Maximum sustainable population
Most obvious limit — food supply

We have seen that the current world population is ~~5.7~~ 6 billion, growing at 1.6% per year (90 million new per year), doubling every 43 years.

Will grow to 8.4 billion even if growth rate $r_t \to 0$ immediately; more realistically to 10–12 billion.

Leads to question — how many people can the Earth support? This the title of Cohen's book.

He shows a graph of estimates by various people who have considered this question.

Estimates range from 1 billion to 1 trillion. Reason — not a strictly scientific question. Possible to make many different assumptions about what what is necessary — or limiting — etc.

I will discuss a few of these estimates to give you the flavor. "Layvenhoke"

First: Anton von Leeuwunhoek — inventor of microscope
"the 150 billion sperm in a single cod ~~[scribbled out]~~ greatly exceed the maximum

Population density of Holland in 1679 was 100 people / km^2 — now 350 people / km^2 — his method applied today would yield $N_{max} = 39$ billion

number of possible people on the Earth.

To deduce the latter he said

$$N_{max} = N_{Holland} \frac{A_{Holland}}{A_{continents}} = 13.4 \text{ billion}$$

better way to do calculation

$A_{ice-free} = 1.3 \cdot 10^8$ km^2

$(100/\text{km}^2) \times (1.3 \cdot 10^8) = 13$ billion

$350/\text{km}^2 \times (1.3 \cdot 10^8) = 45$ billion

Even today, the Netherlands is very densely populated (~ 350 people / km^2) compared to world-wide average ~ 35 / km^2.

It can support such a high density only because the rest of the world does not — it is second behind Denmark in food imports per person, mostly fed to livestock. All of its metals are imported.

Later, more sophisticated estimates focus on resource availability — most obvious possible limiting single resource is food.

If a single resource is limiting:

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

fundamental equation of ecology — not only for humans

↑ known as Penck's equation (1925)

Let's consider the denominator first — human nutritional requirement

> Units: 1 nutritional calorie
> = 1 kcal
> = 4184 J

Basal metabolic rate (keep T at 98.6 F in a state of no activity) depends on body weight, but average is

more for Shaq than for me

BMR = 1200 kcal/day = 5 MJ/day

UN official definition of malnourished = 1.4 times this
= 1700 kcal/day
= 7 MJ

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

= 60 watts — a *dim* light bulb!

World-wide average food consumption

2700 kcal/day = 2.3 × BMR

150 W light bulb

This permits light work — Univ. professor, for example.

US average : 3600 kcal/day = 3 × BMR
Leads to <u>obesity</u>

< 2000 kcal/day in sub-Sahara Africa
33% of Africa is <u>undernourished</u>

Other comparisons:

2700 kcal/day = 11.3 MJ/day

= 150 watts *a bright light bulb*

<u>Total</u> human food consumption

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

$$= 9 \cdot 10^{11} \text{ W}$$

Heat flow from the ⊕ : $4.2 \cdot 10^{13}$ W

human food consumption = 2% heat flow

~~~2006 Real Mag in sub-Saharan Africa~~
~~33% of Africans are chronically undernourished~~

~~US average ~3800 kcal/day ~ 3 x BMR~~
~~leads to obesity.~~

oceanographer — first called attention to CO_2 increase from fossil fuel burning

Roger Revelle (founder of UCSD — my alma mater — head of Harvard Center for Population Studies — ambassador to India) made a careful & well-known estimate in 1976.

He asked "how many people can ⊕ support if each human eats 2500 kcal/day of grain — rice or wheat" (average in China today)

start filling in Pencks eqn 1 on p.6 with this number 2500 kcal/person/day

Made a careful study of amount of land that could — with work — be made arable

~~Traditional~~ Traditional unit:

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

Total continental area (including ice-covered Antarctica & Greenland)

$$1.6 \cdot 10^{8}\ km^2 = 1.6 \cdot 10^{10}\ ha$$

Ice-free land is $1.3 \cdot 10^{10}$ ha.
~~~

Revelle felt that <u>3.8 · 10^9 ha</u> could be made arable — he allowed for multiple crops on some land, reserved 10% for non-food ... <u>read from his account</u>

This is ~~24%~~ 29% of total ice-free land area

Current cropland is 1.5 · 10^9 ha — Revelle felt that 2.5 times this was potentially arable.

From 1850 to 1980 cropland increased from 0.5 · 10^9 to 1.5 · 10^9 ha — a factor of 3.

Population increased by factor of 5 in same period — 1.2 billion in 1850.

The final factor in Penck's equation — grain production / hectare

Note effect of the so-called Green Revolution:

wheat yield in US $4 \frac{kg}{ha\ yr} \rightarrow 50 \frac{kg}{ha\ yr}$

17 times more rapid growth rate after 1950 — new hybrids, better pest control, improved irrigation, etc.

1996 *Economist* article says it is 3% / year
(2% yield increase + 1% cropland area increase)

Current world-wide rate of growth of cereal production is 2.1% / yr

Higher than population growth rate 1.6% / yr. — 1.5% / yr now

Not all regions must be self-supporting.

Food is extensively traded.

The US currently exports $83 \cdot 10^6$ tons / yr

Enough to feed

$$\frac{(83 \cdot 10^6 \text{ tons})(3.5 \cdot 10^6 \frac{\text{kcal}}{\text{ton}})}{2500 \times 365}$$

= 320 million people (more than US population — 270 million)

Africa & Asia are major importers, and their shortfall is increasing

US growth in cereal production due to improved techniques — total cropland has remained ~ constant — with a shift from the northeast to the west

The number of farms has declined {from a high of 6 million to 2 million

Revelle supposed that world-wide yields could be raised to

> 2.7 ~~[illegible]~~ tons / ha / yr
>
> 1 ton = 1 long ton = 1000 kg = 2200 lbs

Current yields in Africa are less than 1 ton / ha.

US yields ~ 3 tons / ha

* see page 6 1/2

~~The maximum sustainable population according to Penck's equ~~

~~N_{max} (3.8 · 10 ha) (3 ton/ha)~~

Revelle's estimate of agricultural capacity

$$(3.8 \cdot 10^9 \text{ ha}) \times \left(2.7 \frac{\text{ton}}{\text{ha}}\right) \cong 10^{10} \text{ tons of grain / yr}$$

10 Gt / year = 6 times greater than current

Finally, we need to know the caloric content of grain — it's roughly the same for wheat & rice:

350 kcal in a 100 g bowl of breakfast cereal

$$3.5 \text{ kcal / g} = 3.5 \cdot 10^6 \frac{\text{kcal}}{\text{ton}}$$

Take a box of spaghetti as a 'prop' — how is this measured — easy — put in a special oven and measure heat released

Then from Penck's equation:

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

$$N_{max} = 40 \text{ billion people}$$

* Current rate of cereal ~~production~~ consumption is

$$\frac{2700 \frac{\text{kcal}}{\text{person day}} \times 365 \frac{\text{days}}{\text{yr}} \times \cancel{5}^{6}.7 \cdot 10^9 \text{ people}}{3.5 \cdot 10^6 \frac{\text{kcal}}{\text{ton}}}$$

$= 1.6$ Gt cereal / day

Note: this does not account for grain fed to cows etc. in developed countries

Revelle's estimate of our agricultural capacity is <u>7 times this</u>

$$\left(3.8 \cdot 10^9 \text{ ha}\right)\left(2.7 \frac{\text{ton}}{\text{ha}}\right)$$

$$= 10.3 \text{ Gt/yr}$$

The maximum sustainable population is thus

$$\boxed{N_{max} = 7 \times N_{now} = 40 \text{ billion}}$$

Basically Revelle estimated that we <u>could</u> <u>produce</u> 7x more food than we currently <u>consume</u> $\Rightarrow N_{max} = 7 \times N_{now}$

Seven times the current population.

Note, however, the underlying assumption, that every person will obtain his/her full nutritional requirements of 2500 kcal/day by eating a strictly vegetarian diet.

People in the US derive approximately $\frac{2}{3}$ of their 3600 kcal/day from eating meat

To produce 1 kcal of beef requires 8 kcal grain
To produce 1 kcal of chicken requires 3 kcal grain.

Say on average 5 kcal multiplier.

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

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

$$= 13{,}000 \text{ kcal}$$ to support an American (5 times a Chinese)

Then N_{max} = 8 billion people

It all depends on your assumptions.

In fact, cropland has not increased as rapidly as Revelle predicted in 1976

Many demographers feel that Revelle's estimate of potentially arable land is extremely high: 2.5 times current cropland.

[illegible]

An alternative approach to estimating N_{max} tries to account for all resource consumption, not just food — focus on land use.

Has led to the of a person's "ecological footprint" — the amount of land needed for a single person's support.

To gain a rough idea of a North American's ecological footprint, ignore trade and note that NA has

$2 \cdot 10^8$ ha cropland
$4.5 \cdot 10^8$ ha grassland & pasture
$9.4 \cdot 10^8$ ha forest & woodland

plus another $\approx 2 \cdot 10^8$ ha other (residential, industrial, recreational)

[illegible]

$\frac{\text{cropland}}{\text{total land}} \approx 10\%$ — same as on a world wide basis

Note — we need all kinds of land
Cows grow on pastures; we eat cows
Forests serve as watersheds for H_2O we drink as well as providing lumber.

Ecological footprint of a North American

$$\frac{(2 + 4.5 + 9.4) \times 10^8}{300 \cdot 10^6 \text{ people}} = 5 \frac{\text{ha}}{\text{person}}$$

A more careful analysis by William Rees of UBC

USA	5 ha
Canada	4.3 ha
Europe	3.5 ha

1 ha ≈ 2 football fields

To give every person on ⊕ a "European" footprint (I'll take mine in the south of France)

$$\frac{1.3 \cdot 10^{10} \text{ ha}}{3.5 \text{ ha/person}} = 3.7 \cdot 10^9 \text{ people}$$

← ice-free land area

less than current population

Would require 1.5 Earth's

Again – projections of the ⊕'s carrying capacity are highly value – ridden.

It all depends on what your assumptions are.

What – you may ask – about the oceans.

Most projections have ignored them because the consumption of fish at present is very small compared to cereals

Fish catch 0.1 Gt/yr, of which 0.06 Gt/yr is used for human consumption.

Compared to 1.6 Gt of cereal, fish accounts for only 3.6% of human diet by weight.

GROWTH RATE COMPARISON

Worldwide, the rate of growth of food production is about

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

About twice as great as the rate of population growth.

The per capita growth rate is thus

$$3\% - 1.6\% \simeq 1.4\%$$

Malnutrition at the present time is not due to inadequate food production but to political instability and other distribution problems, often exacerbated by political instability

1758 Reverend Thomas Robert Malthus wrote his famous essay on population. Asserted that man's ability to produce food grew linearly, not ~~logarithmically~~ exponentially w.r.t. time — This not true

He basically assumed it would always take the same amount of time for a team of oxen to plow a field.

Finally, let us consider present-day food production in the context of the global carbon cycle.

Recall that green plants "fix" carbon into organic matter by photosynthesis

Highly simplified

$$6\,CO_2 + 6\,H_2O \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6\,O_2$$

- $6\,CO_2$ ← in air
- $6\,H_2O$ ← in rain or irrigation
- $C_6H_{12}O_6$ ← carbohydrate
- $6\,O_2$ ← oxygen we breathe

The rate of carbon fixation by terrestrial plants is

50 – 80 Gt of C / yr

Say 65 Gt C / yr

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

The total amount of C in the atmosphere is

760 Gt C in atmosphere

← mostly in CO_2, trace CH_4 – methane

Increasing by ~~[illegible]~~ 3.2 GtC/yr due to fossil fuel burning

If not replenished, photosynthesis would deplete the atmosphere of CO_2 in

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

In fact, prior to the industrial age CO_2 in atmosphere was very constant

−10,000 ybp to industrial age: 270 ppm
or 0.027 %
(by volume)

Respiratory processes of bacteria & people:

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

We use the solar energy stored in the plants when we eat them.

~~Most terrestrial respiration is performed by bacteria~~

Most terrestrial respiration is carried out by bacteria in the <u>leaf litter</u>

This dead terrestial biosphere contains ~ twice as much C as the living biomass

There is also an oceanic carbon cycle that cycles comparable amounts of C.

NPP = 65 Gt/yr is the so-called net primary productivity of the terrestial biomass

NPP ≃ ½ GPP

↑ the gross primary productivity = total amount of C removed from atmosphere by plants/yr

Is this what the 120 Gt/yr in Fig 23.11 of new text is?

yes

The other ½ is respired by the plant to drive its own metabolism.

Let's ask three questions

(1) What is the total rate at which land plants store solar energy for use by respirers, including humans?

The % of carbohydrate by mass that is C is

$$\frac{12 \cdot 6}{12 \cdot 6 + 1 \cdot 12 + 16 \cdot 6} = 0.4$$

↑ mol. wt. of C ↑ mol. wt. of H ↑ mol. wt. of O

$$\frac{12}{12 + 2 + 16} \leftarrow C$$
$C + H_2 + O$

NPP =

$$85 \cdot 10^9 \frac{\text{tons C}}{\text{yr}} \times \frac{1}{0.4} \frac{\text{tons plant}}{\text{tons C}} \times 3.5 \cdot 10^6 \frac{\text{kcal}}{\text{ton plant}}$$

$$= 5.7 \cdot 10^{17} \text{ kcal/yr}$$

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

Twice the geothermal heat flow (including the hydrothermal circulation near ridges) = $4 \cdot 10^{13}$ W. ⇒ biomass burning a viable energy source

(2) What % of all plant growth per year (i.e. what % of NPP) is consumed by humans ?

Two ways to find out:

Humans consume:

$$2700 \frac{\text{kcal}}{\text{person}} \times 6 \cdot 10^9 \text{ people} \times 365$$

$$= 6 \cdot 10^{15} \frac{\text{kcal}}{\text{year}}$$

$$= 2.5 \cdot 10^{19}\ \text{J/yr}$$

$$= 8 \cdot 10^{11}\ \text{W}$$

$$= 1\% \text{ of NPP}$$

This ignores C fed to cows & chickens, which humans then eat. Basically, assumes that everyone is a vegetarian, which is not a bad first approximation.

Or: humans consume

1.6 Gt cereal / yr

$$= (1.6)(0.4) = 0.64 \text{ Gt of C/yr}$$

$$= 1\% \text{ of NPP}$$

Humans consume 1% of all plant growth per year.

$$\Omega/4 = 340 \text{ W/m}^2 = 256 \text{ kcal/cm}^2\text{/yr}$$

(3) What fraction of the sunlight falling on the non-ice covered land area is converted into [illegible] caloric energy stored in biomass by photosynthesis?

The average solar energy flux at the ⊕'s surface is (not allowing for cloud cover)

256 kcal/cm²/yr [illegible]

Only 50% gets to the ⊕'s surface (rest is scattered or absorbed in atmosphere)

[illegible]

[illegible]

[illegible]

or $1.3 \cdot 10^{10}$ kcal/ha/yr

Multiply by ice-free land area $1.3 \cdot 10^{10}$ ha

$1.7 \cdot 10^{20}$ kcal/yr ← total solar energy flux to ice-free land

NPP
↳ $\dfrac{5.7 \cdot 10^{17} \text{ kcal/yr}}{1.7 \cdot 10^{20} \text{ kcal/yr}}$ [illegible]

see table for various crops

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

~~(not all light falls on plants; some that does is reflected~~

Not all light that reaches the ⊕'s surface is intercepted by plant leaves, where photosynthesis occurs.

Some that does is reflected.

Finally, the process itself is not that efficient — theoretical limit is 10%!

Above number is product of all three effects.

Crops are not much more efficient than the biosphere as a whole.

Only 50% reaches the ground
other 50% is reflected by or absorbed by clouds & dust in the atmosphere.

Red pen changes on page 13 account for this effect

But the crop data lists the efficiency for producing food energy — does not count the non edible plant material (corn husks, roots, etc.) ⇒ The GREEN revolution has succeeded in making food production as efficient as terrestial plant production as a whole.

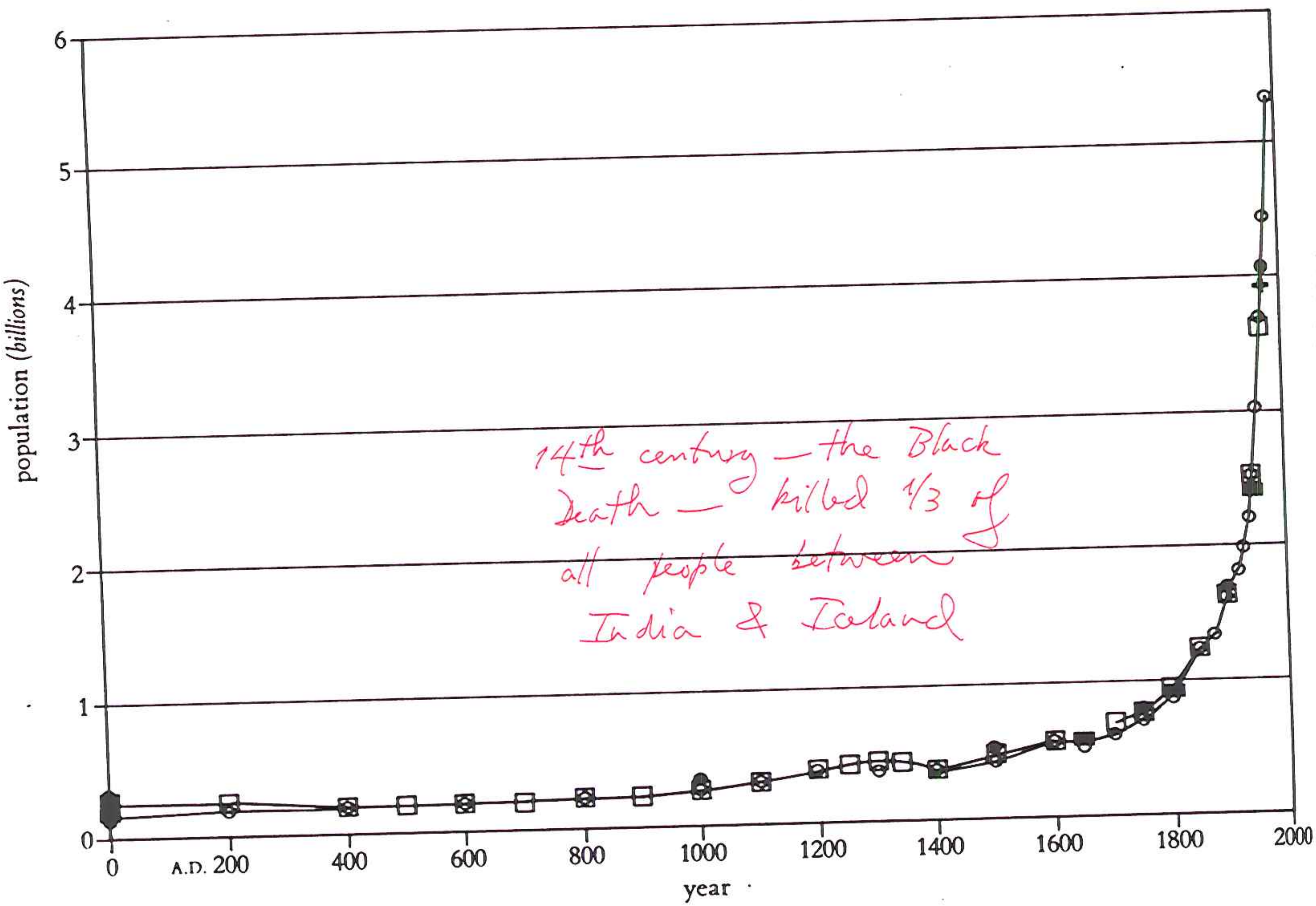


FIGURE 5.3 Estimated human population from A.D. 1 to the present. Different symbols represent estimates from different sources. SOURCE OF DATA: Appendix 2

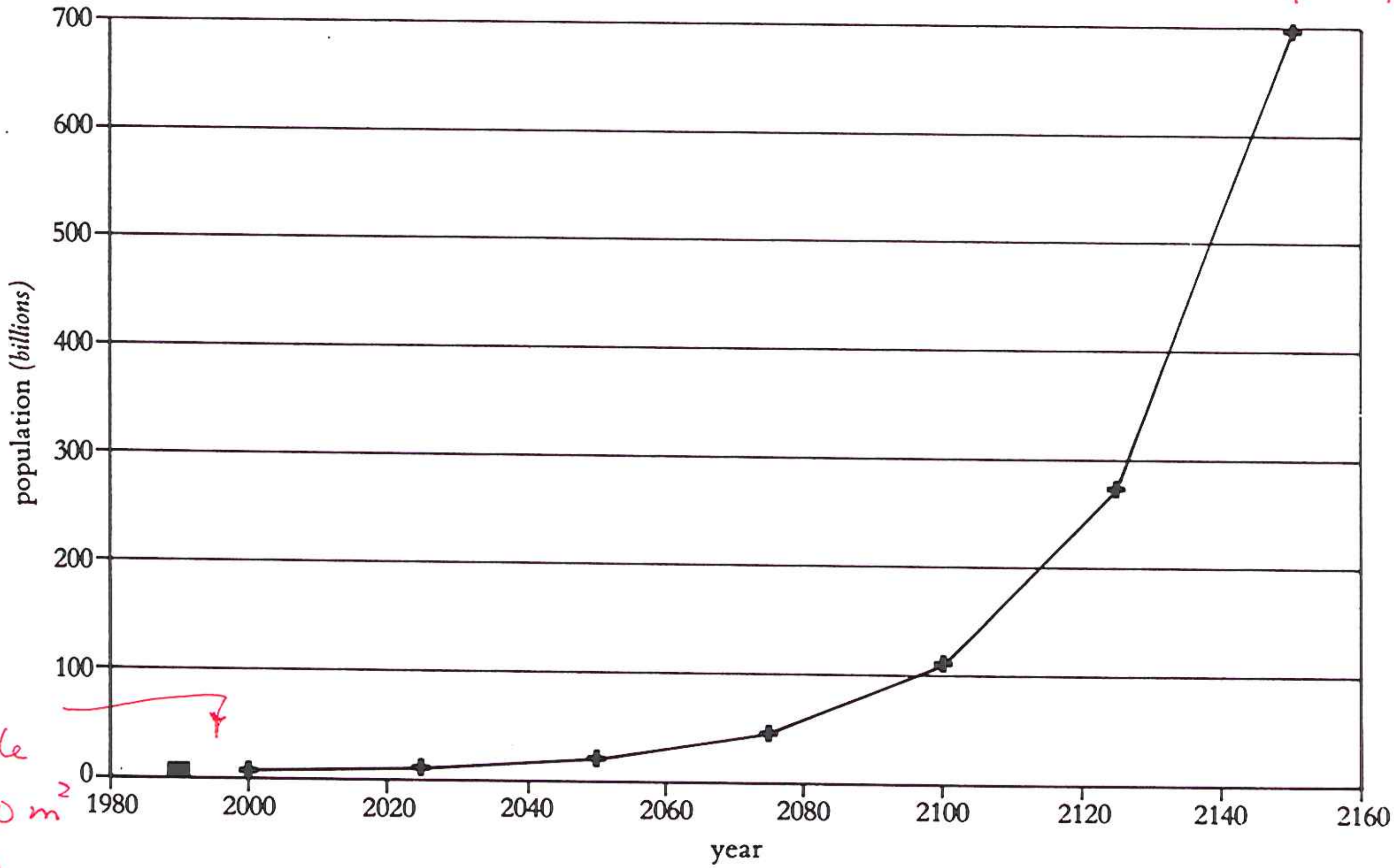


FIGURE 8.1 United Nations' projection of world population, assuming fertility remains constant at its 1990 levels in different regions. SOURCE: original figure drawn according to data of United Nations (1992a)

now: 5.7 billion people ⇒ 150 x 150 m^2 per person ice-free land area (2 football fields)

700 billion people ⇒ 13m x 13 m^2 per person (2-car garage)

medium — stabilize at replacement 2.06
low — "stabilize" at 1.7
high — "stabilize" at 2.5
in next century

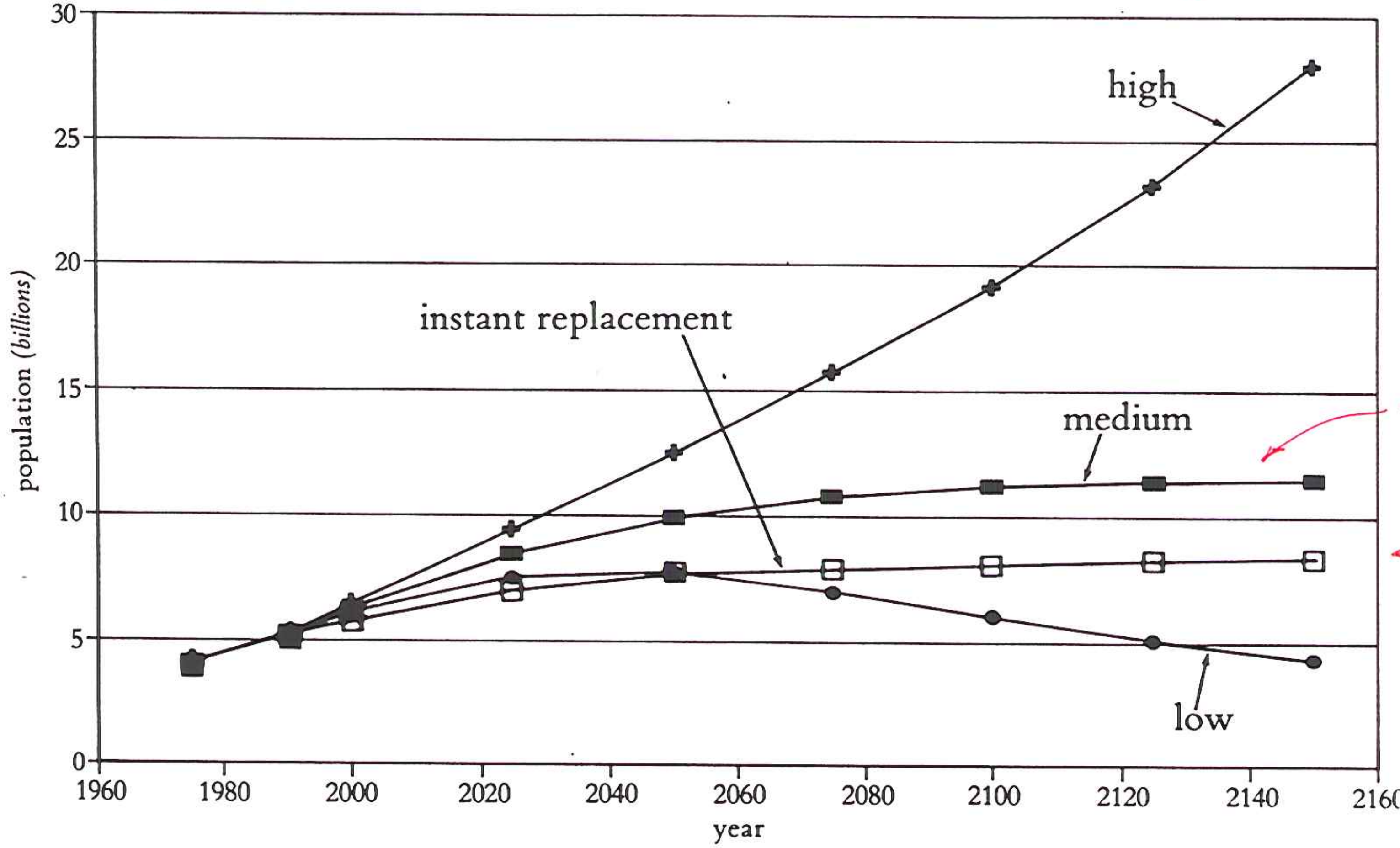
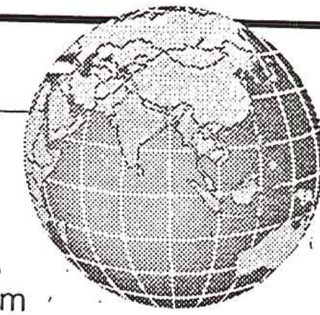


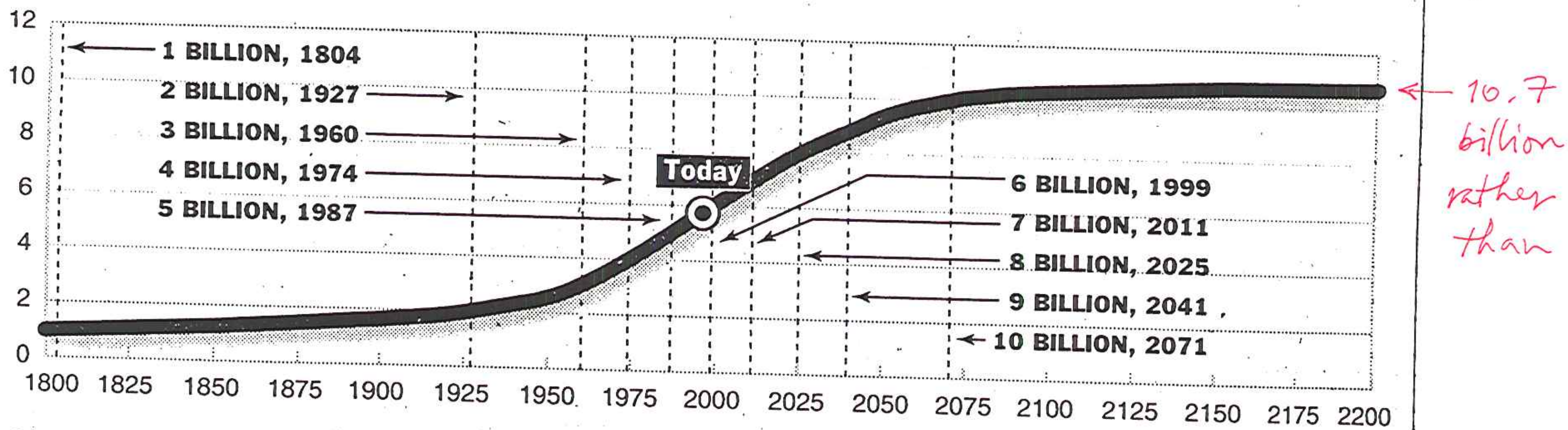
FIGURE 8.2 United Nations' projections of world population, according to high, medium, low and instant-replacement scenarios. SOURCE: original figure drawn according to data of United Nations (1992a)

STATUS REPORT

The Population Explosion Slows Down



A new United Nations study has found that the world's population is growing more slowly than was expected. This suggests that the world's population, now 5.77 billion, will stabilize just after the year 2200 at 10.73 billion. Shown is the world population from 1800 to stabilization based on United Nations projections, in billions.



Source: United Nations

The New York Times

New York Times Nov 17, 1995
update of medium projection
based on latest fertility data
$r_t = 1.5\%$ rather than 1.6%

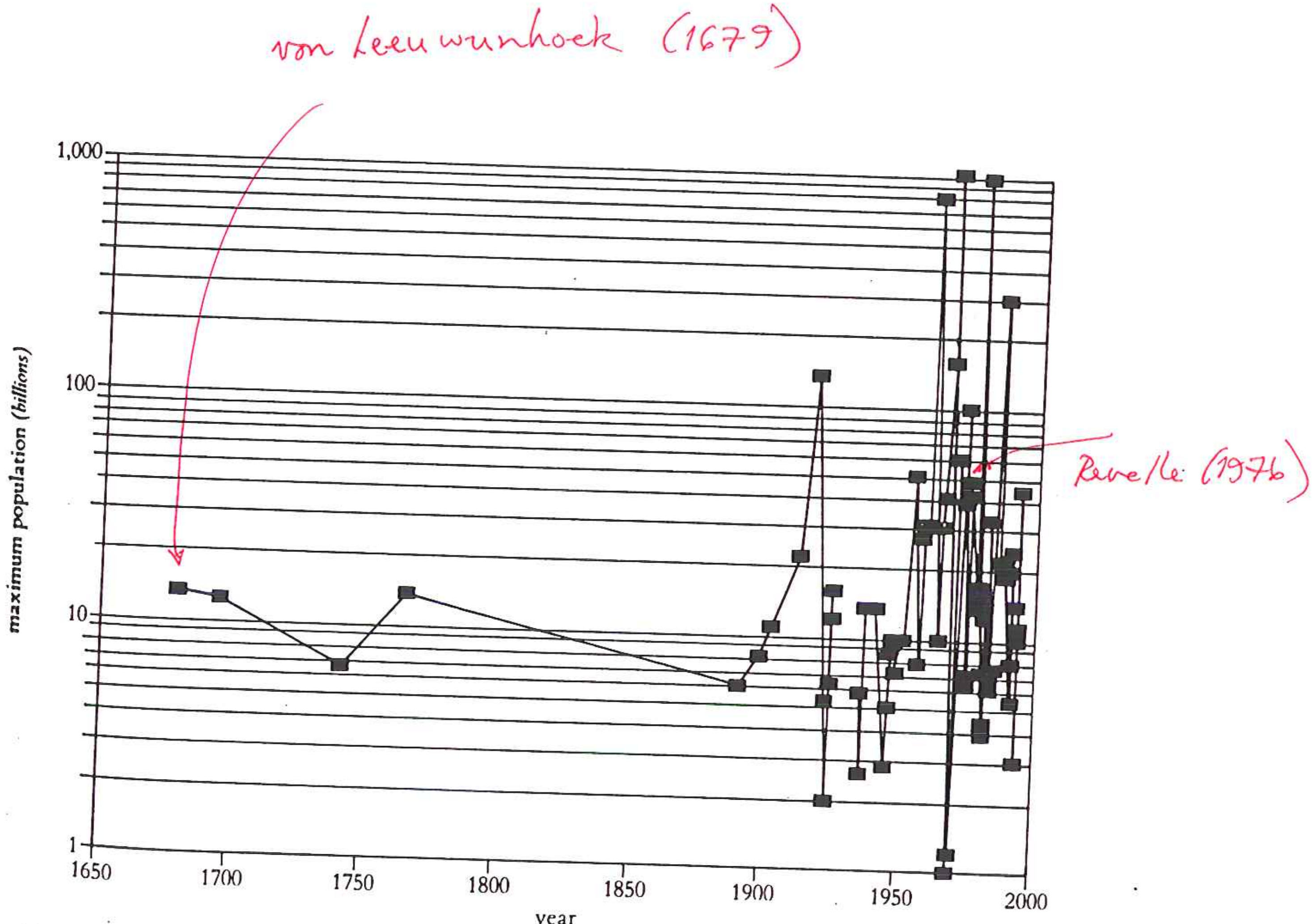


FIGURE 11.1 Estimates of how many people the Earth can support, by the date at which the estimate was made. When an author gave a range of estimates or indicated only an upper bound, the highest number stated is plotted here. The 1964 estimate by J. H. Fremlin would be off the scale and is omitted. SOURCE: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

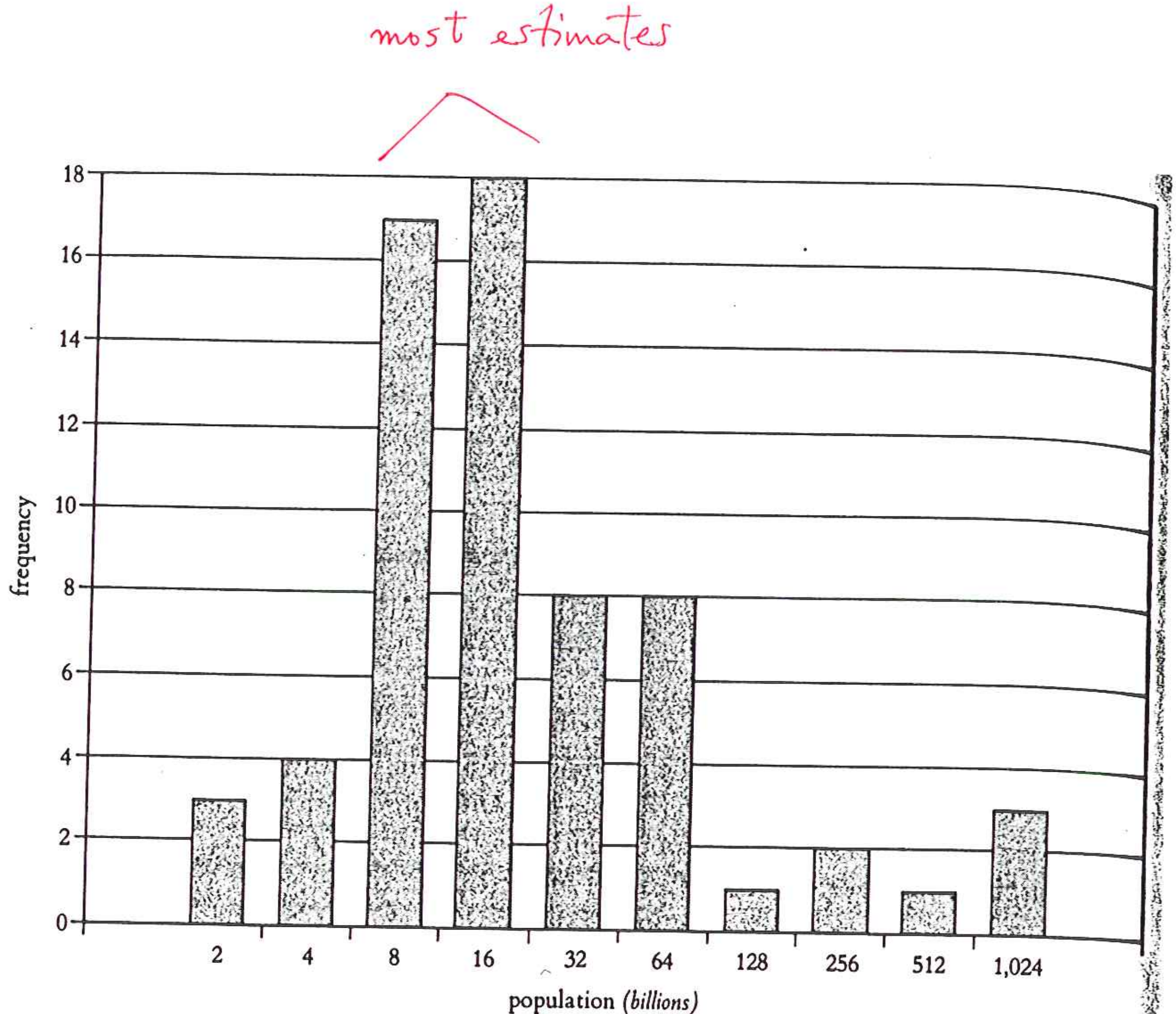


FIGURE 11.2 Frequency distribution of estimates of how many people the Earth can support, based on the highest estimate given by an author. The height of the bar for 4 billion shows the number of estimates greater than the next lower population size shown, that is, 2 billion, and not exceeding 4 billion. 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

In a letter from Delft, Holland, to the Royal Society in London, Leeuwenhoek aimed to show that the 150 billion "little animals in the milt of a cod" greatly exceeded the maximum possible number of people on the Earth. Leeuwenhoek estimated that the Earth's surface contained 9,276,218 square miles. (In seventeenth-century Holland, the linear mile was one-fifteenth of a degree of the Earth's circumference, or approximately 7.4 kilometers.) He supposed that one-third of the surface was land, and that two-thirds of the land, or 2,061,382 square miles, was inhabited. He also assumed that Holland and West-Friesland (roughly today's provinces of North- and South-Holland, plus a small portion of North-Brabant) were a rectangle 22 miles long and 7 miles wide. The area of 154 square miles contained an estimated million people, about 120 people per square kilometer. (Holland had no official census in the seventeenth century, but a capitation was levied in 1622.) ". . . if we assume that the inhabited part of the earth is as densely populated as Holland, though it cannot well be so inhabited, the inhabited earth being 13,385 times larger than Holland yields . . . 13,385,000,000 human beings on the earth."

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 5.6. Prevalence of Chronic Undernutrition in Developing Regions

Region	1969–71		1979–81		1988–90	
	Millions of Under-nourished	*Percent of Total Population*	*Millions of Under-nourished*	*Percent of Total Population*	*Millions of Under-nourished*	*Percent of Total Population*
Africa	101	35	128	33	168	33
Asia	751	40	645	28	528	19
Latin America	54	19	47	13	59	13
Middle East	35	22	24	12	31	12
Total developing regions	941	36	844	26	786	20

Source: *World Resources*, 1994–95.

1/3 of Africans are under-nourished < 1700 kcal per day (< 1/2 x ave

"The 3.2 billion arable hectares cover 24 percent of the land area of the earth, about 2.3 times the currently cultivated area and more than three times the area actually harvested in any given year. Of this total .3 billion hectares require irrigation for even one crop. . . . As a result of the uneven distribution of runoff only a third of the land that is potentially arable with irrigation can actually be irrigated (reducing the total potentially arable land to three billion hectares), and the potential increase of the gross cropped area (that is, the sum of potentially arable areas multiplied by the number of four-month-growing-season crops that could be raised in each area) through irrigation development is limited to 1.1 billion hectares. Without irrigation three crops could be grown on .5 billion hectares in the humid Tropics and two crops on .8 billion hectares in subhumid regions. One crop could be grown without irrigation on 1.5 billion hectares. Hence the potential gross cropped area without irrigation is 4.6 billion hectares and with irrigation is 5.7 billion. Of this total, however, 1.5 billion hectares lies in the humid Tropics—where, except for the island of Java and a few other areas with deep, recently weathered soils, no technology is currently available for high-yielding agriculture on a large scale. The potential gross cropped area accessible to relatively high-yielding cultivation with present technology is therefore somewhat more than 4.2 billion hectares. About 10 percent of the gross cropped area would continue to be needed to grow fibers, beverages and other nonfood crops, leaving a total of 3.8 billion gross cropped hectares outside the humid Tropics for human food production in the future. Making the conservative assumption that lower-quality soils and uneven topography would limit the average yields to half those obtained in the U.S. Midwest, 11.4 billion tons of food grains or their equivalent in food energy could be grown on this potential gross cropped area, enough for a minimum diet of 2,500 kilocalories per day for nearly 40 billion people (if pest losses and nonfood uses could be kept to 10 percent of the harvest)."

from Revelle 1976

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

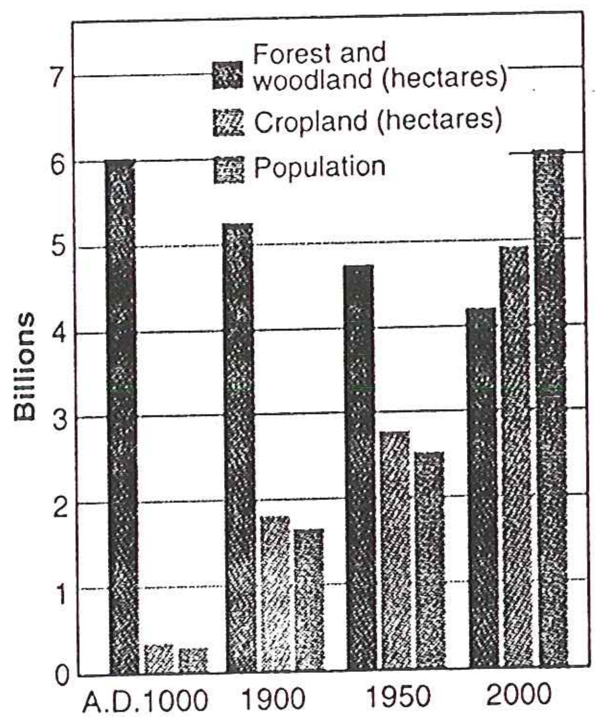
Region	*Land Type*	*Area (million hectares)* 1850	1900	1950	1980	*Percent Change 1850–1980*
Ten regions, total	Forests and woodlands	5,919	5,749	5,345	5,007	–15
	Grasslands and pasture	6,350	6,284	6,293	6,299	–1
	Cropland	538	773	1,169	1,501	179
Tropical Africa	Forests and woodlands	1,336	1,306	1,188	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.

Africa – cropland increasing by 2%/yr

Forest Alarm

Half the world's original forest cover is gone. And the rest is dwindling rapidly, according to a new study, "Forest Futures," by Population Action International. PAI estimates that 1.7 billion people live in countries with "critically low" levels of forest cover and predicts that number could rise to 4.6 billion by 2025.



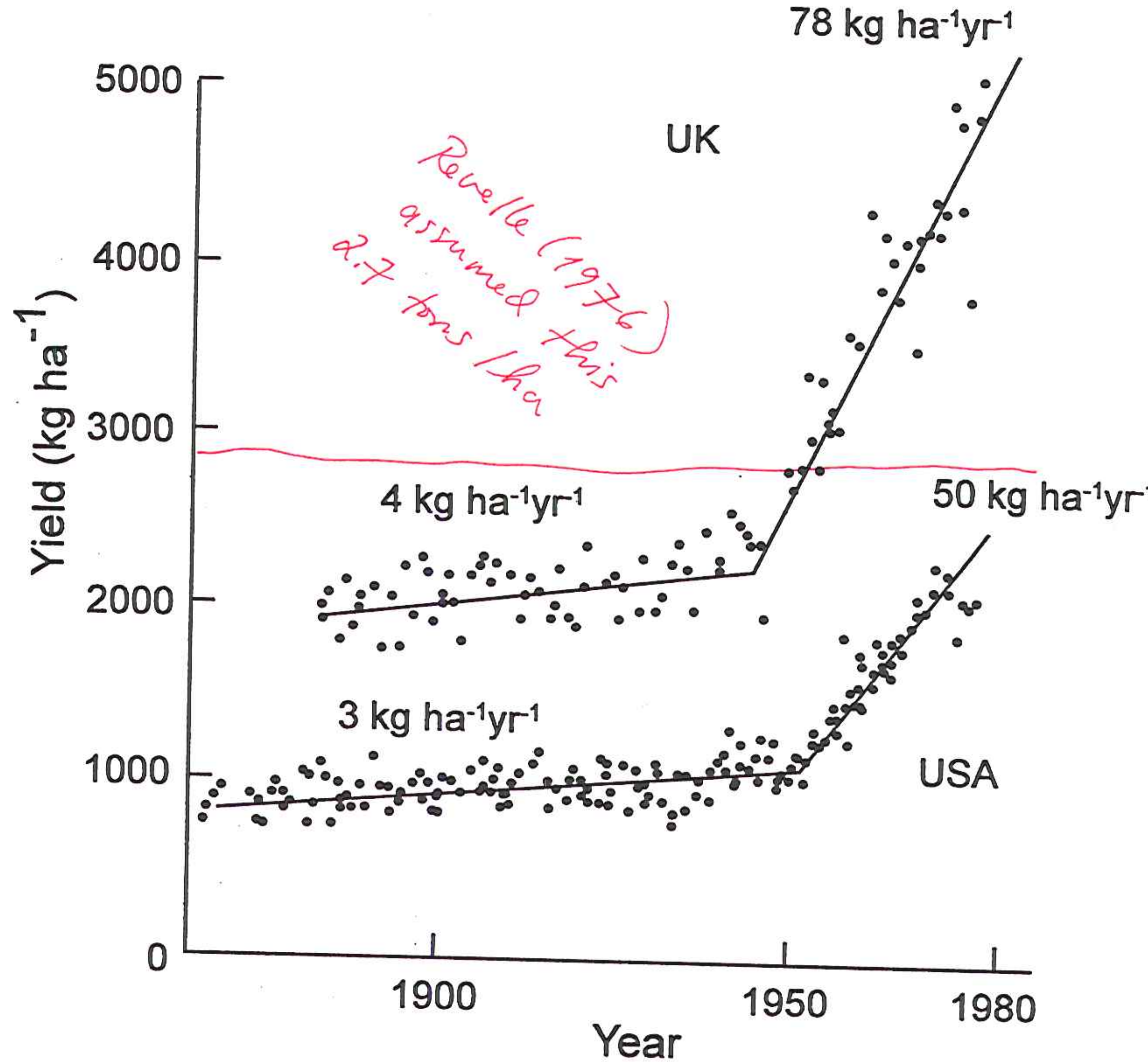


Figure 5.16. Average wheat yields in the United Kingdom during the course of the past century. (Van Keulen and Wolf 1986)

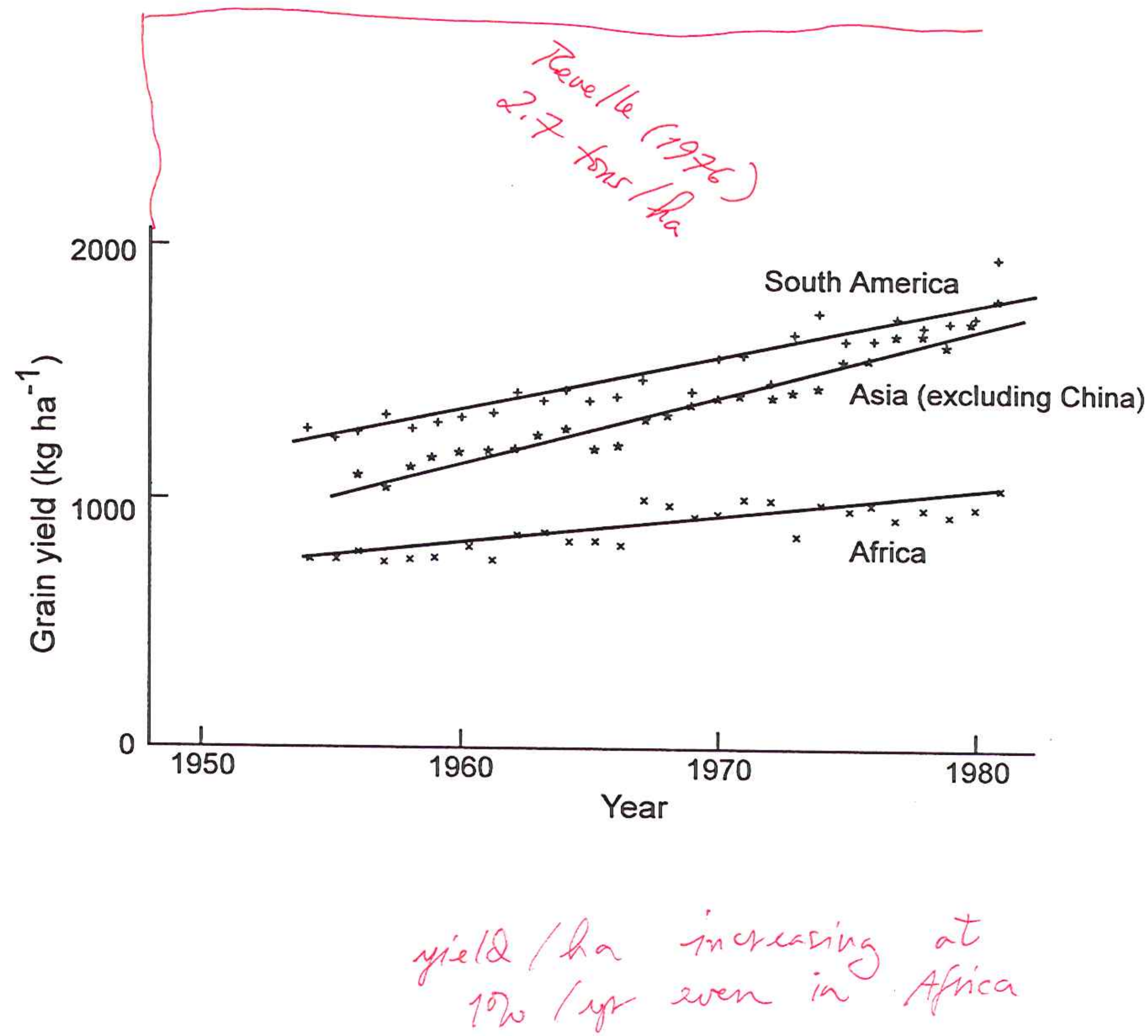


Figure 5.17. Average grain yields from 1954 to 1980 in Africa, Asia, and South America. (Van Keulen and Wolf 1986)

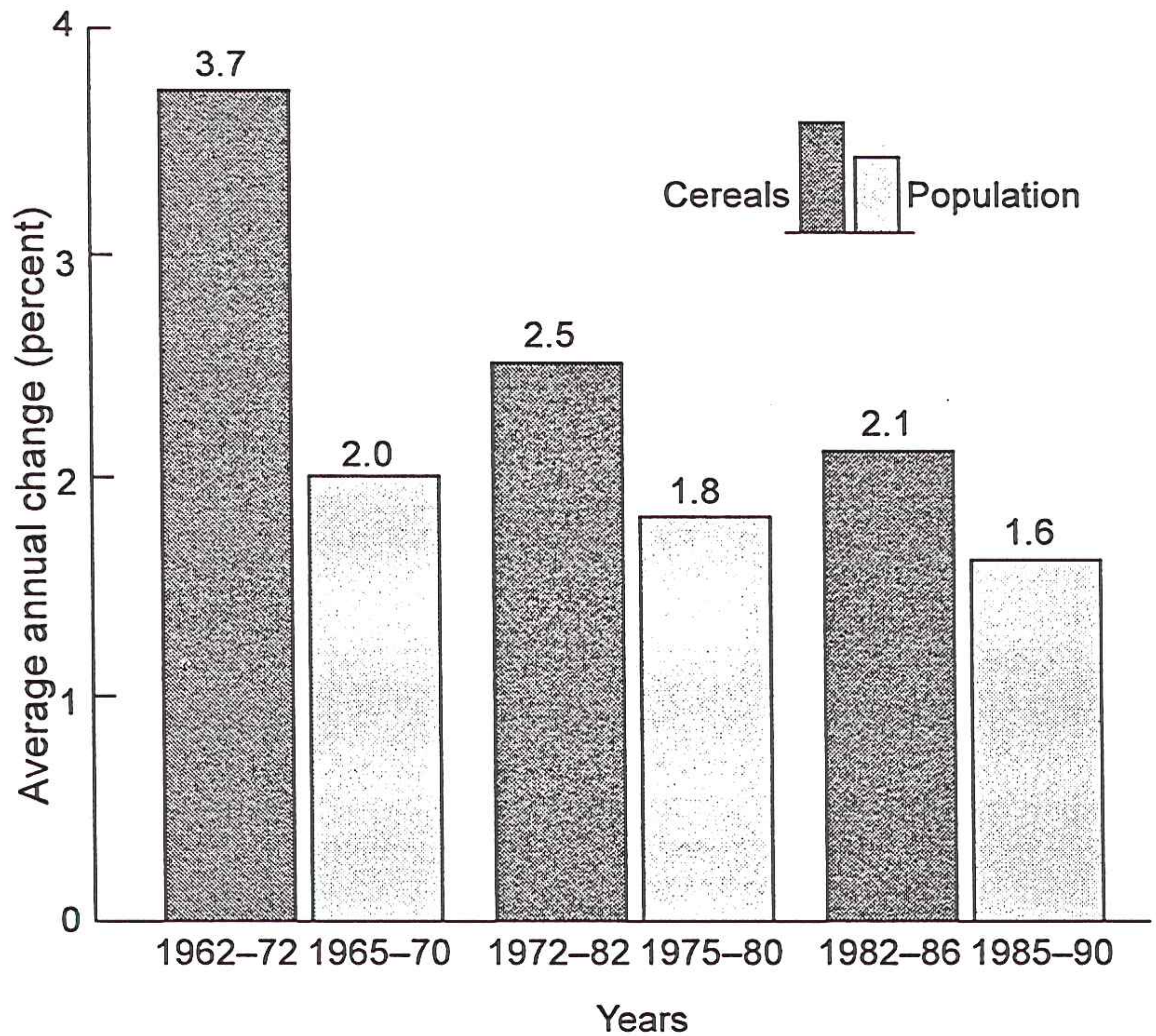
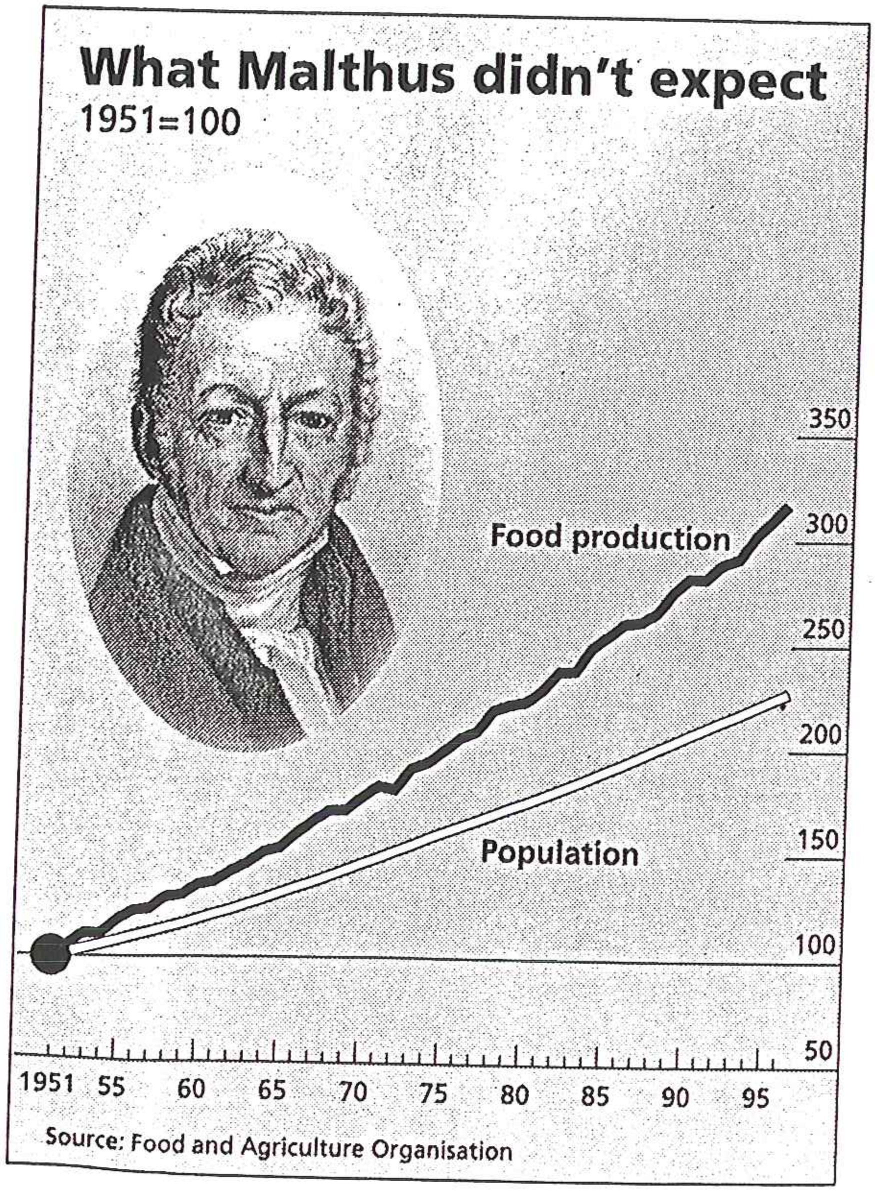


Figure 5.19. World food production is growing faster than world population. The figure shows the annual increase in total production of cereals (darker) and in the world's population (lighter). (Crosson and Rosenberg 1989)



Current rate of population growth
1.5%

Current rate of food-supply growth

3% = 2% + 1%

2% ↑ rate of growth of crop yield / hectare

1% ↑ rate of growth of cropland

TABLE 2.1 Actual and Projected Changes in World Population, Food, Energy, and Economy

	Actual 1950-1993	Reference Scenario 1995-2050
Population	2.2 ×	1.6 ×
Food (Grain)	2.7 ×	1.8 ×
Energy	4.4 ×	2.4 ×
Economy (GDP)	5.1 ×	4.3 ×

Sources: For actual, Brown et al. (1994), courtesy of Worldwatch Institute. For scenarios, Raskin et al. (1998) (see Chapter 3 of this report).

Africa — rate of increase of population exceeds rate of increase of food supply

Everyplace else — per capita food production is increasing

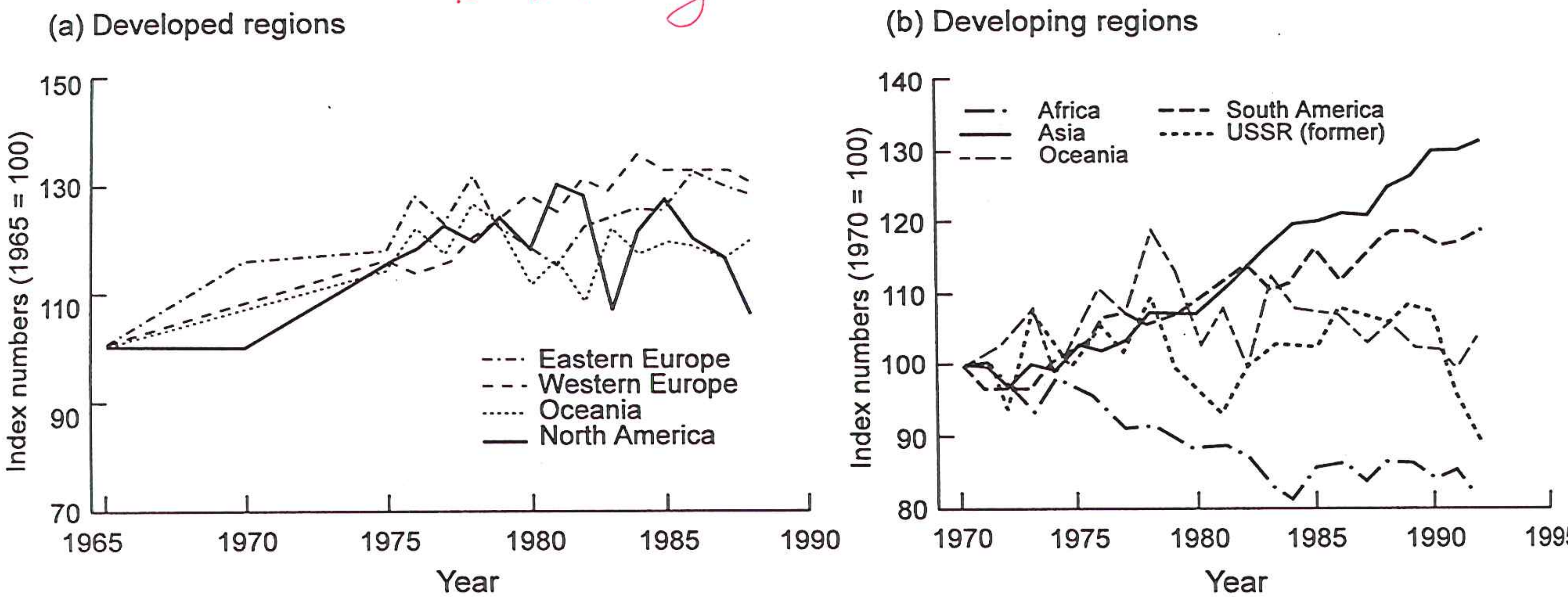


Figure 5.18. Index of per capita food production in the developed and developing regions. (*World Resources 1990–91*, 1990; and *World Resources 1994–95*, 1994)

Lester Brown — Worldwatch Institute — a modern Malthusian

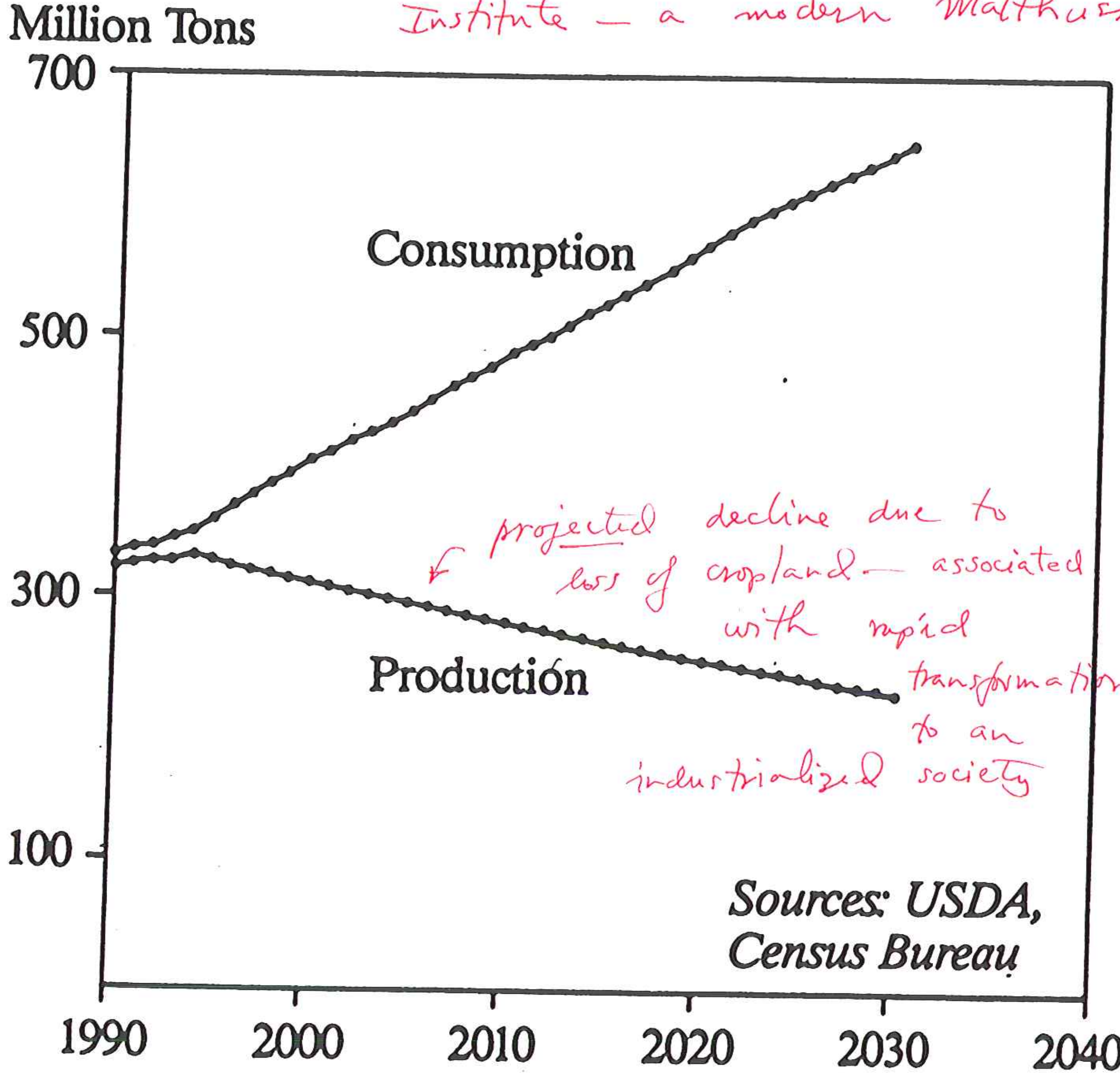


Figure 1-8. Projected Grain Production and Consumption in China, 1990–2030

From State of the World 1995
Worldwatch Institute

US consumers get 2/3 of their protein from eating meat but only 1/3 of their calories

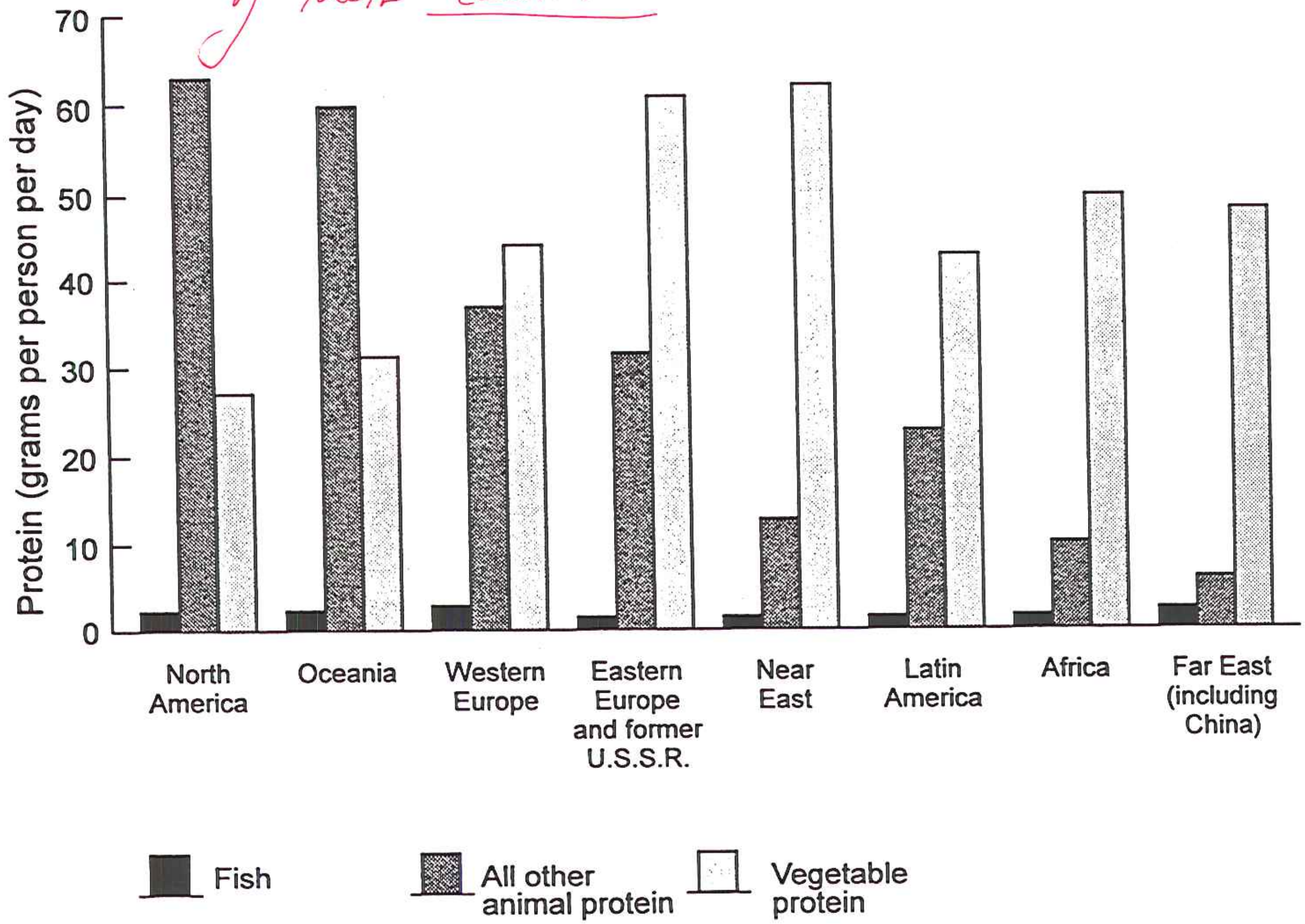


Figure 5.24. The relatively minor role played by fish in the world's total consumption of protein is apparent when the grams of fish eaten per person per day in various parts of the world (left column in each group) are compared with the consumption of other animal protein (middle column) and vegetable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

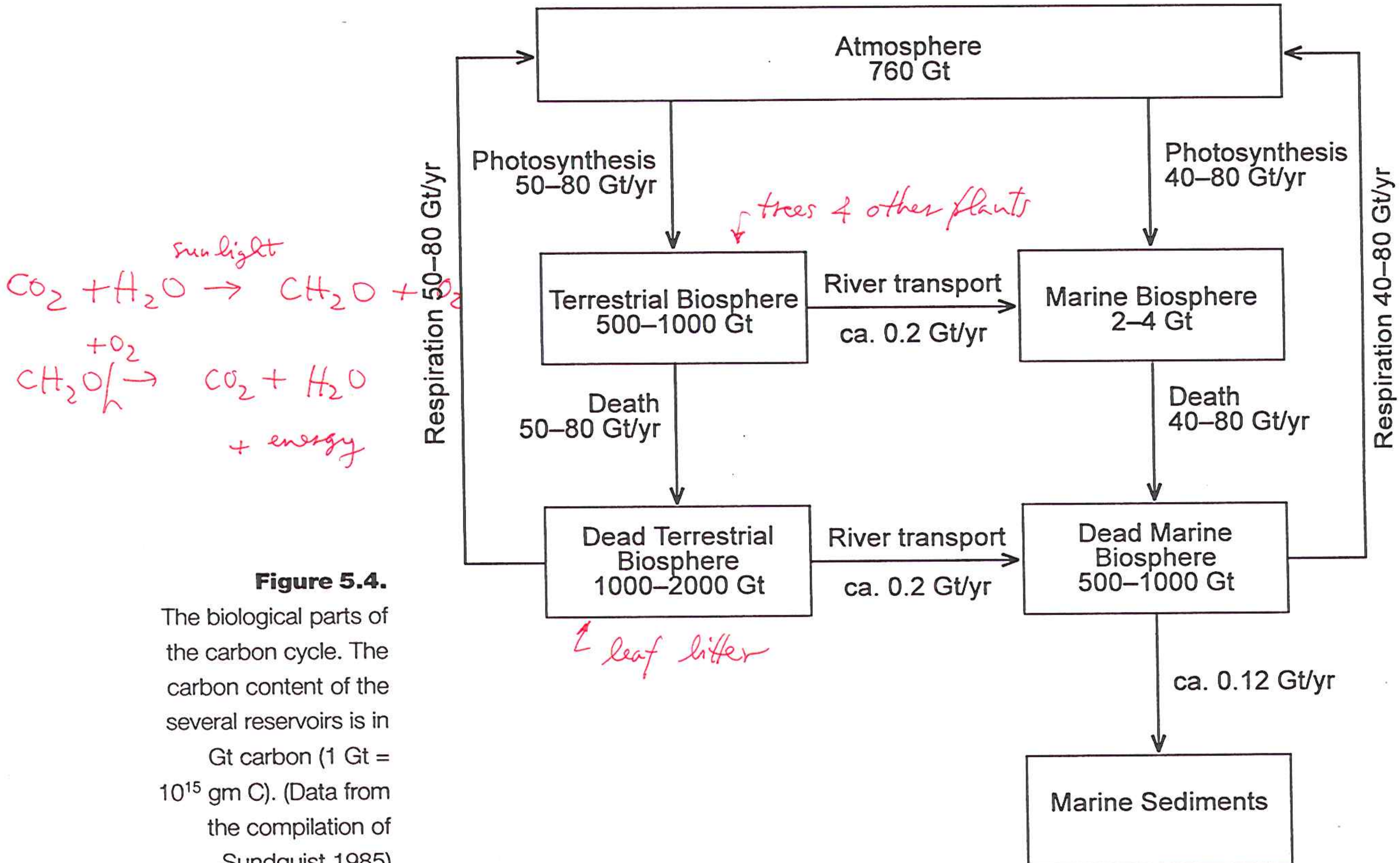
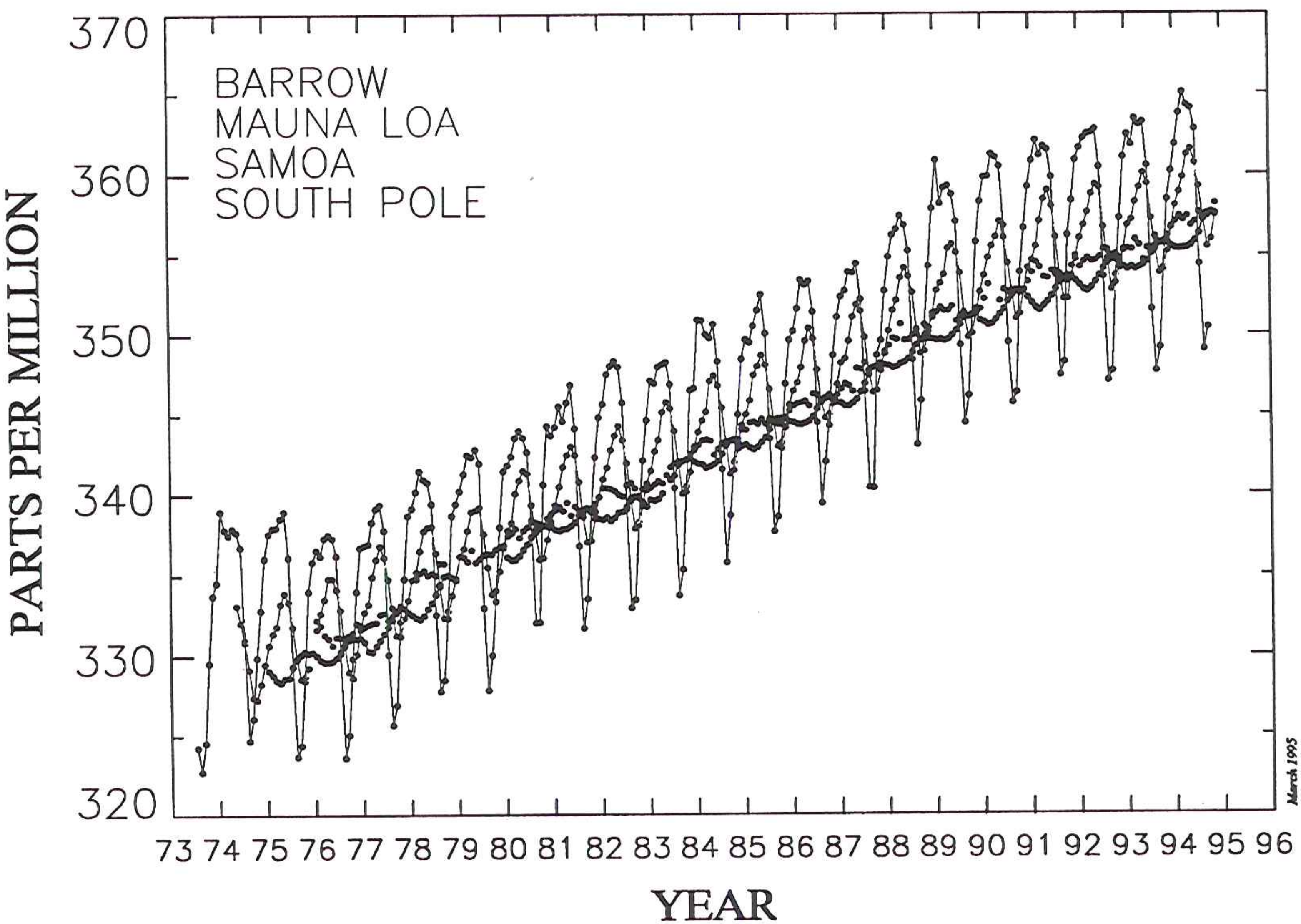


Figure 5.4. The biological parts of the carbon cycle. The carbon content of the several reservoirs is in Gt carbon (1 Gt = 10^{15} gm C). (Data from the compilation of Sundquist 1985)

NOAA/CMDL Monthly Mean Carbon Dioxide



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 5.2. 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 5.1. 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 5.9
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.

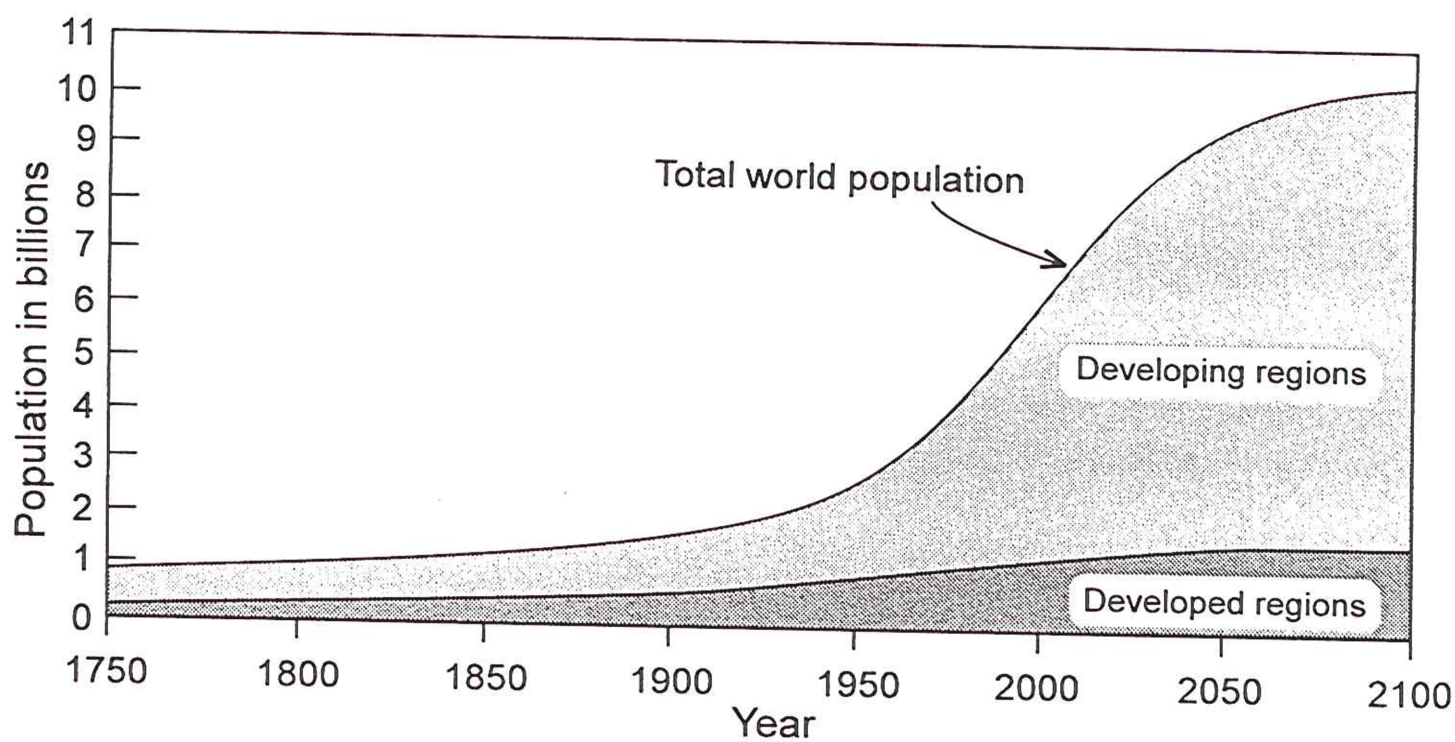
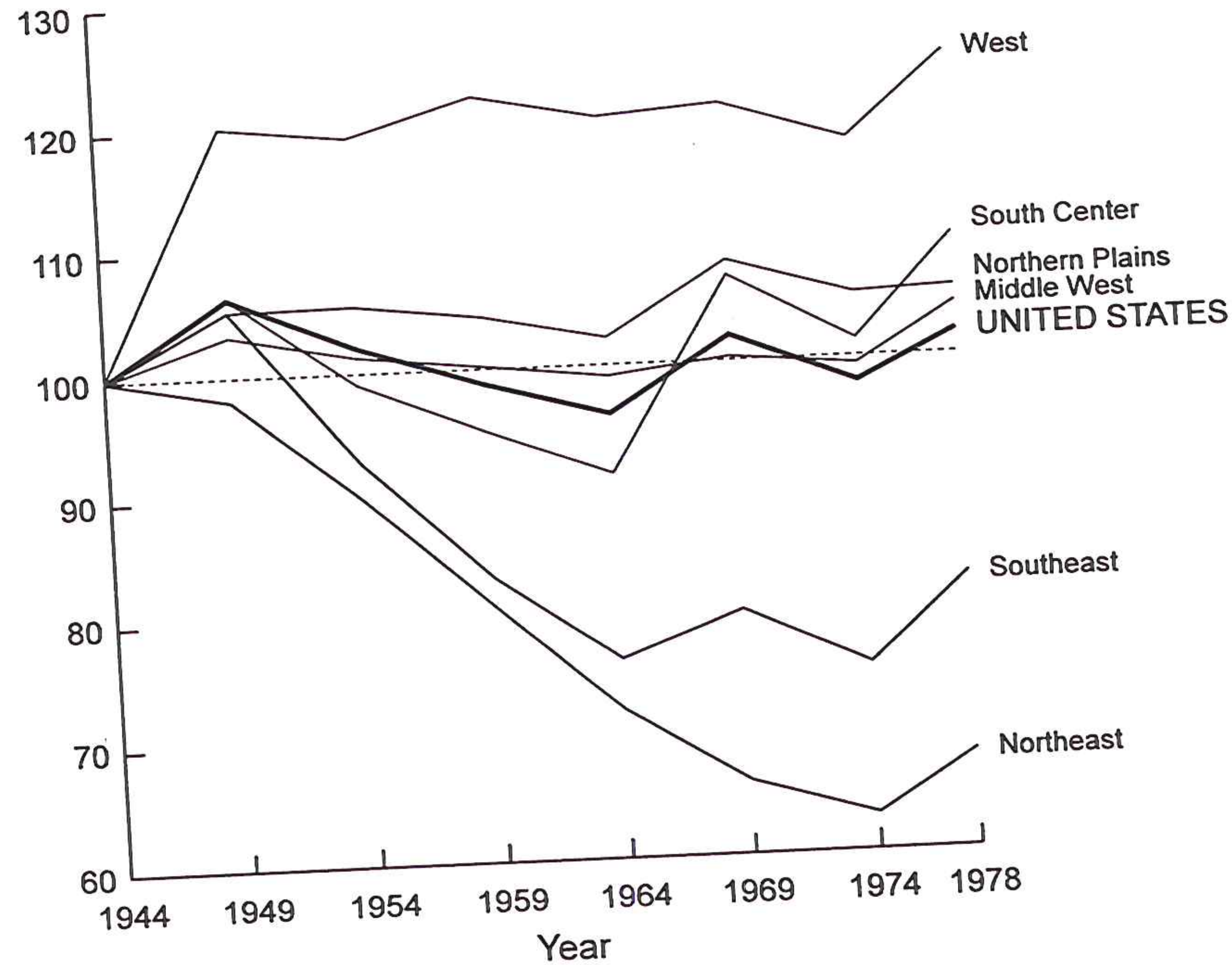


Figure 5.9. Population growth from 1750 to 1980 projected to 2100 in the world, in developing, and in developed regions. (Repetto 1987)

extra from here on

Figure 5.21a. Changes in total cropland area in the major regions of the United States between 1944 and 1978 (1944 = 100). (Hart 1984)



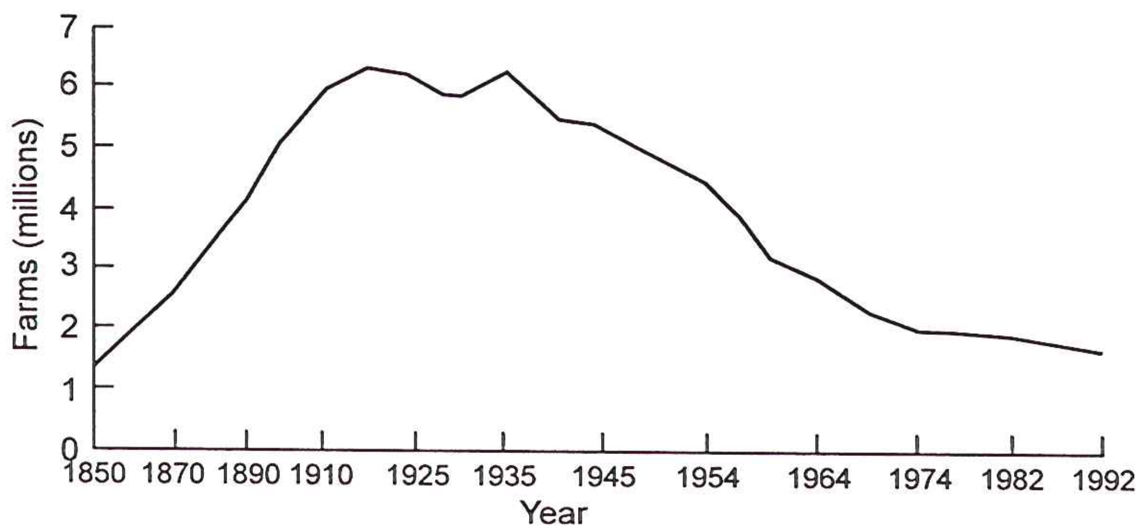


Figure 5.21b. The number of farms (in millions) in the United States from 1850 to 1992. (*New York Times*, November 10, 1994)

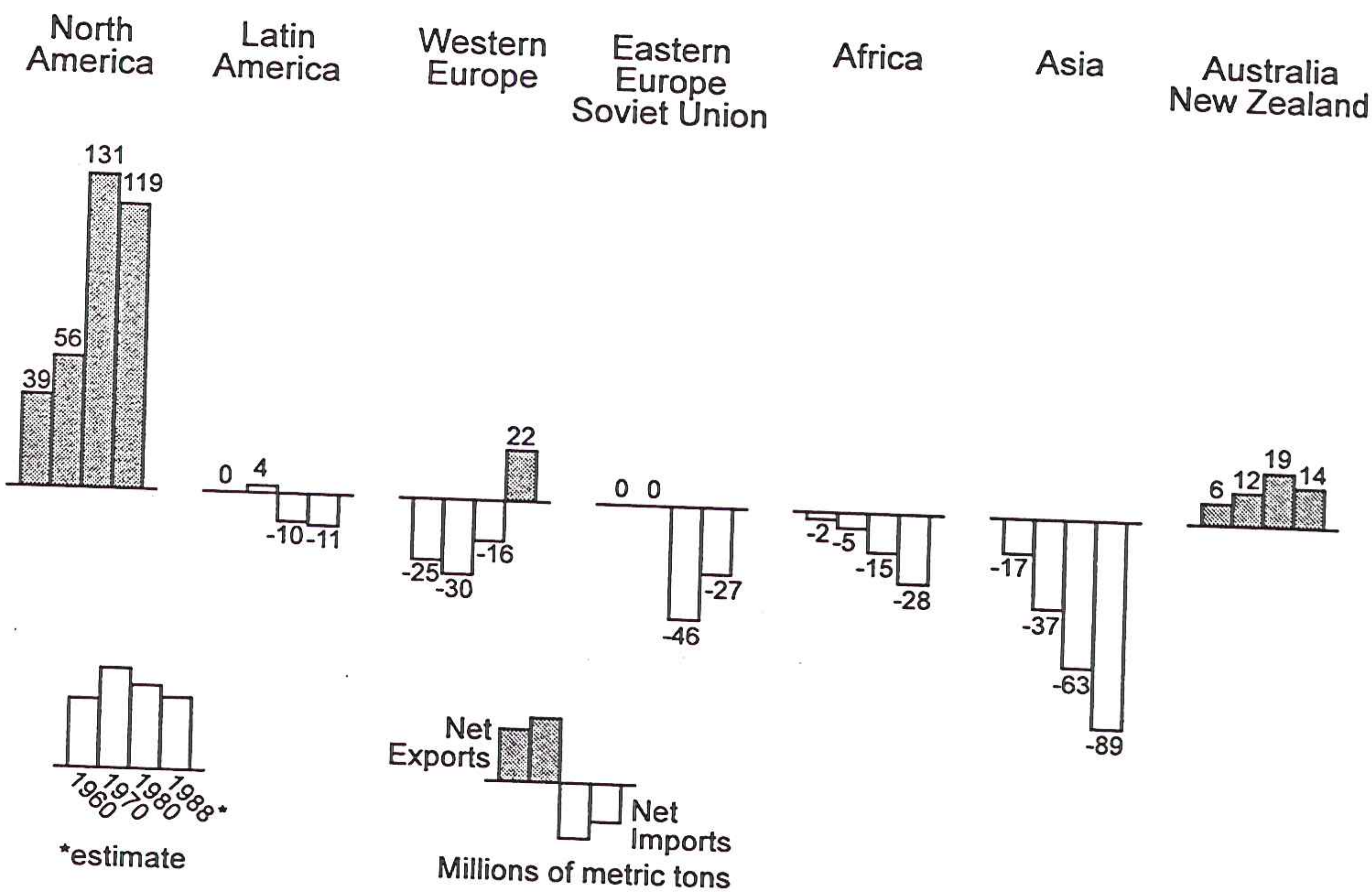


Figure 5.20. The grain trade: who's exporting, who's importing. (*New York Times*, December 11, 1988)

Table 5.8. Major Net Cereal Importers and Exporters, 1987

Importers		*Exporters*	
Country	*Million Metric Tons*	*Country*	*Million Metric Tons*
USSR (former)	29	United States	83
Japan	27	Canada	28
China	16	France	26
Egypt	9	Australia	18
Korea	9	Argentina	9
Saudi Arabia	8	Thailand	6
Iran	6	United Kingdom	4
Italy	5	South Africa	2
Mexico	5	Denmark	1
Iraq	4	New Zealand	0.2

Source: *World Resources*, 1990–91.

Duffy upon hearing of the experiment. Indeed, Duffy has good reason for saying that—he and Wurtz have an unpublished study with results similar to Bradley's.

To prove that these heading-sensitive neurons in the MST really are helping the brain compute heading, researchers in the field would like to see evidence that artificially changing the neurons' responses changes a monkey's perception of heading. They may soon get their wish. In recent unpublished experiments, UC Davis neurophysiologist Ken Britten put monkeys through tasks in which the animals had to discriminate between two simulated headings that were similar enough to make the animals very uncertain about the answer. Under those conditions, Britten's group found they could bias the monkeys' answers toward a particular heading choice by stimulating the MST neurons known to prefer that heading. That is "pretty good evidence," says Warren, that MST neurons "play a functional role in that type of judgment."

How these neurons get their information about eye movements is still unclear, however. It might come in the form of a copy of the neural signal that tells the eyes to move, or alternately the signal could arise from neural sensors activated by the muscle contractions that actually move the eyes. And then there is the question of whether the MST neurons can compensate for the head movements that normally accompany eye movements, a question that the teams of Andersen and Banks plan to address next.

But while not all the questions have been answered, the experiment has shown unequivocally, Andersen says, that the heading neurons "definitely use an eye movement signal to perform the computation." And that, says Warren, is a very satisfying result: "We have evidence [from the human experiments] that extraretinal information helps solve the problem, and they have now come up with a potential physiological basis for that." And therein may lie the answer to how you can enjoy the scenery without driving off the road.

–**Marcia Barinaga**

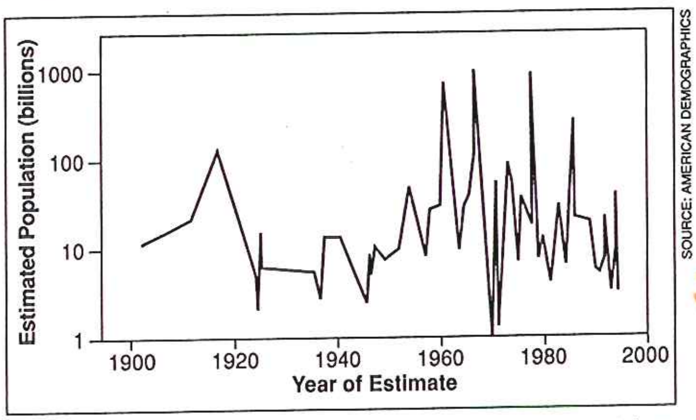
POPULATION

Ecologists Look at the Big Picture

How many people can the Earth support? The answer depends in part on how much land, water, and energy are available, so ecologists have often sought a solution using the same tools they apply to natural systems: looking at current patterns of food production and resource use, then extrapolating. But estimates have ranged from 1.5 billion to as many as 1 trillion people, depending on standard of living, new technologies, and so on.

At a crowded session on human population at the recent ecology meetings,* several speakers noted that resolution may come from a broader approach that includes social and economic dimensions. The bottom line, they say, is that human beings can choose to consume less and so boost Earth's carrying capacity. Such analyses are expected to yield a more realistic outlook and a bleak view of the choices ahead, suggesting, for example, that long-term prospects for maintaining the American lifestyle—or extending it to the nearly 6 billion people now on Earth—are grim.

This may seem all too obvious to some, but it is a novel idea when applied to this question, for most models of carrying capacity have assumed level or increased consumption, notes Cornell University agricultural scientist David Pimentel. The new analyses, he says, "are the first to consider reduced consumption as a realistic option for the future." And while previous models chiefly dealt with a defined set of ecological resources, the new studies wrestle with a dizzying array of variables, from modes of transport to amount of waste generated. "The natural sciences are valuable," says population biologist Joel Cohen of Rockefeller University in New York City. "But they can't stand alone." Yet for all the touted virtues of interdisciplinary work, this new style of analysis has yet to yield hard estimates of just how many people can live on Earth.



Crowd capacity. Estimates of how many humans can live on Earth have fluctuated from 1 billion to 1 trillion and show little sign of stabilizing.

Scientists anxiously watching population shoot up have been trying to calculate Earth's carrying capacity for centuries. But as Cohen noted in his talk, the resulting numbers haven't converged over time. For example, Stanford University biologists Paul Ehrlich, Anne Ehrlich, and Gretchen Daily recently estimated optimal population at about 1.5 billion, while in 1994 Paul Waggoner of the Connecticut Agricultural Experiment Station estimated that Earth could support 1 trillion people, assuming improved agriculture.

Cohen argues that many analyses have come up with wildly different figures because they rely on simple biological parameters, such as the amount of arable land per capita, then extrapolate. That ignores the human choices that influence these parameters at least as much as natural constraints, he says. A billion beef-eaters require much more land than a billion vegetarians, for example, and people may change their preferences as resources become scarce. "Ecological limits appear not as ceilings but as trade-offs," says Cohen, who is now assessing the consequences of such trade-offs. For example, cotton clothes use fewer resources than wool, which requires land for raising sheep.

Similarly, population biologist William Rees of the University of British Columbia presented another type of model that takes into account how a society's choices may affect its "ecological footprint"—the area of productive land needed to support it. His analysis suggests that each American leaves at least a 5.0-hectare footprint, each Canadian 4.3 hectares, and most Europeans 3.5 hectares. To bring the developing world up to the living standard of Canada, assuming available technology, would require two more planet Earths, says Rees.

This approach, marrying natural constraints with human economic choices, gets high marks from some. "Mr. Cohen's reasoned resolution of the issues points the way to a reconciliation" of diverse estimates, says Harvard University sociologist Nathan Keyfitz.

But Cohen is so convinced that estimates of carrying capacity are elastic, depending on standard of living, that he won't give a numerical estimate—a position that draws scorn from other scientists. It's "not helpful in the policy arena," says Ehrlich, who claims that his own work also incorporates social variables, although not in the same detail. "Science draws conclusions, and he draws none," Ehrlich says. But there is at least one point on which Cohen and his critics can agree: There are some serious limits to sustaining the lifestyles common in the developed world.

–**Anne Simon Moffat**

* Meeting of the Ecological Society of America, 11–14 August, Providence, RI.

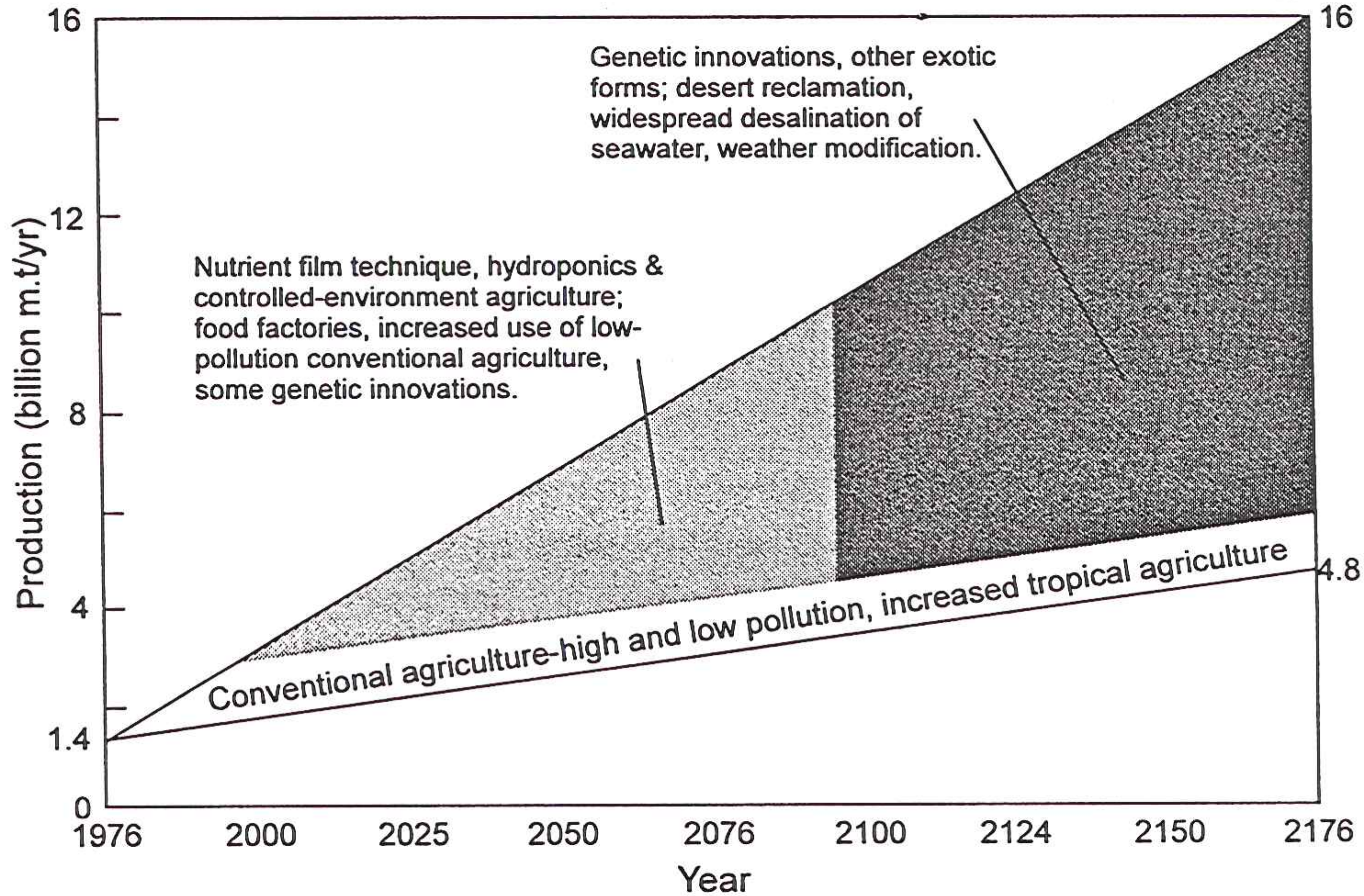


Figure 5.25. A reasonably optimistic forecast for the increase in equivalent grain production between 1976 and 2176. (Kahn et al. 1976)

Table 5.10. Socioeconomic Indicators, Selected Countries, about 1960 and 1984

Country	Population (millions) mid-1984	Average Annual Growth of GNP per Capita (percent) 1965–84	Average Index of Food Production per Capita (1965–67 = 100) 1982–84	Life Expectancy at Birth (years)	
				1960	1984
Low-income	2,389.5	2.8	111.4	36	60
China	1,029.2	4.5	138.2	51	69
India	749.2	1.6	117.7	42	56
Kenya	19.6	2.1	72.2	43	54
Middle-income	1,187.6	3.0	108.2	49	61
Brazil	132.6	4.6	131.1	56	64
Egypt	45.9	4.3	94.6	45	60
Indonesia	158.9	4.9	140.4	40	55
Mexico	76.8	2.9	101.9	56	66
Nigeria	96.5	2.8	85.4	34	50
Industrial market	733.4	2.4	117.9	70	76
Japan	120.0	4.7	97.4	67	77
United States	237.0	1.7	119.7	70	76
East European nonmarket	389.3	—	117.4	66	68
USSR (former)	275.0	—	114.1	68	67

Source: Repetto 1987.

Table 5.11. Life Expectancy at Birth, African and Other Developing Countries, 1960 and 1979

Country Group	*Life Expectancy* 1960	1979	Increase	*1979 GNP per Capita (U.S. Dollars)*	*Index of per Capita Food Production 1977–79 (1969–71 = 100)*	*Daily Calorie Supply per Capita, 1977* Calories	Percentage of Requirement
Africa*							
Low-income	38	46	8	239	91	2,040	91
Low-income, semi-arid	37	43	6	187	88	1,992	89
Low-income, other	39	47	8	247	91	2,086	93
Middle-income oil importers	41	50	9	532	95	2,180	97
Middle-income oil exporters	39	48	9	669	86	1,970	89
Sub-Saharan Africa	—	47	—	411	91	—	—
Selected low-income countries	42	50	8	200	97	2,052	91
India	43	51	8	180	100	2,021	91
Bangladesh	40	47	7	90	90	1,812	78
Developing countries by per capita income							
Less than $390	42	50	8				
$390–1,050	46	55	9				
$1,060–2,000	47	64	7				
$2,040–3,500	65	71	6				

Source: Johnson 1984. * Excludes South Africa.

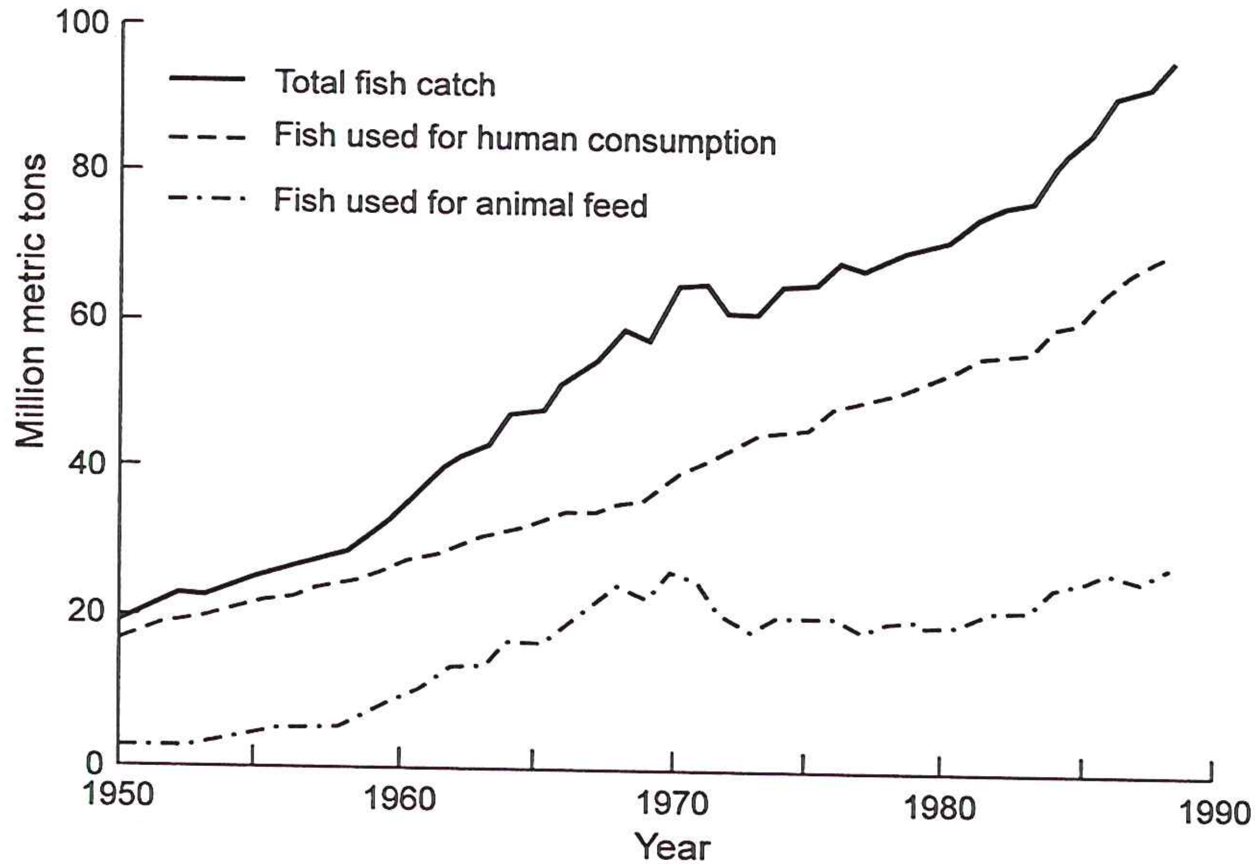


Figure 5.23. World fish catch by use from 1950 to 1988. (*World Resources 1990–91*, 1990)

Table 5.2. Average Total Composition of Dehydrated Living Matter

	Percent of Dry Weight	
Element	*Adult (Homo sapiens)*	*Alfalfa (Medicago sativa)*
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