Carbon Cycle at Global, Ecosystem and Regional Scales

Dennis Baldocchi
University of California, Berkeley

Bev Law
Oregon State University, Corvallis
Topics

• Concepts
  – Stores, pools, fluxes, processes

• Carbon Stores and Fluxes
  – Stores: Vegetation and Soil C = f(x,y,z)
  – Fluxes: NEP = f(x,y,t)
  • Global Fluxes
  • Regional Fluxes (WA, OR, CA)
Big Questions

• How Does Contemporary Carbon Cycle Differ from Pre-Settlement Times?
• 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?
Methods To Assess Terrestrial Carbon Budgets at Landscape to Continental Scales, and Across Multiple Time Scales

- Global Circulation Model Inversion
- Remote Sensing
- Eddy Flux Measurements/Flux Networks
- Ice Cores
- Forest/Biomass Inventories
- Physiological Measurements/Manipulation Expts.
- Biogeochemical/Ecosystem Dynamics Modeling
CO₂ => 280 ppm during Inter-Glacial, over 10k years
CO₂ => 180 ppm during Glaciation, over 100k years
Dust, Life, Oceans, CO₂ and CH₄ Amplify Feedbacks on Climate

- Vegetation Decreases → More Dust to Ocean → Ocean NPP Increases
- CO₂ Solubility in Ocean Increases/ DIC Stored in Deep Ocean → [CO₂] Decreases
- Ice Expands/ Sea Level Drops → Methane Hydrates Released from Continental Shelf/ CH₄ Increases
- Solar Forcing → Climate Cools
- Solar Forcing → Climate Warms
- Terrestrial Photosynthesis Increases → Terrestrial Respiration Outpaces Photosynthesis
- Ice Melts/ Sea Level Rises/ Freshwater in Ocean → CO₂ Solubility in Ocean Decrease
- [CO₂] Rises
- Less Dust to Ocean → Ocean NPP Decreases
- C₄ Plants Expand/ Soil C pools Grow
- More Dust to Ocean → Ocean NPP Increases
- CO₂ Solubility in Ocean Increases/ DIC Stored in Deep Ocean

Graphs and images show correlations between dust, CO₂, CH₄, climate, and other environmental factors.
Contemporary CO₂ Record

Mauna Loa
Keeling data

Sources:
- Fossil Fuel Combustion
- Deforestation
- Cement Production
- Soil and Plant Respiration
- Volcanoes

Sinks:
- Photosynthesis,
- Land/Ocean
- C Burial in Wetlands

CO₂ (ppm)

year

Global Carbon Cycle: Gross Fluxes and Pools

Atmosphere
- [843 PgC @ 385 ppm]
- 88 PgC/y
- 90 PgC/y
- 7.6 PgC/y
- 1.5 PgC/y

Soil
- ~1500 PgC

Vegetation
- ~600 PgC
- 60 PgC/y

Ocean
- ~38,000 PgC

Fossil Fuel Combustion

Deforestation
How much is C in the Air?

- Mass of Atmosphere
  - \( F = \text{Pressure} \times \text{Area} = g \times \text{Mass} \)
  - Surface Area of the Globe = \( 4\pi R^2 \)
  - \( M_{\text{atmos}} = 101325 \, \text{Pa} \times 4\pi (6378 \times 10^3 \, \text{m})^2 / 9.8 \, \text{m}^2 \, \text{s}^{-1} = 5.3 \times 10^{21} \, \text{g air} \)

- Compute C in Atmosphere @ 380 ppm

\[
M_{\text{atmos}} = \frac{P \cdot 4\pi R^2}{g}
\]

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

\[
M_c / (\frac{p_c}{P}) = 2.19 \quad \text{Pg/ppm}
\]
CO₂ in 50 years with 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 than 157 GtC into the atmosphere PERIOD
  – Natural Growth in Population and Economies has Anthropogenic emissions slated to grow to 16 GtC/y by 2050.
C Fluxes Across the World
Schulze, 2006 Biogeosciences

- NBP
- NEP
- GPP
- NPP
- $R_h$
- $R_a$
FLUXNET: From Sea to Shining Sea
500+ Sites, circa 2009
Probability Distribution of Published NEE Measurements, Integrated Annually

FLUXNET Database

mean = -225 +/- 227 gC m^{-2} y^{-1}

n=254
Harvard Forest, 1992-2002

Season Course in Daily GPP and Reco for a temperate deciduous forest

Data of Wofsy et al; Urbanski et al. JGR 2008
Conceptual Paradigm:
Net Ecosystem Productivity ($P_N$) is a function of age, in responses to changes in Biomass (B), gross primary productivity ($P_G$) and respiration (R).

Odum, 1969, Science
C fluxes of a Middle-Age Temperate Deciduous Forest Continue to change with Stand Age

Re-growth after 1938 Hurricane

Urbanski et al. 2007, JGR
Ecosystem Respiration ($F_R$) Scales with Ecosystem Photosynthesis ($F_A$), But with an Offset by Disturbance

Baldocchi, Austral J Botany, 2008
Interannual Variations in Photosynthesis and Respiration are Coupled

Baldocchi, Austral J Botany, 2008
C Cycling, Below Ground

Law and Ryan, 2005, Biogeochemistry
Soil Respiration and Temperature, Adequate Soil Moisture

Soil Respiration and Declining Soil Moisture

860 ANA REY et al.

(a) CONTROL
SR = 0.84 * e^{0.065T}
R^2 = 0.82

(b) CONTROL
SR = 0.84 + 0.22 ρ
R^2 = 0.70
Regional Carbon Budget Approach
Washington, Oregon, California

Objectives:
• Reduce uncertainty in estimates
• Multiple modeling approaches
• Multiple observation datasets
• Effects of disturbance and climate on carbon balance (past 35 years)
ORCA Top-Down Modeling Concept

**Sources**
- Biosphere CO2 flux model
- Fossil fuel CO2 inventories for conterminous US
- Background CO2 (CarbonTracker)
- Atmospheric CO2 observations:
  - AmeriFlux data
  - 5 Monitoring sites in Oregon

**Sinks**
- Atmospheric transport modeling

**System Components**
- WRF: Weather Research and Forecasting
- STILT: Stochastic Time Inverted Lagrangian Transport Model
- MODIS fPAR
- Spatial met data

**Initial and boundary met**
- Surface maps
Diagnostic Carbon Flux Model (BioFlux)

Surface information
- Stand Age
- Disturbance History
- Ecoregion
- Land cover type
- MODIS fPAR

Reference Flux Data
- A-priori parameter optimization
- \[ GPP = a_1 \cdot f(T, VPD, APAR, cloud, age, SWC) \]
- \[ R_A = a_2 \cdot f(T, GPP, fPAR) \]
- \[ R_H = a_3 \cdot f(age, T_{soil}, SWC, fPAR) \]

Meteorological data (SOGS)
- Temperature
- VPD
- Radiation
- Pressure
- Precipitation

Solve for optimized flux baserates

25m - 1km resolution
MODIS in 8d bins

1km resolution
Timestep refined to sub-daily (1hr)
Oregon & California Carbon Budget (1996-2000 means)

OR: C sequestered as NBP + accum. in forest products = 50% ff

CA: 10% of equivalent fossil fuel emissions
(NBP = NEP – harvest – fire; OR 17 - 10.7 – 0.4 = 5.9 TgC)
Carbon Emission and Ecosystem Services

- US accounts for about 25% of Global C emissions
  - $0.25 \times 7.0 \times 10^{15} \text{ gC} = 1.75 \times 10^{15} \text{ gC}$
- Per Capita Emissions, US
  - $1.75 \times 10^{15} \text{ gC}/300 \times 10^6 = 5.833 \times 10^6 \text{ gC/person} = 5.833 \text{ mtC}$
- Ecosystem Service, net C uptake
  - ~100-200 gC m$^{-2}$
- Land Area per Person
  - $3.03 \times 10^4 \text{ m}^2/\text{person} \sim 1.5-3.0 \text{ ha/person}$
- US Land Area
  - $9.1 \times 10^8 \text{ ha}$
  - $8.75 \times 10^8 \text{ to } 1.75 \times 10^9 \text{ ha needed by US population to offset its C emissions Naturally!}$
The Ratio between Respiration and Photosynthesis is Constant: Regardless of Plant Size, Treatment etc

Emerging and Useful Ecological Rules

Gifford, 1994, Australian J Plant Physiol
GPP and Climate Drivers

Climate explains 70% of variation in GPP

Luyssaert et al. 2007, GCB
NEP and Climate Drivers

Climate explains 5% of variation in NEP

Luyssaert et al. 2007, GCB