Terrestrial Carbon Cycle, Part 1

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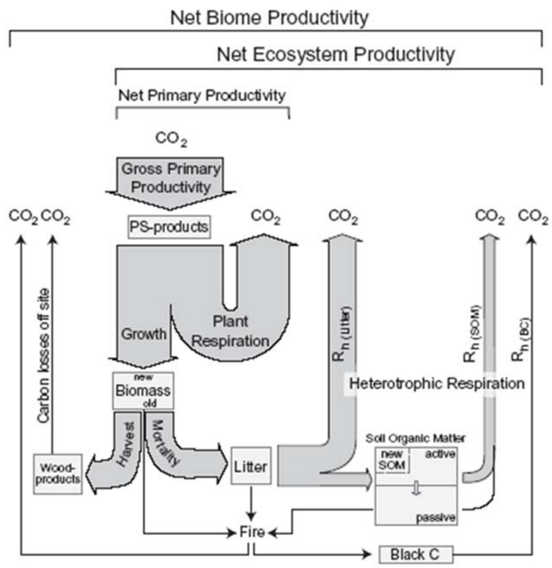
Terms and Units

- 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

I want to stress that these ecosystem carbon fluxes should refer to annual integrations of flux densities



Schulze, 2006 Biogeosciences

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

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The vector thickness relates to the relative size of the fluxes and their direction. GPP is the source of carbon and it is then partitioned, or used, in terms of growth and plant respiration. Growth is then lost through mortality and harvest. Litter fall and root turnover is consumed through heterotrophic respiration, and this is consumed through fast and slow pools of carbon. At other scales fire is a consumer of carbon and carbon can be stored for long periods as black carbon.

GPP

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

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

These assimilation fluxes are functions of CO_2 (C), light (Q), temperature (T), nutrition (N), and Soil Moisture (Θ)

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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Personally I feel there is a misuse of the term GPP. It should refer to annually integrated fluxes of carbon, which short term fluxes should be called canopy or ecosystem photosynthesis. At the physiological level it should scale with leaf area index and is a function of the carbon assimilation through carboxylation, minus carbon lost by photorespiration, or oxygenation. The later is distinct from dark respiration of the mitochondria.

Net Primary Productivity, NPP

NPP is GPP minus autotrophic Respiration, R_{auto}

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

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.

NPP is GPP minus autotrophic respiration. Ra is a function of mass of the plants, their growth rates and temperature. We should know above and below ground Ra, but often only above ground respiration is estimated. Knowing root respiration remains a challenge.

Net Ecosystem Production, NEP

NEP is NPP minus Heterotrophic Respiration, R_{hetero}

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

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

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Net ecosystem production is NPP minus heterotrophic respiration, respiration by microbes, creeply clawers (invertebrates), funghi, you and me. At the basic level it is a function of temperature, but also related to soil moisture, how much standing biomass and recent photosynthesis (a topic my group is pushing hard).

Atmospheric scientists like me use the term NEE rather than NEP. They are opposite signs and depend if the atmosphere is gaining or losing carbon, or if the ecosystem is gaining or losing carbon. So NEE is negative when NEP is positive.

Net Biome Production, NBP

NBP is NEP minus Carbon Loss via Disturbance

$$NBP = NEP - F_C(fire, herbivory, disturbance...)$$

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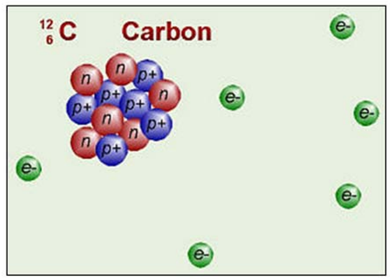
On longer time scales and at the landscape scale one has to consider episodic carbon loses due to fire, herbivory and disturbance. For example, carbon inversion studies may sample the mosaic of NBP and NEP, while an undisturbed eddy flux tower will only be sampling NEP, so there will be differences if the methods are compared as they are sampling different things.

Current State of the Terrestrial C Cycle



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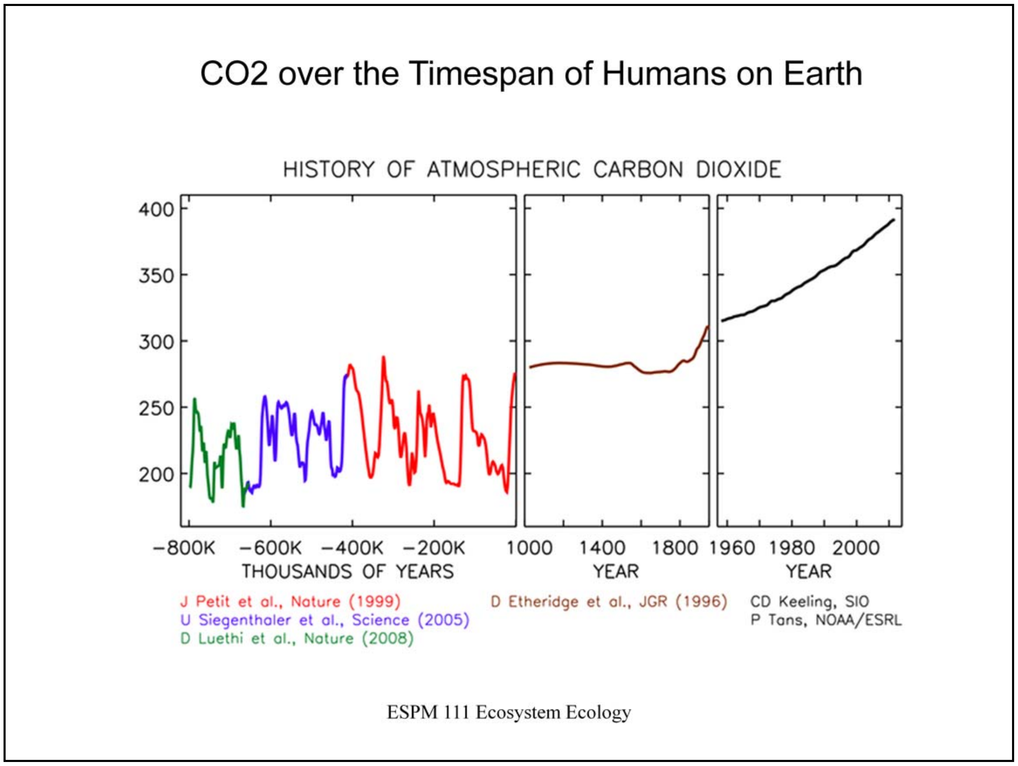
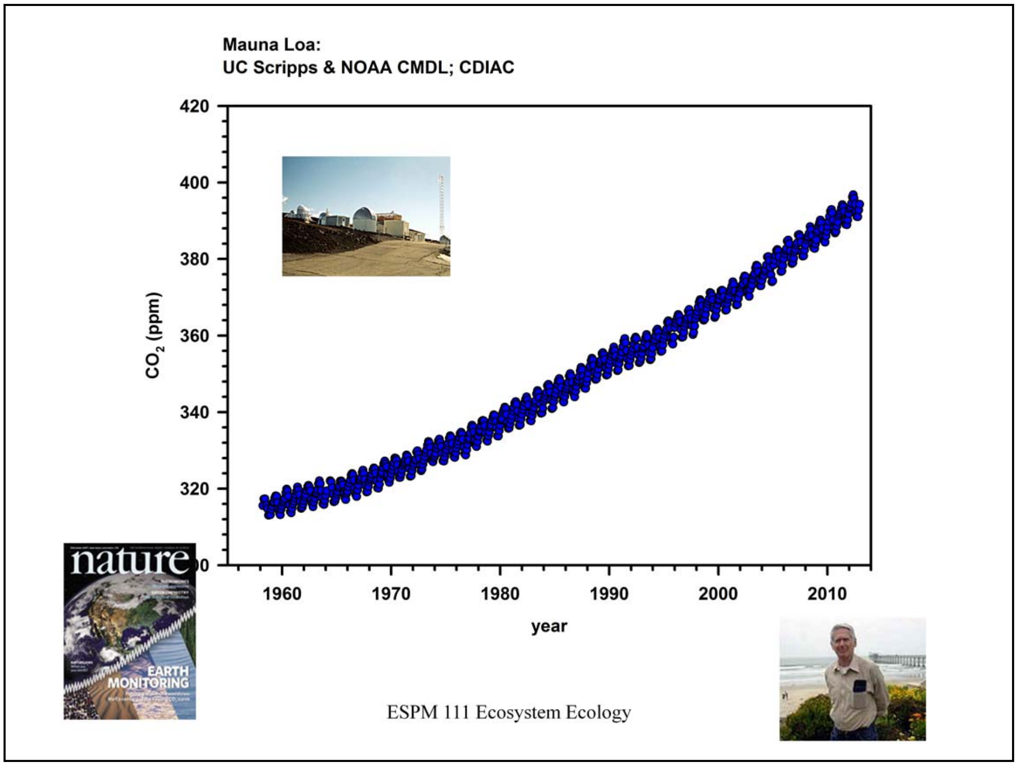
I like to keep up with the recent literature and give you the most recent review of the state of carbon. Look at the global carbon project as a source of recent data each year

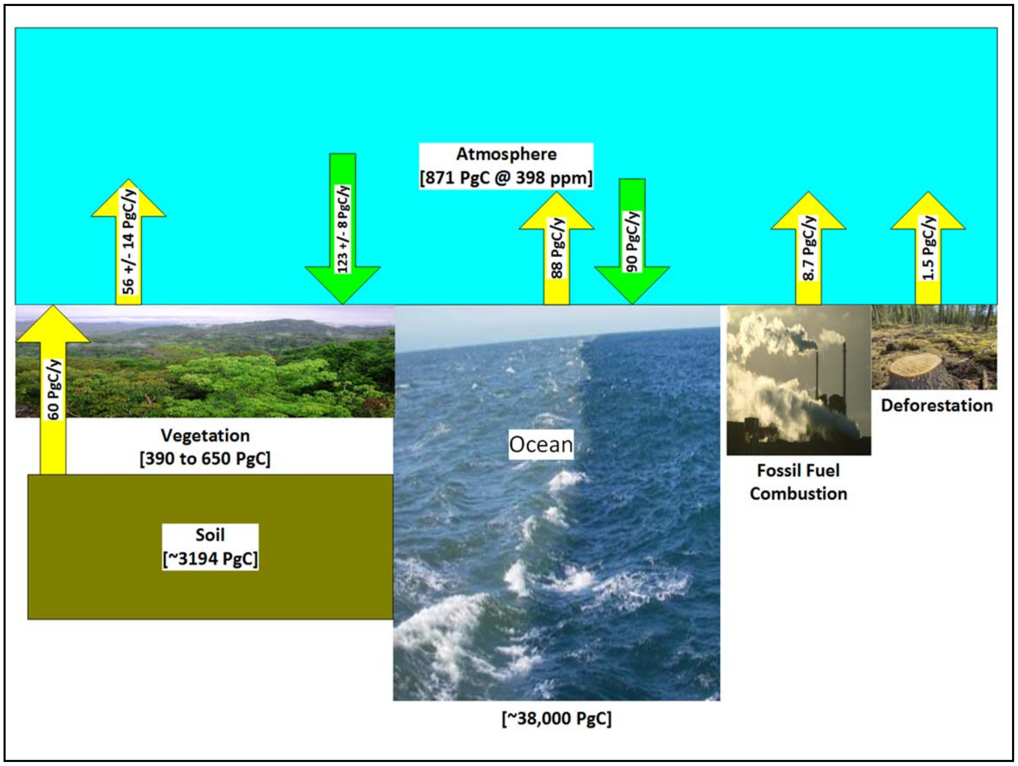
http://www.globalcarbonproject.org/



Here is a plot dovetailing the paleo record, with the pre industrial and post industrial CO2 records



The famous Mauna Lao CO2 record. At the end of 2012 it was 394 ppm. Since then this remote and well mixed local has seen 400 ppm. I am measuring CO2 at my field sites in CA and am already seeing concentrations above 400 ppm during the well mixed part of the day!



Circa 2013

Most carbon is in the ocean (38000 PgC), followed by soils (>3000PgC), the atmosphere (> 850 PgC), and then the plants (650 PgC); a new review by Pan et al 2013 puts vegetation biomass at 393 PgC; another paper puts the microbial C pool at 15 PgC.

At global and annual scales, best estimates of global photosynthesis are on the order of 120 PgC/y, with half of this value lost by autotrophic respiration and the other half by heterotrophic respiration (~ 60 PgC/y). Small differences lead to carbon uptake or losses as the world experiences a warmer, wet/dry, and higher CO2 world with more N deposition, as well as forest growth and aggradation in the developed world. Disturbance by fire and deforestation lead to about 1.5 PgC loss and fossil fuel emissions put another 7 to 8 PgC into the atmosphere each year

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 10^{15} gC/100 10^{12} m^2~10g m^{-2}=10 cm^3 m^{-2}
  - Equivalent to a 10 micron layer of water per meter-squared across the terrestrial globe
  - 1g = 1 cm^3
  - 1 m^3 = 10^6g = 1 Mt
  - 1 km^3 = 1Gt

Units are important and are throw around with impunity. Here is a short primer. Now be careful as some carbon budgets are in terms of CO2 and others in C. I like budgets in C, but there is a 44/12 ratio between the masses of CO2/C

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

- Mass of Atmosphere
  - F=M a = Mass x gravity = Pressure x Area
  - Surface Area of the Globe = 4π R^2
  - M_{atmos} = 101,325 Pa 4π (6378 10^3 m)^2/9.8 m^2 s^{-1}=
  - 5.3 10^{21} g air
- Compute C in Atmosphere @ 393 ppm (393 10^{-6})

$$\frac{Mg}{Area} = P$$

$$M_{atmos} = \frac{P \cdot 4\pi R^2}{g}$$

$$M_c = M_{atmos} \frac{p_c}{P} \frac{m_c}{m_a} = 860 \cdot 10^{15}\, gC$$

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

$$M_c / (\frac{p_c}{P}) = 2.19 \quad \text{Pg/ppm}$$

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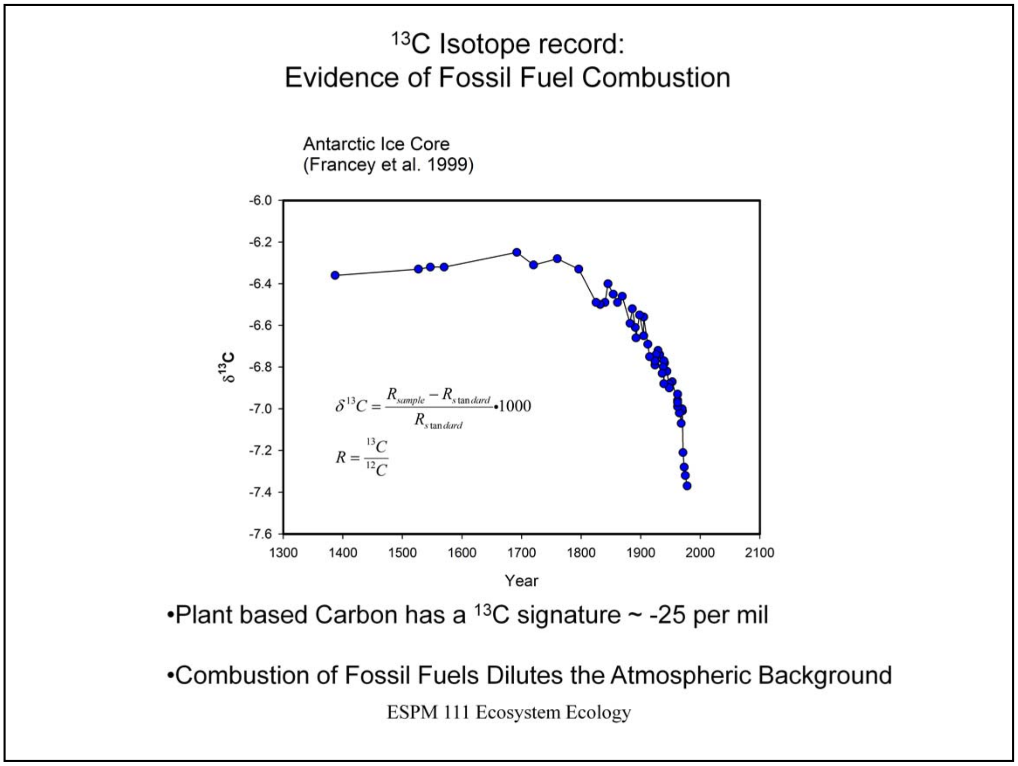
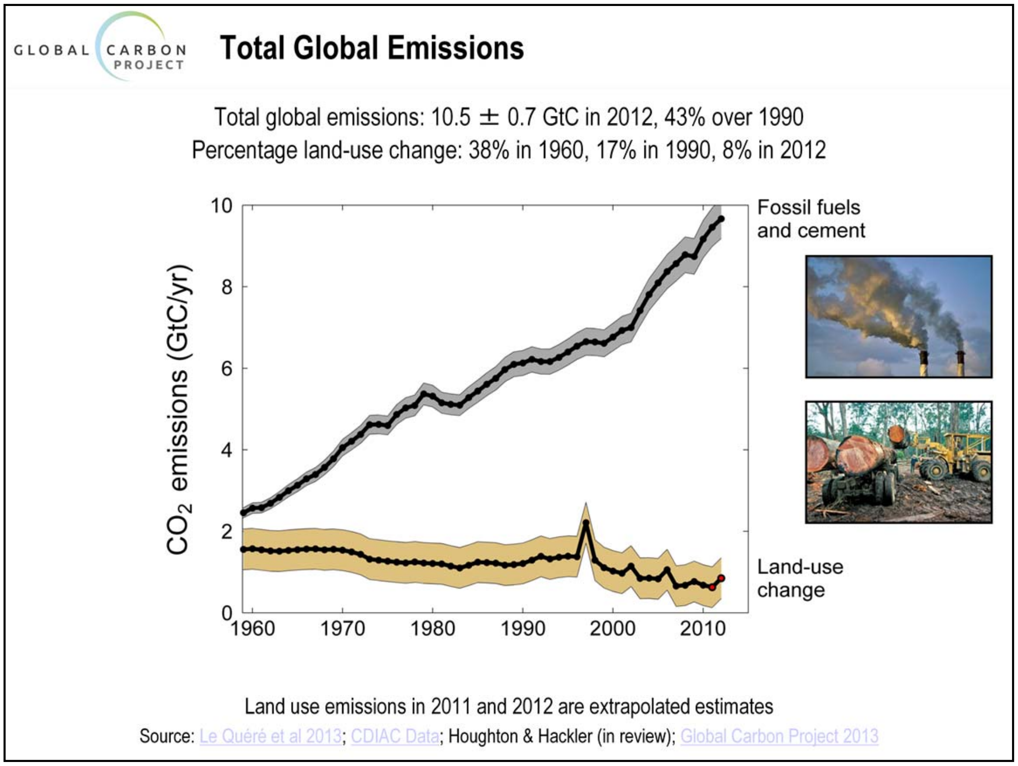
The other problem we face is translating information between CO2 and emissions. This primer is handy for this conversion



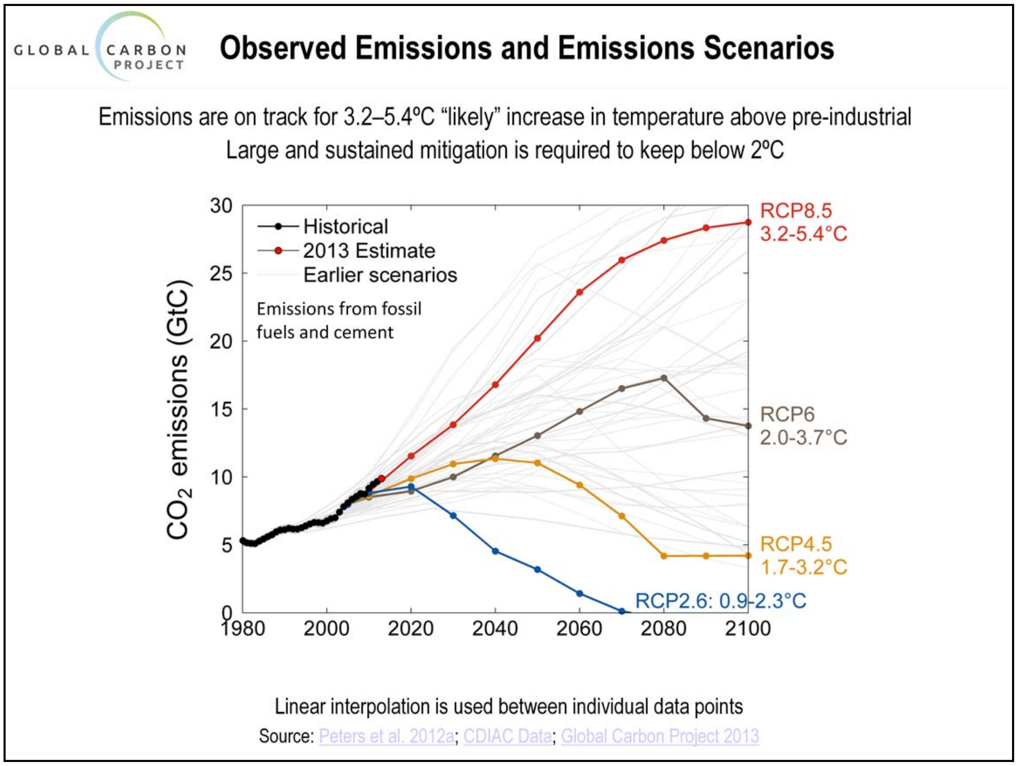
I get tired of hearing people say I don't believe in global warming and human kind is not responsible. The smoking gun is the combination of the direct measurements of CO2 in the atmosphere, shown above, and the trend in the stable isotope 13C. Photosynthesis discriminates between 12C and 13C, so carbon in fossil fuel has a distinct isotopic signature due to its C3 photosynthesis (~ -25 per mill). So the combustion of this fuel will dilute the atmospheric signal and make the 13C signal of the air more negative, as has been observed since the onset of the industrial revolution!

$$\delta^{13}C = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000 \text{ ‰}$$

where R = 13C/12C



Most recent carbon emission budget. It keeps trending upward. If you have listened to my lectures in the past, we MUST reverse this trend not only now, but we should have decades ago. With changes in life style, population and economic growth and persistence on using fossil fuels to drive our world, we will only expect more and higher emissions into the future

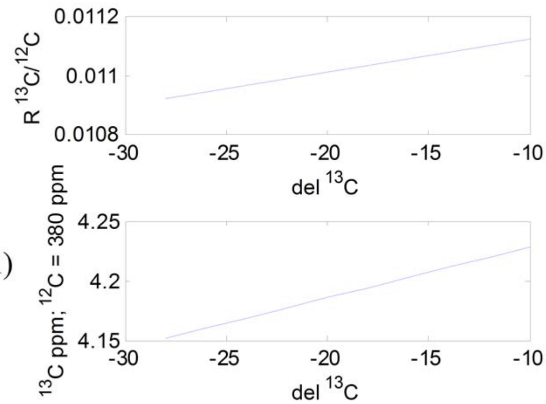


How Serious are Contemporary C Emissions?:
We Are Exceeding the More Extreme Scenarios,
So it is Less Likely Warming will be < +2 C

Stable Isotopes

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

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



R_{std} = Peedee Belemnite = 0.0112372

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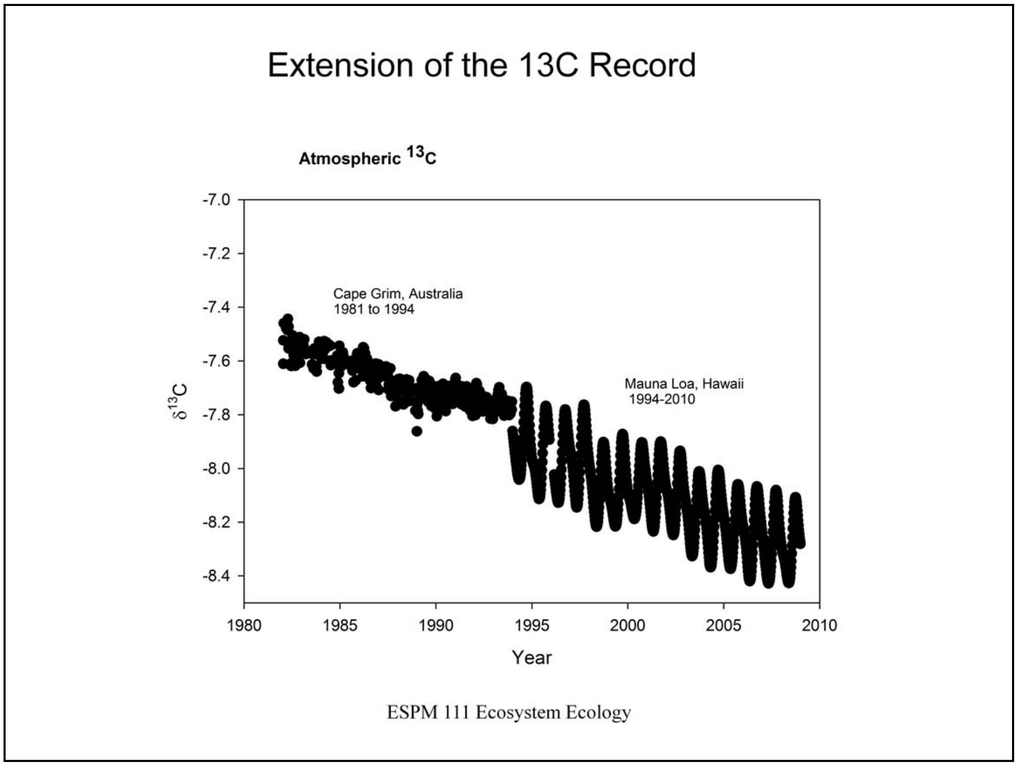
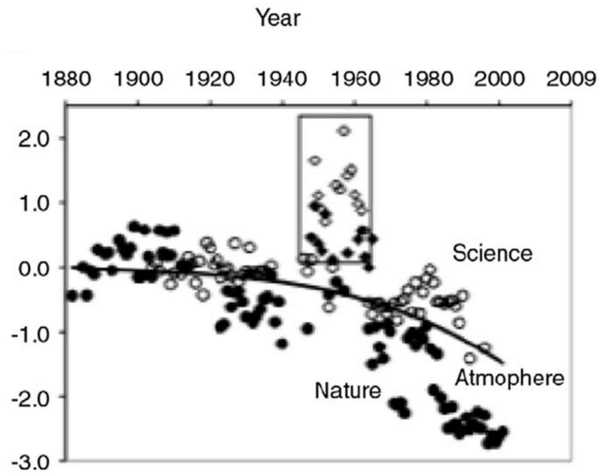
Graphical and numerical explanation of del 13C



I like to add more recent data and here it is. Trends in decreasing -13C continue to today

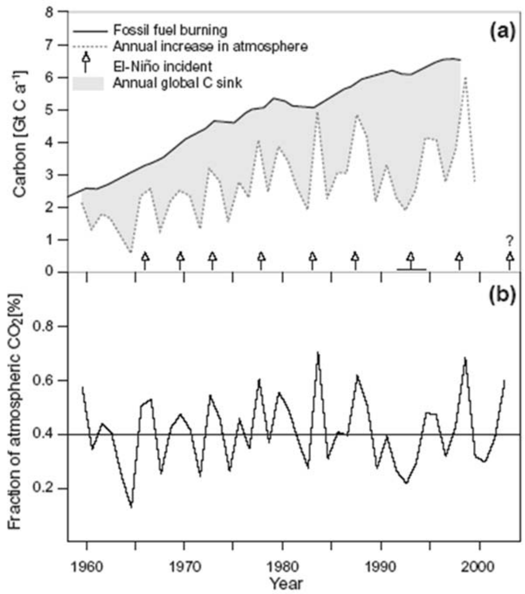
^{13}C Recorded in Old and New Newspapers

Environ. Res. Lett. **6** (2011) 034007



Yakir, 2011

Clever science. Dan Yakir 2011 ERL sampled 13C from Newspapers! To add to the record from icecores



Ecosystem Service:
Only ~45% of CO_2 emitted into the atmosphere remains there

Schulze 2006, Biogeosciences

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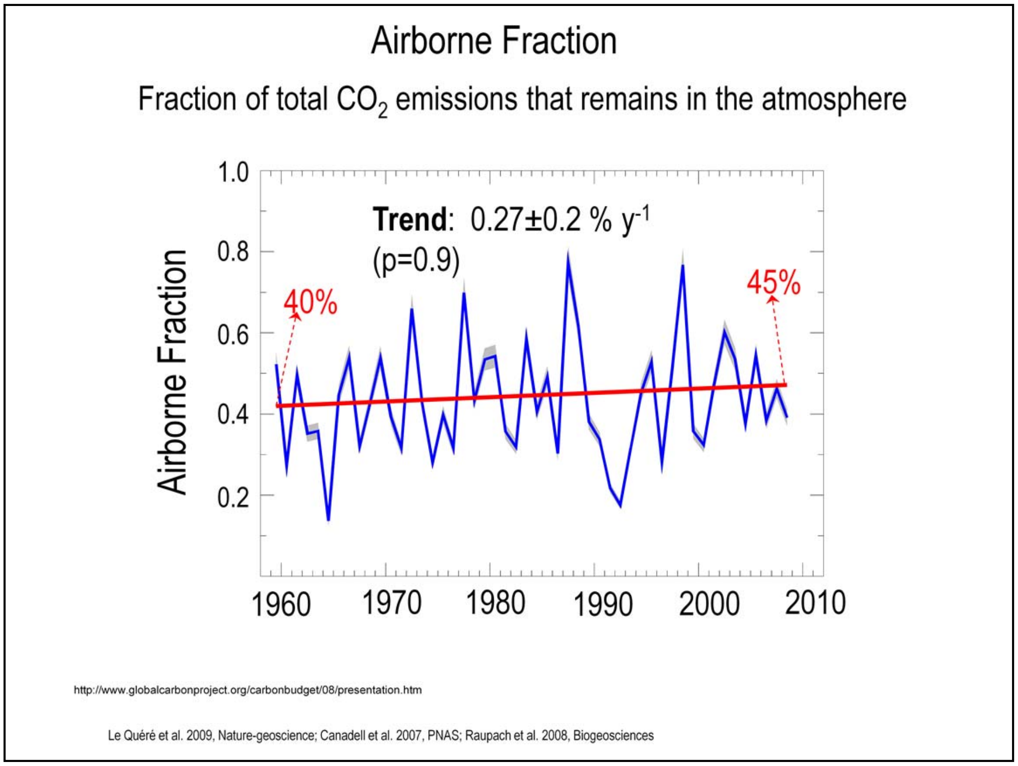
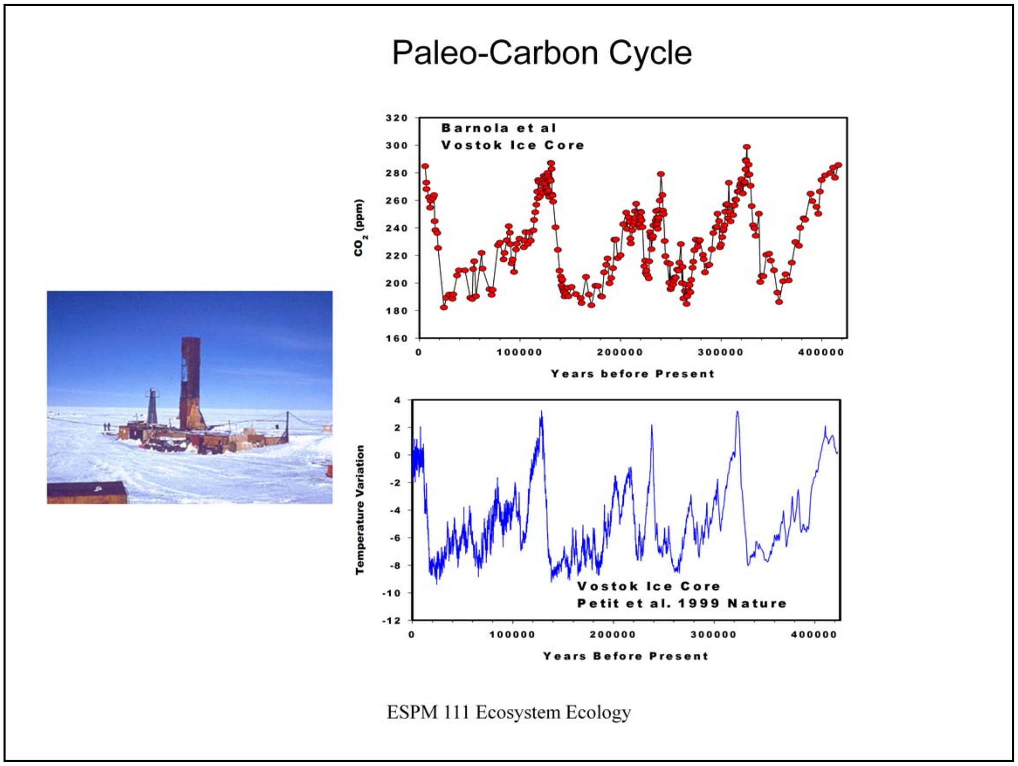
The good news is that Not all of the Carbon we emit into the atmosphere stays there. The airborne fraction is about 45%. The land and oceans provide a huge ecological service by pulling out a large fraction of this carbon



The bad news is that the airborne fraction is trending upward. The efficacy of the biosphere to take up carbon is declining as the worlds forests are aging, the oceans are acidifying, and photosynthesis acclimates to high co2

Natural land and ocean CO2 sinks removed 57% (or 5.3 PgC per year) of all CO2 emitted from human activities during the 1958-2008. During this period the size of the natural sinks has grown but at slower pace than emissions have grown, although year-to-year variability is large. This implies a decline in the efficiency of the sinks in removing atmospheric CO2 over time (from 60% fifty years ago down to 55% in recent years), a trend expected to continue the future. Models suggest the sinks are responding to climate change and variaiblity..

Compared to the last previous three years, the CO2 sink in 2008 was larger on land (in terms of uptake rate) and smaller in the ocean, because El Niño/Southern Oscillation (ENSO) was in a positive (La Niña) state in 2008. Both ocean and land sinks are modelled (see next two sections) but their results need to agree with the closing of the budget, that is all carbon sources should equal all carbon sinks (either measured or modelled). For the period 2000-2008, the difference is 0.3 PgC of the 9.1 PgC per year average emissions during the period. This residual is probably due to errors in the estimate of the land sink.



What fascinates me is how the glacial record of temperature and CO2 are in nearly lock step. During ice ages CO2 drops to about 180 ppm, time and time again. During the interglacial periods CO2 is capped at about 280 ppm. This is clear in this record going back 400,000 years and continues if we inspect the ice core record back 900,000 years; I did not show it because it becomes cluttered.

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

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I like to show these changes in the carbon budget as a perspective toward our contemporary carbon budget that is changing by the biosphere on the order of several petagrams per years, rather than terra grams. It shows to me the degree to which our current carbon budget is way out of equilibrium.

CO_2 in the past

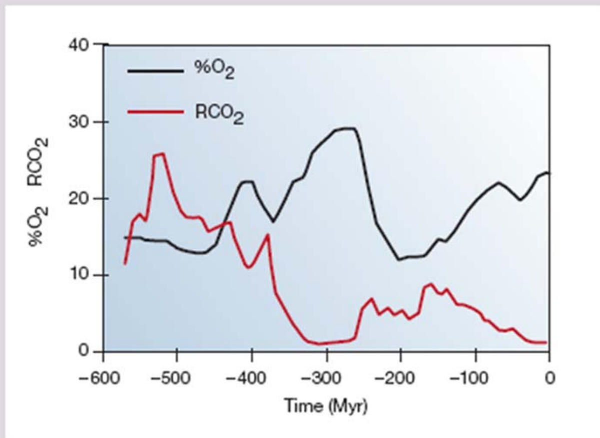

Figure 5 Plots of RCO_2 (the ratio of the mass of carbon dioxide in the atmosphere in the past to that for the pre-industrial present) and $\%O_2$ during the Phanerozoic eon. (Values of RCO_2 from the GEOCARB III model[33]; values of $\%O_2$ from ref. 11 using the ^{13}C data of refs 12 and 13). Estimated errors are ±50% for RCO_2 and ±7% for O_2.

Berner, Nature, 2003

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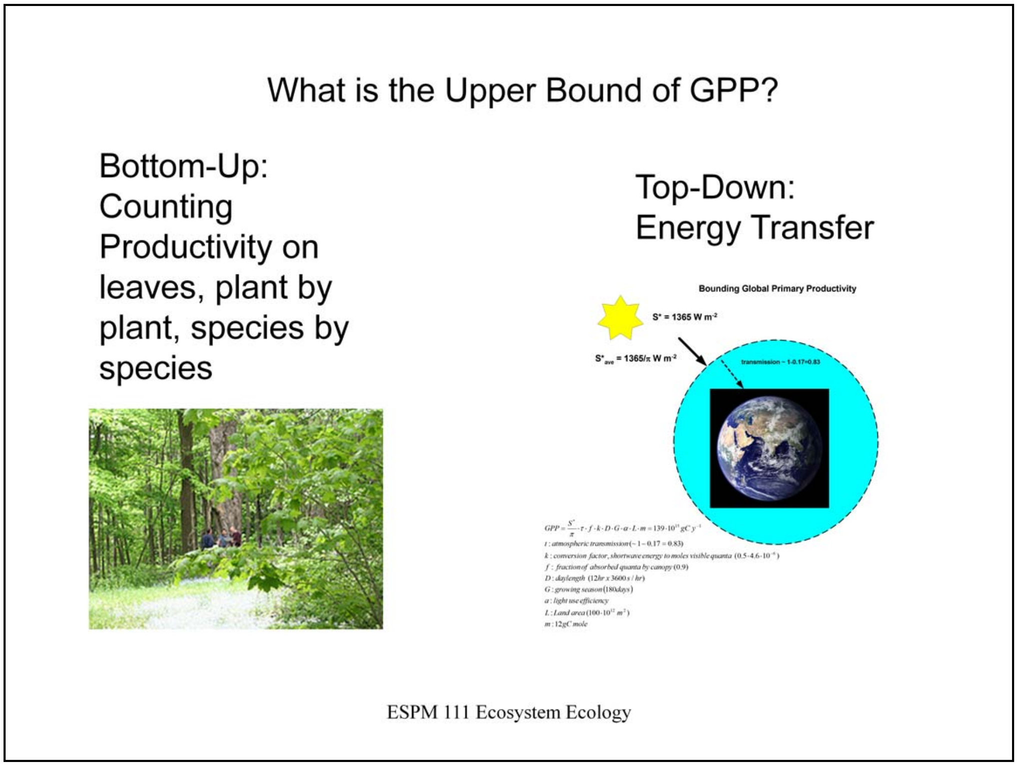
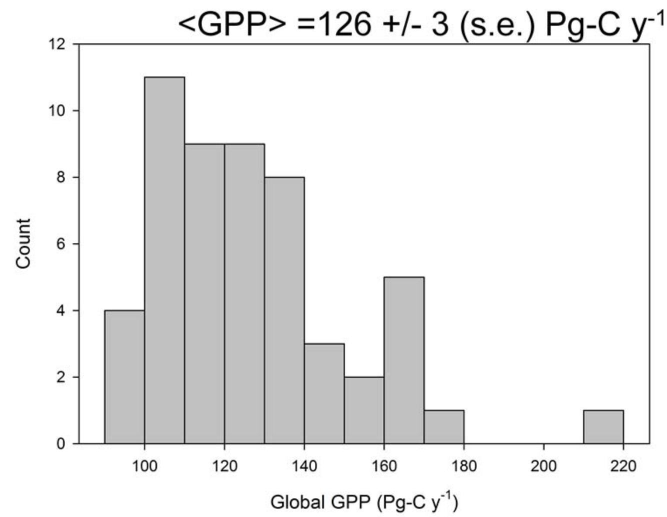
I want you to realize ecosystem ecology occurred in the geological past, just different constraints in terms of plants, land mass, climate and the resulting carbon in the atmosphere and whether it was sequestered or not. You can see during the carboniferous large drawdown in CO2, and that CO2 levels were more than 10x today. Hence the net and gross fluxes of C of those ecosystems were much different than today.

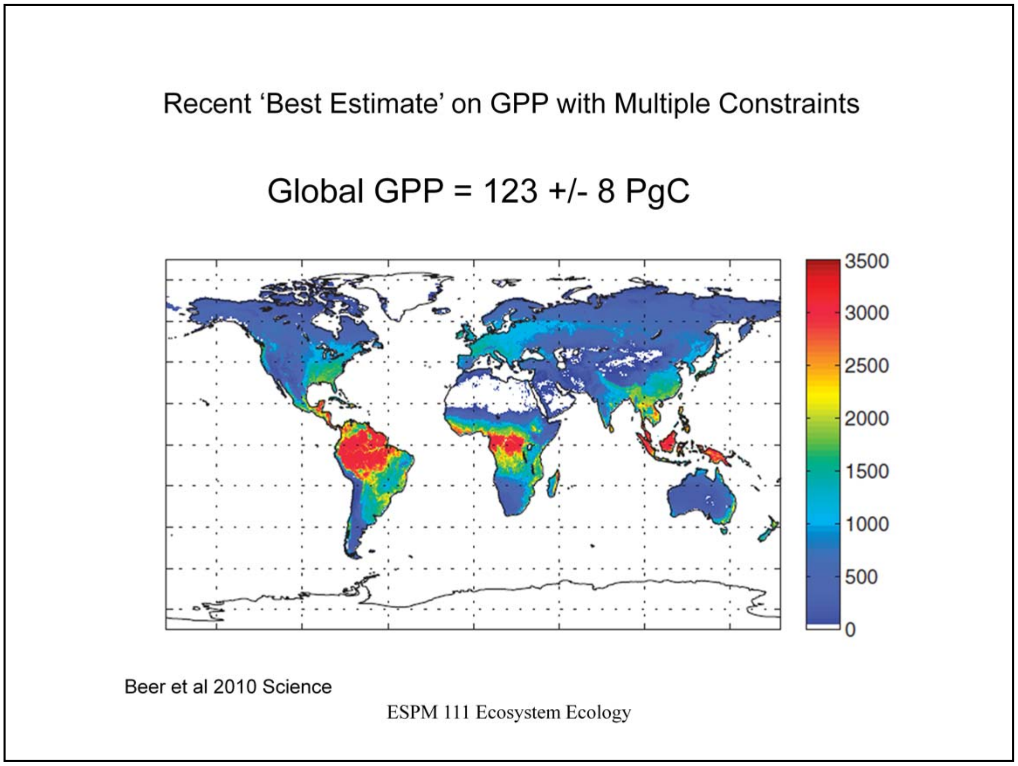


Prior to the previous study, I used to ask myself, for the sake of teaching this material what is the upper limit, if we start with the sun, solar constant and perform some back of the envelope computations

Annual Global Primary Productivity, GPP, Remains Highly Uncertain



My survey of the literature shows a wide range of plausible, and implausible estimates of global gpp. Numbers on the high side, if true, would be solving the worlds carbon problem. So I feel they are not credible. I tend to fancy values on the order of 120 PgC/y. My frustration is lately as the models have gotten more 'sophisticated' they seen to be producing larger and more incredible numbers. As a biometeorologist I criticize and challenge many of these models because they do not consider the upscaling of non linear processes that require us to compute photosynthesis on the sunlit and shaded portions of plant canopies. When we do this we get more realistic estimates of GPP that tend to converge with the data driven estimates of global photosynthesis.



Here is the data driven estimate of GPP I was referring to. I was a co-author of this paper, where the lead authors used a data driven approach based on satellite remote sensing, gridded climate data and the fluxnet database of direct measurements of GPP to map and integrate annual fluxes. This is probably the most intense data driven method to date. I will admit no method is perfect as there is not instrument to measure global, annual GPP. We have to put the pieces together as best we can. Hence more opportunities for ecoinformatics and data mining..jobs of the future.

Upper-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)
- 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 10^{12}*43200*180*12/(4 10^6)=120 * 10^{15} gC y^{-1}

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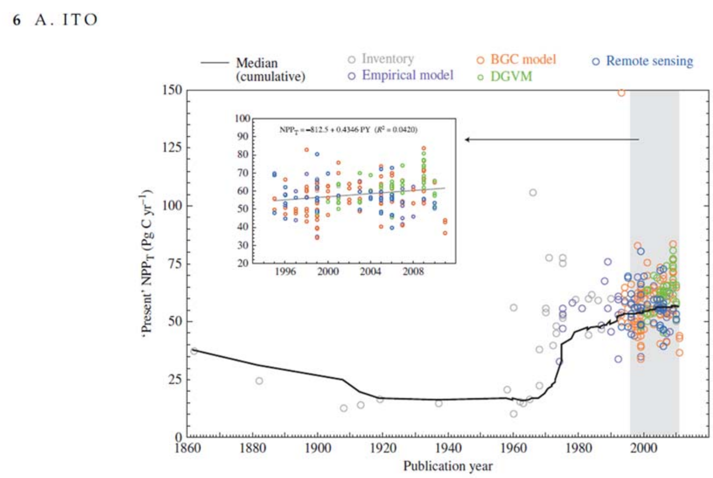
Interestingly I come up with a value on the order of 120 PgC/y of GPP with a set of assumptions and unit conversions

NPP = 56.4 PgC/y +/- 14



Ito 2011, GCB

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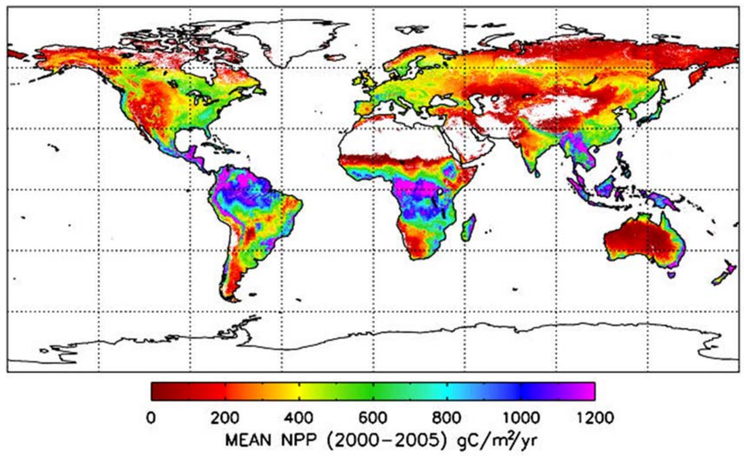
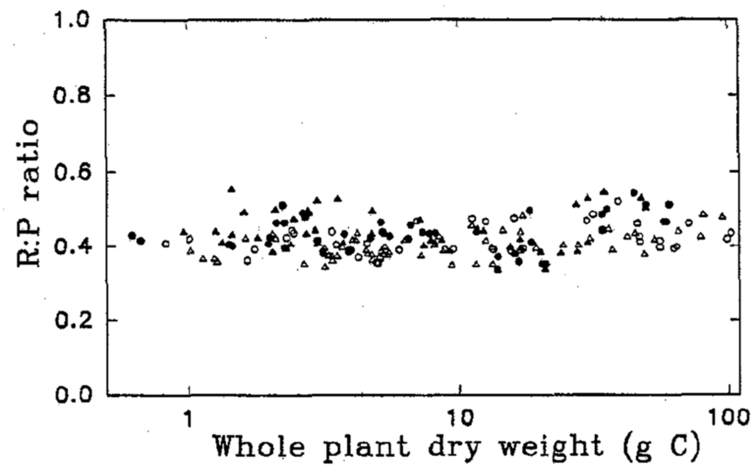
Ito did a nice job surveying the NPP literature and shows how it is converging on a value near 56 PgC/y. Yet, here too there is much uncertainty, +/- 14 PgC/y. Remember back on the interglacial changes in CO2 we deduce changes to be on the order of 2-20 TgC/y (land and ocean). So our current ability to measure and evaluate NPP and GPP remain highly noisy and uncertain. Room for future and better work. Needed to attribute changes in the carbon cycle due to global change (CO2, N deposition, aggrading and degrading forests, land use change, warming, changing water cycle)

NPP ~ 0.5 GPP



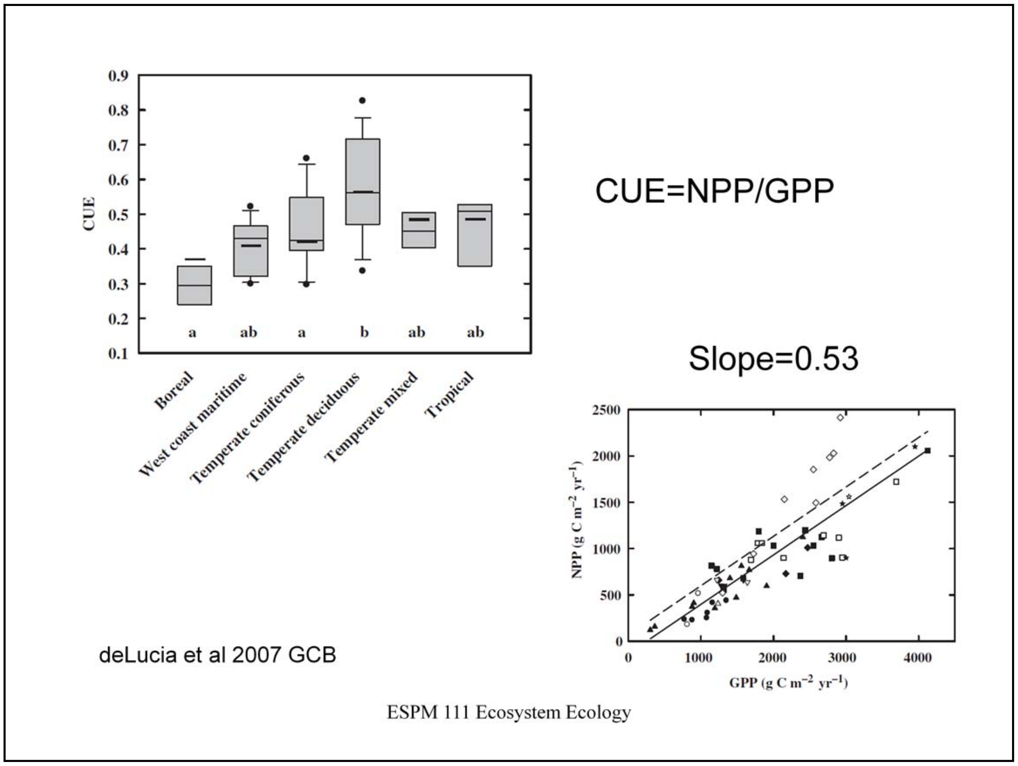
http://secure.ntsg.umt.edu/projects/files/images/mod17/Figure6.jpg

A common rule of thumb is that NPP is one half GPP.



Gifford 1994 Aust J Plant Physiol

I tend to favor this simple ratio based on the detailed whole plant studies reported in Gifford, 1994. Across a spectrum of plant sizes this ratio held. Now granted this was mostly for herbaceous plants, not trees and woody plants which may experience different allocation costs. But this paper is strong since they could measure whole plant respiration, rather than infer it from sporadic measurements.



Conventional wisdom is that CUE is constant, near 0.47 based on studies by Gifford, Waring and Landsberg. deLucia surveys the literature and argues that how CUE is derived may mask some of the natural variability in CUE. This is partly true, but I tend to worry and be critical of ratios, so called efficiencies, used in the ecological literature. They can be numerically unstable if the denominator is small, if the measurements possess high sampling errors, or if the denominator is derived from the numerator, as is much of the CUE literature. I prefer to like looking as slopes, dNPP/dGPP to study relationships, as they fit data through lots of the natural noise. I am also a bit sympathetic to the idea that NPP/GPP is close to 0.5 from the early work of Gifford, who did greenhouse studies on many plants and saw a tight relation and the insights of Dick Waring and Joe Landsberg.

Concepts, Fluxes, Pools and Time Constants

$$\frac{dC}{dt} = (F_{in} - F_{out}) / V$$

Flux, F: moles/y
Volume, V: m^3
Mole Density, C: mole/m^3

$$\frac{F}{V} = \frac{C}{\tau}$$

Flux per Volume ~ Mole Density/turnover time

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

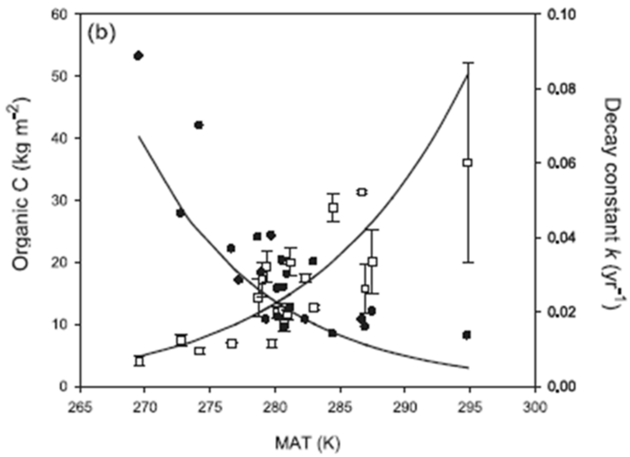
C Turnover Time:
Mass/Flux

- 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

Biome	Area 10^6 km^2	Soil C (Pg)	Plant C (Pg)	NPP (Pg y^{-1})
Tropical Forest	17.5	692	340/**262**	21.9
Temperate forest	10.4	262	139/**47**	8.1
Boreal forest	13.7	150	57/**54**	2.6
Arctic Tundra	5.6	144	2	.5
Mediterranean Shrubland	2.8	124	17	1.4
Crops	13.5	248	4/**11**	4.1
Tropical Savanna and Grassland	27.6	345	79	14.9
Temperature Grassland	15	172	6	5.6
Desert	27.7	208	10	3.5
Total	149.3	2344	652/**394**	62.6

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

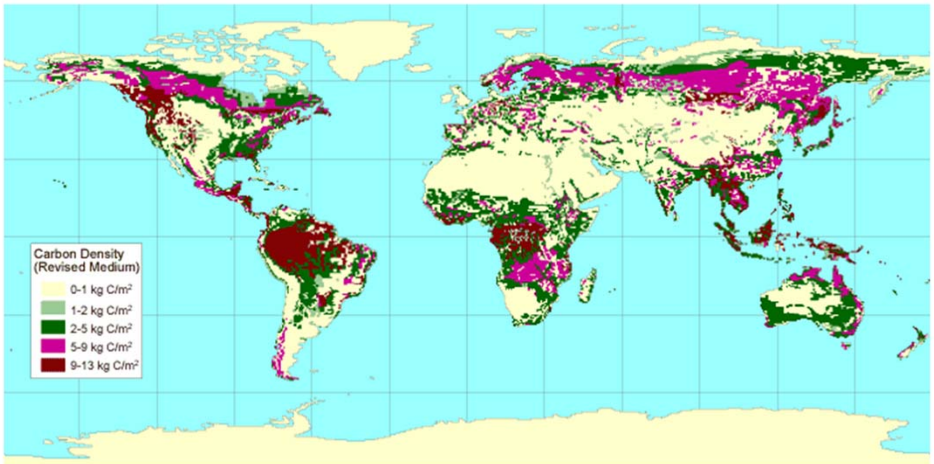
Saugier et al/Sabine et al/ **Pan**

GPP by Biome

Biome	GPP (PgC y-1)
Tropical Forest	40.8
Temperate Forest	9.9
Boreal Forest	8.3
Tropical Savanna/grassland	31.3
Temperate Grassland/Shrubland	8.5
Desert	6.4
Tundra	1.6
Crops	14.8

Beer et al., 2010 Science

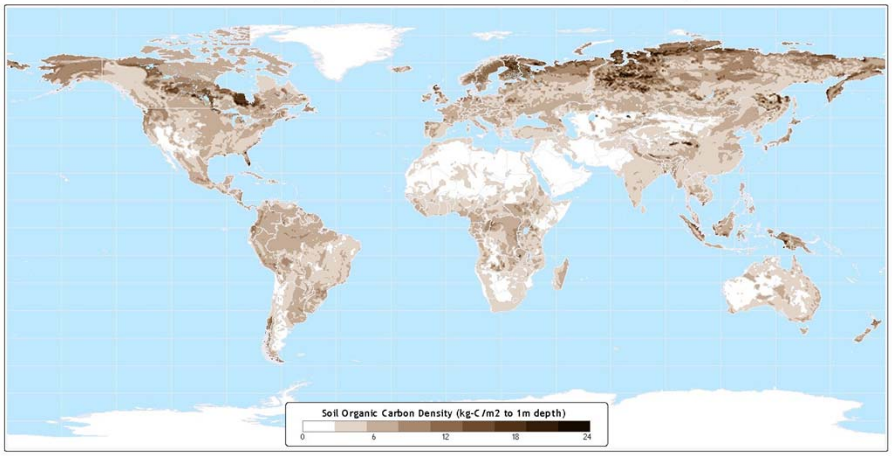
Global Vegetation Carbon Content



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

Newest data from Pan et al 2013 Ann Rev Ecol, reports global carbon content of vegetation is 393 PgC. This is lower than numbers I have seen reported in the past. They report that global vegetation carbon was about 770 PgC 10,000 years ago, pre agricultural, and near the post glacial period

Soil Organic Carbon Density



Data taken from: IGBP-DIS Global Soils Dataset (1998)

Atlas of the Biosphere
Center for Sustainability and the Global Environment
University of Wisconsin - Madison

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Soil carbon maps are getting better as scientist are digging deeper into the permafrost. Old estimates were low by 1000 PgC!

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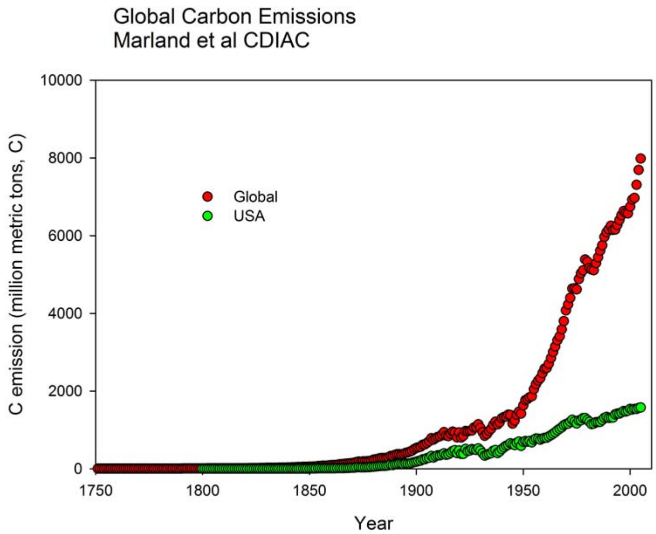
Gross Carbon Fluxes

- Gross Terrestrial Photosynthesis
  - 120 10^{15} gC/y
- Net Terrestrial Photosynthesis
  - 60 10^{15} gC/y
- Autotrophic Respiration
  - 60 10^{15} gC/y
- Heterotrophic Respiration
  - 60 10^{15} gC/y
- Oceanic Photosynthesis
  - 90 10^{15} gC/y
- Oceanic Respiration
  - 88 10^{15} gC/y
- Ocean Net Primary Production
  - 48 10^{15} gC/y

US Directly accounts for about ¼ of Global C emissions,
More if we consider C emissions for Imports from China



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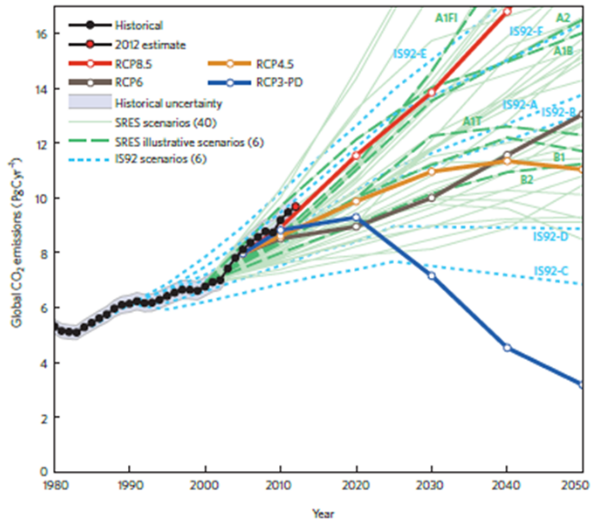
How Serious are Contemporary C Emissions?: We Are Exceeding the More Extreme Scenarios, So it is Less Likely Warming will be < +2 C



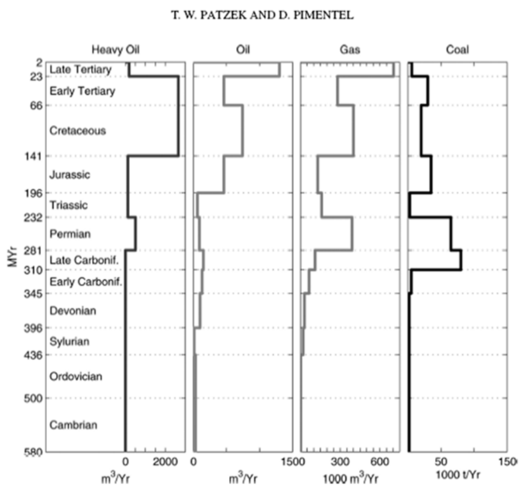
Peters et al 2012, Nature Geoscience

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 77),
shales (600 mg kg-1),
limestone (73 mg kg-1 78)

[Wlotzka, 1972].

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



Most Coal Deposited during Carboniferous, 300 Ma

Patzek and Pimental, 2005 Crit Rev Plant Sci

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Depletion of Fossil Fuel store: 1 year vs 175,000 years of C input