How many people can the Earth support?

Many estimates focus on resource availability.

Most obvious single limiting resource — food.

If a single resource is limiting:

$$N_{max} = \frac{\text{production / unit area} \times \text{productive area}}{\text{resource requirement per person}}$$

↑ known as Penck's equation (1925)

Consider the denominator — human nutritional requirement:

Units: 1 nutritional calorie = 1 kcal = 4184 J

Basal metabolic rate (BMR): energy intake required to keep body temperature at 98.6°F in a state of no activity.

BMR depends on body weight and other factors, but average is

$$\text{BMR} = 1200 \text{ kcal/day} = 5 \text{ MJ/day}$$

For comparison:

$$5 \text{ MJ/day} = 5 \cdot 10^6 \text{ J/day} \,/\, 86{,}400 \frac{\text{sec}}{\text{day}}$$

$= 60$ watts — a dim light bulb.

World-wide average food consumption:

2700 kcal/day = 2.3 × BMR

UN official definition of undernourished:

1700 kcal/day = 1.4 × BMR

US consumption:

3600 kcal/day = 3 × BMR — leads to obesity.

Total human food consumption:

2700 kcal/day = 150 watts — a bright light bulb

$$\left(150 \frac{W}{\text{person}}\right)\left(6 \cdot 10^{9} \text{ people}\right) = 9 \cdot 10^{11} \text{ W}$$

For comparison — heat flow from ⊕ : $4.2 \cdot 10^{13}$ W

human food consumption = 2% of ⊕ heat flow

A well-known estimate of N_{max} was made by Roger Revelle (1976).

He used 2500 kcal/day of grain (rice or wheat) in the denominator of Penck's equation — average in China today.

To estimate the first term in the numerator he made a careful study of <u>potentially</u> arable land.

1 hectare (ha) = 100 m × 100 m
= 2.25 acres
≈ 2 football fields

Total ice-free land on ⊕: $1.3 \cdot 10^{10}$ ha

Revelle felt that $3.8 \cdot 10^9$ ha were potentially arable ≅ 29 % of total.

Final factor in Penck's equation — grain production / ha

Revelle felt that world-wide grain yields could be increased to 2.7 tons / ha

1 ton = 1 "long" ton = 1000 kg = 2200 lb

Finally, we need to know the caloric content of grain. This is basically the same for all plant matter

caloric content of vegetable matter = 3.5 kcal / g = $3.5 \cdot 10^6 \frac{\text{kcal}}{\text{ton}}$

Thus, from Penck's equation

$$N_{max}^{Revelle} = \frac{(3.8 \cdot 10^9 \text{ ha})(2.7 \text{ ton / ha/yr})(3.5 \cdot 10^6 \frac{\text{kcal}}{\text{ton}})}{(2500 \text{ kcal / person / day})(365 \text{ days / year})}$$

= 40 billion people — seven times the current population

Note that this is how many people the Earth could support if each person consumed a Chinese vegetarian diet.

People in the US derive ~2/3 of their 3600 kcal/day from eating <u>meat</u>

To produce 1 kcal of $\left\{ \begin{matrix} \text{beef} \\ \text{chicken} \end{matrix} \right\}$ requires $\left\{ \begin{matrix} 8 \\ 3 \end{matrix} \right\}$ kcal of grain.

Say on average an "inefficiency factor" of 5.

To provide every individual with a US rather than Chinese diet would require

$$3600 \times \left(\frac{1}{3} \text{ vegetable} + 5 \times \frac{2}{3} \text{ meat} \right)$$

$$= 13{,}000 \text{ kcal/day}$$ (5 times as much as a Chinese person)

Then $N_{max} =$ 8 billion people.

It all depends on your assumptions.

The world-wide rate of growth of food production (also exponential) is about

3%	=	1%	+	2%
		rate of growth of cropland		rate of growth of crop yield

About twice as large as rate of population growth

Present-day food production in context of global carbon cycle.

Green plants "fix" carbon into organic matter by photosynthesis — highly simplified reaction

$$\underset{\text{in air}}{6\,CO_2} + \underset{\text{in rain or irrigation}}{6\,H_2O} \xrightarrow{\text{sunlight}} \underset{\text{carbohydrate}}{C_6H_{12}O_6} + \underset{\text{oxygen we breathe}}{6\,O_2}$$

Rate of carbon fixation by terrestrial plants (the so-called <u>net</u> <u>primary</u> <u>productivity</u> or NPP):

$$\boxed{NPP = 65 \text{ Gt C/yr}}$$

$$1 \text{ Gt} = 10^9 \text{ tons} = 10^{12} \text{ kg} = 10^{15} \text{ g} = 1 \text{ petagram}$$

The total amount of carbon in the atmosphere is

$$\boxed{760 \text{ Gt C in atmosphere}}$$ ← mostly in CO_2, also methane CH_4

<u>Residence time</u> of a C atom in atmosphere is:

$$\frac{760}{65} = 12 \text{ years}$$

CO_2 is returned to the atmosphere by respiration (mostly by bacteria in the leaf litter)

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

Question #1: What is total rate at which terrestrial plants store solar energy for use by respirers, including humans?

The % of carbohydrate that is carbon (by mass) is

$$\frac{C}{C + H_2 + O} = \frac{12}{12+2+16} = 0.4 \quad (40\%)$$

$$NPP = 6.5 \cdot 10^{10} \frac{\text{tons C}}{\text{yr}} \times \frac{1}{0.4} \frac{\text{tons plant}}{\text{tons C}}$$

$$\times\ 3.5 \cdot 10^{6} \frac{\text{kcal}}{\text{tons plant}} = 5.7 \cdot 10^{17} \frac{\text{kcal}}{\text{yr}}$$

$$\boxed{NPP = 2.4 \cdot 10^{21}\ \text{J/yr} = 7.7 \cdot 10^{13}\ \text{W}}$$

↖ twice the total heat flow from the Earth ($4 \cdot 10^{13}$ W)

Question # 2: What percent of all plant growth (i.e. what percent of NPP) is consumed by humans?

$$2700\ \text{kcal/day} \times 6 \cdot 10^{9}\ \text{people} \times 365\ \text{days/yr}$$

$$= 6 \cdot 10^{15}\ \text{kcal/year} = 2.4 \cdot 10^{19}\ \text{J/yr} = 1\%\ \text{of NPP.}$$

Question #3: What fraction of the sunlight falling on the non-ice covered land is converted into caloric energy stored in biomass by photosynthesis?

The average solar flux at top of ⊕'s atmosphere is: ~~[illegible]~~

256 kcal/cm^2/yr

Only ~50% gets to the ground — rest is scattered or absorbed by atmosphere or reflected by clouds

$$\underbrace{1.3 \cdot 10^{10} \text{ kcal/ha/yr}}_{\text{sunlight reaching ⊕ surface}} \times \underbrace{1.3 \cdot 10^{10} \text{ ha}}_{\text{non-ice covered land}}$$

$$= 1.7 \cdot 10^{20} \text{ kcal/yr}$$

$$\frac{5.7 \cdot 10^{17} \text{ kcal/yr} \leftarrow \text{NPP}}{1.7 \cdot 10^{20} \text{ kcal/yr}} = 0.0034$$

NPP is 0.34% of solar influx — this is the efficiency of photosynthesis

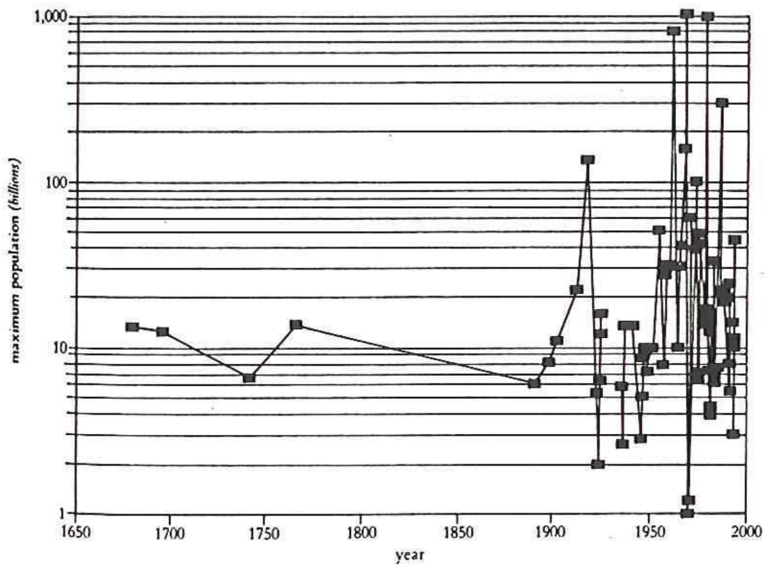


FIGURE 11.1 Estimates of how many people the Earth can support, by the date at which the estimate was made. When an author gave a range of estimates or indicated only an upper bound, the highest number stated is plotted here. The 1964 estimate by J. H. Fremlin would be off the scale and is omitted. SOURCE: Appendix 3

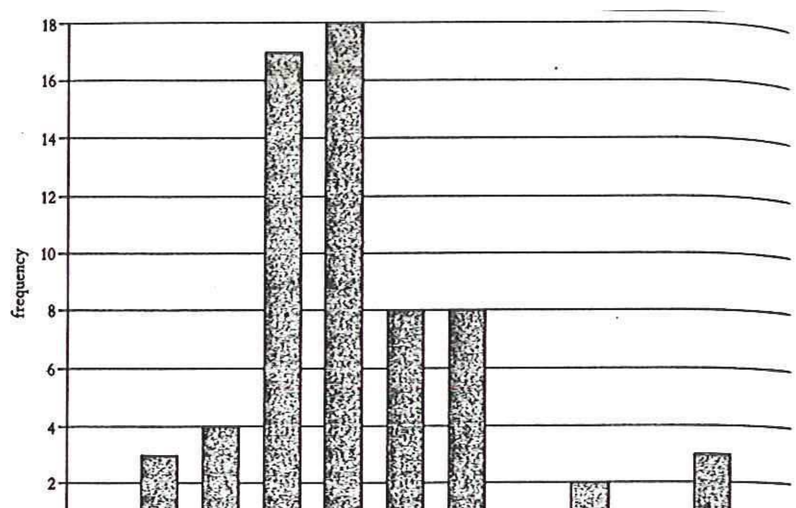


FIGURE 11.2 Frequency distribution of estimates of how many people the Earth can support, based on the highest estimate given by an author. The height of the bar for 4 billion shows the number of estimates greater than the next lower population size shown, that is, 2 billion, and not exceeding 4 billion. Each bar (after the first two) covers a range of population sizes twice as wide as the preceding bar. The 1964 estimate by J. H. Fremlin would be off the scale and is omitted. SOURCE: Appendix 3

Table 5.7. Food Available for Direct Human Consumption (nutritional calories per capita per day)

	1961–63	*1969–71*	*1979–81*	*1984–86*
World total	2,300	2,440	2,600	2,690
Developing countries				
Africa (sub-Saharan)	2,040	2,100	2,140	2,060
Near East/North Africa	2,240	2,390	2,870	3,050
Asia	1,830	2,030	2,260	2,430
Asia[a]	1,970	2,070	2,200	2,280
Latin America	2,380	2,520	2,670	2,700
Low-income countries	1,850	2,020	2,200	2,360
Middle-income countries	2,160	2,340	2,620	2,680
Developed countries	3,060	3,230	3,340	3,380
North America	3,180	3,380	3,510	3,620
Western Europe	3,090	3,230	3,370	3,380
Other developed market economies	2,590	2,810	2,900	2,930
European centrally planned economies	3,140	3,330	3,390	3,410

Source: *World Resources, 1990–91.*

[a] Does not include China.

Table 5.5. World Land Use, by Region, 1850–1980

		Area (million hectares)				*Percent Change*
Region	*Land Type*	*1850*	*1900*	*1950*	*1980*	*1850–1980*
Ten regions, total	Forests and woodlands	5,919	5,749	5,345	5,007	−15
	Grasslands and pasture	6,350	6,284	6,293	6,299	−1
	Cropland	538	773	1,169	1,501	179
Tropical Africa	Forests and woodlands	1,336	1,306	1,188	1,074	−20
	Grassland and pasture	1,061	1,075	1,130	1,158	9
	Cropland	57	73	136	222	288
North Africa and Middle East	Forests and woodlands	34	30	18	14	−60
	Grassland and pasture	1,119	1,115	1,097	1,060	−5
	Cropland	27	37	66	107	294
North America	Forests and woodlands	971	954	939	942	−3
	Grassland and pasture	571	504	446	447	−22
	Cropland	50	133	206	203	309
Latin America	Forest and woodlands	1,420	1,394	1,273	1,151	−19
	Grassland and pasture	621	634	700	767	23
	Cropland	18	33	87	142	677
China	Forests and woodlands	96	84	69	58	−39
	Grassland and pasture	799	797	793	778	−3
	Cropland	75	89	108	134	79
South Asia	Forests and woodlands	317	299	251	180	−43
	Grassland and pasture	189	189	190	187	−1
	Cropland	71	89	136	210	196
Southeast Asia	Forests and woodlands	252	249	242	235	−7
	Grassland and pasture	123	118	105	92	−25
	Cropland	7	15	35	55	670
Europe	Forests and woodlands	160	156	154	167	4
	Grasslands and pasture	150	142	136	138	8
	Cropland	132	145	152	137	−4
USSR (former)	Forests and woodlands	1,067	1,014	952	941	−12
	Grassland and pasture	1,078	1,078	1,070	1,065	−1
	Cropland	94	147	216	233	147
Pacific developed countries	Forests and woodlands	267	263	258	246	−8
	Grassland and pasture	638	634	625	608	−5
	Cropland	6	14	28	58	841

Source: Repetto 1987.

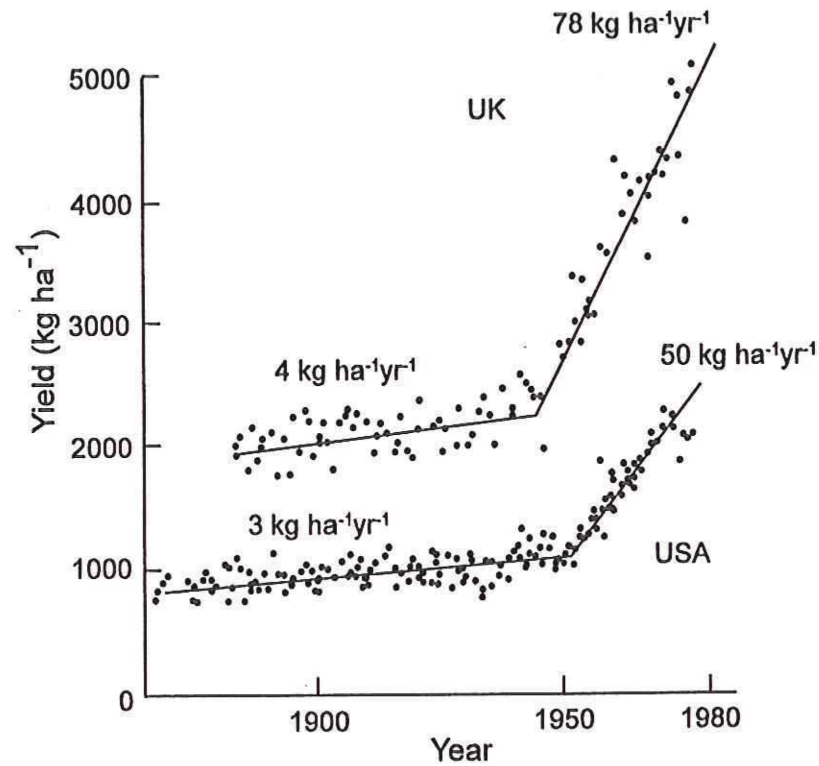


Figure 5.16.
Average wheat yields in the United Kingdom during the course of the past century. (Van Keulen and Wolf 1986)

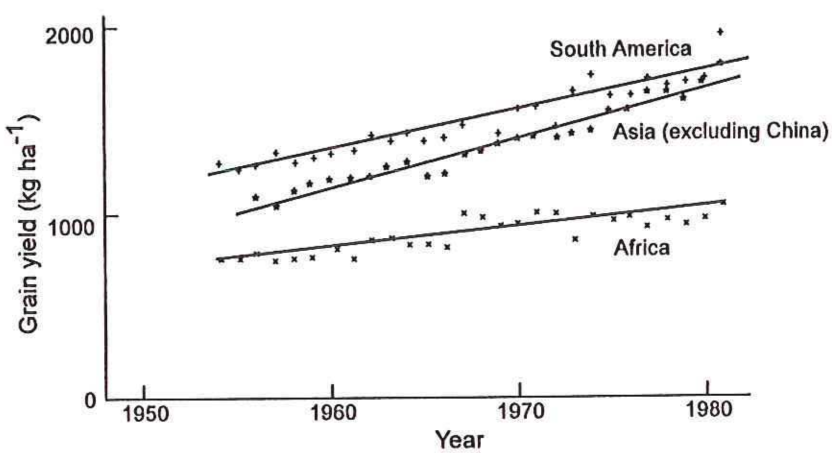


Figure 5.17.
Average grain yields from 1954 to 1980 in Africa, Asia, and South America. (Van Keulen and Wolf 1986)

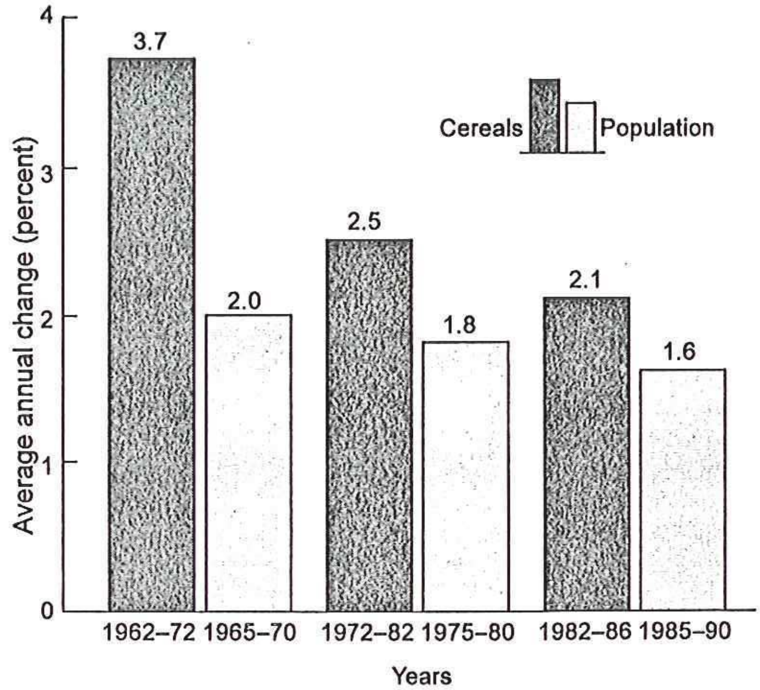
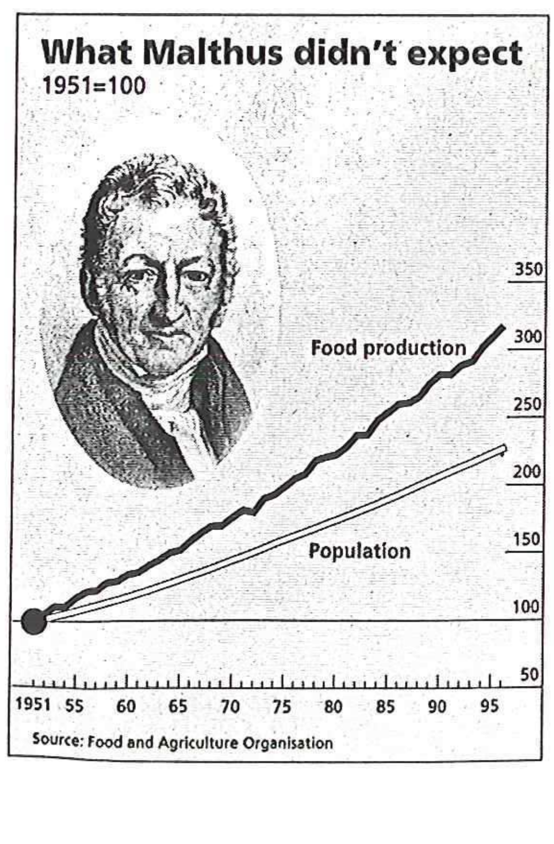


Figure 5.19. World food production is growing faster than world population. The figure shows the annual increase in total production of cereals (darker) and in the world's population (lighter). (Crosson and Rosenberg 1989)



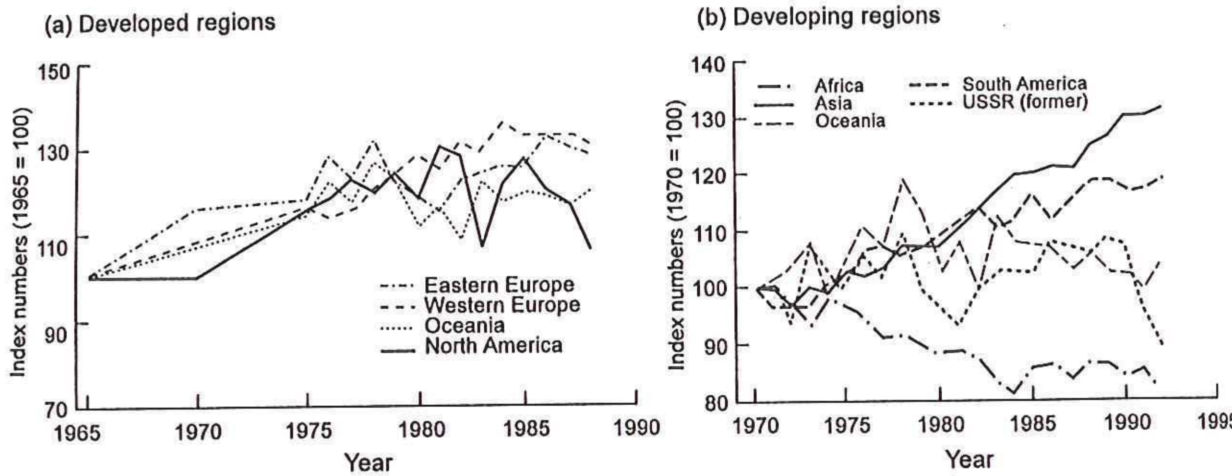
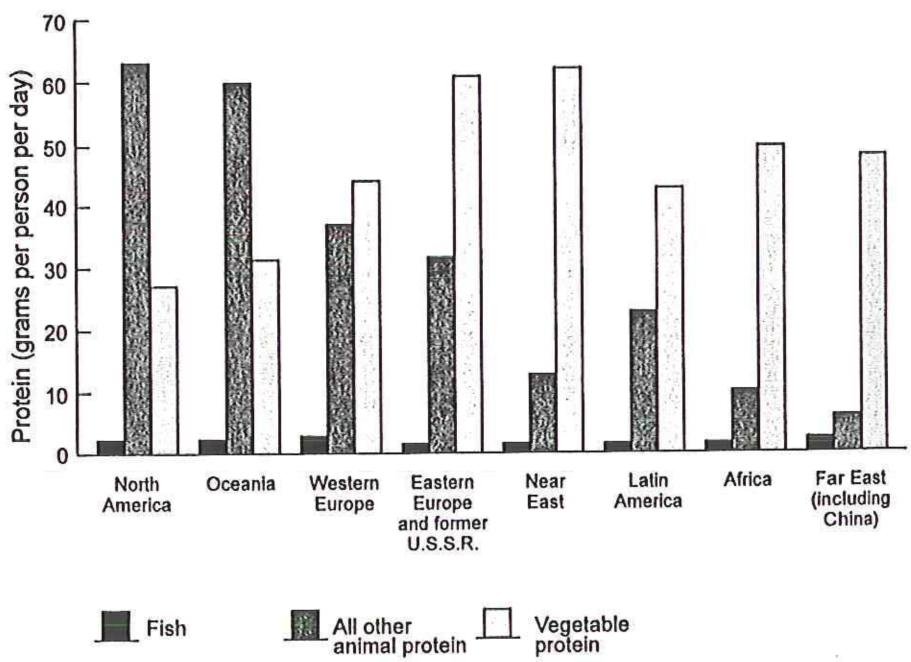


Figure 5.18. Index of per capita food production in the developed and developing regions. (*World Resources 1990–91*, 1990; and *World Resources 1994–95*, 1994)

Figure 5.24. The relatively minor role played by fish in the world's total consumption of protein is apparent when the grams of fish eaten per person per day in various parts of the world (left column in each group) are compared with the consumption of other animal protein (middle column) and vegetable protein (right column). (Holt 1969)



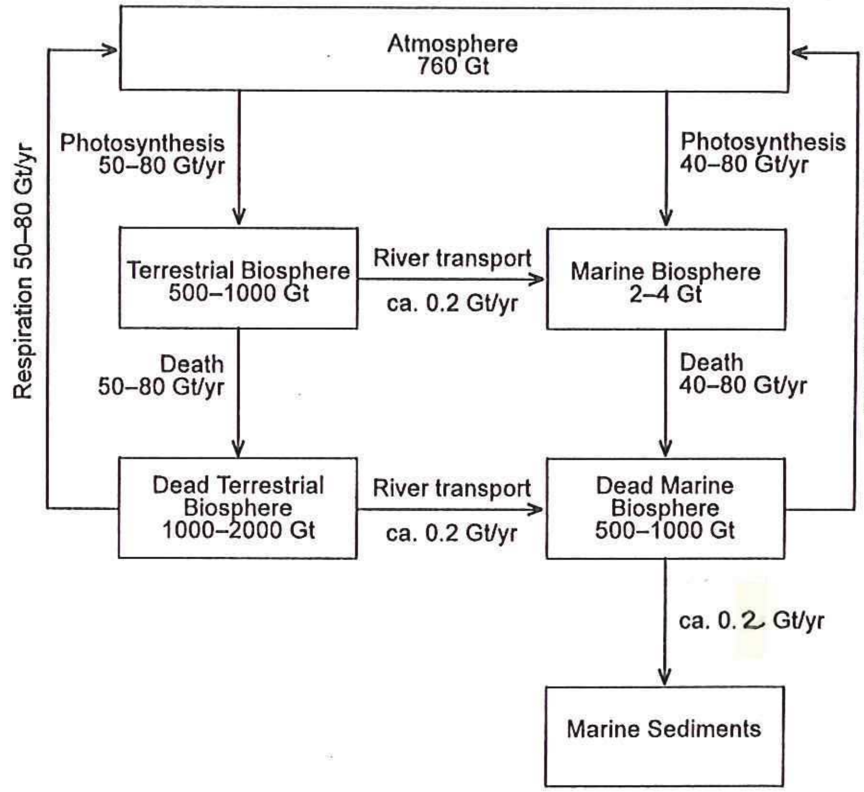
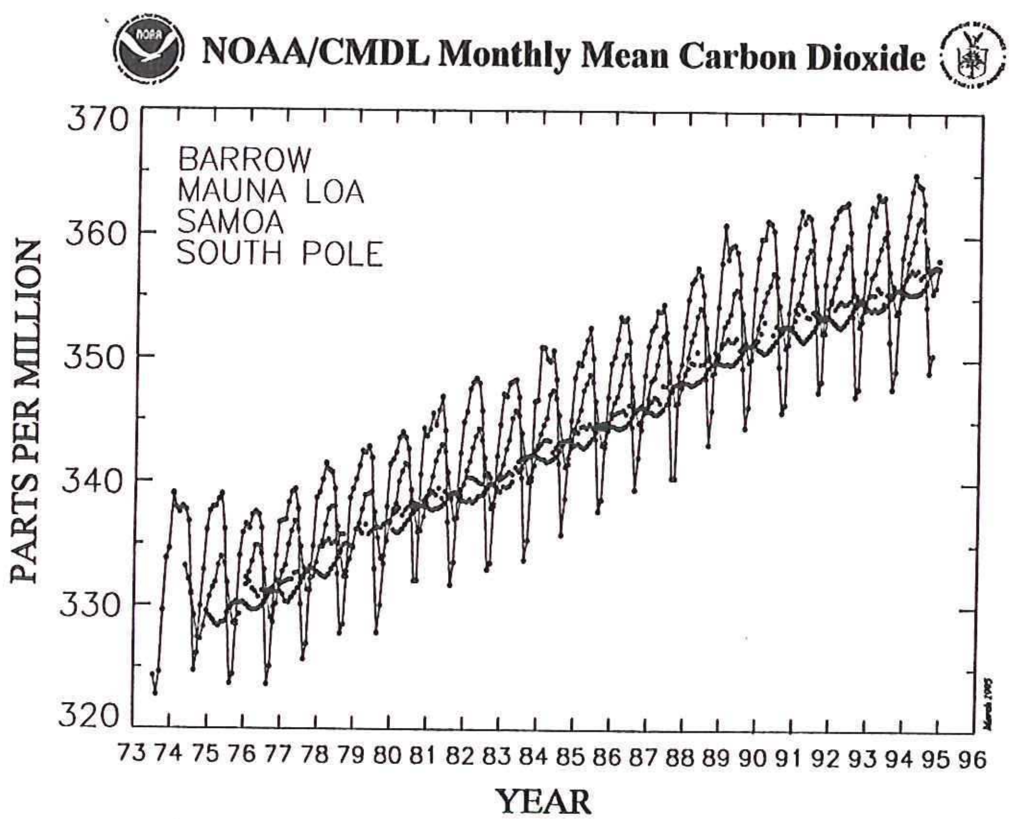


Figure 5.4. The biological parts of the carbon cycle. The carbon content of the several reservoirs is in Gt carbon (1 Gt = 10^{15} gm C). (Data from the compilation of Sundquist 1985)



Atmospheric carbon dioxide mixing ratios determined from the continuous monitoring programs at the 4 NOAA/CMDL baseline observatories. Principal Investigator: Pieter Tans, NOAA/CMDL Carbon Cycle Group, Boulder, Colorado, (303) 497-6678, ptans@cmdl.noaa.gov.

Table 5.1. Average Chemical Composition of Organic Matter

	Percentage Composition by Weight		
Element	*Carbohydrates*	*Fats*	*Proteins*
O	49.38	17.90	22.4
C	44.44	69.05	51.3
H	6.18	10.00	6.9
P		2.13	0.7
N		0.61	17.8
S		0.31	0.8
Fe			0.1
Total	100.00	100.00	100.00

Source: Rankama and Sahama 1950.

Table 5.2. Average Total Composition of Dehydrated Living Matter

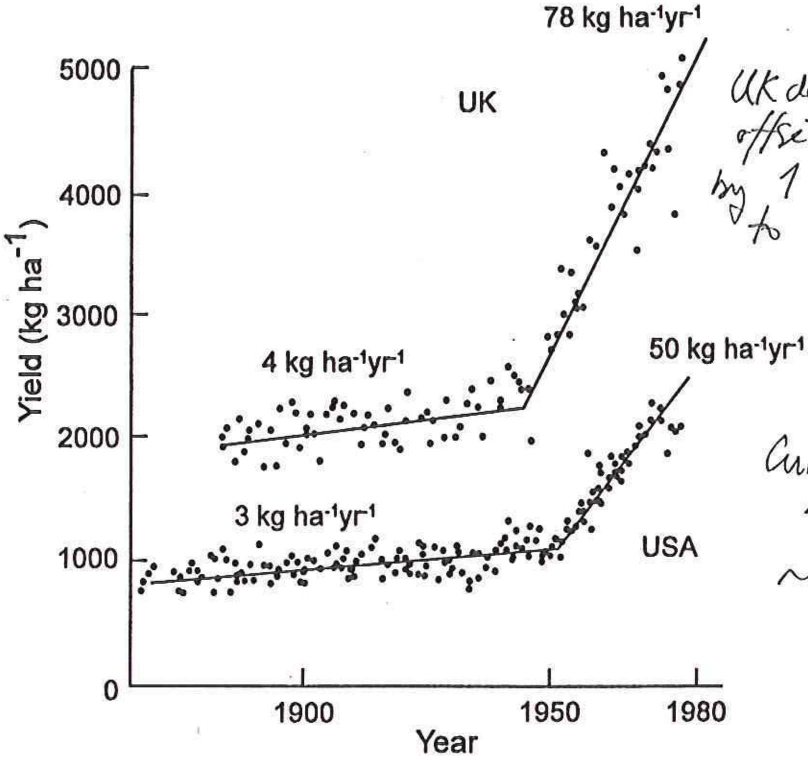
	Percent of Dry Weight	
Element	*Adult (Homo sapiens)*	*Alfalfa (Medicago sativa)*
C	48.43	45.37
O	23.70	41.04
N	12.85	3.30
H	6.60	5.54
Ca	3.45	2.31
S	1.60	0.44
P	1.58	0.28
Na	0.65	0.16
K	0.55	0.91
Cl	0.45	0.28
Mg	0.10	0.33
Total	99.96	99.96

Source: Rankama and Sahama 1950.

Table 5.9
Efficiency of Conservation of Light Energy in Various Crops

Crop	*Efficiency of Use of Sunlight (%)*	*Crop*	*Efficiency of Use of Sunlight (%)*
Wheat (Netherlands)	0.35	Soybeans (Canada)	0.18
Wheat (world average)	0.10	Soybeans (world average)	0.10
Corn (United States)	0.35	Sugar cane (Hawaii)	0.95
Corn (world average)	0.17	Sugar cane (Cuba)	0.30
Rice (Japan)	0.42	Sugar beets (Netherlands)	0.56
Rice (world average)	0.18		
Potatoes (United States)	0.31		
Potatoes (world average)	0.17		

Source: Good and Bell 1980.



UK data are offset upward by 1 ton/ha to avoid overlap

Current US yield is ~ 3 tons/ha

Figure 5.16. Average wheat yields in the United Kingdom during the course of the past century. (Van Keulen and Wolf 1986)

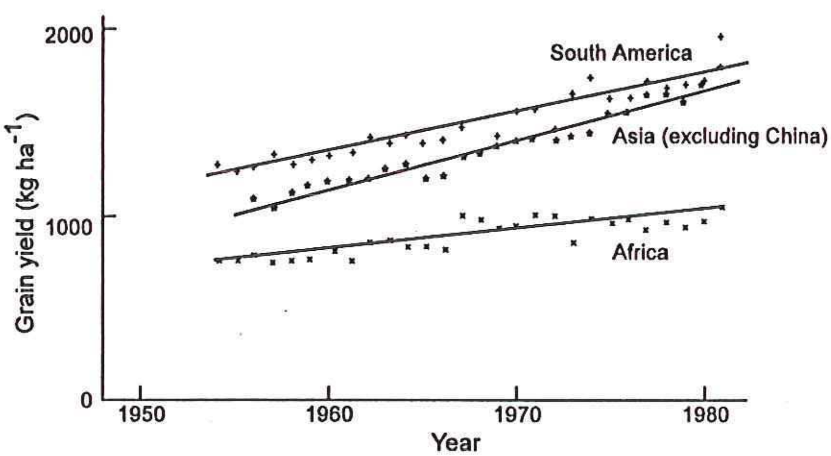


Figure 5.17. Average grain yields from 1954 to 1980 in Africa, Asia, and South America. (Van Keulen and Wolf 1986)