Terrestrial Carbon Cycle, Part 1

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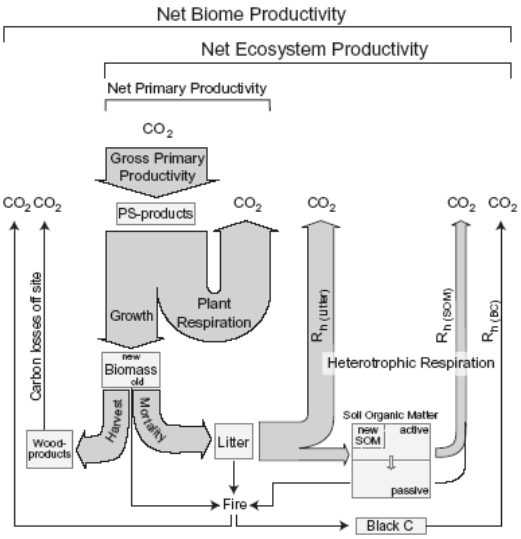


- NBP
- NEP
- GPP
- NPP
- R_h
- R_a

Schulze, 2006 Biogeosciences

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

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)

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.

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;

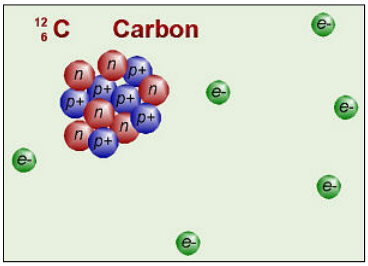
It is a function of temperature, soil moisture, carbon content, its lability, and priming from recent photosynthesis

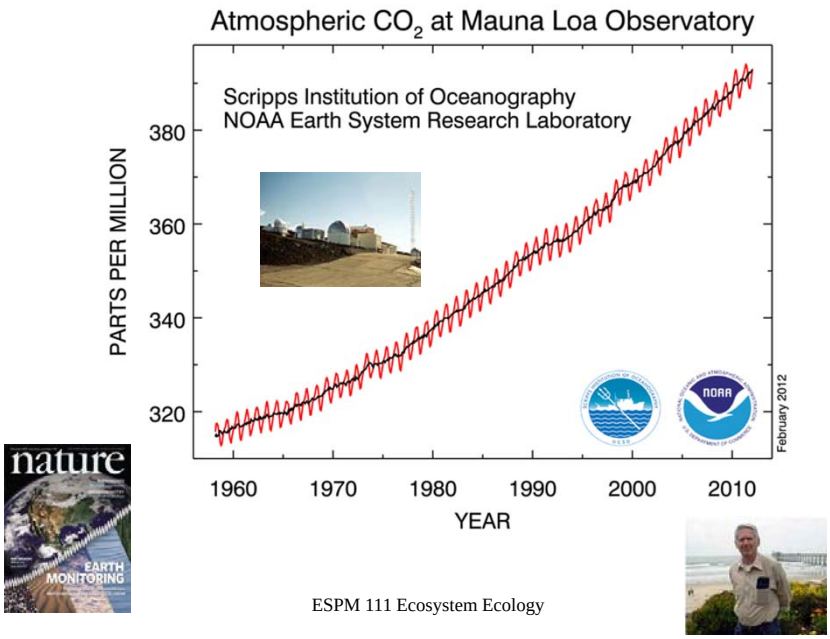
Net Biome Production, NBP

NBP is NEP minus Carbon Loss via Disturbance

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

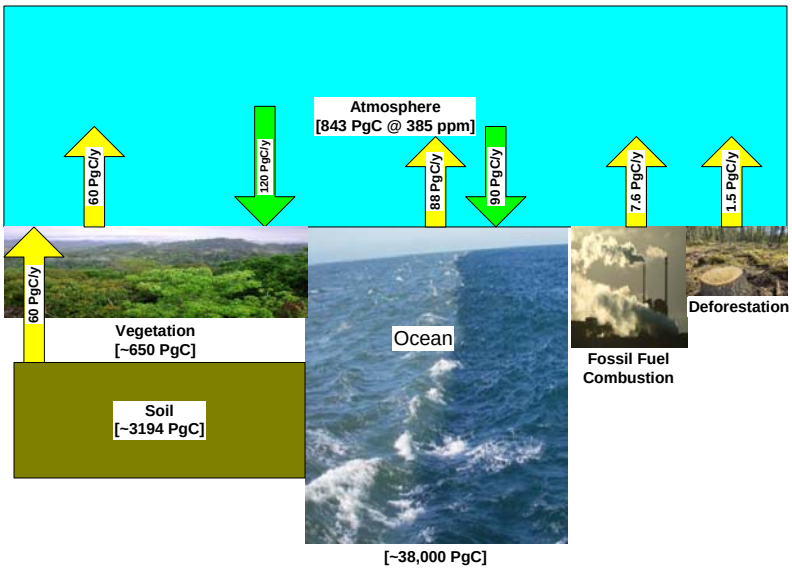
Current State of the Terrestrial C Cycle





ESPM 111 Ecosystem Ecology

Global Carbon Cycle: Gross Fluxes and Pools



ESPM 111, Ecosystem Ecology

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

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 = $4\pi R^2$
  - 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})

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

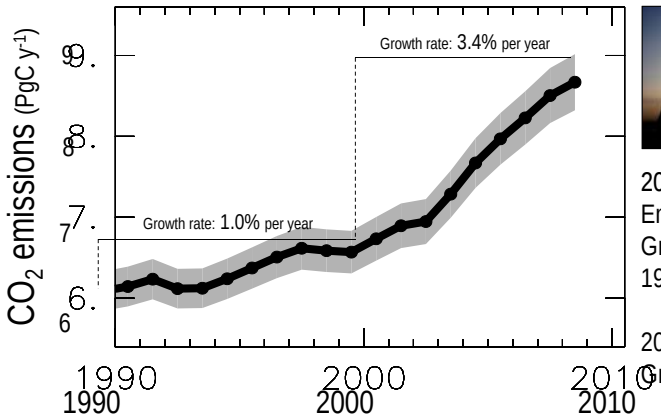
$$M_c = M_{atmos} \frac{p_c}{P} \frac{m_c}{m_a} = 860 \cdot 10^{15} gC$$

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

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

Fossil Fuel Emissions and Cement Production

[1 Pg = 1 Petagram = 1 Billion metric tonnes = 1 Gigatonne = $1x10^{15}$g]

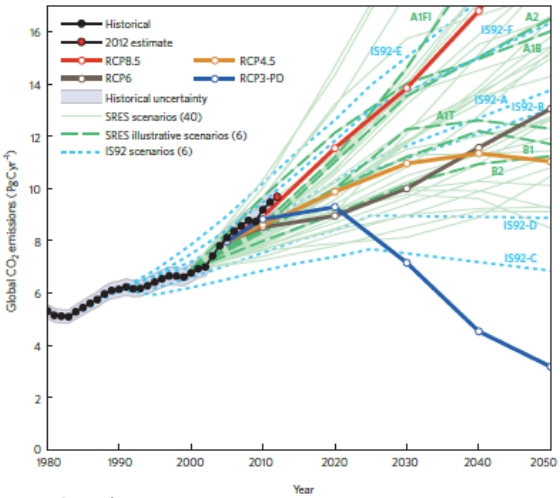


2008:
Emissions: 8.7 PgC
Growth rate: 2.0%
1990 levels: +41%

2000-2008
Growth rate: 3.4%

Le Quéré et al. 2009, Nature-geoscience; CDIAC 2009

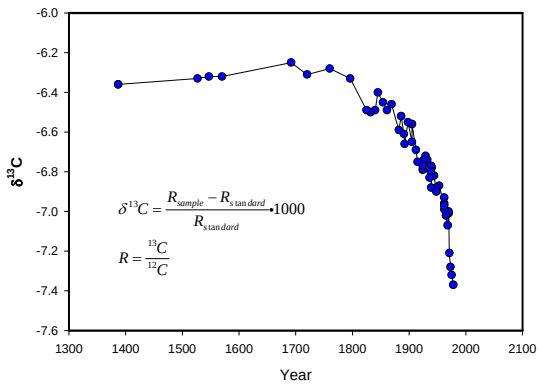
How Serious are Contemporary C Emissions?: We Are Exceeding the More Extreme Scenarios, So it is Less Likely Warming will be < +2 C



Peters et al 2012, Nature Geoscience

^{13}C Isotope record: Evidence of Fossil Fuel Combustion

Antarctic Ice Core
(Francey et al. 1999)



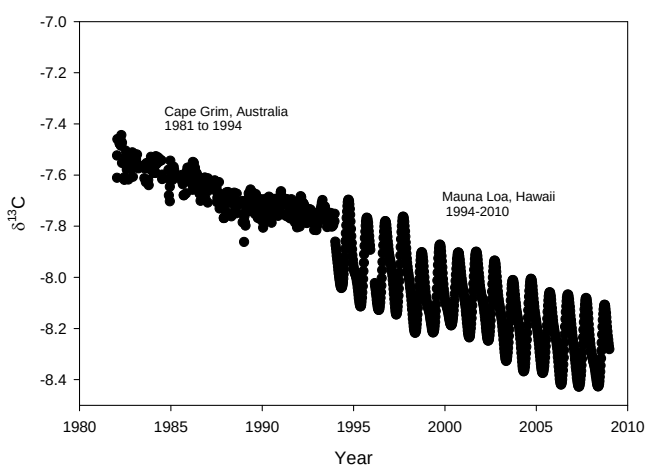
$$\delta^{13}C = \frac{R_{sample} - R_{standard}}{R_{standard}} \bullet 1000$$

$$R = \frac{^{13}C}{^{12}C}$$

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

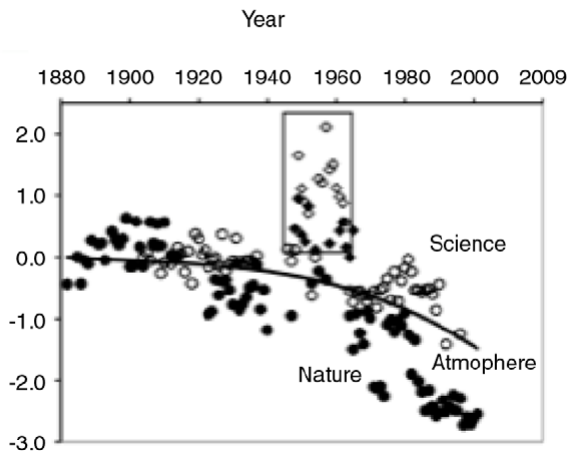
Extension of the 13C Record

Atmospheric ^{13}C



^{13}C Recorded in Old and New Newspapers

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



Yakir, 2011

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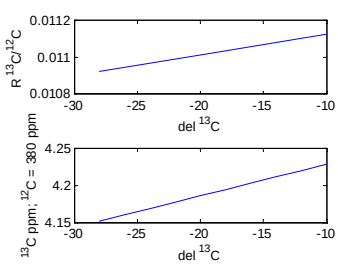
Stable Isotopes

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

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

R_{std} = Peedee Belemnite = 0.0112372



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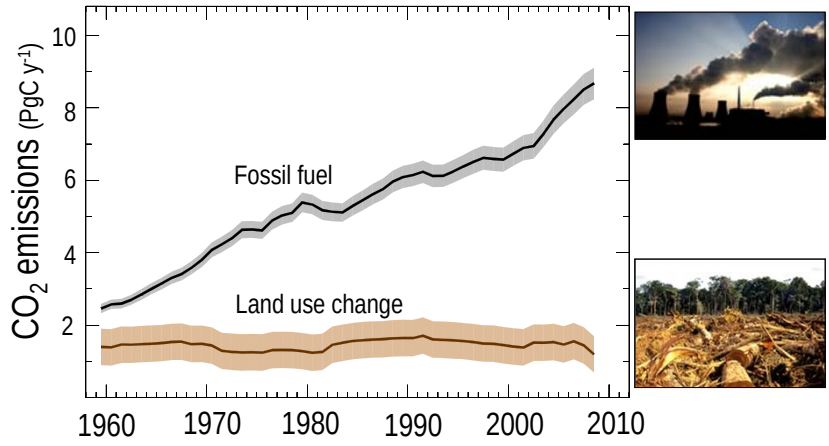
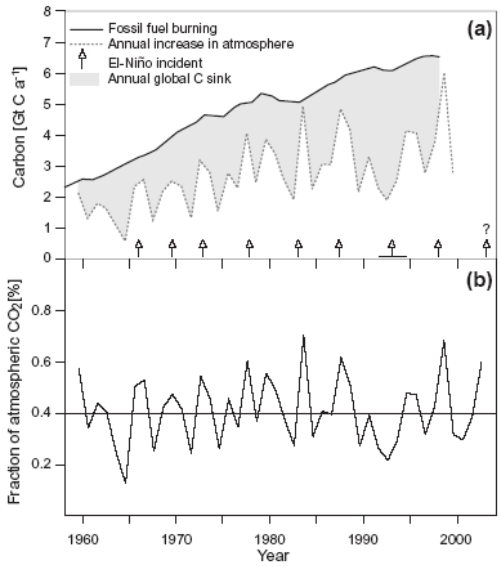
CO_2 Emissions from Land Use Change



Le Quéré et al. 2009, Nature-geoscience; Data: CDIAC, FAO, Woods Hole Research Center 2009

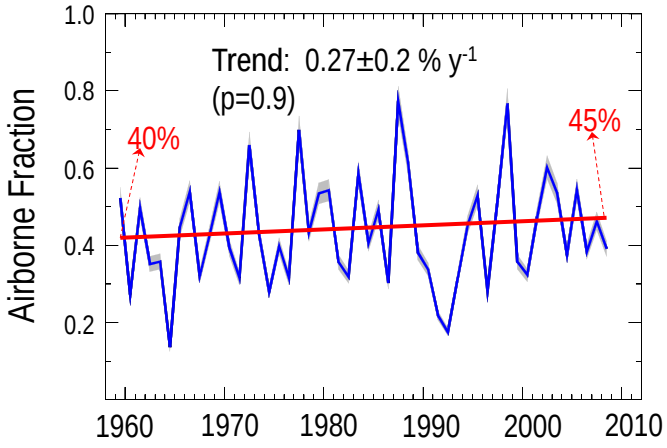


Ecosystem Service:
Only ~45% of CO_2 emitted into the atmosphere remains there

Schulze 2006, Biogeosciences

Airborne Fraction

Fraction of total CO_2 emissions that remains in the atmosphere



http://www.globalcarbonproject.org/carbonbudget/08/presentation.htm

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

CO_2 in the past

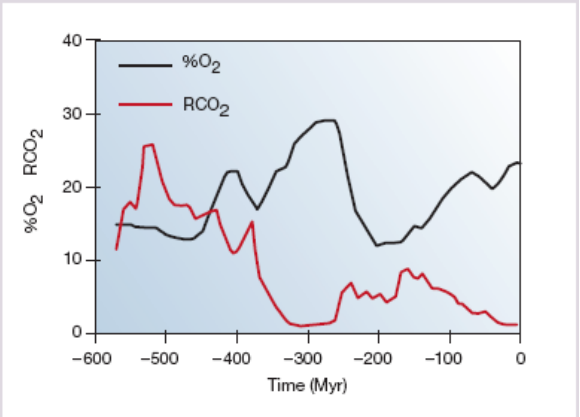
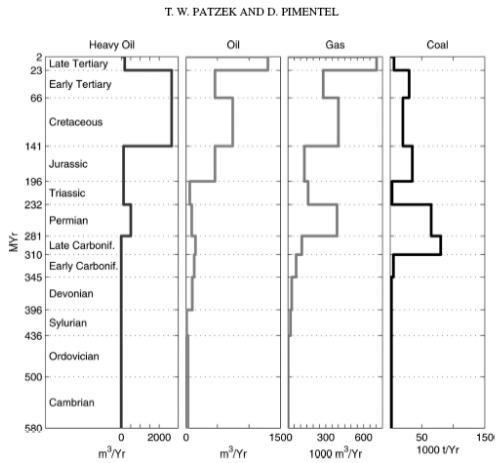


Figure 5 Plots of RCO_2 (the ratio of the mass of carbon dioxide in the atmosphere in the past to that for the pre-industrial present) and $\%O_2$ during the Phanerozoic eon. (Values of RCO_2 from the GEOCARB III model[33]; values of $\%O_2$ from ref. 11 using the ^{13}C data of refs 12 and 13). Estimated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

Berner, Nature, 2003

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



Most Coal Deposited during Carboniferous, 300 Ma

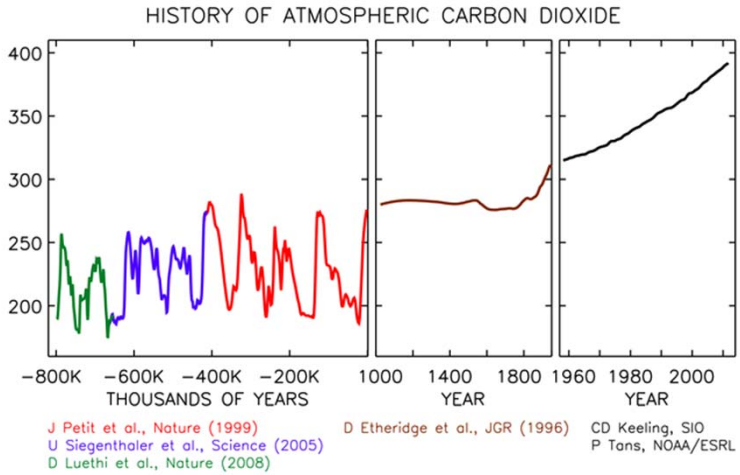
Patzek and Pimental, 2005 Crit Rev Plant Sci

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].

CO2 over the Timespan of Humans on Earth



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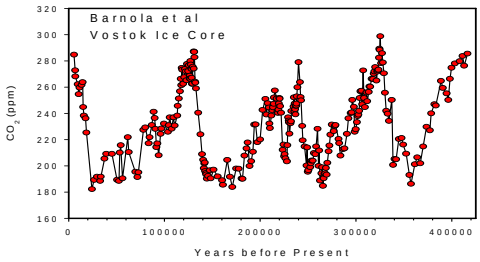
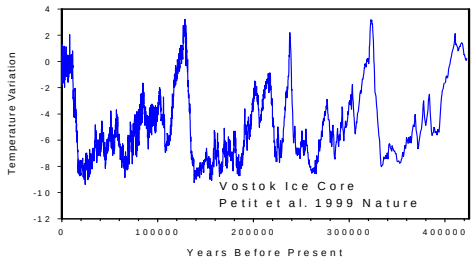
Paleo-Carbon Cycle





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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

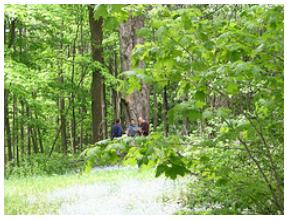
Flux = 2.19 Pg/ppm * +100 ppm/10,000 = + 21.9 TgC/y

TgC = 10^{12} gC

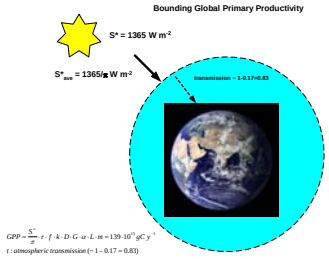
Lesson: Today' Pg C Fluxes are Way out of Equilibrium with Historic Conditions

What is the Upper Bound of GPP?

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



Top-Down:
Energy Transfer

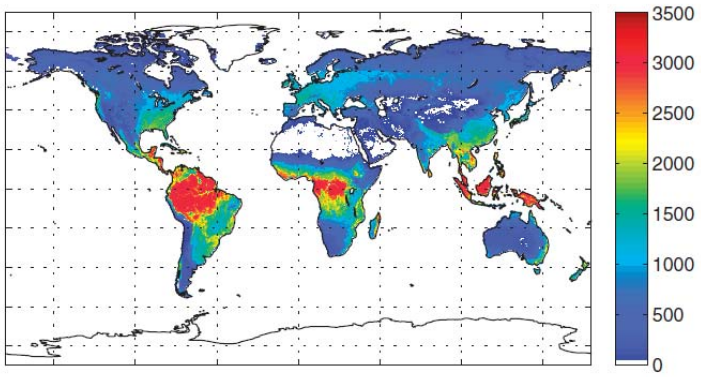


$$GPP = \frac{S^*}{\pi} \cdot \tau \cdot f \cdot k \cdot D \cdot G \cdot a \cdot L \cdot m = 139 \cdot 10^{15}\ gC \cdot y^{-1}$$

τ : atmospheric transmission (~ 1 – 0.17 = 0.83)
k : conversion factor, shortwave energy to moles visible quanta ($0.5 \cdot 4.6 \cdot 10^{-6}$)
f : fraction of absorbed quanta by canopy (0.9)
D : daylength (12hr x 3600 s / hr)
G : growing season (180 days)
a : light use efficiency
L : Land area ($100 \cdot 10^{12}\ m^2$)
m : 12gC/mole

Recent 'Best Estimate' on GPP with Multiple Constraints

Global GPP = 123 +/- 8 PgC



Beer et al 2010 Science

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)

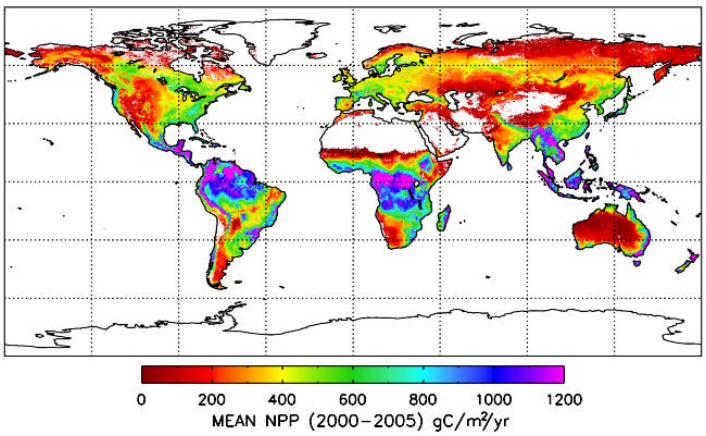
GPP = 1366*0.83*0.5*4.6*0.9*0.02*110 10^{12}*43200*180*12/(4 10^6)=120 * 10^{15} gC y^{-1}

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

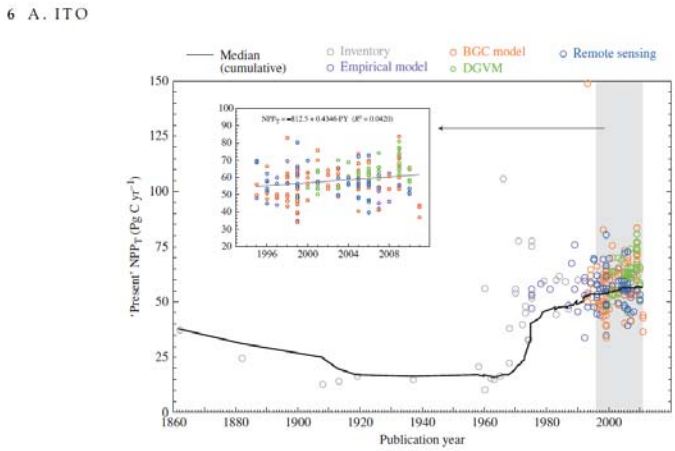
Beer et al., 2010 Science

NPP ~ 0.5 GPP



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

NPP = 56.4 PgC/y +/- 14



Ito 2011, GCB

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

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

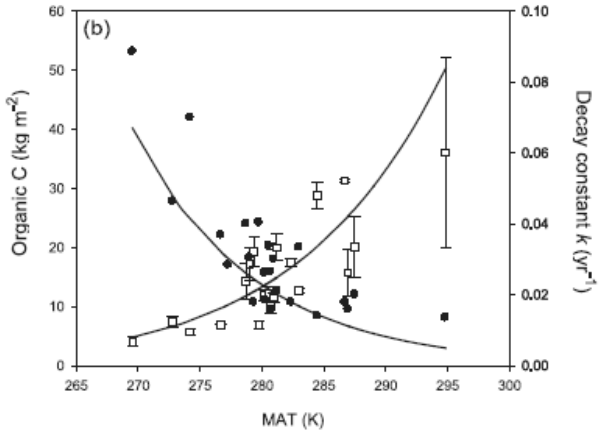
Flux per Volume ~ Mole Density/turnover time

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

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

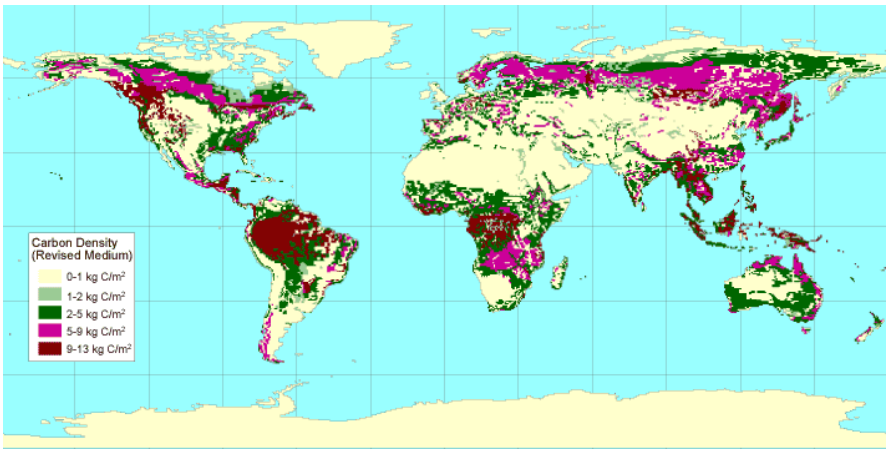
Vegetation and Soil C by Biome

Biome	Area 10^6 km^2	Soil C (Pg)	Plant C (Pg)	NPP (Pg y^{-1})
Tropical Forest	17.5	692	340	21.9
Temperate forest	10.4	262	139	8.1
Boreal forest	13.7	150	57	2.6
Arctic Tundra	5.6	144	2	.5
Mediterranean Shrubland	2.8	124	17	1.4
Crops	13.5	248	4	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	62.6

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

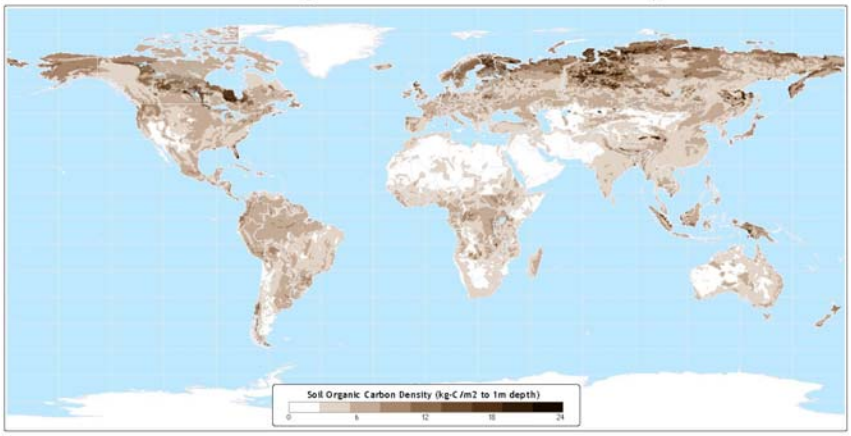
Saugier et al/Sabine et al

Global Vegetation Carbon Content



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

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

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

Global Carbon Emissions
Marland et al CDIAC