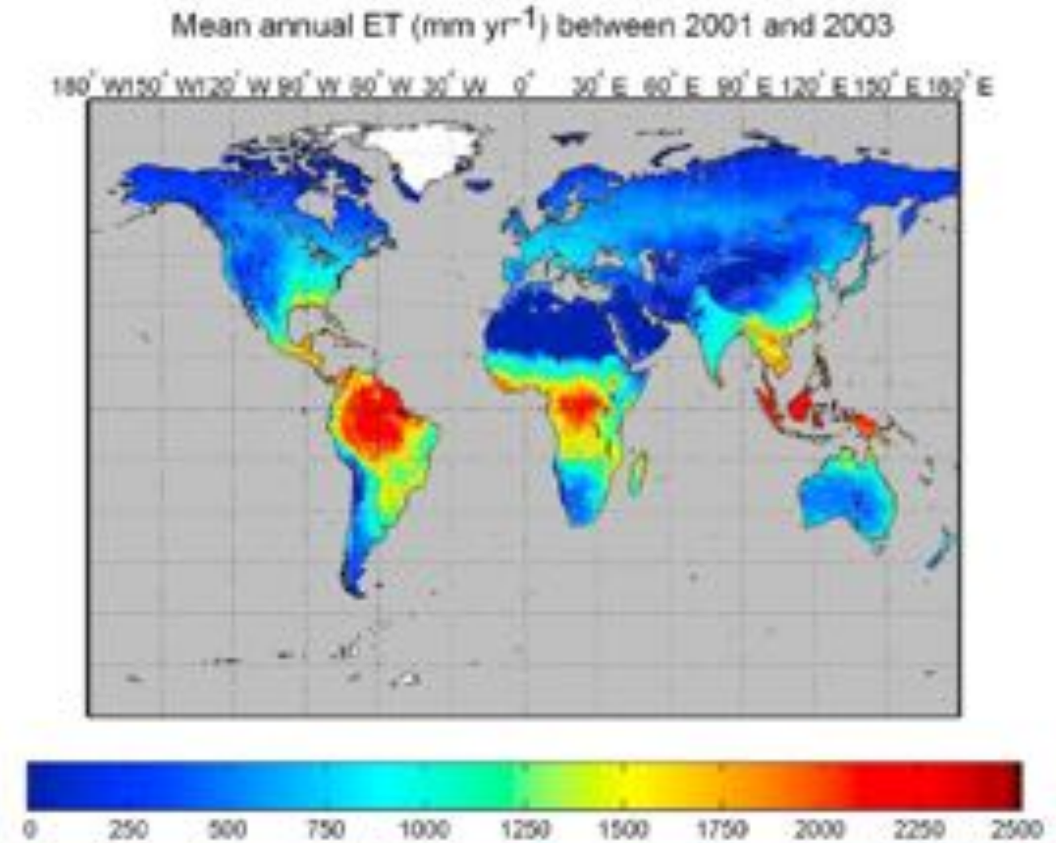


GPP = 123 +/- 8 PgC y-1

GPP-CLM ~ 160 PgC y-1

Beer et al., 2010 Science

Global Terrestrial Evaporation

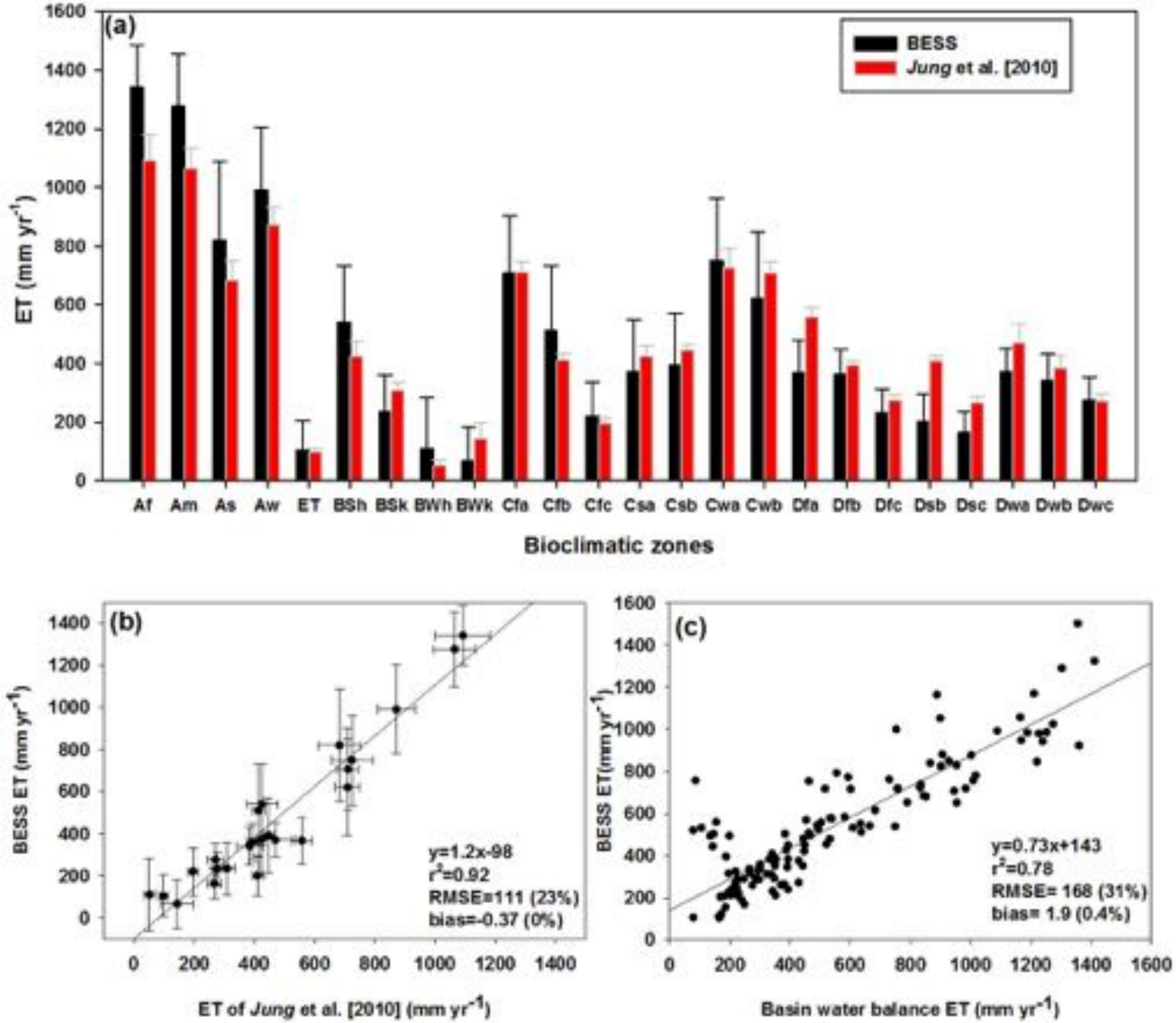


Global ET: 63,000 +/- 13000 km^3/y

Global ET: Trenberth~ 73,000 km3/y

Ryu et al 2012 GBC

BESS vs Machine Learning Upscaling Method



Ryu et al (2012) Global Biogeochemical Cycles

Conclusions

- New Opportunities Exist to Expand and Sustain Flux Networks, which are Critical Partners in Upscaling Fluxes in Time and Space with Models and Remote Sensing
- Long-Term Networks are Required to Study Changes in the Global Environment
- Revolution in Sensors Enables Use to Expand to Other Trace Gases
- New Data Products are Refining Past Global Budgets that were Poorly Constrained or Based on Residuals

Necessary Attributes of Global Biophysical Model: Applying Lessons from the Berkeley Biomet/Ecosystem Ecology Classes and CANVeg

- Treat Canopy as Dual Source (Sun/Shade), Two-Layer (Vegetation/Soil) system
  - Treat Non-Linear Processes with Statistical Rigor (Norman, 1980s)
- Requires Information on Direct and Diffuse Portions of Sunlight
  - Monte Carlo Atmospheric Radiative Transfer model (Kobayashi + Iwabuchi,, 2008)
- Couple Carbon-Water Fluxes for Constrained Stomatal Conductance Simulations
  - Photosynthesis and Transpiration on Sun/Shade Leaf Fractions (dePury and Farquhar, 1996)
  - Compute Leaf Energy Balance to compute Leaf Saturation Vapor Pressure and Respiration Correctly
  - Photosynthesis of C_3 and C_4 vegetation Must be considered Separately
- Light transfer through canopies MUST consider Leaf Clumping to Compute Photosynthesis/ Stomatal Conductance correctly (Baldocchi and Harley, 1995)
  - Apply New Global Clumping Maps of Chen et al./Pisek et al.
- Use Emerging Ecosystem Scaling Rules to parameterize models, based on remote sensing spatio-temporal inputs
  - Vcmax=f(N)=f(albedo) (Ollinger et al; Hollinger et al; Wright et al.)
  - Seasonality in Vcmax is considered (Wang et al., 2008)
  - Vcmax scales with Jmax (Wullschleger, 1993)

Spatial Patterns in Net Carbon Exchange

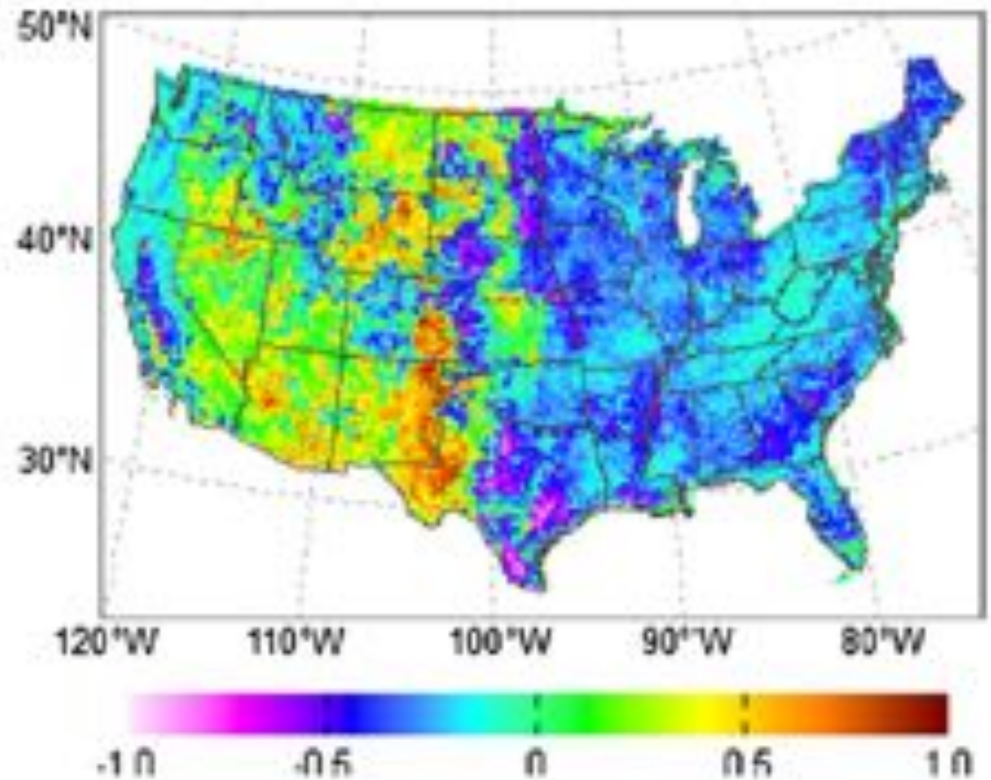
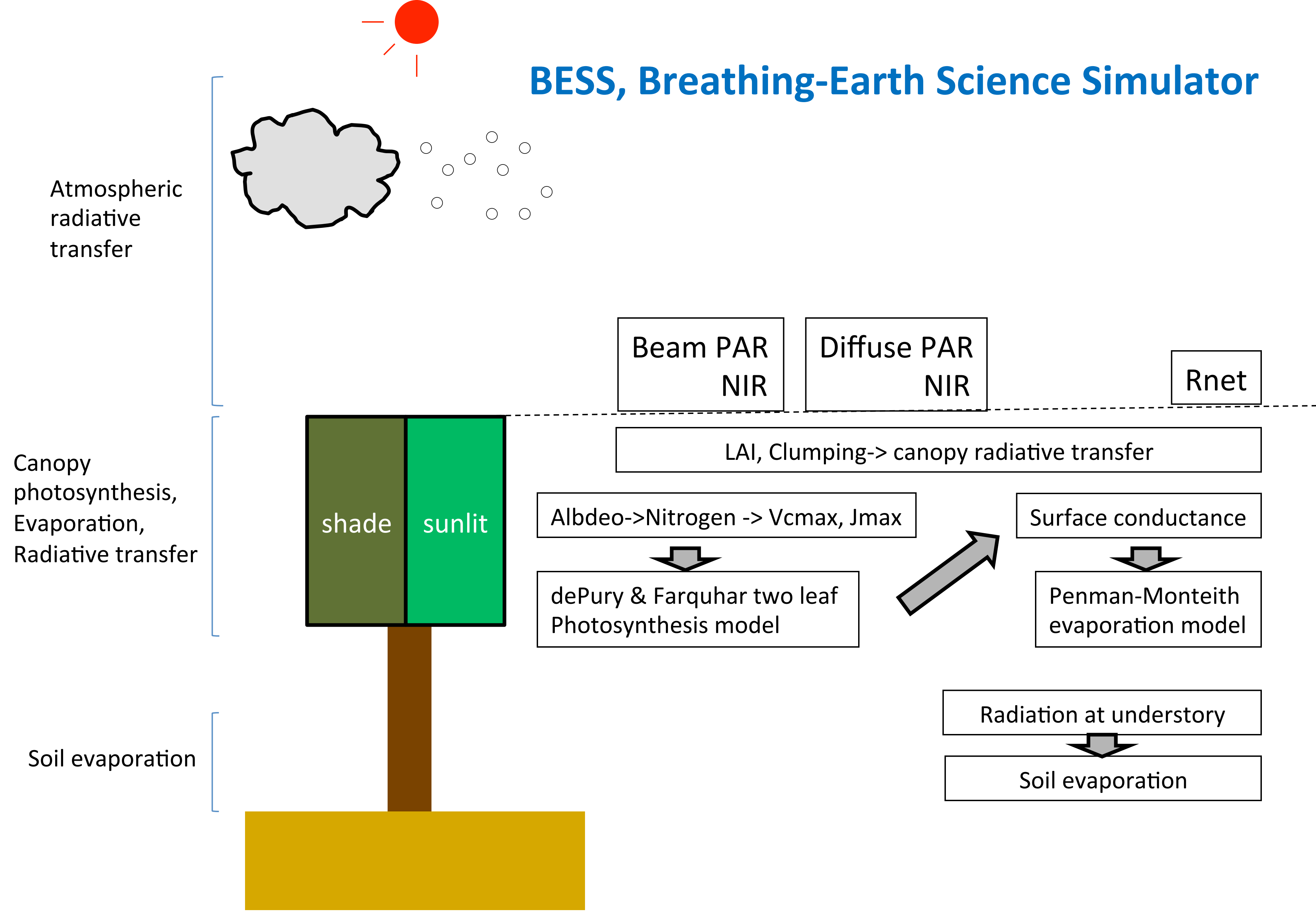


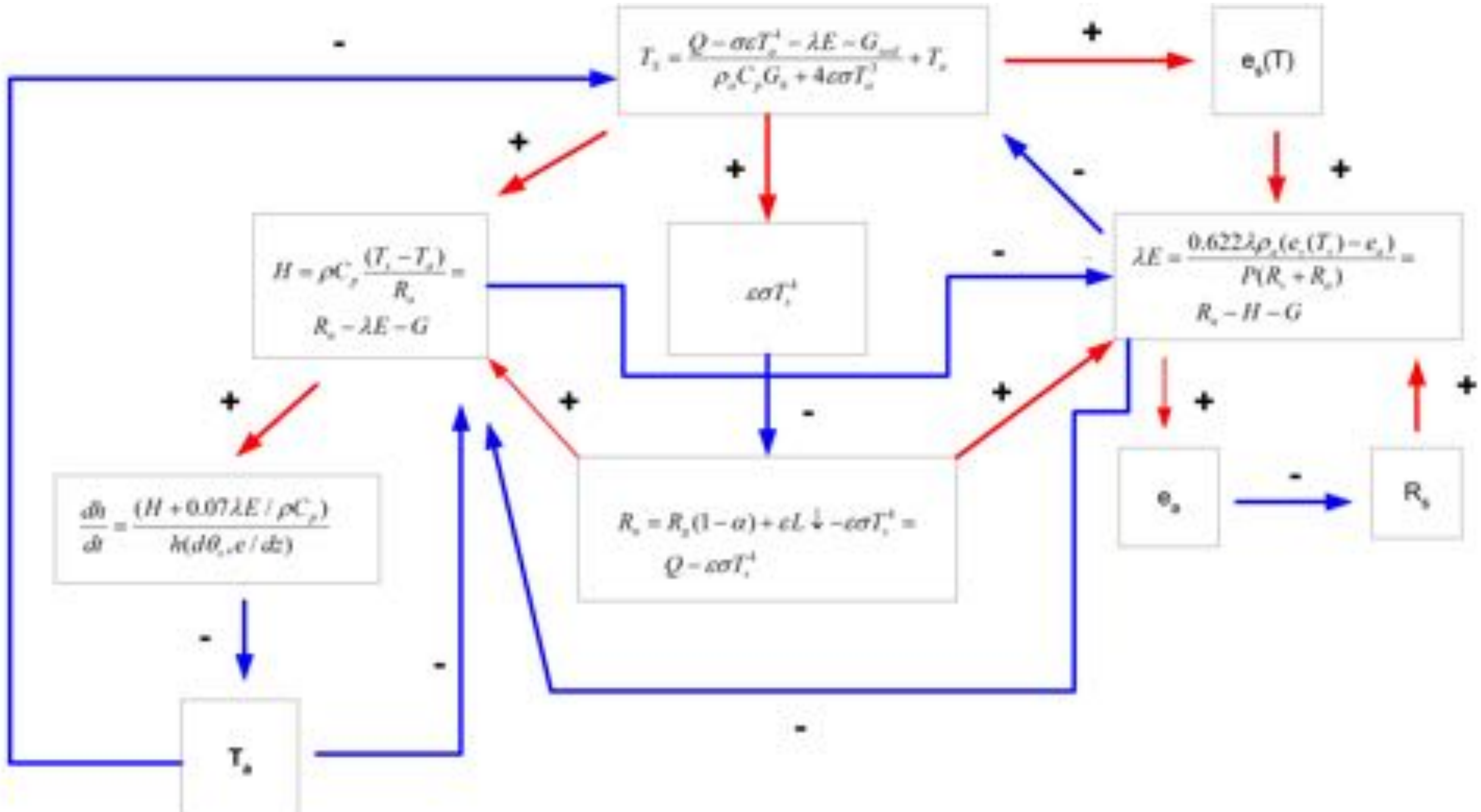
Fig. 8. Interannual variability of annual NEE across the conterminous U.S. over the period 2001–2006 characterized by the coefficient of variation (CV).

Xiao et al 2011 AgForMet

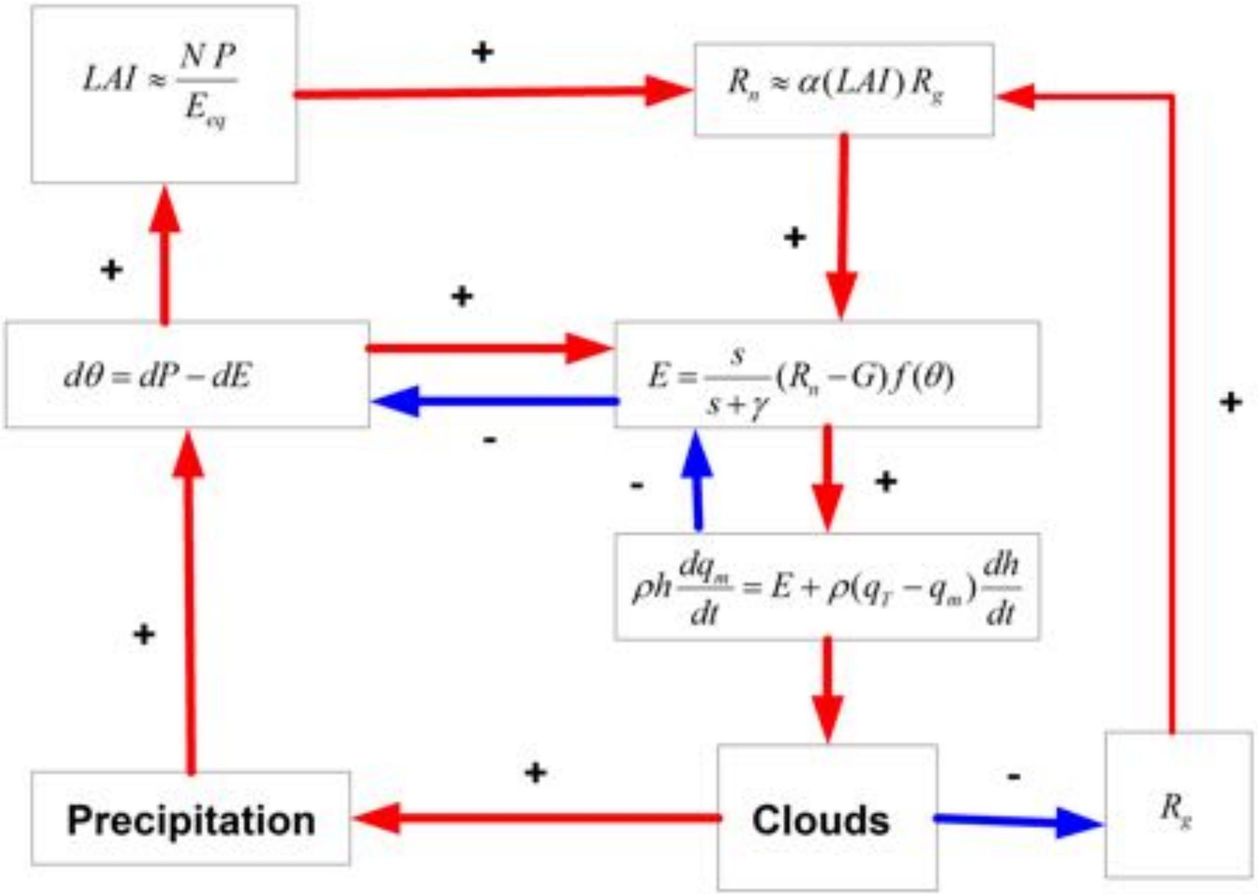
BESS, Breathing-Earth Science Simulator



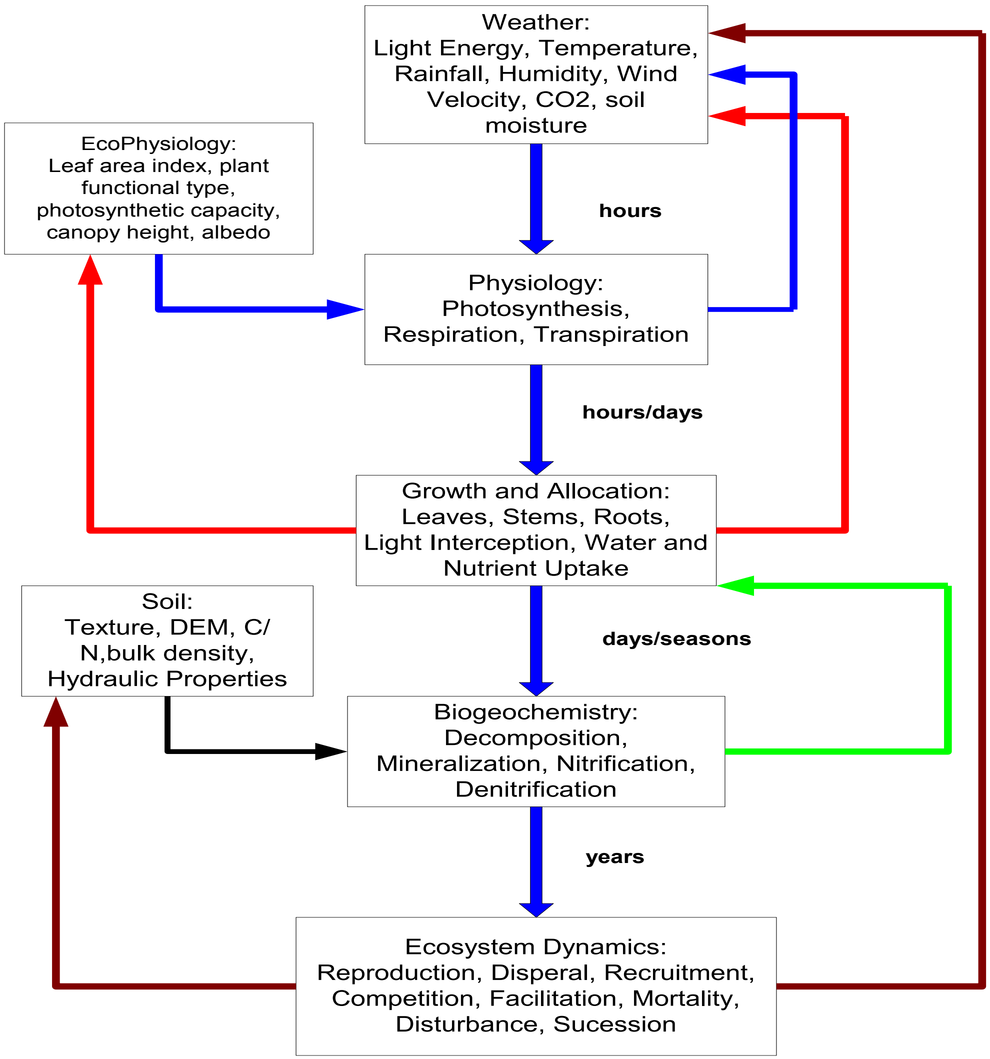
Positive and Negative Feedbacks affecting Surface Temperature



Soil Moisture-Rainfall-Evaporation Feedbacks



Biometeorology/Ecosystem Ecology, v2, the Processes



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

- Numerous Feedbacks,
- Positive and Negative

Discerning Cause and Effect

- Issues
  - Complexity
  - Multiple Scales
  - Multiple Feedbacks
  - Multiple, Coupled Processes

Granger Causality

Compute Lagged Auto-Regressive Function on a time series, Xt,
Determine if the Variance is Reduced if the other Variable, Yt,
is included

Multi-Variate Model

$$X_t = a_0 + \sum a_{1,k} X_{t-k} + \sum a_{2,k} Y_{t-k} + \varepsilon$$

$$Y_t = b_0 + \sum b_{1,k} X_{t-k} + \sum b_{2,k} Y_{t-k} + \xi$$

Univariate Model

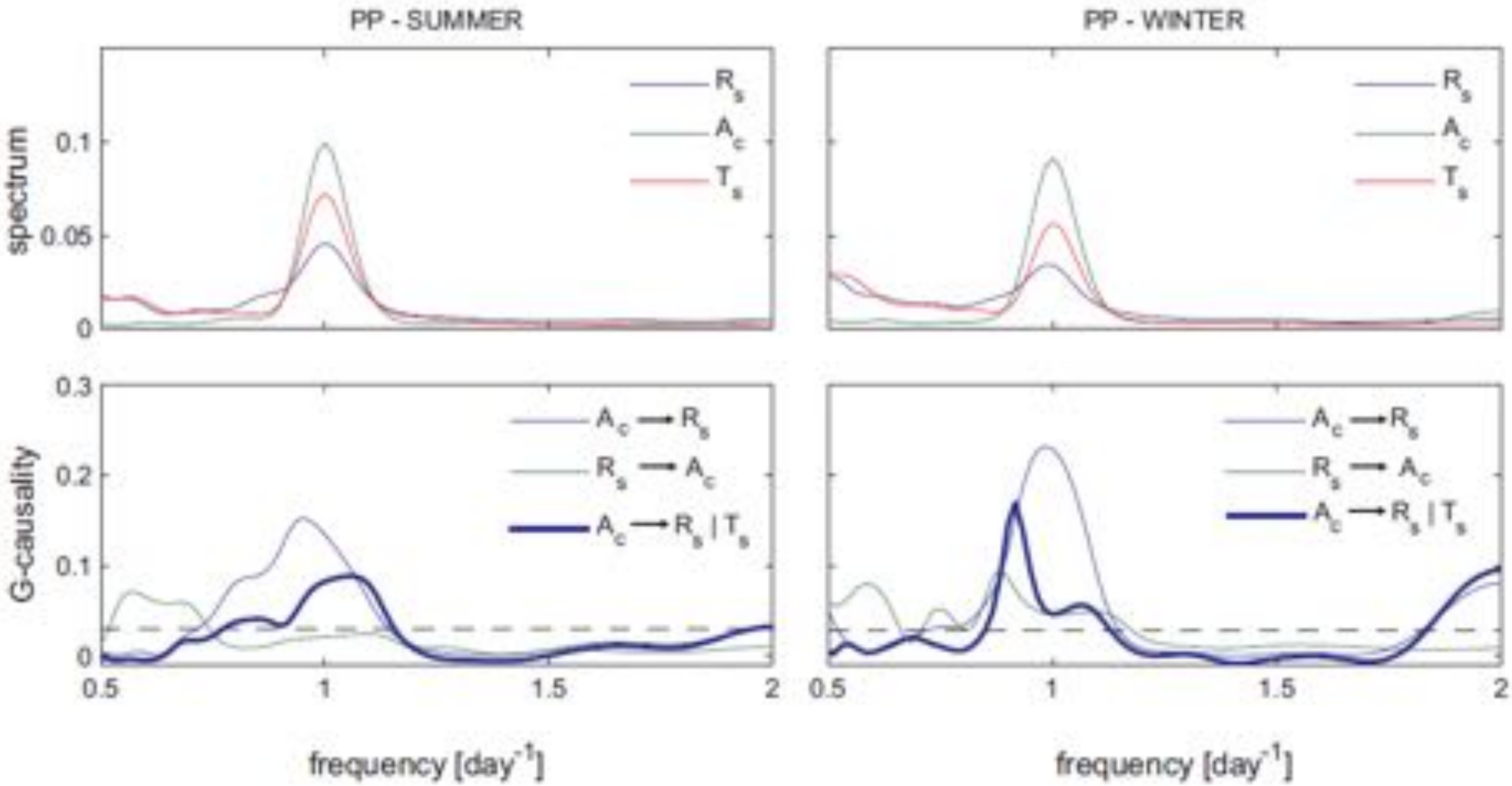
$$X_t = a_0 + \sum b_k X_{t-k} + \eta$$

Test If Muli-variate model is better than Uni-Variate

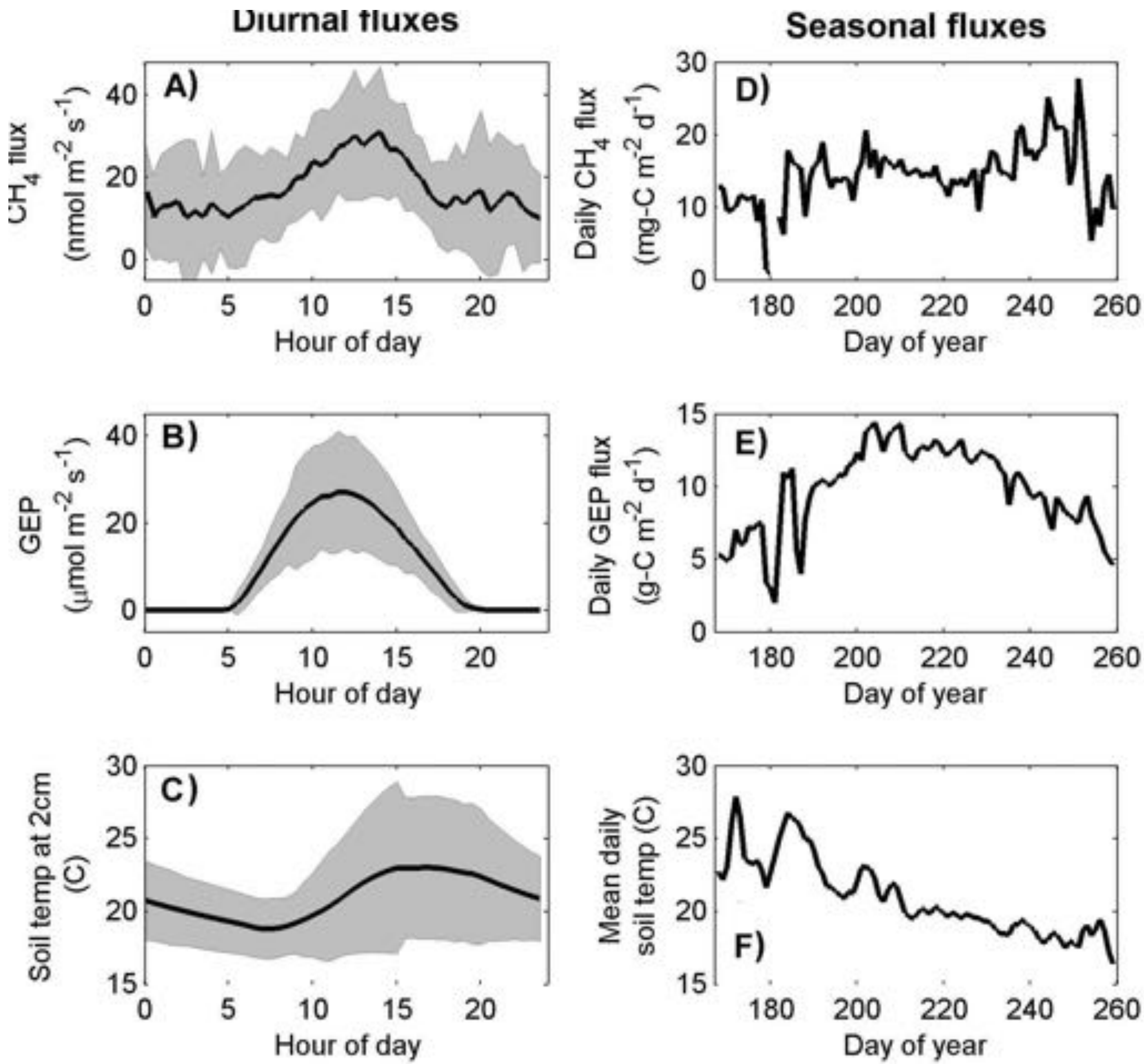
$$G_{y \to x} = \ln\left(\frac{\sigma_\eta^2}{\sigma_\varepsilon^2}\right)$$

$$\sigma_\varepsilon^2 < \sigma_\eta^2$$

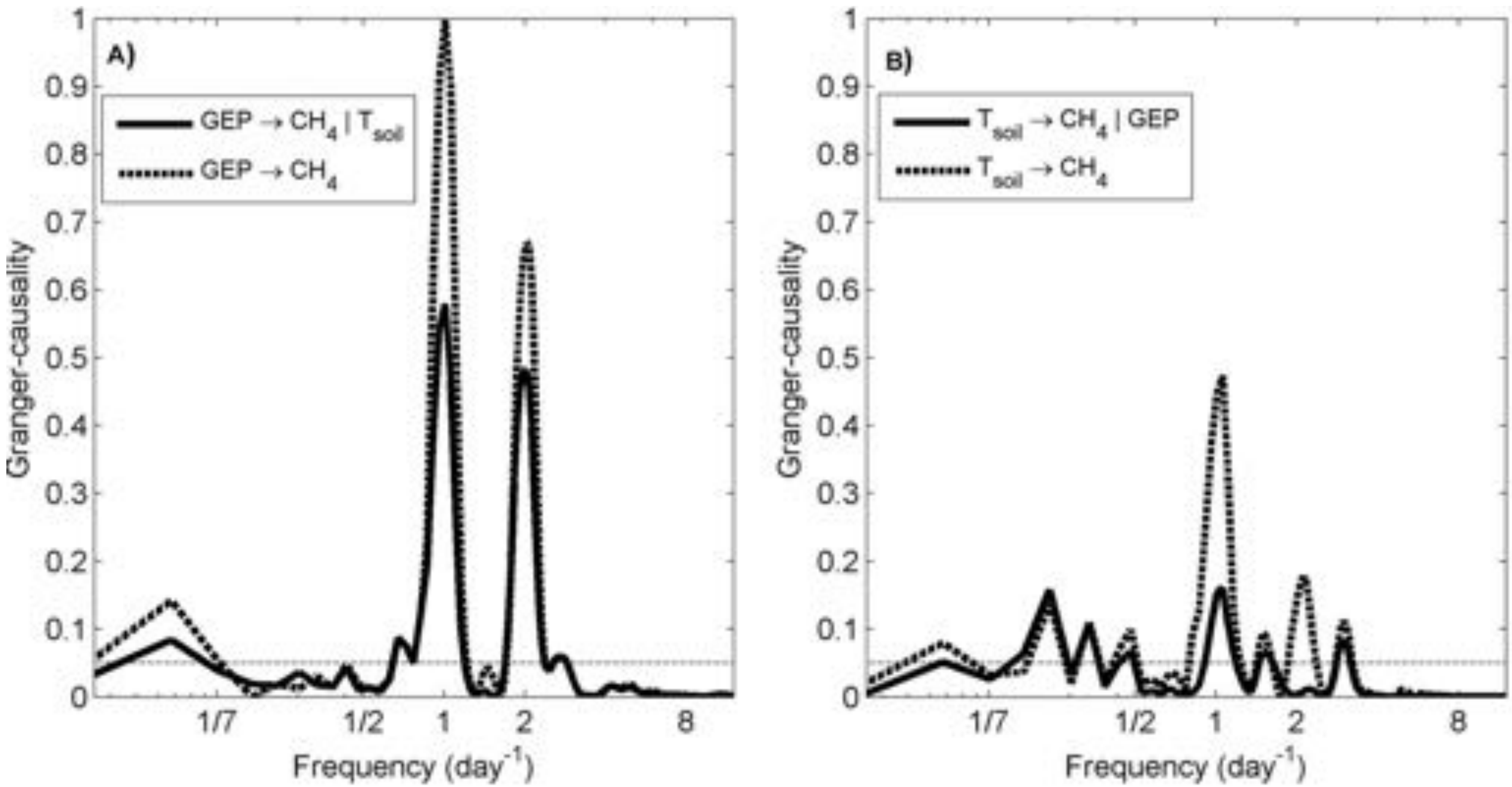
Does Photosynthesis 'Granger-Cause' Respiration?



Detto et al. 2012 Am Nat


Diurnal fluxes
Seasonal fluxes
A)
CH_4 flux (nmol m^{-2} s^{-1})
Hour of day
D)
Daily CH_4 flux (mg-C m^{-2} d^{-1})
Day of year
B)
GEP (μmol m^{-2} s^{-1})
Hour of day
E)
Daily GEP flux (g-C m^{-2} d^{-1})
Day of year
C)
Soil temp at 2cm (C)
Hour of day
F)
Mean daily soil temp (C)
Day of year

Photosynthesis Causes Methane Production to Lead Temperature



Hatala et al 2012 GRL

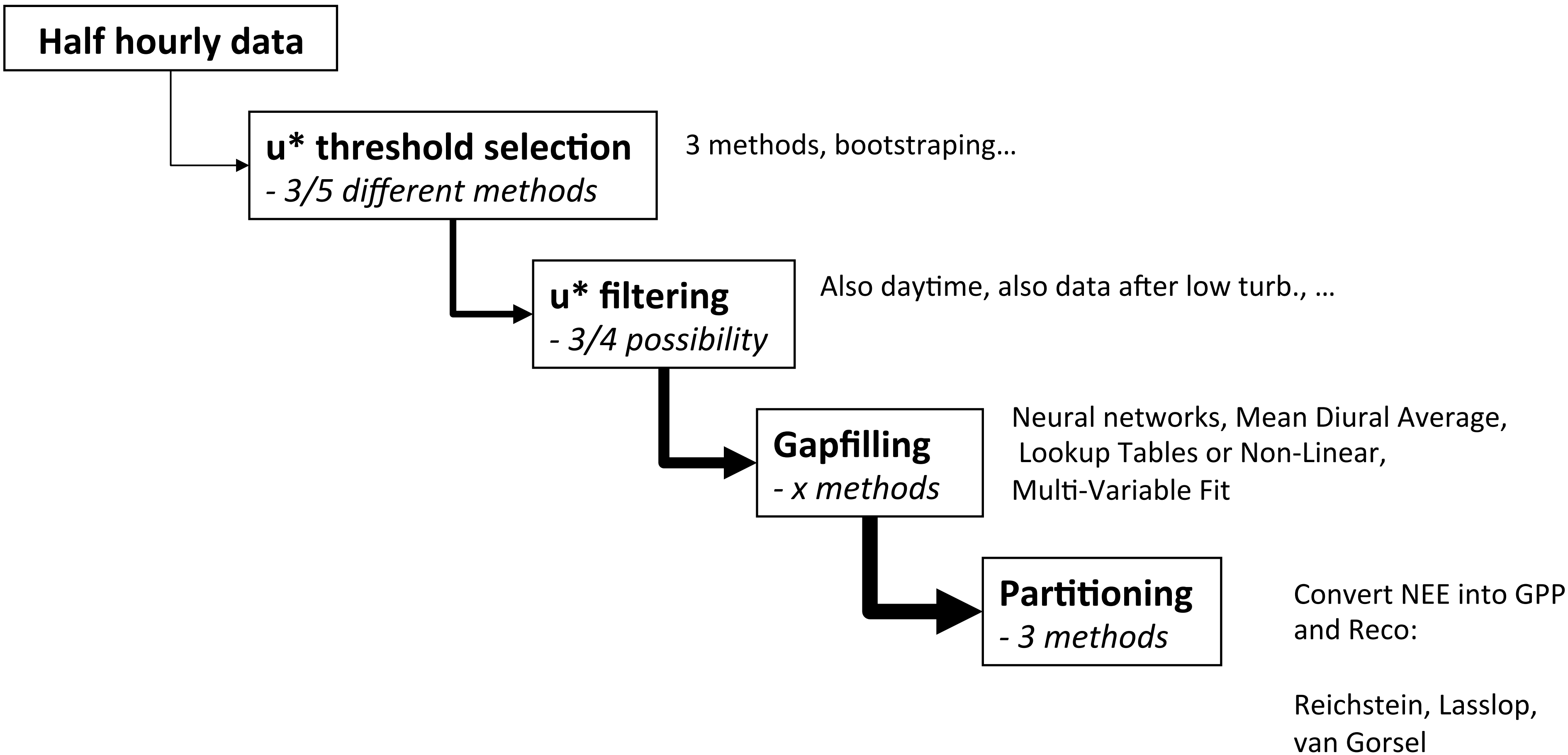
Try pbl model and Granger Causality

Try Vostock Ice core, CO_2, CH_4 and T and Causality

Transfer Entropy

$$T(X_t^{(i)} \rightarrow X_t^{(j)}, \tau) = \sum_{x_t^{(j)}, x_{t-\Delta t}^{(j)}, x_{t-\tau\Delta t}^{(i)}} p(x_t^{(j)}, x_{t-\Delta t}^{(j)}, x_{t-\tau\Delta t}^{(i)}) \log \frac{p(x_t^{(j)} \mid (x_{t-\Delta t}^{(j)}, x_{t-\tau\Delta t}^{(i)}))}{p(x_t^{(j)} \mid x_{t-\Delta t}^{(j)})}$$

Data processing, Value Added Products and Uncertainty Estimation



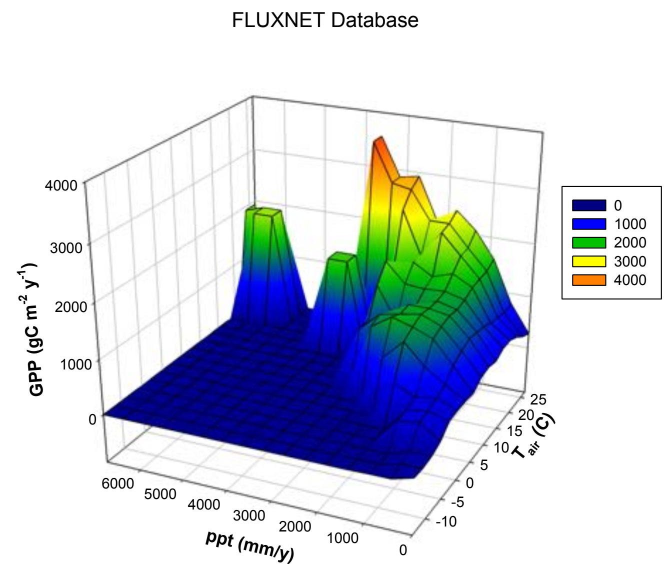
Mobile Methane Flux System

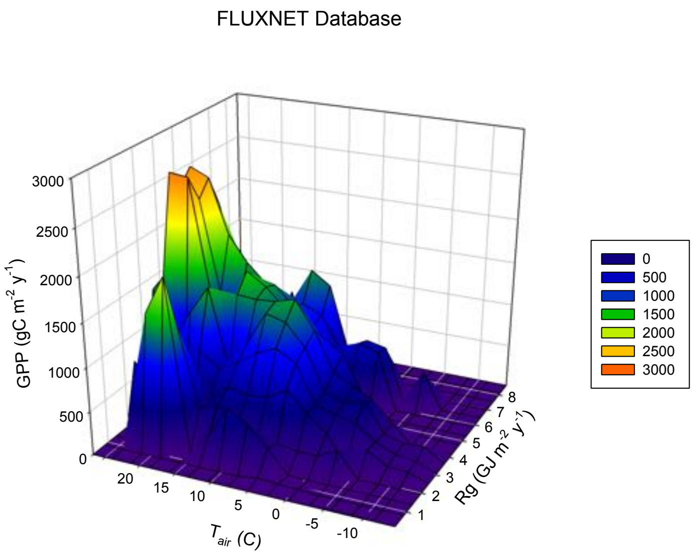
Expected Values of GPP from joint-pdfs

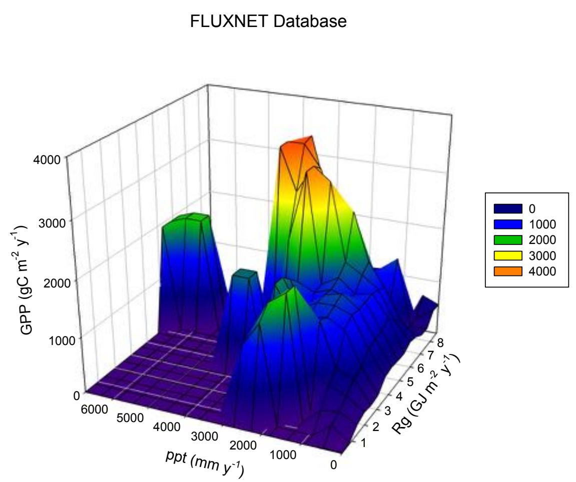
$E[GPP(Rg, T)] = 1237\ gC\ m^{-2}\ y^{-1} \sim 136\ PgC/y$

$E[GPP(Rg, ppt)] = 1901\ gC\ m^{-2}\ y^{-1}$

$E[GPP(ppt,T)] = 1753\ gC\ m^{-2}\ y^{-1}$







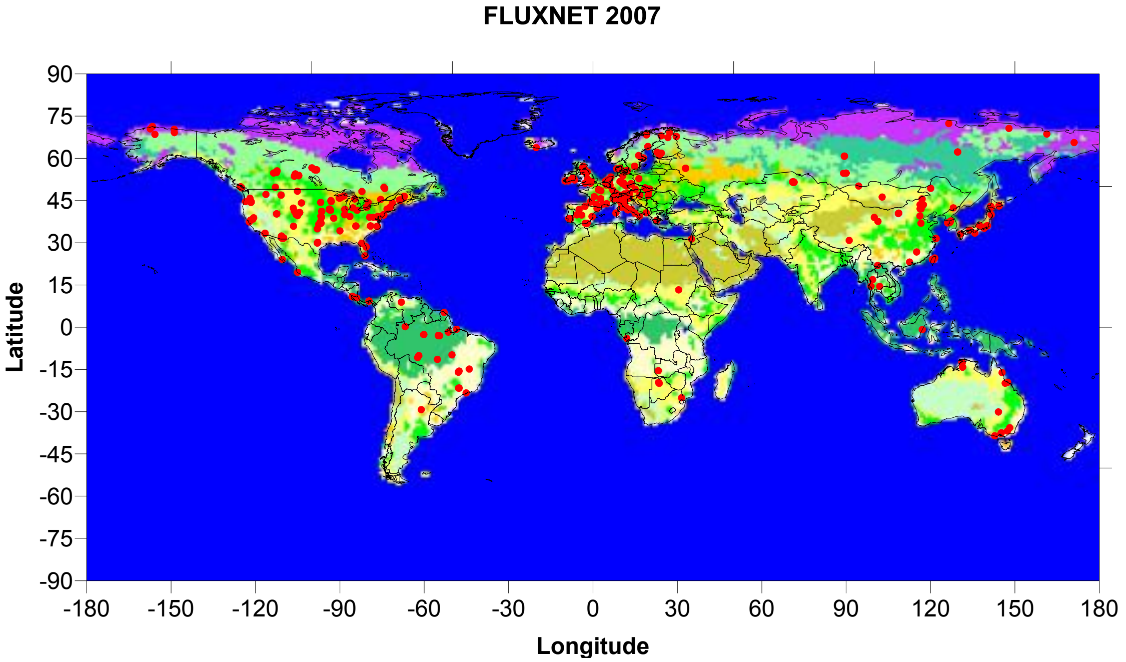
Apply Bayes Theorem to FLUXNET?

$$p(Flux \mid \text{climate}) = \frac{p(\text{climate} \mid flux)\, p(flux)}{p(\text{climate})}$$

p(flux) from FLUXNET
p(climate|flux) prior from FLUXNET
p(climate) from climate database

Estimate Global flux by Integrating p(Flux|climate) across Globally-gridded Climate space

Global Flux Networks—FLUXNET—Offer opportunities to Parameterize, Test and Validate Models across a Spectrum of Climates and Biomes



www.fluxdata.org