Terrestrial Carbon Cycle, Part 1

Dennis Baldocchi
Ecosystem Science Division/ESPM
University of California, Berkeley

Schulze, 2006 Biogeosciences

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Terms and Units

- Gross Primary Productivity, GPP, gC m\(^{-2}\) y\(^{-1}\)
- Net Primary Productivity, NPP
- Autotrophic Respiration, \(R_a\)
- Heterotrophic Respiration, \(R_h\)
- Net Ecosystem Productivity, NEP
- Net Ecosystem Carbon Exchange, NEE
- Net Biome Productivity, NBP

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GPP

GPP = gross canopy photosynthesis, via carboxylation \((V_c)\) minus photorespiration, oxygenation \((0.5 V_o)\)

\[
GPP \approx LAI \cdot (V_c(C,Q,T,N) - 0.5 \cdot V_o(C,T))
\]

These assimilation fluxes are functions of CO\(_2\) (C), light (Q), temperature (T), nutrition (N)

We assume, first approximation, that the leaf-level carbon assimilation fluxes scale up to the canopy scale by multiplying average leaf level fluxes by leaf area index (LAI)

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Net Primary Productivity, NPP

NPP is GPP minus autotrophic Respiration, $R_{auto}$

$$NPP = GPP - R_{auto} \text{(mass, growth, } T)$$

Autotrophic respiration is respiration of the self-feeders, the plants (leaves, stems and roots);

$R_{auto}$ is a function of growth rate, temperature, mass of the organism.

Net Ecosystem Production, NEP

NEP is NPP minus Heterotrophic Respiration, $R_{hetero}$

$$NEP = GPP - R_{auto} - R_{hetero} \text{ (} T, \theta, LAI, P_s \text{) } = -NEE$$

Heterotrophic respiration is respiration of fungi, aerobic bacteria, invertebrates and vertebrates in the soil;

It is a function of temperature, soil moisture, carbon content, its lability, and priming from recent photosynthesis
Net Biome Production, NBP

NBP is NEP minus Carbon Loss via Disturbance

\[ NBP = NEP - F_c(\text{fire, herbivory, disturbance}...) \]

Current State of the Terrestrial C Cycle
Global Carbon Cycle: Gross Fluxes and Pools

- Atmosphere: \[843 \text{ PgC} @ 385 \text{ ppm}\]
- Vegetation: \[\sim 650 \text{ PgC}\]
- Soil: \[\sim 3194 \text{ PgC}\]
- Ocean: \[\sim 38,000 \text{ PgC}\]
- Fossil Fuel Combustion
- Deforestation

Atmospheric CO₂ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

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Units and Perspective

• How big is 1 Pg (10^{15} g) or 1 GtC?
  – Billion (10^9) metric tons of C (mt = 1000 kg; or 10^6 g)
• Spread across the Land’s Surface
  – 1 \times 10^{15} gC/100 \times 10^{12} m^2\sim 10 g m^{-2}=10 \text{ cm}^3 m^{-2}
  – Equivalent to a 10 micron layer of water per meter-squared across the terrestrial globe
  – 1 g = 1 cm^3
  – 1 m^3 = 10^6 g = 1 Mt
  – 1 km^3 = 1 Gt

How much is C in the Air?:
Resolving Differences between ppm and Pg?

• Mass of Atmosphere
  – \text{F}=\text{M a} = \text{Mass x gravity = Pressure x Area}
  – Surface Area of the Globe = 4\pi R^2
  – M_{\text{atmos}} = 101,325 \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 @ 393 ppm (393 \times 10^{-6})

\[ M_c = M_{\text{atmos}} \frac{p_c m_c}{P m_a} = 860 \times 10^{15} \text{ gC} \]

P: atmospheric pressure
p_c: partial pressure CO2
m_c: molecular wt of C, 12 g/mole
m_a: molecular wt of air, 28.96 g/mole

\[ M_c / (\frac{p_c}{P}) = 2.19 \text{ Pg/ppm} \]
Fossil Fuel Emissions and Cement Production

CO₂ emissions (PgC y⁻¹)

Growth rate: 3.4% per year

2008:
Emissions: 8.7 PgC
Growth rate: 2.0%
1990 levels: +41%
2000-2008 Growth rate: 3.4%


How Serious are Contemporary C Emissions?:
We Are Exceeding the More Extreme Scenarios,
So it is Less Likely Warming will be < +2 C

Peters et al 2012, Nature Geoscience
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13C Isotope record:
Evidence of Fossil Fuel Combustion

Antarctic Ice Core
(Francey et al. 1999)

\[ \delta^{13}C = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000 \]

- Plant based Carbon has a $^{13}$C signature ~ -25 per mil
- Combustion of Fossil Fuels Dilutes the Atmospheric Background

Extension of the 13C Record

Atmospheric $^{13}$C

- Cape Grim, Australia 1981 to 1994
- Mauna Loa, Hawaii 1994-2010

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Stable Isotopes

\[ \delta^{13} = 1000 \left( \frac{R_{\text{sample}}}{R_{\text{std}}} - 1 \right) \]

\[ \frac{^{13}C}{^{12}C} = R_{\text{sample}} = R_{\text{std}} \left( \frac{\delta^{13}}{1000} + 1 \right) \]

\[ R_{\text{std}} = \text{Peedee Belemnite} = 0.0112372 \]
CO₂ Emissions from Land Use Change


CO₂ emissions (PgC yr⁻¹)

Fossil fuel

Land use change


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Ecosystem Service:
Only ~45% of CO₂ emitted into the atmosphere remains there

Schulze 2006, Biogeosciences

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Airborne Fraction
Fraction of total CO$_2$ emissions that remains in the atmosphere

Trend: $0.27 \pm 0.2 \% \ \text{y}^{-1}$
($p=0.9$)

40%
45%

Le Quéré et al. 2009, Nature-geoscience; Canadell et al. 2007, PNAS; Raupach et al. 2008, Biogeoosciences

CO$_2$ in the past

Figure 8: Plots of RCO$_2$ (the ratio of the mass of carbon dioxide in the atmosphere in the past to that for the pre-industrial present) and $\%$O$_2$ during the Phanerozoic eon. Values of RCO$_2$ from the GEOCARB III model$^{10}$; values of $\%$O$_2$ from ref. 11 using the $^14$C data of refs. 12 and 13. Estimated errors are $\pm 0.5\%$ for RCO$_2$ and $\pm 1\%$ for $\%$O$_2$.

The amount of fuel we burn in 1 year took 175,000 years to sequester

Most Coal Deposited during Carboniferous, 300 Ma

Reservoirs containing the highest concentrations of N per mass are:

- petroleum (100-20,000 mg kg⁻¹),
- coals (2000-30,000 mg kg⁻¹),
- modern marine sediment (1772 mg kg⁻¹),
- shales (600 mg kg⁻¹),
- limestone (73 mg kg⁻¹)

[Wlotzka, 1972].
CO2 over the Timespan of Humans on Earth

Paleo-Carbon Cycle
Change in Atmospheric CO$_2$ Burden over Middle to Late Pleistocene

Inter-glacial to Glacial
CO$_2$ from 280 to 180 ppm over 100,000 years

Flux = 2.19 Pg/ppm * -100 ppm/100,000 = - 2.19 TgC/y

Glacial to Inter-Glacial
CO$_2$ from 180 to 280 ppm over 10,000 years

Flux = 2.19 Pg/ppm * +100 ppm/10,000 = + 21.9 TgC/y

TgC = 10$^{12}$ gC

Lesson: Today’ Pg C Fluxes are Way out of Equilibrium with Historic Conditions

What is the Upper Bound of GPP?

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

Top-Down:
Energy Transfer
Recent ‘Best Estimate’ on GPP with Multiple Constraints

Global GPP = 123 +/- 8 PgC

Upper-Bound on Global Gross Primary Productivity

- Global GPP is ~ 120 * 10^{15} \, gC \, y^{-1}
- Solar Constant, S^* (1366 W m^{-2})
- Average 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 (0.02)
- Arable Land area (~110 * 10^{12} m^2)
- Length of daylight (12 hours * 60 minutes * 60 seconds = 43200 s/day)
- Length of growing season (180 days)
- Gram of carbon per mole (12)

GPP = 1366*0.83*0.5*4.6*0.9*0.02*110 \times 10^{12}^*43200^*180^*12/(4 \times 10^6) = 120 \times 10^{15} \, gC \, y^{-1}
### GPP by Biome

<table>
<thead>
<tr>
<th>Biome</th>
<th>GPP (PgC y⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Forest</td>
<td>40.8</td>
</tr>
<tr>
<td>Temperate Forest</td>
<td>9.9</td>
</tr>
<tr>
<td>Boreal Forest</td>
<td>8.3</td>
</tr>
<tr>
<td>Tropical Savanna/grassland</td>
<td>31.3</td>
</tr>
<tr>
<td>Temperate Grassland/Shrubland</td>
<td>8.5</td>
</tr>
<tr>
<td>Desert</td>
<td>6.4</td>
</tr>
<tr>
<td>Tundra</td>
<td>1.6</td>
</tr>
<tr>
<td>Crops</td>
<td>14.8</td>
</tr>
</tbody>
</table>

Beer et al., 2010 Science

### NPP ~ 0.5 GPP

[Map Image]

http://secure.ntsg.umt.edu/projects/files/images/mod17/Figure6.jpg

ESPME 11 Ecosystem Ecology
NPP = 56.4 PgC/y +/- 14

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Concepts, Fluxes, Pools and Time Constants

\[ \frac{dC}{dt} = \frac{(F_{in} - F_{out})}{V} \]

Flux, \( F \): moles/y  
Volume, \( V \): m³ 
Mole Density, \( C \): mole/m³

\[ \frac{F}{V} = \frac{C}{\tau} \]

Flux per Volume \( \sim \) Mole Density/turnover time

\[ NEP = GPP - \frac{C_{veg}}{\tau_{veg}} - \frac{C_{soil}}{\tau_{soil}} \]

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C Turnover Time: Mass/Flux

- Atmosphere
  - M/NBP
  - 843 Pg C/4 Pg C/y = 210 yr

- Vegetation
  - M/NPP
  - 600 Pg C/60 Pg C/y = 10 yr

- Soil
  - M/Rh
  - 1500 Pg C/60 Pg C/y = 25 yr

Carbon Content and Turnover Time are f(T)

Sanderman et al, 2003 Glob Biogeochem Cycles
### Vegetation and Soil C by Biome

<table>
<thead>
<tr>
<th>Biome</th>
<th>Area $10^6$ km²</th>
<th>Soil C (Pg)</th>
<th>Plant C (Pg)</th>
<th>NPP (Pg y⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Forest</td>
<td>17.5</td>
<td>692</td>
<td>340</td>
<td>21.9</td>
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<tr>
<td>Temperate forest</td>
<td>10.4</td>
<td>262</td>
<td>139</td>
<td>8.1</td>
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<tr>
<td>Boreal forest</td>
<td>13.7</td>
<td>150</td>
<td>57</td>
<td>2.6</td>
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<tr>
<td>Arctic Tundra</td>
<td>5.6</td>
<td>144</td>
<td>2</td>
<td>.5</td>
</tr>
<tr>
<td>Mediterranean Shrubland</td>
<td>2.8</td>
<td>124</td>
<td>17</td>
<td>1.4</td>
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<tr>
<td>Crops</td>
<td>13.5</td>
<td>248</td>
<td>4</td>
<td>4.1</td>
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<tr>
<td>Tropical Savanna and Grassland</td>
<td>27.6</td>
<td>345</td>
<td>79</td>
<td>14.9</td>
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<tr>
<td>Temperature Grassland</td>
<td>15</td>
<td>172</td>
<td>6</td>
<td>5.6</td>
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<tr>
<td>Desert</td>
<td>27.7</td>
<td>208</td>
<td>10</td>
<td>3.5</td>
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<tr>
<td>Total</td>
<td>149.3</td>
<td>2344</td>
<td>652</td>
<td>62.6</td>
</tr>
</tbody>
</table>

+++ Frozen soil ~400 Pg; Wetland ~450 Pg

Saugier et al/Sabine et al

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### Global Vegetation Carbon Content


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**Gross Carbon Fluxes**

- Gross Terrestrial Photosynthesis
  - $120 \times 10^{15}$ gC/y
- Net Terrestrial Photosynthesis
  - $60 \times 10^{15}$ gC/y
- Autotrophic Respiration
  - $60 \times 10^{15}$ gC/y
- Heterotrophic Respiration
  - $60 \times 10^{15}$ gC/y
- Oceanic Photosynthesis
  - $90 \times 10^{15}$ gC/y
- Oceanic Respiration
  - $88 \times 10^{15}$ gC/y
- Ocean Net Primary Production
  - $48 \times 10^{15}$ gC/y
US Directly accounts for about ¼ of Global C emissions, More if we consider C emissions for Imports from China