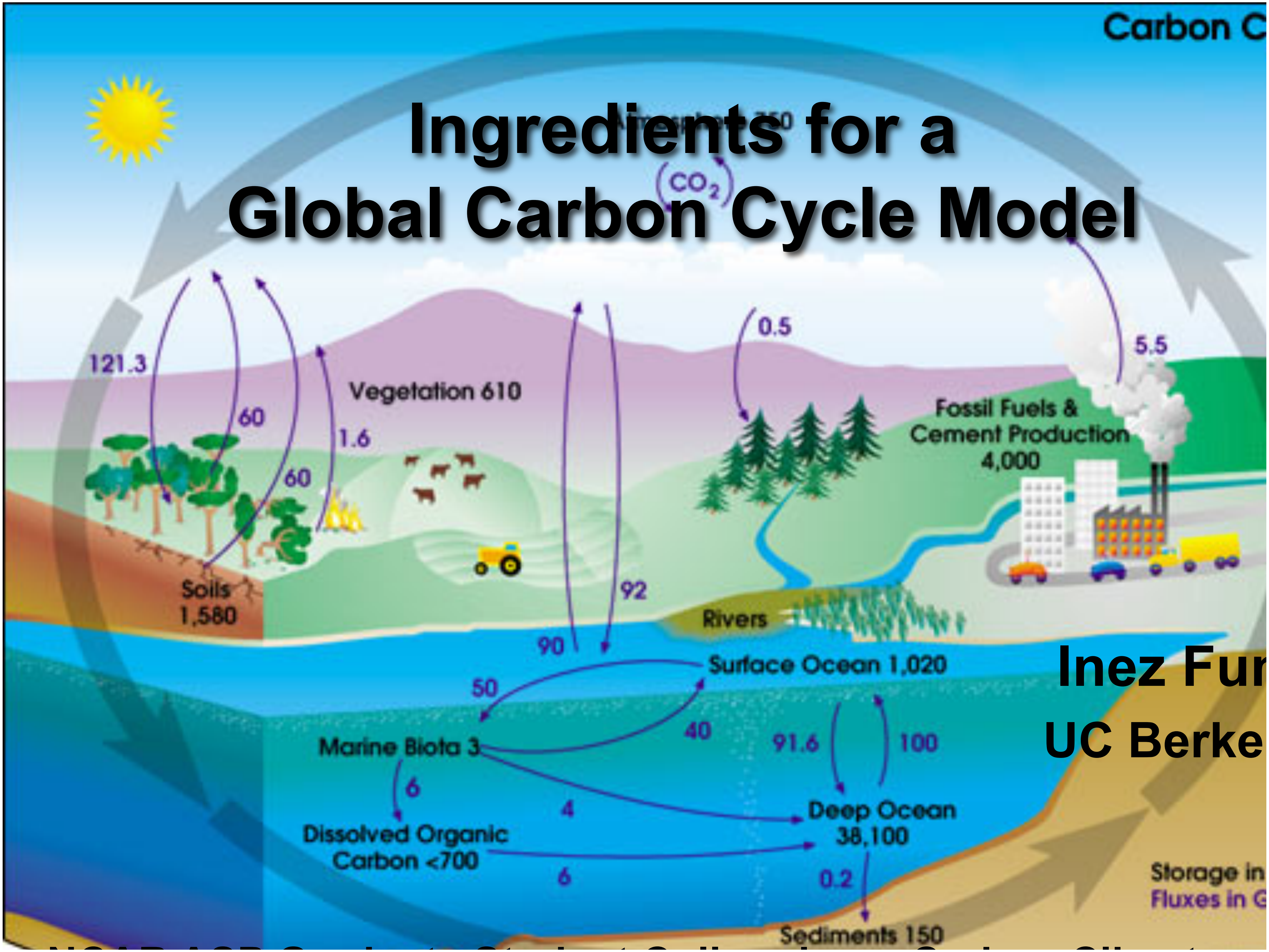
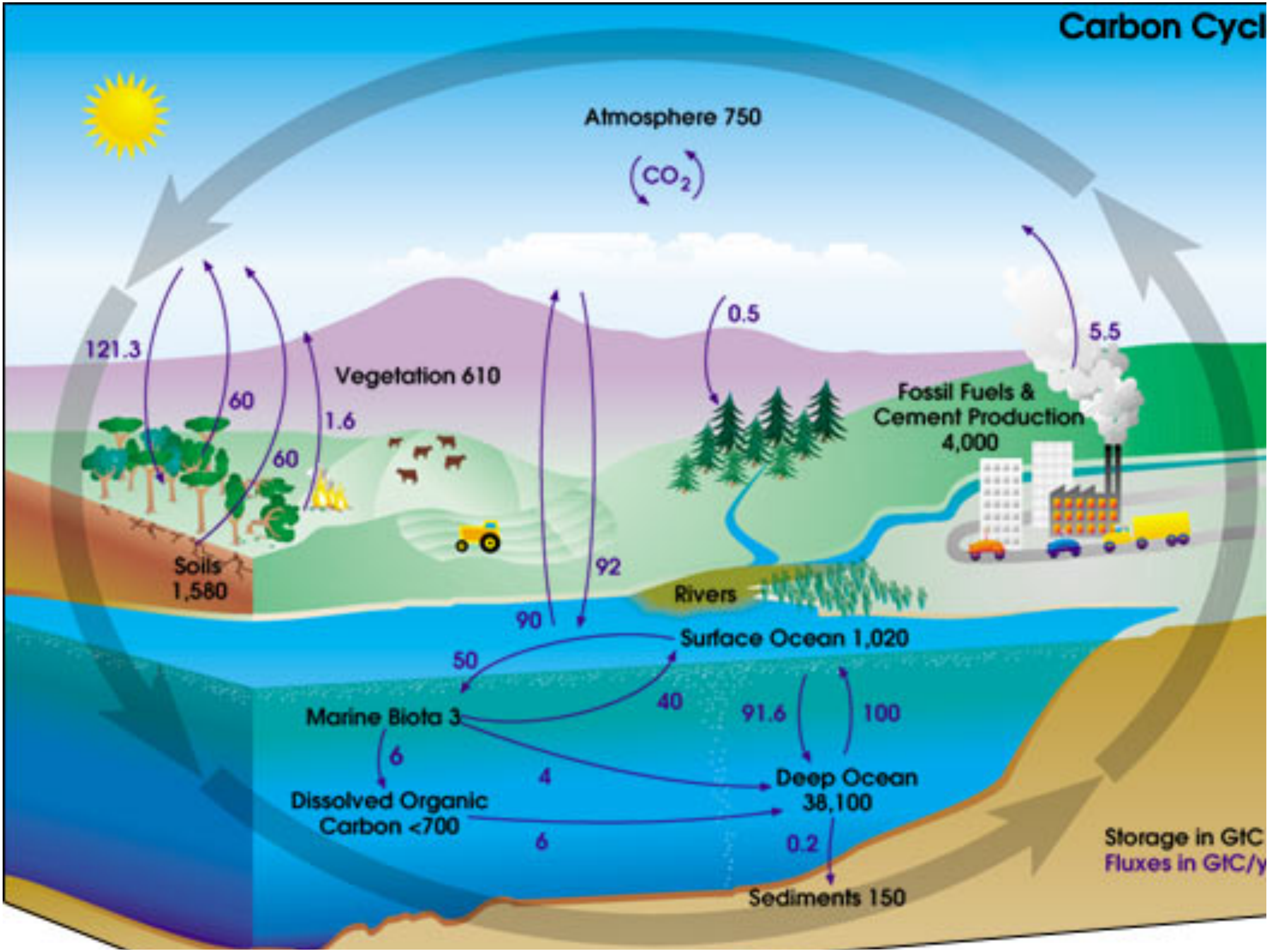
Ingredients for a Global Carbon Cycle Model

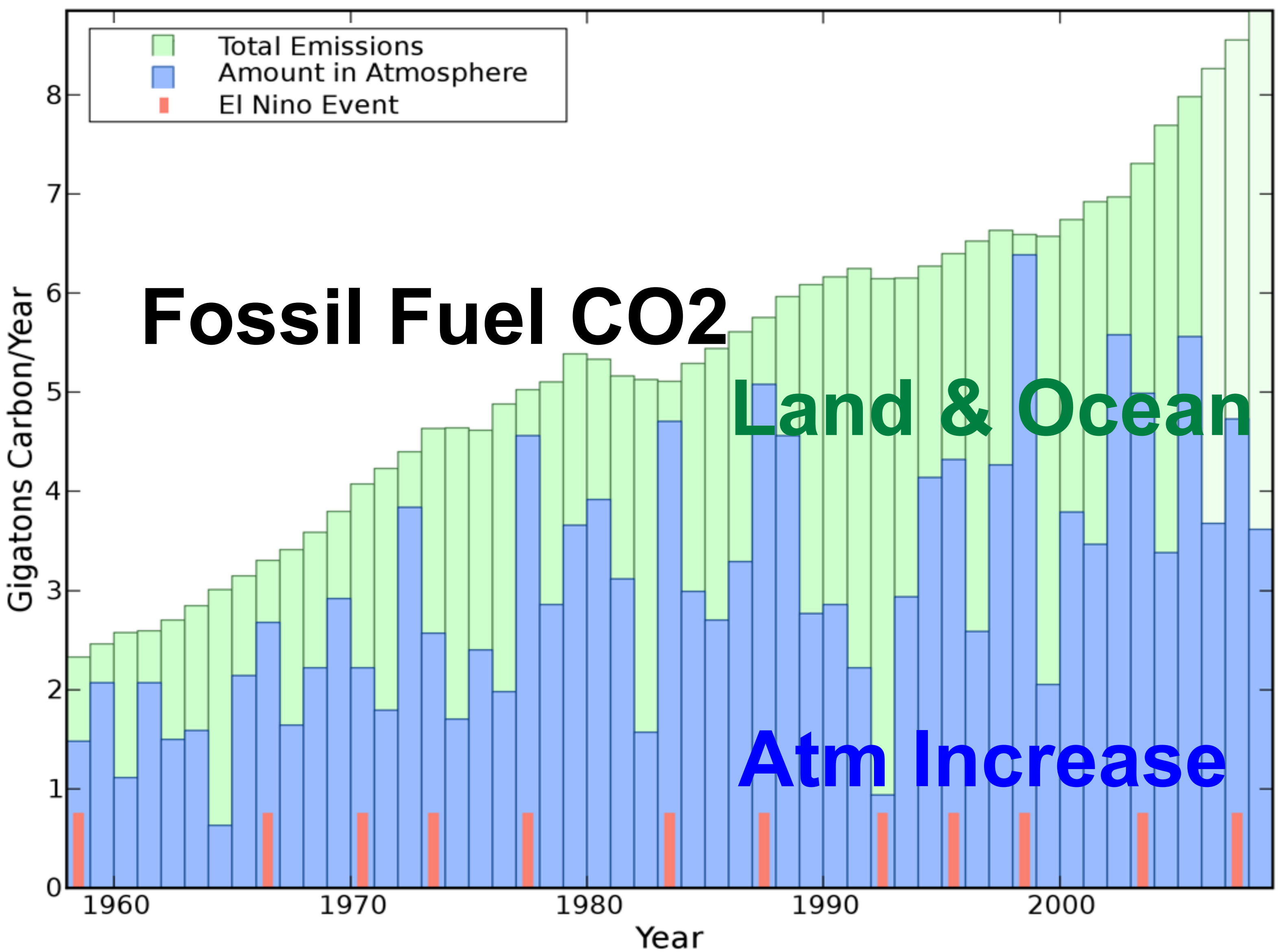


Inez Fur

UC Berke


Carbon Cycl
Atmosphere 750
CO_2
121.3
60
60
1.6
Vegetation 610
90
92
0.5
5.5
Fossil Fuels &
Cement Production
4,000
Soils
1,580
Rivers
Surface Ocean 1,020
50
40
Marine Biota 3
91.6
100
6
4
Deep Ocean
38,100
Dissolved Organic
Carbon <700
6
0.2
Sediments 150
Storage in GtC
Fluxes in GtC/y

Challenge: Co-variation of Climate and Carbon Sinks



Focus of Coupled Carbon Climate Model

- Changes in CO2 and $\frac{\partial CO2}{\partial t}$ that are radiatively important
- Time scale of investigation:
  - **Eqm**: e.g. Last Glacial Max; 2xCO2
  - **Transient**: modern (now +/- several centuries). Leave out geology (and interactions with geology) if using complex Earth System Model.

Units: 1 Pg = 1 Gt = 10^{15} gram

$$C(kgC/m^3) = \rho(kgAir/m^3) \times X(moleC/moleAir) \times (MWt_C/MWt_{air})$$

$$MWt_C = 12gm/mole; MWt_{air} = 29gm/mole$$

$$Area = \int dx\,dy\,dz = 5 \times 10^{14}(m^2)$$

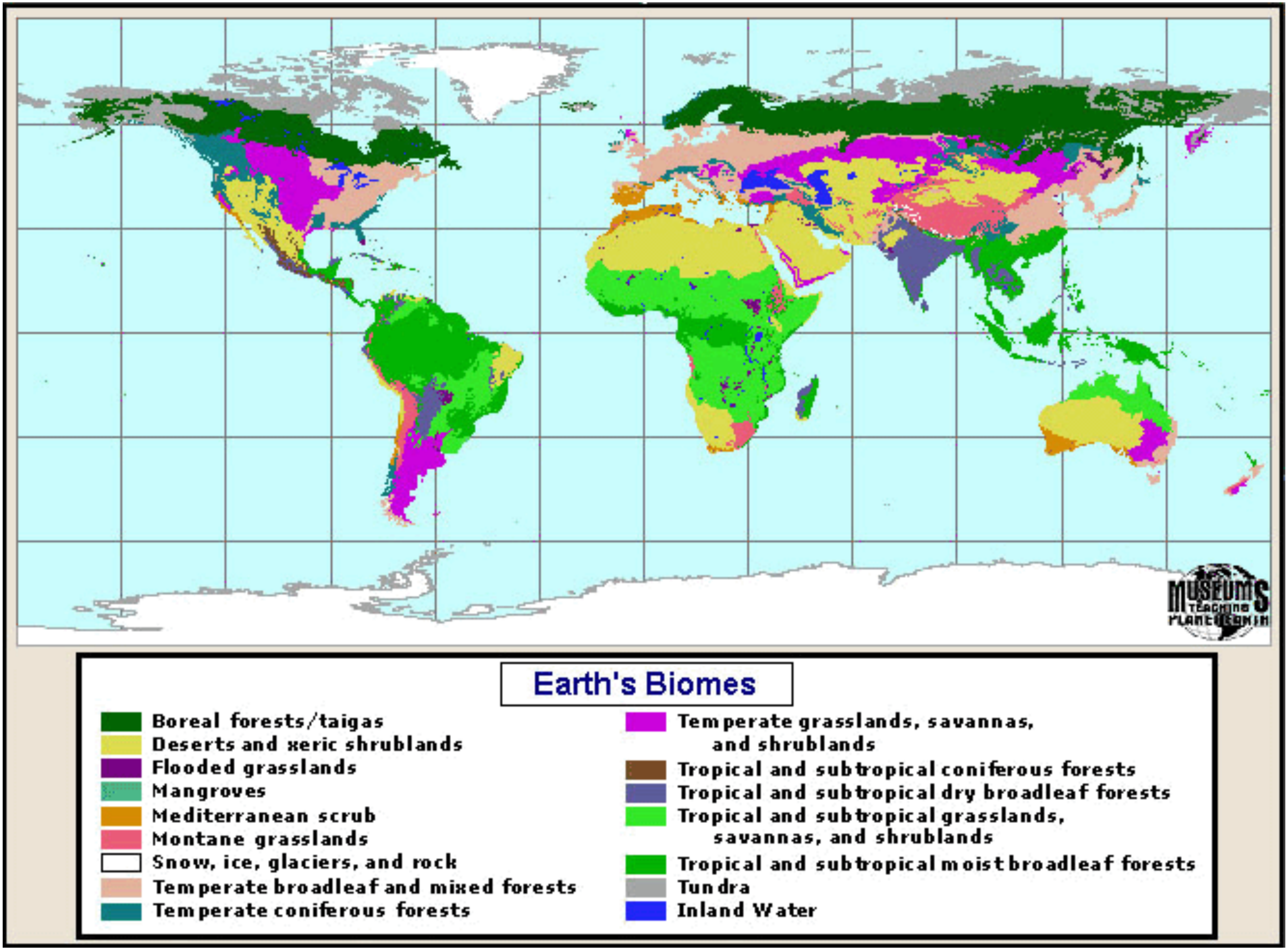
$$MassAtm = \int \rho\,dx\,dy\,dz = \frac{100P_{mb}}{g}(kgAir/m^2) \times Area \sim 5 \times 10^{18}\,kgAir$$

$$MassC(300\,ppmv) = MassAtm \times (300x10^{-6}) \times ({}^{12}/_{29})$$

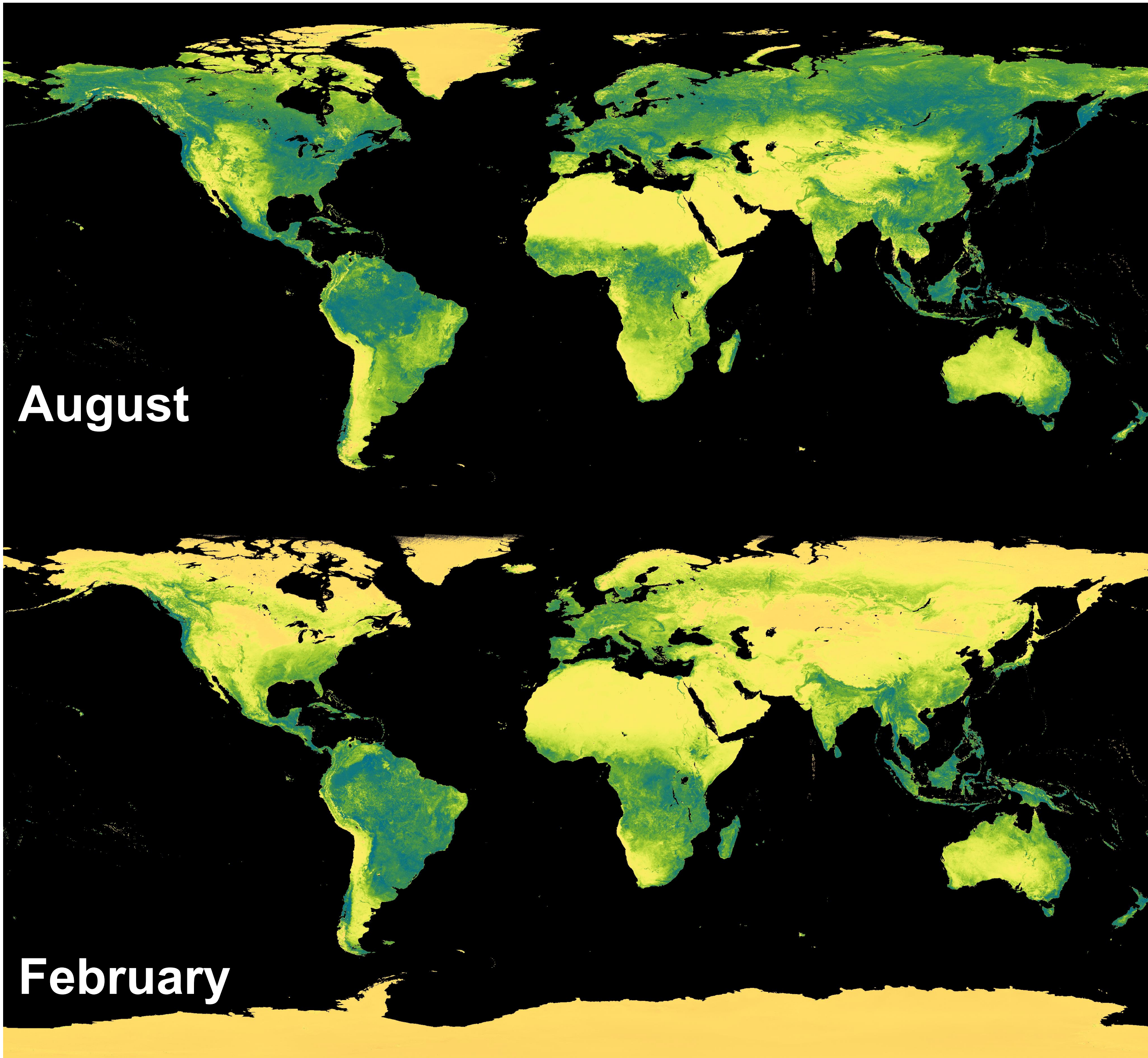
$$\sim 600 \times 10^{12}kg = 600PgC = 600GtC$$

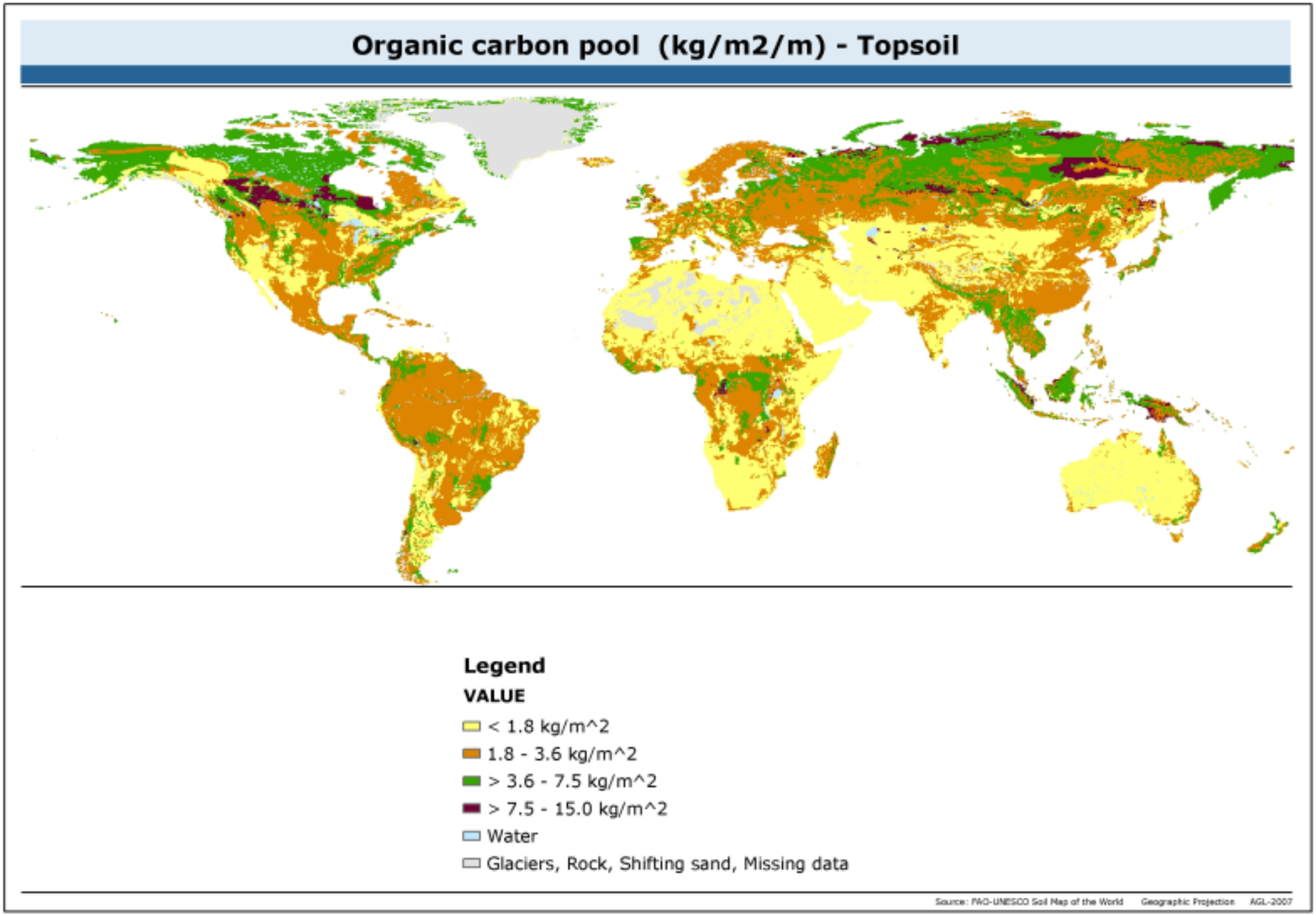
$$1PgC \rightarrow 0.5\,ppmv(mixed\_entireAtm)$$

LAND BIOSPHERE


MUSEUMS TEACHING PLANET EARTH
Earth's Biomes
Boreal forests/taigas
Deserts and xeric shrublands
Flooded grasslands
Mangroves
Mediterranean scrub
Montane grasslands
Snow, ice, glaciers, and rock
Temperate broadleaf and mixed forests
Temperate coniferous forests
Temperate grasslands, savannas, and shrublands
Tropical and subtropical coniferous forests
Tropical and subtropical dry broadleaf forests
Tropical and subtropical grasslands, savannas, and shrublands
Tropical and subtropical moist broadleaf forests
Tundra
Inland Water

Satellite Greenness index: NDVI



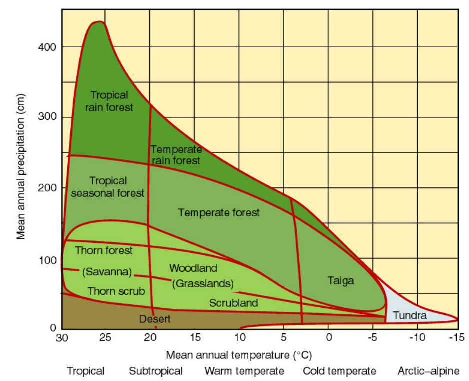


High soil carbon found when there is abundant organic matter input, and slow decomposition (cold, not well aerated).

(1) Who: Name Calling

1. Taxa/Species

2. **Physionomic/structural**: Biomes e.g. desert, rainforest - albedo, roughness



3. **Bioclimatic + CO2 +…**

4. **Functional:** based on satellite photosynthesis index:

$$\{\%tree/shrub\} \times \begin{Bmatrix} deciduous \\ evergreen \end{Bmatrix} \times \begin{Bmatrix} broadleaved \\ needleleaved \end{Bmatrix}$$

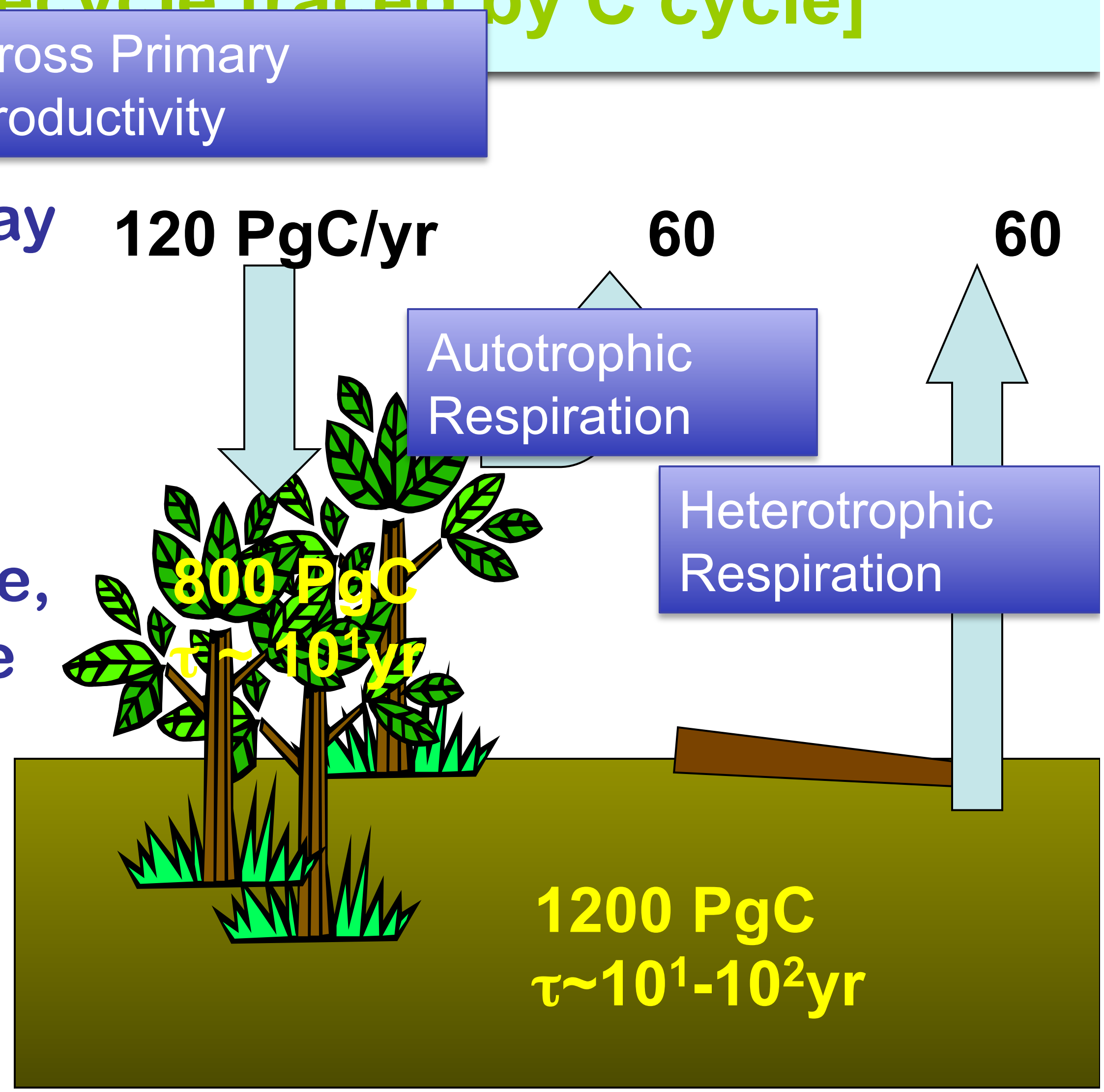
$$\{\%herbaceous/crops\} \times \begin{Bmatrix} C3 \\ C4 \end{Bmatrix}$$

$$\{\%bare\}$$

Static land cover: typically 4 --> lookup table of structural properties and BGC chacteristics. Prognostic land cover: 3+

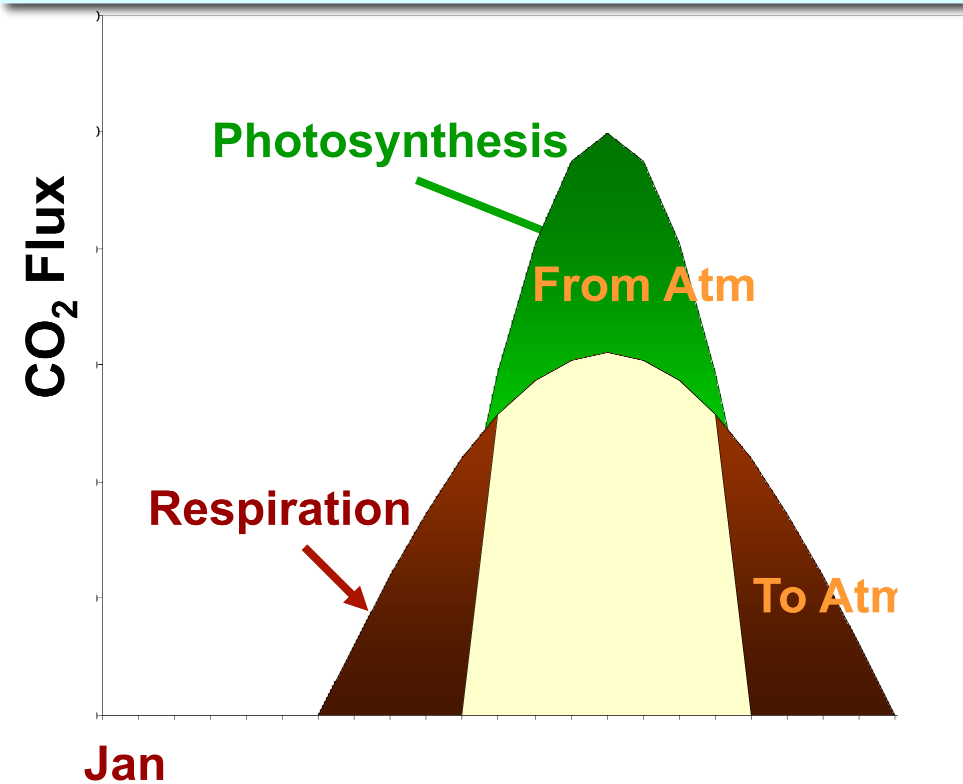
(2) What? [lifecycle traced by C cycle]

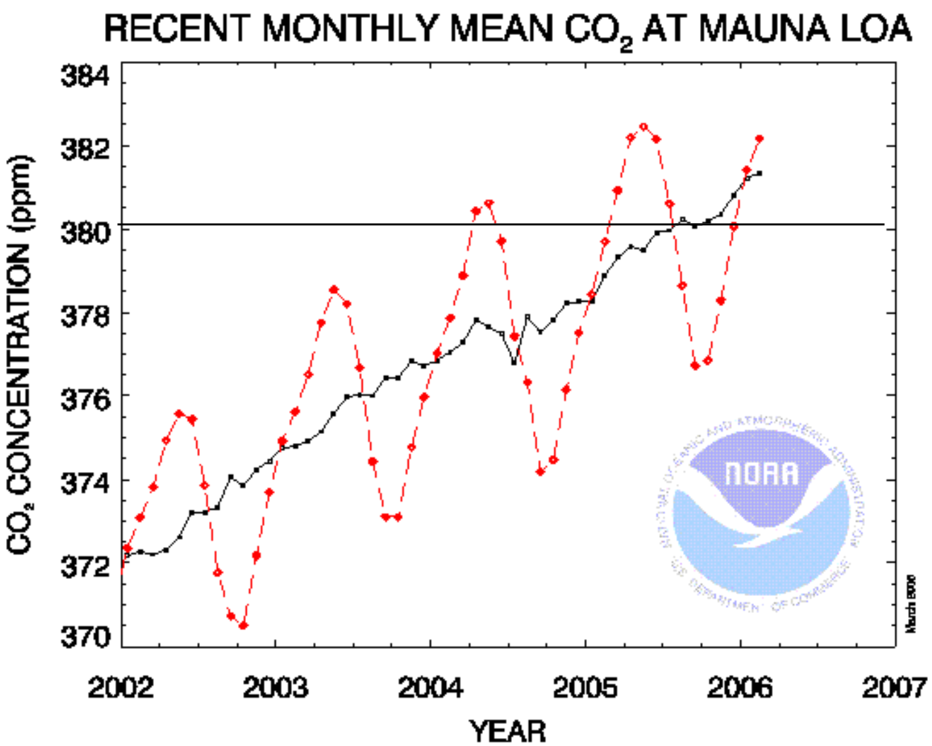
- Growth, mortality, decay
- Population: {ages}
- Photosynthesis (climate, CO_2, soil H_2O, resource limitation)
- Decay (T, soil H_2O,..)



Net Primary Production (NPP) = GPP – R_auto

Two major fluxes - seasonal cycle





- **Seasonal asynchrony** between photosynthesis and decomposition

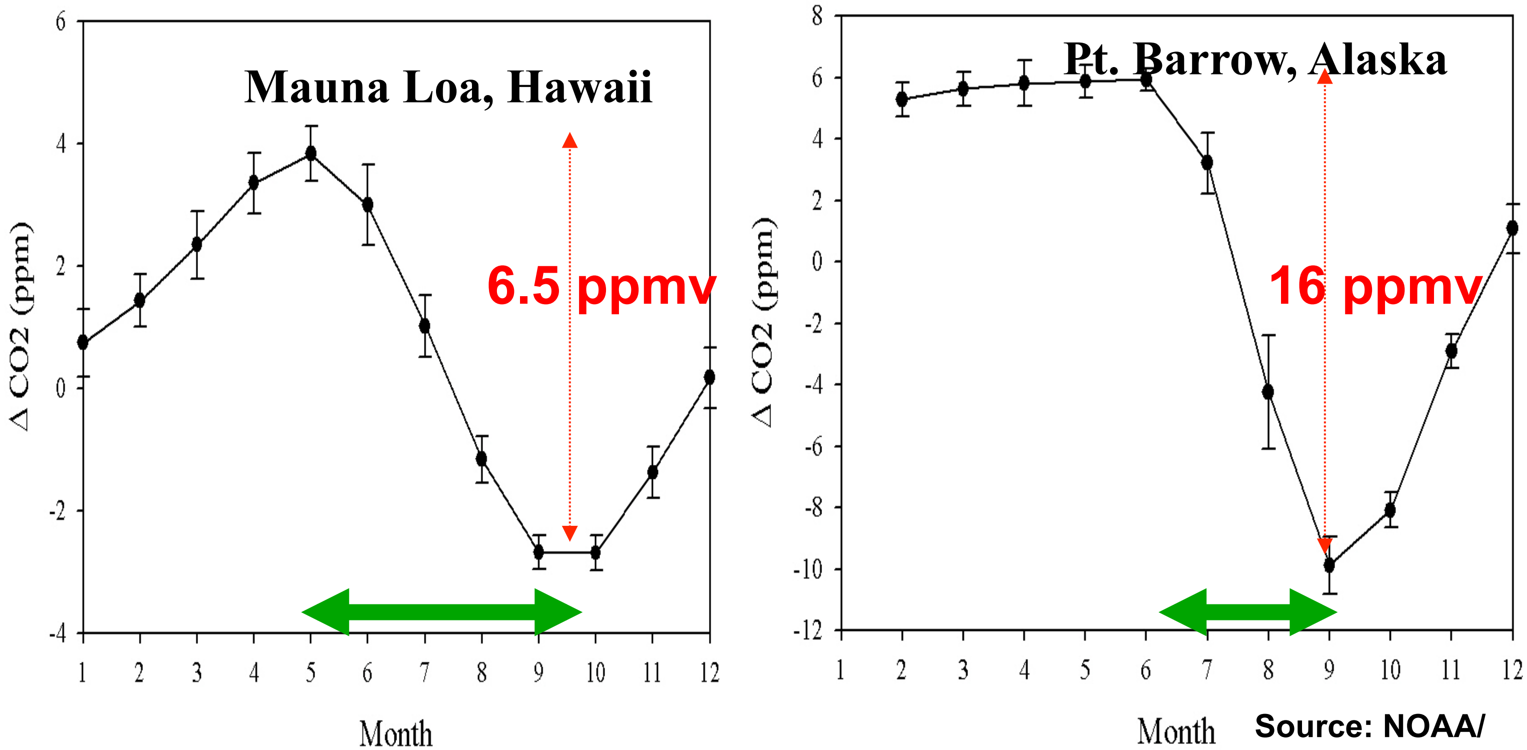
→ net fluxes of CO_2 to and from atm
→ seasonal cycle of CO_2 in atm

- **Annual imbalance** → carbon source/sink

Fung et al JGR 1983, 1987:

Simple prescriptions of seasonality. 1987 based on satellite obs + temperature

Atmospheric CO_2 Signature of Ecosystem C Exchange: Seasonal Cycle

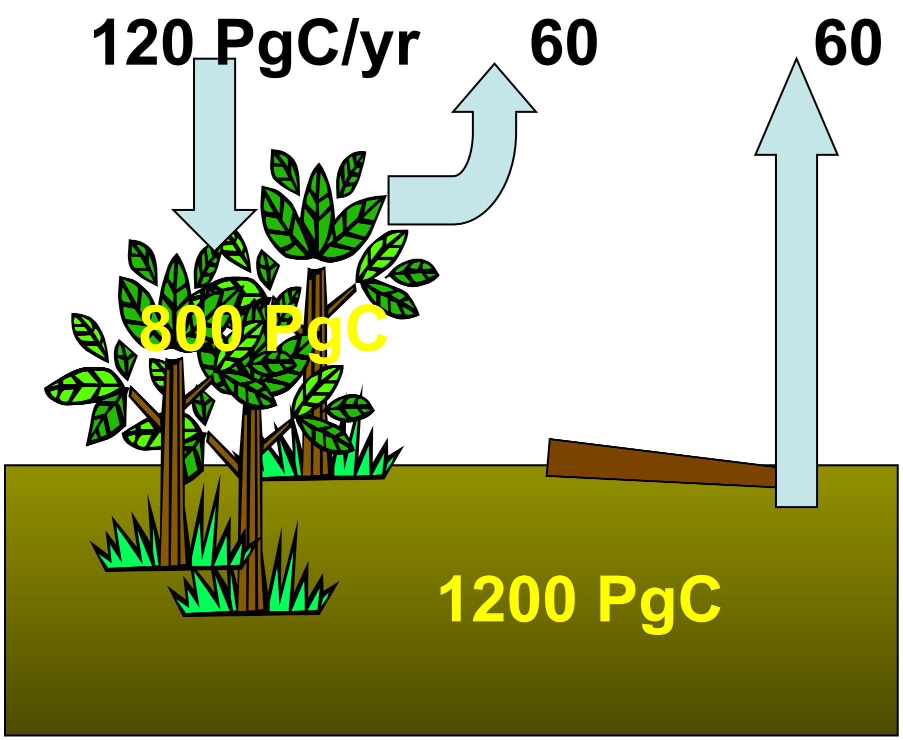


Source: NOAA/ CMDL

- Amplitude of atmospheric CO_2 seasonal cycle increases poleward: telecoping of growing season and greater asynchroneity bet' fluxes

- Growing season net flux ~15-20% of annual NPP

(3.1) How?
First simple toy model: carbon only



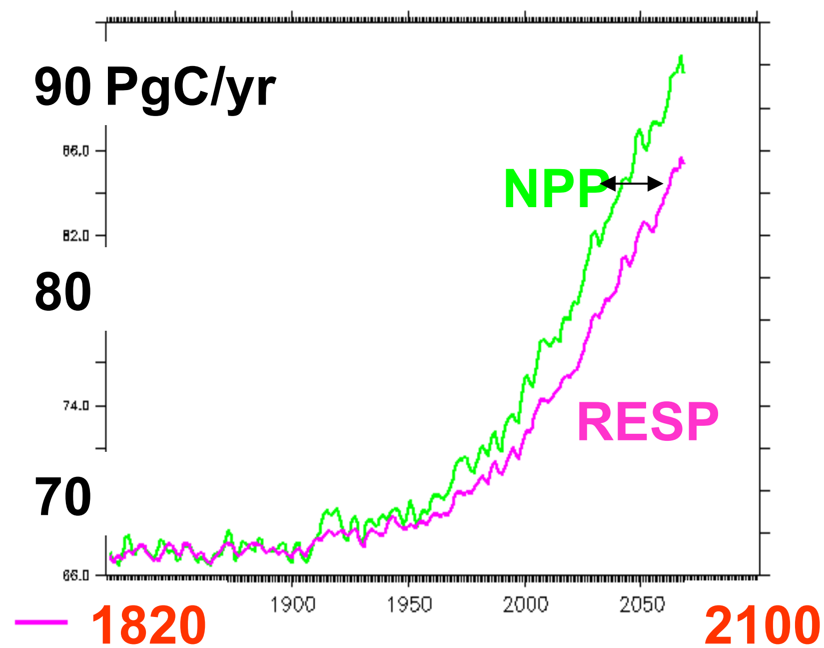
$$\frac{\partial M_{veg}}{\partial t} = NPP - \frac{M_{veg}}{\tau_{veg}}$$

$$\frac{\partial M_{soil}}{\partial t} = \frac{M_{veg}}{\tau_{veg}} - (1-\gamma)\frac{M_{soil}}{\tau_{soil}} - \underbrace{\gamma \frac{M_{soil}}{\tau_{soil}}}_{Het\,Resp}$$

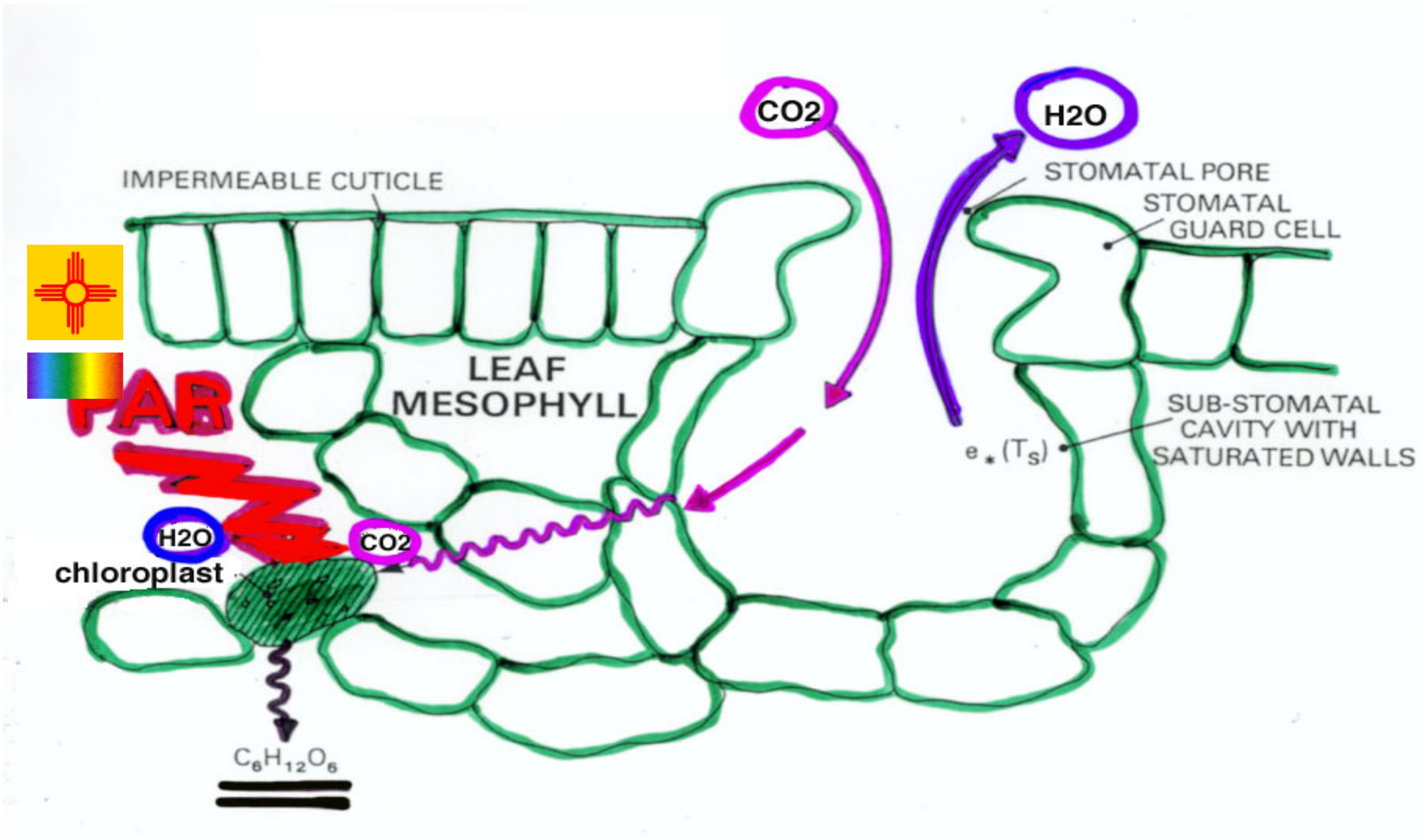
Turnover times (climate)

τ_{veg} ~ 15 yr

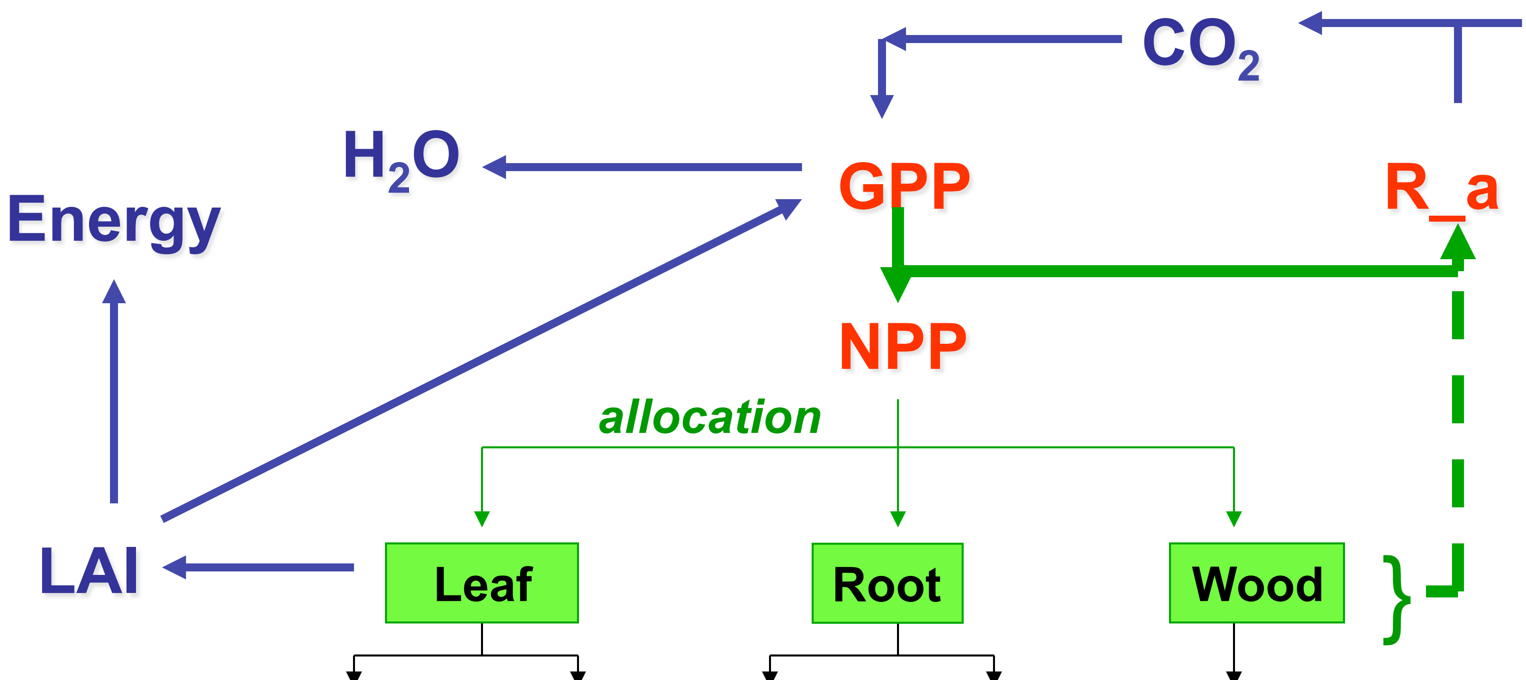
τ_{soil} ~ 25 yr



(3.2.1) Leaf Photosynthesis



(3.2.2) Photosynthesis --> Growth

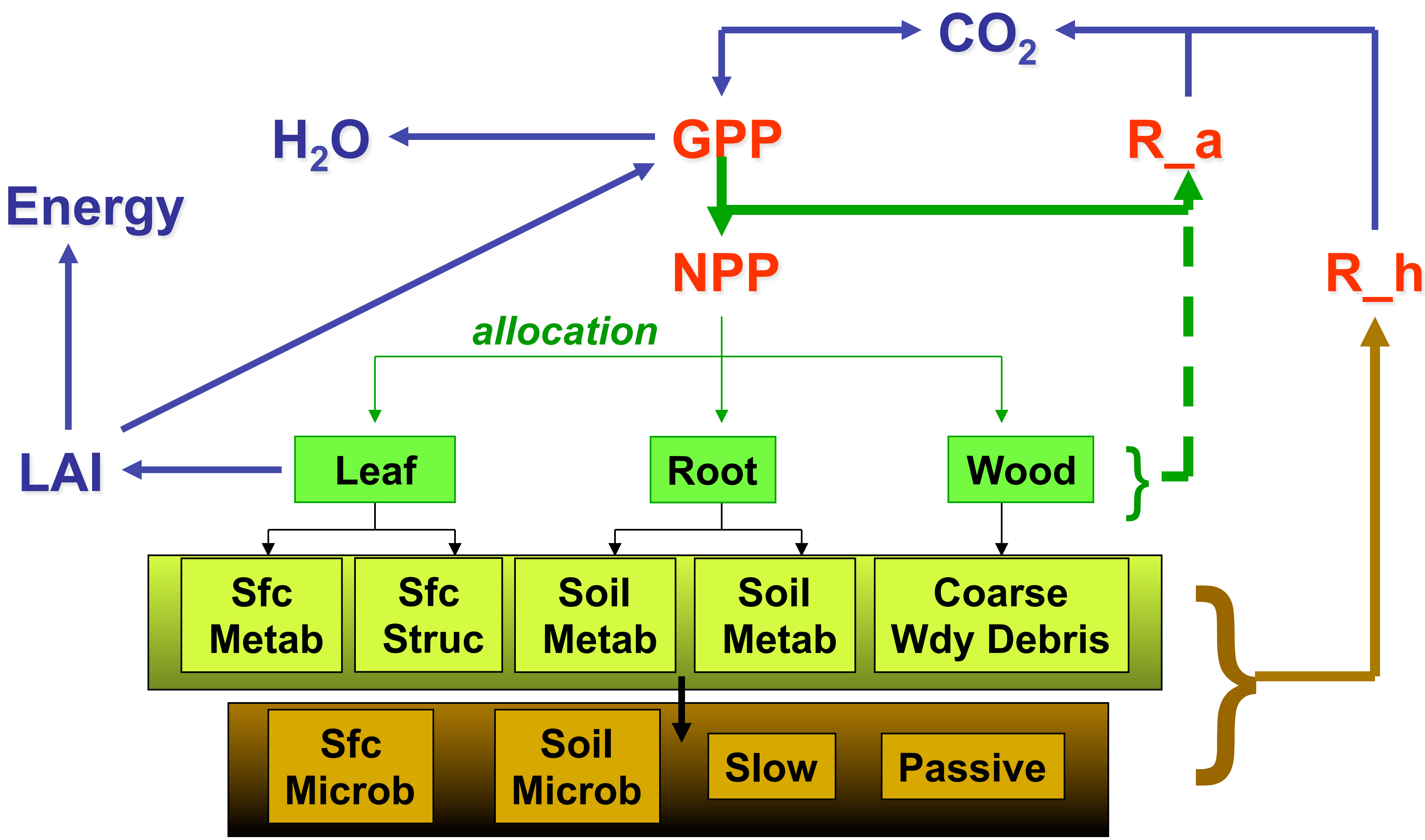


<u>Strategy for survival</u>: allocate new C to

Roots when water and nutrient limited

Wood when light limited

(3.2.3) Photosynthesis, Growth, Mortality & Decay



(3.3) Prognostic Carbon Cycle (with transpiration and dynamic albedo)

Atm

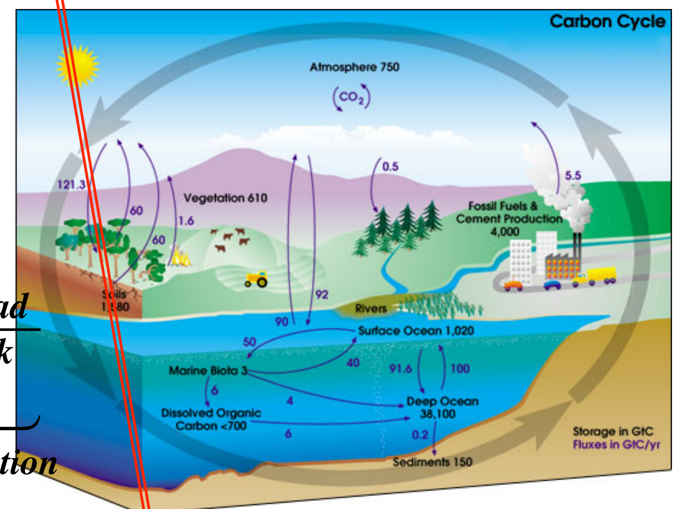
$$\frac{DC_a}{Dt} = \left(FF + Def + \underbrace{F_{oa}\Updownarrow}_{air-sea\_flux} + \underbrace{F_{ba}\Updownarrow}_{atm-land\_flux}\right)\Bigg|_0 + \Im(C_a)$$

Land-live

$$\frac{\partial C^k_{b\_live}}{\partial t} = -\alpha^k \underbrace{F_{ab}\downarrow}_{photosynthesis}\Bigg|_0 - \underbrace{\frac{C^k_{b\_live}}{\tau^k_{live}}}_{mortality}$$

Land-dead

$$\frac{\partial C^k_{b\_dead}}{\partial t} = \underbrace{\frac{C^k_{b\_live}}{\tau^k_{live}}}_{mortality} + \sum_j F_{jk} - \underbrace{\frac{C^k_{b\_dead}}{\tau^k_{dead}}}_{decomposition}$$

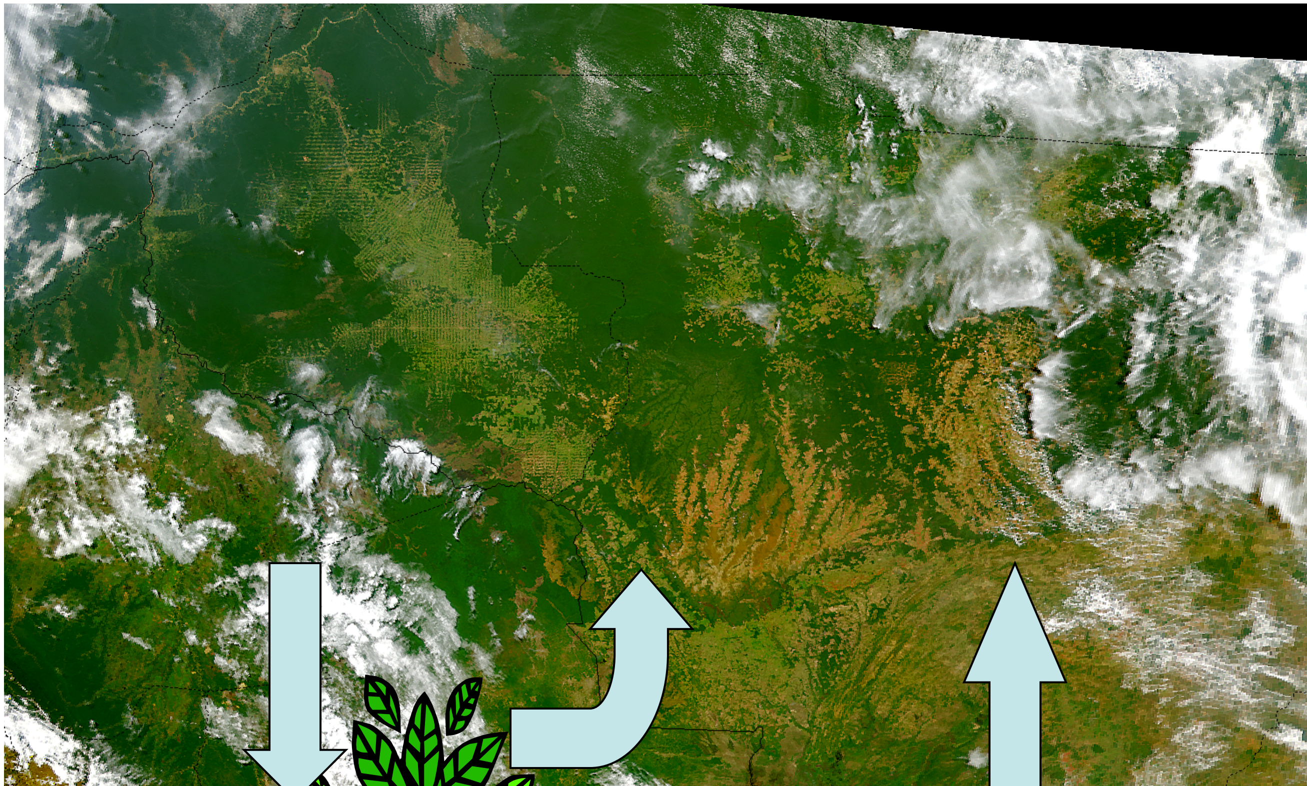


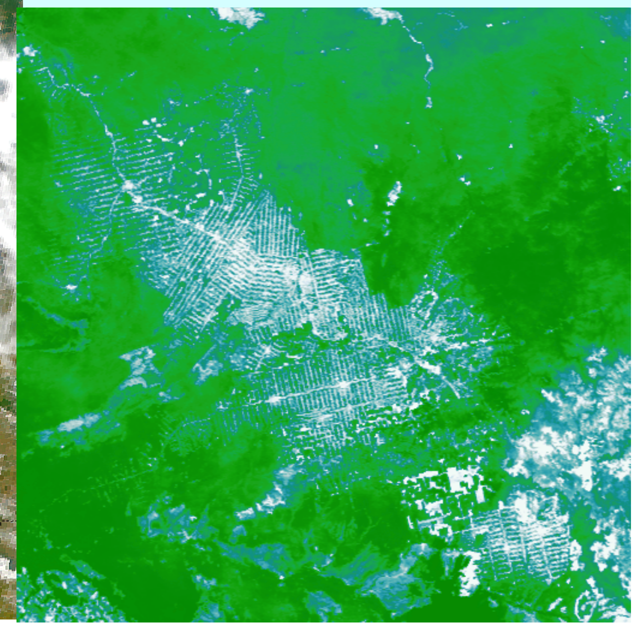
Changes climate

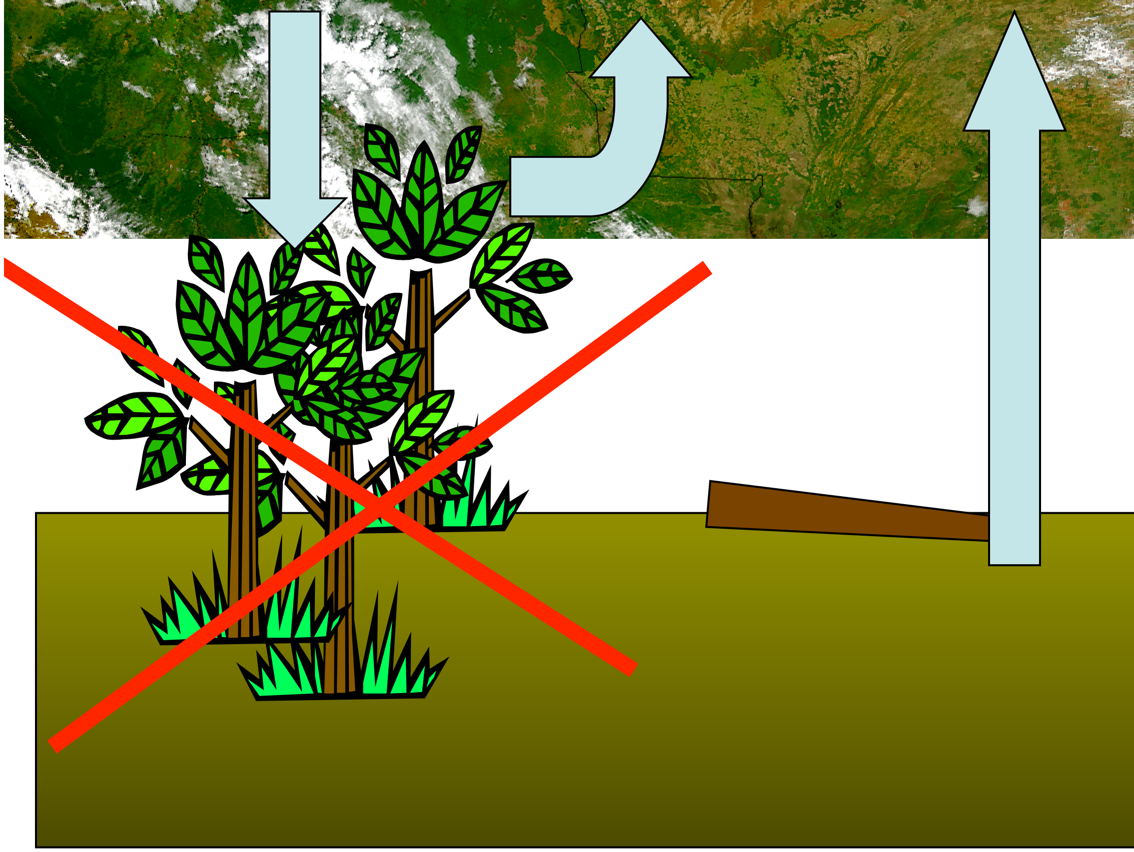
Responds to climate change

DEFORESTATION

Deforestation







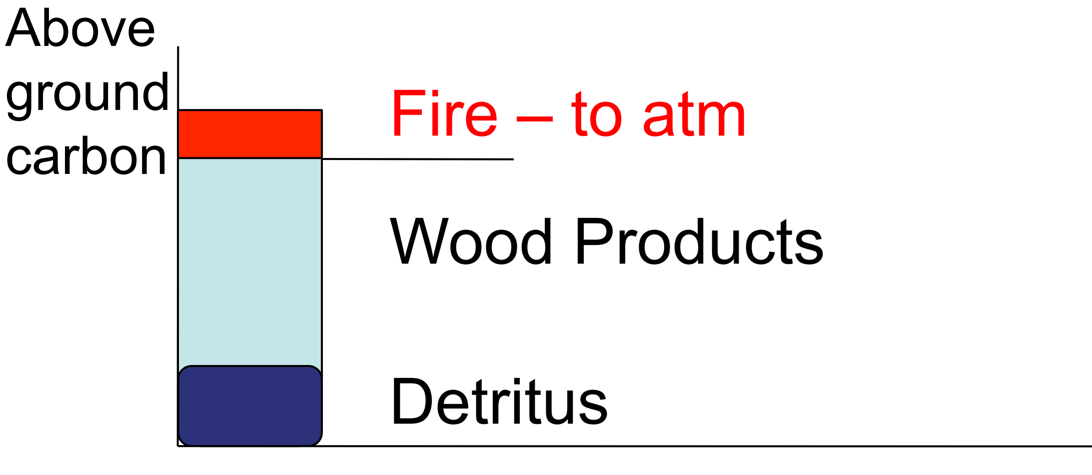
Tough to estimate

- **deforested area**
- **Carbon inventory before deforestation**
- **Fate of removed carbon**
- **Fate of litter and soil carbon**

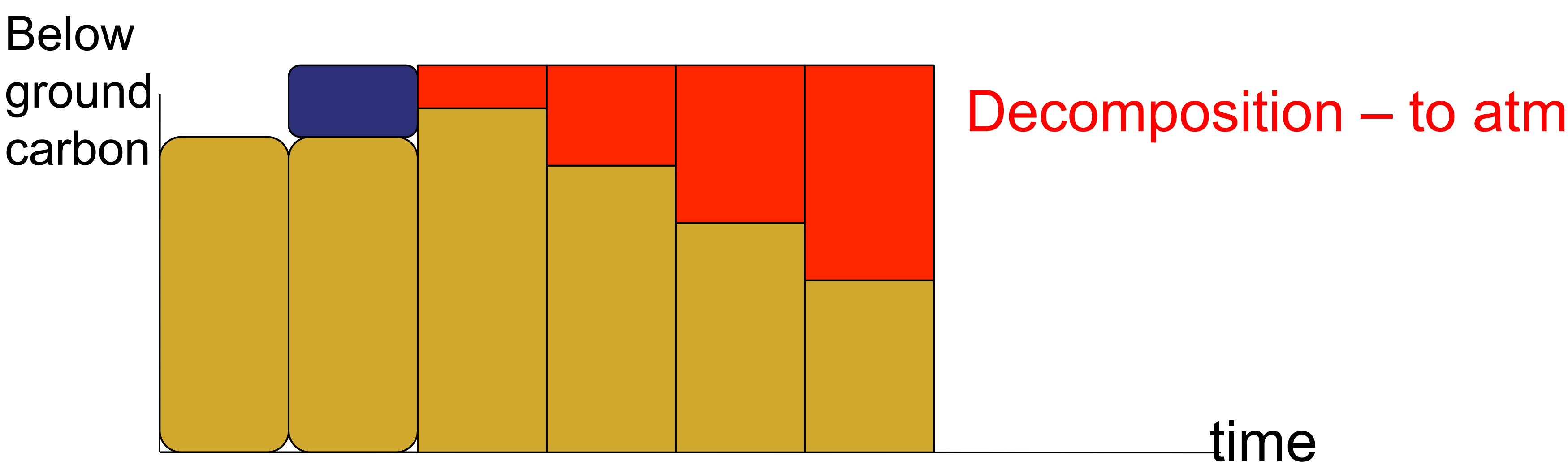
Tough to discriminate atm CO2 signature

Fate of Carbon

Cropping cycle: accumulate above ground carbon during growth. Carbon balance depends on the treatment of the detritus, time between crop and fallow, tilling practice,…

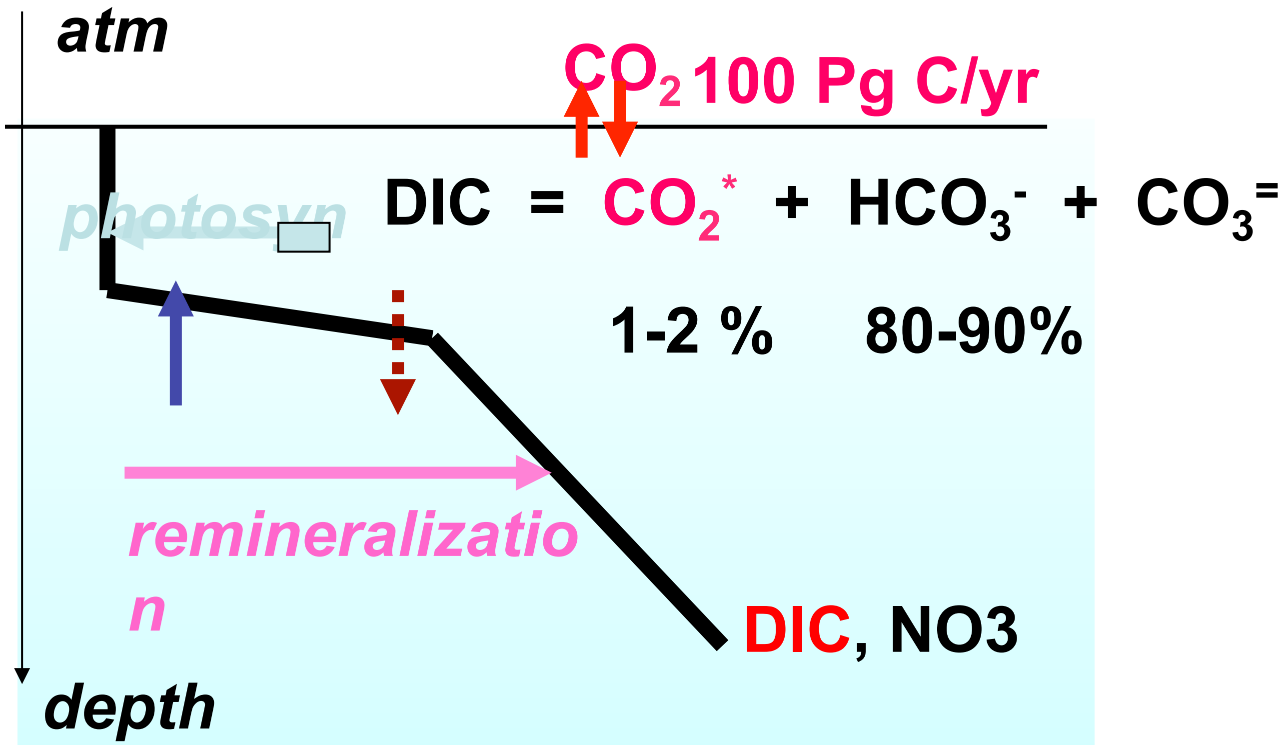


time



OCEAN CARBON

Ocean C from the Atm's Perspective:



$$F_{oa} - F_{ao} = \underbrace{k}_{GasExchRate(m/s)} \times (\underbrace{CO2^*_{sfc\_ocn}}_{moleC/m3} - \underbrace{\beta}_{solubility(T)} \times pCO2_{atm\_sfc})$$

(1) Simplified Carbonate Chemistry

Chemical Equilibrium

$$CO_2 + H_2O \leftarrow\rightarrow H^+ + HCO_3^-$$
$$CO_3^= + H^+ \leftarrow\rightarrow HCO_3^-$$

$$K(T,S) = \frac{[HCO3][HCO3]}{[CO2][CO3]}$$

Mass and Charge Balance

$$\Sigma CO2 = TC = DIC = CO_2 + HCO_3^- + CO_3^=$$

CO2 increases with increasing DIC

$$ALK = HCO_3^- + 2[CO_3^=]$$

CO2 decreases with increasing ALK

Henry's Law

$$pCO_2 = k_H * CO_2$$

pCO_2 : partial pressure (CO2 gas), in atm

Atm View: Summary of Carbonate Chemistry

$$\frac{\partial}{\partial t}(h \cdot DIC) = k \cdot solub \cdot pCO2_a - k \cdot \boxed{CO2_{ml}} + Prod\_bio - Loss\_bio$$

$$\frac{1}{CO2^*} d(CO2^*) = d(\ln(CO2^*))$$

$$= \underbrace{\frac{d \ln CO2^*}{d \ln DIC}}_{\sim 10} d \ln DIC$$

Revelle factor

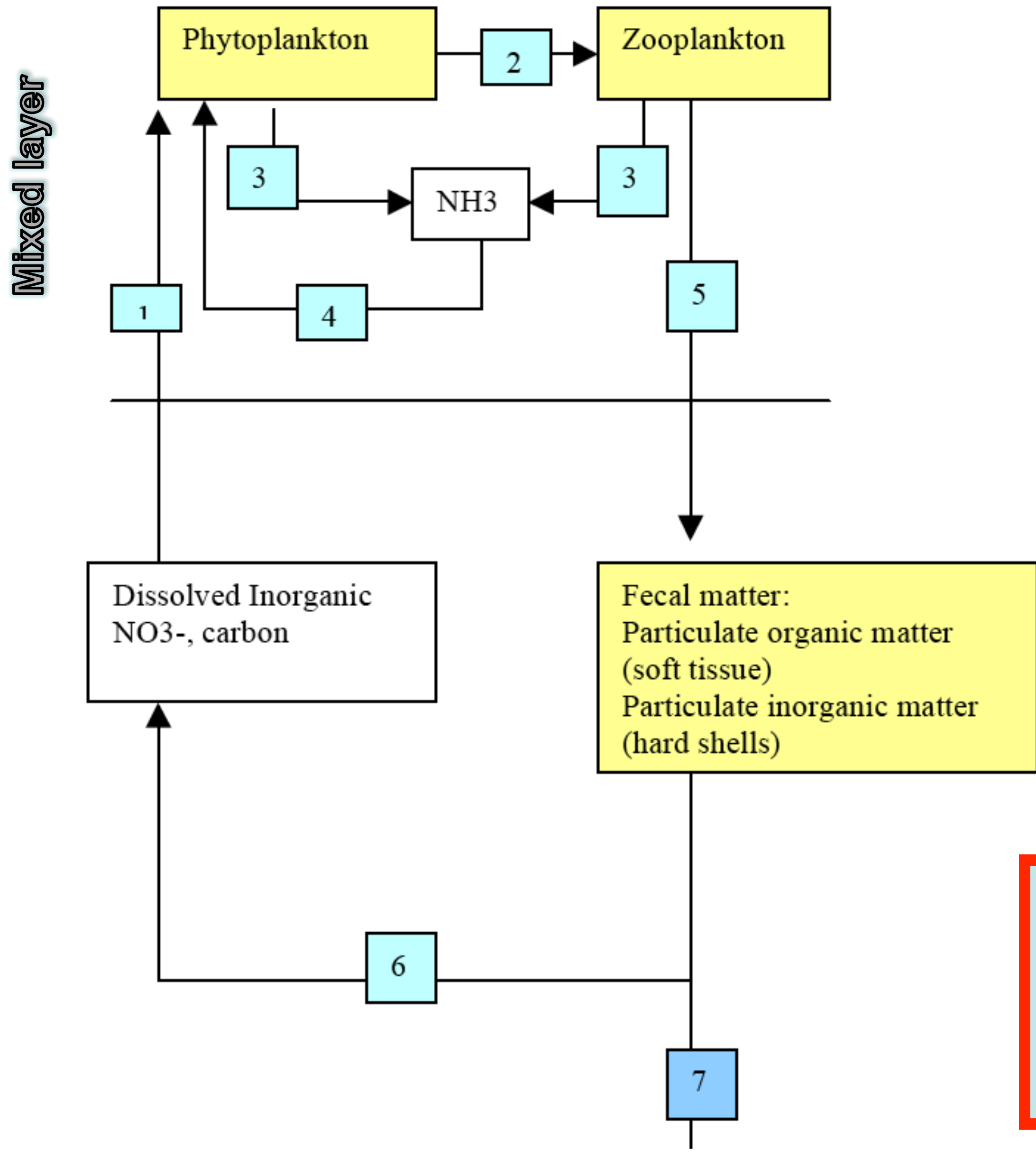
$$+ \underbrace{\frac{d \ln CO2^*}{d \ln TALK}}_{\sim -9} d \ln TALK$$

$$+ \underbrace{\frac{d \ln CO2^*}{dT}}_{\sim 4\% / K} dT$$

Solubility Pump

$$+ \frac{d \ln CO2^*}{dS} dS$$

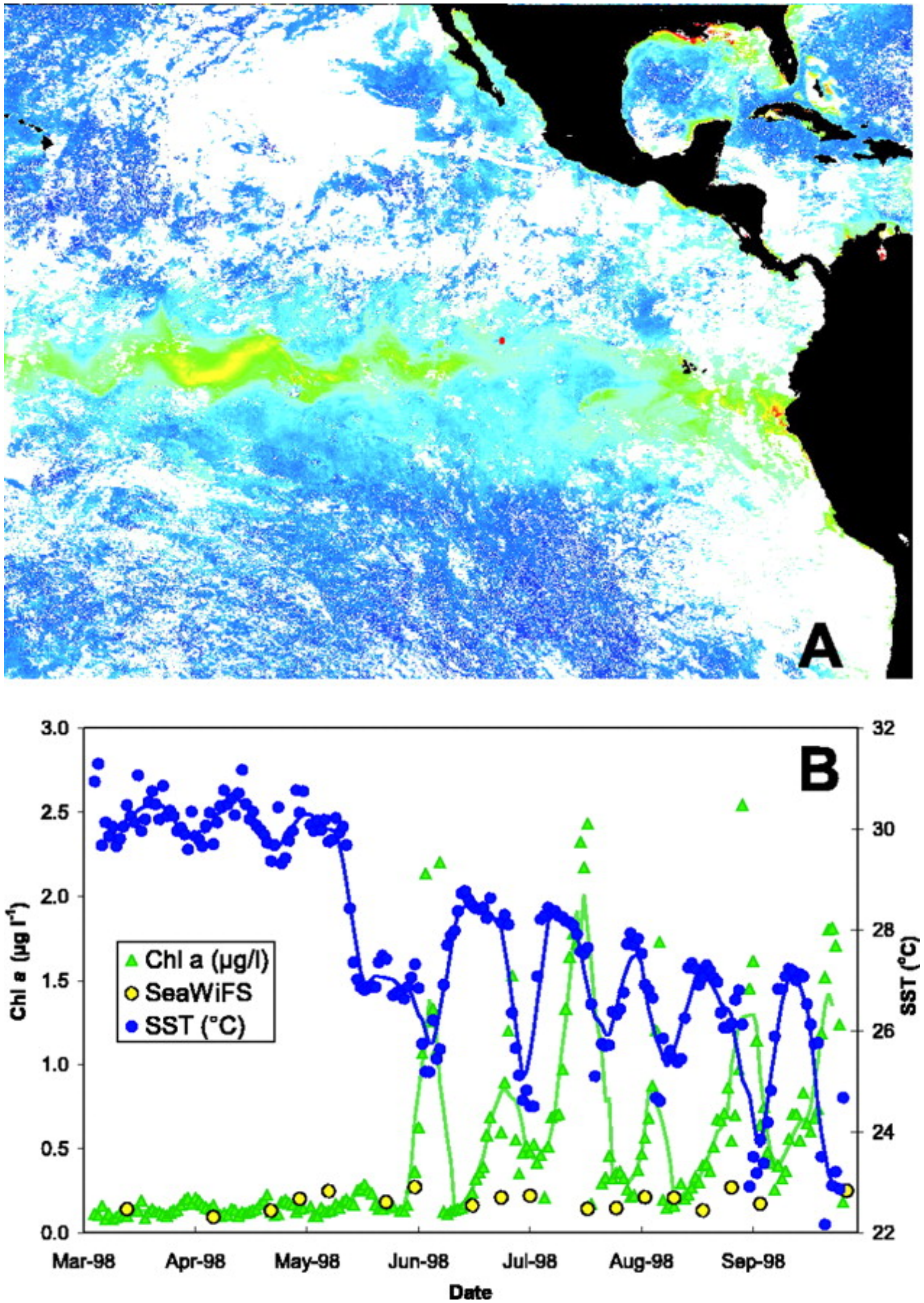
(2.1) Marine Biota – Biological Carbon Pump



1. Upwelling (new production)
2. grazing of phytoplankton by zooplankton
3. mortality and remineralization - bacteria
4. recyling: production
5. mortality of zooplankton, sinking, export from euphotic zone
6. remineralization
7. sinking to greater depths – carbonate dissolution or burial in sediments

Dissolved Inorganic C
Dissolved Organic C
Particulate Inorganic C
Particulate Organic C

Marine Productivity



Is possible when **upwelling** brings:

- Nutrients from below to euphotic zone
- Cold water

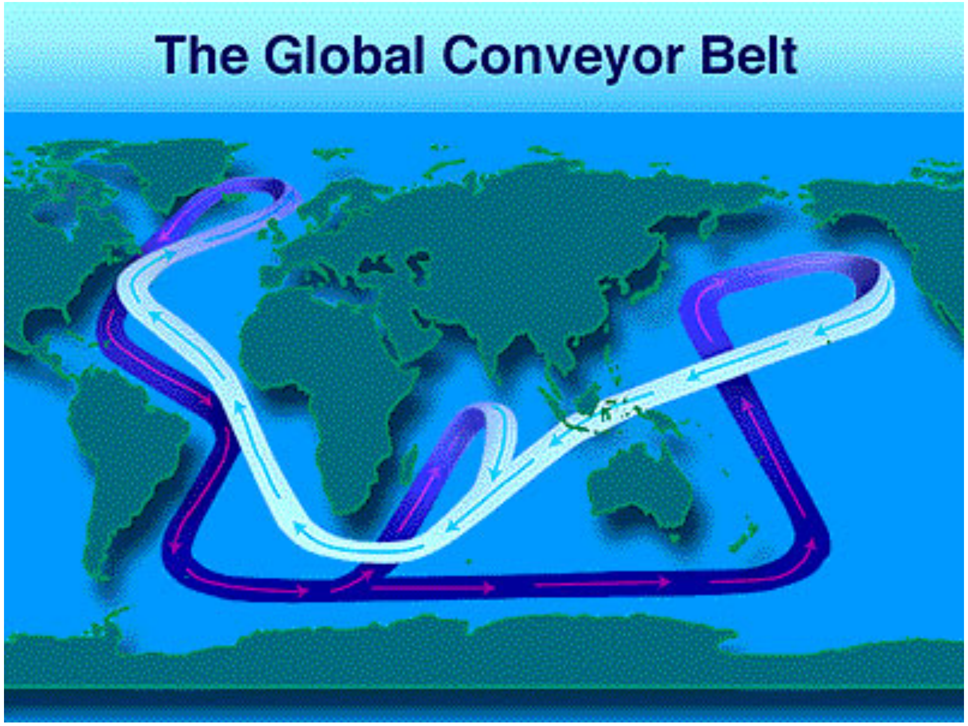
Small Flux, small inventory of organic C
But alters DIC(z)

Biological C Pump

Redfield ratio = C:N:P in organic matter ~103: 16: 1

		DIC	TALK	[CO2]
Formation of POC (surface ocean)	$CO_2 + H_2O \rightarrow CH_2O + O_2$; $NO_3^- + 2H_2O \rightarrow NH3^+ + OH^- + 2O_2$	- 1 unit	+ (16/103)*1 (Redfield * charge)	↓
Formation of CaCO3 (surface)	$Ca^{++} + CO_3^{=} \rightarrow CaCO3$	- 1 unit	- 2 units	↑
Remineralization of organic matter		+ 1 unit	- 16/103	↑
Dissolution of shells		+ 1 unit	+ 2	↓

(2.3) OceanC : Mainly Dissolved Inorganic Carbon (DIC)

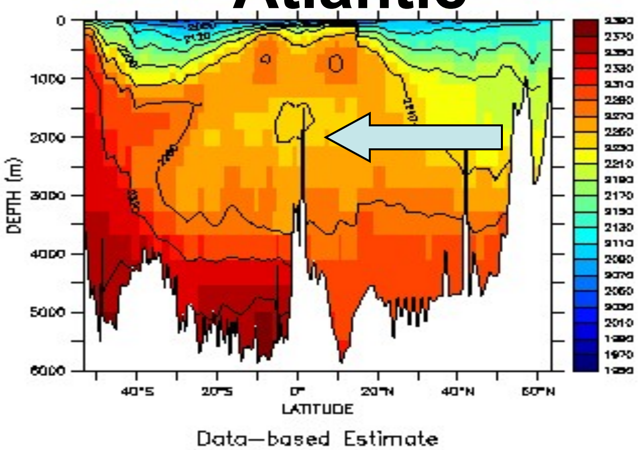


Conveyor Belt Transport of DIC:

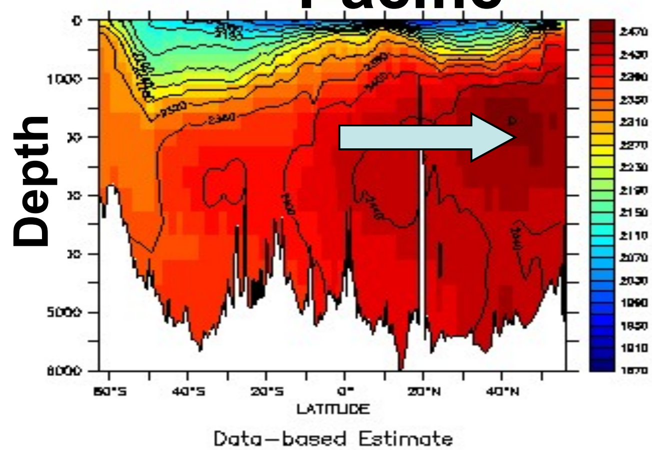
- Southward in Atlantic
- Northward in Pacific

Ocn currents ~ cm/s
Time scale ~ 10^3 yr

Atlantic



Pacific

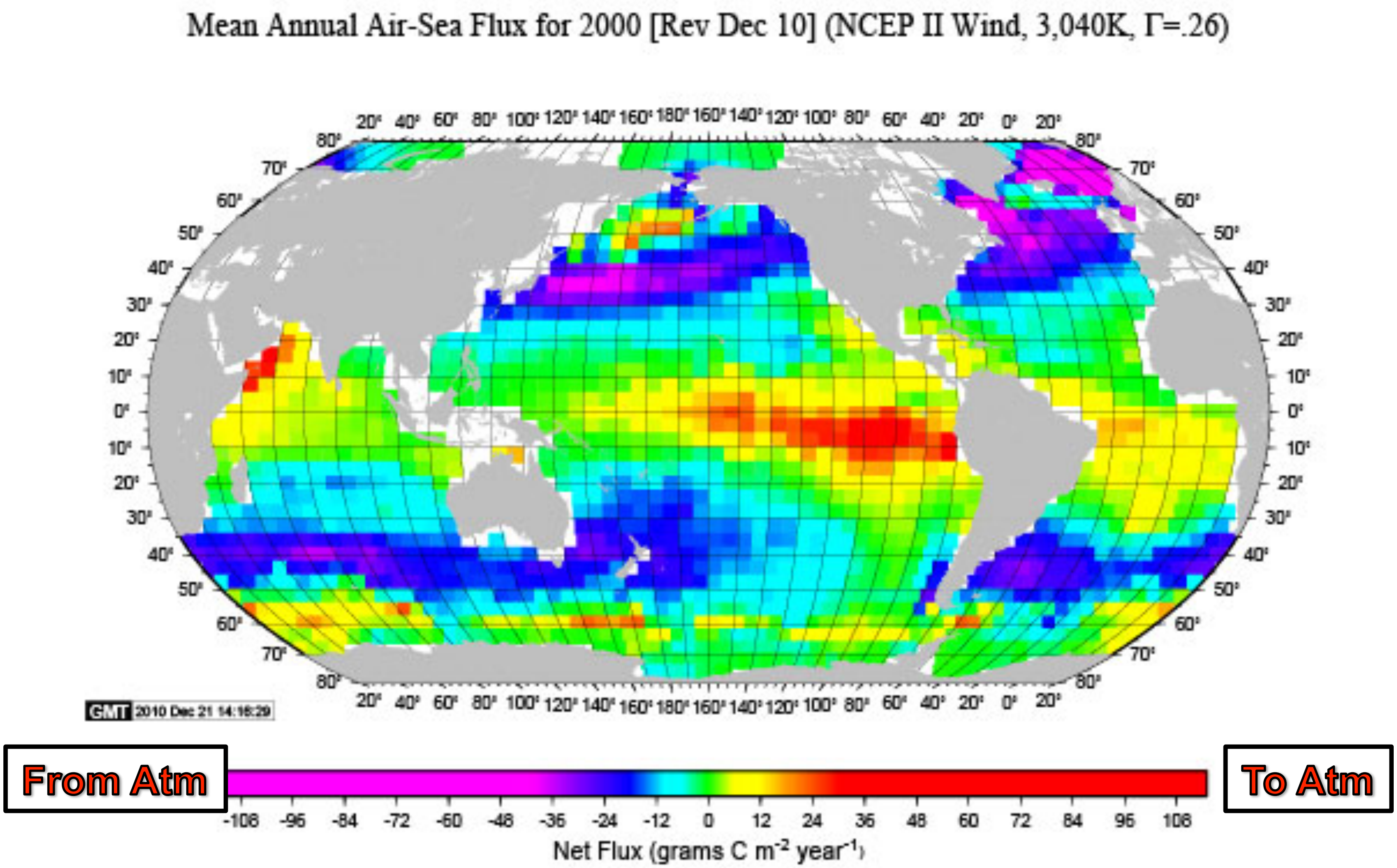


Latitude → N

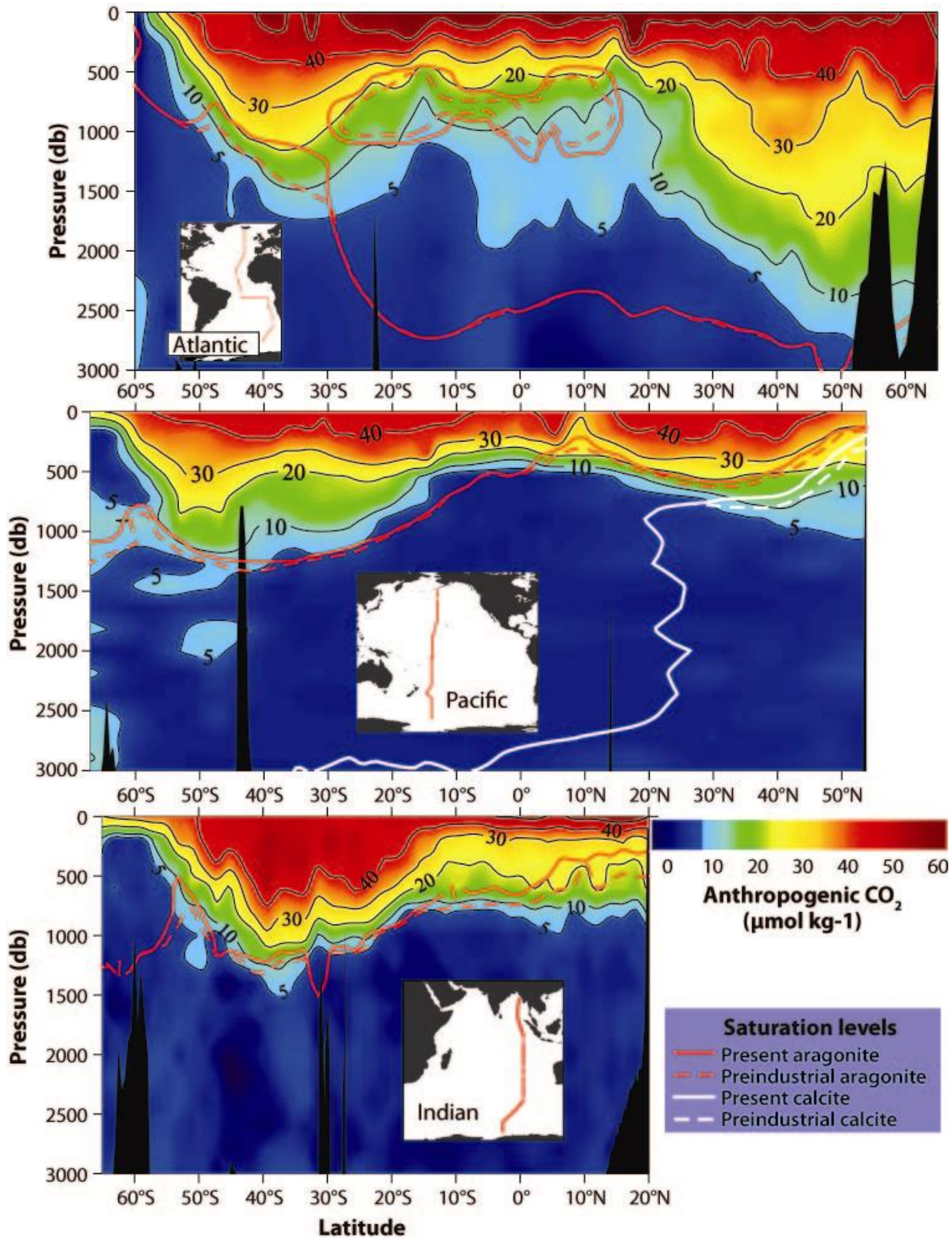
Biology and DIC:

- Depletion near sfc
- Enrichment at Depth

First barrier to Ocean Uptake: Air-Sea CO2 Flux

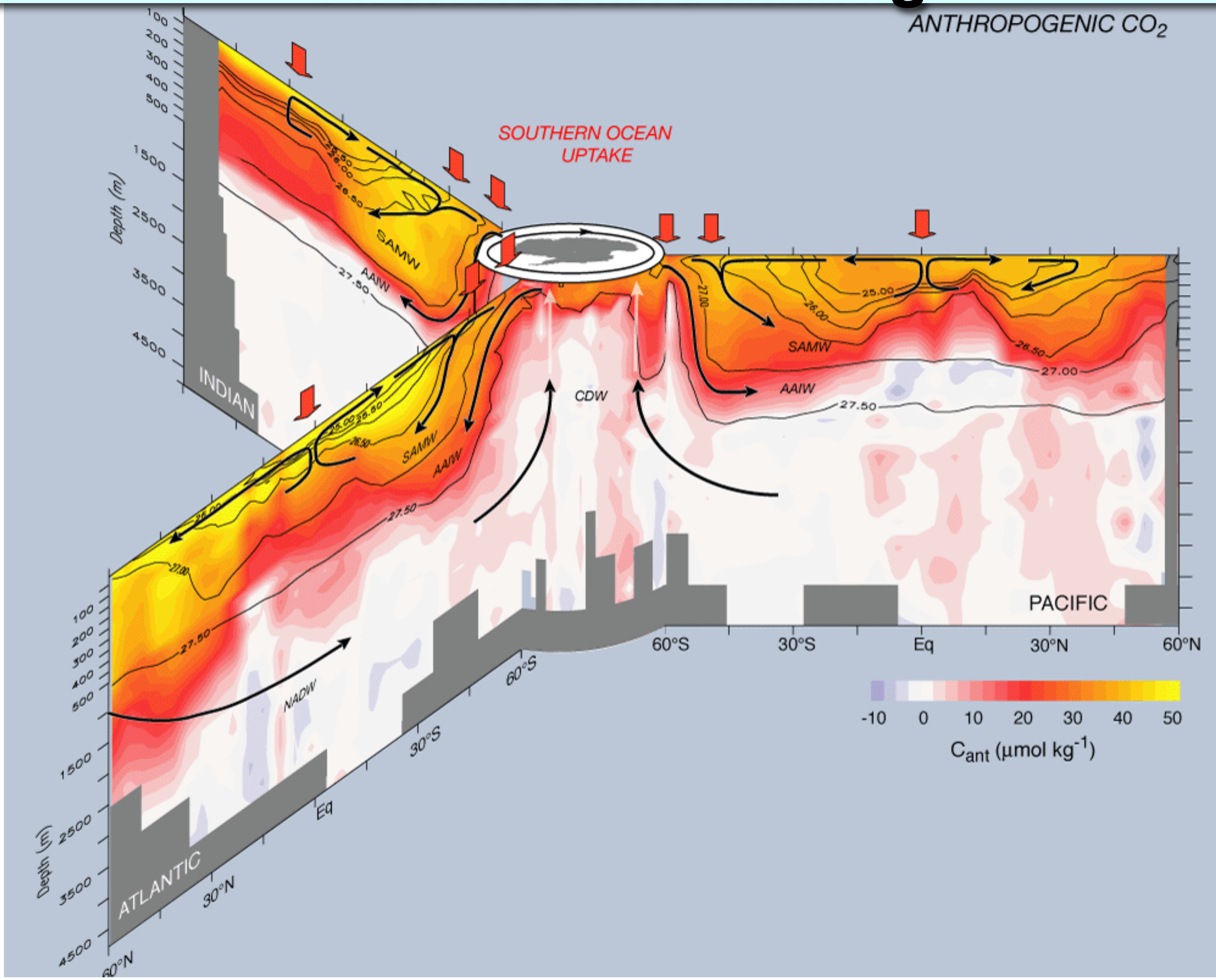


http://www.ldeo.columbia.edu/res/pi/CO2/carbondioxide/pages/air_sea_flux_2010.html



Doney SC, et al. 2009.
Annu. Rev. Mar. Sci. 1:169–92

Second Barrier to Ocean Uptake: Thermocline Mixing



SUMMARY

Prognostic Carbon Cycle

Atm

$$\frac{\partial C_a}{\partial t} + \frac{\partial}{\partial x}(u_a C_a) + \ldots = \left(FF + Def + \underbrace{F_{oa}\Updownarrow}_{\text{air-sea\_flux}} + \underbrace{F_{ba}\Updownarrow}_{atm-land\_flux}\right)\Big|_0 + \underbrace{\Im(C_a)}_{\text{turbulent\_mixing}}$$

Ocean

$$\frac{\partial C_o}{\partial t} + \frac{\partial}{\partial x}(u_o C_o) + \ldots = -F_{oa}\Updownarrow\Big|_0 + \underbrace{P - L}_{\text{biology}} + \Im(C_o)$$

Land-live

$$\frac{\partial C^k_{b\_live}}{\partial t} = -\alpha^k \underbrace{F_{ab}\downarrow}_{photosynthesis}\Big|_0 - \underbrace{\frac{C^k_{b\_live}}{\tau^k_{live}}}_{mortality}; \quad \sum_k \alpha^k = 1$$

Land-dead

$$\frac{\partial C^k_{b\_dead}}{\partial t} = \underbrace{\frac{C^k_{b\_live}}{\tau^k_{live}}}_{mortality} + \sum_j F_{jk} \underbrace{- (1-\gamma^k)\frac{C^k_{b\_dead}}{\tau^k_{dead}} - \gamma^k \frac{C^k_{b\_dead}}{\tau^k_{dead}}}_{decomposition}$$

$$\sum_k \gamma^k \frac{C^k_{b\_dead}}{\tau^k_{dead}} = F_{ba}$$