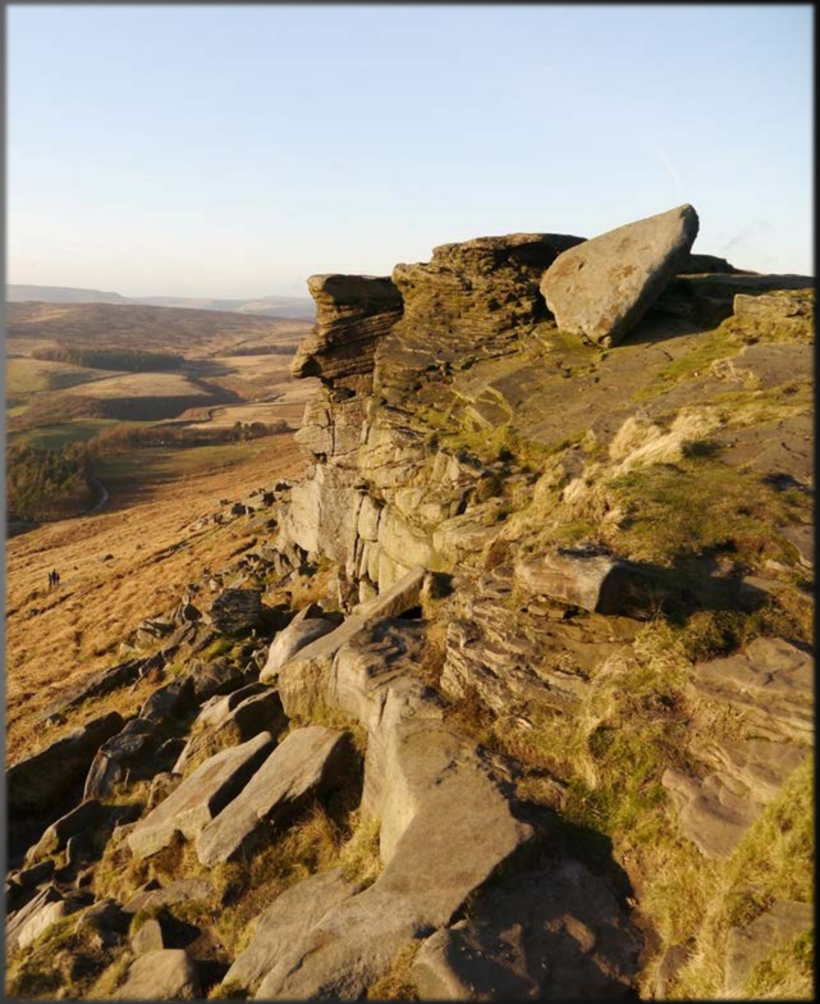
Linking the Water and Carbon Cycles

Prof. Andy Hodson

Outline

- 1000 – 1045: Introduction
- 1045 – 1100: Coffee
- 1100 – 1200: Data Exercise: CO_2 evasion from River Amazon
- 12 – 1230: Lunch
- 1230: 1400: Field excursion
- 1400 – 1600: Practical Exercise: Carbon content upland streams
- 1600: Depart



My Expectations

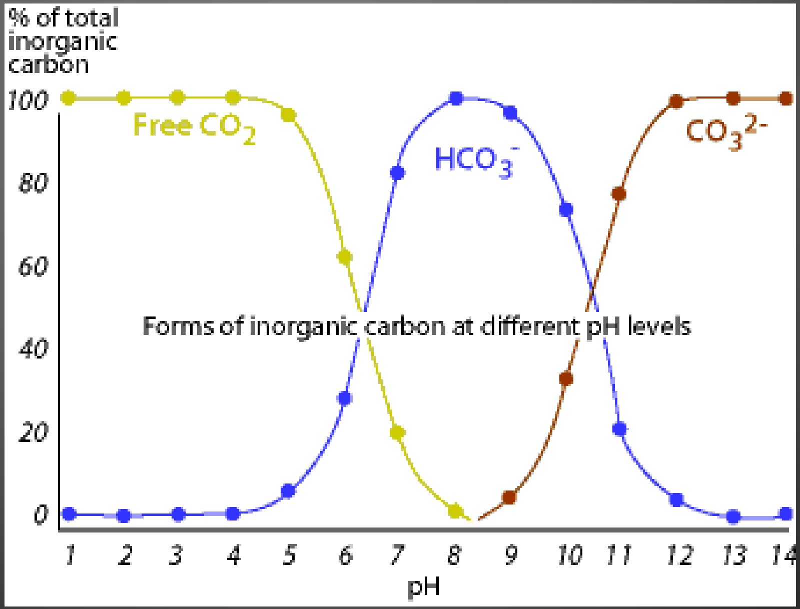
A. Test/feedback for two lesson plans developed for *Water and Carbon Cycles* element of A Level curriculum

B. Learn about curriculum implementation from your perspectives (problems/anxieties)

A. Refine A) based upon B) and plan any meaningful further actions (e.g. more case studies)

Dissolved Carbon

- DIC and DOM: Dissolved inorganic and dissolved organic carbon
- What is “dissolved”: operational definition usually everything < 0.45 µm
- For DIC this works fine because the forms depends upon pH and they are broadly similar to CO_2 molecules in size:



http://www.cotf.edu/ete/modules/waterq3

$CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^- = 2H^+ + CO_3^{2-}$

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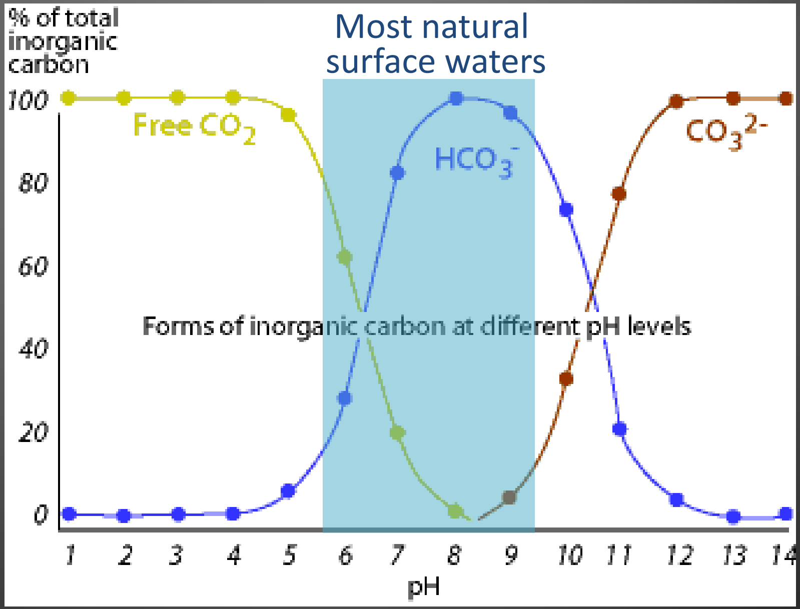

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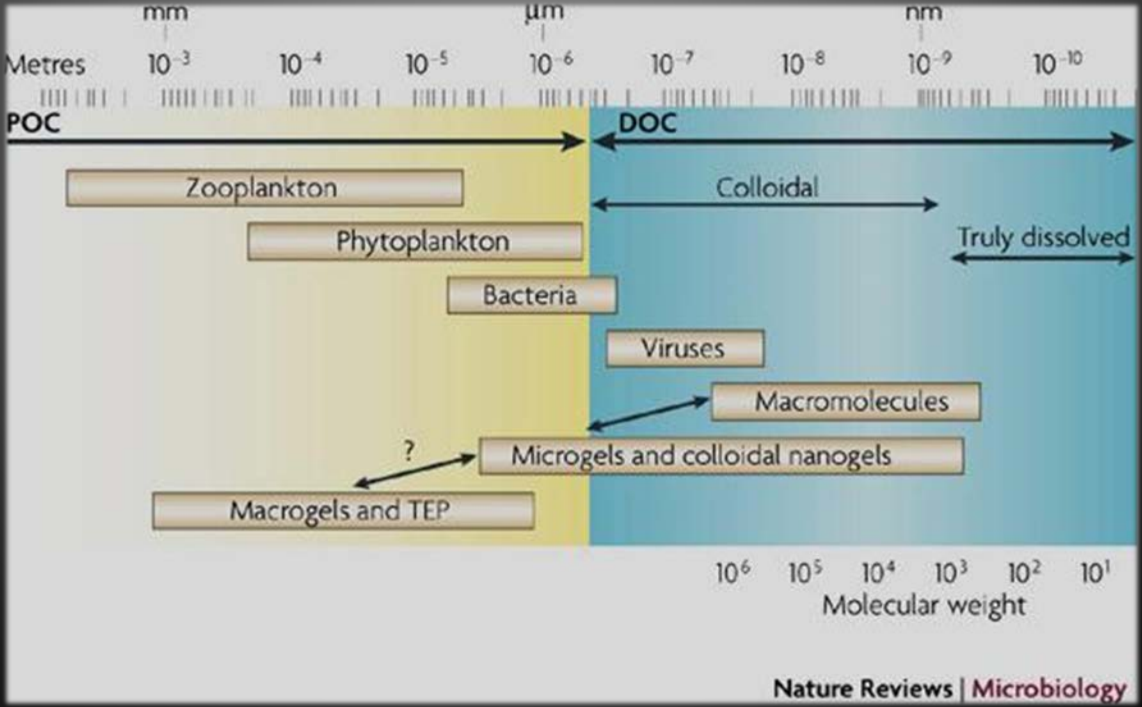
Aquatic DOM (or “DOC”!)



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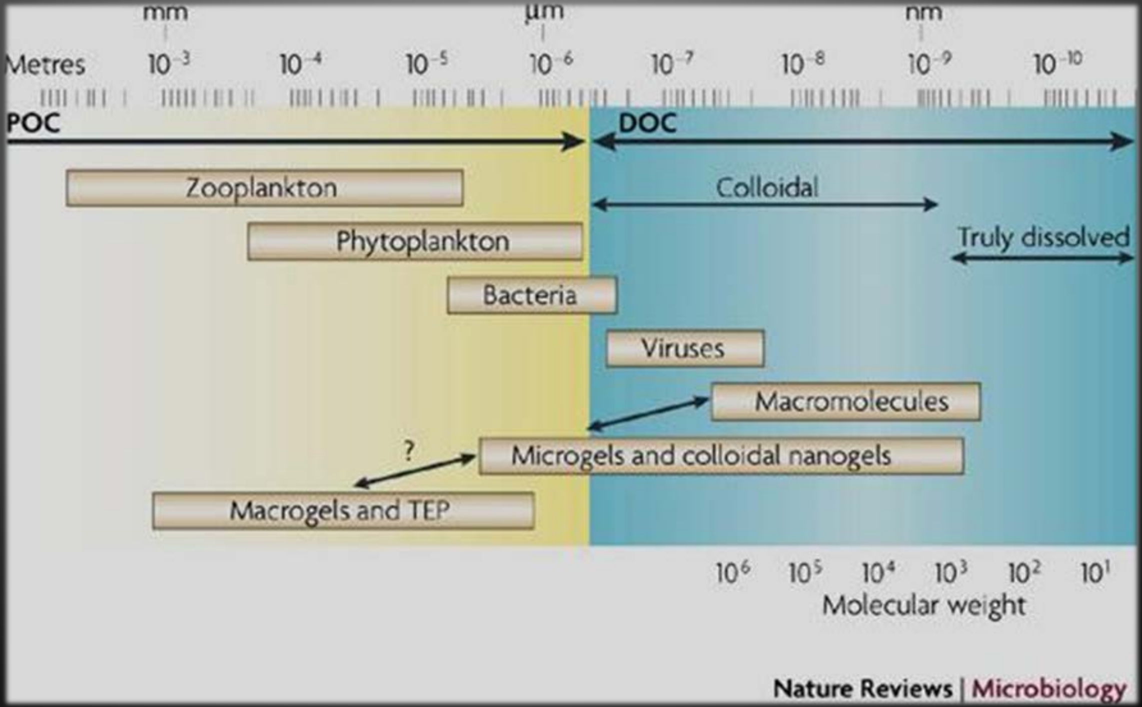
Aquatic DOM (or “DOC”!)

- The 0.45 µm size distinction is not useful: many “dissolved” organic carbon forms are colloidal, with large molecular weights (even living cells)
- Quantifying forms of DOC challenging: mol. wt. classes, light absorption/fluorescence properties or broad compound classes used
- Therefore, while “colour” makes DOM easily recognisable to students, analytical difficulty probably precludes lab or field work in schools
- Do you think there is more DOC than DIC in your local streams?



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Fizzy water

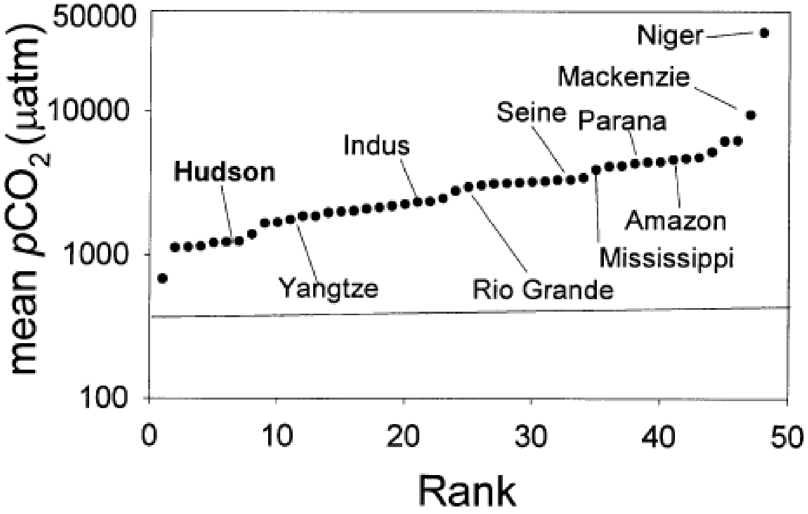
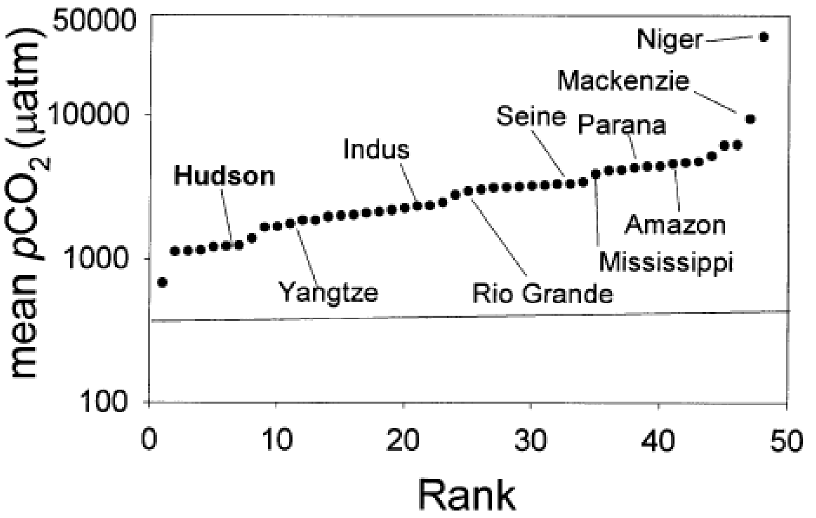


Fig. 5. Average partial pressure of CO_2 (pCO_2) in a series of 47 rivers with a near-global distribution (see text). Each point represents the mean pCO_2 in a different river, calculated from pH, temperature and alkalinity (Table 1); data for the Hudson are direct measurements (see text). Some of the individuals are labelled for reference. The rivers are ordered along the X-axis from the least to the most supersaturated in CO_2. The solid line denotes approximate equilibrium with air. Note log scale. (Cole and Caraco, 2001)

Fizzy water

- Cole and Caraco (2001): world's major rivers are super-saturated with CO_2
- Sources: the atmosphere, soil microbial respiration, aquatic microbial respiration, photolytic production and mineral weathering
- The production of inorganic carbon (CO_2 and HCO_3) by biotic and abiotic processes is a major sink of DOM
- Rivers then release their "excess" to the atmosphere and the rest is carried to the oceans (for burial or assimilation or release to atmosphere)



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Riverine carbon transfer: a Himalayan Case Study

- Rivers transport DIC derived from the chemical weathering of Earth's rocks. Much of this can be from the atmosphere, so do these fluxes influence our climate?

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Riverine carbon transfer: a Himalayan Case Study

- Rivers transport DIC derived from the chemical weathering of Earth's rocks. Much of this can be from the atmosphere, so do these fluxes influence our climate?
- The answer is "yes" - weathering exerts a long-term control upon Earth's atmospheric CO_2. Read: Berner, 1990
- Further, physical erosion enhances chemical denudation, turning mountain ranges into continental-scale carbon pumps
- For this reason the Himalayas has received significant research attention

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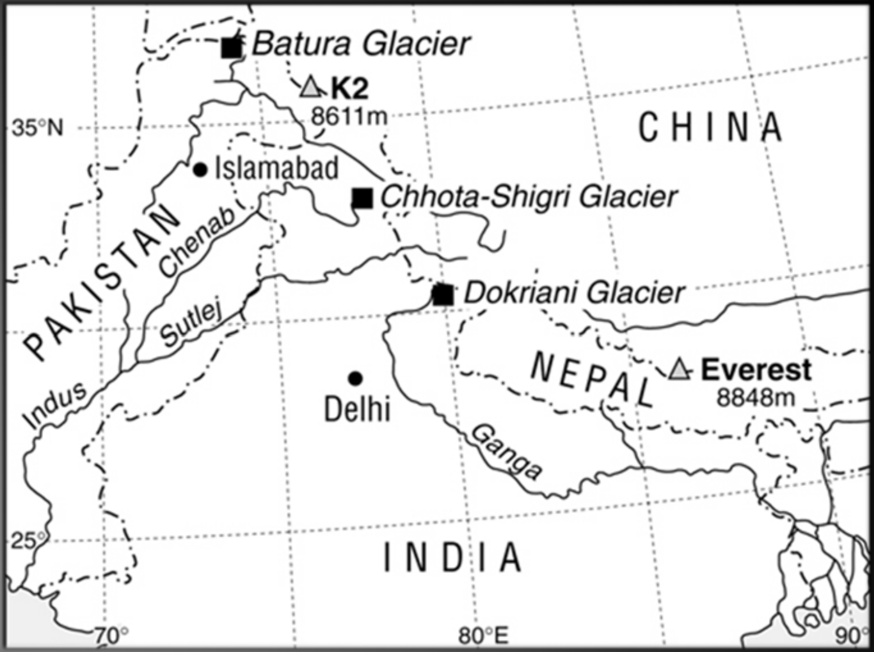
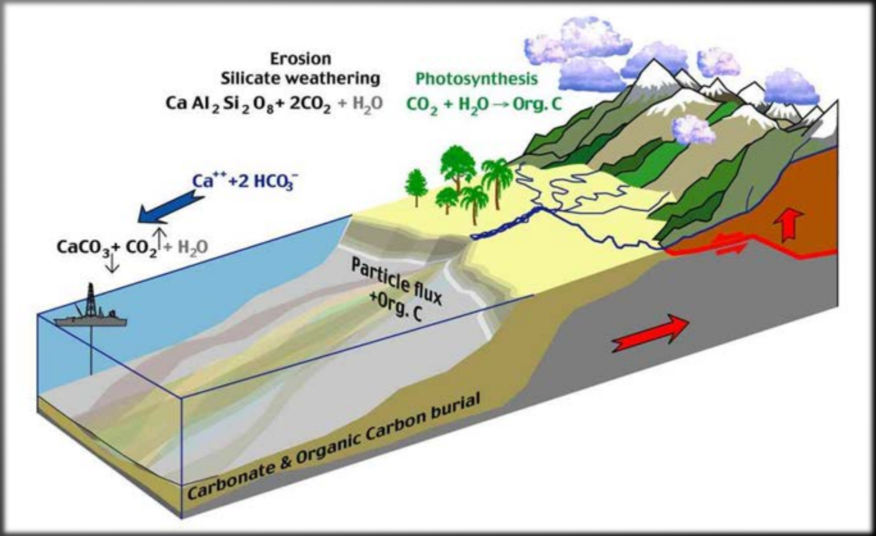
The Himalayas

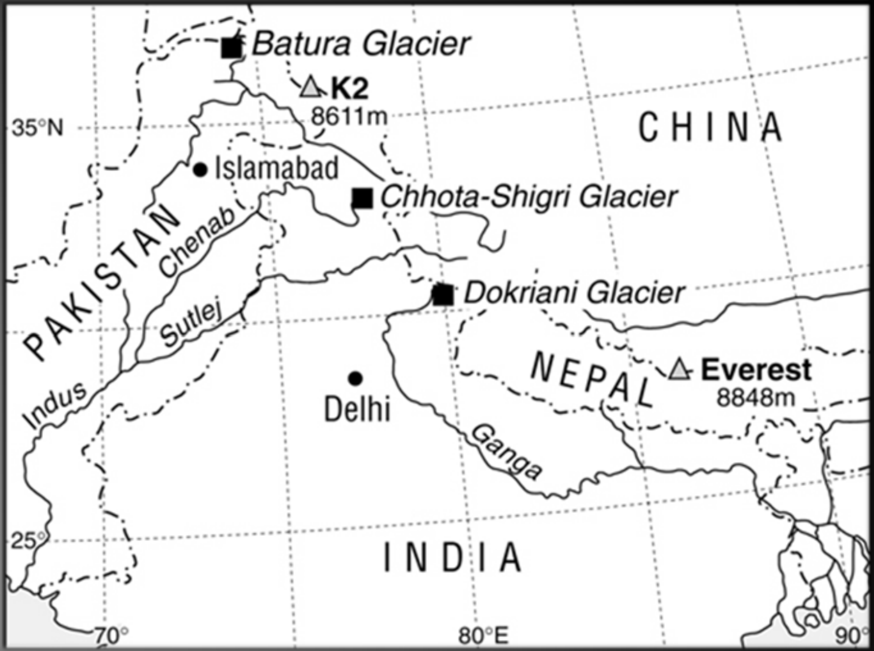
- A 50 million year old crash scene
- Monsoon and uplift: a recipe for chemical weathering. Read Raymo and Ruddiman (1992)
- Glaciation: erosion of rock to produce reactive, fine mineral surface.

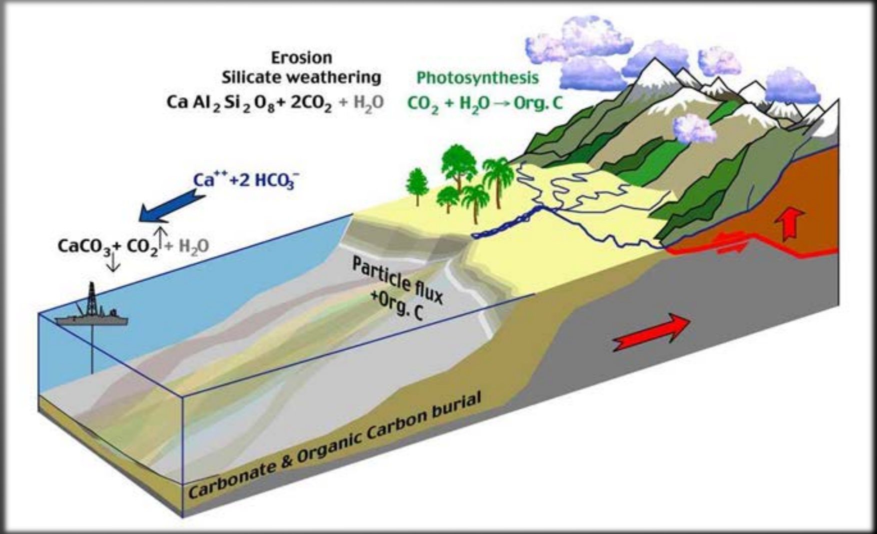




The Himalayas

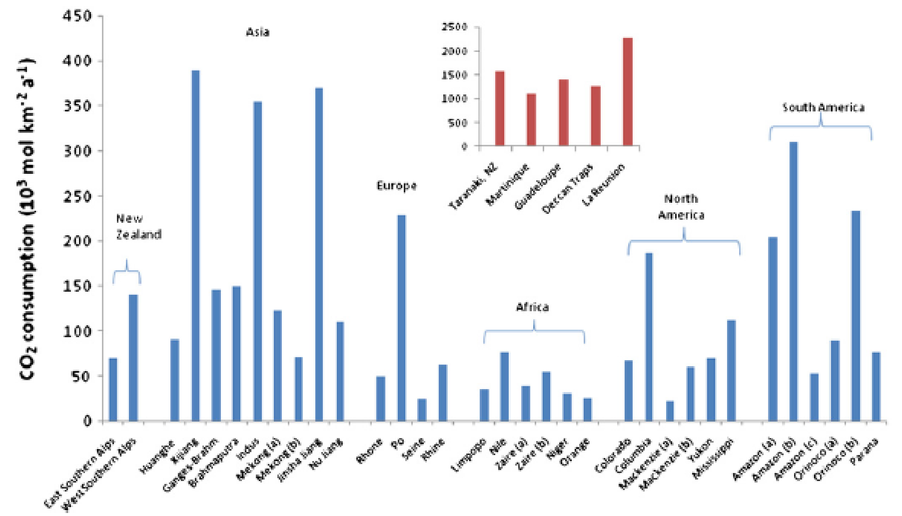
- A 50 million year old crash scene
- Monsoon and uplift: a recipe for chemical weathering. Read Raymo and Ruddiman (1992)
- Glaciation: erosion of rock to produce reactive, fine mineral surface.
- Weathering is enhanced by acidity. One of the key acid sources is carbonic acid. The more it is used the more CO_2 is removed from the atmosphere
- These are called "carbonation reactions"





Carbonation reactions

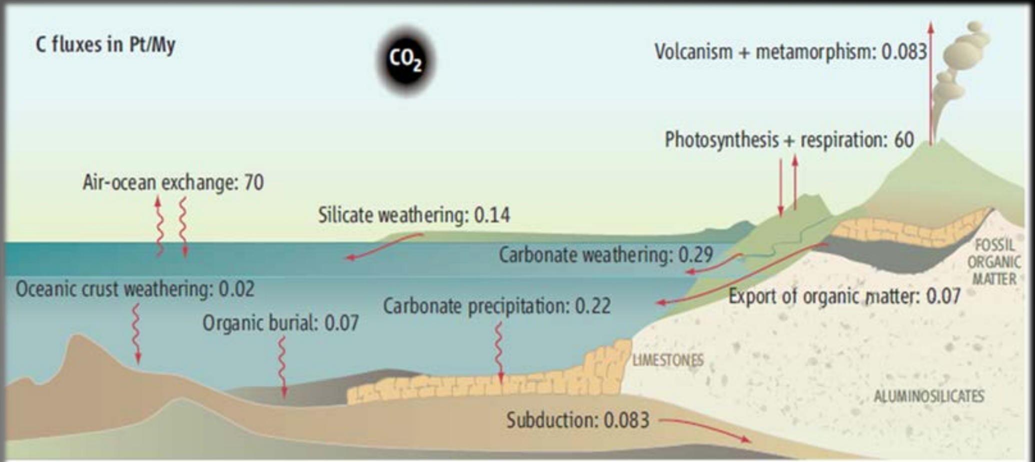
- Goudie and Viles (2012) explore the importance of tectonics and geomorphology for these CO_2 fluxes and show how warm climates in basalt terrain have far greater CO_2 drawdown rates, but Himalayas important
- Hodson et al (2000) also found rock type important, but carbonates as reactive as basalt when effect of runoff volume accounted for
- More basalt rocks being exposed to physical and chemical weathering in the tropics would therefore mean lower atmospheric CO_2 levels



Long-term (silicate-only) CO_2 drawdown

A mass balance model for Himalaya weathering and carbon cycling

- Complications in calculating source of carbon in Himalayan rivers included “metamorphic CO_2” (burial of organic C-rich sedimentary rocks in collision zone resulting in meta-morphosis)



The geological carbon cycle. The natural regulation of atmospheric CO_2 implies different carbon reservoirs playing roles on different time scales. Ocean and biomass reservoirs play a role at time scales lower than a couple of thousand years. At longer (geological) time scales, carbonate weathering is balanced by carbonate precipitation in the ocean, but the volcanic input of CO_2 to the atmosphere is only compensated by the weathering of Ca-Mg silicate minerals in soils ($CaSiO_3 + CO_2 = CaCO_3 + SiO_2$). For each mol of C precipitated into carbonate, a mol of C is released to the atmosphere, and the net sequestration of atmospheric carbon is 0.07 PgC/year. The organic sequestration in the form of fossil organic matter buried in sediments is thought to be compensated by the oxidation of ancient organic matter on land (not shown). New findings (*4, 5*) in the Himalaya lead to a new flux of CO_2 degassing in mountain ranges and make mountains a locus of CO_2 production instead of CO_2 consumption. Fluxes in PgC/year or PtC/My.

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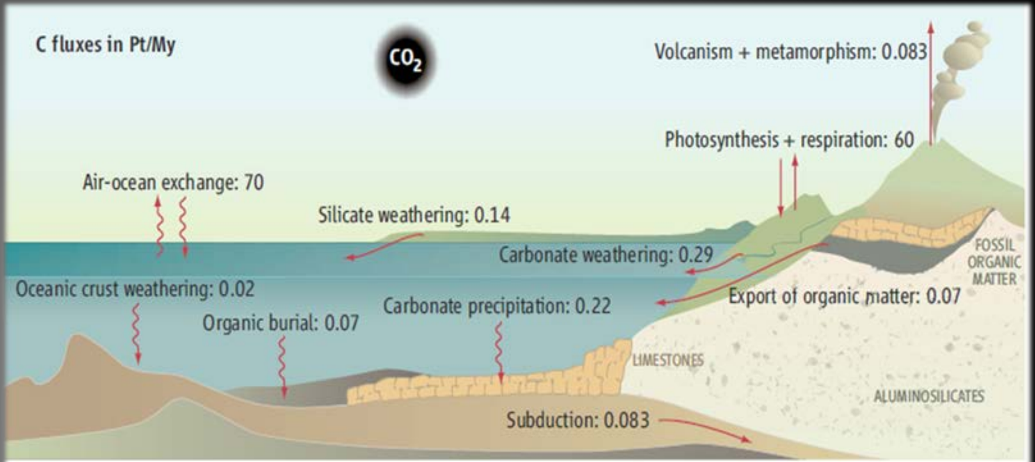

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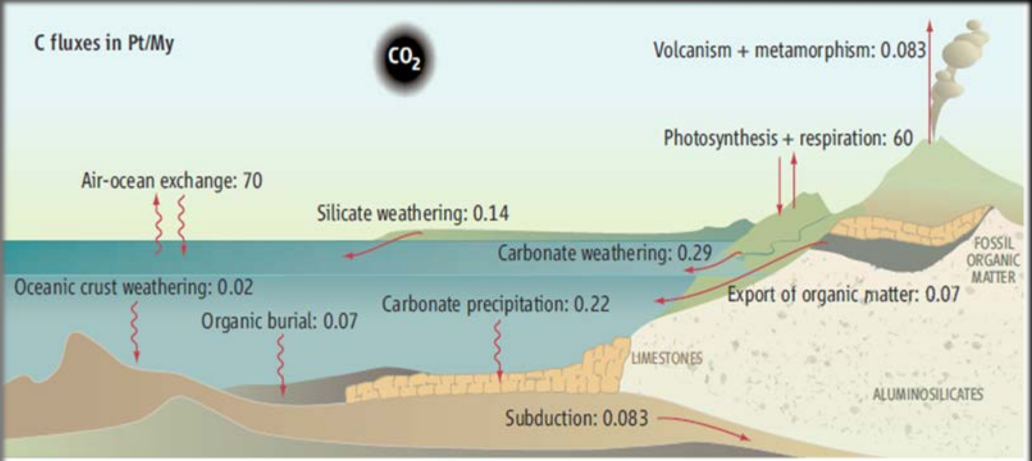

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- So, in spite of a very promising initial concept by Raymo and Ruddiman (1992), it appears the Himalayas are in fact a net source of CO_2!
- The debate continues because the mass balance terms still have large errors. Read: Gaillardet and Gaily, 2008

CO_2 outgassing from rivers (evasion)

- Outgassing is rapid (enhanced by turbulence) and can be an important landscape CO_2 pathway (especially if terrestrial ecosystem is a net sink: Hope et al, 2004)

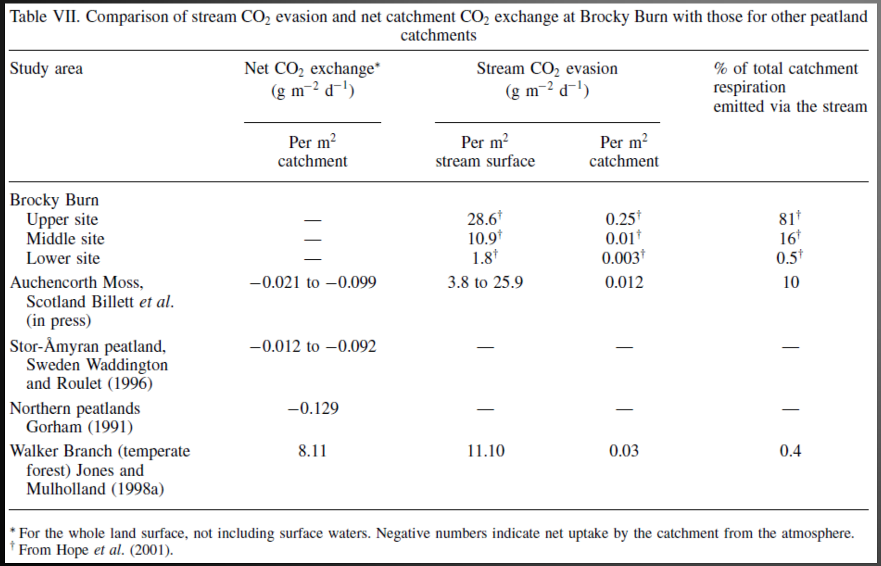

Table VII. Comparison of stream CO_2 evasion and net catchment CO_2 exchange at Brocky Burn with those for other peatland catchments

Study area	Net CO_2 exchange* ($g\ m^{-2}\ d^{-1}$)	Stream CO_2 evasion ($g\ m^{-2}\ d^{-1}$)		% of total catchment respiration emitted via the stream
	Per m^2 catchment	Per m^2 stream surface	Per m^2 catchment	
Brocky Burn				
Upper site	—	28.6[†]	0.25[†]	81[†]
Middle site	—	10.9[†]	0.01[†]	16[†]
Lower site	—	1.8[†]	0.003[†]	0.5[†]
Auchencorth Moss, Scotland Billett *et al.* (in press)	−0.021 to −0.099	3.8 to 25.9	0.012	10
Stor-Åmyran peatland, Sweden Waddington and Roulet (1996)	−0.012 to −0.092	—	—	—
Northern peatlands Gorham (1991)	−0.129	—	—	—
Walker Branch (temperate forest) Jones and Mulholland (1998a)	8.11	11.10	0.03	0.4

[*] For the whole land surface, not including surface waters. Negative numbers indicate net uptake by the catchment from the atmosphere.
[†] From Hope *et al.* (2001).

(Hope et al, 2004)

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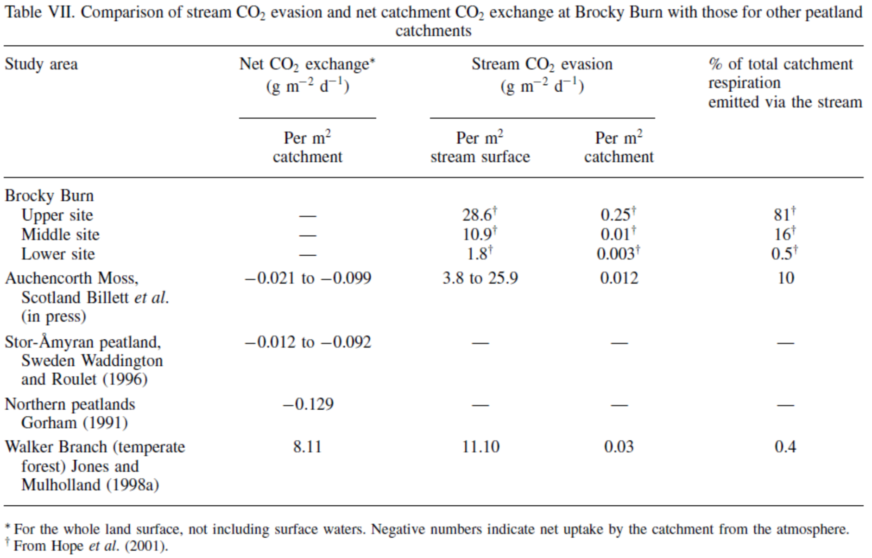
- The most impressive study so far has been the Amazon Basin



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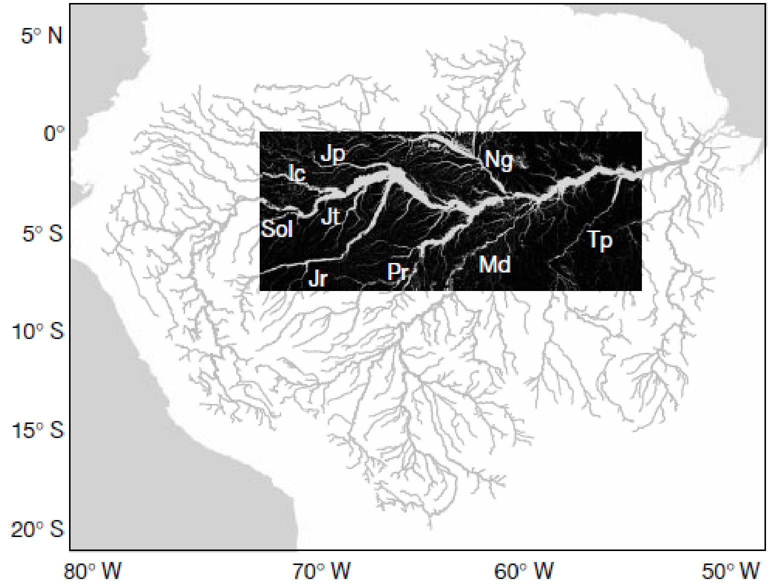

Figure 1 Flooded area of the central Amazon basin at high water, as mapped from the Japanese Earth Resources Satellite radar data (May–June 1996). The flooded area is shown as light areas in dark inset (the study quadrant). Underlying the inundation image is a digital river network (derived from the Digital Chart of the World, the GTOPO30 digital elevation model and ancillary cartographic information). Major tributaries are labelled: Negro (Ng), Japurá (Jp), Içá (Ic), Solimões (Sol, the Amazon mainstem exiting Peru), Jutaí (Jt), Juruá (Jr), Purus (Pr), Madeira (Md), and Tapajós (Tp).

Amazon outgassing case study: Richey et al (2002)

- Novel estimation of:
  i) stream surface area by remote sensing
  ii) CO_2 super-saturation in 1800 water samples
  iii) Gas diffusion flux (F) model:

$$F=K(Cs-Co)$$

Cs = concentration, Co is the equilibrium concentration and K is exchange coefficient

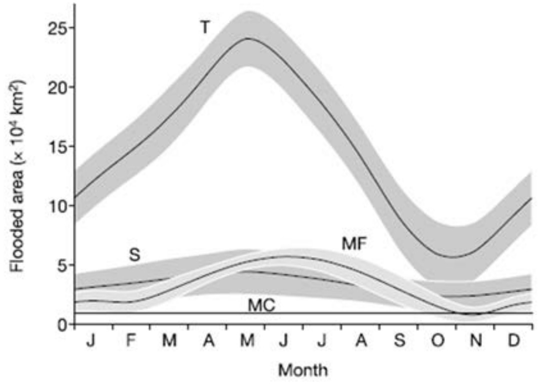

Figure 2 Spatially integrated annual sequences of surface water area for hydrographic environments as determined from JERS-1 radar data and multi-year hydrographic records. Hydrographic environments are divided into: the Amazon mainstem channel (MC); the mainstem floodplain (MF); the channels and floodplains of tributaries over 100 m wide (T); and the streams and riparian zones less than 100 m wide (S). Shaded regions represent 67% confidence intervals determined by Monte Carlo error propagation of both measurement uncertainties and interannual variability in river stage data.

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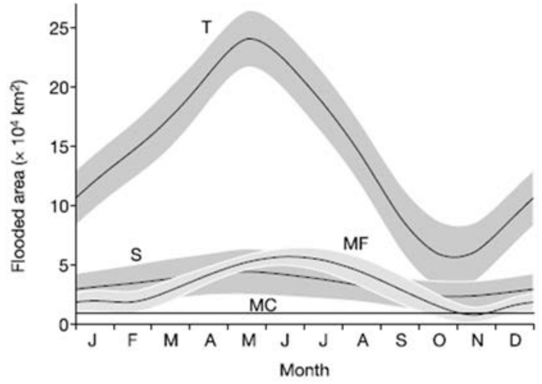
- Results: 1.2 Mg C ha^{-1} a^{-1} or 0.5 Pg C a^{-1}: more than 10 times riverine input of organic C to the sea
- What factors govern K?
  Wind, temperature and turbulence
  Quantified with tracer gas additions but do you think it was possible to conduct enough of them for this system?



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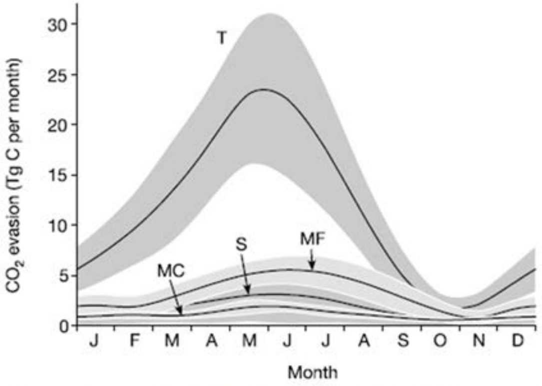

Figure 4 Spatially integrated sequences of monthly carbon dioxide evasion for the respective hydrographic environments (identified in Fig. 2). Lines represent the best estimate of long-term means, whereas shaded regions represent the 67% confidence interval for the range of values likely in a particular year. The upper confidence limit for streams, hidden from view, extends nearly to the upper limit for the mainstem floodplain.

Synthesis

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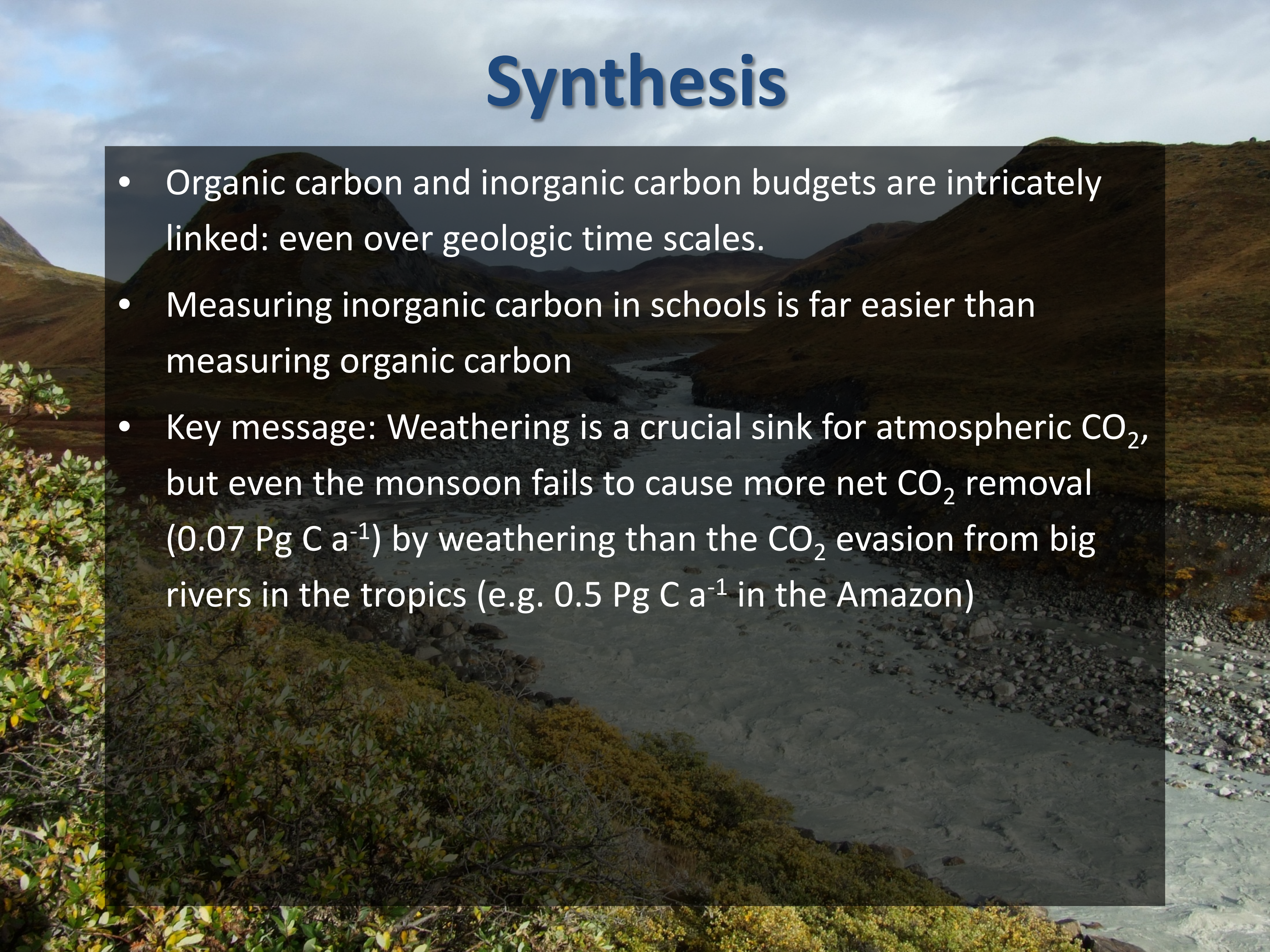
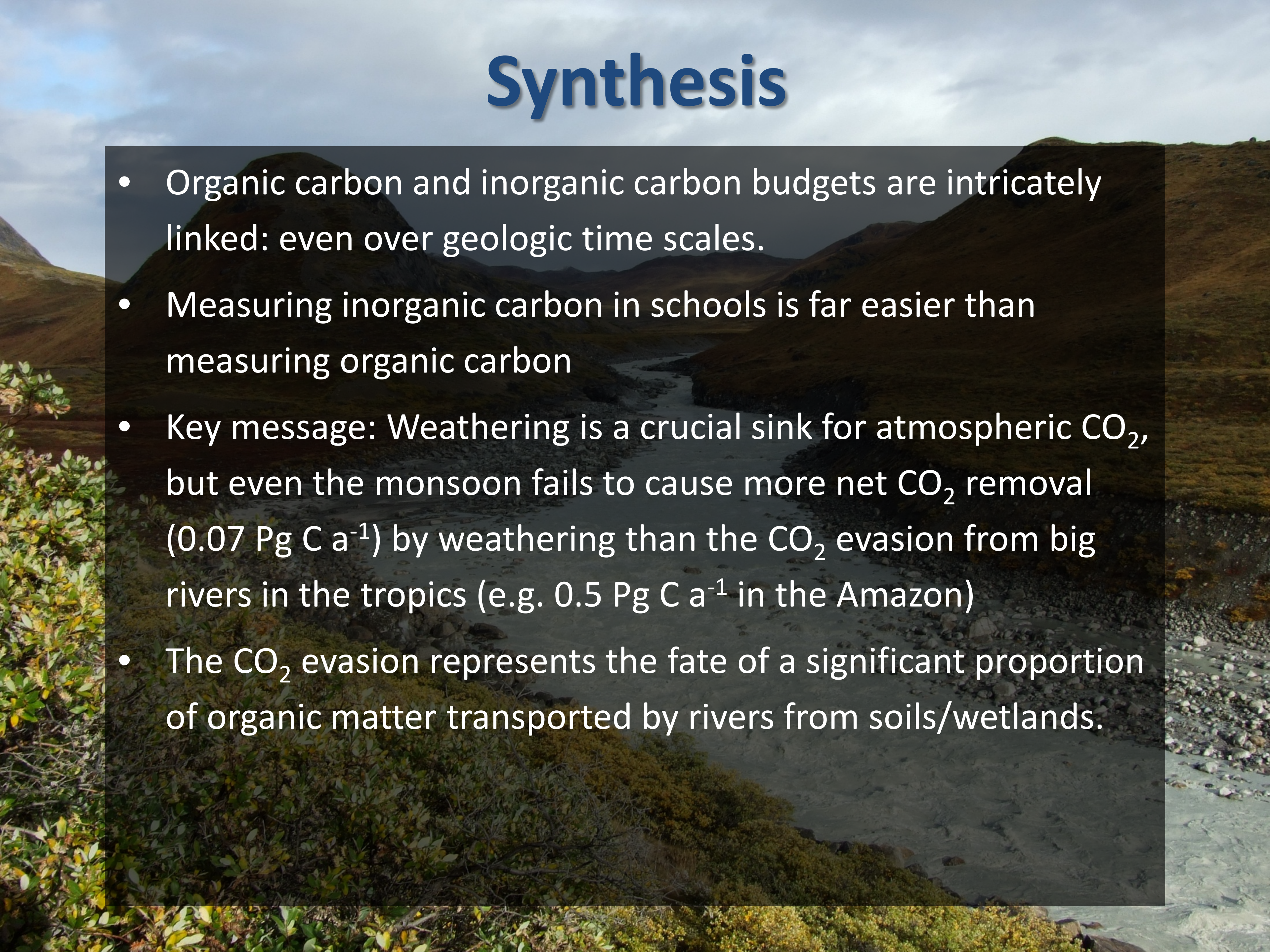


- Organic carbon and inorganic carbon budgets are intricately linked: even over geologic time scales.
- Measuring inorganic carbon in schools is far easier than measuring organic carbon
- Key message: Weathering is a crucial sink for atmospheric CO_2, but even the monsoon fails to cause more net CO_2 removal (0.07 Pg C a^{-1}) by weathering than the CO_2 evasion from big rivers in the tropics (e.g. 0.5 Pg C a^{-1} in the Amazon)



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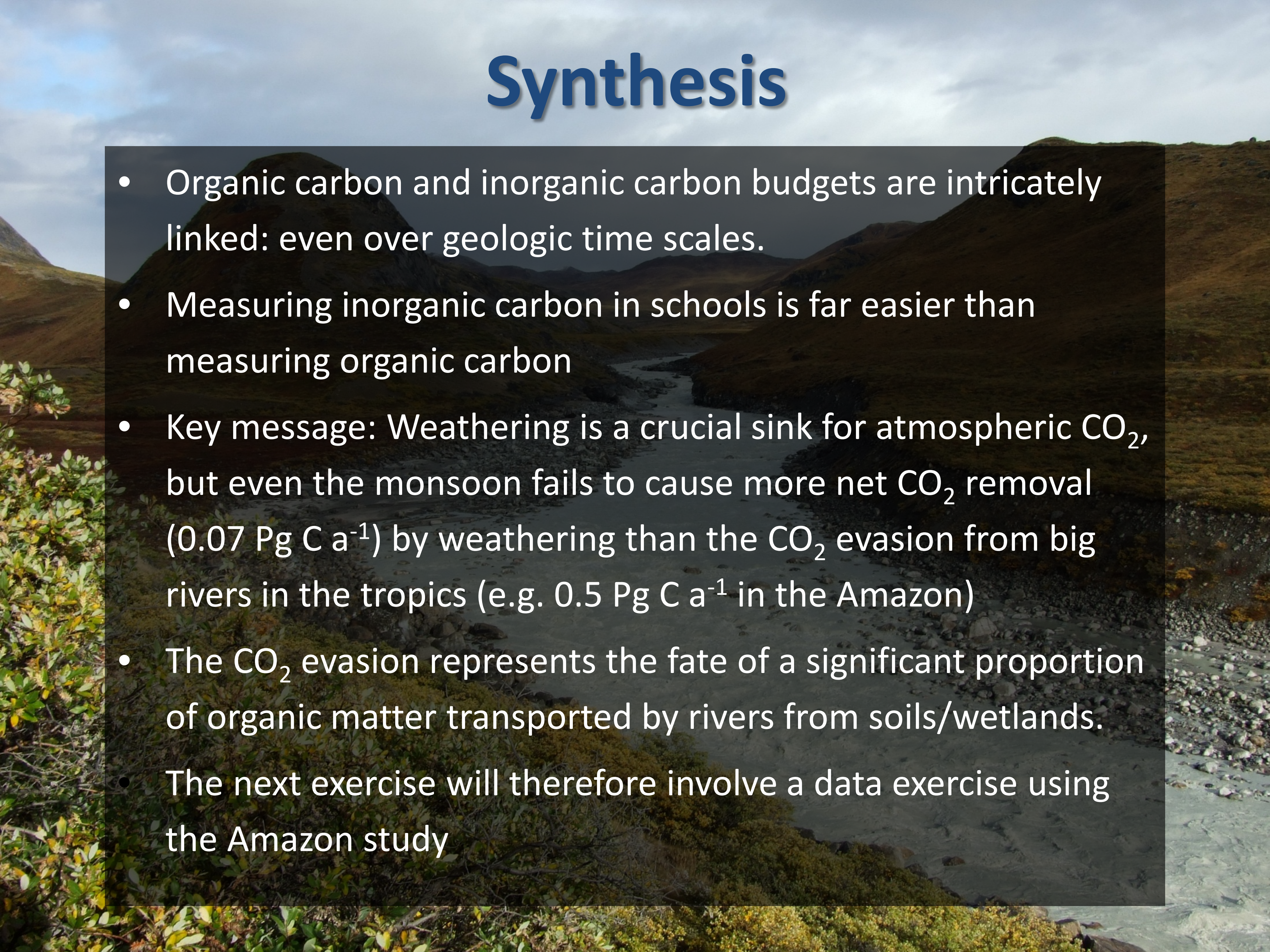
- The CO_2 evasion represents the fate of a significant proportion of organic matter transported by rivers from soils/wetlands.



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- The next exercise will therefore involve a data exercise using the Amazon study

Carbon inventory for planet Earth

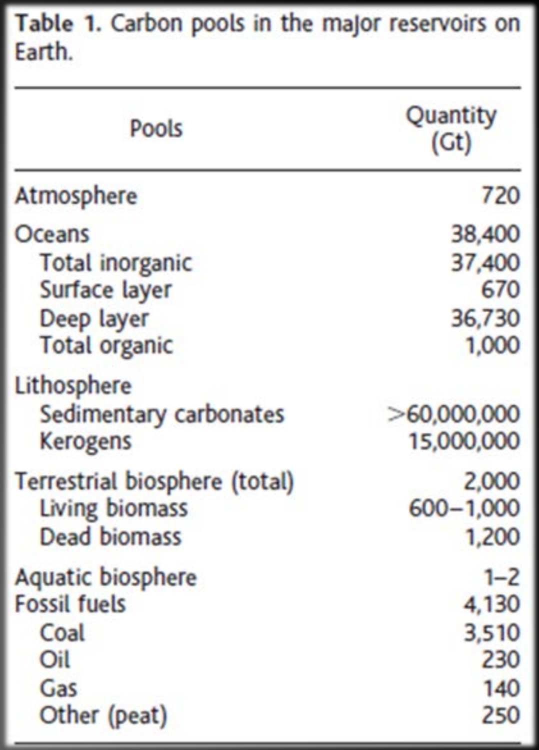


Table 1. Carbon pools in the major reservoirs on Earth.

Pools	Quantity (Gt)
Atmosphere	720
Oceans	38,400
Total inorganic	37,400
Surface layer	670
Deep layer	36,730
Total organic	1,000
Lithosphere	
Sedimentary carbonates	>60,000,000
Kerogens	15,000,000
Terrestrial biosphere (total)	2,000
Living biomass	600–1,000
Dead biomass	1,200
Aquatic biosphere	1–2
Fossil fuels	4,130
Coal	3,510
Oil	230
Gas	140
Other (peat)	250

Falkowski et al, 2000

- Carbon on Earth is dominated by lithospheric (rock) stores with long residence times due to the pace of the erosion cycle and the greater recalcitrance of kerogen (e.g. bitumen)

Carbon inventory for planet Earth

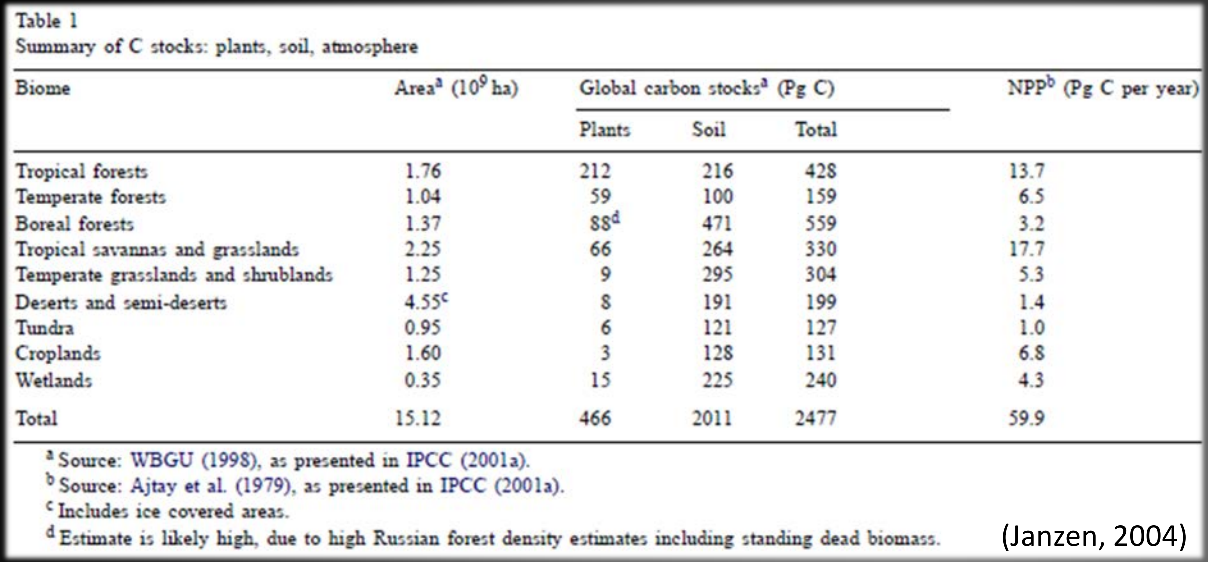
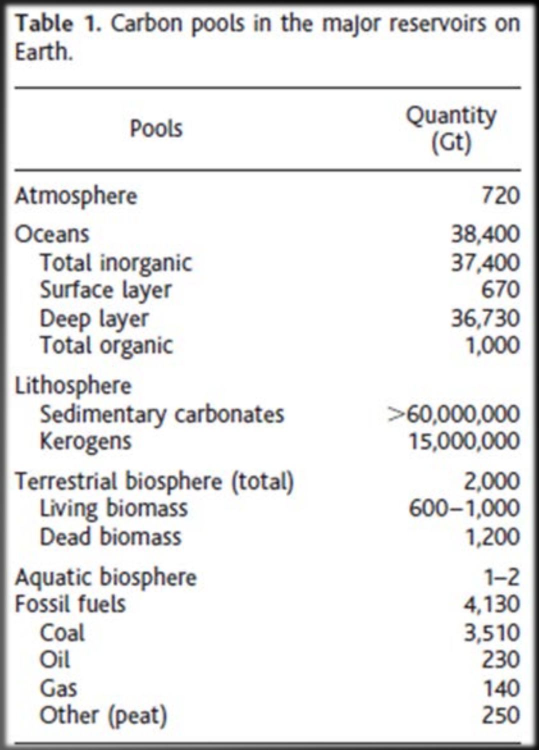


Table 1
Summary of C stocks: plants, soil, atmosphere

Biome	Area[a] (10^9 ha)	Global carbon stocks[a] (Pg C)			NPP[b] (Pg C per year)
		Plants	Soil	Total	
Tropical forests	1.76	212	216	428	13.7
Temperate forests	1.04	59	100	159	6.5
Boreal forests	1.37	88[d]	471	559	3.2
Tropical savannas and grasslands	2.25	66	264	330	17.7
Temperate grasslands and shrublands	1.25	9	295	304	5.3
Deserts and semi-deserts	4.55[c]	8	191	199	1.4
Tundra	0.95	6	121	127	1.0
Croplands	1.60	3	128	131	6.8
Wetlands	0.35	15	225	240	4.3
Total	15.12	466	2011	2477	59.9

[a] Source: WBGU (1998), as presented in IPCC (2001a).
[b] Source: Ajtay et al. (1979), as presented in IPCC (2001a).
[c] Includes ice covered areas.
[d] Estimate is likely high, due to high Russian forest density estimates including standing dead biomass.

(Janzen, 2004)



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Falkowski et al, 2000

- Carbon on Earth is dominated by lithospheric (rock) stores with long residence times due to the pace of the erosion cycle and the greater recalcitrance of kerogen (e.g. bitumen)
- Terrestrial ecosystems dominated by soil organic matter (SOM): vulnerable to erosion

Carbon inventory for planet Earth

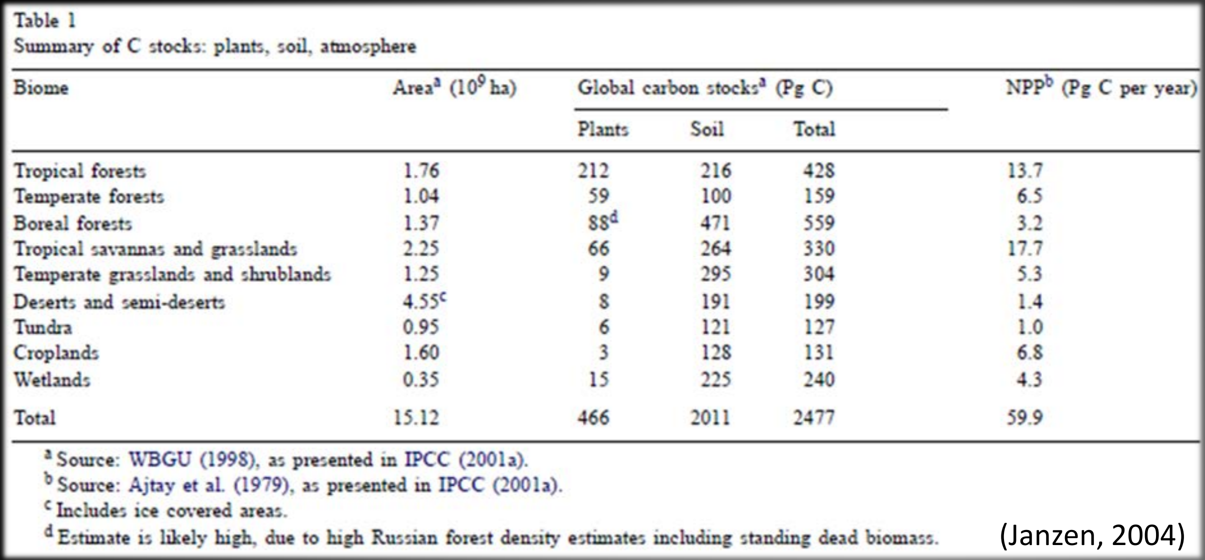


Table 1
Summary of C stocks: plants, soil, atmosphere

Biome	Area[a] (10^9 ha)	Global carbon stocks[a] (Pg C)			NPP[b] (Pg C per year)
		Plants	Soil	Total	
Tropical forests	1.76	212	216	428	13.7
Temperate forests	1.04	59	100	159	6.5
Boreal forests	1.37	88[d]	471	559	3.2
Tropical savannas and grasslands	2.25	66	264	330	17.7
Temperate grasslands and shrublands	1.25	9	295	304	5.3
Deserts and semi-deserts	4.55[c]	8	191	199	1.4
Tundra	0.95	6	121	127	1.0
Croplands	1.60	3	128	131	6.8
Wetlands	0.35	15	225	240	4.3
Total	15.12	466	2011	2477	59.9

[a] Source: WBGU (1998), as presented in IPCC (2001a).
[b] Source: Ajtay et al. (1979), as presented in IPCC (2001a).
[c] Includes ice covered areas.
[d] Estimate is likely high, due to high Russian forest density estimates including standing dead biomass.

(Janzen, 2004)

- Carbon on Earth is dominated by lithospheric (rock) stores with long residence times due to the pace of the erosion cycle and the greater recalcitrance of kerogen (e.g. bitumen)
- Terrestrial ecosystems dominated by soil organic matter (SOM): vulnerable to erosion
- Dissolved inorganic carbon (DIC) dominates in the oceans and is 50 times that of the atmosphere. Most of it is at depth.

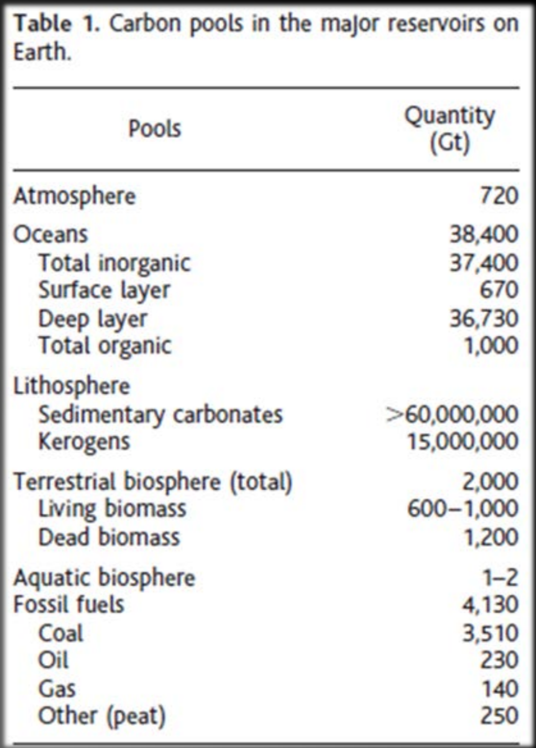
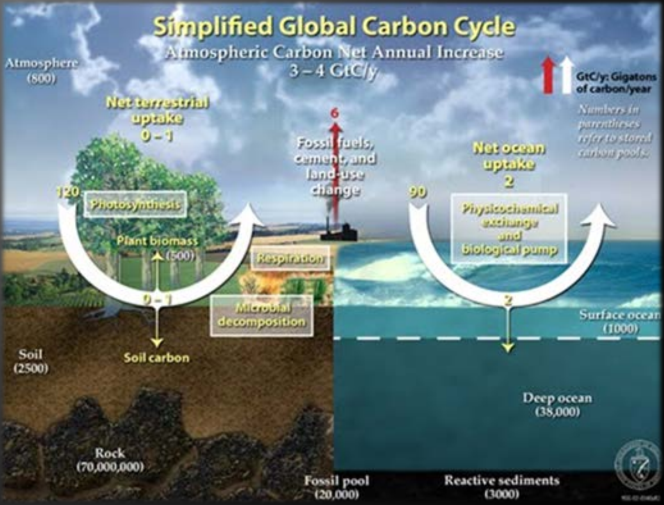


Table 1. Carbon pools in the major reservoirs on Earth.

Pools	Quantity (Gt)
Atmosphere	720
Oceans	38,400
Total inorganic	37,400
Surface layer	670
Deep layer	36,730
Total organic	1,000
Lithosphere	
Sedimentary carbonates	>60,000,000
Kerogens	15,000,000
Terrestrial biosphere (total)	2,000
Living biomass	600–1,000
Dead biomass	1,200
Aquatic biosphere	1–2
Fossil fuels	4,130
Coal	3,510
Oil	230
Gas	140
Other (peat)	250

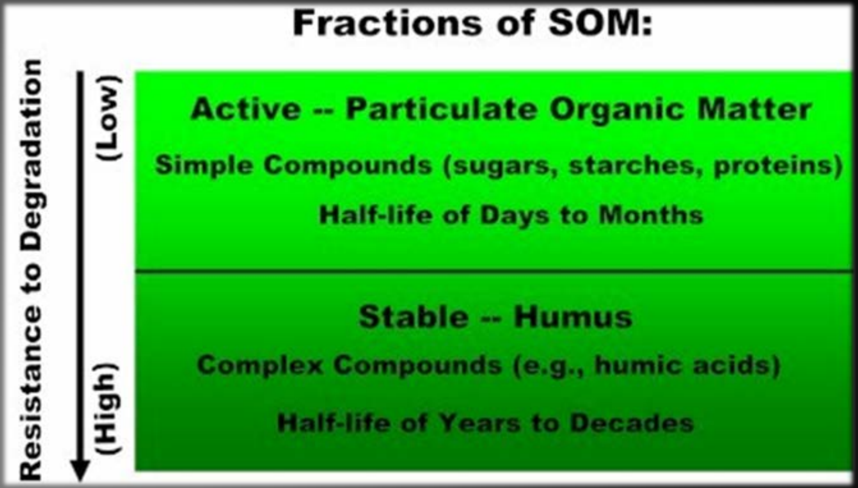
Falkowski et al, 2000

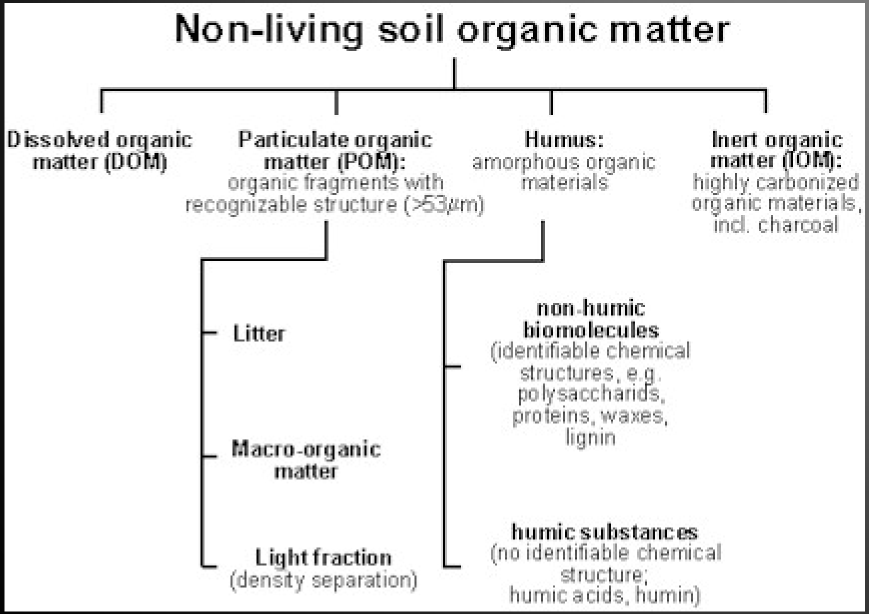


Soil Organic Matter (SOM)

(http://www.treepower.org/soils/)

- Labile pool: carbs., amino acids, proteins: all rapidly recycled by soil microorganisms
- Recalcitrant pool: humus (residual, broken-down and stable OM) and carbonised forms (e.g. black carbon)





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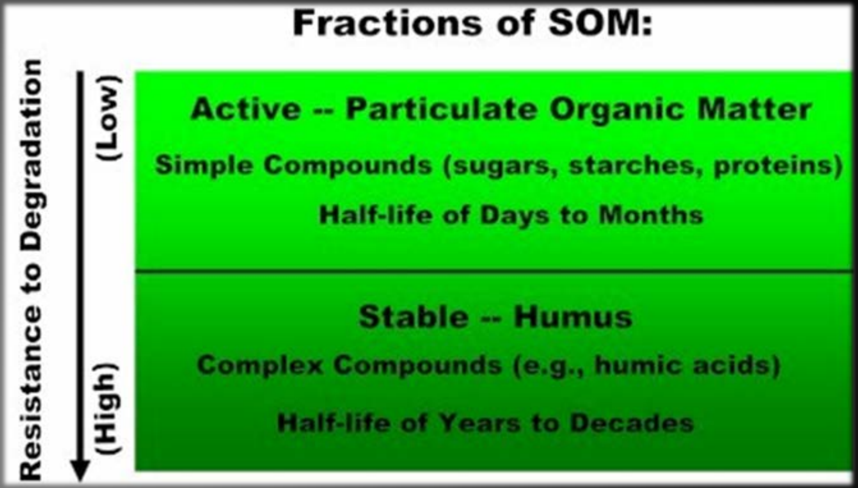
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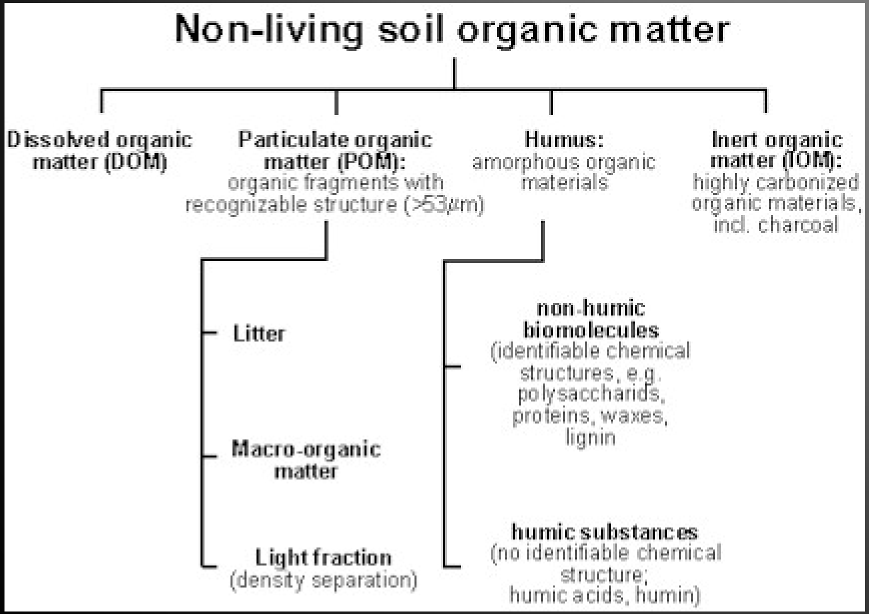


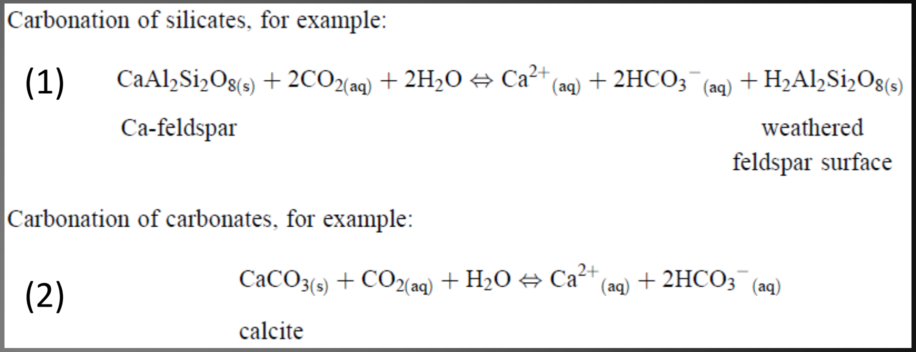
- Soil is now referred to the "Critical Zone": a fragile skin often < 1m thick that supports life on Earth
- Essential reading: Anderson et al, 2007; Chorover et al, 2007 (Elements Special Edition 2007), or http://www.czen.org/biblio
- Watch the Sheffield CZ expert:

http://www.youtube.com/watch?v=RIhU3FxfbMM

Carbonation reactions in the Himalayas: the river flux approach

- Chemical weathering: complex set of equations. Read Hodson et al (2000).
- Transient versus long-term CO_2 drawdown. Long term is less due to marine carbonate precipitation – which reverses equation 2

Transient CO_2 drawdown



Carbonation of silicates, for example:

(1) $$CaAl_2Si_2O_{8(s)} + 2CO_{2(aq)} + 2H_2O \Leftrightarrow Ca^{2+}{}_{(aq)} + 2HCO_3{}^{-}{}_{(aq)} + H_2Al_2Si_2O_{8(s)}$$

Ca-feldspar

weathered
feldspar surface

Carbonation of carbonates, for example:

(2) $$CaCO_{3(s)} + CO_{2(aq)} + H_2O \Leftrightarrow Ca^{2+}{}_{(aq)} + 2HCO_3{}^{-}{}_{(aq)}$$

calcite

- Atmospheric CO_2 removal is the product of riverine runoff times the concentration of HCO_3 derived from 50% of (Ca+Mg) silicate weathering and all (Na+K) weathering.

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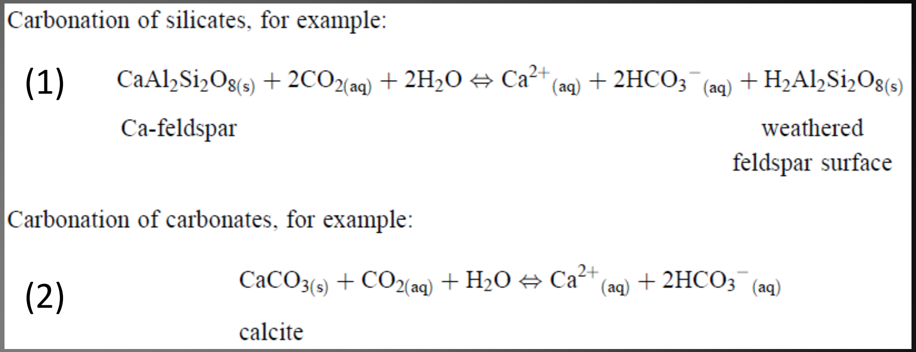

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- Complications: substitutions between (Ca+Mg) and (Na+K) and separating carbonate-derived (Ca+Mg) from silicate-derived (Ca+Mg)!
- Also not all carbonic acid directly from atmosphere (microbial respiration of OM, metamorphic CO_2). More on this later.