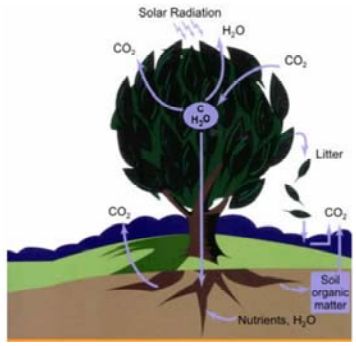
Carbon Cycle



Dennis Baldocchi
University of California, Berkeley

Fall, 2015

11/3/2015 ESPM 2, The Biosphere

The flows of carbon are central to the cycles of life. Any story on the biosphere must include a thorough description and understanding of the carbon cycle

Topics

- Background
  - Big Questions?
- Concepts
  - pools, fluxes, processes
  - Scales, Leaf, Ecosystem, Globe
- Carbon Stores and Fluxes
  - Stores: Vegetation and Soil C = f(x,y,z)
    - Soil Surveys
    - Biomass Inventories
  - Fluxes: NEP = f(x,y,t)
    - Global Fluxes

Big Questions, Carbon Cycle

- How can we measure and predict gross and net carbon fluxes at the Global scale?
  - What are these Fluxes and Pools?
- Will the Biosphere remain an Effect C sink with Elevated CO_2 concentrations and Global Warming?
- How Will the Tropical Forests and Northern Peatlands respond to elevated CO_2 and Global Warming?;
  - Will they Force a Negative or Positive feedback Loop?
- How is elevated CO_2 affecting the Acidification of the Oceans?
  - How will this affect the Airborne Fraction of CO2
- What Factors caused CO_2 to be limited between 180 and 280 ppm between Glacial and Inter-Glacial Periods?
- ?

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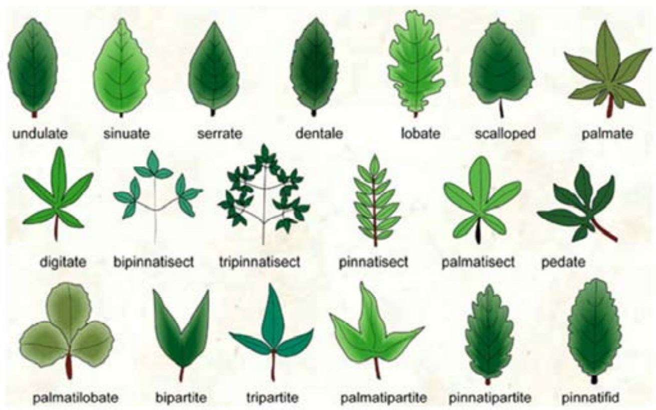
These are some general big questions. Can you think of others pertaining to the carbon cycle and your interests

Carbon Assimilation by Leaves



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Let's start with carbon assimilation by leaves.

Leaves have many sizes and shapes, but their jobs are essentially the same: to be a vehicle for housing chloroplasts and chlorophyll, act as organs that intercept sunlight, while providing an architecture that facilitates the diffusion of CO_2 to the site of carbon fixation, yet provide structures, like waxy cuticle and stomatal pores that prevent water to be lost to the atmosphere

Physiological Attributes of Plants

- **photosynthetic pathways**
  - C_3
    - Dicots/moncots, Trees/Shrubs/Herbs
  - C_4
    - Tropical Grasses
  - CAM
    - Cactii, pineapple

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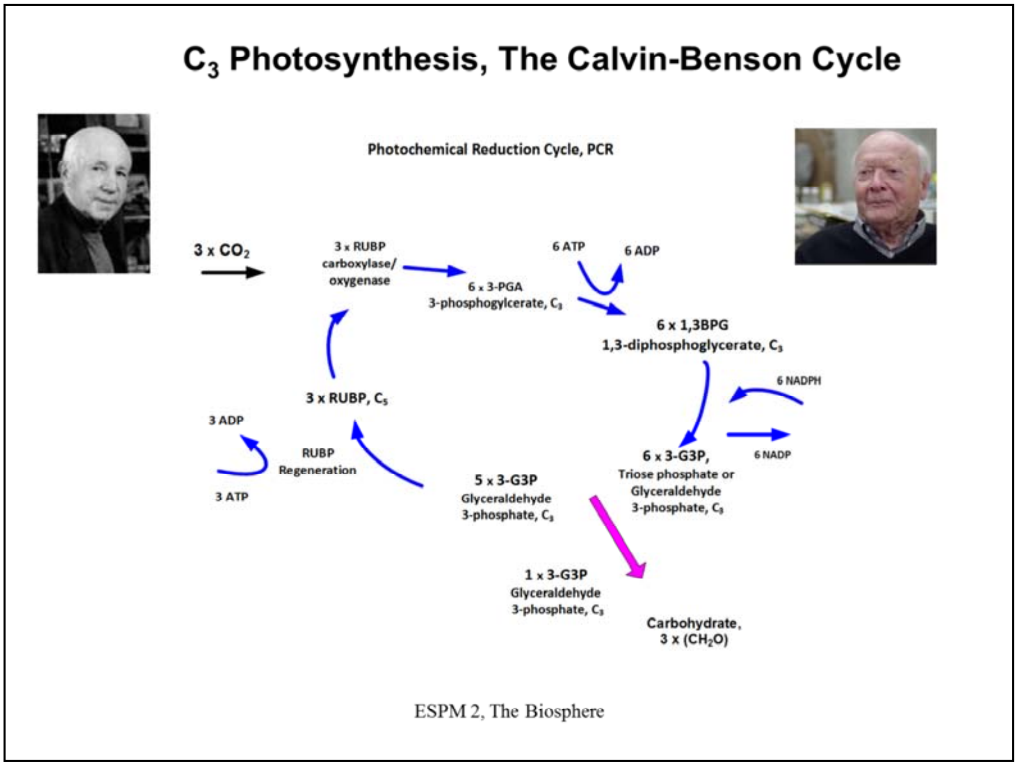
There are 3 major biochemical pathways for fixing CO2 by plants. The most abundant is the C3 pathway which uses the Calvin-Benson cycle (developed here at Berkeley, for which Melvin Calvin won a Nobel Prize, and Andrew Benson did not).

The C4 pathway is associated with many tropical grasses and is most efficient in warmer temperatures and during periods with low O2. It evolved about 10 Million years ago

CAM pathway is associated with cactus and pineapple. It is an efficient path to conserve water as stomata remain closed during the day while the plant captures light energy, then dark reactions proceed at night when the transpiration demand is less.



An example of the stoichiometry of the photosynthetic carbon reduction (PCR) and the photosynthetic carbon oxidation (photorespiration cycles). In this case, it is scaled with in an input of 3 CO2 molecules

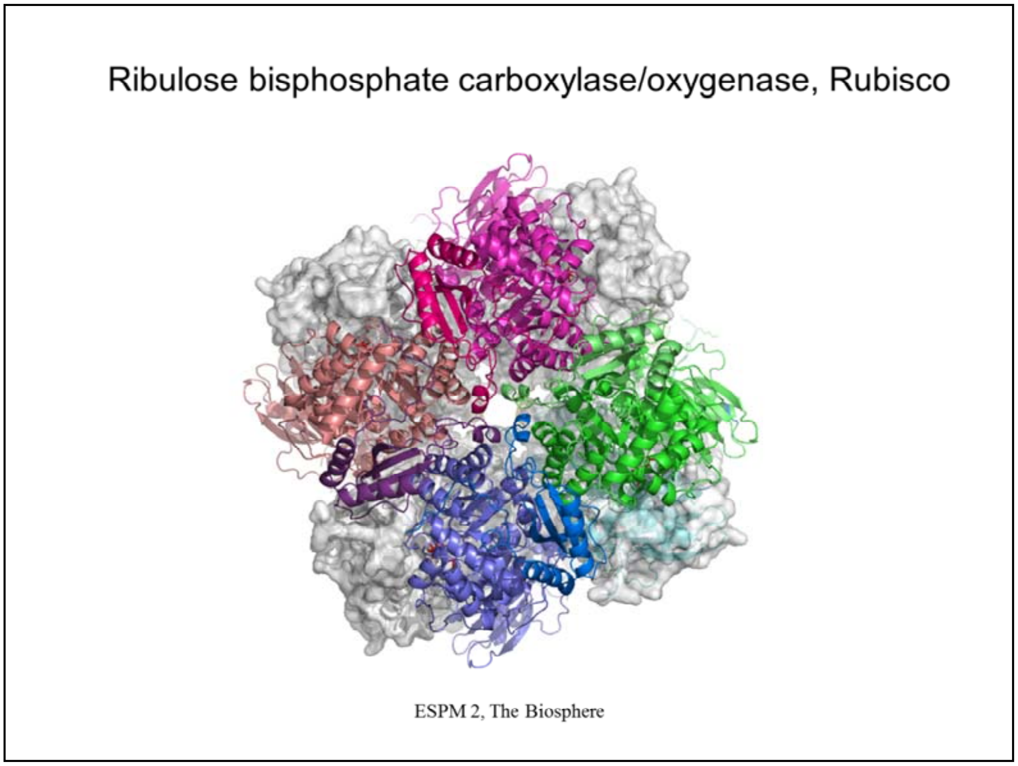
The enzyme ribulose-1,5-bisphosphate carboxylase (Rubisco) catalyzes the reaction between gaseous carbon dioxide and ribulose-1,5-bisphosphate (RuBP).

Product of the reaction are two molecules of 3-phosphoglyceric acid for each CO2 molecule

$C_5O_3H_8(PO_4^{2-})_2 + CO_2 \rightarrow 2\ C_3O_3H_4PO_4^{2-}$

Chemical Energy (NADPH & ATP) is used to regenerate RUBP

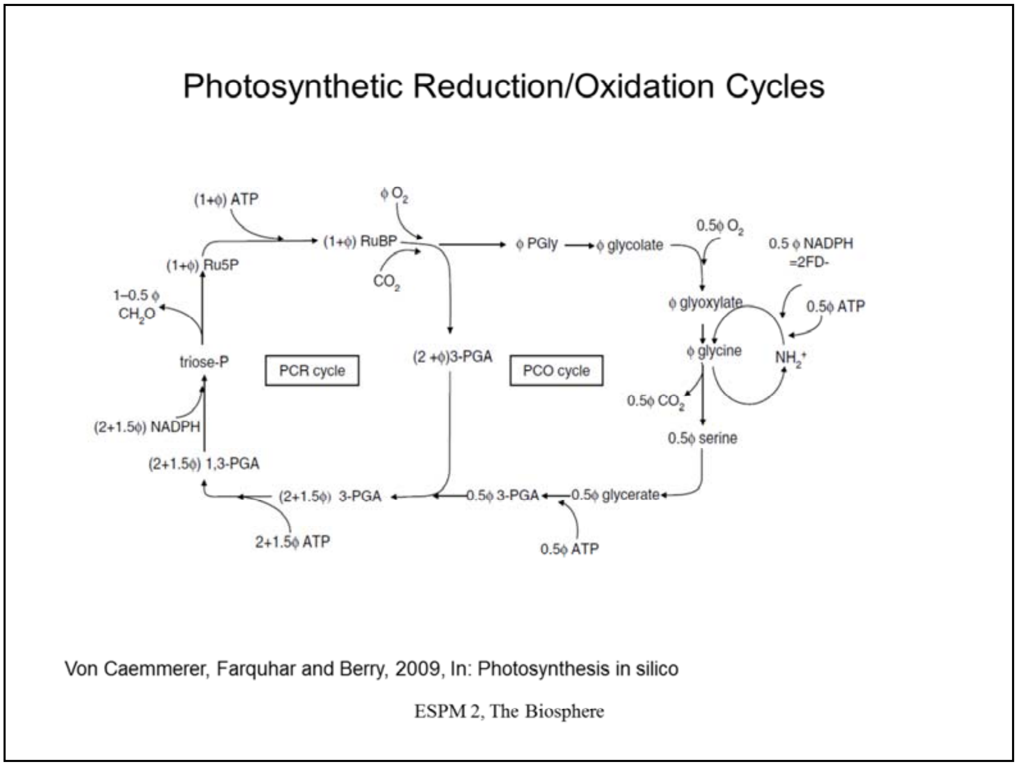
Resource: von Caemmerer. 2000. Biochemical models of leaf photosynthesis, CSIRO Publishing



We can observe the structure of Rubisco with X ray chrystallography. It has an affinity to either CO2 or O2.

The enzyme RuBisCO comprises 16 subunits: 8 small and 8 large units. The small units influence the stability and specificity of the large units, whereas the large units are the actual production sites. The interconnectivity affects catalysis, either in specificity or catalytic rate. (source: http://xray.bmc.uu.se/~michiel/research.php)

Plants invest large amounts of nitrogen in Rubisco; it comprises more than 50% of leaf protein in C_3plants



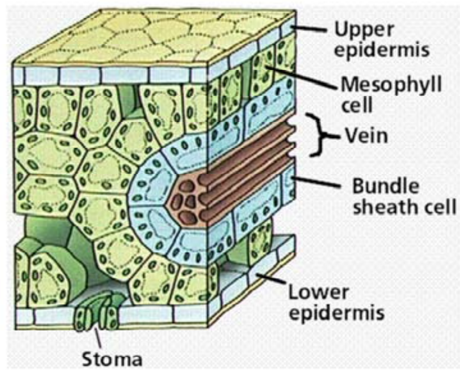
RUBISCO has an affinity for both CO_2 and O_2, with the later leading to photorespiration, a loss of $CO_{2.}$ The rate of competitive oxygen fixation is a proportional to the oxygen concentration time the ratio of oxygenation (Vo) to carboxylation (Vc). At ambient conditions Vo/Vc is about 0.27 (2 times the CO2 compensation point divided by CO2; ~ 2 x 38/280). In practice for each CO2 consumed by carboxylation 0.5 CO2 times Vo/Vc are lost by photorespiration; hence the amount of photorespiration decreases as CO2 concentrations increase.

Theta is the ratio of the oxygenation (Vo) to carboxylation (Vc) rates.

Critical Steps in C_3 Photosynthesis
Calvin-Benson Cycle

- Light Reactions
  - Chlorophyll, in chloroplasts, captures photons
  - Light energy is used to produce chemical energy in the forms of NADPH and ATP
  - Oxygen is produced
- Dark Reactions
  - A 3-C compound, PGA, is formed at the first Carboxylation step via the reaction between CO_2 and RUBP, a C_5 compound, and its subsequent cleaving (C_6 => 2 C_3)
  - The enzyme RUBISCO catalyzes the reaction between CO_2 and RUBP
  - RUBISCO has an affinity for both CO_2 and O_2, with the later leading to photorespiration, a loss of CO_2
  - Chemical Energy (NADPH & ATP) is used to regenerate RUBP
  - A carbohydrate, CH_2O, is formed

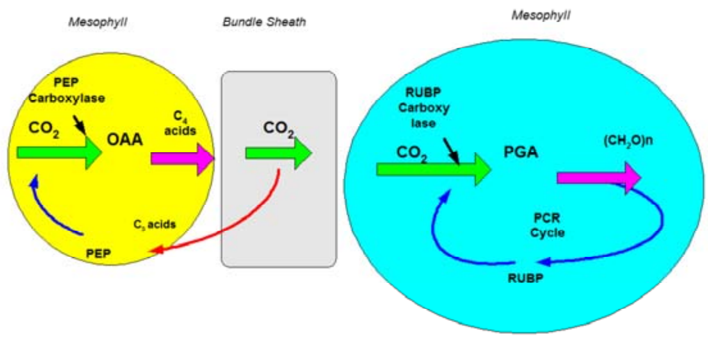
C_4 leaf



http://www.emc.maricopa.edu/faculty/farabee/BIOBK/C4leaf.gif

C4 leaves have a unique anatomy, bundle sheaths

C_4 Photosynthesis



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The enzyme PEP Carboxylase catalyzes a reaction between CO_2 and phosophenolpyruvate (PEP) to form a C_4 compound, OAA

The C_4 compound is transported into the specializes cells, the bundle sheaths, and is decarboxylated

CO_2 is released into a low oxygen environment and photosynthesis is completed via the C_3 cycle

Photorespiration is low; RUBISCO favors CO_2 in this environment because the ratio between CO_2:O_2 is high

Critical Steps in C_4 Photosynthesis

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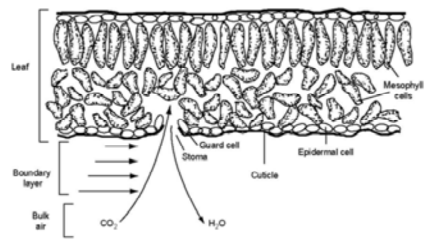
Key Points C_3 vs C_4

- C_3 compound formed
- Uses enzyme called RuBP carboxylase/oxygenase in first dark fixation step
- Suffers from photorespiration
- Was one of the Earliest Pathways for Photosynthesis and has remained unchanged for ++100s Million years

- C_4 compound formed
- Uses enzyme called PeP Carboxylase in the first dark fixation step
- Bundle Sheath anatomy allows photosynthesis to occur in low O_2 environment and avoid photorespiration
- Evolved several times over last 10M years

Photosynthesis:
A balance between Supply and Demand



- Physical limitation: delivery of CO_2 to leaf
  - Diffusion through Leaf Boundary Layer
  - Diffusion through Stomatal Pores
  - Potential Gradient between free Atmosphere and substomatal Cavity
- Biochemical limitation: carboxylation rate
  - Light limitation
  - Enzyme limitation

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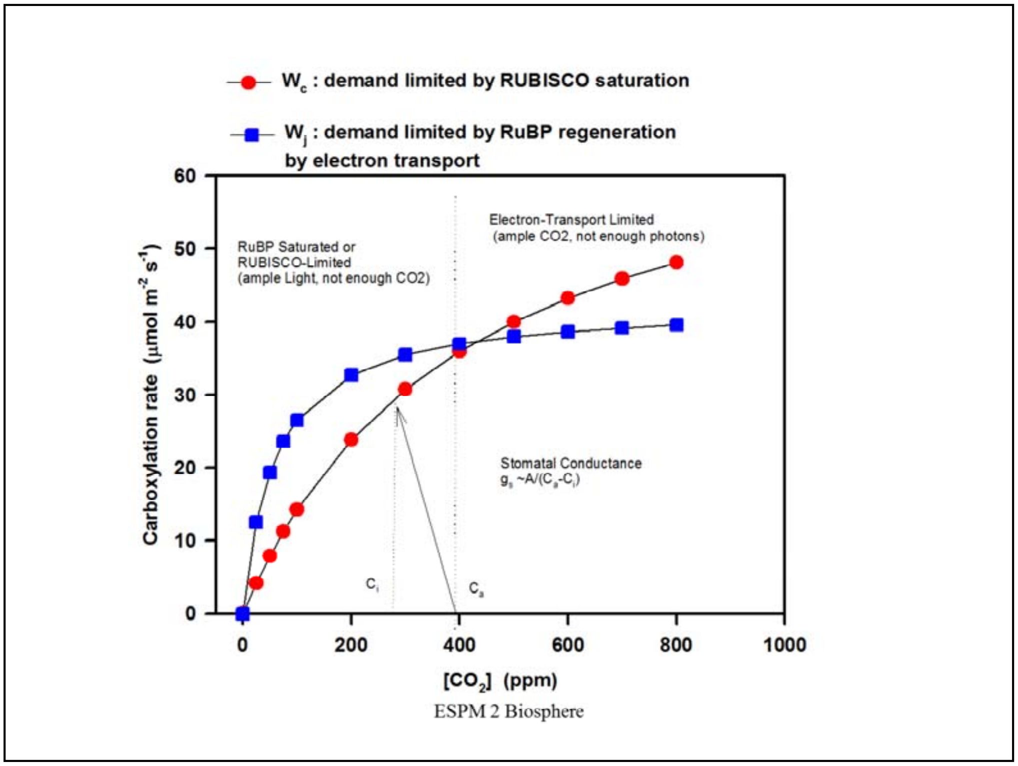
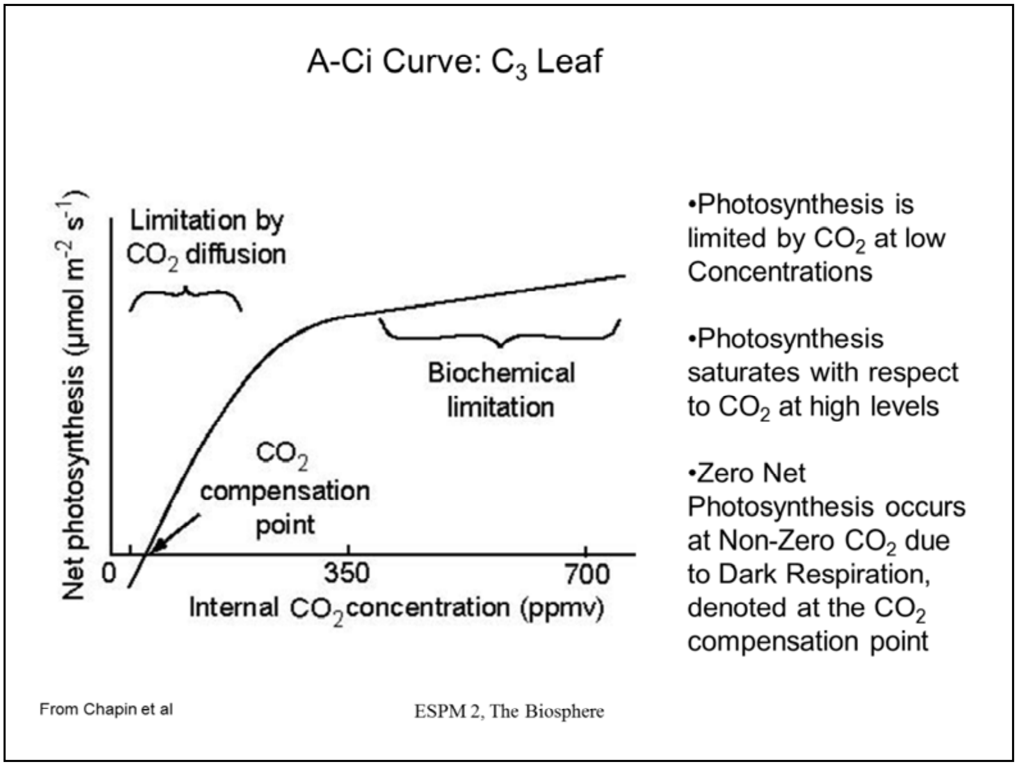
Photosynthesis responds to changes in light and CO2 because it is a balance between Supply and Demand

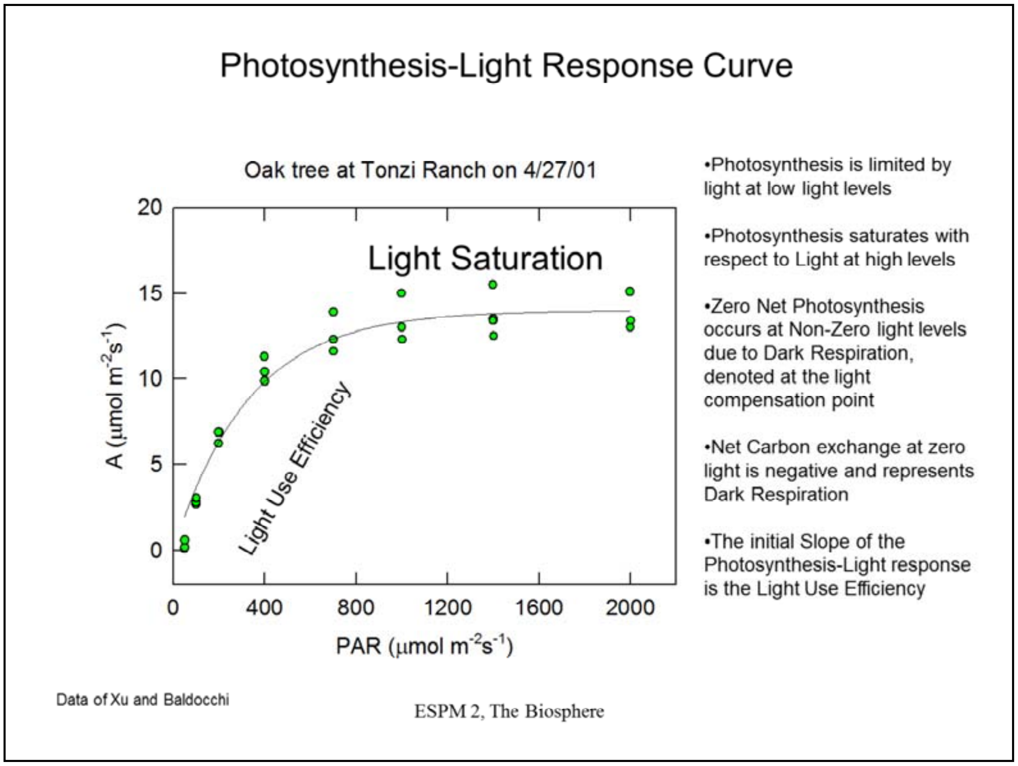


Under ample light, the carboxylation rate is limited by CO2 and follows the RuBP-saturate rate of Michaelis-Menton enzyme kinetics.

Under ample CO2, the carboxylation rate is limited by light, which provides the electrons to ATP and NADPH to regenerate RuBP.



The response curve between photosynthesis and CO2 experiences several key states and a non-linear, saturating response.



The response curve between photosynthesis and light also experience a non-linear response and key states

CO_2 Response of C_3 and C_4 Leaves

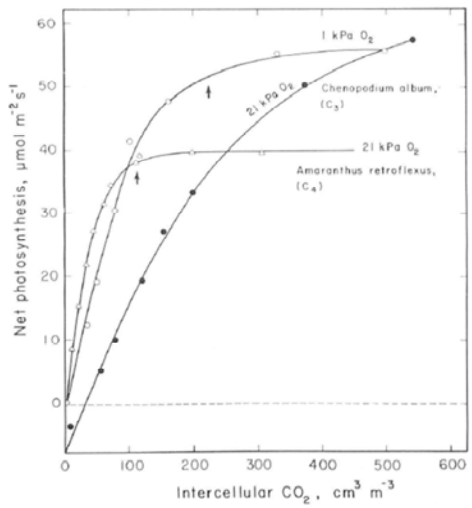


Figure 1. Photosynthetic response to intercellular CO_2 concentration for *Amaranthus retroflexus* and *Chenopodium album*. The measurements were done at 27°C and 2.0 mmol m^{-2} s^{-1} photon flux. Arrows indicate the observed intercellular CO_2 concentration under ambient CO_2 concentrations.

- C_3 leaves exposed to low O_2 behave like C_4 plants at low CO_2 because photorespiration is inhibited
- C_4 leaves had a physiological advantage during the Ice Age when CO_2 was about 180 ppm because they don't photo-respire like C_3 plants

Pearcy and Ehleringer, 1984 PCE

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Explains why C4 grasses advanced during the ice age..

Temperature Response of C_3 and C_4 Leaves

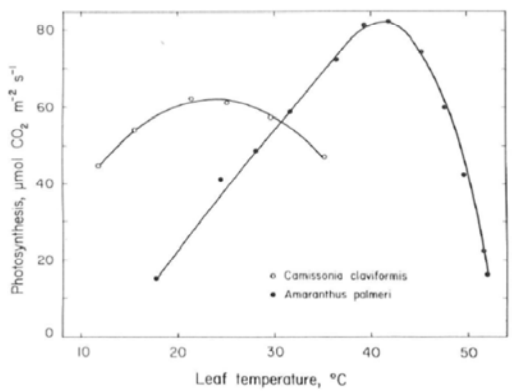


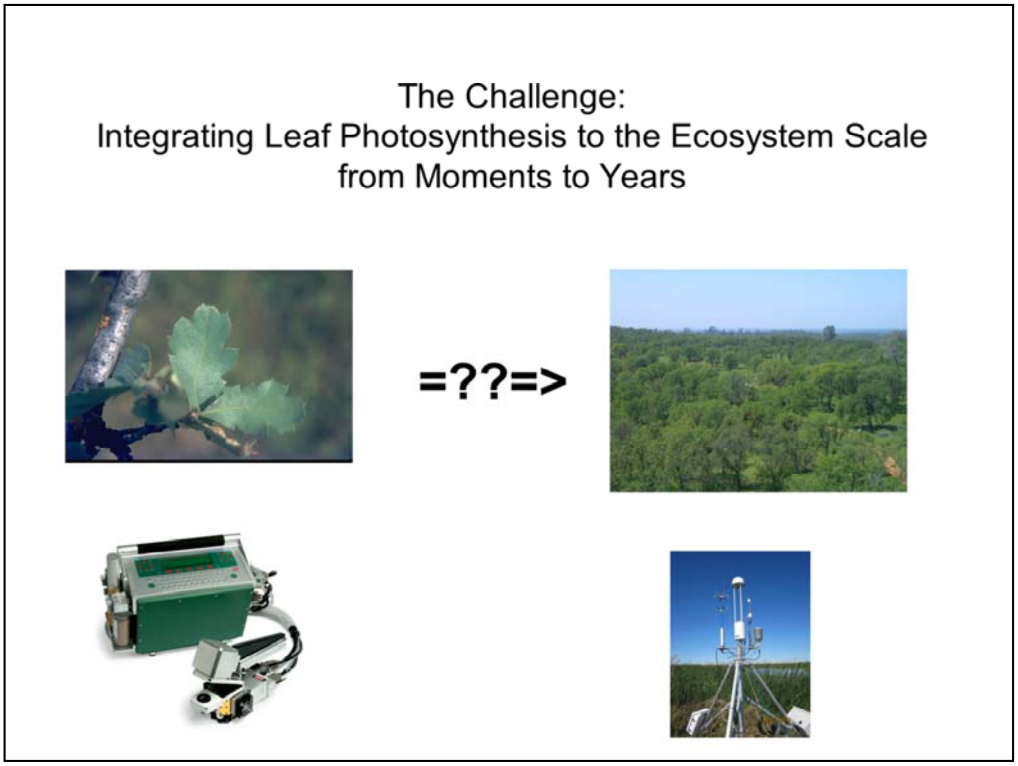
Figure 10. Response of photosynthesis to leaf temperature in the winter active C_3 desert ephemeral *Camissonia claviformis* and the summer active C_4 desert ephemeral *Amaranthus palmeri*. Data are redrawn from Mooney *et al.* (1976a) and Ehleringer (1983).

Photosynthesis of C_4 Plants is better adapted to High temperatures

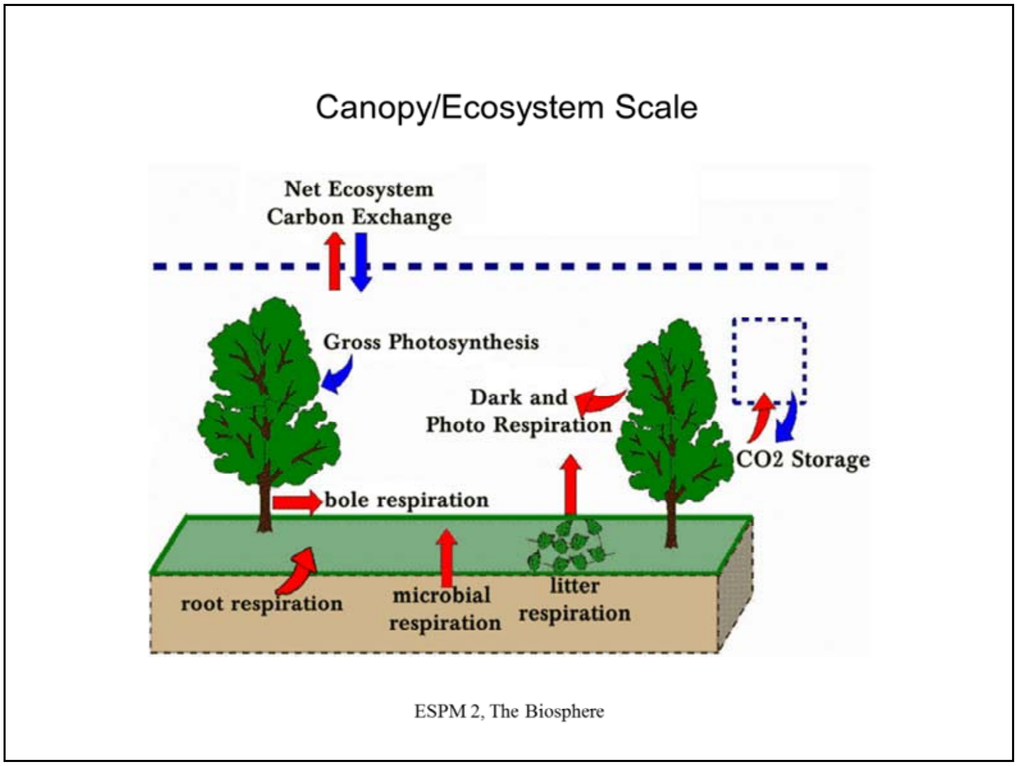
Pearcy and Ehleringer, 1984 PCE

Key Points

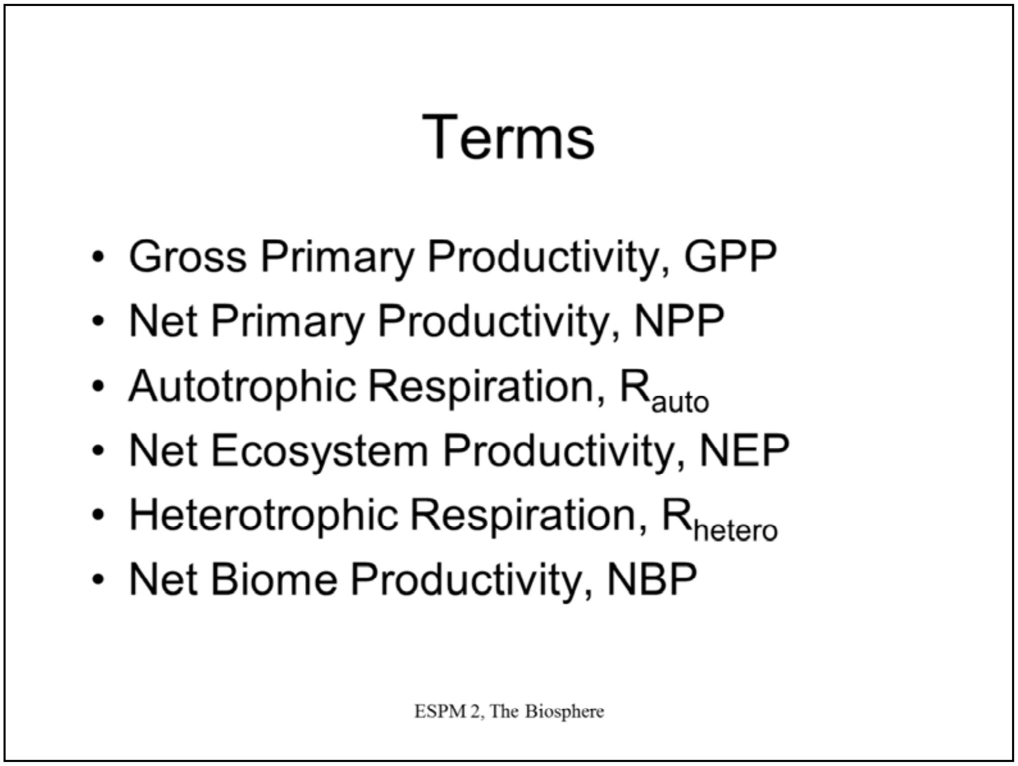
- Know how photosynthesis varies with light, temperature, CO_2 and photosynthetic pathway



This lecture will cover material spanning ideas on how leaves assimilate carbon and how we produce integrated information at the ecoystem scale and how this integrates to over year and across the globe



Classic carbon balance of an ecosystem. Know sources and sinks of carbon



Key terms to understand regarding gross and net carbon fluxes and their sources and sinks

Concepts

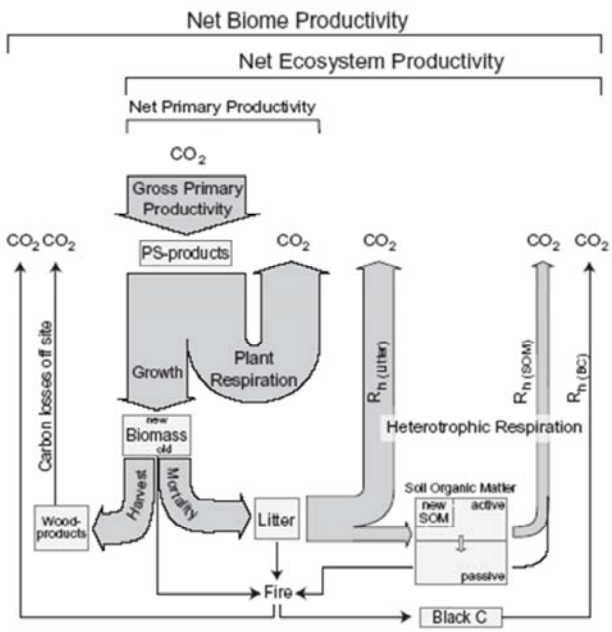
GPP = Gross Carbon Fixation minus Photo-Respiration

NPP = GPP minus Autotrophic Respiration

NEP = NPP minus Heterotrophic Respiration

NBP = NEP minus C loss by disturbance, fire, harvest

What the terms mean. Know the difference between autotrophic respiration (respiration by self-feeders, like plants) and heterotrophic respiration (respiration by microbes, fungi, animals)



- •NBP
- •NEP
- •GPP
- •NPP
- •R_h
- •R_a

Schulze, 2006 Biogeosciences

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Visual graphic of the flows of carbon in and out of the biosphere. The thickness of the arrows gives you relative sense of the magnitudes of the in and out fluxes.

C Fluxes Across the World

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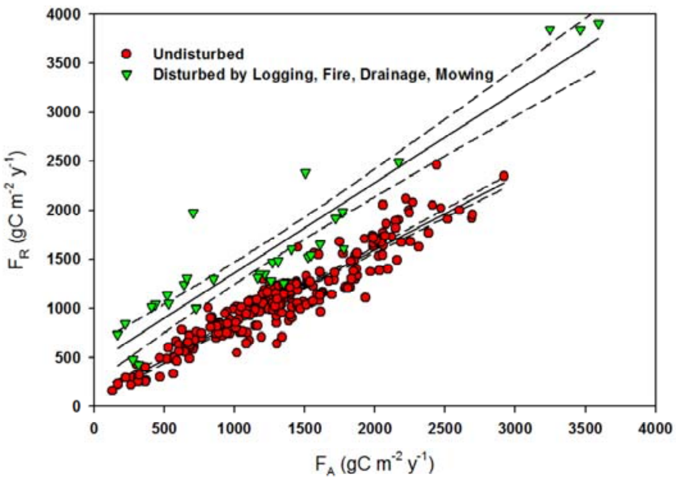
Ecosystem Respiration (F_R) Scales with Ecosystem Photosynthesis (F_A), But with an Offset and Parallel Line is associate with Disturbed Sites



Baldocchi, Austral J Botany, 2008

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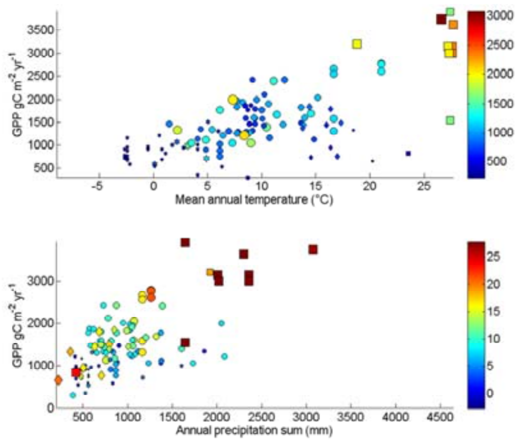
GPP and Climate Drivers

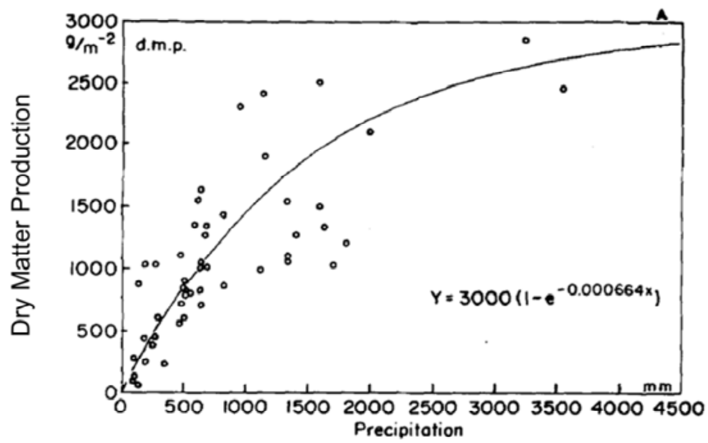


Climate explains 70% of variation in GPP

Luyssaert et al. 2007, GCB

NPP and Rain

Lieth



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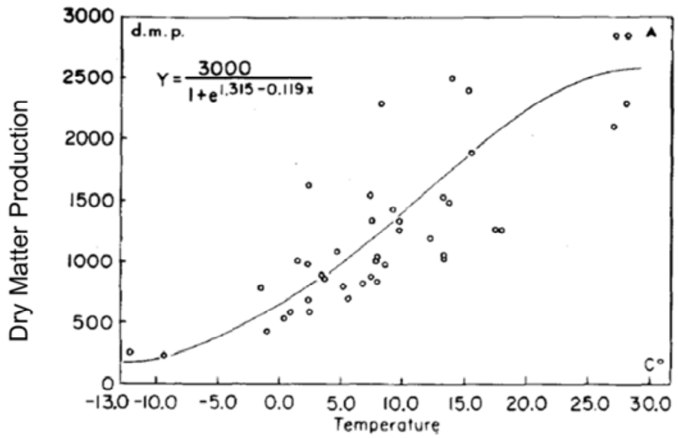
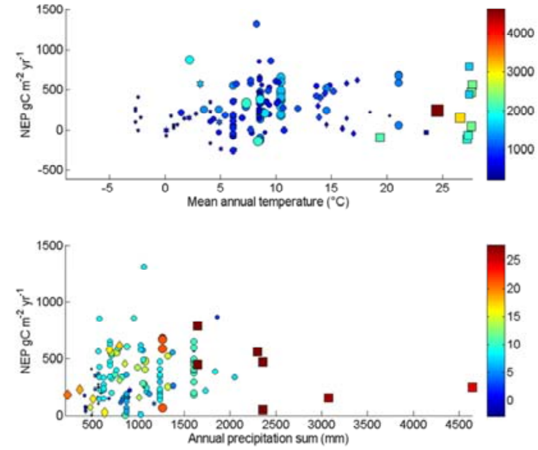
NPP and Temperature

Lieth



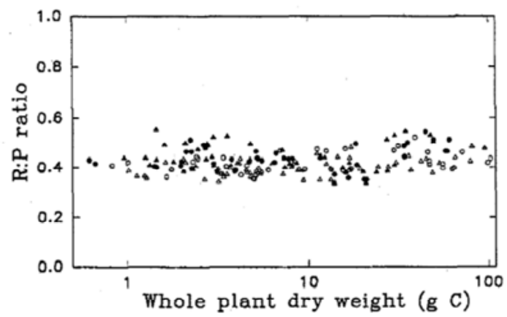
NEP and Climate Drivers



Climate explains 5% of variation in NEP

Luyssaert et al. 2007, GCB

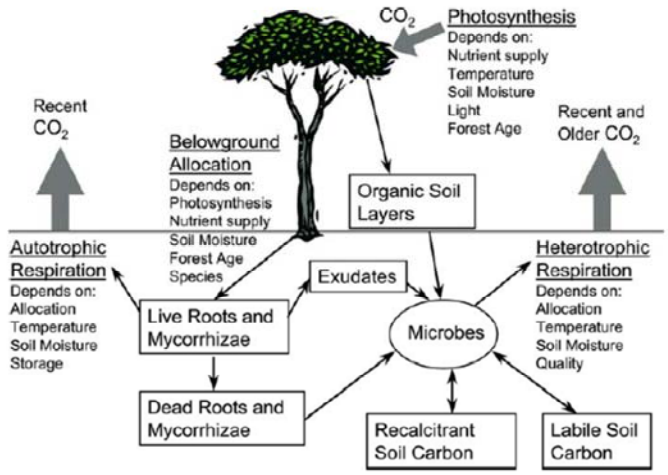
The Ratio between Autotrophic Respiration (R) and Photosynthesis (P) is Constant:
Regardless of Plant Size, Treatment etc



Emerging and Useful Ecological Rules

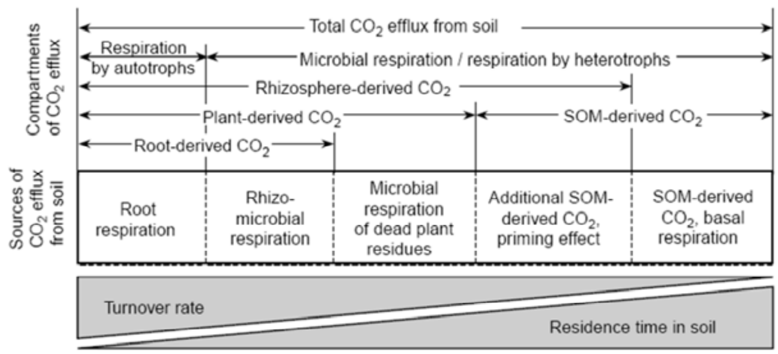
Gifford, 1994, Australian J Plant Physiol

C Cycling, Below Ground



Law and Ryan, 2005, Biogeochemistry

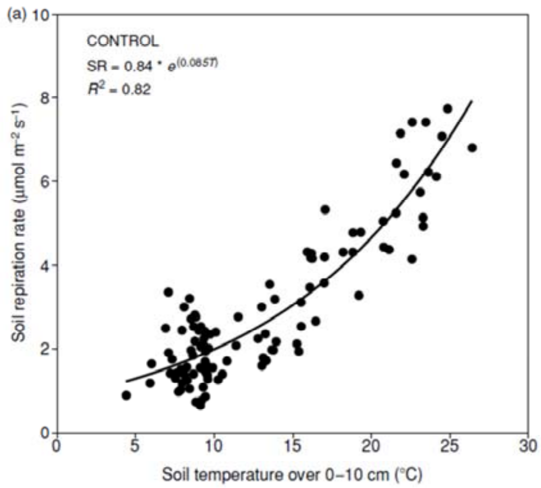
De-Convolving Soil Respiration



Kuzyakov, 2006

Soil Respiration and Temperature, Adequate Soil Moisture

860 ANA REY *et al.*



- Respiration increases Exponentially with Temperature and Respiration Rates tend to Double with every 10 C increase in Temperature

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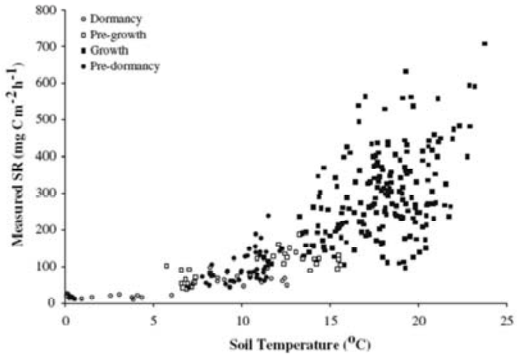
Soil Respiration, Temperature and Phenology



Extra Respiration incurred by Summer Growth, Photosynthesis, Reproduction Complicate the Classic T-Respiration Function

deForest et al Int J Biomet, 2007

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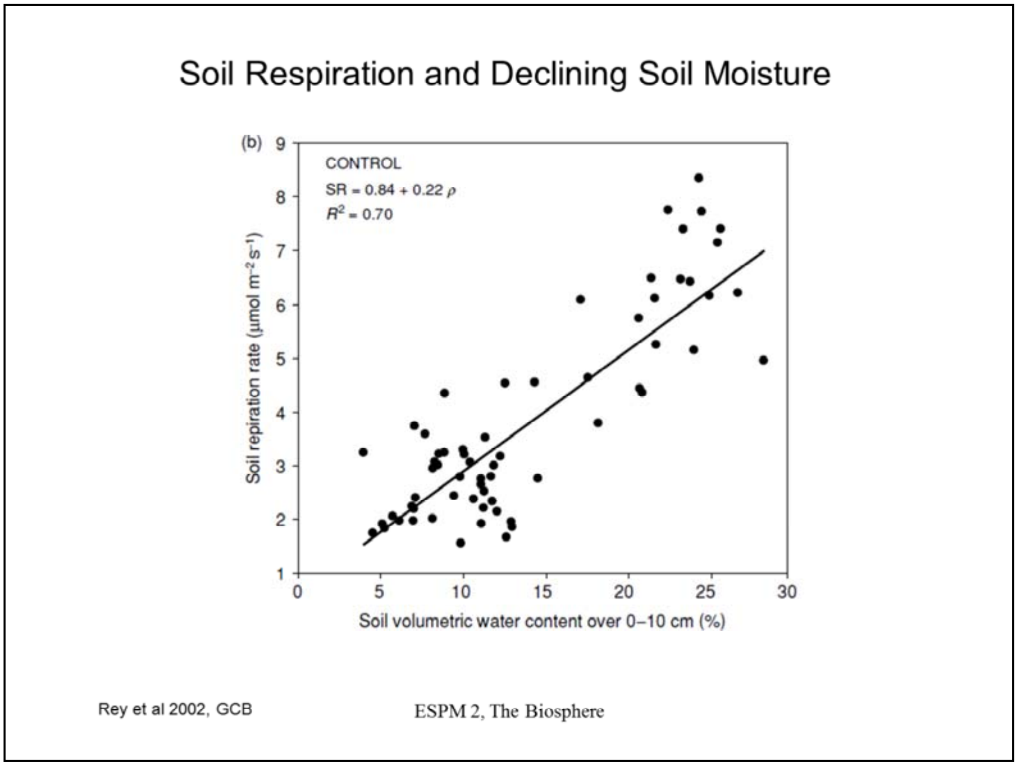
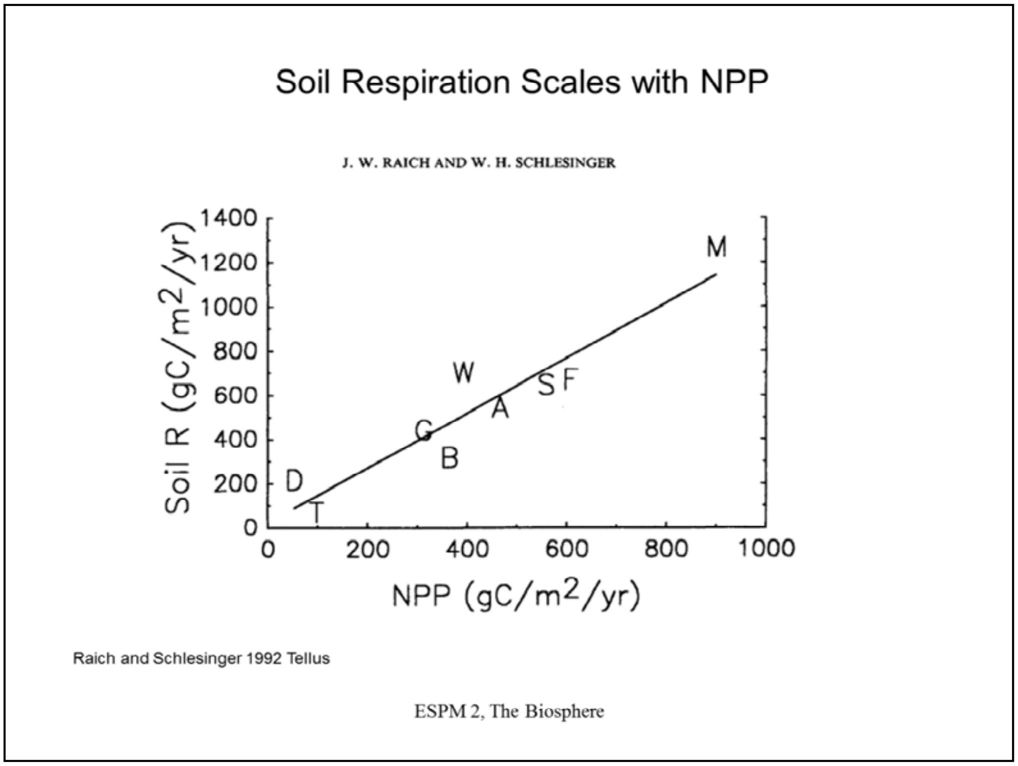
Temperature drives soil respiration, but so do other factors like leaf area, metabolic activity



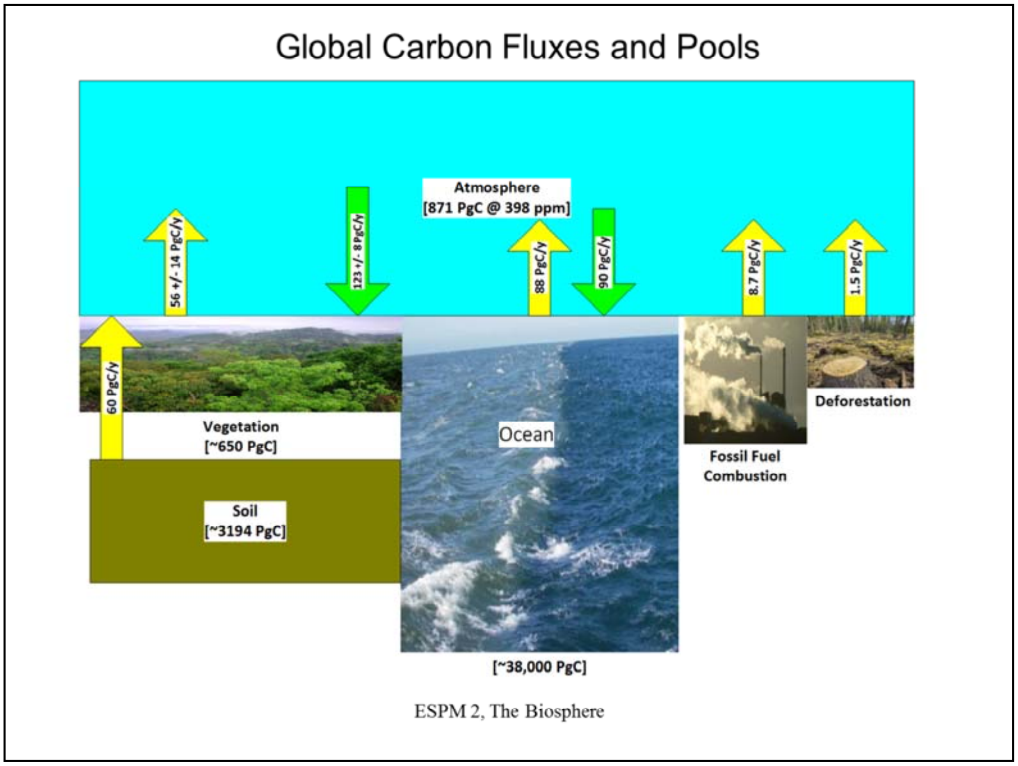
Soil dryness reduces soil respiration



Soil respiration scales strongly with C inputs, eg NPP. Most productive systems have the greatest soil respiration

Key Points

- Know the flows and Fluxes of Carbon dioxide in and out of an ecosystem. What are the different terms and are they associated with leaves, stems, roots, soil, microbes?
- Know how the net and gross carbon fluxes vary with environmental variables



Carbon pools and fluxes, circa 2013 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.

Pan et al show forests are a sink of 2.4 +/- 0.4 PgC per year over 1990-2007. But we are losing 2.9 PgC/y year from deforestation; this is compensated by 1.6 PgC/y regrowth. So net effects of forests from enhanced growth minus deforestation is a sink of 1.1 +/- 0.8 PgC/y

Friedlingstein, P. et al., 2010. Update on CO2 emissions. Nature Geoscience, 3(12): 811-812.

Pan, Y. et al., 2011. A large and persistent carbon sink in the world's forests. Science, 333(6045): 988-93.

Le Quere, C., Raupach, M.R., Canadell, J.G. and Marland et al., G., 2009. Trends in the sources and sinks of carbon dioxide. 2(12): 831-836.

Perspective

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

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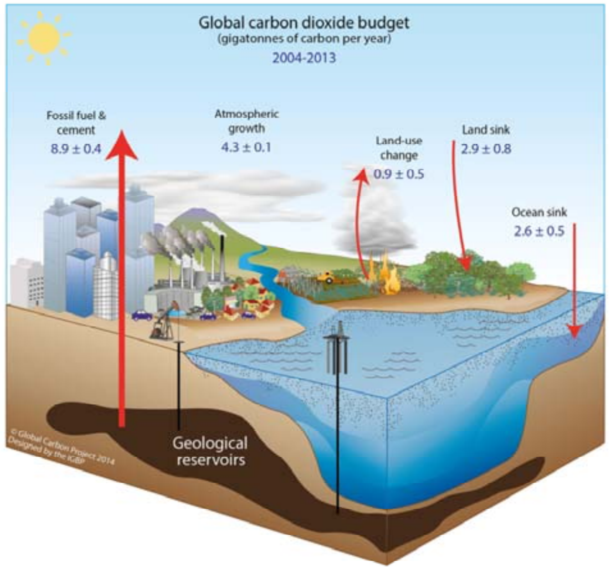
It is important to try and think about these huge numbers in human context, both globally and locally.

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

How CO2 is Changing



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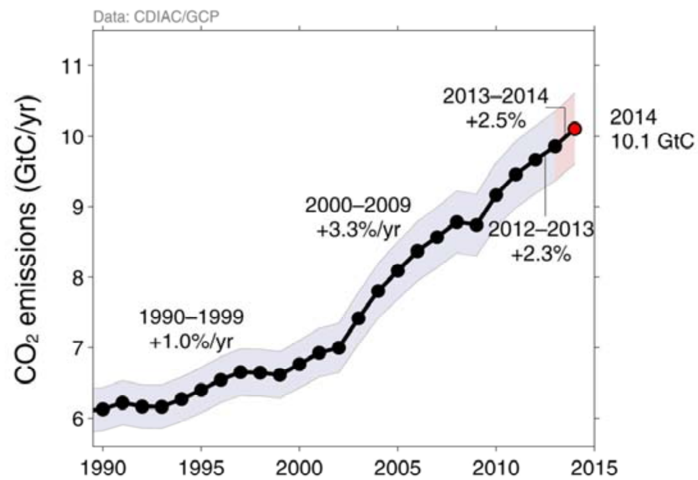
Circa 2015, Global Carbon Project, http://www.globalcarbonproject.org/

Fossil Fuel Emissions and Cement Production



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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 → $CaO + CO_2$

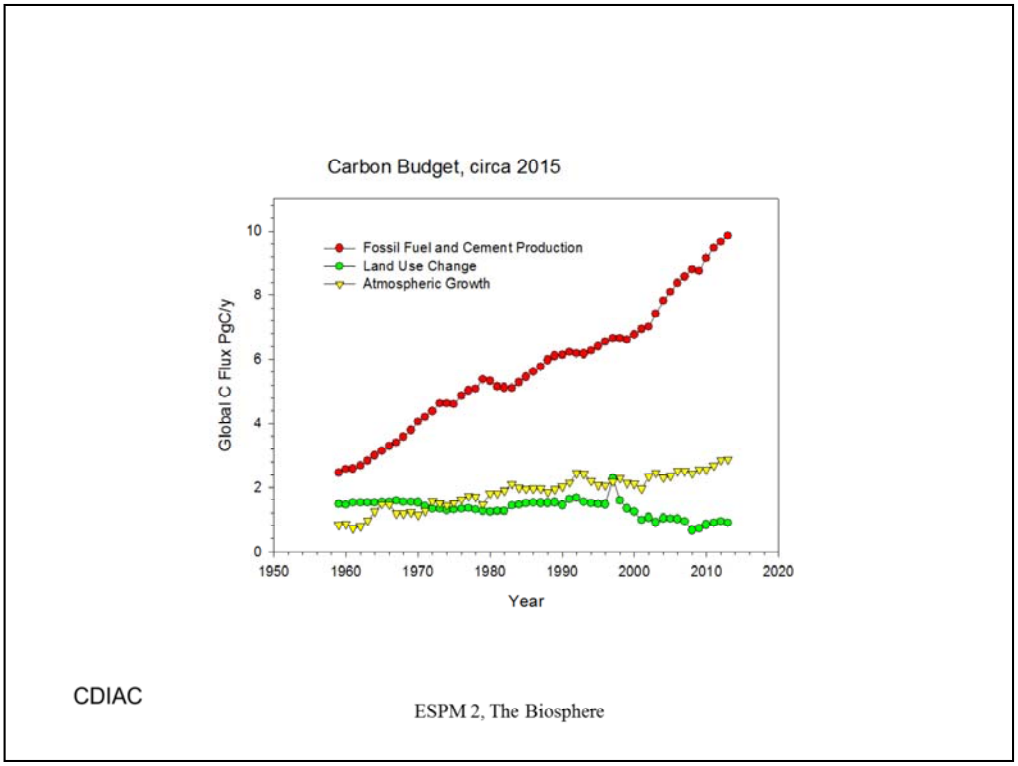
Why is there CO2 lost from cement production?

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

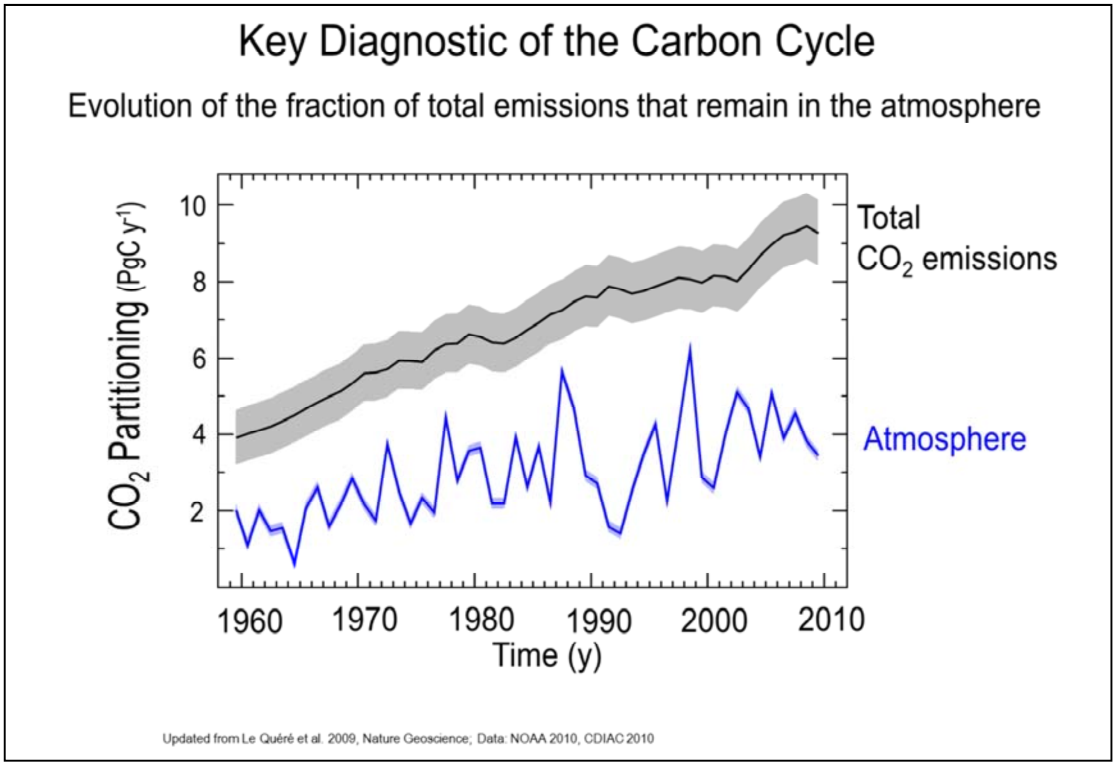
Calera is trying to produce low carbon cement

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



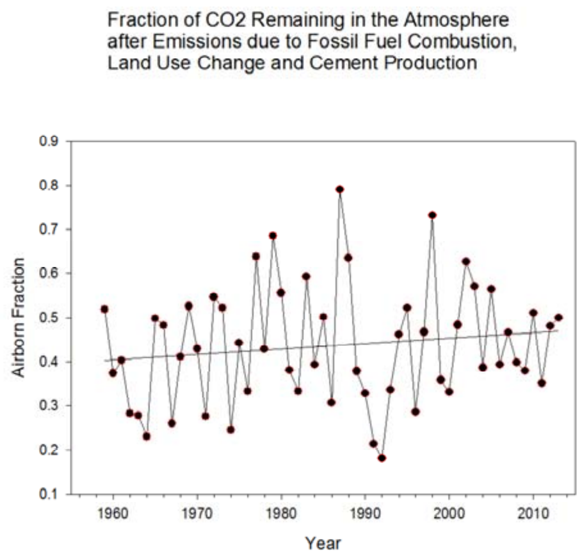
All values in billion tonnes of carbon per year (GtC/yr), for the globe. For values in billion tonnes of carbon dioxide ($GtCO_2$) per year, multiply the numbers below by 3.664. Note: 1 billion tonnes C = 1 petagram of carbon (10^15 gC) = 1 gigatonne C = 3.664 billion tonnes of CO2 All uncertainties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



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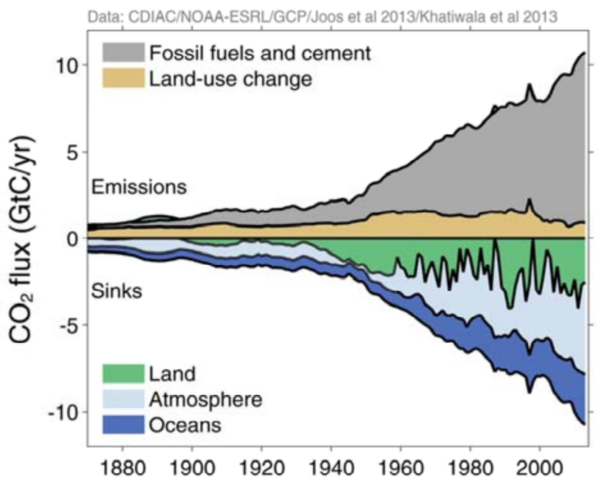
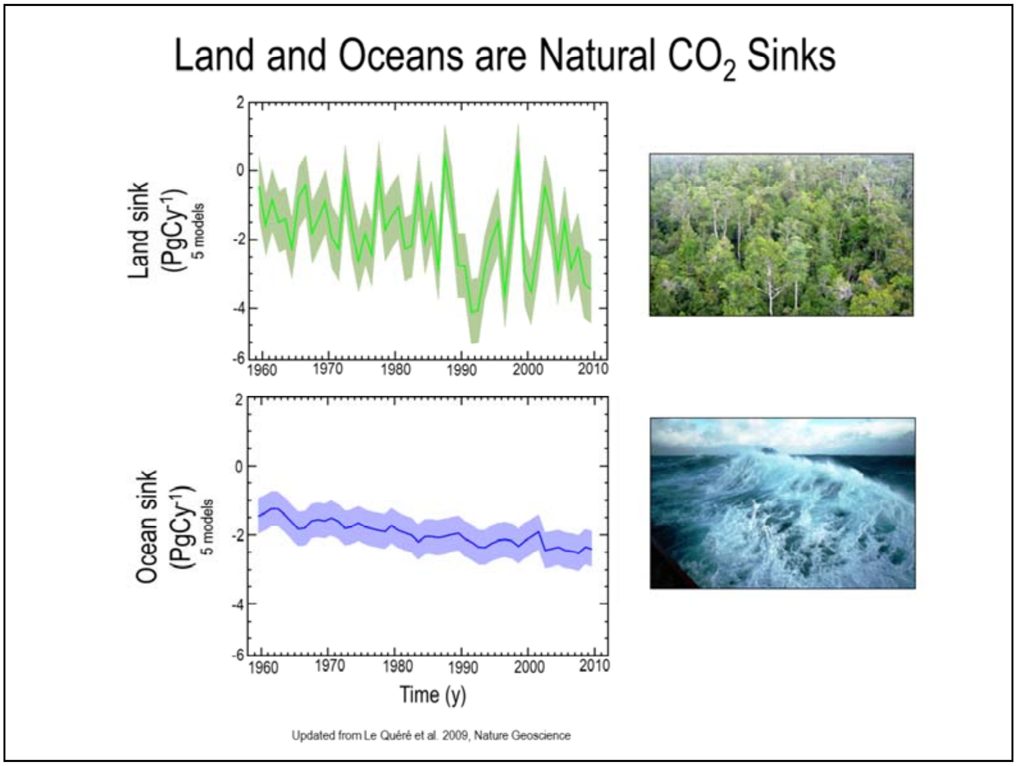
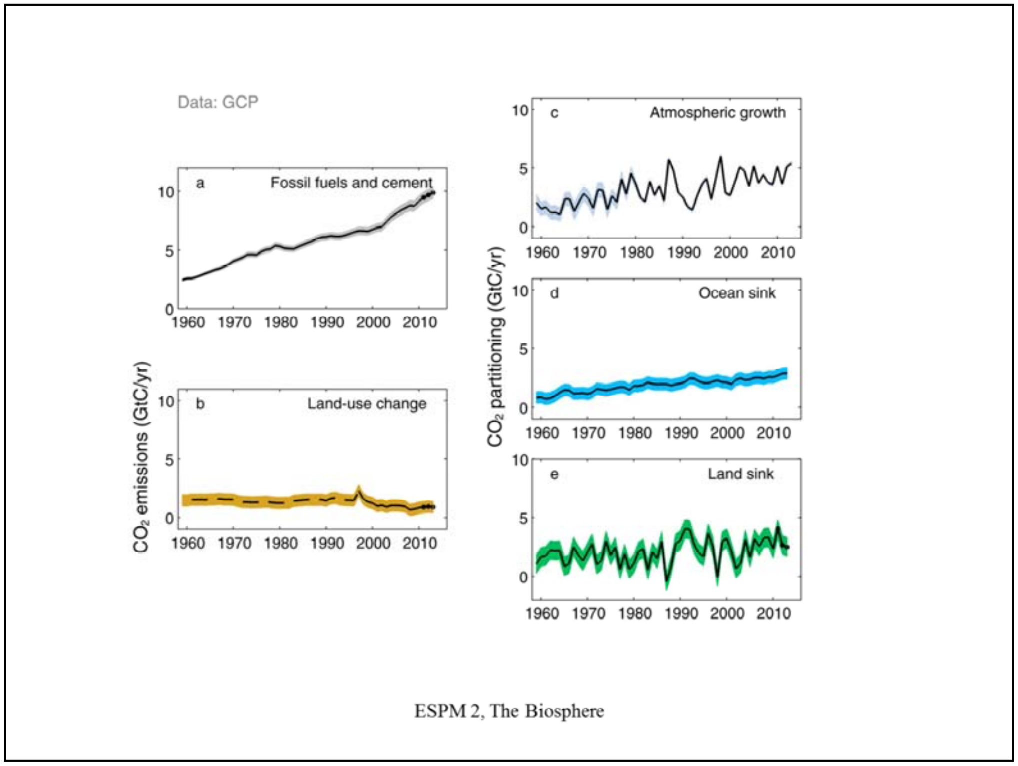
CDIAC and Global Carbon Project, circa 2014

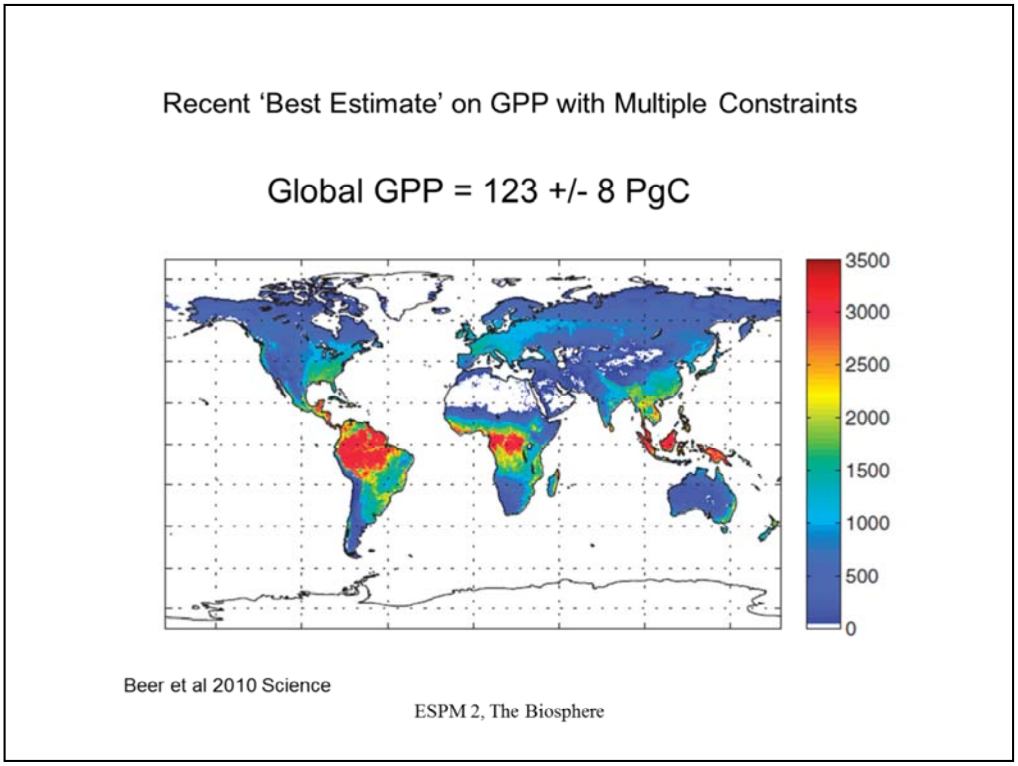

Data: CDIAC/NOAA-ESRL/GCP/Joos et al 2013/Khatiwala et al 2013
Fossil fuels and cement
Land-use change
Emissions
Sinks
Land
Atmosphere
Oceans
CO_2 flux (GtC/yr)
10
5
0
-5
-10
1880
1900
1920
1940
1960
1980
2000



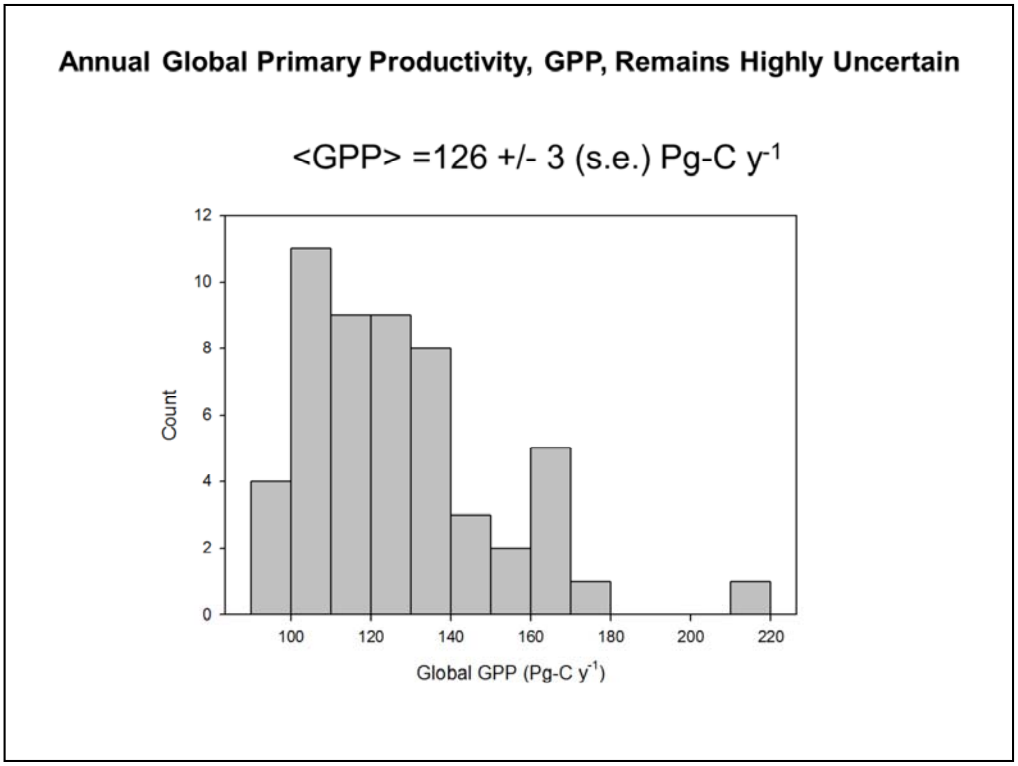
Both the land and ocean are effective sinks for carbon. Lately the land has been taking up 2 to 4 PgC y-1 and the ocean is taking up about 2 Pg-C y-1



2015 Figures from CDIAC



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 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

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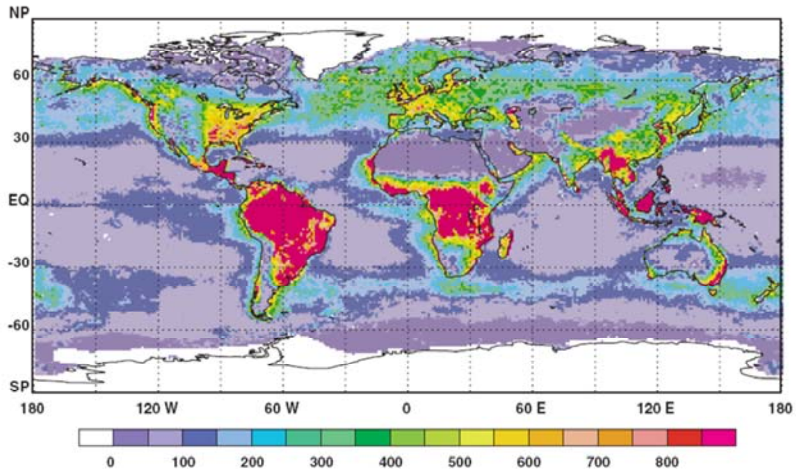
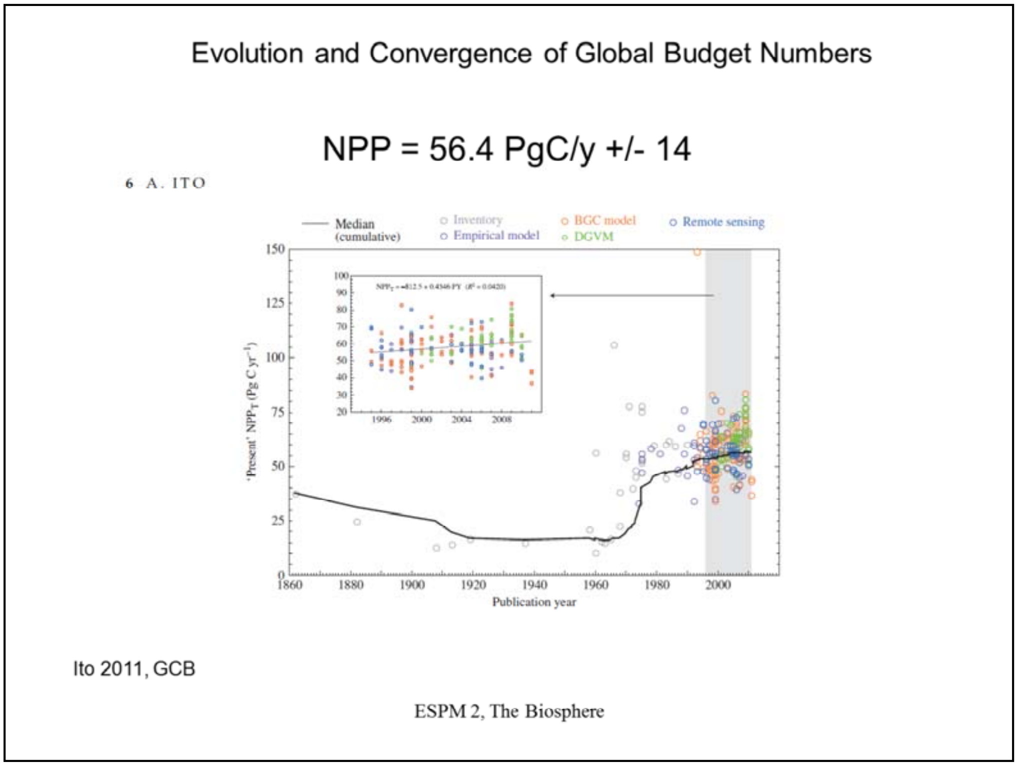
Tropical forests and savannas are the largest C sinks. They possess long growing seasons, large area, high leaf area

Global Scale



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

Field et al. 1998, Science

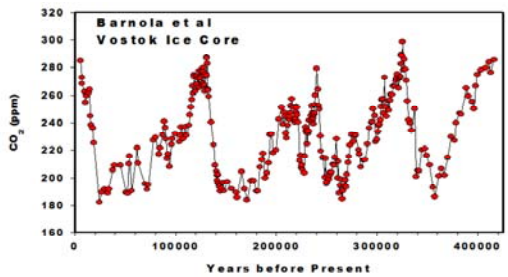


NPP is the difference between GPP and carbon lost as autotrophic respiration.

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

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}



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

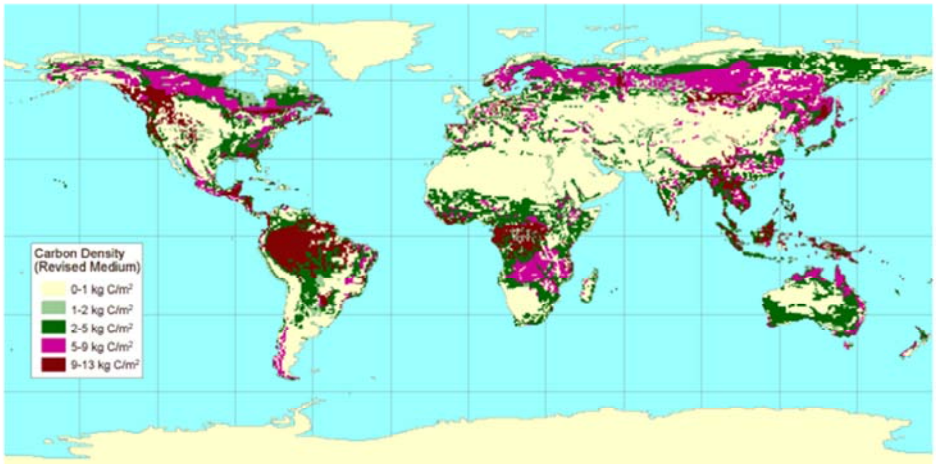
Turnover Time:
Mass/Flux

- Atmosphere
  - M/NBP
  - 850 Pg/3 Pg/y = 283 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

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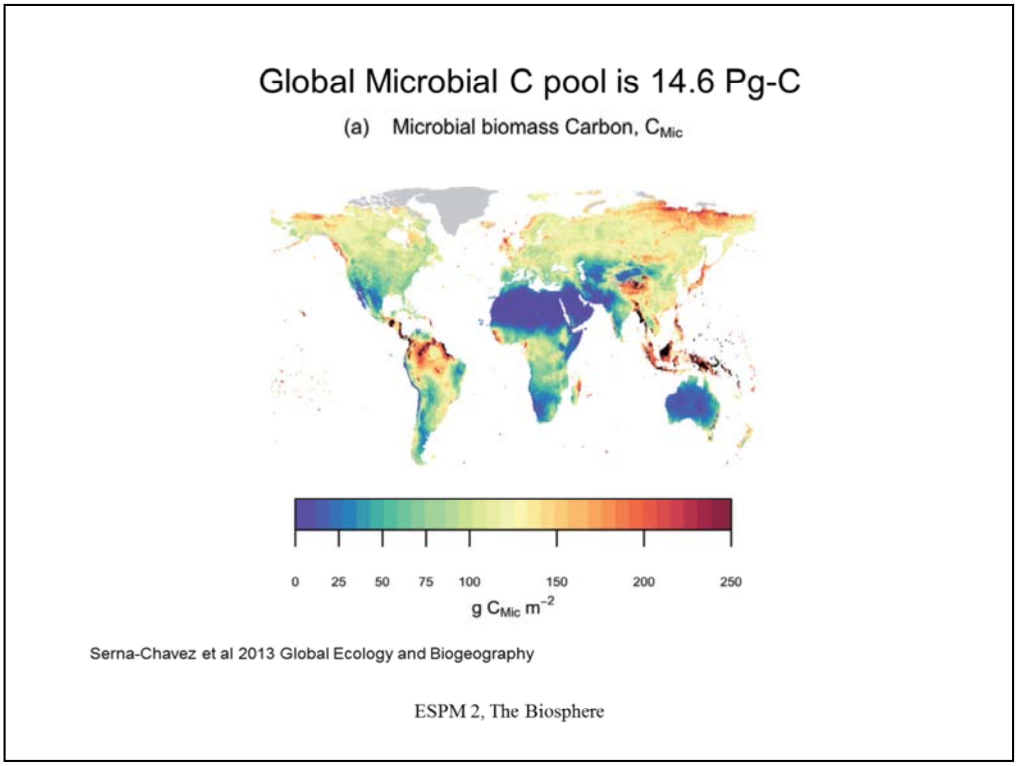
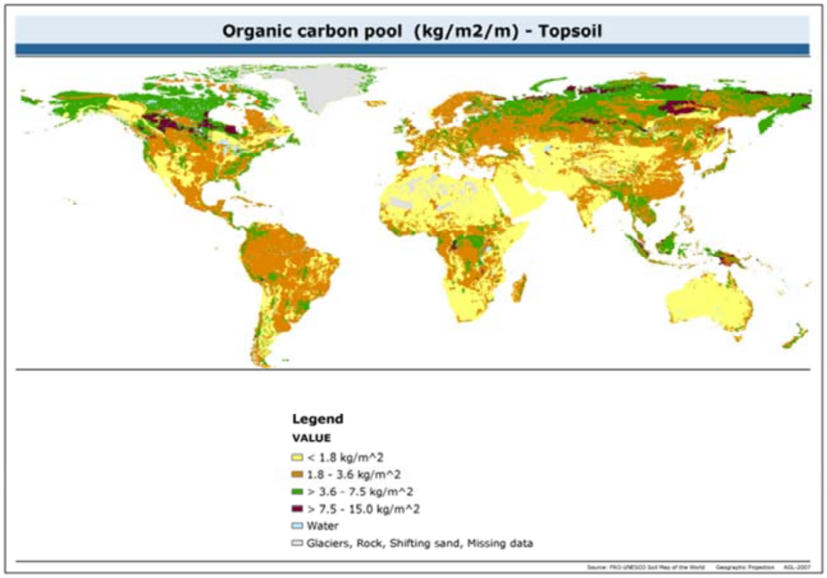
Most carbon in vegetation is in the tropical and boreal forests of the world



Global microbial C pool is 14.6 Pg-C



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Hotspots of soil carbon are the great grasslands and the peat soils of the northern wetlands and tundra

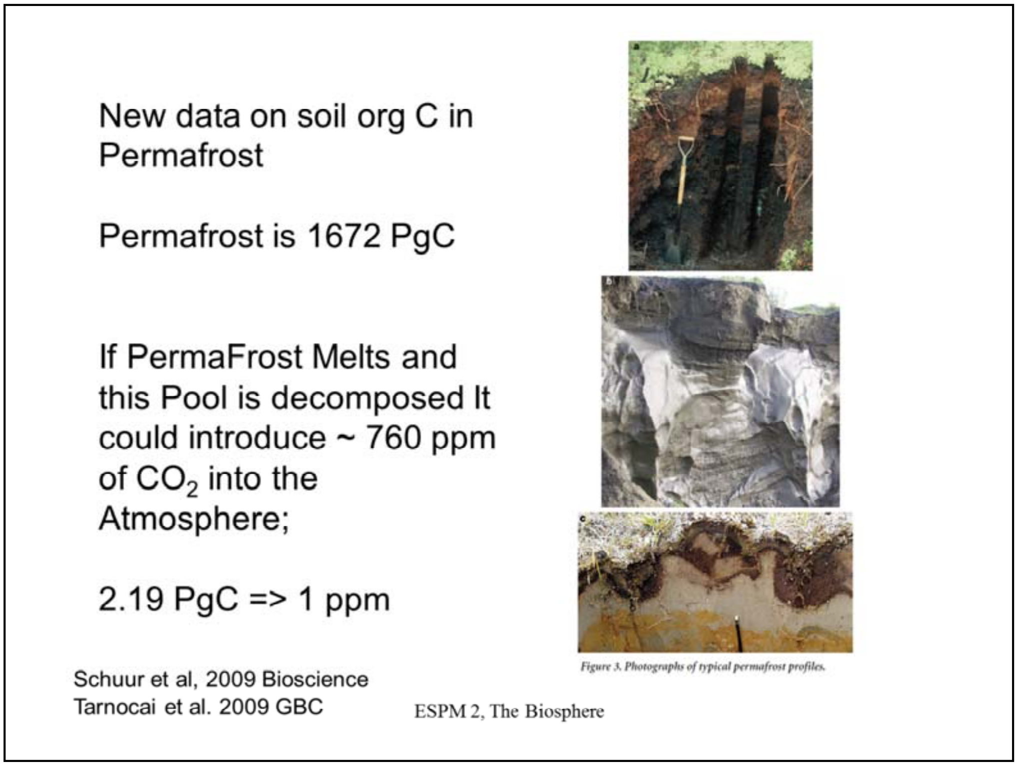
http://www.fao.org/fileadmin/templates/nr/images/resources/images/Maps/geonetwork/cp_t.png

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



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

- Three Biochemical Pathways exist for fixing CO_2
  - C3, C4 and CAM
- Photosynthesis is greatest under sunny, warm, moist conditions
- Respiration scales with temperature and photosynthesis
- Biosphere is serving the planet by taking up < 50% of C emitted into the Atmosphere by Fossil Fuel Combustion
- Ranking of C pools
  - Ocean > Soils > Atmosphere > Plants