An Introduction to Coupled Biogeochemical Cycles

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Biology pervasive in the geochemical cycles of today’s Earth

Earth’s inventory of 22 x 10^{22} g C

in the crust and upper mantle (Zhang and Zindler 1993).

Current burial of carbon (organic and carbonate) by

organisms,

ca. 0.5 x 10^{15} g C/yr,

if for the past 500 million years yields cumulative burial of

25 x 10^{22} g C.

Thus,

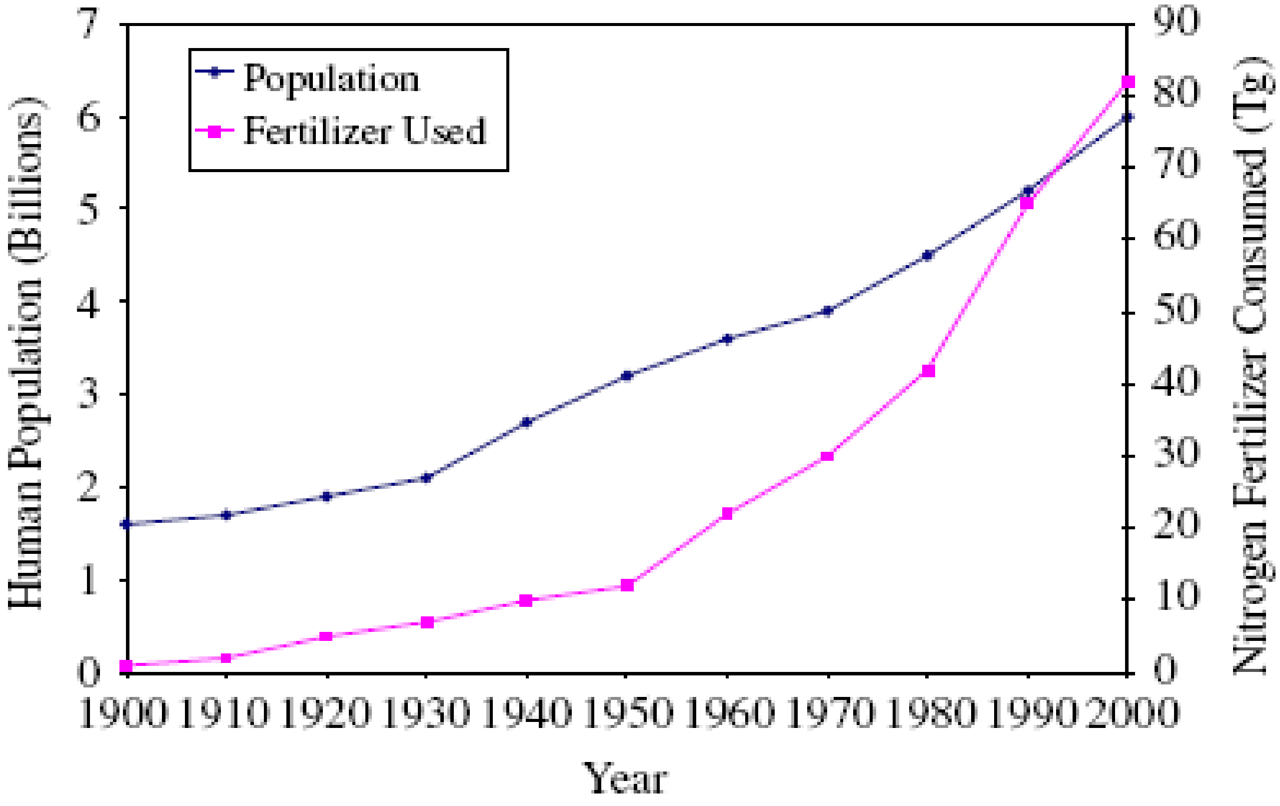
1. Most of the inventory of carbon on the planet has spent some time in the biosphere.

2. We should be thankful for tectonic activity on our planet as a renewal for life.

(N.B. Today’s volcanic flux is about 0.02–0.05 x 10^{15} C/yr)

Contributions of Biotic and Abiotic Processes, Including Humans, to Global Biogeochemical Cycles

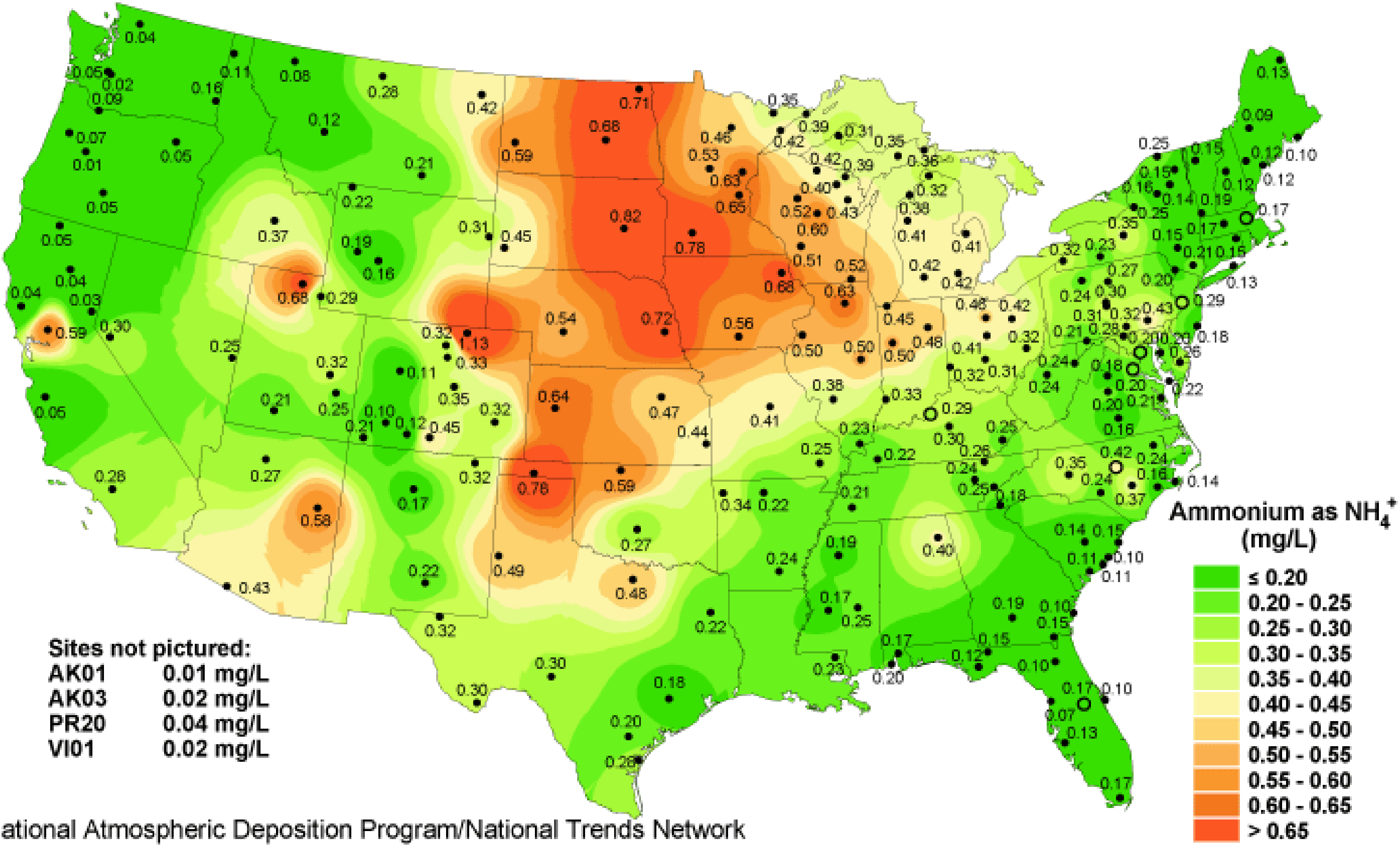
	Biotic Cycle	Human Mobilization	Human/Biotic
	10^{12} g/yr		%
Boron	9	< 1	6.8
Carbon	105,000	7,000	6.7
Nitrogen	9,200	156	1.7
Phosphorus	1,260	13	1.1
Sulfur	500	150	30.0
Chloride	0	142	ND



Population increase and use of nitrogen fertilizer from 1900 to 2000.

Aneja et al. 2008.

Ammonium ion concentration, 2006

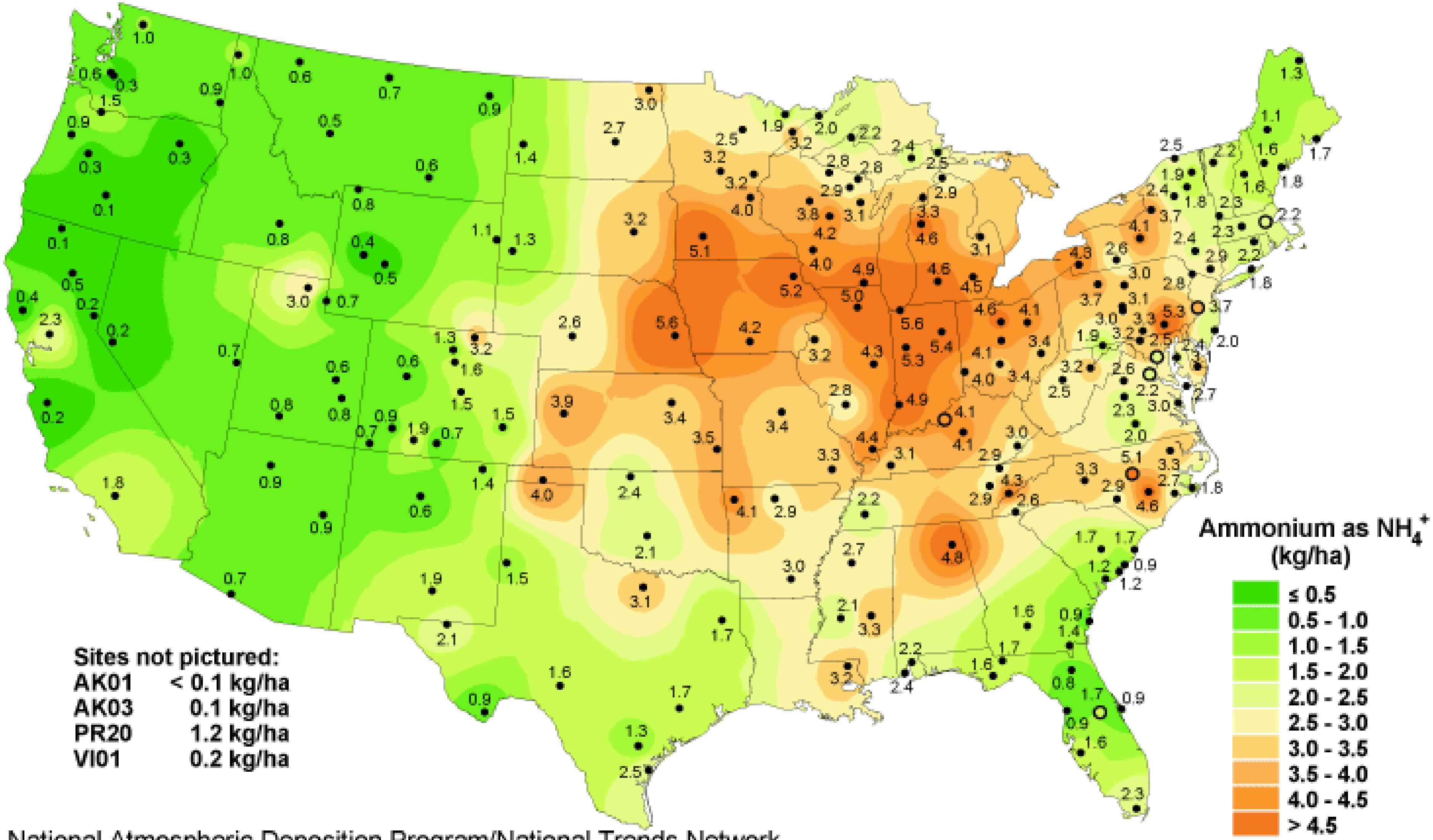


Sites not pictured:

AK01	**0.01 mg/L**
AK03	**0.02 mg/L**
PR20	**0.04 mg/L**
VI01	**0.02 mg/L**

National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

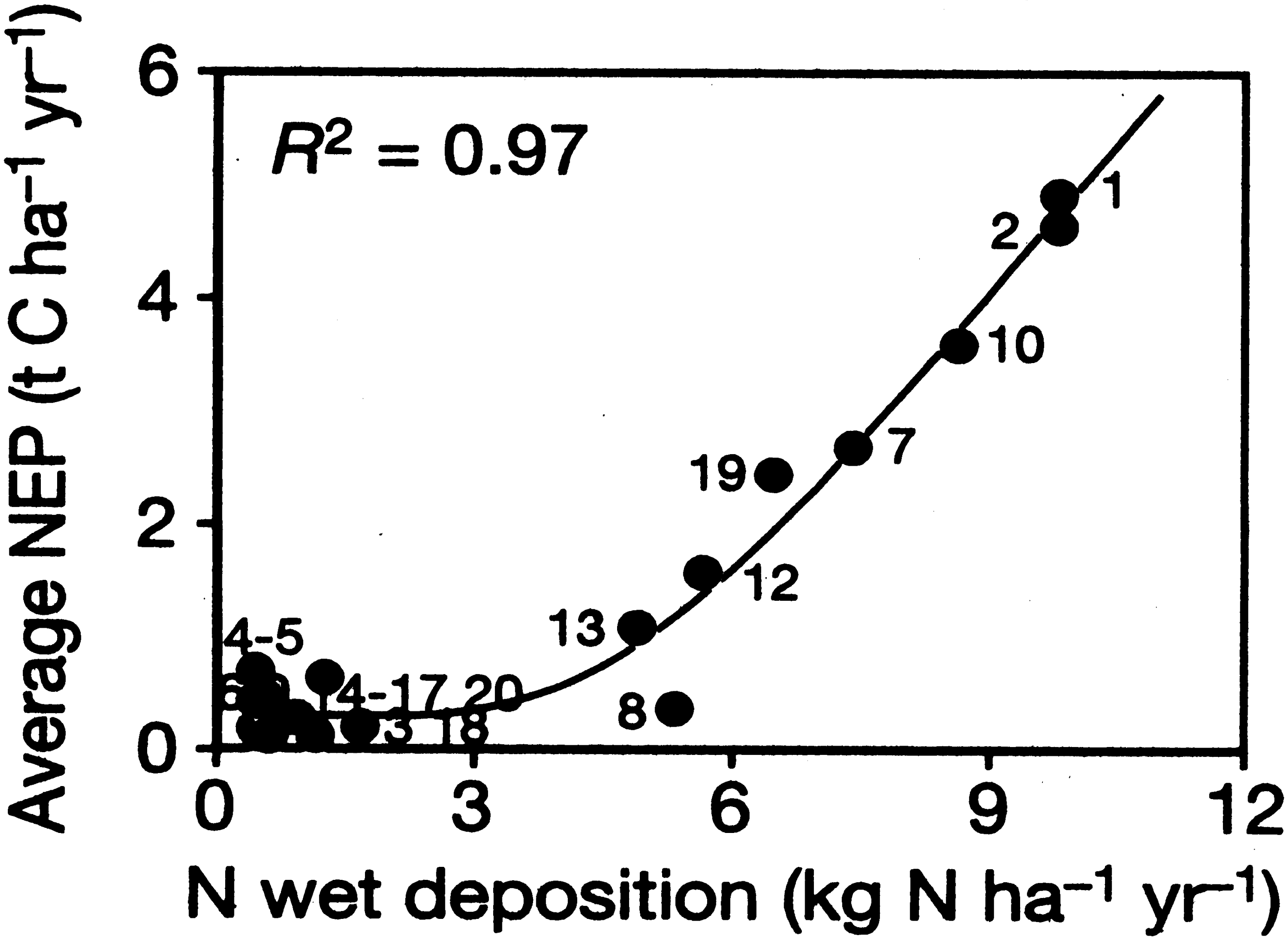
Ammonium ion wet deposition, 2006



Sites not pictured:

AK01	**< 0.1 kg/ha**
AK03	**0.1 kg/ha**
PR20	**1.2 kg/ha**
VI01	**0.2 kg/ha**

National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu



Magnani et al. 2008

First Principle

Coupling of Biogeochemical Cycles, due to:

1. Some basic stoichiometry for life—in biomass

   First articulated by Liebig (1840),
   and later advanced by Redfield (1958), Reiners (1986),
   Sterner and Elser (2002), and Cleveland and Liptzin (2007)

Complementary Models for Ecosystems

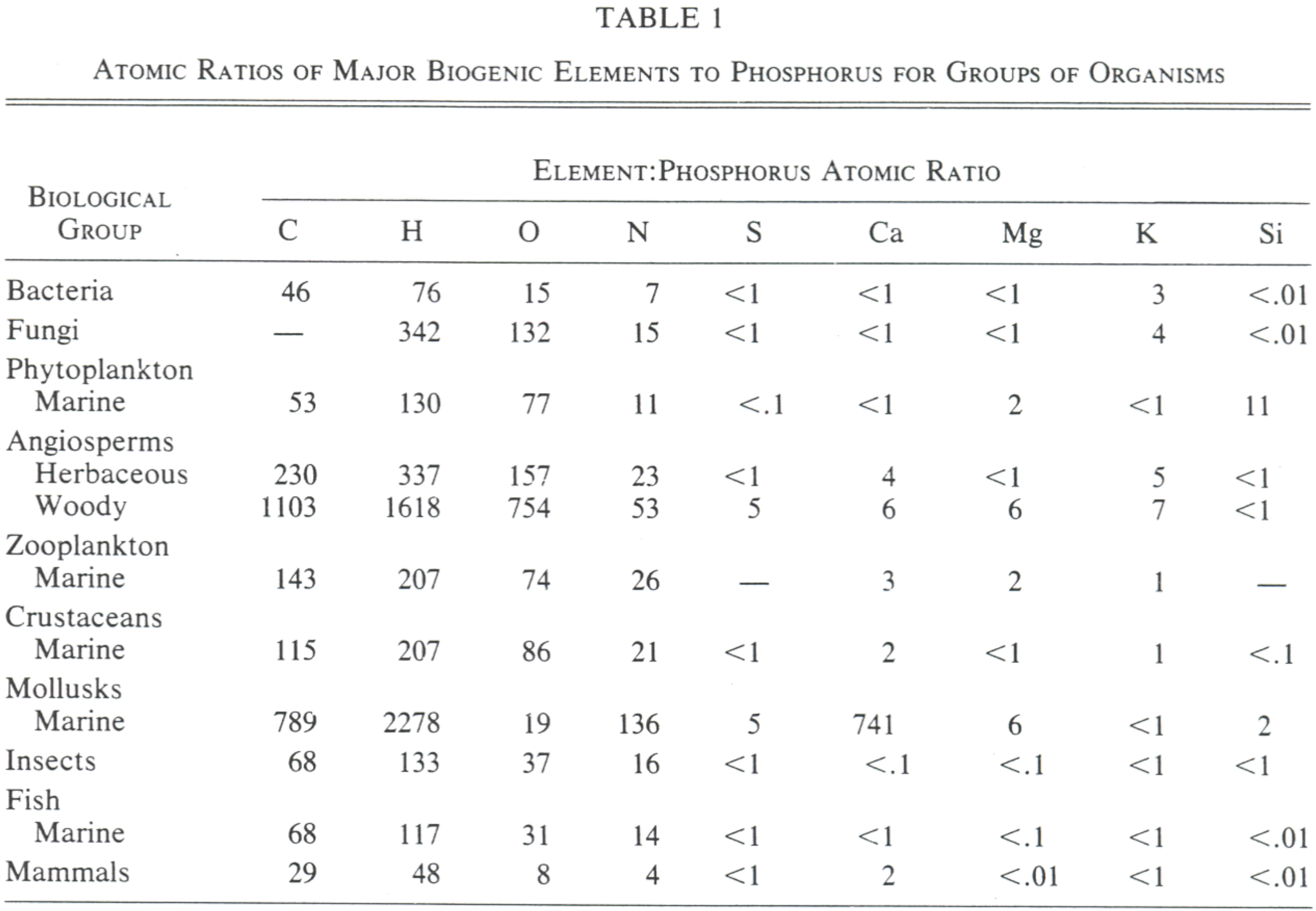
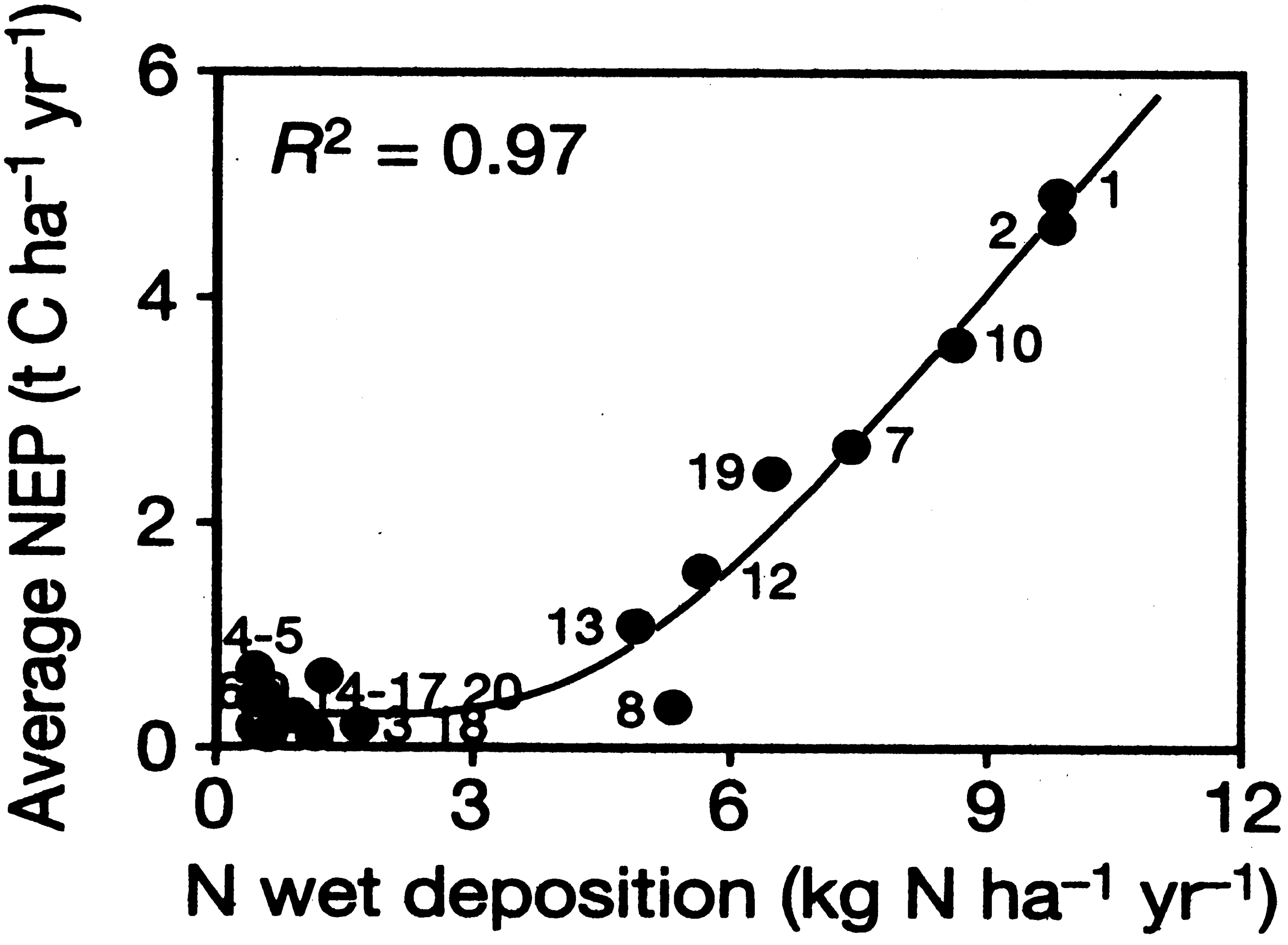


TABLE 1

ATOMIC RATIOS OF MAJOR BIOGENIC ELEMENTS TO PHOSPHORUS FOR GROUPS OF ORGANISMS

BIOLOGICAL GROUP	ELEMENT:PHOSPHORUS ATOMIC RATIO								
	C	H	O	N	S	Ca	Mg	K	Si
Bacteria	46	76	15	7	<1	<1	<1	3	<.01
Fungi	—	342	132	15	<1	<1	<1	4	<.01
Phytoplankton									
Marine	53	130	77	11	<.1	<1	2	<1	11
Angiosperms									
Herbaceous	230	337	157	23	<1	4	<1	5	<1
Woody	1103	1618	754	53	5	6	6	7	<1
Zooplankton									
Marine	143	207	74	26	—	3	2	1	—
Crustaceans									
Marine	115	207	86	21	<1	2	<1	1	<.1
Mollusks									
Marine	789	2278	19	136	5	741	6	<1	2
Insects	68	133	37	16	<1	<.1	<.1	<1	<1
Fish									
Marine	68	117	31	14	<1	<1	<.1	<1	<.01
Mammals	29	48	8	4	<1	2	<.01	<1	<.01

Reiners, W.A. 1986



Magnani et al. 2008

My first principle leads to the first message for today:

Given the universal stoichiometry of biomass, do not overlook the power of examining ratios—C/N etc.—to see if your data are compatible with common sense.

If you see a major deviation, and it stands up to scrutiny, you may really be up to something!

Coupling of biogeochemical cycles, due to:

2. The flow of electrons in the oxidation/reduction reactions—

   First articulated by Kluyver (1926),
   and later advanced by Morowitz, Nealson, Falkowski,
   and many others

Oxidized → Reduced

Oxidized ↑ Reduced

	H_2O/O_2	**C**	**N**	**S**
H_2O/O_2	X	Photosynthesis $CO_2 \longrightarrow C$ $H_2O \longrightarrow O_2$		
C	Respiration $C \longrightarrow CO_2$ $O_2 \longrightarrow H_2O$	X	Denitrification $C \longrightarrow CO_2$ $NO_3 \longrightarrow N_2$	Sulfate-Reduction $C \longrightarrow CO_2$ $SO_4 \longrightarrow H_2S$
N	Heterotrophic Nitrification $NH_4 \longrightarrow NO_3$ $O_2 \longrightarrow H_2O$	Chemoautotrophy Nitrification $NH_4 \longrightarrow NO_3$ $CO_2 \longrightarrow C$	Anammox $NH_4 + NO_2 \rightarrow N_2 + 2H_2O$	?
S	Thiobacillus thioxidans $S \longrightarrow SO_4$ $O_2 \longrightarrow H_2O$ (Acid-mine Drainage)	Sulfur-based Photosynthesis and Chemoautotrophy $S \longrightarrow SO_4$ $CO_2 \longrightarrow C$	Thiobacillus denitrificans and Thioploca $NO_3 \longrightarrow N_2/NH_4$ $S \longrightarrow SO_4$	X

Denitrification

$5CH_2O + 4H^+ + 4NO_3^- \rightarrow$

$2N_2 + 5CO_2 + 7H_20$

Intermediates include NO and N_2O

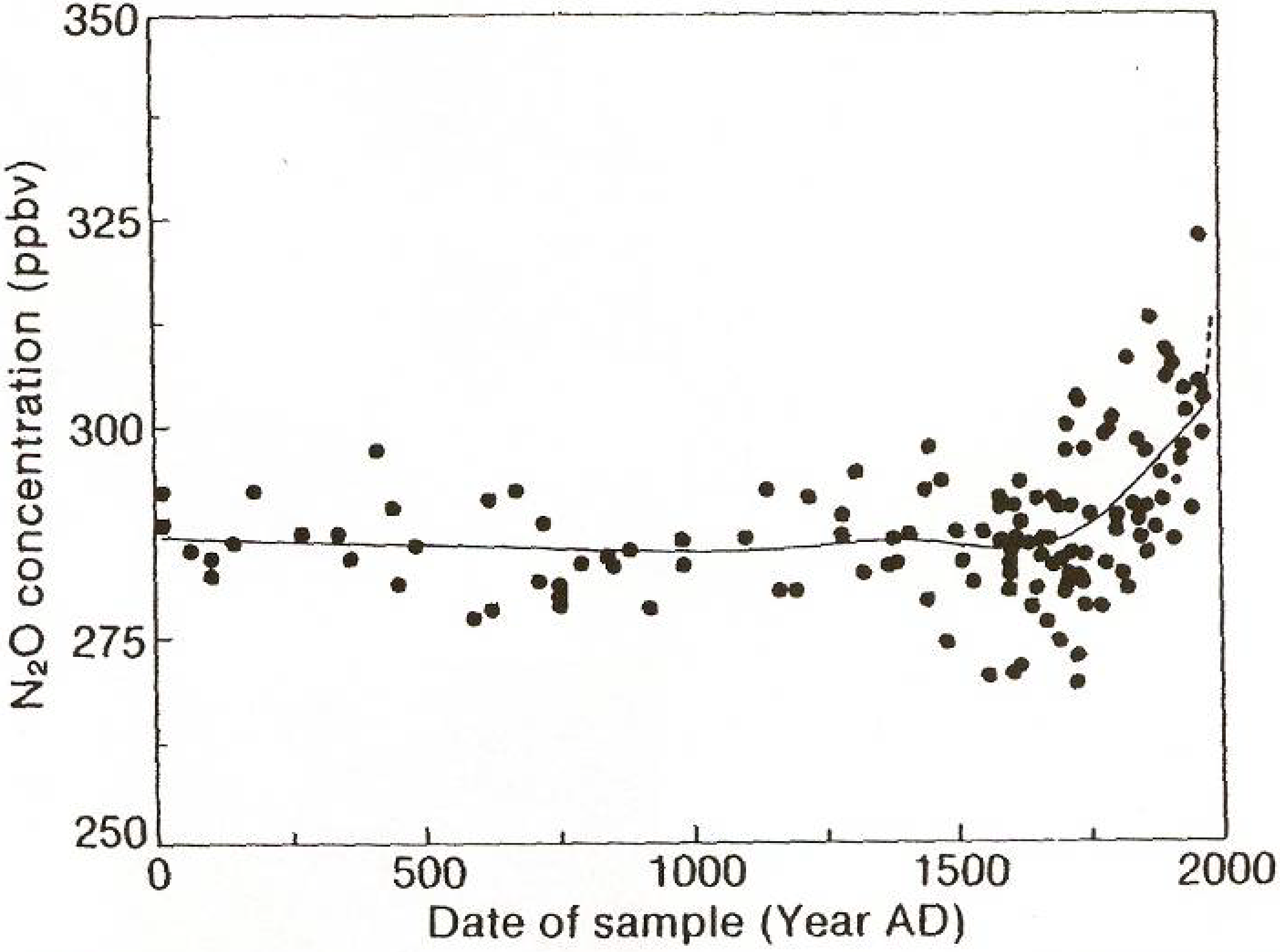


Figure 12.5 Nitrous oxide measurements from ice-core samples, as compiled by Watson et al. (1990).

$$\frac{\Delta\ N_2O}{\dfrac{N_2O}{N_2 + N_2O}} = \text{TOTAL}$$

$N_2O/(N_2 + N_2O)$ in Denitrification

	Weier et al. (1993)	**0.02 to 1.0**
Flooded Soils	**Beaulieu et al. *in press***	**.01**
	Mean of 21	**.082 ± .023**
Upland Soils	**Mean of 13**	**.51 ± .082**
Agricultural Soils	**Mean of 32**	**.37 ±.046**

Calculation of change in denitrification from N_2O

124 Tg (0.37) + 110 Tg (0.082) = 234 Tg (0.246)

4 TgN_2O/yr / 0.25 = 17 TgN/yr

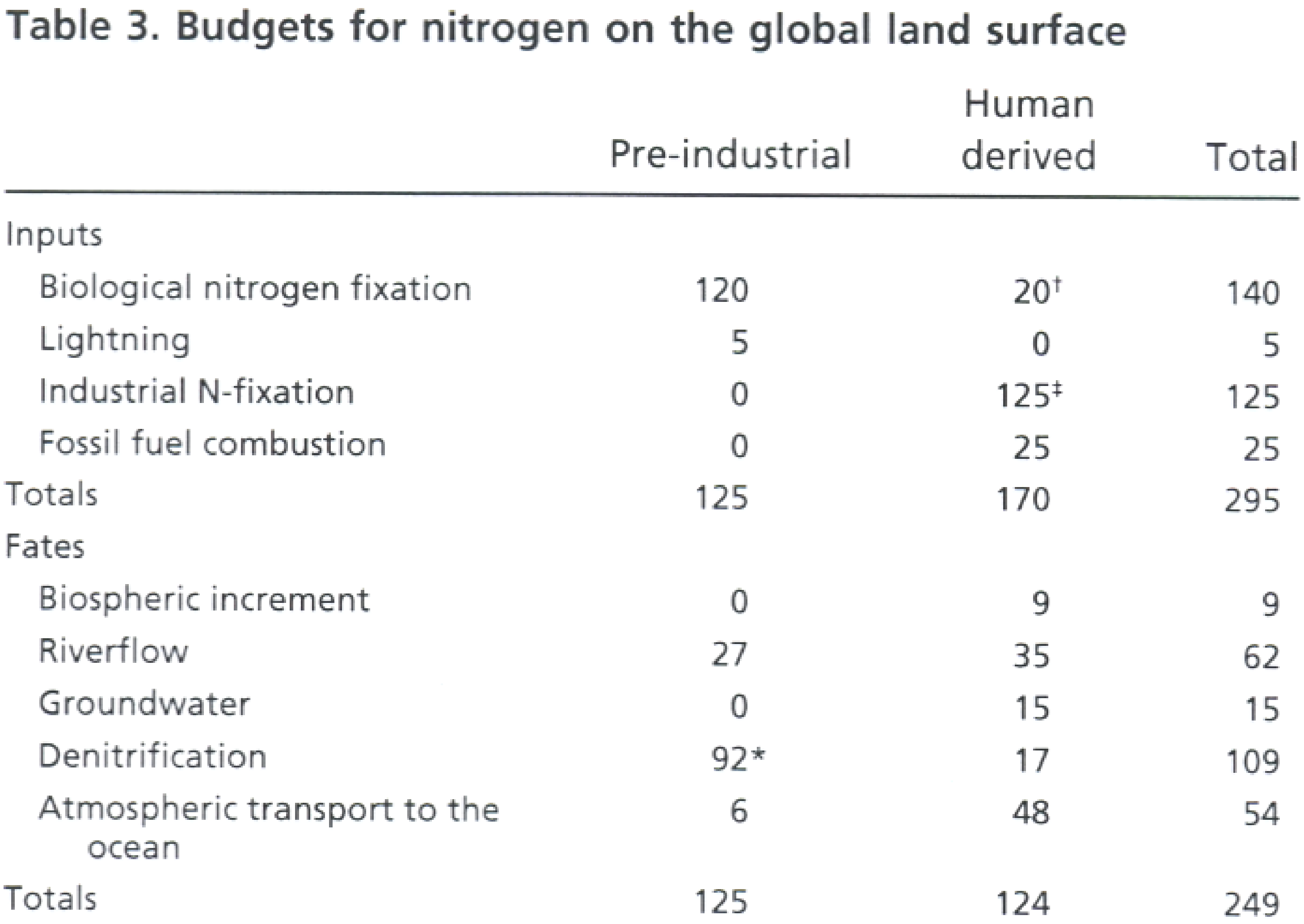


Table 3. Budgets for nitrogen on the global land surface

	Pre-industrial	Human derived	Total
Inputs			
Biological nitrogen fixation	120	20†	140
Lightning	5	0	5
Industrial N-fixation	0	125‡	125
Fossil fuel combustion	0	25	25
Totals	125	170	295
Fates			
Biospheric increment	0	9	9
Riverflow	27	35	62
Groundwater	0	15	15
Denitrification	92*	17	109
Atmospheric transport to the ocean	6	48	54
Totals	125	124	249

Schlesinger 2009

My second message today:

The coupling of biogeochemical cycles, with its basis in metabolism, allows the diversity of the microbial biosphere today, upon which all higher life depends. And, it also allows us to measure/estimate some difficult processes

Coupling of biogeochemical cycles to carbon through chelation

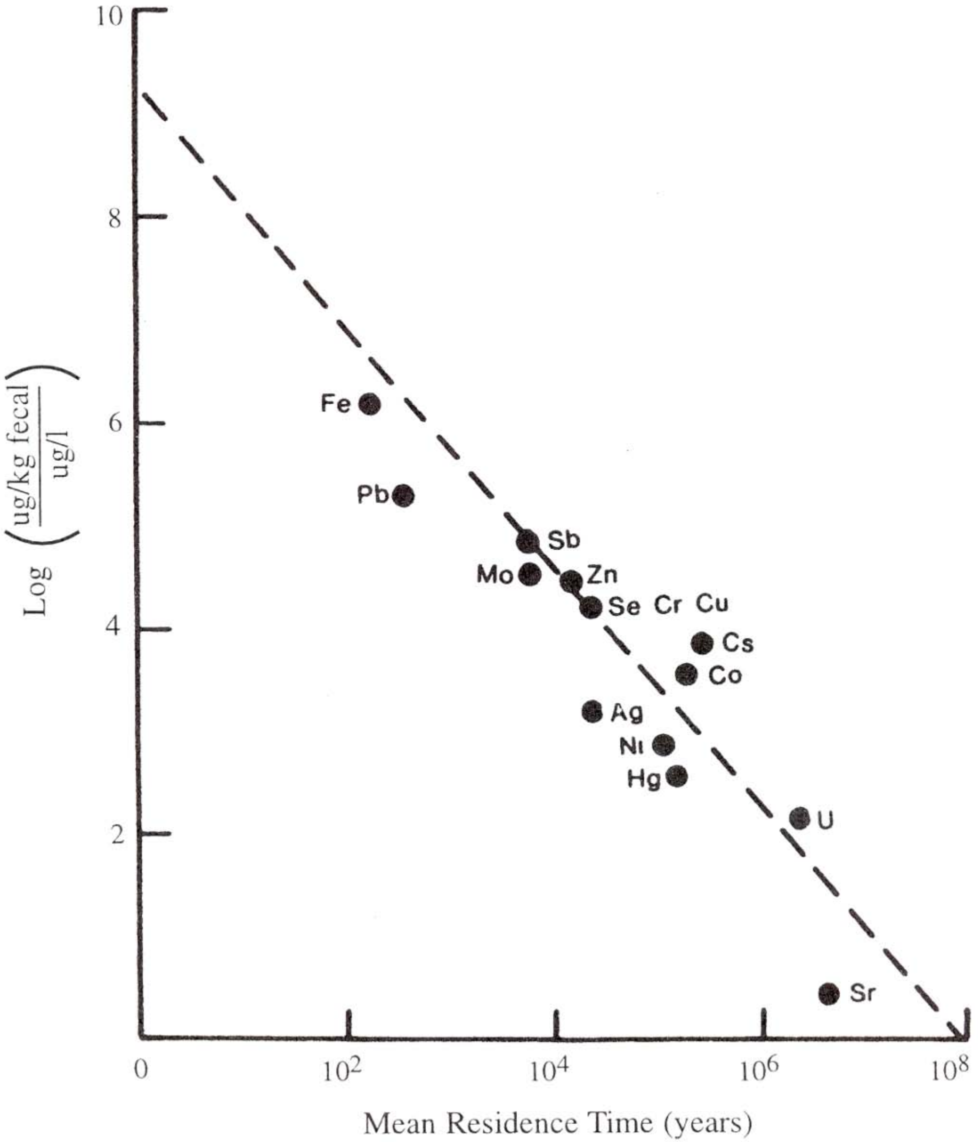


Figure 9.21 The ratio between the concentration of an element in sinking fecal pellets (μg/kg) and its concentration in seawater (μg/liter), plotted as a function of its mean residence time in the ocean. From Cherry et al. (1978).

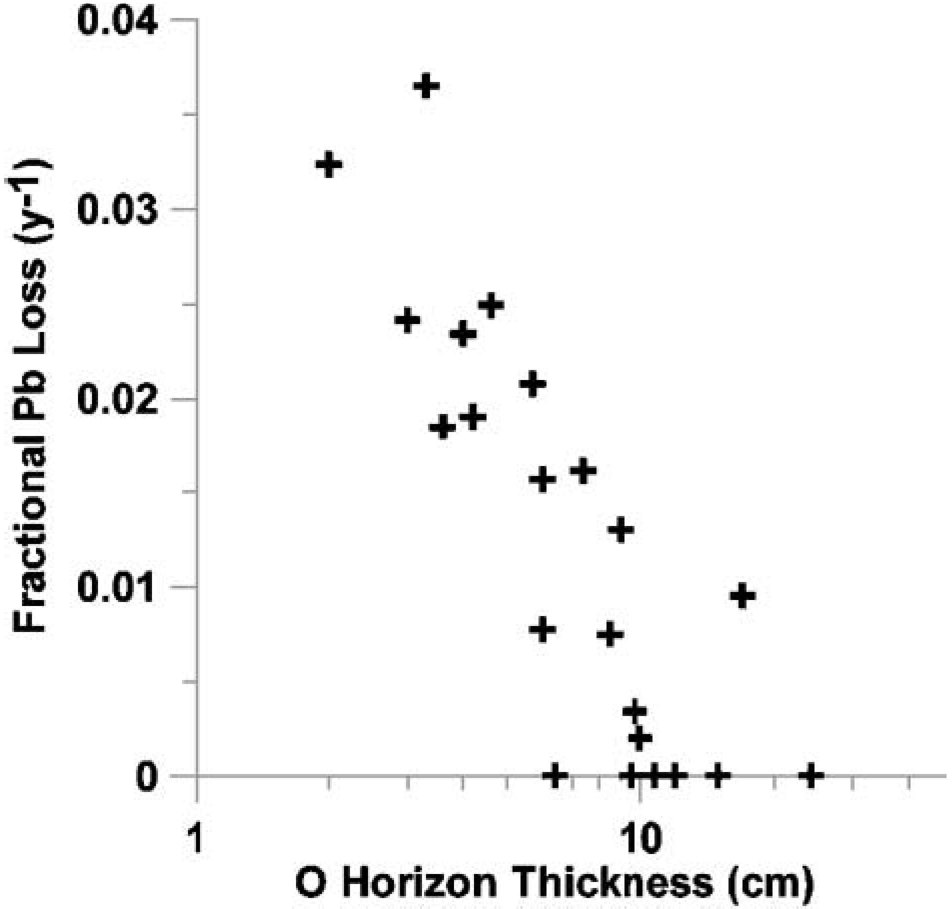


Fig. 2. The fractional amount of Pb loss calculated over the study period is significantly correlated with the thickness (cm) of the forest floor at each site. A logarithmic fit to these data give $r^2 = 0.65$.

Kaste et al. 2006.

My third message today:

Biology leaves its signature on the chemistry of the surface of the Earth by chelation of elements that have a greater affinity for carbon than for alumino-silicates.

Principles of coupled biogeochemical cycles apply to geo-engineering


COALE 4
TRACE METALS/PLANKTON
MOSS LANDING
MARINE LABORATORIES
MOSS LANDING CA
16%

For example, if we wanted to sequester a billion metric tons of C in the oceans by enhancing NPP with Fe fertilization

Current marine NPP = 50×10^{15} g C/yr

F-ratio of 0.15 means that 7.5×10^{15} g C/yr sinks through the thermocline

An additional 1×10^{15} g C/yr sinking would require ~7×10^{15} g C/yr additional NPP, so

7×10^{15} g C x 23×10^{-6} Fe/C = 1.6×10^{11} g Fe (Lab uptake), or
x 6×10^{-4} = 4.2×10^{12} (Field observation)
Buesseler & Boyd (2003)

Versus, the global production of Fe annually (1900×10^{12} g Fe/yr)

Alternatively, to provide a sink for 1 x 10^{15} gC/yr in the world's soils by fertilizing them:

Current terrestrial NPP = 50 x 10^{15} g C/yr

Preservation ratio of 0.008; i.e., global NEP – 0.4 g C/yr (Schlesinger 1990)

To store an additional 1.0 x 10^{15} g C in soils would require adding 75 x 10^{15} g C/yr to terrestrial NPP

75 x 10^{15} g C/yr x 1 N/50 C = 1.5 x 10^{15} g N as fertilizer each year

1.5 x 10^{15} g C @ 0.857 g C released as CO_2 per g N = 1.28 x 10^{15} g C/yr released in fertilizer production

My fourth message today:

There is an increasing role for biogeochemists to contribute to the understanding and fruitful solutions to global environmental problems.

Biogeochemistry has come of age!

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