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

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Lecture 6:
ESPM 228
Contemporary $\text{CO}_2$ Record

Mauna Loa
Keeling data

$\text{CO}_2$ (ppm)

year

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 Model
Carbon Satellite, OCO
Satellites

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

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

Remedy
New Satellite platforms (EOS)
Validate Algorithms with Direct Eddy Flux Measurements
CBL Budgets

- **Pro**
  - Provides mixed layer estimate of CO₂ for inversion models
  - Provides landscape scale fluxes

- **Con**
  - Valid only under ideal conditions
  - Affected by Advection
  - Needs information on CO₂ above PBL

**Remedy**

Improve estimates of entrainment fluxes
Micrometeorological Eddy Fluxes

**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

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

**Remedy**
C isotope studies
More root and below ground measurements
Eddy Covariance Technique

\[ F = \rho_w s \sim \rho_a \cdot w' s' \]

\[ s = \left( \frac{\rho_c}{\rho_a} \right) \]
Objectives

• Network Background
• 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
FLUXNET: From Sea to Shining Sea
400+ Sites, circa 2007
Flux Networks
Network Representativeness

Sundareshwar et al, 2007 Science
Distribution of Flux Towers by Landcover (MOD12Q1)
Black - 466 Flux Towers
Red - Land Area
March 2007

Landcover codes:
C-shrubland - closed shrubland
DBL - deciduous broadleaf
DNL - deciduous needleleaf
EBL - evergreen broadleaf,
ENL - evergreen needleleaf
O-shrubland - open shrubland
Global distribution of Flux Towers with Respect to Climate

Running et al.
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
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
LaThuile Fluxnet Workshop, Feb. 2007

- New Gap-Filled, Qa/Qc Dataset
- 250 Sites; 930 Site-years of Data
- www.fluxdata.org
‘Failures’/’Un-resolved’ Issues

- 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
  - Being Rectified at LaThuile with Participation of New Generation of Fluxnet Scientists
Temporal Dynamics of C Fluxes

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

- Pulses
- Lags
- Switches
Annual Time Series of Trace Gas Exchange

Vaira Grassland 2001

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**
Probability Distribution of Published NEE Measurements, Integrated Annually

mean: -182.9 gC m⁻² y⁻¹
std dev: 269.5
n: 506

Baldocchi, Austral J Botany, in press
Does pdf change with Time and/or as the Network Grows?

FLUXNET Database: n ~ 300 in 2003; n ~ 430 in 2005
Does Net Ecosystem Carbon Exchange Scale with Photosynthesis?

Ecosystems with greatest GPP don’t necessarily experience greatest NEE

Baldocchi, Austral J Botany, in press
Ecosystem Respiration Scales Tightly with Ecosystem Photosynthesis, But Is with Offset by Disturbance

![Graph showing the relationship between ecosystem respiration ($F_R$) and photosynthesis ($F_A$). The graph includes data points for undisturbed conditions and disturbed conditions caused by logging, fire, drainage, and mowing. The data is plotted on a log-log scale, and the relationship between $F_R$ and $F_A$ is shown with trend lines for each condition.]

Baldocchi, Austral J Botany, in press
Net Ecosystem Carbon Exchange Scales with Length of Growing Season

Baldocchi, Austral J Botany, in press
Decadal Plus Time Series of NEE:
Flux version of the Keeling’s Mauna Loa Graph

Harvard Forest, 1991-2004

Data of Wofsy, Munger, Goulden, et al.
Interannual Variation and Long Term Trends in Net Ecosystem Carbon Exchange ($F_N$), Photosynthesis ($F_A$) and Respiration ($F_R$)

Harvard Forest

Carbon Flux (gC m$^{-2}$ y$^{-1}$)

Year

Urbanski et al 2007 JGR
Power Spectrum of CO$_2$ Fluxes

1997

canoak data

$nS_{wc}(n)/w'c'$
n, cycles per hour

0.0001 0.001 0.01 0.1 1

0.0001 0.001 0.01 0.1 1
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

Interannual Variability in $F_N$

Coefficients:

\[ b[0] = -4.496 \]
\[ b[1] = 0.704 \]
\[ r^2 = 0.607 \]
\[ n = 164 \]

Baldocchi, Austral J Botany, in press
Lag Effects Due to 2003 European Drought/Heat Stress

Knohl et al. Max Planck, Jena
Emerging Processes
Light and Photosynthesis: Emergent Processes at Leaf and Canopy Scales

D 208 Oak leaf, forest floor
T leaf: 25°C
CO₂: 360 ppm

\[
\text{absorbed PAR (µmol m}^{-2} \text{s}^{-1})
\]

\[
F_c \quad \text{(µmol m}^{-2} \text{s}^{-1})
\]

\[
\text{PPFD (µmol m}^{-2} \text{s}^{-1})
\]
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

GPP at 2% efficiency and 365 day Growing Season

GPP at 2% efficiency and 182.5 day Growing Season

FLUXNET 2007 Database
Optimal NEE: Acclimation with Temperature

\[ b[0] = 3.192 \]
\[ b[1] = 0.923 \]
\[ r^2 = 0.830 \]

E. Falge et al 2002 AgForMet; Baldocchi et al 2001 BAMS
Linking Water and Carbon: Potential to assess $G_c$ with Remote Sensing

$G_c$ (mol m$^{-2}$s$^{-1}$)

GPP RH/C$_a$ (mol m$^{-2}$s$^{-1}$)

Xu + DDB, 2003 AgForMet
Gc Scale Invariance?
Task to Expand with New Database

FLUXNET Data

Stomatal Conductance Survey
Dennis Baldocchi; UC Berkeley

Processed by M. Falk
Environmental Controls on Respiration

Fast growth period data

Soil volumetric water content (m$^3$ m$^{-3}$)

Xu + Baldocchi, AgForMet 2004
Quantifying the impact of rain pulses on respiration

Xu, Baldocchi, Tang, 2004
Global Biogeochem Cycles
Soil Respiration Lags Photosynthesis on Hourly Scale

June, 2003

Flux Density

July, Rsoil-Ps lag

Tang et al. 2006, GCB
Soil Temperature: An Objective Indicator of Phenology??

Data of Pilegaard et al.
Soil Temperature: An Objective Measure of Phenology, part 2

Temperate Deciduous Forests

Day, $T_{soil} > T_{air}$

Baldocchi et al. Int J. Biomet, 2005
Spatial Variations in C Fluxes

First Global Photosynthesis from MODIS
Daily rates over the period June 17 - June 24, 2000

University of Montana SCF / NTSG
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
Upscaling Tower Measurements with Neural Network Model and Remote Sensing

What are Pros and Cons?

Papale and Valentini, 2003 GCB
Limits to Landscape Classification by Functional Type

- Stand Age/Disturbance
- Biodiversity
- Fire
- Logging
- Insects/Pathogens
- Management/Plantations
- Kyoto Forests
Time Since Disturbance Affects Net Ecosystem Carbon Exchange

Conifer Forests, Canada and Pacific Northwest

Data of teams lead by Amiro, Dunn, Paw U, Goulden
Effects of Stand Age: After Logging

\[ y = -239.4 + 399.9 \exp(-0.5 \cdot \ln(x/95.63)/1.098)^2 \]

Adj \( r^2 = 0.61 \)

Law et al. 2003 Global Change Biology
Northern Manitoba: Black Spruce chronosequence (Goulden et al.)
Other Activities and Uses of Fluxnet Data

- Ecosystem Modeling
- EcoHydrology
- Biodiversity
- Climate
Ecosystem Model Testing and Development

Kucharik et al., 2006 Ecol Modeling
Net ecosystem exchange of CO2 (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

Temperate/Boreal Broadleaved Forests
Summer Growing Season

\( \lambda_E / \lambda_{E,eq} \)

Number of Dominant Tree Species (> 5% of area or biomass survey)

Baldocchi, 2004: Data from Black, Schmid, Wofsy, Baldocchi, Fuentes
Testbed for Ecohydrological Theory

Energy Flux Biogeography

FLUXNET database

![Graph showing energy flux (Rg) vs. latitude](image-url)
Mean Soil Temperature Scales with Mean Air Temperature

FLUXNET Database

\[ b[0] = 0.6243257655 \]
\[ b[1] = 0.9216133206 \]
\[ r^2 = 0.9342107631 \]
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 CO₂, Trace Gas Deposition/Emission (O₃, 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 CO₂ 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 2007++
New Issues/Questions Raised

- Production of New, Expanded 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, ++++