Global Carbon Cycle

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ESPM 2, The Broucher, 2017
Big Questions

• How much Carbon is stored in the different reservoirs of the biosphere?
• What are the fluxes to and from these reservoirs and their residence time?
• How are these pools and fluxes changing with time due to human induced changes and feedbacks between the atmosphere and ecosystems?
It is important to try and think about these huge numbers in human context, both globally and locally.

These numbers are important because they help us understand how we may have released about 500 Million tons of carbon since the industrial age. The new IPCC is urging us to target a total global emission of 1 trillion tons of carbon
Global Carbon Cycle

Atmosphere

Photosynthesis

Autotrophic Respiration

Diffusion + Carbonate Chemistry

Plants

Autotrophic Respiration

Litterfall + Decomposition

Soil

Runoff

Upper Ocean

Phytoplankton

Phytoplankton Respiration

Photosynthesis

Mixing UpWelling

Decomposition

Biological Pump

Deep Ocean

Sedimentation

Ocean Sediments

ESPM 2, The Biosphere, 2017
Carbon pools and fluxes, circa 2017 from state of art reviews.

Key points. There is more carbon in the atmosphere than in vegetation (871 vs 650 Pg-C). There is 10x more carbon in the ocean than in the soils (3000 vs 38,000 PgC).

New data show the C pool of soil microbes is about 15 PgC.

In general half of GPP is lost as autotrophic respiration and the other half is lost by heterotrophic respiration. A small residual can account for a growing carbon sink due to many effects like N deposition, elevated CO2, land use change and ecological succession.

Oceans are a small (2 PgC/y) net sink, which is leading to acidification of the oceans.

We must consider volcano emissions on Geological time scales.

Sources of carbon to the atmosphere from human activities include fossil fuel combustion, production of cement and deforestation.
<table>
<thead>
<tr>
<th>Biome</th>
<th>Area $10^6$ km$^2$</th>
<th>Soil C (Pg)</th>
<th>Plant C (Pg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Forest</td>
<td>17.5</td>
<td>692</td>
<td>340</td>
</tr>
<tr>
<td>Temperate forest</td>
<td>10.4</td>
<td>262</td>
<td>139</td>
</tr>
<tr>
<td>Boreal forest</td>
<td>13.7</td>
<td>150</td>
<td>57</td>
</tr>
<tr>
<td>Arctic Tundra</td>
<td>5.6</td>
<td>144</td>
<td>2</td>
</tr>
<tr>
<td>Mediterranean Shrubland</td>
<td>2.8</td>
<td>124</td>
<td>17</td>
</tr>
<tr>
<td>Crops</td>
<td>13.5</td>
<td>248</td>
<td>4</td>
</tr>
<tr>
<td>Tropical Savanna and Grassland</td>
<td>27.6</td>
<td>345</td>
<td>79</td>
</tr>
<tr>
<td>Temperature Grassland</td>
<td>15</td>
<td>172</td>
<td>6</td>
</tr>
<tr>
<td>Desert</td>
<td>27.7</td>
<td>208</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>149.3</strong></td>
<td><strong>2344</strong></td>
<td><strong>652</strong></td>
</tr>
</tbody>
</table>

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

Saugier et al/Sabine et al

ESPM 2, The Biosphere, 2017
NPP is the difference between GPP and carbon lost as autotrophic respiration.

As you can see there has been an evolution in the values of global NPP over the decades and Century. Today the grand mean is narrowing to about 56 PgC. Since NPP is about $\frac{1}{2}$ of GPP, this would be consistent with a GPP value of about 112 PgC/y, or more to the point values less than 120 Pg-C/y

While there seems to be a convergence on 1500 PgC for the soil C pool, those working in the Arctic and examining C in the permafrost and at depths below 1 m argue that there may be another 1500 PgC.

Circa 2014, CDIAC and Global Carbon Project. It is a bit depressing that we are NOT Flattening, or reducing our carbon consumption. When I first started teaching this class, around 2008, we were emitting about 8-9 PgC y⁻¹. Now we are exceeding 10 Pg-C. This has to be a wake up call. This rate of carbon emissions are NOT Sustainable.
Why is there CO₂ lost from cement production?

CO₂ is produced as limestone, CaCO₃, is converted to lime, CaO, and by direct fossil fuel combustion in the process as CaCO₃ is heated.

Calera is trying to produce low carbon cement


Why is CO₂ produced by cement production
All values in billion tonnes of carbon per year (GtC/yr), for the globe. For values in billion tonnes of carbon dioxide (GtCO₂) per year, multiply the numbers below by 3.664. Note: 1 billion tonnes C = 1 petagram of carbon (10^15 gC) = 1 gigatonne C = 3.664 billion tonnes of CO2 All uncertainties represent ± 1 sigma error (68 % chances of being in the range provided) Emissions from fossil fuel combustion and cement production (uncertainty of ±5% for a ± 1 sigma confidence level): Emissions from land-use change (uncertainty of ±0.5 GtC/yr):

The atmospheric CO₂ growth rate (variable uncertainty averaging 0.18 GtC/yr during 1980-2011) is estimated directly from atmospheric CO₂ concentration measurements, and provided by the US National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL). http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html The ocean sink (uncertainty of ±0.5 GtC/yr) was estimated a combination of global ocean biogeochemistry models. How to cite: Le Quéré et al. 2013 (see Summary) The land sink (uncertainty of ±0.8 GtC/yr on average) was estimated from the residual of the other budget terms: land_sink = fossil_fuel + land_use_change - atm_growth - ocean_sink. How to cite: Le Quéré et al. 2013 (see Summary)
Fortunately only part of the CO2 emitted into the atmosphere remains there. Looking at data from 2008, for example, we see that the world emitted up to 9 PgC y⁻¹. But between 3 and 4 PgC y⁻¹ remained in the atmosphere. How many ppm per year will [CO2] change by?

Note society has emitted about 500 Million tons of carbon since the industrial revolution ~ 2.2 (400ppm-280ppm) x 2..the factor of 2 accounts for the airborne fraction of emitted CO2 that remains in the atmosphere vs what is emitted.

If we continue to emit carbon at a rate of about 10 PgC/y we will emit the next 500 Million tons (Pg-C) in the next 50 years, your lifetime.
CDIAC and Global Carbon Project, circa 2014
Both the land and ocean are effective sinks for carbon. Lately the land has been taking up 2 to 4 PgC y⁻¹ and the ocean is taking up about 2 Pg·C y⁻¹.
510 e12 m2 surface area of the globe....about 100k years to decrease, about 10k to increase!!
2015 Figures from CDIAC
If We Continue to add 5 PgC per year to the Atmosphere, what will the CO2 concentration be in 10 years?
How can we ‘weigh’ the atmosphere? We can use the laws of physics to compute the mass of the atmosphere by knowing the surface area of the planet, pressure at the surface and the acceleration of gravity. Remember Pressure is Force per area and Force is Mass times acceleration. So Pressure is Mass of the Atmosphere times the acceleration of gravity (9.8 m s$^{-2}$) divided by the Surface area of the planet. So we can solve for Mass
What is the Mass of the Atmosphere?

**Pressure** \((P)\) equals **Mass** \((M_A)\) of overhead atmosphere times **acceleration** due to gravity \((g)\), per unit area

\[
P = \frac{\text{Force}}{\text{Area}} = \frac{M_A g}{\text{Area}} \quad \left[\frac{\text{kg m s}^{-2}}{\text{m}^2}\right] = \left[\text{kg m}^{-1} \text{s}^{-2}\right]
\]

\[
M_A = \frac{P}{g} \cdot \text{Area} = 5.28 \cdot 10^{18} \text{ kg}
\]

\(P = 101.3 \text{ kPa}; \ g = 9.8 \text{ m s}^{-2}; \ A = 4 \pi R^2; \ R = 6378 \text{ km}\)

Here is the math..

\[
101.3 \text{ kPa} / 9.80 \times 4 \times \pi \times (6378 \times 10^3)^2 = 5.28 \times 10^{18} \text{ kg}
\]
So if we know the mixing ratio of a gas, like CO2, we can also compute its mass in the atmosphere.

Why do these simple computations? In this lecture and those to follow I want you to be able to interconvert information on the atmospheric burden of gases like CO2 in terms of mass vs their mixing ratio. This will help you better understand if we release $x\, \text{Pg-C}$ in the next year or decade what that will do to the mixing ratio.

With this equation, if we know the net flux of CO2 into the atmosphere we can compute future concentrations
2.18 PgC/ppm

873 Pg C (@400 ppm) + 5 PgC/y * 10 years = 923 PgC/y

923 PgC/y / 2.18 PgC/ppm = 423 ppm

ESNM 3, The Biosphere, 2017
Carbon Math,
Keeping under 450 ppm and a 2°C Warming

• Current [CO2] = 400 ppm
• Burden: 873 PgC
• Gross Emissions: 10 PgC/y
• Airborne Fraction: 0.5
• Net Emission: 5 PgC/y
• Burden at 450 ppm: 981 PgC
• Net Emissions Possible: 981-873=108 PgC
• Time: 21 years at Current Emission Rates
The map was based on an integration of the global flux networks, satellite remote sensing and empirical models to fill gaps in time and space and paint numbers for regional GPP at high spatial resolution. In my opinion this is one of the better products since it is data based.
Despite all the science that has been conducted over the past 30 years, our ability to know global primary productivity remains highly uncertain and poorly constrained. We need to do better to close the carbon budget and understand the net effects of deforestation, stimulation and inhibition of plant growth to a changing world and to set policy on C emissions from human activities.

Point to be made, if the high GPP numbers were true we would not be having a CO2 problem. C emissions from combustion would not remain in the atmosphere.
What is the Order of Magnitude Bound on GPP?

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

Top-Down:
Energy Transfer, Scales

GPP ~ Available Solar Energy * Light Use Efficiency

ESP 7, The Biosphere, 2017
Order of Magnitude Bound on Global Gross Primary Productivity

- ??? Global GPP is ~ $120 \times 10^9$ gC yr$^{-1}$

- Solar Constant, $S$ (1366 W m$^{-2}$)
  - Ave across disk of Earth $S/4$

- Transmission of sunlight through the atmosphere (1-0.17=0.83, Aeronet)

- Conversion of shortwave to visible sunlight (0.5)

- Conversion of visible light from energy to photon flux density in moles of quanta ($4.6 \times 10^9$)
  - Mean photosynthetic photon flux density, $Q_d$

- Fraction of absorbed $Q_d$ (1-0.1=0.9)

- Photosynthetic efficiency, $\alpha$ (0.02, FLUXNET)

- Arable land area (~ 110 * $10^2$ m$^2$; p.comm. Steve Running)

- Length of daylight (12 hours * 60 minutes * 60 seconds = 43200 s/day)

- Length of growing season (180 days; p.comm, Mark Freidl, FLUXNET database)

- Gram of carbon per mole (12)

GPP = $1366 \times 0.83 \times 0.5 \times 4.6 \times 0.9 \times 0.02 \times 110 \times 10^{12} \times 43200 \times 180 \times 12 / (4 \times 10^9) = 120.4 \times 10^{11}$ gC yr$^{-1}$

Add Reichstein figures tooo
Tropical forests and savannas are the largest C sinks. They possess long growing seasons, large area, high leaf area
Global Scale

Terrestrial and Ocean NPP, gC m\(^{-2}\) y\(^{-1}\)

Field et al. 1998, Science
Turnover Time: Mass/Flux

- Atmosphere
  - M/NBP
  - 882 Pg/3 Pg/y = 294 yr

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

- Soil
  - M/rh
  - 3000 Pg/60 Pg/y = 50 yr
Most carbon in vegetation is in the tropical and boreal forests of the world
Global microbial C pool is 14.6 Pg-C
Hotspots of soil carbon are the great grasslands and the peat soils of the northern wetlands and tundra.

Here is why I want you to be able to work back and forth between units of ppm CO2 in the Atmosphere and stores of carbon in terms of PgC. Changes in these pools tell us how CO2 concentrations will change.
Take Home Points

- Biosphere is serving the planet by taking up < 50% of C emitted into the Atmosphere by Fossil Fuel Combustion
- We will cross 2 C Threshold (450 ppm) in 26 years at Current Emission Rates
- Ranking of C pools
  - Ocean > Soils > Atmosphere > Plants