Global Carbon Cycle

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ESPM 2

Fall 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?

Perspective

- How big is 1 Peta (10^{15}) gram?
  - 1 Giga-ton (Gt)
  - Billion-Million grams
  - Billion cars (@ 1 ton each)
  - $1\ 10^{15}$ gC/100 10^{12} m^{-2}~10g m^{-2}=10 cm^3 m^{-2}
  - Equivalent to a 10 micron layer of water over a meter-squared surface across the land
  - 1g = 1 cm^3
  - 1 m^3 = 10^6g = 1 Mt
  - Water Reservoir, 1 km^3 = 1Gt

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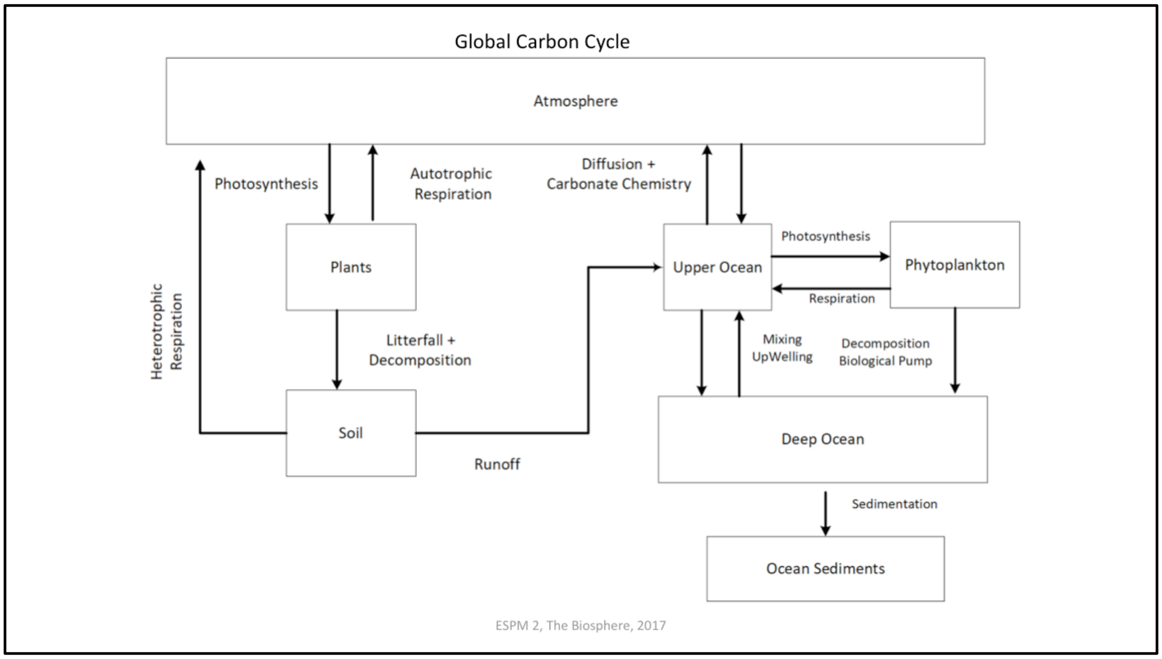
It is important to try and think about these huge numbers in human context, both globally and locally.

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
Heterotrophic Respiration
Litterfall + Decomposition
Soil
Runoff
Upper Ocean
Photosynthesis
Phytoplankton
Respiration
Mixing UpWelling
Decomposition Biological Pump
Deep Ocean
Sedimentation
Ocean Sediments
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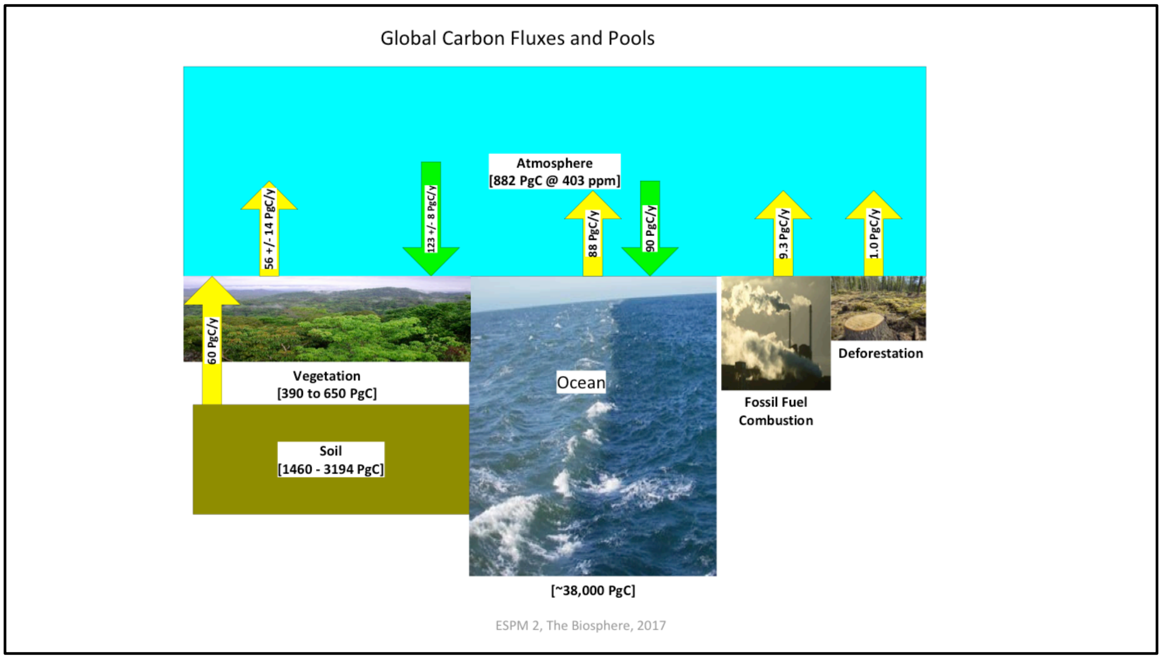


Carbon pools and fluxes, circa 2017 from state of art reviews .

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.

Vegetation and Soil C by Biome

Biome	Area 10^6 km^2	Soil C (Pg)	Plant C (Pg)
Tropical Forest	17.5	692	340
Temperate forest	10.4	262	139
Boreal forest	13.7	150	57
Arctic Tundra	5.6	144	2
Mediterranean Shrubland	2.8	124	17
Crops	13.5	248	4
Tropical Savanna and Grassland	27.6	345	79
Temperature Grassland	15	172	6
Desert	27.7	208	10
Total	149.3	2344	652

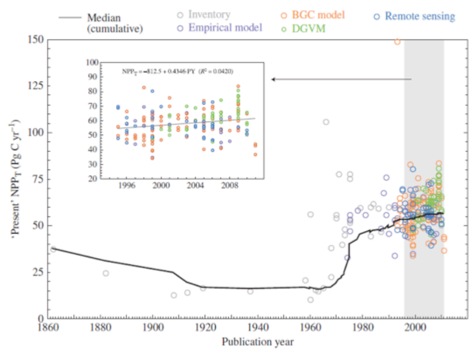
+++ Frozen soil ~400 Pg; Wetland ~450 Pg

Saugier et al/Sabine et al

Evolution and Convergence of Global Budget Numbers

NPP = 56.4 PgC/y +/- 14

6 A. ITO



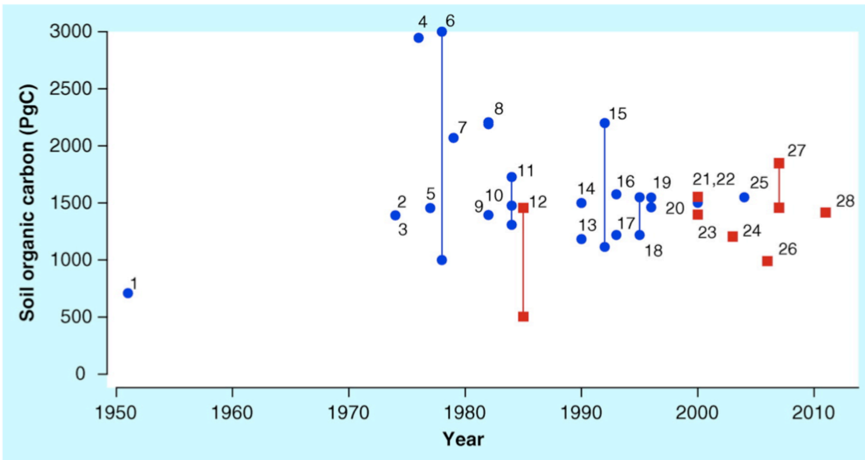
Ito 2011, GCB

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 ½ 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

Estimates of Global Soil Carbon Pool

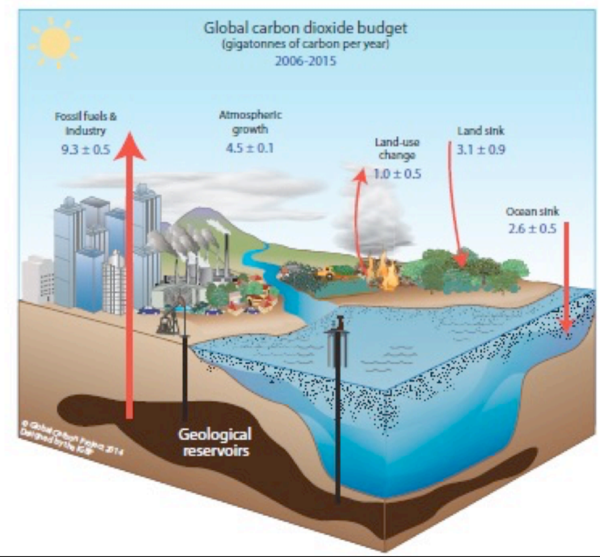


ESPM 2, The Biosphere, 2017

Scharlemann, J. P. W., E. V. J. Tanner, R. Hiederer, and V. Kapos. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management **5**:81-91.

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.

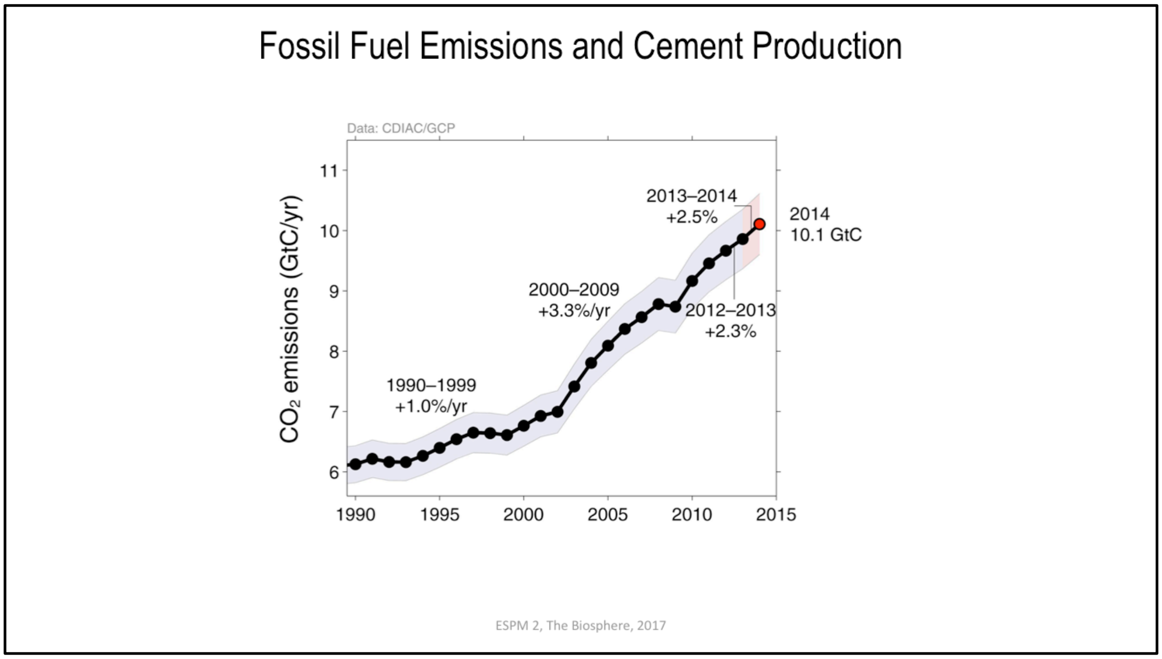
How CO2 is Changing



Le Quere et al 2016

Circa 2016, Global Carbon Project, http://www.globalcarbonproject.org/

Le Quéré, C., R. M. Andrew, J. G. Canadell, S. Sitch, J. I. Korsbakken, G. P. Peters, A. C. Manning, T. A. Boden, P. P. Tans, R. A. Houghton, R. F. Keeling, S. Alin, O. D. Andrews, P. Anthoni, L. Barbero, L. Bopp, F. Chevallier, L. P. Chini, P. Ciais, K. Currie, C. Delire, S. C. Doney, P. Friedlingstein, T. Gkritzalis, I. Harris, J. Hauck, V. Haverd, M. Hoppema, K. Klein Goldewijk, A. K. Jain, E. Kato, A. Körtzinger, P. Landschützer, N. Lefèvre, A. Lenton, S. Lienert, D. Lombardozzi, J. R. Melton, N. Metzl, F. Millero, P. M. S. Monteiro, D. R. Munro, J. E. M. S. Nabel, S. I. Nakaoka, K. O'Brien, A. Olsen, A. M. Omar, T. Ono, D. Pierrot, B. Poulter, C. Rödenbeck, J. Salisbury, U. Schuster, J. Schwinger, R. Séférian, I. Skjelvan, B. D. Stocker, A. J. Sutton, T. Takahashi, H. Tian, B. Tilbrook, I. T. van der Laan-Luijkx, G. R. van der Werf, N. Viovy, A. P. Walker, A. J. Wiltshire, and S. Zaehle. 2016. Global Carbon Budget 2016. Earth System Science Data **8**:605-649.



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.

CO$_2$ Emission from Cement Production

- Converting Limestone to Lime
- Cement Production uses about 2% of Global Energy Production and releases about 5% of Global CO$_2$ emissions
- $CaCO_3$ + heat → $CaO + CO_2$

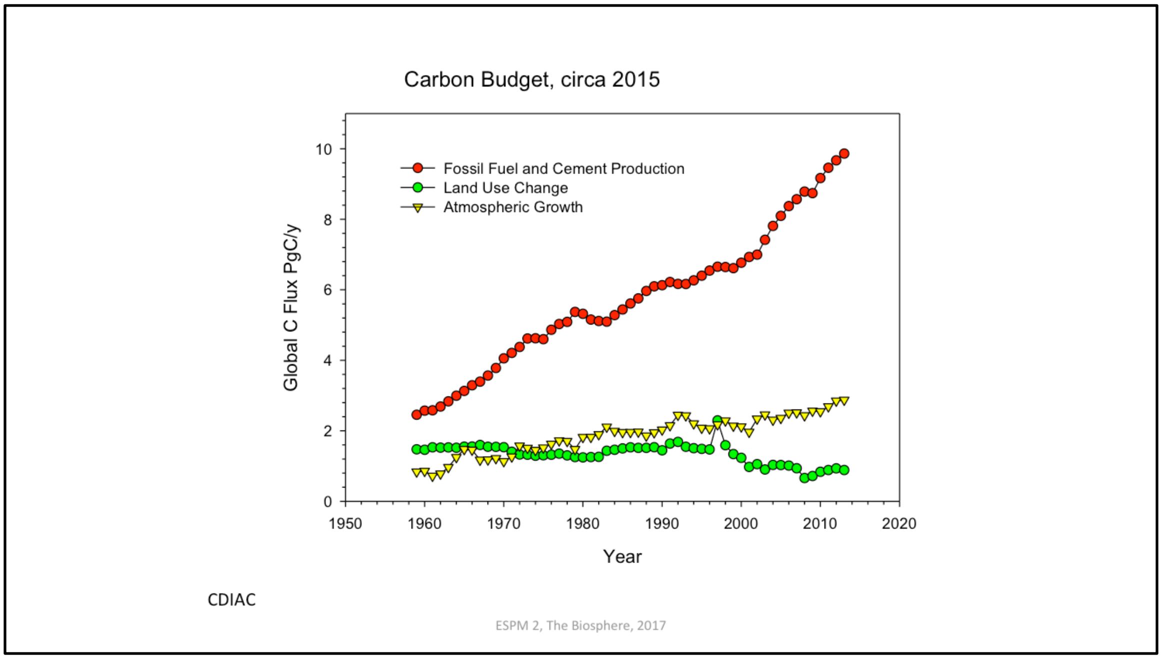
Why is there CO2 lost from cement production?

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

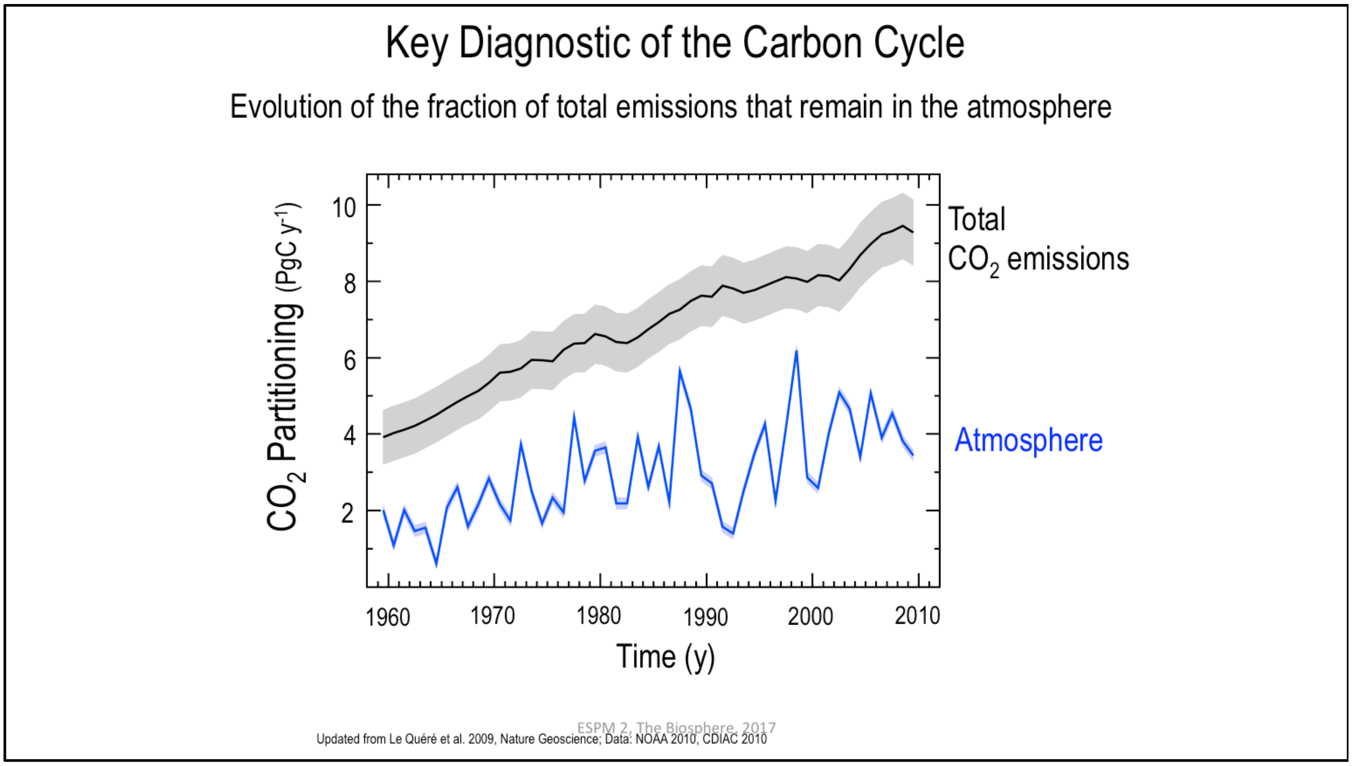
Calera is trying to produce low carbon cement

Worrell, E., Price, L., Martin, N., Hendriks, C. and Meida, L.O., 2001. CARBON DIOXIDE EMISSIONS FROM THE GLOBAL CEMENT INDUSTRY1. Annual Review of Energy and the Environment, 26(1): 303-329.

Why is CO2 produced by cement production



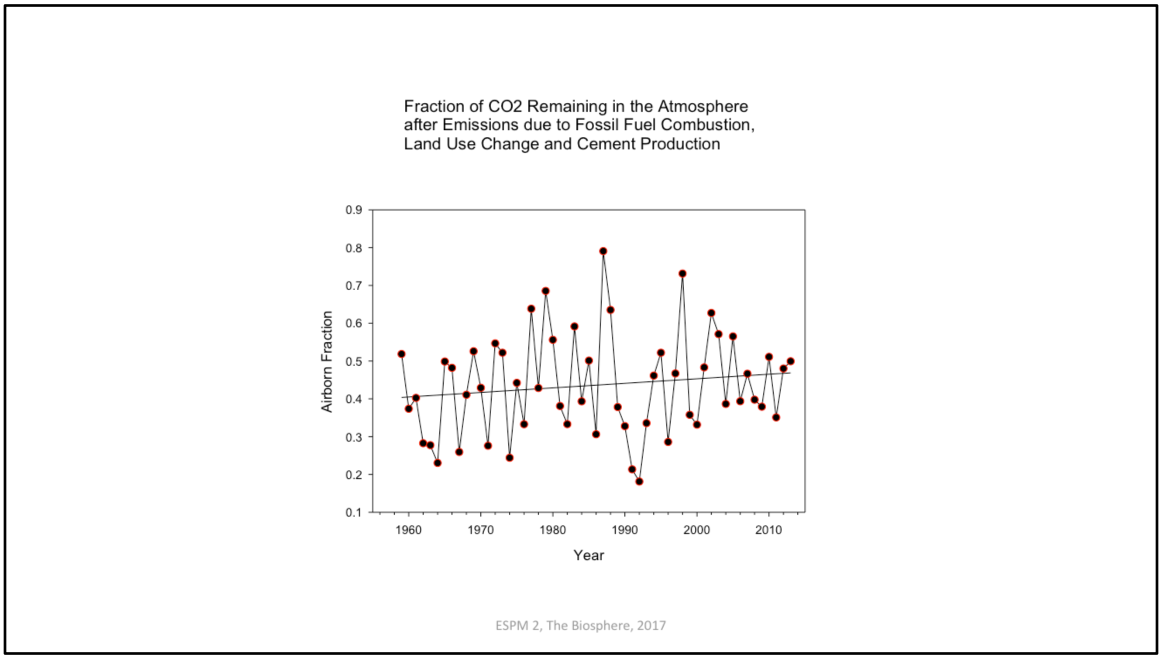
All values in billion tonnes of carbon per year (GtC/yr), for the globe. For values in billion tonnes of carbon dioxide ($GtCO_2$) per year, multiply the numbers below by 3.664. Note: 1 billion tonnes C = 1 petagram of carbon (10^15 gC) = 1 gigatonne C = 3.664 billion tonnes of CO2 All uncertainties 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)



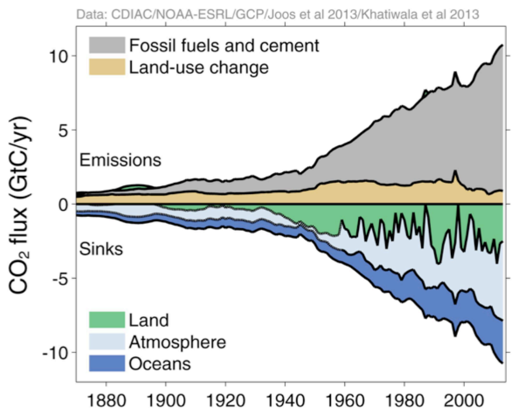
Fortunately only part of the CO2 emitted into the atmosphere remains there. Looking at data from 2008, for example, we see that the world emitted up to 9 PgC y-1. But between 3 and 4 PgC y-1 remained in the atmosphere. How many ppm per year will [CO2] change by?

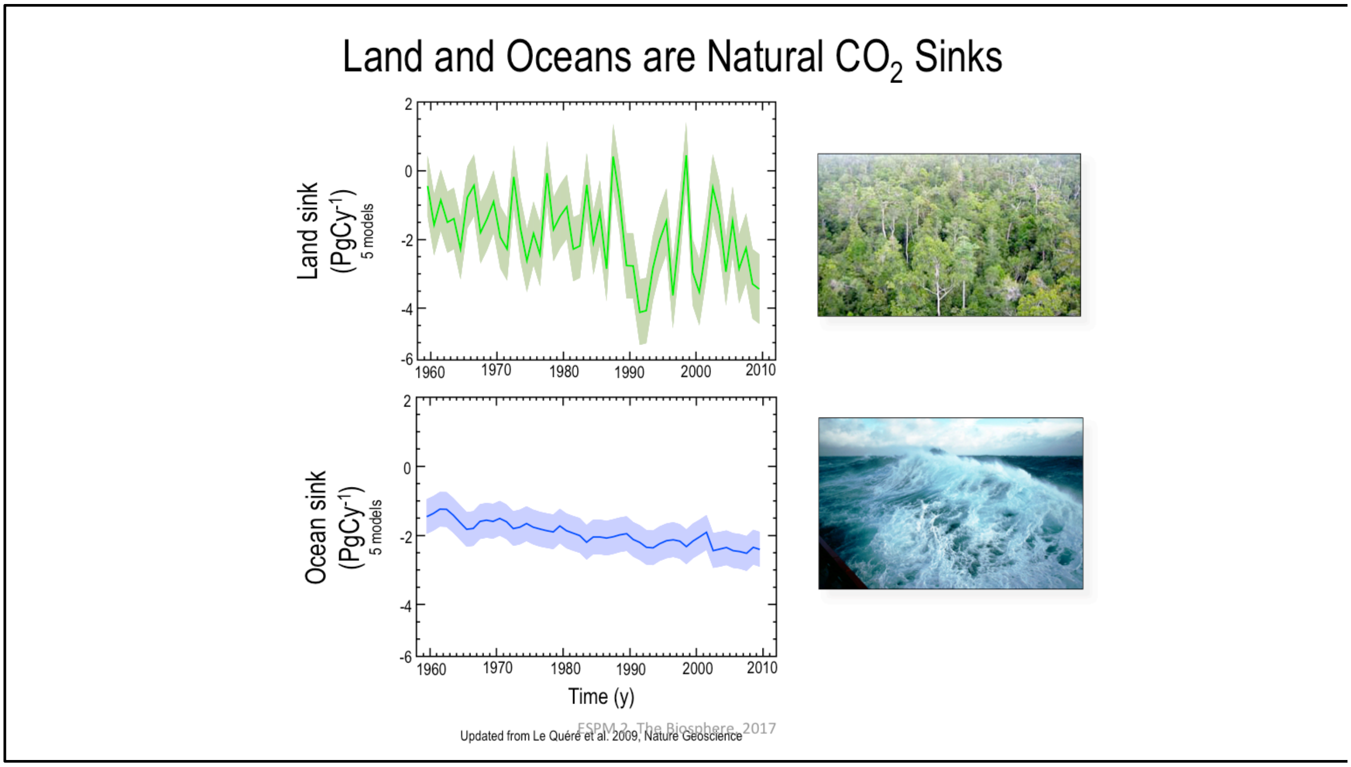
Note society has emitted about 500 Million tons of carbon since the industrial revolution ~ 2.2 (400ppm-280ppm) x 2..the factor of 2 accounts for the airborne fraction of emitted CO2 that remains in the atmosphere vs what is emitted.

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

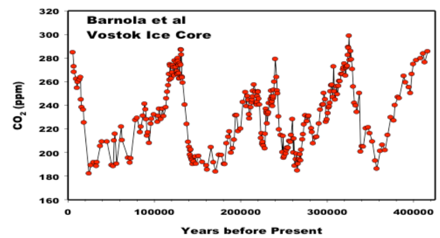

Data: CDIAC/NOAA-ESRL/GCP/Joos et al 2013/Khatiwala et al 2013
Fossil fuels and cement
Land-use change
Emissions
Sinks
Land
Atmosphere
Oceans
CO2 flux (GtC/yr)
10
5
0
-5
-10
1880
1900
1920
1940
1960
1980
2000



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

Rate of Net C Exchange,
or Imbalance between C Gains and Losses,
over Geological Time has been Tiny

- 100 ppm between Glacial and Inter-glacial periods
- ~200 Pg C
- Imbalance in Carbon Cycle
- dC/dt ~ 2 10^{12} gC/y
- 3.9 mgC m^{-2} y^{-1}



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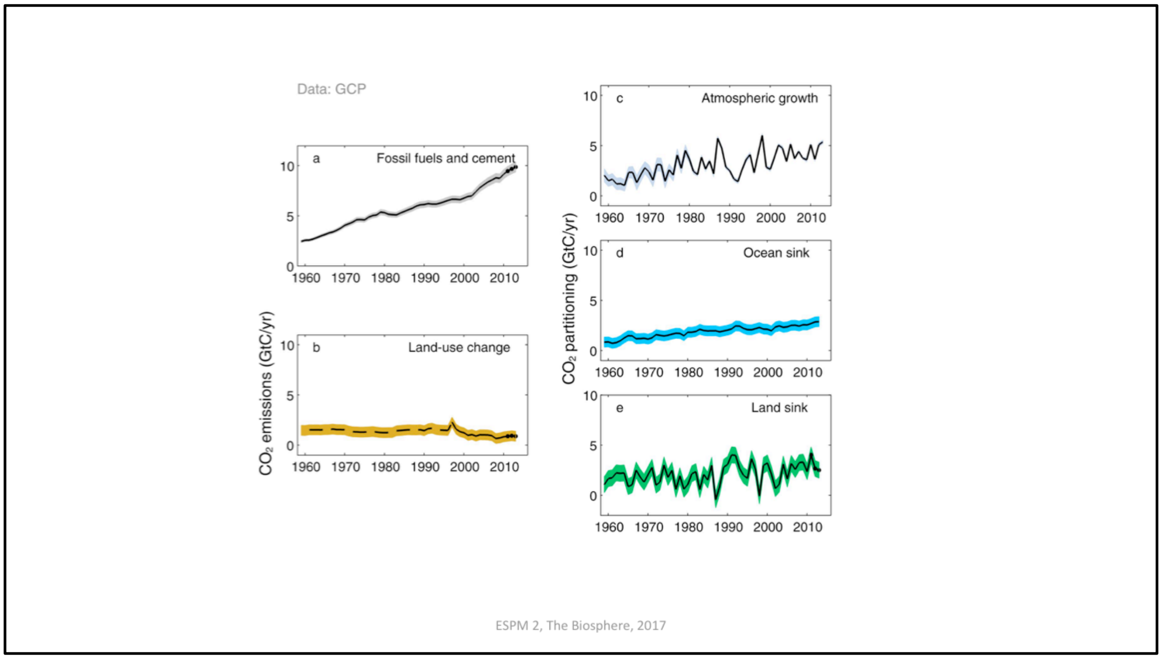
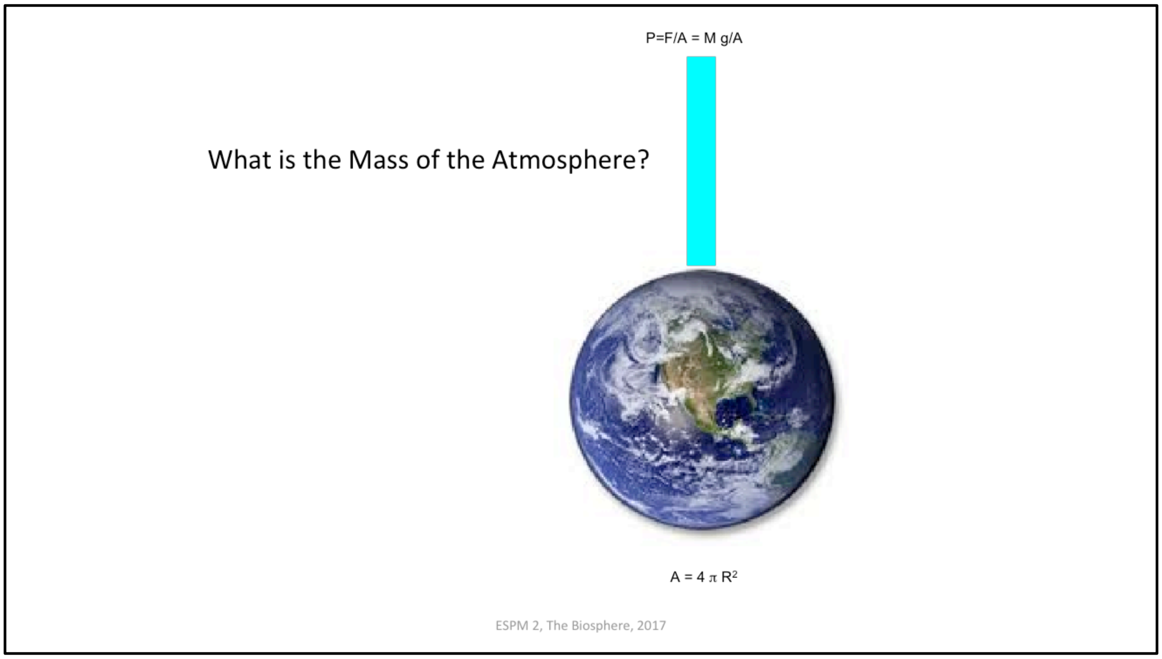
510 e12 m2 surface area of the globe….about 100k years to decrease, about 10k to increase!!



2015 Figures from CDIAC

If We Continue to add 5 PgC per year to the Atmosphere, what will the CO_2 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

$$P = \frac{Force}{Area} = \frac{M_A g}{Area} \qquad [\frac{kg\, m\, s^{-2}}{m^2}] = [kg\, m^{-1}\, s^{-2}]$$

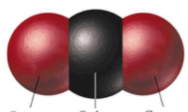
$$M_A = \frac{P}{g} \cdot Area = 5.28 \cdot 10^{18}\, kg$$

P = 101.3 kPa; g=9.8 m s^{-2}; A = 4 π R^2; R = 6378 km

Here is the math..

101.3 kPa/9.80 *4 * pi * (6378 10^3)^2 = 5.28 10^18 kg

Mass of Carbon Dioxide in the Atmosphere



$$\frac{p_c}{P} = 400\,ppm = 400 \cdot 10^{-6}$$ Pa/Pa

$$M_c = M_a \frac{m_c}{m_a} \frac{p_c}{P}$$

$M_c = 5.28\ 10^{21}\ (12/29)\ 400\ 10^{-6} = 873\ 10^{15}$ g = 873 Pg-C

m_c = 12 g/mole-C; m_a = 29 g/mole-air

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 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

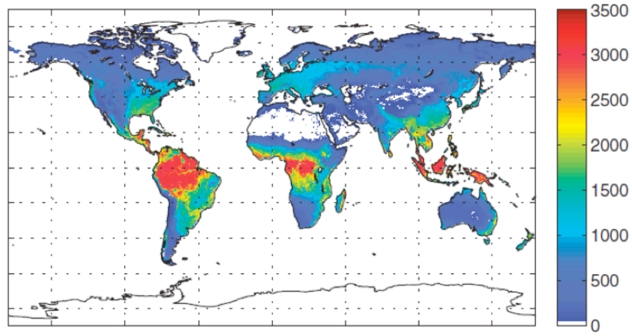
923 PgC/y/2.18 PgC/ppm = 423 ppm

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

Recent 'Best Estimate' on GPP with Multiple Constraints

Global GPP = 123 +/- 8 PgC

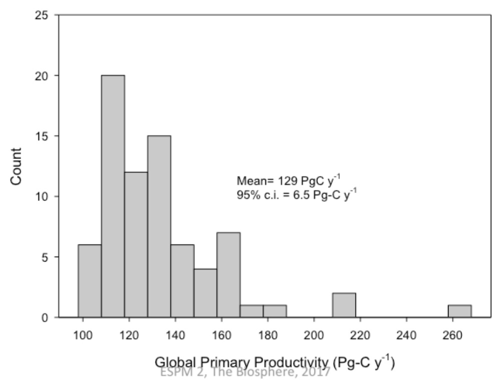


Beer et al 2010 Science

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.

Annual Global Primary Productivity, GPP, Remains Highly Uncertain

<GPP> =129 +/- 6 (s.e.) Pg-C y^{-1}

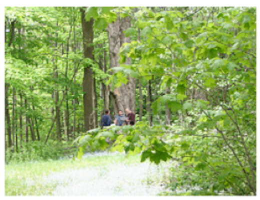


Despite all the science that has been conducted over the past 30 years, our ability to know global primary productivity remains highly uncertain and poorly constrained. We need to do better to close the carbon budget and understand the net effects of deforestation, stimulation and inhibition of plant growth to a changing world and to set policy on C emissions from human activities.

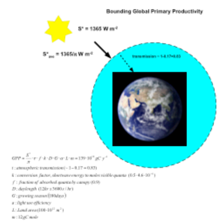
Point to be made, if the high GPP numbers were true we would not be having a CO2 problem. C emissions from combustion would not remain in the atmosphere.

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

Order of Magnitude Bound on Global Gross Primary Productivity

- ??? Global GPP is ~ 120 * 10^{15} gC y^{-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 (4.6/10^6)
  - Mean photosynthetic photon flux density, Q_p
- Fraction of absorbed Q_p (1-0.1=0.9)
- Photosynthetic efficiency, α (0.02, FLUXNET)
- Arable Land area (~ 110 * 10^{12} 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*0.83*0.5*4.6*0.9*0.02*110 10^{12}*43200*180*12/(4 10^6)=120.4 * 10^{15} gC y^{-1}

Add Reichstein figures tooo

What are the Key Carbon Sinks?

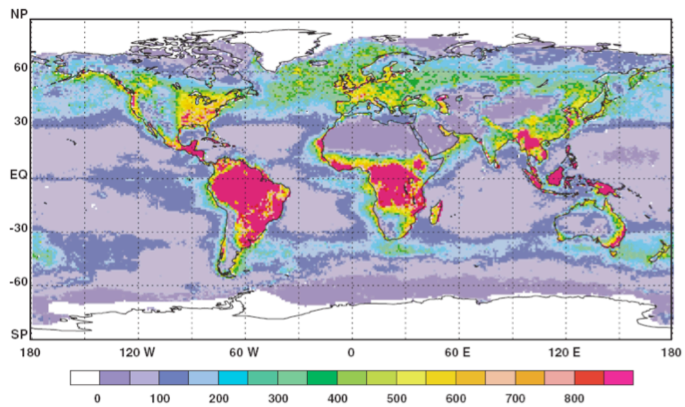
Biome	GPP (Pg C $year^{-1}$)	GPP = 2 × NPP* (Pg C $year^{-1}$)
Tropical forests	40.8	43.8
Temperate forests	9.9	16.2
Boreal forests	8.3	5.2
Tropical savannahs and grasslands	31.3	29.8
Temperate grasslands and shrublands	8.5	14
Deserts	6.4	7
Tundra	1.6	1
Croplands	14.8	8.2
Total	121.7	125.2

*Based on integrated numbers for biomes (*6, 7*)

Beer et al. 2010 Science

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

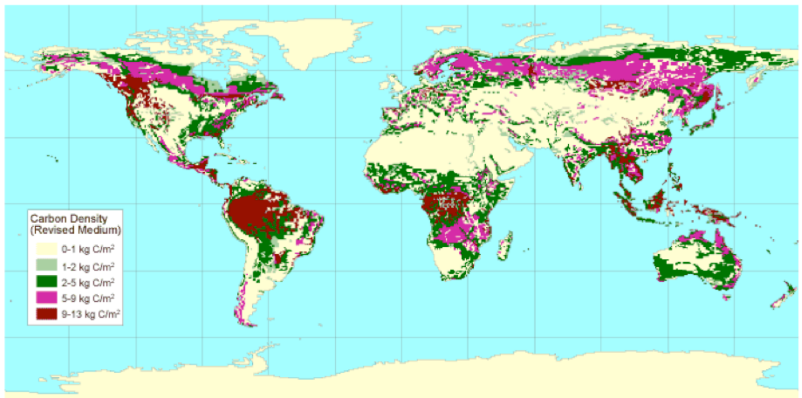
Turnover Time:
Mass/Flux

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

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

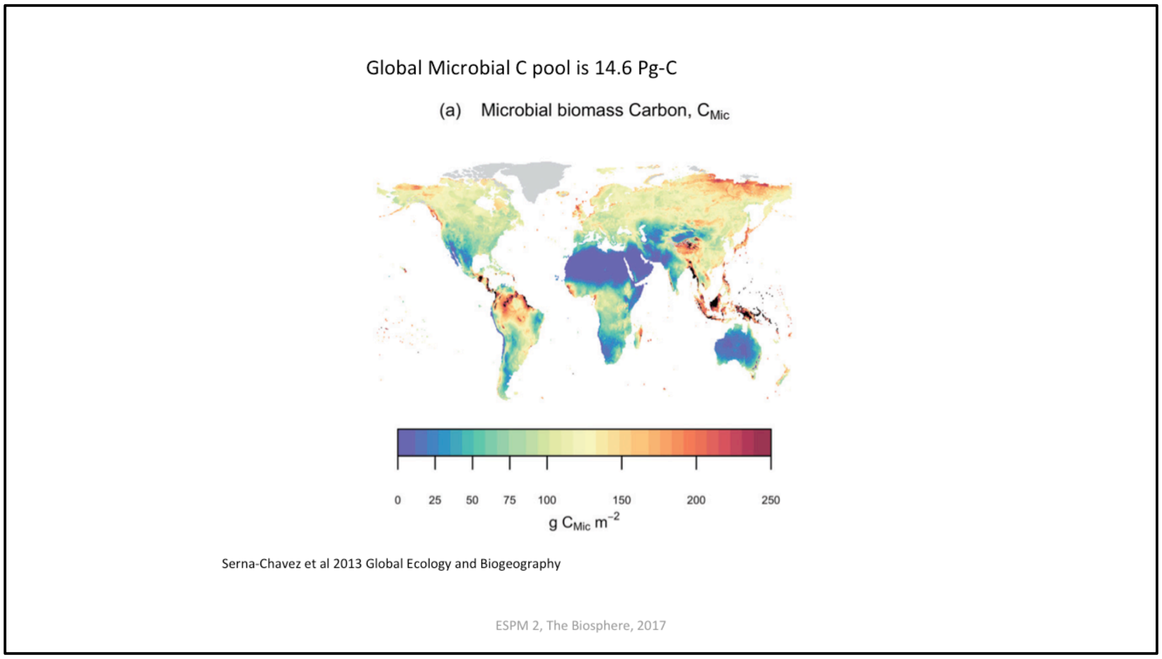
- Soil
  - M/Rh
  - 3000 Pg/60 Pg/y = 50 yr

Global Vegetation Carbon Content

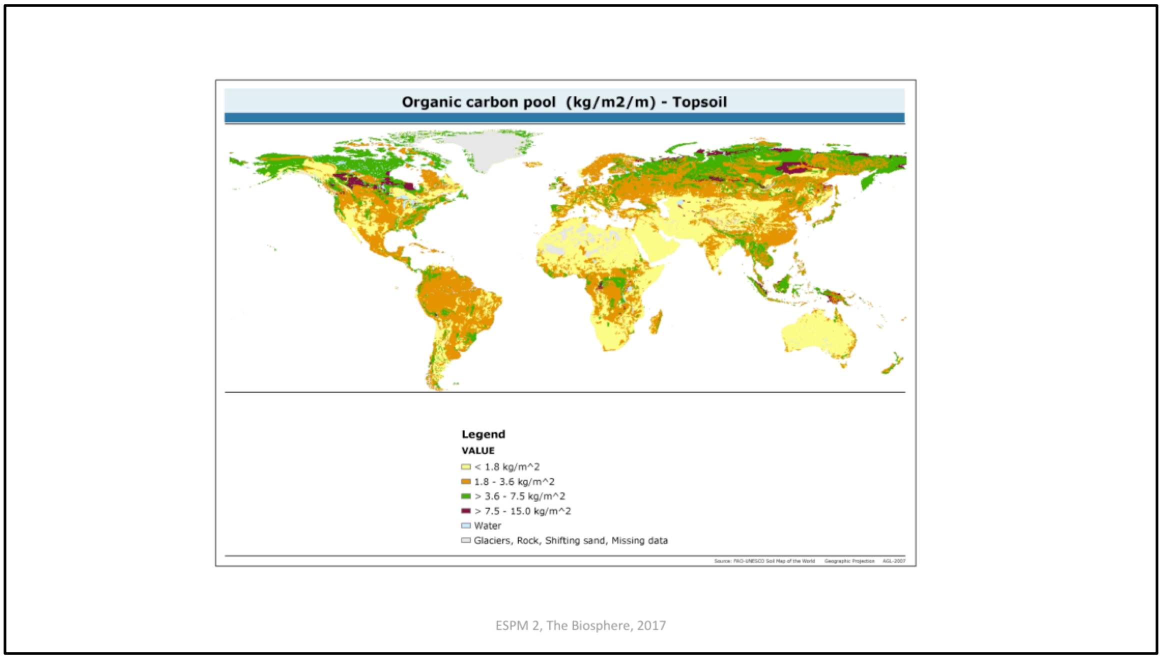


Olson, J.S, J.A. Watts, and L.J. Allsion. 1985, ORNL, CDIAC

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
http://www.fao.org/fileadmin/templates/nr/images/resources/images/Maps/geonetwork/cp_t.png

New data on soil org C in Permafrost

Permafrost is 1672 PgC

If PermaFrost Melts and this Pool is decomposed It could introduce ~ 760 ppm of CO_2 into the Atmosphere;

2.19 PgC => 1 ppm

Figure 3. Photographs of typical permafrost profiles.

Schuur et al, 2009 Bioscience
Tarnocai et al. 2009 GBC

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