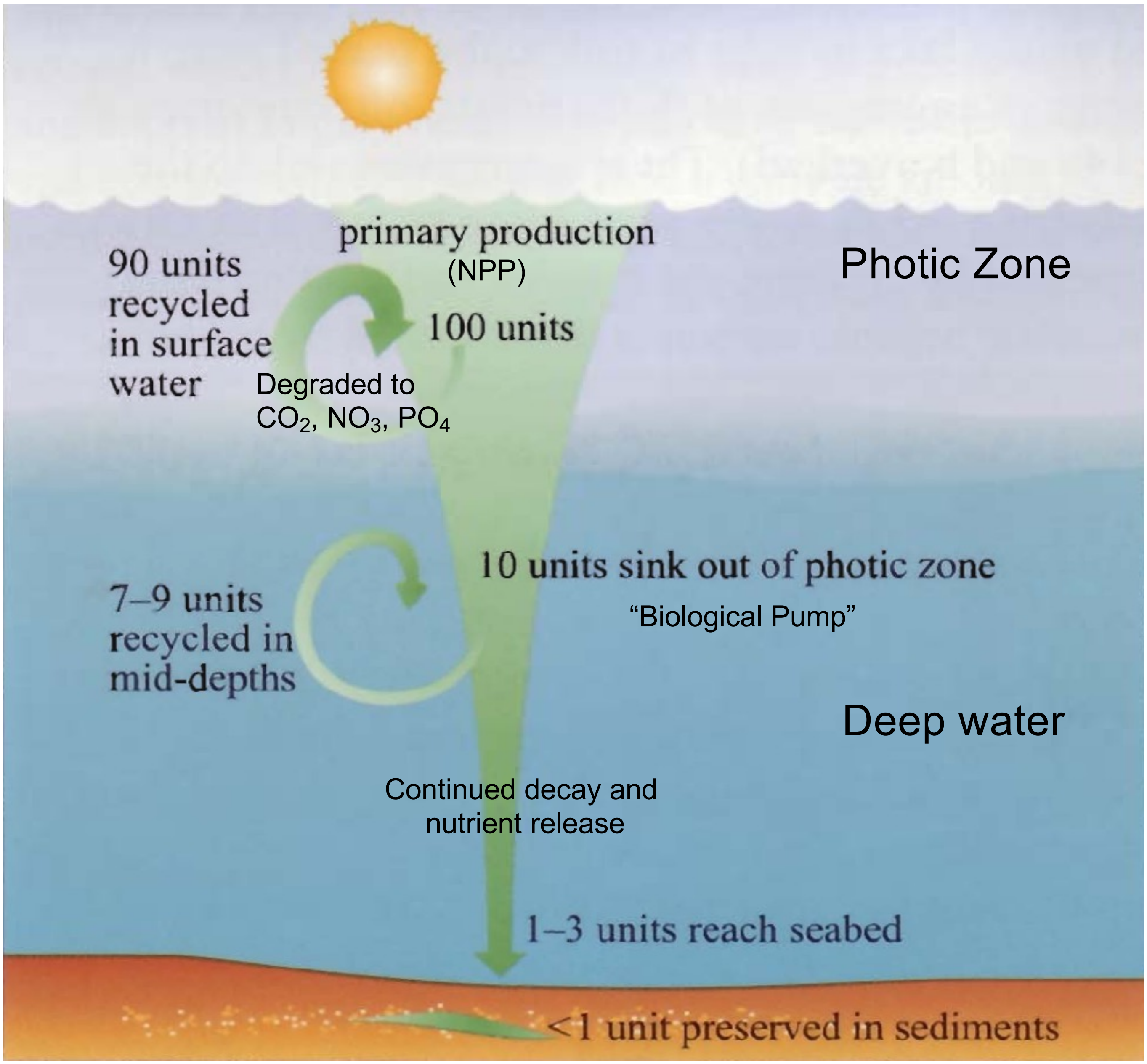
Marine NPP

20-44 Pg C/yr -> 30-60 % global NPP (land + sea)

Greatest per unit area in photic zone, coastal, & upwelling areas

80% of total in open ocean due to large area



~80% on continental shelf

NEP > 0 resulting in O_2 release to atmosphere

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 10, NO. 1, PAGES 57–69, MARCH 1996

Oceanic primary production
2. Estimation at global scale from satellite (coastal zone color scanner) chlorophyll

David Antoine, Jean-Michel André,[1] and André Morel

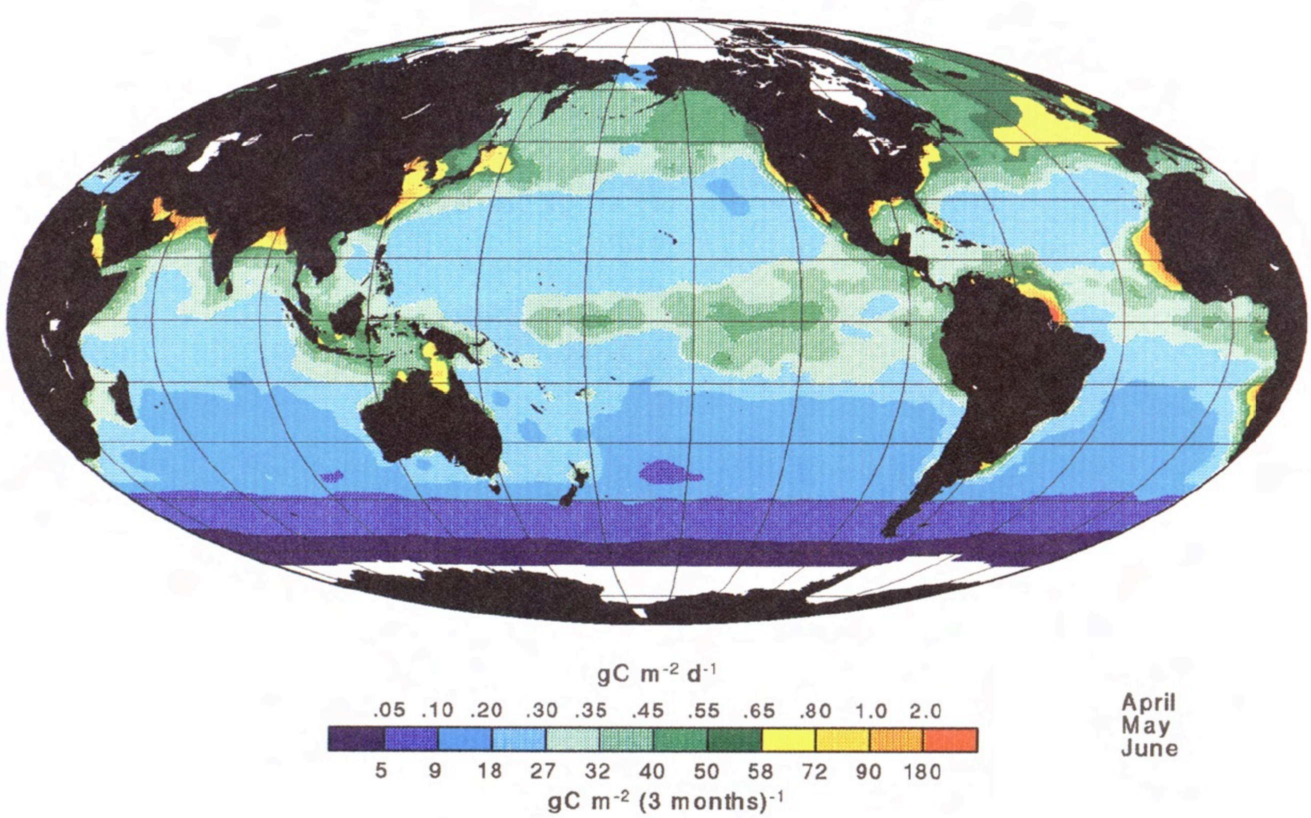


Plate 1b. As in Plate 1a, but for the April - May - June period.

Global Nutrient Cycles
(AKA Global Biogeochemical Cycles)

The Global C Cycle

The breathing Earth

The importance of the processes involved depends on the time scale.

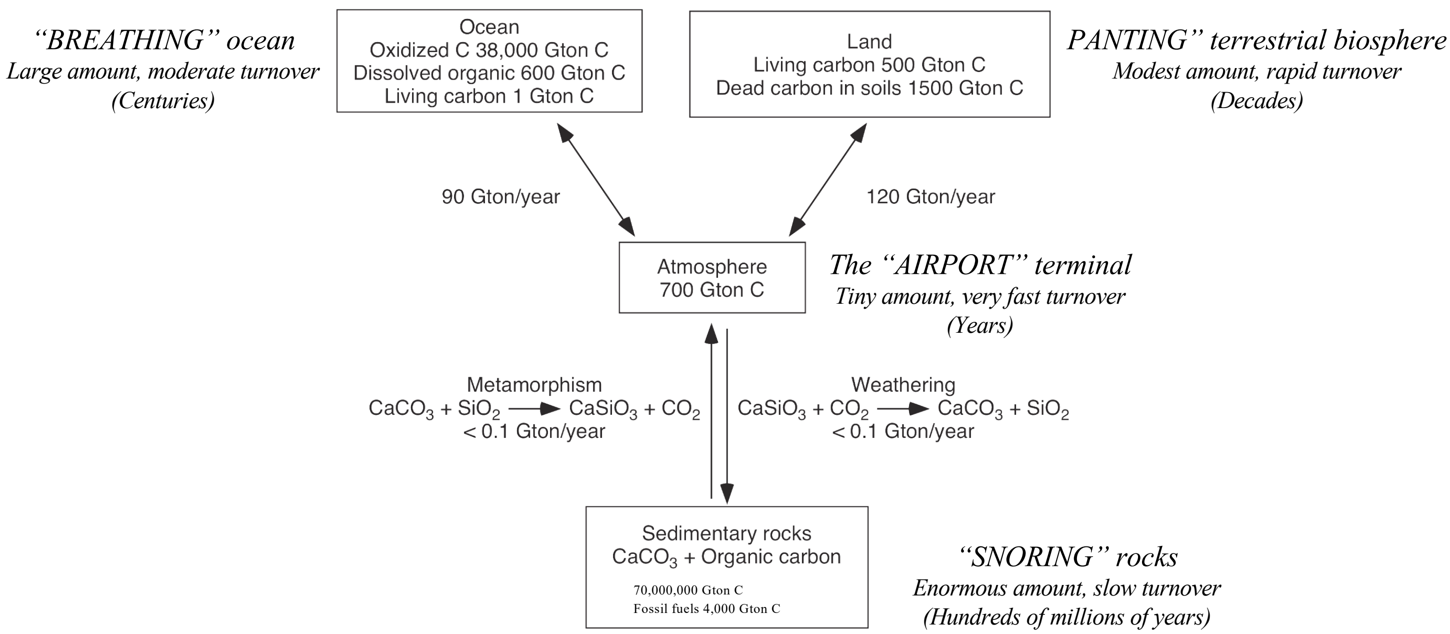
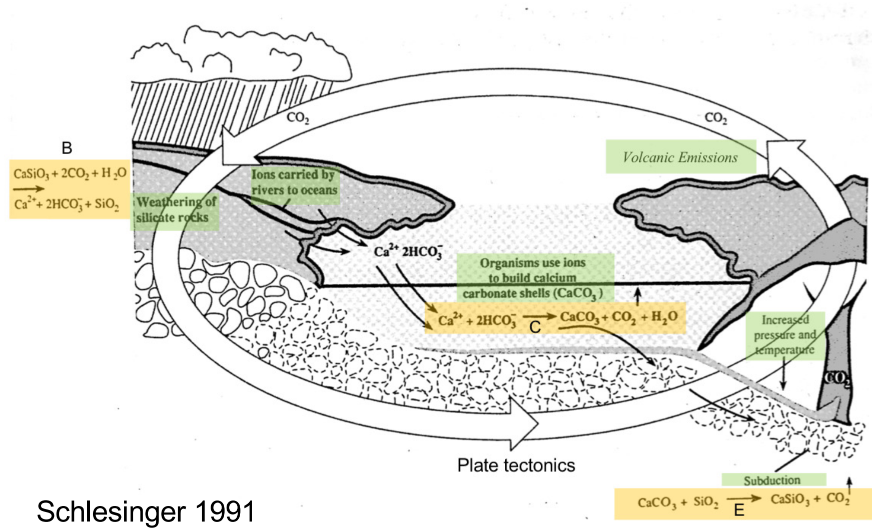


Figure 8-1 Carbon reservoirs on Earth and carbon fluxes between them.

The silicate weathering CO_2 thermostat

Regulates atmospheric CO_2 and climate on geologic time scales.



Schlesinger 1991

Distribution of Actively Cycled Carbon
(~3% of total carbon in the crust)

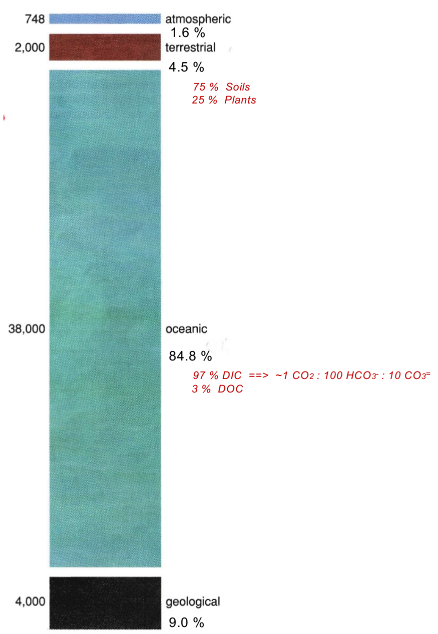
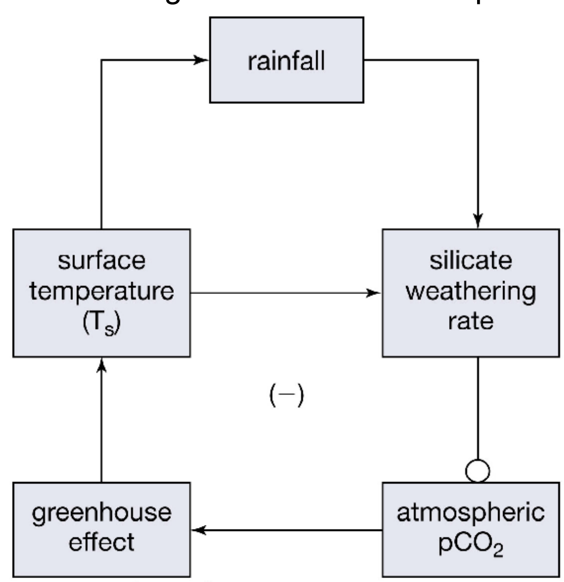


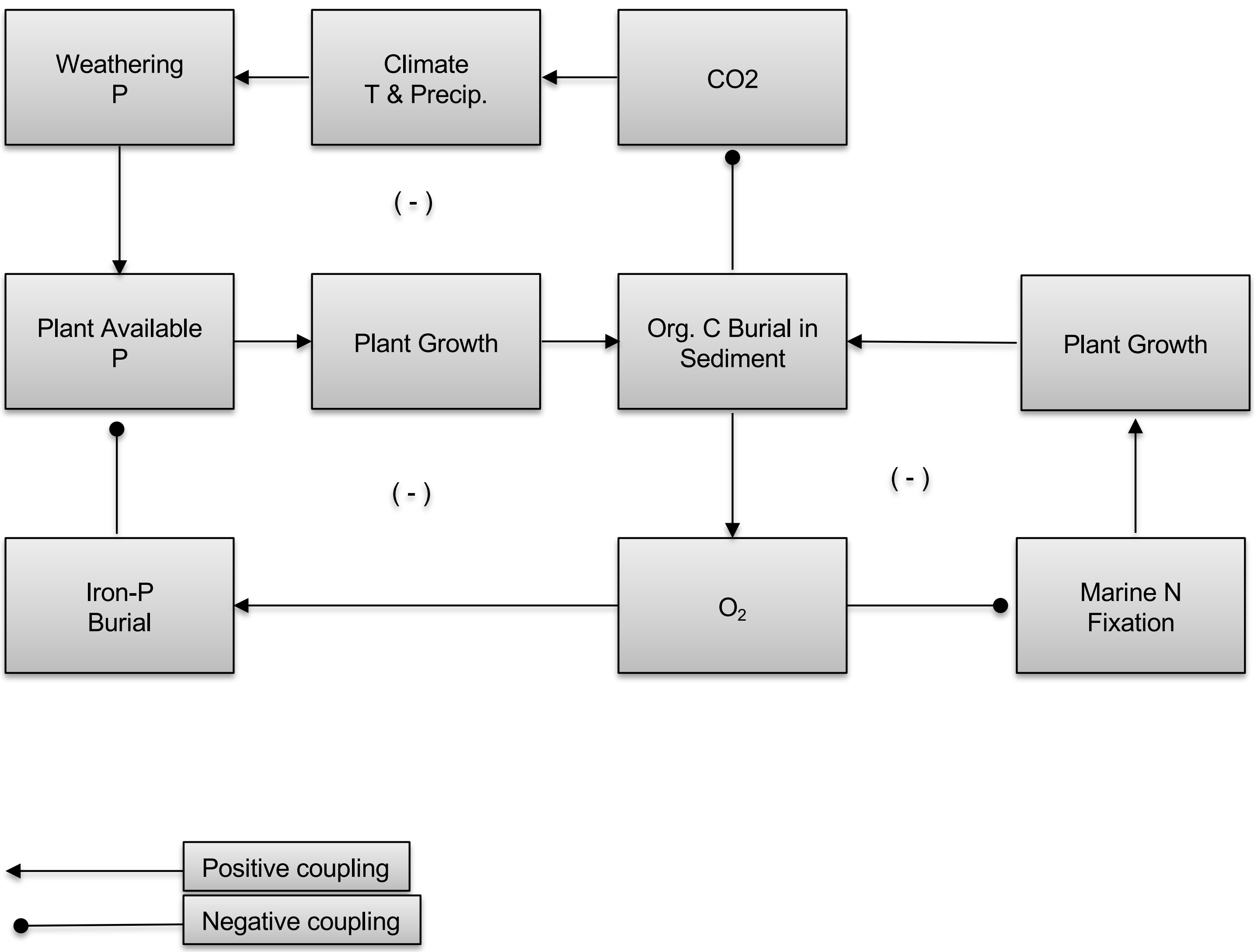
Figure 6. Major active reservoirs in the natural global carbon cycle are the oceans, terrestrial system and atmosphere. The oceans are the largest active reservoir; the atmosphere, the smallest. Geological stores of recoverable fossil fuels form a reservoir that was relatively inactive in the carbon cycle before people began mining and burning fossil fuels. Reservoir sizes are expressed in gigatons of carbon.

Carbonate-Silicate
Long-Term Feedback Loop



Kump et al. 2010 Fig.8-18

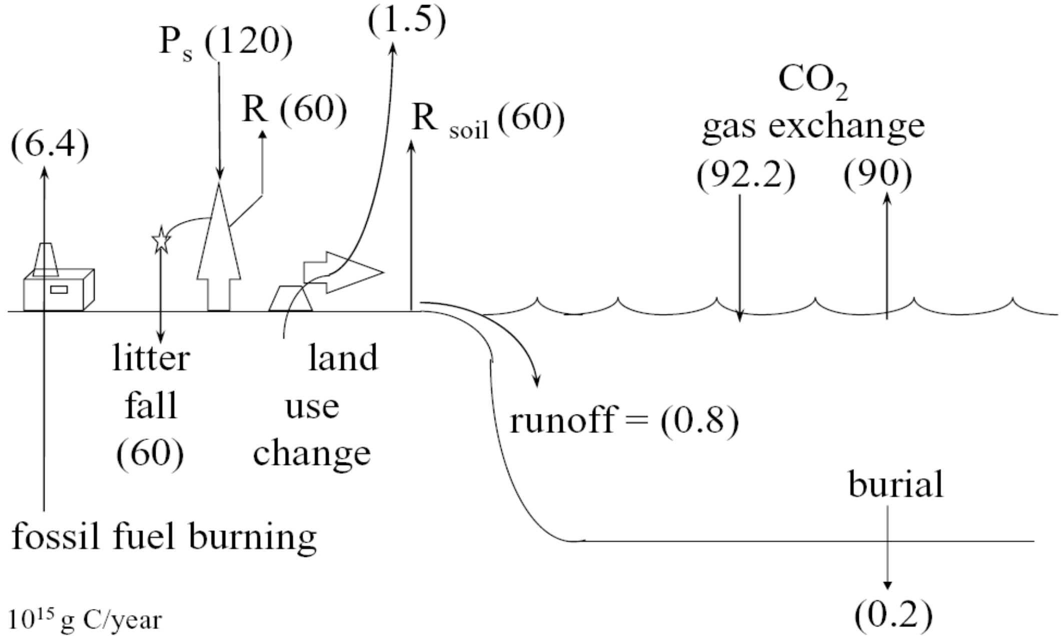
Organic Carbon
Long-Term Feedback Loops



Berner 2004 (Fig. 3.1)

The Global Carbon Cycle

Biologically controlled carbon fluxes are large!



units = 10^{15} g C/year

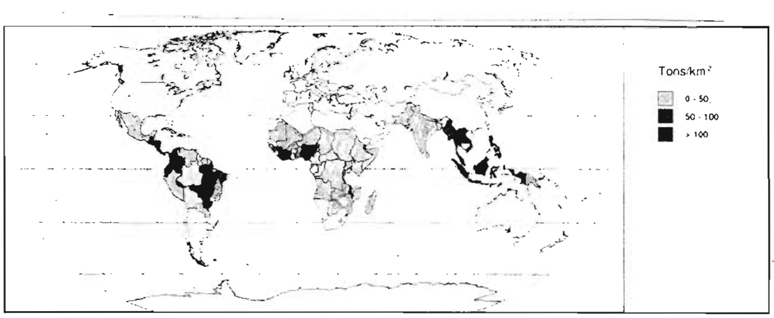


Figure 23.4 Geographic distribution of the net flux of carbon from terrestrial ecosystems to the atmosphere in 1980 as a result of deforestation and agricultural expansion. Source: Houghton et al. 1987.

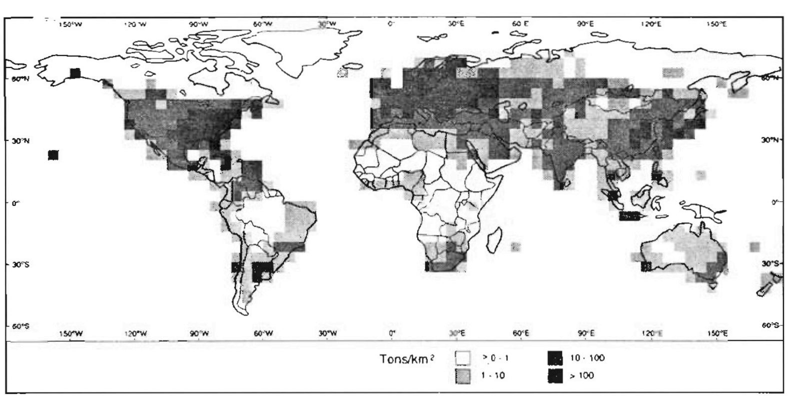


Figure 23.5 Geographic distribution of the emissions of carbon from combustion of fossil fuels in 1980. Source: Marland, Rotty, and Treat 1985. Houghton + Skole 1990

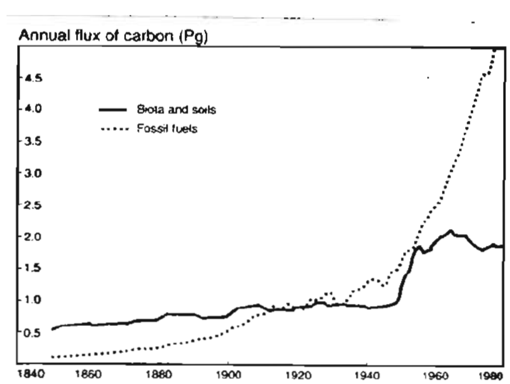
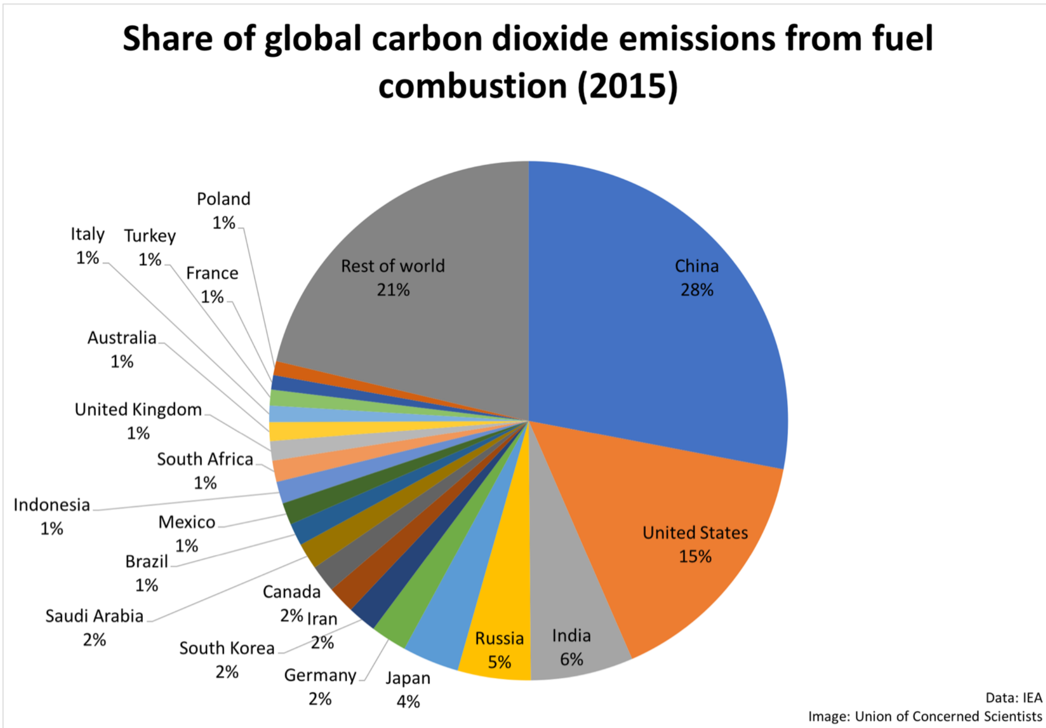
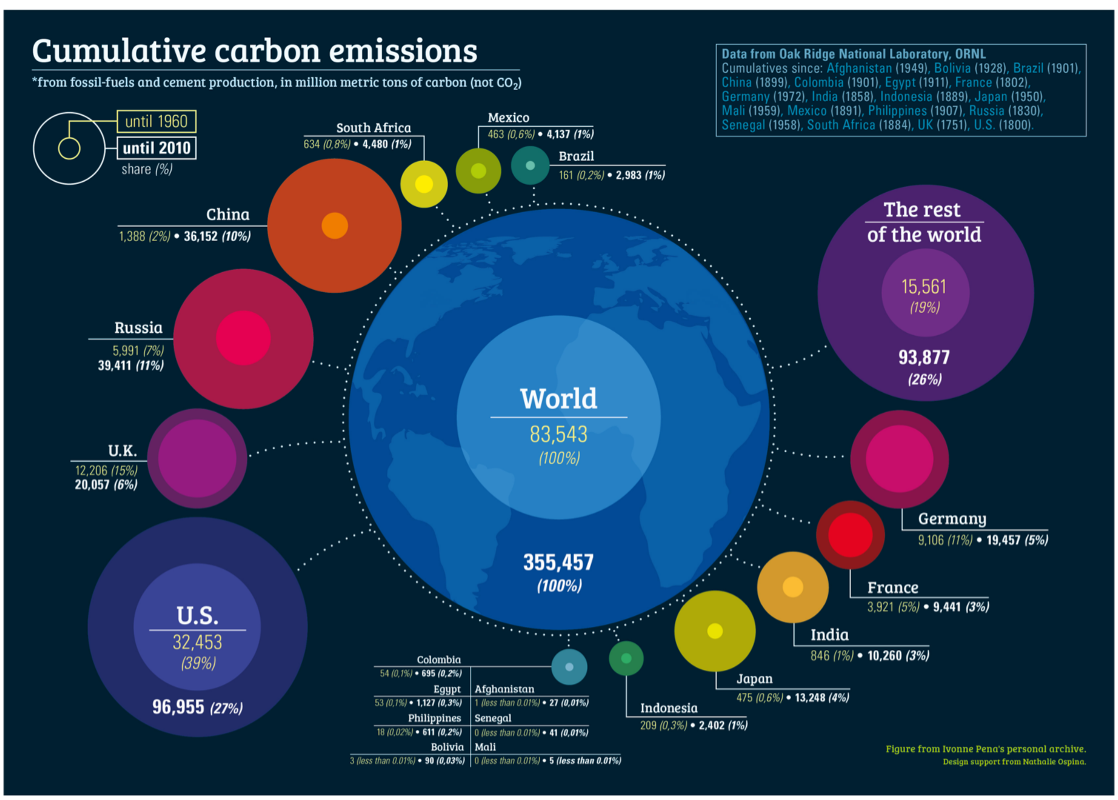


Figure 23.3 The annual net releases of carbon from changes in land use (solid line) and the annual emissions of carbon from combustion of fossil fuels (dotted line) between 1850 and 1980.

Houghton + Skole 1990


Share of global carbon dioxide emissions from fuel combustion (2015)
China 28%
United States 15%
India 6%
Russia 5%
Japan 4%
Germany 2%
South Korea 2%
Iran 2%
Canada 2%
Saudi Arabia 2%
Brazil 1%
Mexico 1%
Indonesia 1%
South Africa 1%
United Kingdom 1%
Australia 1%
Italy 1%
Turkey 1%
France 1%
Poland 1%
Rest of world 21%
Data: IEA
Image: Union of Concerned Scientists


Cumulative carbon emissions
*from fossil-fuels and cement production, in million metric tons of carbon (not CO_2)
until 1960
until 2010
share (%)
Data from Oak Ridge National Laboratory, ORNL
Cumulatives since: Afghanistan (1949), Bolivia (1928), Brazil (1901), China (1899), Colombia (1901), Egypt (1911), France (1802), Germany (1972), India (1858), Indonesia (1889), Japan (1950), Mali (1959), Mexico (1891), Philippines (1907), Russia (1830), Senegal (1958), South Africa (1884), UK (1751), U.S. (1800).
South Africa
634 (0,8%) • 4,480 (1%)
Mexico
463 (0,6%) • 4,137 (1%)
Brazil
161 (0,2%) • 2,983 (1%)
China
1,388 (2%) • 36,152 (10%)
Russia
5,991 (7%)
39,411 (11%)
U.K.
12,206 (15%)
20,057 (6%)
U.S.
32,453
(39%)
96,955 (27%)
World
83,543
(100%)
355,457
(100%)
The rest of the world
15,561
(19%)
93,877
(26%)
Germany
9,106 (11%) • 19,457 (5%)
France
3,921 (5%) • 9,441 (3%)
India
846 (1%) • 10,260 (3%)
Japan
475 (0,6%) • 13,248 (4%)
Indonesia
209 (0,3%) • 2,402 (1%)
Colombia
54 (0,1%) • 695 (0,2%)
Egypt
53 (0,1%) • 1,127 (0,3%)
Afghanistan
1 (less than 0.01%) • 27 (0,01%)
Philippines
18 (0,02%) • 611 (0,2%)
Senegal
0 (less than 0.01%) • 41 (0,01%)
Bolivia
3 (less than 0.01%) • 90 (0,03%)
Mali
0 (less than 0.01%) • 5 (less than 0.01%)
Figure from Ivonne Pena's personal archive.
Design support from Nathalie Ospina.

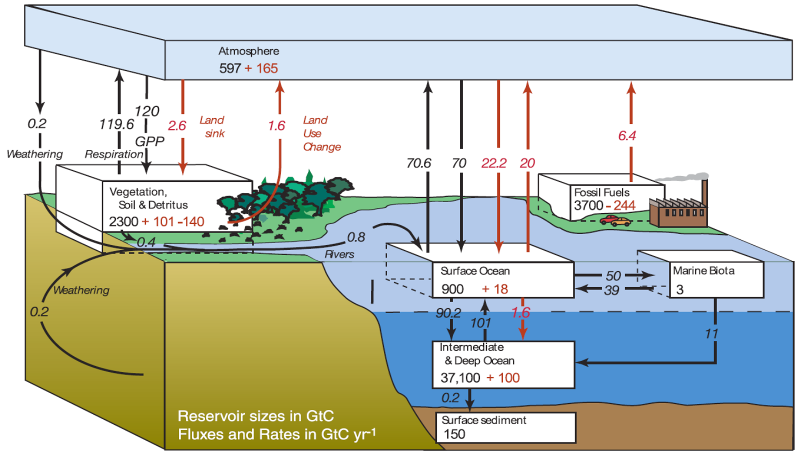
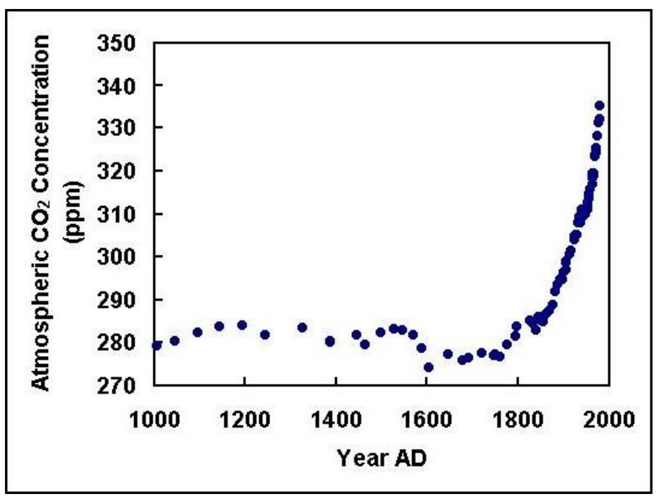
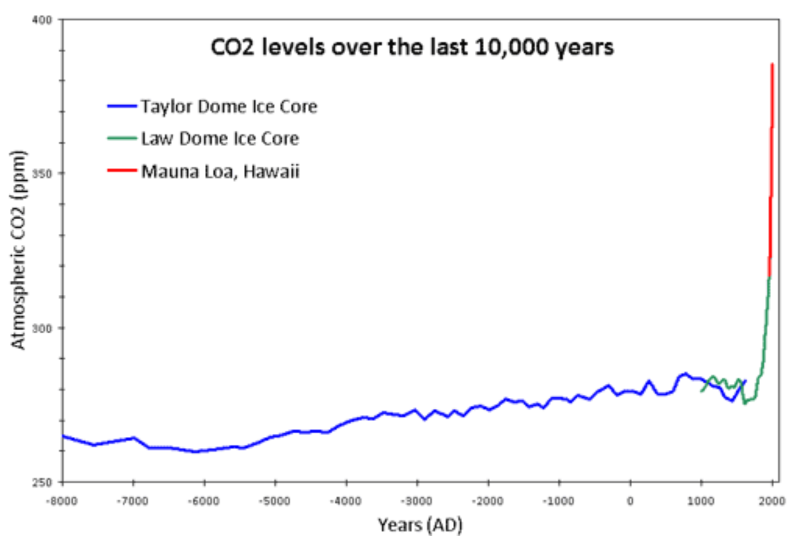


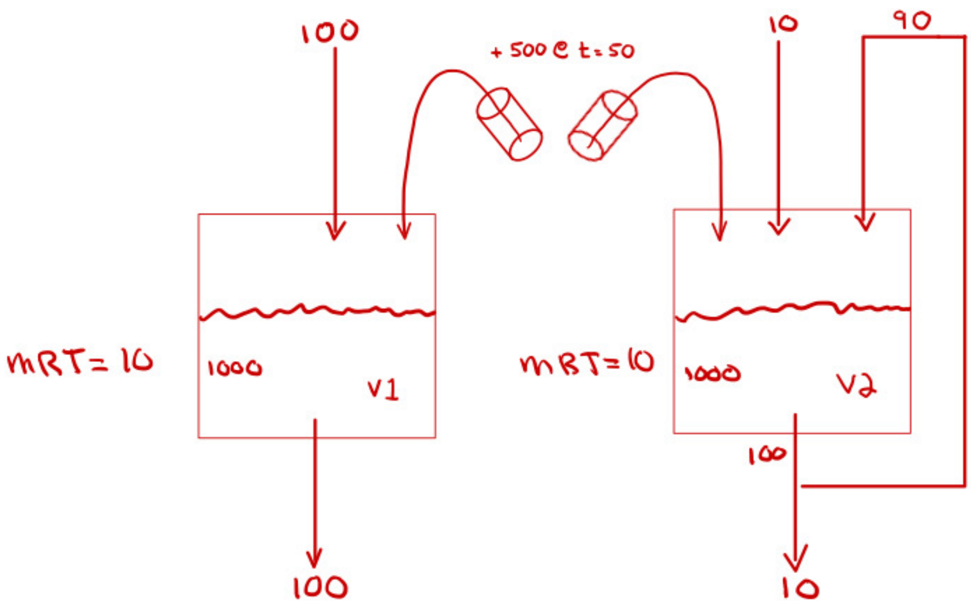
Figure 7.3. *The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr^{-1}: pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red (modified from Sarmiento and Gruber, 2006, with changes in pool sizes from Sabine et al., 2004a). The net terrestrial loss of –39 GtC is inferred from cumulative fossil fuel emissions minus atmospheric increase minus ocean storage. The loss of –140 GtC from the 'vegetation, soil and detritus' compartment represents the cumulative emissions from land use change (Houghton, 2003), and requires a terrestrial biosphere sink of 101 GtC (in Sabine et al., given only as ranges of –140 to –80 GtC and 61 to 141 GtC, respectively; other uncertainties given in their Table 1). Net anthropogenic exchanges with the atmosphere are from Column 5 'AR4' in Table 7.1. Gross fluxes generally have uncertainties of more than ±20% but fractional amounts have been retained to achieve overall balance when including estimates in fractions of GtC yr^{-1} for riverine transport, weathering, deep ocean burial, etc. 'GPP' is annual gross (terrestrial) primary production. Atmospheric carbon content and all cumulative fluxes since 1750 are as of end 1994.*

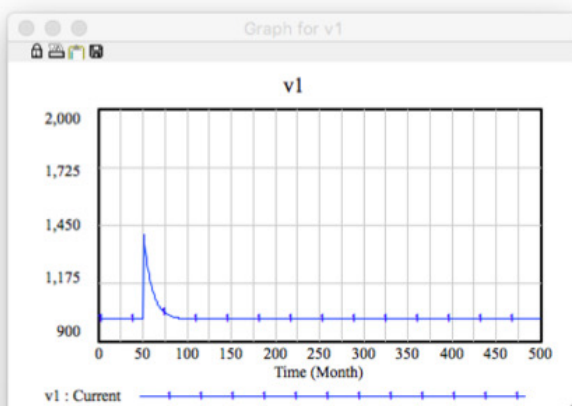
IPCC 2007 Chpt. 7

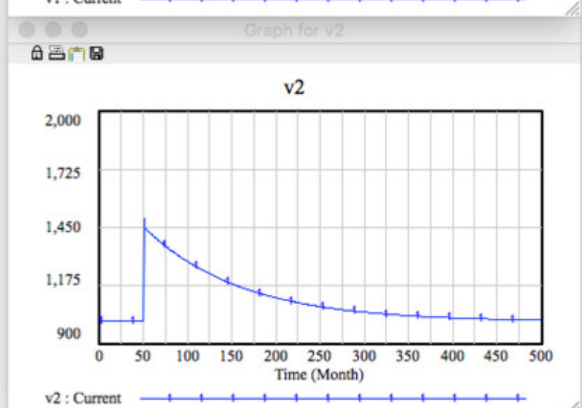




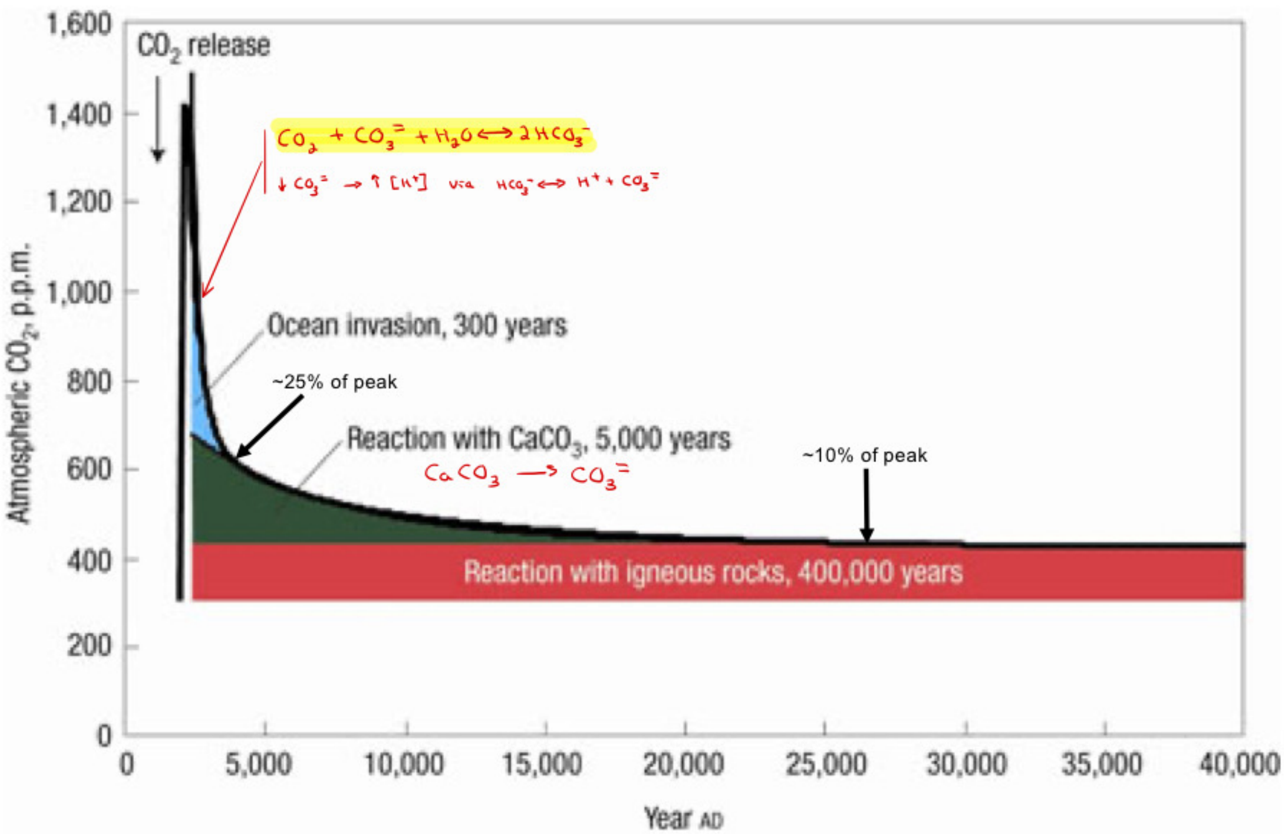
Short MRT of CO_2 in atmosphere
BUT long recovery time.



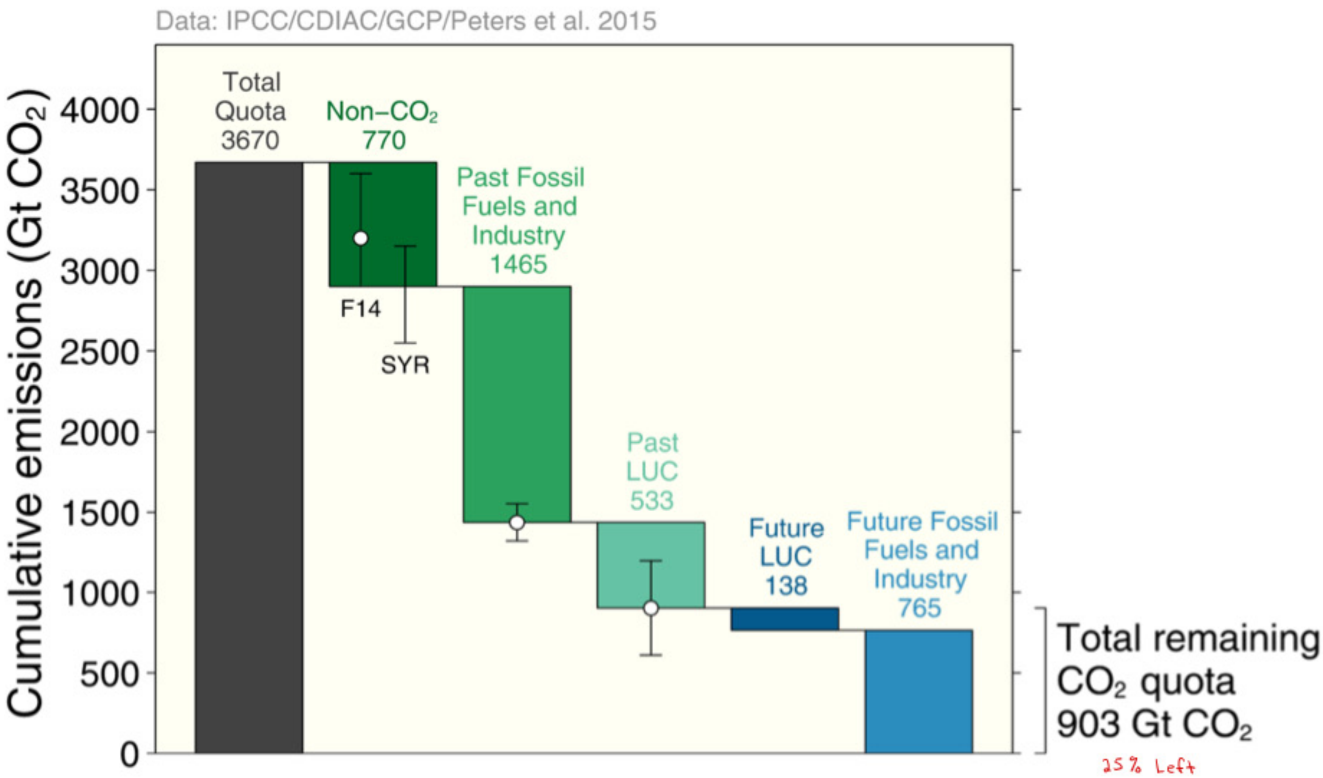




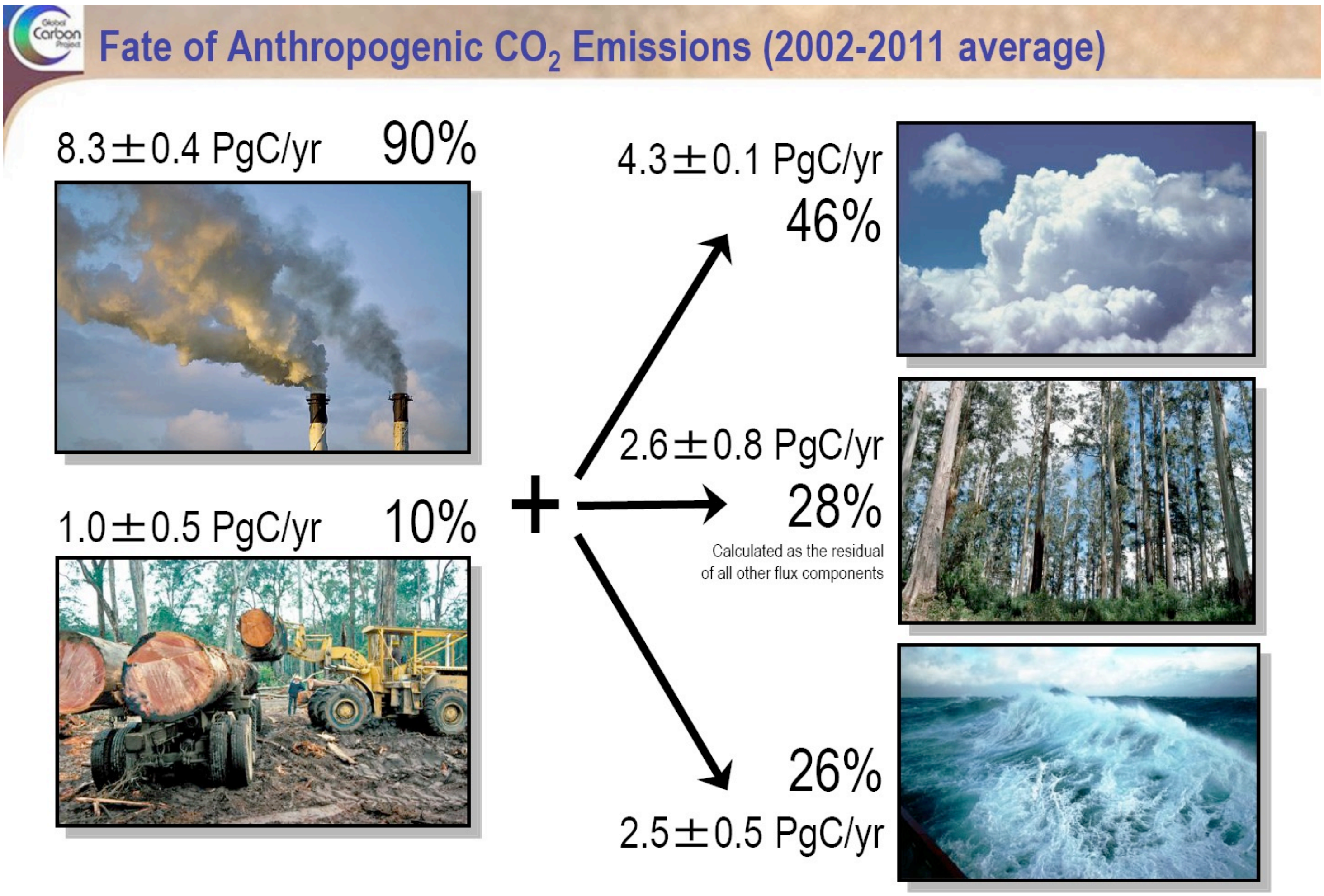
“The Long Thaw”



The remaining carbon quota for 66% chance <2°C



Mother nature mitigates climate change to some extent.



Source: Le Quéré et al. 2012; Global Carbon Project 2012

The Woods Hole Research Center

THE MISSING CARBON SINK

For the decade of the 1980s, the global carbon cycle can be summarized as follows (units are PgC. One Pg [petagram] = one billion metric tonnes = 1000 x one billion kg):

Atmospheric increase	=	Emissions from fossil fuels	+	Net emissions from changes in land use	-	Oceanic uptake	-	Missing carbon sink	
3.3(±0.2)		5.5(±0.5)		1.6(±0.7)		2.0(±0.8)		1.8(±1.2)	1980's
4.3	=	8.3	+	1.0	-	2.5	-	2.6	2002-2011

Attention on the global carbon cycle over more than 25 years has focused on the apparent imbalance in the carbon budget in the above equation - the so-called "missing sink," missing because the accumulation of carbon has not been observed. The average annual emissions of 7.1 PgC during the 1980s (5.5 ± 0.5 Pg from combustion of fossil fuels and 1.6 ± 0.7 Pg from changes in land use) are greater than the sum of the annual accumulation of carbon in the atmosphere (3.3 ± 0.2) and the annual uptake by the oceans (2.0 ± 0.8 PgC/yr). An additional sink of 1.8 PgC/yr is required for balancing the budget. The terms in the global carbon equation can be shown graphically over the period 1850-1990 [Figure 1].

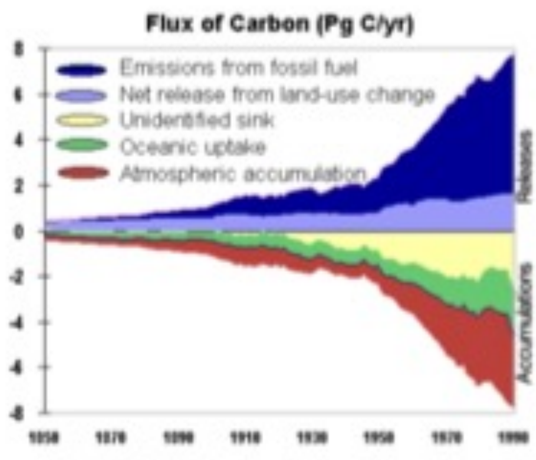


Figure 1

https://www2.nau.edu/~gaud/bio326/class/ecosyst/whrcmissc.htm

Mother nature may be getting tired.

Volume 579 Issue 7797, 5 March 2020

Subscribe

Saturation point

Tropical forests, such as the one in the Democratic Republic of the Congo pictured, are important carbon sinks, removing about 15% of anthropogenic carbon dioxide over the course of the 1990s and early 2000s. In this week's issue, Wannes Hubau and his colleagues examine the rates at which such forests in Africa and Amazonia have taken up carbon between 1983 and 2015 – and find marked differences between the two regions. They reveal that the ability of forests in Africa to act as a carbon sink was stable until the 2010s when it began to decline, in contrast to the previously documented decline in Amazonian forests since the 1990s. They conclude that both continents show a pattern of carbon-sink saturation and decline, with asynchronous timing and different rates of reduction. The researchers extrapolate their findings to predict that by 2030 the carbon sink in Africa will have shrunk by 14% compared with 2010–15, and that the Amazonian sink will reach zero in 2035. This decline has significant implications for the goal of limiting global warming to below 2 °C. show less

Cover image: Jabruson/NPL

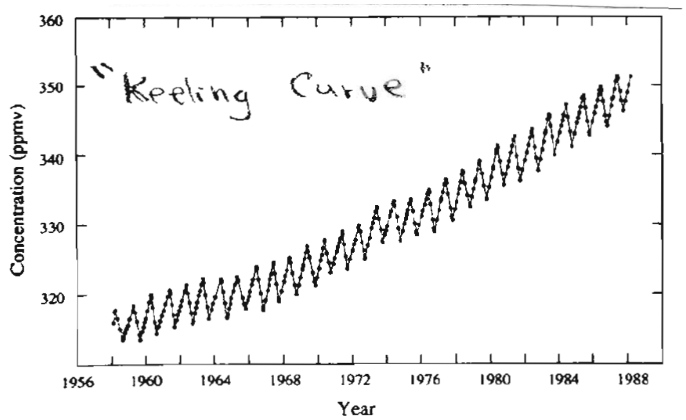
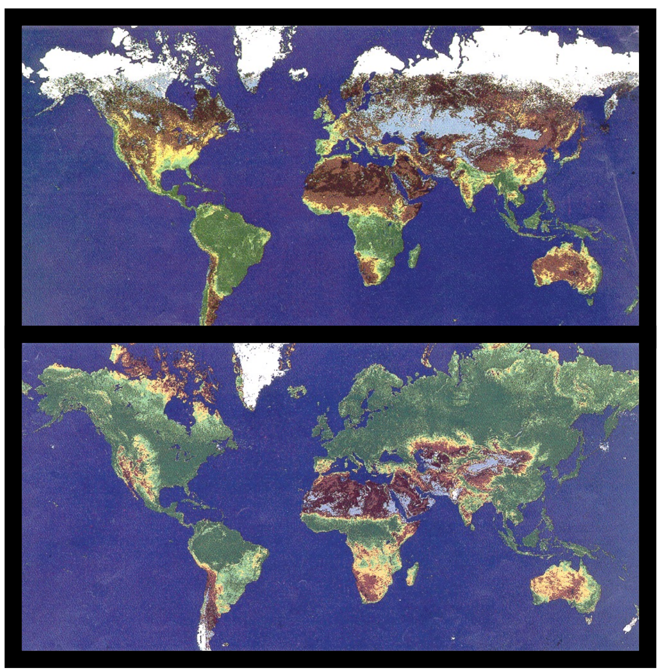


Figure 1.3 The concentration of atmospheric CO_2 at Mauna Loa Observatory in Hawaii, expressed as a mole fraction in parts per million of dry air. The annual oscillation reflects the seasonal cycles of photosynthesis and respiration by land biota in the northern hemisphere, while the overall increase is largely due to the burning of fossil fuels. From Keeling (1986).
Schlesinger 1991

The Breathing Earth

Jan. - Feb.

July - Aug.



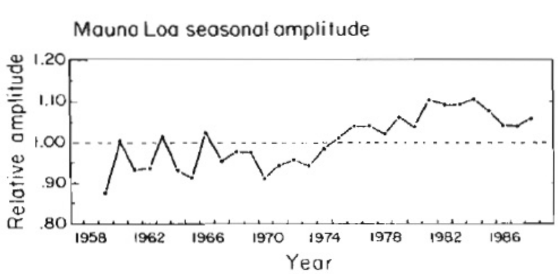
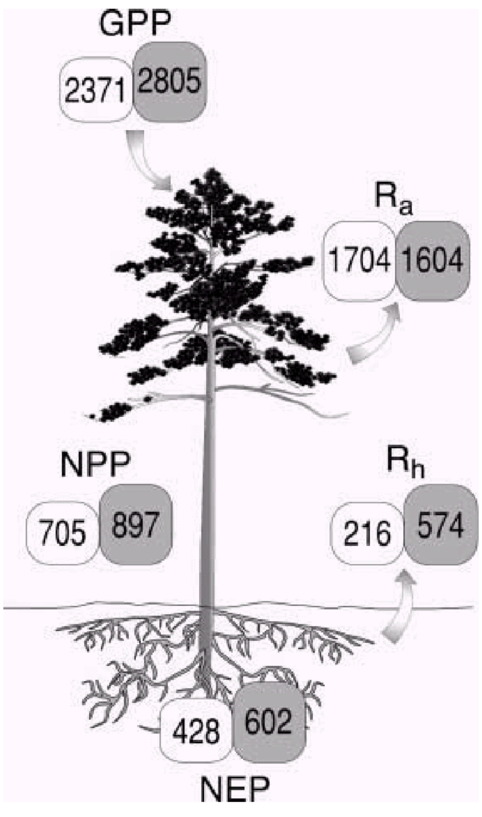
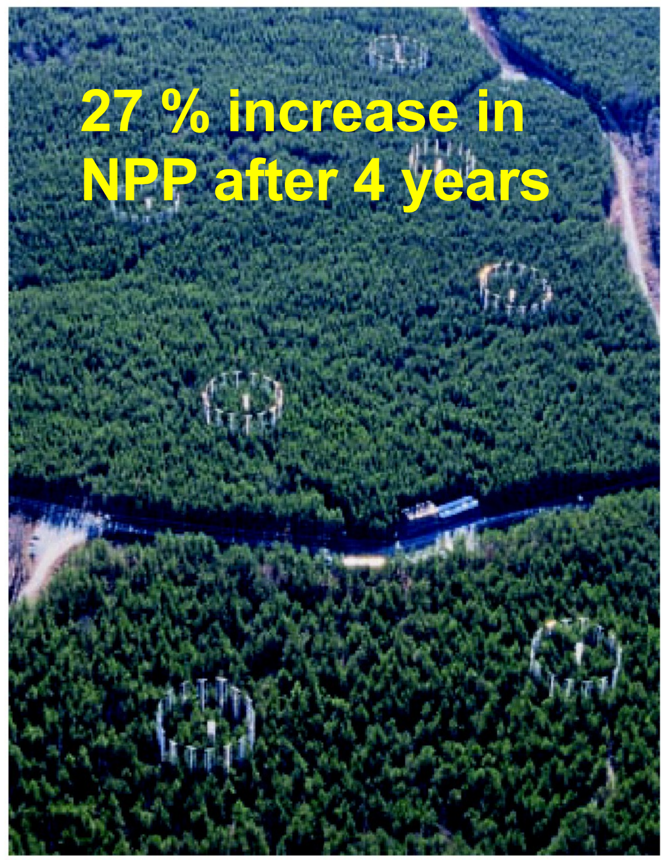


Fig. 6. The changing amplitude of the seasonal carbon dioxide concentration at Mauna Loa Observatory (from Keeling et al. 1989*a*). Mooney 1990

Duke FACE Experiment





Hamilton et al. 2002

Science 2020

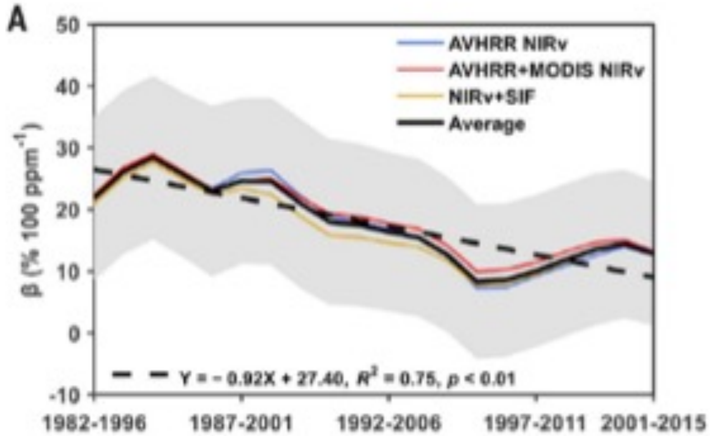
RESEARCH ARTICLE

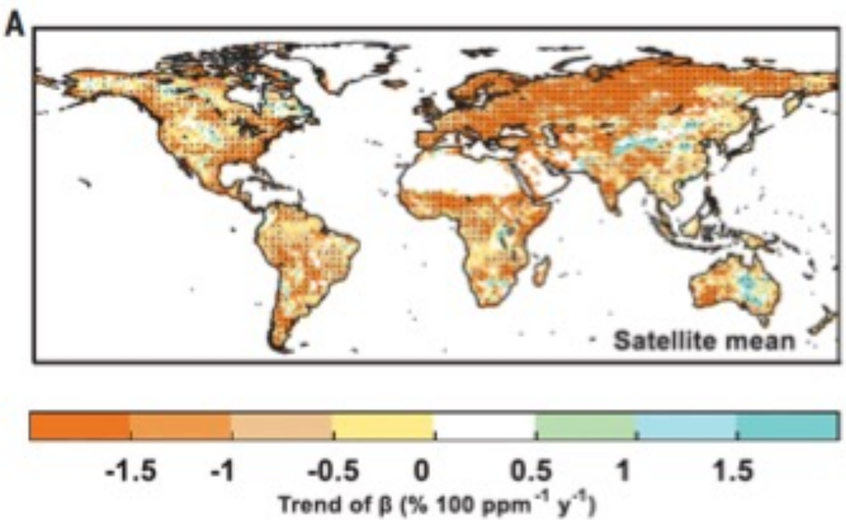
CLIMATE CHANGE

Recent global decline of CO_2 fertilization effects on vegetation photosynthesis

Songhan Wang[1,2], Yongguang Zhang[1,2,3]*, Weimin Ju[1,2], Jing M. Chen[1,4], Philippe Ciais[5], Alessandro Cescatti[6], Jordi Sardans[7,8], Ivan A. Janssens[9], Mousong Wu[1,2], Joseph A. Berry[10], Elliott Campbell[11], Marcos Fernández-Martínez[9], Ramdane Alkama[6], Stephen Sitch[12], Pierre Friedlingstein[13], William K. Smith[14], Wenping Yuan[15], Wei He[1,2], Danica Lombardozzi[16], Markus Kautz[17], Dan Zhu[5], Sebastian Lienert[18], Etsushi Kato[19], Benjamin Poulter[20], Tanja G. M. Sanders[21], Inken Krüger[21], Rong Wang[22], Ning Zeng[23,24], Hanqin Tian[25], Nicolas Vuichard[5], Atul K. Jain[26], Andy Wiltshire[12], Vanessa Haverd[27], Daniel S. Goll[5,28], Josep Peñuelas[7,8]

The enhanced vegetation productivity driven by increased concentrations of carbon dioxide (CO_2) [i.e., the CO_2 fertilization effect (CFE)] sustains an important negative feedback on climate warming, but the temporal dynamics of CFE remain unclear. Using multiple long-term satellite- and ground-based datasets, we showed that global CFE has declined across most terrestrial regions of the globe from 1982 to 2015, correlating well with changing nutrient concentrations and availability of soil water. Current carbon cycle models also demonstrate a declining CFE trend, albeit one substantially weaker than that from the global observations. This declining trend in the forcing of terrestrial carbon sinks by increasing amounts of atmospheric CO_2 implies a weakening negative feedback on the climatic system and increased societal dependence on future strategies to mitigate climate warming.





nature geoscience

LETTERS

PUBLISHED ONLINE: 22 DECEMBER 2009 | DOI:10.1038/NGEO721

Increased tree carbon storage in response to nitrogen deposition in the US

R. Quinn Thomas[1]*, Charles D. Canham[2], Kathleen C. Weathers[2] and Christine L. Goodale[1]

Human activities have greatly accelerated emissions of both carbon dioxide and biologically reactive nitrogen to the atmosphere[1,2]. As nitrogen availability often limits forest productivity[3], it has long been expected that anthropogenic nitrogen deposition could stimulate carbon sequestration in forests[4]. However, spatially extensive evidence for deposition-induced stimulation of forest growth has been lacking, and quantitative estimates from models and plot-level studies are controversial[5-10]. Here, we use forest inventory data to examine the impact of nitrogen deposition on tree growth, survival and carbon storage across the northeastern and north-central USA during the 1980s and 1990s. We show a range of growth and mortality responses to nitrogen deposition among the region's 24 most common tree species. Nitrogen deposition (which ranged from 3 to 11 kg ha^{-1} yr^{-1}) enhanced the growth of 11 species and decreased the growth of 3 species. Nitrogen deposition enhanced growth of all tree species with arbuscular mycorrhizal fungi associations. In the absence of disturbances that reduced carbon stocks by more than 50%, above-ground biomass increment increased by 61 kg of carbon per kg of nitrogen deposited, amounting to a 40% enhancement over pre-industrial conditions. Extrapolating to the globe, we estimate that nitrogen deposition could increase tree carbon storage by 0.31 Pg carbon yr^{-1}.

some doubt on both the magnitude and the direction, of future forest C responses. Spatial covariation between N deposition and patterns of tropospheric ozone and sulphur pollution may further offset N-induced growth enhancement[19]. Here, we use spatially extensive forest inventory data to discern the effect of N deposition on the growth and survival of the 24 most common tree species of the northeastern and north-central US, as well as the effect of N deposition on C sequestration in trees across the breadth of the northeastern US.

Species-level responses to N deposition are critical to projections of how tree communities will change as a result of a range of factors, including succession, climate change and host-specific pests[20]. Individual tree growth responded to N deposition for 14 of the 24 species examined; however, the direction, shape and magnitude of the response varied by species (Fig. 1, Table 1). Three of the four most abundant species (*Acer rubrum, A. saccharum and Quercus rubra)* showed strong positive growth responses (>4% increase in C increment per kg N ha^{-1} yr^{-1}). The largest growth enhancements (16–18% per kg N ha^{-1} yr^{-1}) occurred in *Liriodendron tulipifera* and *Prunus serotina*, two valuable timber species. Mycorrhizal association may also influence the response to N deposition, as all five of the tree species with arbuscular mycorrhizal associations responded positively (*Acer rubrum, A. saccharum, Fraxinus americana, Liriodendron tulipifera*, and *Prunus*

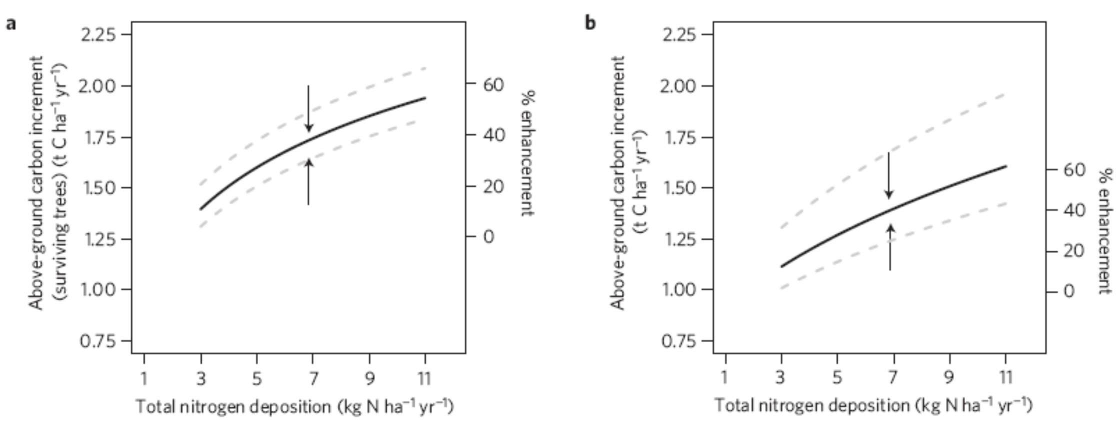


Figure 2 | Annual above-ground carbon increment increases with nitrogen deposition. a,**b**, The relationship between total (wet + dry) inorganic N deposition and annual above-ground growth of surviving trees (**a**) and net annual above-ground carbon increment (excluding plots with >50% loss of carbon stocks) (**b**) at the plot level. The per cent enhancement uses preindustrial N deposition (1 kg N ha^{-1} yr^{-1}) as a baseline and a linear extrapolation of the response. The mean annual N deposition (6.9 kg N ha^{-1} yr^{-1}) estimated for the forest inventory data is shown with the arrows. Two-unit support intervals are plotted as grey-dashed lines.

The recipe for life contains more than carbon!

It is mostly... CHNOPS

The stoichiometric formula for a living human being is:

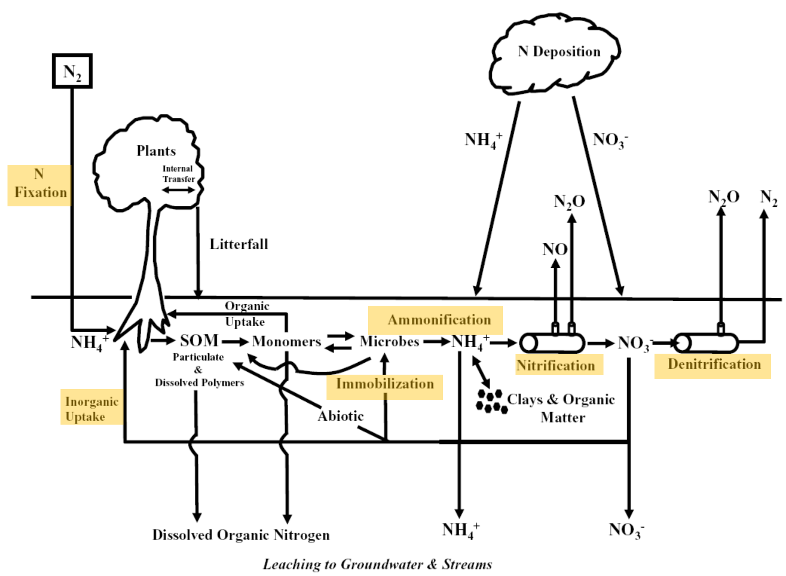
$$H_{375,000,000}\,O_{132,000,000}\,C_{85,700,000}\,N_{6,430,000}\,Ca_{1,500,000}\,P_{1,020,000}\,S_{206,000}\,Na_{183,000}\,K_{177,000}\,Cl_{127,000}\,Mg_{40,000}\,Si_{38,600}\,Fe_{2,680}\,Zn_{2,110}\,Cu_{76}\,I_{14}\,Mn_{13}\,F_{13}\,Cr_{7}\,Se_{4}\,Mo_{3}\,Co_{1}$$

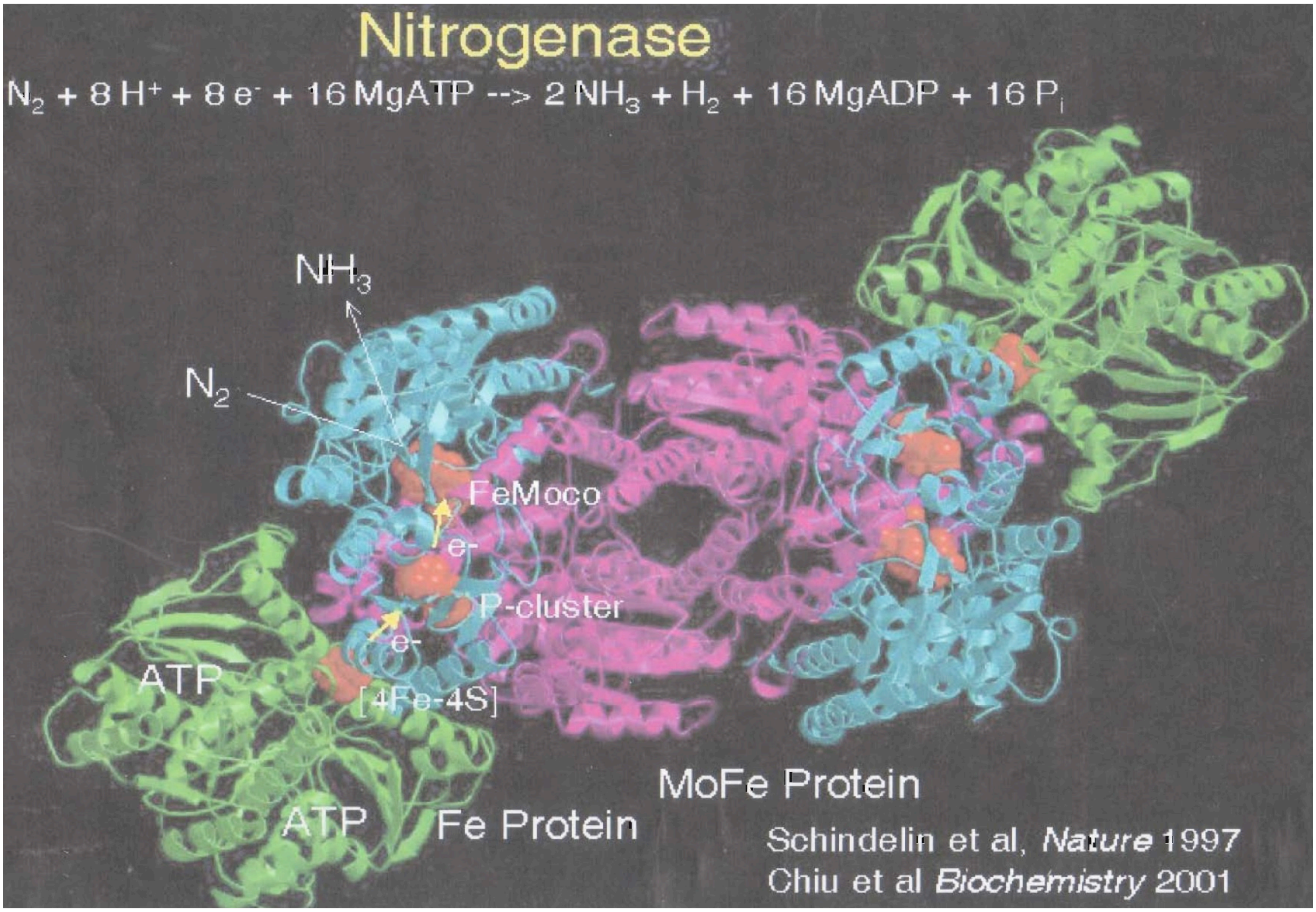
The Global N Cycle

TABLE 3-7
Chemical Forms of Nitrogen

Formula	*Name*	*Oxidation number**	*Comments*
NH_3	Ammonia	−3	Major nutrient form
NH_4^+	Ammonium ion	3	From NH_3 dissolved in water
NH_2^+	Amino group	−1	Constituent of protein
N_2	Nitrogen gas	0	Bulk of atmosphere
N_2O	Nitrous oxide	+1	Laughing gas, controls natural ozone cycle
NO	Nitric oxide	+2	Combustion product
NO_2^-	Nitrite ion	+3	Link in N cycle
NO_2	Nitrogen dioxide	+4	From NO oxidized in atmosphere
NO_3^-	Nitrate ion	+5	Principal nutrient form

*Negative oxidation numbers denote more-reduced forms, and positive oxidation numbers, more-oxidized forms. Ehrlich et al. 1977




Nitrogenase
N2 + 8 H+ + 8 e- + 16 MgATP --> 2 NH3 + H2 + 16 MgADP + 16 Pi
NH3
N2
FeMoco
e-
P-cluster
e-
ATP
[4Fe-4S]
MoFe Protein
ATP
Fe Protein
Schindelin et al, Nature 1997
Chiu et al Biochemistry 2001

Free living & symbiotic (mutualistic)

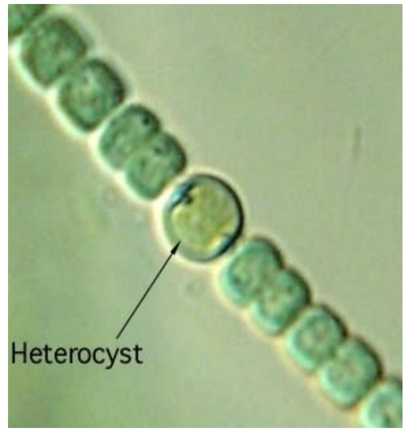
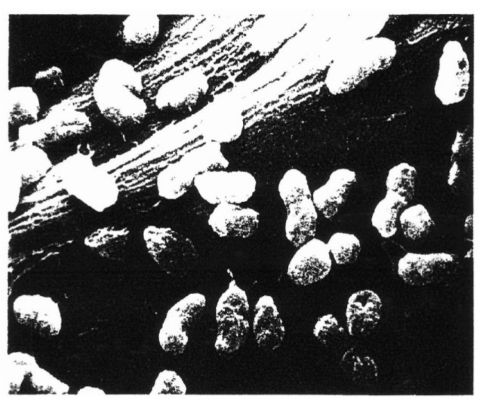
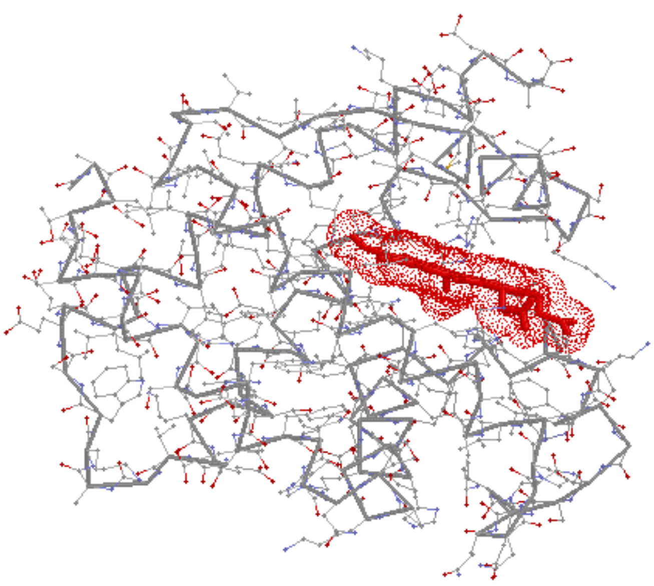
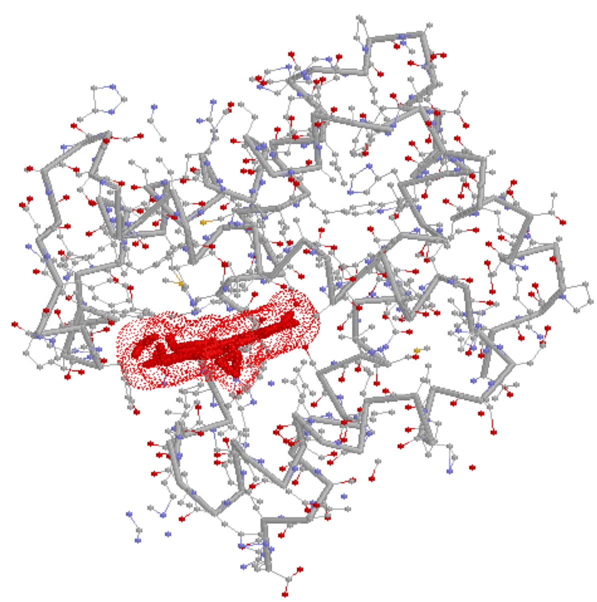


Figure 10.2. Scanning electron micrographs of [illegible] absorbed to root hairs of maize (top, from Patriquin, 1982) and millet (bottom; [illegible] courtesy of F. Dazzo).

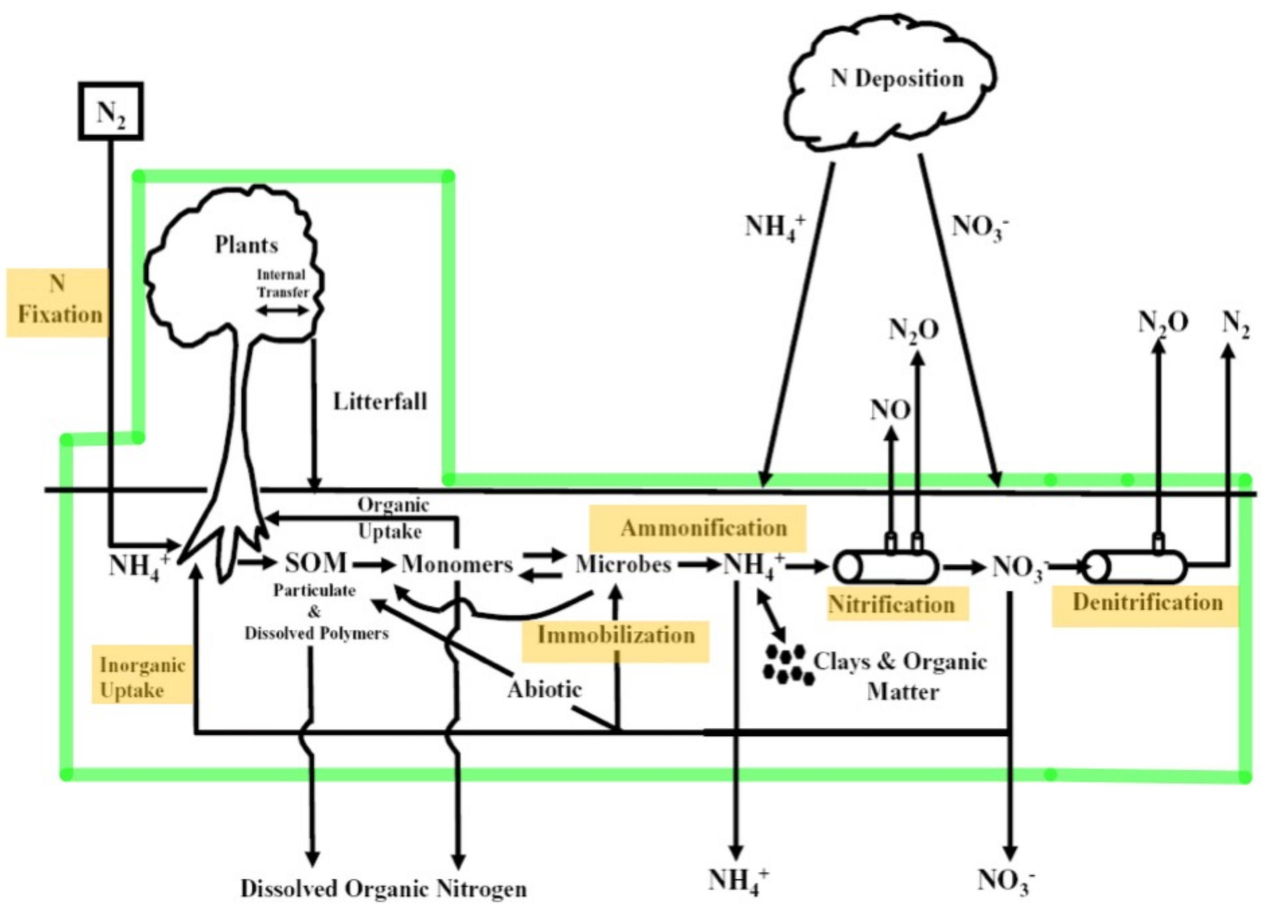




Leghemoglobin



Human hemoglobin, chain A



Leaching to Groundwater & Streams

Internal N Cycling in Soils
(ammonification, nitrification, uptake/immobilization)

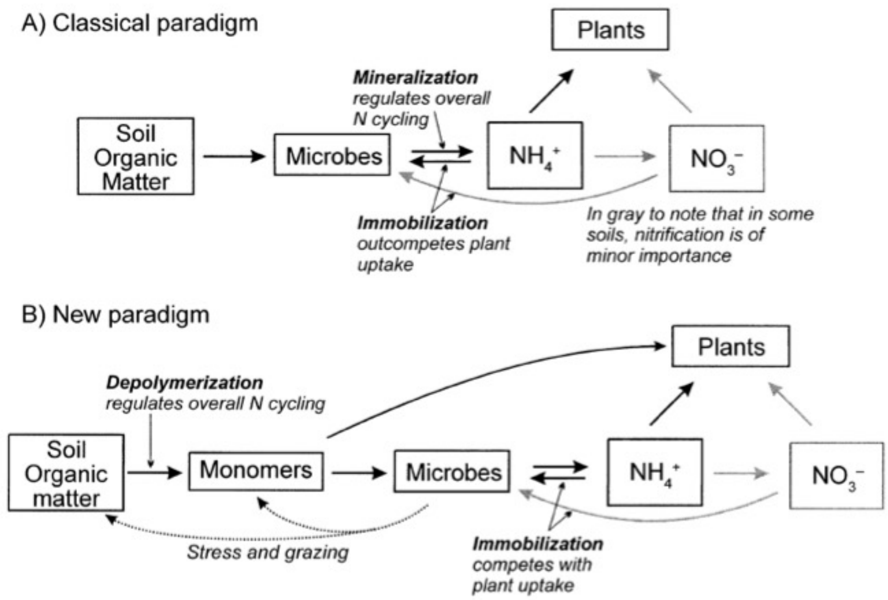


FIG. 1. The changing paradigm of the soil N cycle. (A) The dominant paradigm of N cycling up through the middle 1990s. (B) The paradigm as it developed in the late 1990s.

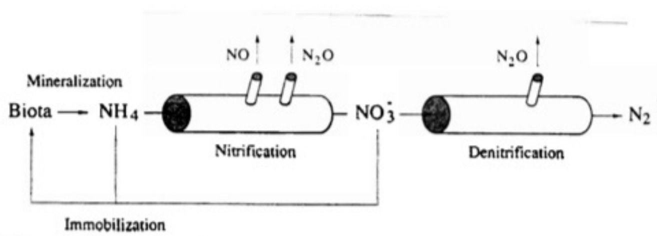


Figure 6.10 Transformations producing nitrogen gases during nitrification and denitrification. Based on an unpublished diagram of M. Firestone.

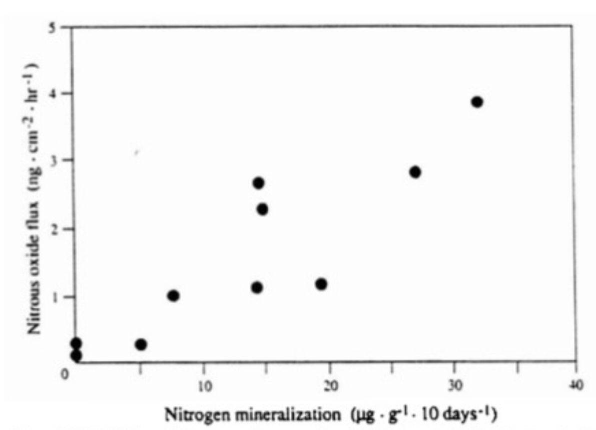
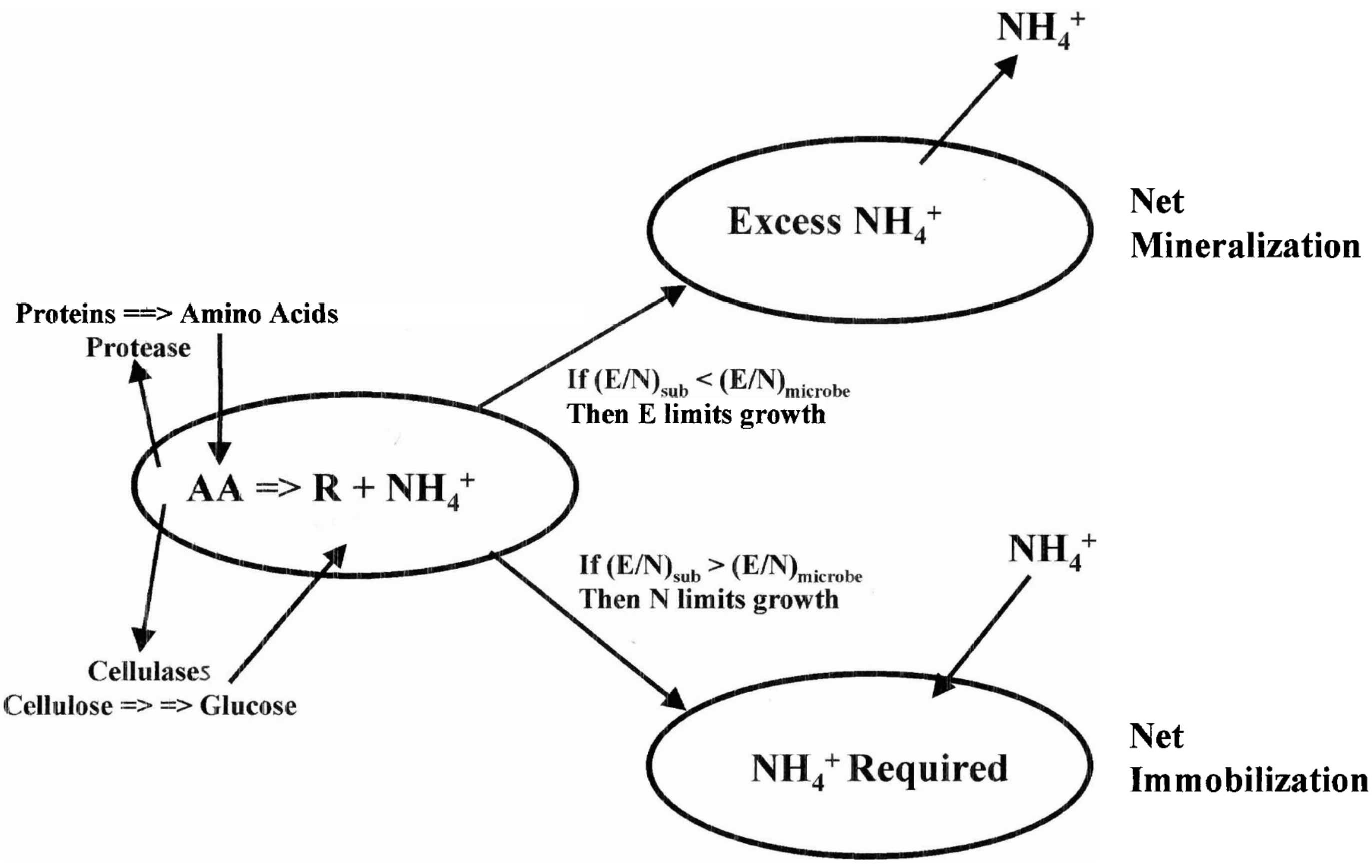


Figure 6.12 Relationship between nitrogen mineralization measured in laboratory incubations and loss of N_2O from 10 tropical forest soils. From Matson and Vitousek (1987).

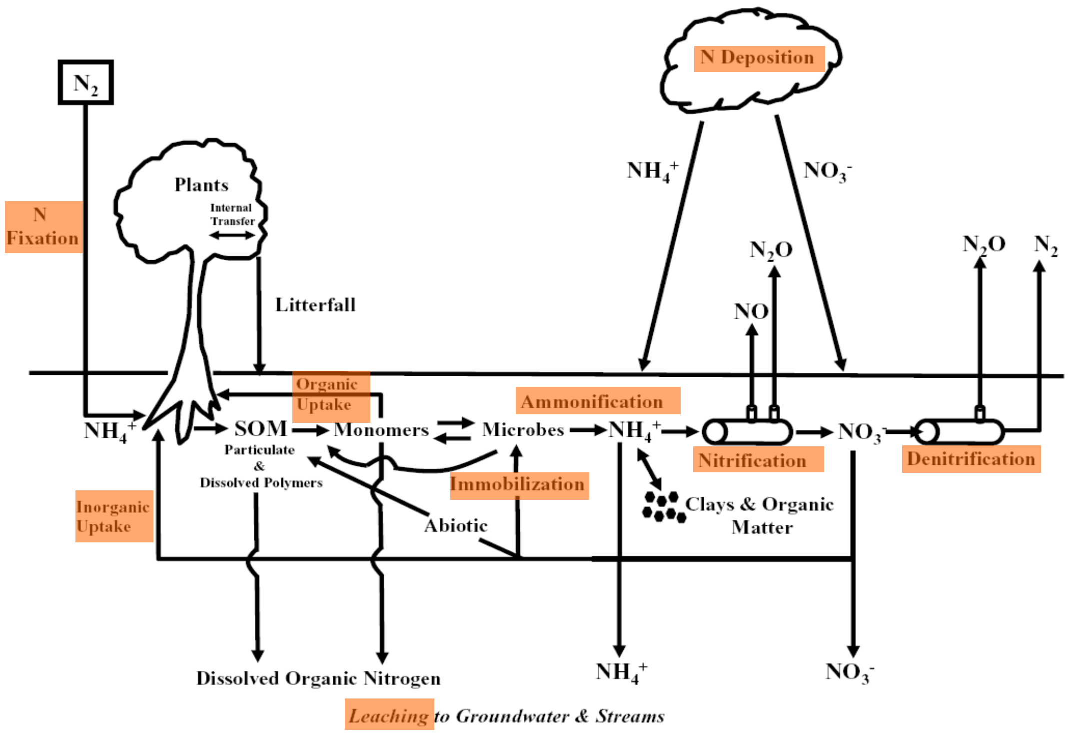
What determines whether microbes release or acquire inorganic N from the soil solution?



Denitrification

(major pathway that returns N to the atmosphere)

In Defense of Mud



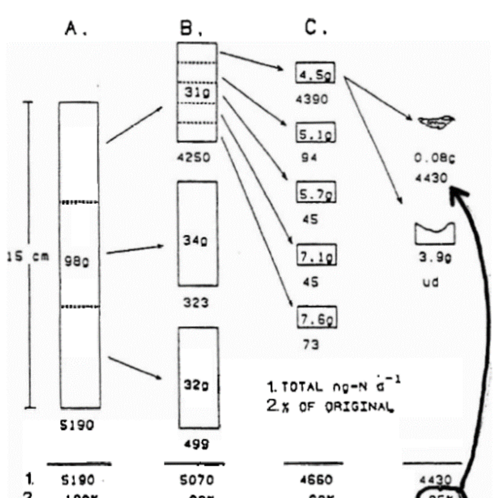


Fig. 3. Results of a core segmentation experiment to identify active denitrifying sites in soil. All incubations were conducted under a headspace atmosphere of 18-kPa O_2 and 10-kPa C_2H_2.

Parkin 1987

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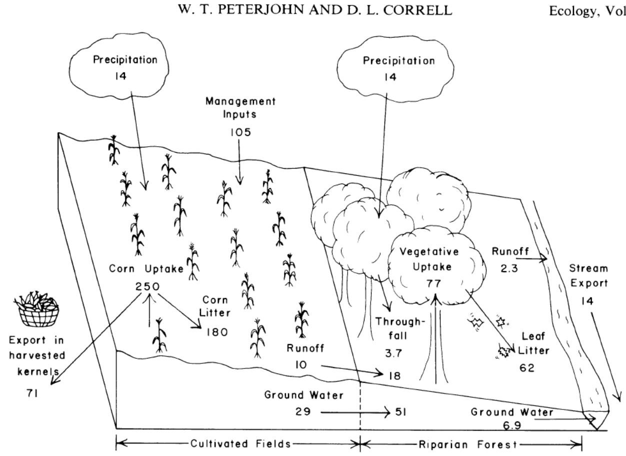


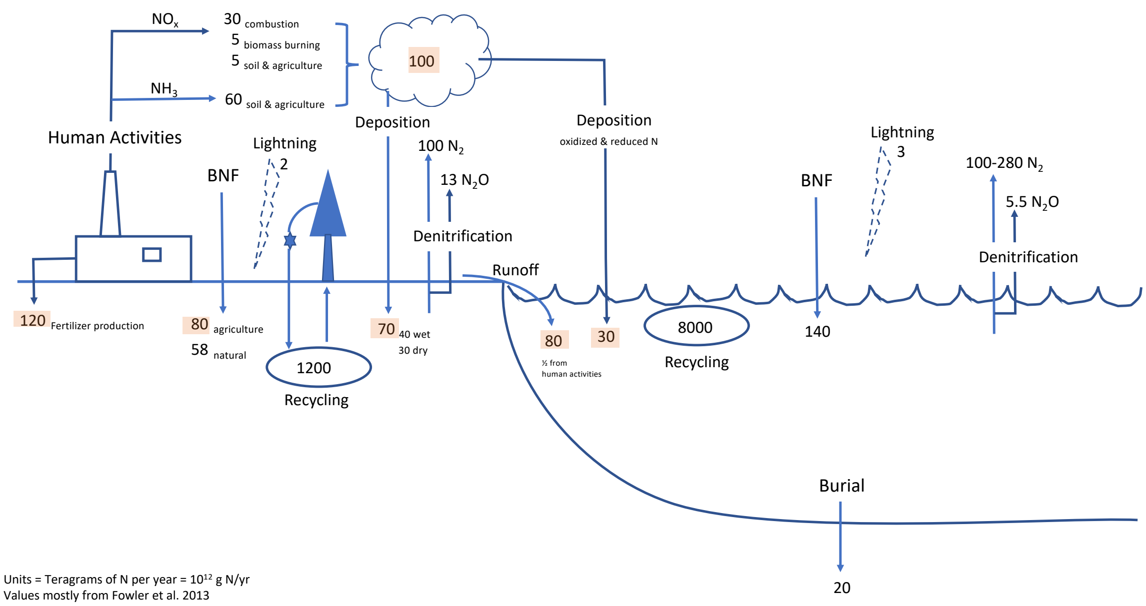
FIG. 2. Diagram of total-N flux and cycling in the study watershed from March 1981 to March 1982. All values are kilograms per hectare of the respective habitats (cropland and riparian forest/streams).

Major global reserviors of N

Reservior	Estimated Total (Pg N)
Igneous Rock	36,000,000
Atmosphere	3,800,000
Ocean	21,000
Soil Organic Matter	95
Terrestrial Biota	3.5
Anthropomass	0.006

Sources: Schlesinger 1991; Smil 1990

Global N Cycle



Units = Teragrams of N per year = 10^{12} g N/yr
Values mostly from Fowler et al. 2013

Humans Fix Nitrogen Too !

The Haber Process

$3CH_4 + 6\ H_2O \Rightarrow 3CO_2 + 12\ H_2$

$4N_2 + 12\ H_2 + \text{catalyst} \Longrightarrow 8\ NH_3$

at 500°C & several hundred atmospheres of pressure

Fritz Haber

https://radiolab.org/episodes/180132-how-do-you-solve-problem-fritz-haber

Atmospheric N deposition has increased in time & space

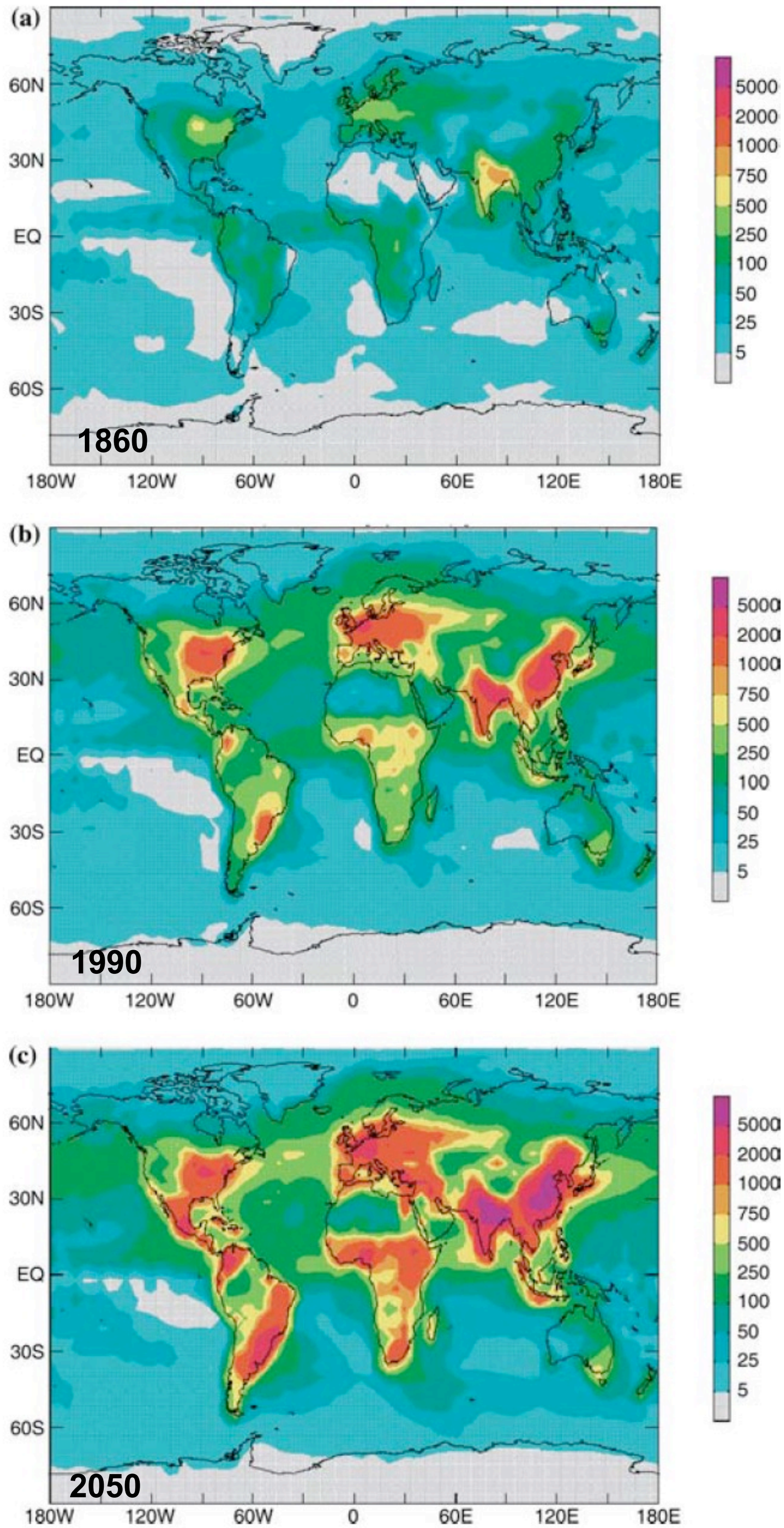
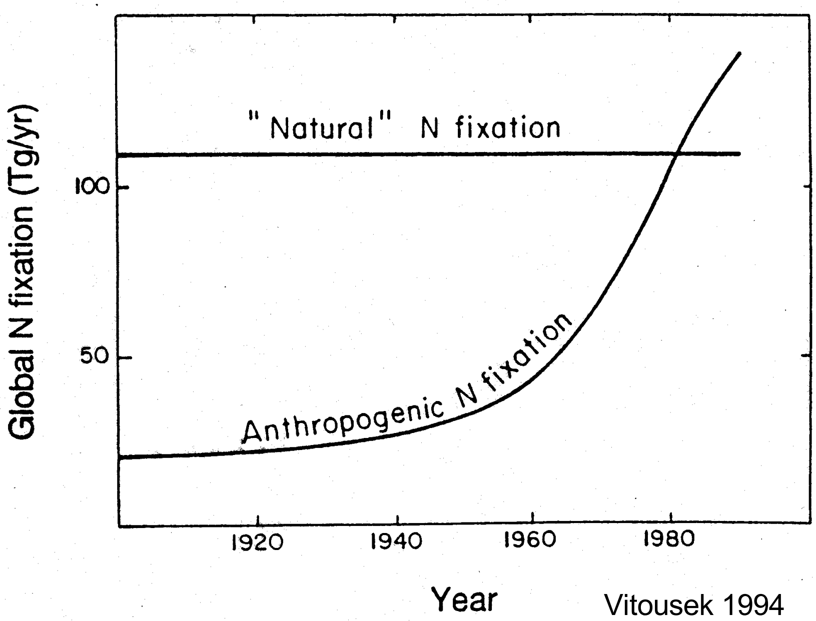


Figure 2. Spatial patterns of total inorganic nitrogen deposition in (a) 1860, (b) early 1990s, and (c) 2050, $mg\,N\,m^{-2}\,yr^{-1}$.

Galloway et al. 2004



Vitousek 1994

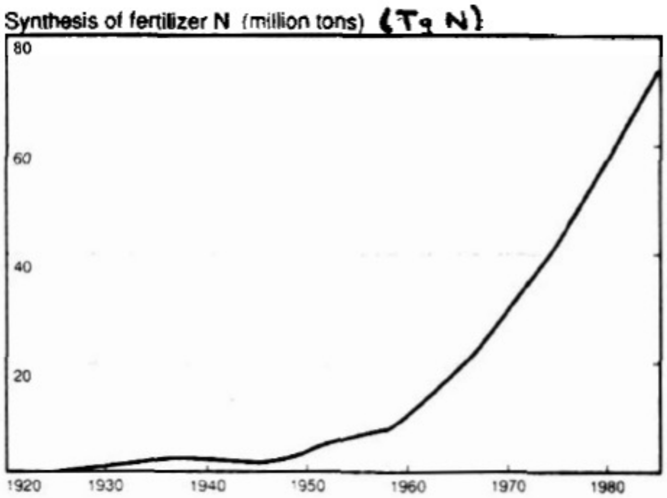


Figure 25.3 Exponential rise of global synthesis of nitrogenous fertilizers between 1920 and 1985. Assembled from a variety of historical statistics and from FAO 1986. Smil 1990

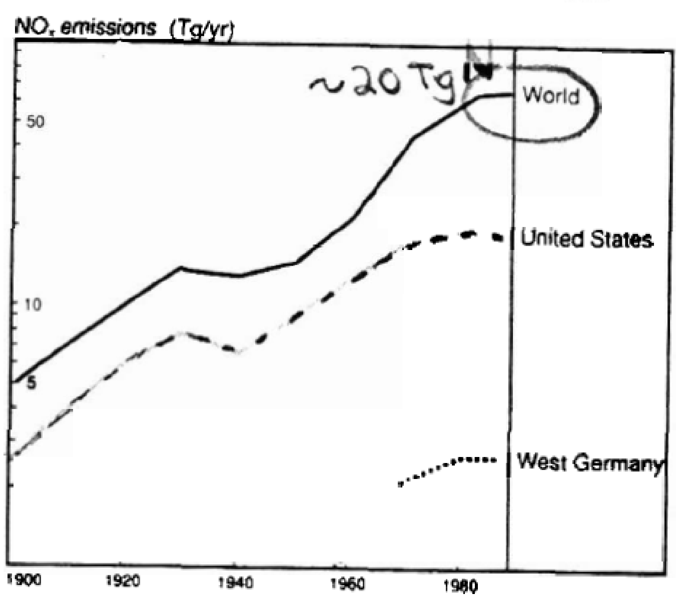


Figure 25.4 Historical rates of NO_x emissions. Sources: World Resources Report 1986 and author's calculations.
Smil

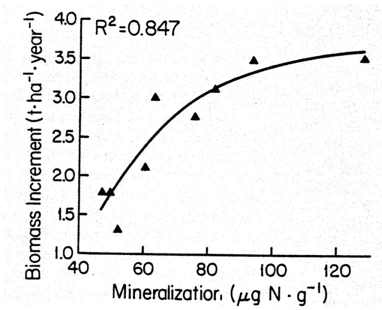
Table 12.3 Estimated Sources and Sinks of N_2O Typical of the Last Decade (10^{12}g N/yr)[a]

Sources	
Natural	
Oceans	4
Tropical soils	
Wet forests	3
Dry savannas	1
Temperate soils	
Forests	1
Grasslands	1
Total identified natural sources	10
Anthropogenic	
Cultivated soils	3.5
Biomass burning	0.5
Industrial sources	1.3
Cattle and feed lots	0.4
Total identified anthropogenic sources	5.7
Total identified sources	15.7
Sinks	
Stratospheric destruction	12.3
Soil microbial activity	?
Atmospheric increase	3.9
Total identified sinks	16.2

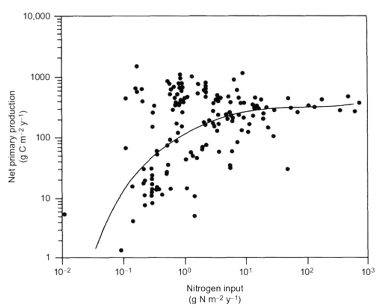
[a] From Prather et al. (1995), except ocean flux (Nevison et al. 1995).

You can too much of a good thing!

Nitrogen saturation is a sustained supply of available N in excess of biotic demand



Zak et al. 1989 CJFR



Schlesinger & Bernhardt 2013 from Levin 1989
NPP vs N inputs to terrestrial, marine, & aquatic systems

N saturation may:

- deplete soils of exchangeable nutrient cations
- increase toxic Al^{+++} levels
- alter soil- and stream-water chemistry
- reduce the growth of trees
- reduce species diversity

After 13 years of N additions

Fig. 9. View of the control (top panel), low N (middle panel) and high N (bottom panel) canopy in the pine stand at the Harvard Forest (images courtesy of Christian Arabia).

Are these the shadows of the things that Will be, or are they shadows of things that May be, only?

Charles Dickens
A Christmas Carol