Anton von Leeuwenhoek 1679

$$N_{max} = N_{Holland} \frac{A_{Holland}}{A_{conts}}$$

$$= 13.4 \text{ billion}$$

Suppose a single resource – say food – is limiting. Then...

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

Roger Revelle (founder of Scripps, Harvard Center for Population Studies, Ambassador to India) well-known estimate (1976)

nutritional requirement = 2500 kcal/day
(current world level)
~ 3600 in NA
< 2000 in sub-Sahara Africa

potentially arable land 3.2 billion hectares, 24% land area of ⊕
~~(86% of land area~~
more than twice current cropland
1.5 billion ha
allow for multiple crops → 4.2 billion ha
– 10% for non-food → 3.8 billion

[illegible] $\times\ 3300\ \frac{\text{kcal}}{\text{kg}} \times 3.8\cdot10^{9}$ ha

$$\frac{3300\ \frac{\text{kcal}}{\text{kg}} \times 3.8\cdot10^{9}\ \text{ha} \times 3000\ \frac{\text{kg}}{\text{ha}}}{2500\ \text{kcal}}$$

$3.8\cdot10^{9}\ \text{ha} \times 10^{3}\ \frac{\text{kg}}{\text{ha}}$

$= 3.8\ 10^{12}\ \text{kg}$

$3800\cdot10^{9}$ 3.8 billion tons

$3.8\cdot10^{9}$ ha × 3 tonnes / ha

$= 11.4\cdot10^{9}$ tons

$\boxed{11.4\ \text{Gt}}$

$\times\ 3.5\ \frac{\text{kcal}}{\text{g}}\cdot10^{6}\ \frac{\text{kg}}{\text{ton}}$

$$= \frac{4\cdot10^{16}\ \text{kcal}}{2500\ \text{kcal}} = 16\cdot10^{9}\ \text{people?},$$

$16\cdot10^{12}$ people

huh?

$\boxed{\text{aha — } 365.25\ \text{days / yr}}$

Revelle (1972) careful study of arable land $3.8 \cdot 10^9$ ha

$3.8 \cdot 10^9$ ha × 3 tonne / ha yield

$= 11.4 \cdot 10^9$ tonne

$$\frac{3.8 \cdot 10^9 \text{ ha} \times 3 \frac{\text{tonne}}{\text{ha}} \times 3.5 \cdot 10^6 \frac{\text{kcal}}{\text{tonne}}}{2500 \text{ kcal / day} \times 365.25 \text{ days / yr}}$$

$= \underline{40 \text{ billion people}}$

Another way to think of it — "ecological footprint"

NA is self-sufficient in food
& has
$2 \cdot 10^8$ ha cropland
$4.5 \cdot 10^8$ ha grassland & pasture
$9.4 \cdot 10^8$ ha forest & woodland

pastures grow cows — we eat cows
forests → O_2 we breathe, protect watersheds for H_2O in addition to providing lumber for houses

÷ 300 billion people ⟹ 5 ha / person

A more careful analysis by William Rees
of UBC

USA	5.0	1 ha = 2 football fields
Canada	4.3	
Europe	3.5	

To give every person on ⊕ a "European footprint"

~~$1.4 \cdot 10^9$ km^2~~
~~$= 1.4 \cdot 10^{11}$ ha~~

$$1.6 \cdot 10^8 \text{ km}^2 = \frac{1.6}{3.5} \cdot 10^{10} \text{ ha}$$

~~4.5 billion~~
4.6 billion

4.6 billion

but this counts Antarctica.

caloric requirements

basal metabolic rate

5 – 8.5 MJ / day

= ~~[illegible]~~ kcal / day
1200 – 2000

Say 5 MJ / day or ~~1700~~ ~~1250~~ 1200 kcal / day

Starvation = 1.4 × that = 1700 kcal / day

World average 2700 kcal / day = 2× BMR
permits light work — U. prof
or student

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

= ~~70~~ 60 watts a light bulb!

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

33% of Africans are chronically
undernourished.

US exports ~ 100 million = 10^8 tonnes
of grain / year

This enough to feed $\frac{10^8 \text{ tonnes} \times 3.5 \cdot 10^6 \frac{kcal}{tonne}}{2000 \times 365.25}$

= 380 million people

Holland & Petersen say we grow

$\boxed{\text{4 Gt grain / yr currently}}$

Check this — $1.5 \cdot 10^9$ ha cropland

~~2-3000 kg/ha~~

2-3 t/ha = 4 Gt grain

By comparison fish plays a minor role — 100 Mt = 0.1 Gt

Food production within context of C cycle

56 - 50 Gt C fixed / year

2700 kcal/day = 11.3 MJ/day

= 130 Watts

$\times 5.7 \cdot 10^9$ people

$= 7.4 \cdot 10^{11}$ W

⊕ heat flow $4.2 \cdot 10^{13}$ W   2% of ⊕ heat flow

NPP = 0.5 × GPP

carbohydrate is 44% C

50 – 80 Gt C /yr say 65

⇒ 150 Gt plant /yr

NPP = 75 Gt

10^{12} kg = 10^9 t = Gt

$C_6H_{12}O_6$

$$\% \, C = \frac{6 \cdot 12}{6 \cdot 12 + 12 + 6 \cdot 16}$$

$$= \frac{72}{180} = 0.4$$

What % of total annual plant growth eaten by humans

1.6 Gt food /yr × 0.4 = 0.6 Gt C/yr

humans eat 4 Gt grain /year
= 1.6 Gt C /yr

terr. plants fix 50 – 80 Gt C /yr

1% of all C fixed /year

$$\frac{\text{cropland}}{\text{cropland} + \text{pasture} + \text{forest}} = 12\% \text{ of all land}$$

Where does the 4 Gt food/year come from?

$$2700 \frac{\text{kcal}}{\text{person}} \times 5.7 \cdot 10^9 \text{ persons}$$

↗ per day

$$\div\ 3.5 \cdot 10^6 \frac{\text{kcal}}{\text{tonne}} \times 365\tfrac{1}{4}$$

= [illegible] [illegible]

1,2 1.6 Gt/yr

50 – 80 Gt of C/yr is the npp

≈ ½ gpp other half used to drive plant's own metabolic processes

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

on average 1 kcal meat — 5 kcal grain

$npp = \overset{65}{\cancel{75}}$ [illegible] Gt C/yr

What's this in [illegible] kcal/yr

$$\frac{65\ \cancel{75}\ [\text{illegible}] \cdot 10^9\ t}{0.4} \times 3.5 \cdot 10^6\ \frac{kcal}{t}$$

[illegible]

$$= \overset{5.7}{\cancel{6.6}} \cdot 10^{17}\ kcal/yr$$

$$npp = \overset{2.4}{\cancel{2.8}} \cdot 10^{\overset{21}{[illegible]}}\ J/yr$$

$$3.5 \cdot 10^6\ \frac{kcal}{t} = 1.5 \cdot 10^{10}\ \frac{J}{t} = 1.5 \cdot 10^4\ \frac{J}{g}$$ check with Harte

$$7.5 \cdot 10^{16}\ t/yr = 75\ Gt/yr$$

$$npp = \overset{2.4}{\cancel{2.8}} \cdot 10^{21}\ \frac{J}{yr} = \overset{8}{[illegible]} \cdot 10^{13}\ W$$

twice heat flow

rate of food consumption

$$5.7 \cdot 10^9 \cdot 2700\ \frac{kcal}{person} \cdot \frac{4.184 \cdot 10^6}{1000}$$

$$\frac{2.4 \cdot 10^{19}}{2.4 \cdot 10^{21}} = \cancel{0.008}\ (1\%) = 2.4 \cdot 10^{19}\ J/yr$$

~~energy consumption / yr~~

fossil fuel consumption

$80 + 75 + 125 = 260$ EJ

$260 \cdot 10^{18}$ J

what fraction of npp is this?

$2.6 \cdot 10^{20}$ J versus

$2.4 \cdot 10^{21}$ J $\boxed{11\%}$

Good problems —

Harte Ex. 3 & 4 page 18

Say $\frac{1}{4}$ of protein is meat

$\frac{3}{4} + \frac{5}{4} = \frac{8}{4} = \boxed{\text{twice as much}}$

US $\begin{array}{r} 27 \\ 63 \\ \hline 90 \end{array}$ 62

$\frac{63}{90} \cdot 5 + \frac{27}{90} = \boxed{3.8}$ $\frac{3600}{2700}$

$\frac{40}{5} = \boxed{8 \text{ million}}$

$M_{\odot} = 2 \cdot 10^{30}$ kg

^{4}He 4.003

2~~p~~H + 2n = 4.034

$$\begin{array}{r} 4.034 \\ 4.003 \\ \hline .031 \end{array} \Rightarrow 29 \text{ MeV}$$

29 MeV / fusion

1 MeV = $1.6 \cdot 10^{-13}$ W sec

$4.6 \cdot 10^{-12}$ $\frac{\text{W sec}}{\text{fusion}}$

sun 5800 K radius $7 \cdot 10^{8}$ m

$u = \sigma T^4$

$= 5.67 \cdot 10^{-8} (5800)^4$

$= 6.4 \cdot 10^{7}$ W/m^2

÷4 since
reaction
consumes
4 H atoms

$6.4 \cdot 10^{7} \cdot 4\pi (7 \cdot 10^{8})^2$

$= 3.9 \cdot 10^{26}$ W emitted by sun

fusions/sec × $4.6 \cdot 10^{-12}$ = $3.9 \cdot 10^{26}$

$8.6 \cdot 10^{37}$ $\frac{\text{fusions}}{\text{sec}}$ $8.5 \cdot 10^{27}$

10

H atoms = $\frac{2 \cdot 10^{30} \text{ kg}}{1.7 \cdot 10^{-27}}$ kg/amu = $1.2 \cdot 10^{57}$

~10^{11} yrs

$4.5 \cdot 10^{11}$ yrs $1.4 \cdot 10^{19}$ sec

$$\frac{4.2 \cdot 10^{15} \text{ kcal/yr}}{3.5 \cdot 10^{6}}$$

$$65 \; \frac{\cancel{\text{Gt C}}}{\text{yr}} \quad \frac{1}{0.4} \; \frac{\text{Gt plant}}{\cancel{\text{Gt C}}} \times 3.5 \cdot 10^{6}$$

$$65 \cdot 10^{9} \; \frac{\text{tons of C}}{\text{yr}} \times \frac{1}{0.4} \; \frac{\text{tons plant}}{\text{tons C}} \times 3.5 \cdot 10^{6} \; \frac{\text{kcal}}{\text{ton}}$$

$$=$$

Cumulative anthropogenic release
since ind. rev.

3000 GtC

130,000 quads

Carbon friendly

	kg C / MBtu	GtC / quad
gas	14 – 15	0.15
oil	19 – 22	0.2
coal	25	0.25
shale oil	30 — 110	0.3 — 1.1

oil reserves 12,000 quads

$$\text{kg C / MBTU} = \text{kg C} / 10^6 \text{ BTU}$$

$$= 10^9 \text{ kg C / quad}$$

$$= 10^6 \text{ ton C / quad}$$

$$= 10^{-3} \text{ GtC/quad}$$

oil 12,000 quads = 1800 GtC — all pumpable oil
coal 80,000 quads = 20,000 GtC
gas 8,000 quads = 1200 GtC

burn all 2000 bbl oil in
next 100 years at 20 bbl/day

12,000 quads = another 1800 GtC

300 + 1800 = 2100 2.7 × pre-industrial

⇒ $\boxed{\text{750 ppm in atmosphere}}$

Gas is more carbon friendly

Coal is worse & oil shale even worse

25 | 150
150
11
700

8100 quads gas = 1200 GtC

Dilemma — ~~[illegible]~~ least CO_2 friendly (coal) ~~(gas) [illegible] [illegible] [illegible] 60 % as much CO_2 as coal~~ 1.7 times as much CO_2 as gas — is most abundant, particularly in US → switch will entail increasing reliance of foreign sources for US

8215 595

H209

Like making the glass a little thicker

CO$_2$ warming

IPCC say 2X CO$_2$ would increase IR re-radiation by 4 W/m^2

What would increase in T if no feedback effects?

$$\sigma T^4 = (1.14)(340) + 4$$

287.54 → 288.28

<u>0.75° C</u>

$$1.14 \times 340 = 388 \frac{W}{m^2}$$

$$\sigma(T+\Delta T)^4 - \sigma T^4 = 4$$

$$4\sigma T^3 \Delta T = 4\sigma T^4 \frac{\Delta T}{T}$$

$$= 4\cdot 388 \frac{\Delta T}{T} = 4$$

$$\boxed{\frac{\Delta T}{T} = \frac{1}{388}} =$$

$$\frac{\Delta T}{T} = \frac{\Delta IR}{4\cdot 388}$$

Say we want 1°C change → $\Delta IR = 5.4 \frac{W}{m^2}$

ocean uptake occurs slowly
time scale of centuries

Even if fix emissions at current
rate CO_2 in atmosphere continues
to grow

CO_2 conc. in atm. increasing at
1.5 ppm/yr or 0.4%/yr

What's this in GtC/yr

$$0.4\% \times 760 \text{ Gt} = 3.2 \text{ GtC/yr}$$

emissions are 5.5 GtC/yr

This is the "missing carbon" problem

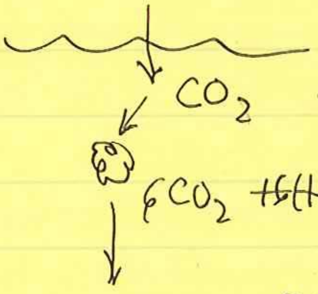
Much recent work

$$\text{fossil fuel burning}^{\swarrow 5.5} + \text{tropical}^{\swarrow 1.6} \text{ deforestation} = 7.1 \text{ GtC/yr}$$

Because of

Why does CO_2 continue to build up in atmosphere even ~~though~~ if we were to "freeze" the emission levels?

Because the uptake by the oceans, particularly the deep oceans occurs on a time scale of centuries



CO_2 gas exchange

$6CO_2 + 6H_2O \xrightarrow{h\nu}$ ~~CH_2O~~ $C_6H_{12}O_6 + 6O_2$

die, fall to deep ocean

<u>Suess</u> effect ^{14}C in tree rings

10^{16} moles

12
$\underline{5.3}$
36
$\underline{60}$
$64 \cdot 10^{16}$ gm
= 640 pg = 640 Gt

$12 \cdot 5 \cdot 10^4 \cdot 10^{10}$
~~600~~ G

$5 \cdot 10^5$ organic C
$\underline{\cdot 12}$
$6 \cdot 10^6$ GtC

(moon)

ave. temp. surface of Mercury

junk mail

Adam & Eve

Harte p. 72 #3

plot ln N_t — find r_t 1970–90 & 1950–70

biomass burning

10^9 t
1 t = 10^6 g
1 Gt = 10^{15} g

Venus 400°C – 450°C

must be 10^{14} ⟹ 760 Gt atmosphere

Sediments (10^{10} moles C)

~~11,000 Gt~~
~~11 million Gt~~

carbonates	91,000	11,000 Gt
organic	50,000	6000 Gt
Ocean	326	1 Gt = 10
Land	15	
Atmos	5	

Venus atmosphere ~ same

If the Antarctic & Greenland ice caps should completely melt, what ~~the~~ would be the worldwide rise in ♁ ?

Area of oceans = $3.6 \cdot 10^8$ km^2

Mean depth = 4 km

Volume of ice $2.9 \cdot 10^7$ km^3

Temp of ☾ $a_{☾} = 0.07$ — many dark mare

Temp of Mercury $a = 0.06$

Both