Human population dynamics

Lecture 3

Human carrying capacity

Joel E. Cohen
Laboratory of Populations
Rockefeller University & Columbia University, New York
cohen@rockefeller.edu

University of Tokyo

20190707

20170510 Sawaguchiyama Sumata-kyo Shizuoka Japan

Copyright page

Multiple choice test

1. How many people can the Earth support?
<10 billion; ≥10 billion; don't know

2. The human population of the Earth is now and will in the future be limited by food.
T, F

3. Rapid population growth helps human well-being because it creates more people to solve problems.
T, F

Outline

→ *How many people can Earth support?* (1995)

Lessons since then

- Education
- Nutrition

Carrying capacity: origins

1. International shipping (1840s)
2. Nonhuman populations in natural systems (1870s), range & wildlife management (early 20th century)
3. *K* in logistic growth model (20th century)
4. Number of humans Earth can support (neo-Malthusians, since mid-20th century)

Sayre 2008 "Genesis, history, and limits of carrying capacity"

Carrying capacity in wildlife management: example

"A piece of land can support only so many animals on a continuous basis. …

- Manage population levels to stay within carrying capacity; and
- Manage habitat to maintain or increase carrying capacity."

Knight, *Manage Your Land for Wildlife,* 2008

Existence of "carrying capacity" is weakly or not supported by data. Sayre 2008

"Carrying capacity" is ideal, static, & numerical.

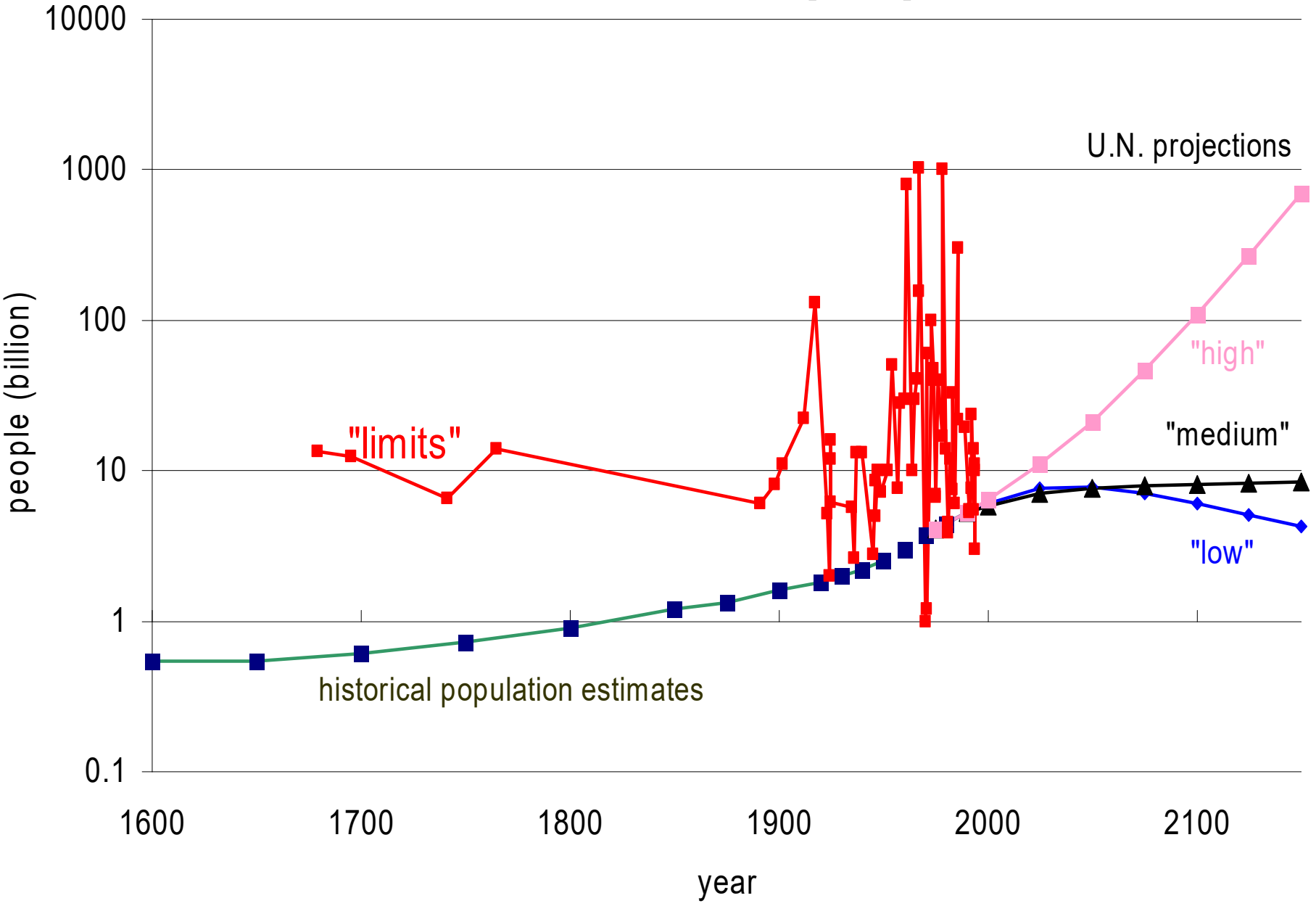
Shipping payloads are ideal, static, & numerical. Carrying capacity is an engineered characteristic of containers of undifferentiated weight (tons of stuff).

Sayre 2008

For human carrying capacity, carrying capacity is not static. It reflects qualitative values. And whose ideal sets the limit?

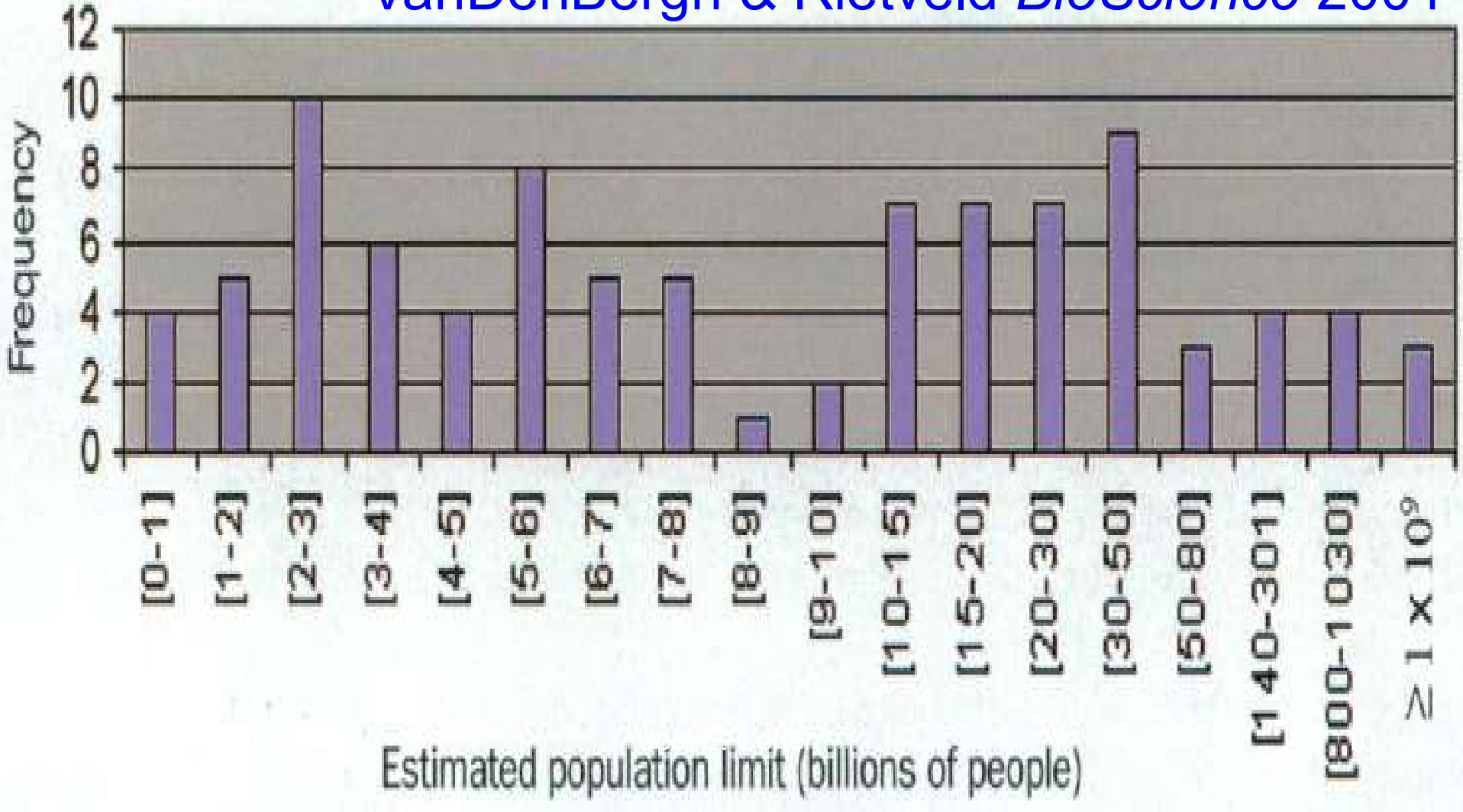
How many people can Earth support?
(1995)

“Limits” of human population

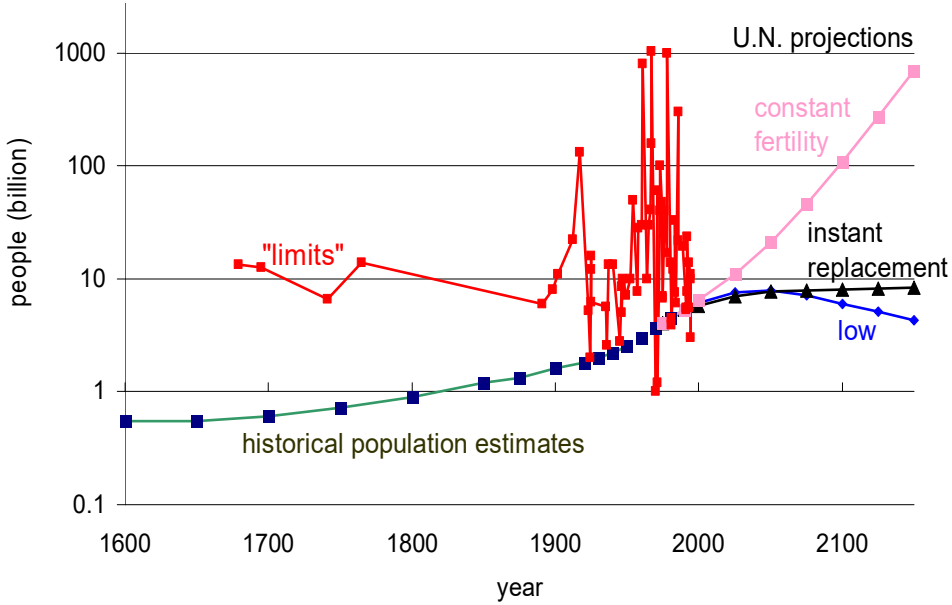


94 estimates ranged from 0.5 billion to 10^{21} billion.

VanDenBergh & Rietveld *BioScience* 2004



What do these estimates reveal?



1. Range in last 50 years: <1 billion to >1000 billion. They cannot all be right.

2. Variation of estimates increase with time.

Numbers are more political than scientific.

3. Half of estimates lie in range 4-16 billion.

Humans have entered a zone of concern.

Methods of estimating human carrying capacity

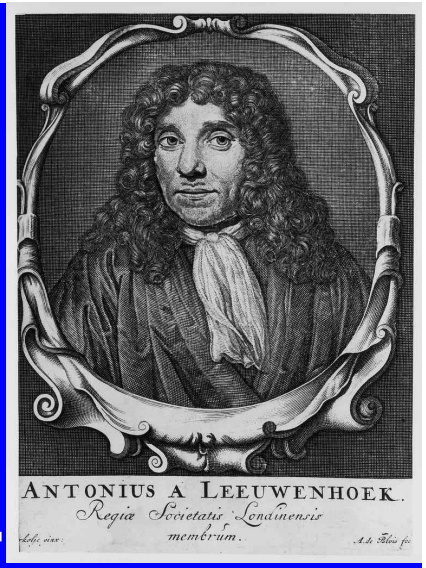
1. Assertion:

   It is true because I say so!

   Advantage: method requires few data.

   Disadvantage: estimates are highly uncertain.
   Even the uncertainty is uncertain.

Methods of estimating human carrying capacity



1. Assertion
2. Maximum density

Antoni van Leeuwenhoek 1679:
Holland has ~1 million people.
World could never be as dense as Holland.
Inhabited Earth is 13,385 times area of Holland.
Hence maximum population is 13,385 times 1 million = 13.385 billion.

Van Leeuwenhoek's method: applicable today?

Population of Holland (not Netherlands) in 2017 was ~6.47 million.

Therefore, is the human carrying capacity 6.47 million x 13,385 ~ 86.6 billion?

Methods of estimating human carrying capacity

1. Assertion
2. Maximum density by latitude

Gregory King 1695:

Maximum population depends on latitudinal bands on both sides of equator:

0-30°, 30-55°, 55-70°, 70-90°

Depending on assumed maximum density, maximum population is 6.3-12.5 billion.

Methods of estimating human carrying capacity

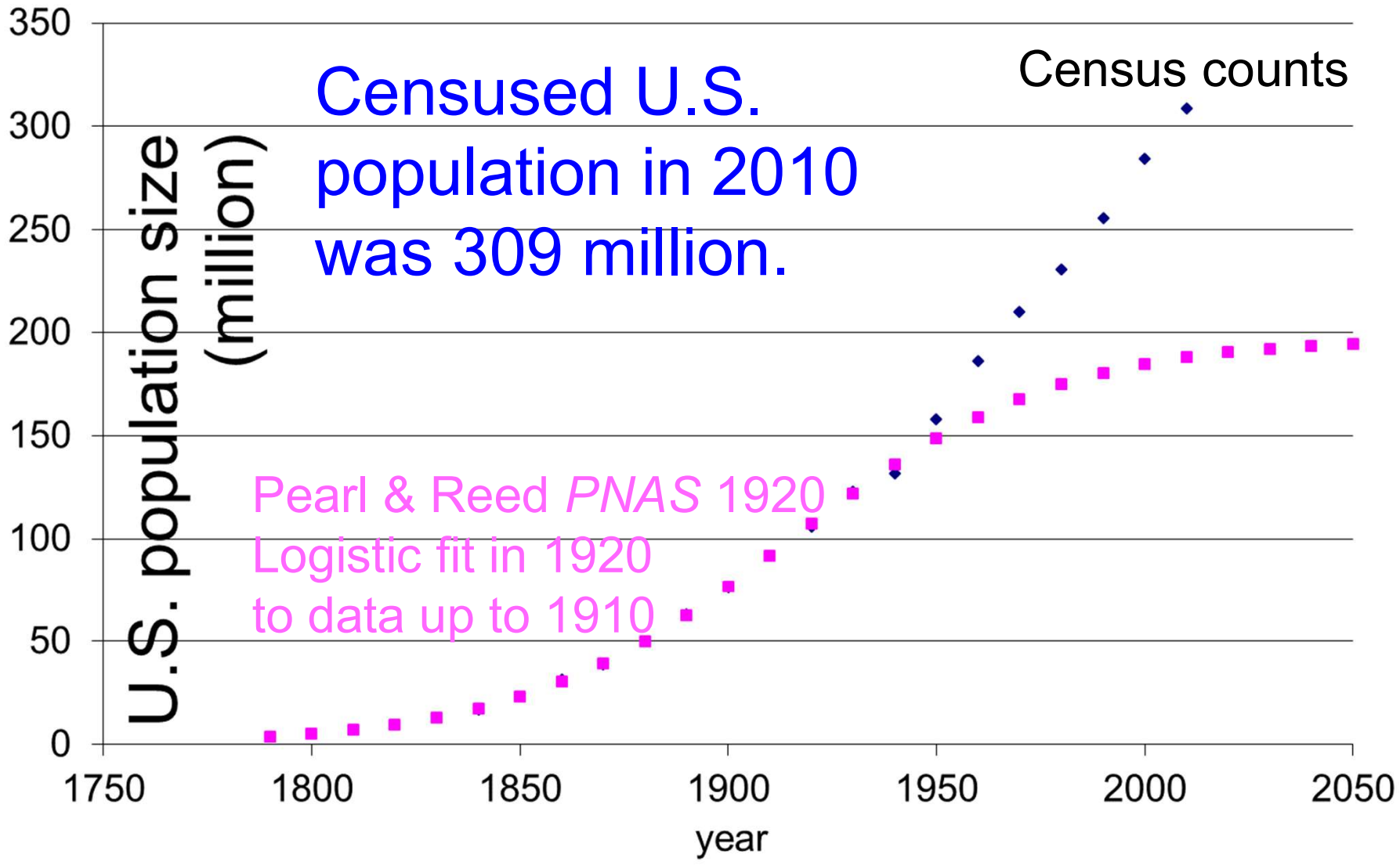
1. Assertion
2. Maximum density (by latitude)
3. Logistic curve (Verhulst 1838, Pearl 1920):

$P(t)$ = population at time t,

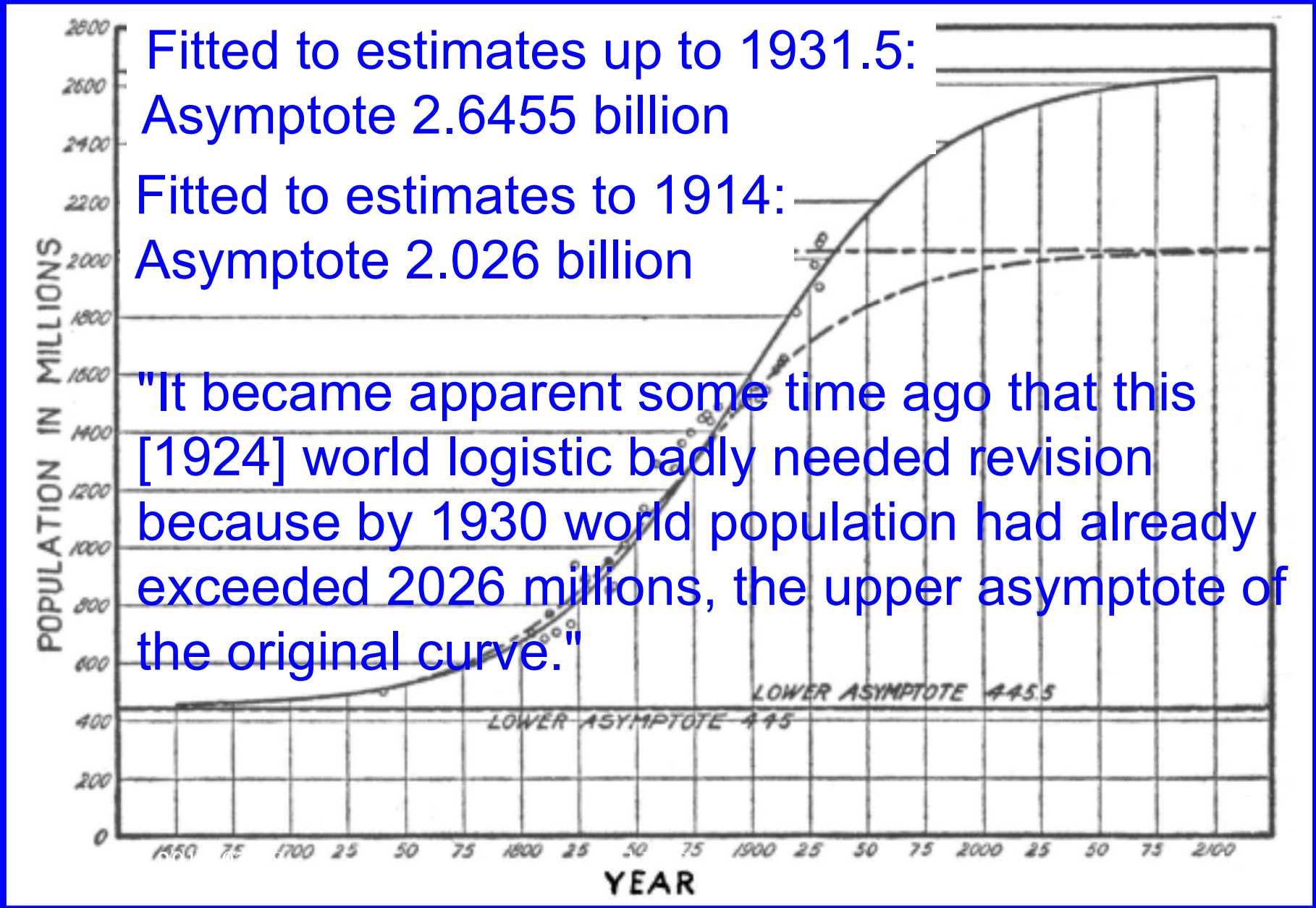
K = "carrying capacity"

$$\frac{dP(t)}{dt} = rP(t)\big(K - P(t)\big).$$

Logistic predicted maximum U.S. population would be 197,274,000.



"World Population Growth," Pearl & Gould 1936



"World population growth"

Pearl & Gould *Human Biology* 1936

"A logistic curve fitted to the data on world population growth leads to an upper asymptotic value for the present cycle of 2,645.5 million, rather closely approached by about 2100 A. D."

"We wish to emphasize again that we have no inside information as to whether the asymptote … will reasonably accord with reality in the year 2100, and are not to be understood as advocating its absolute validity or significance."

Malthus Condorcet model

Cohen *Science* 269:341-346, 1995

Verhulst's logistic: $\frac{dP(t)}{dt} = rP(t)(K - P(t))$.

Condorcet: *K* can change. Set $K = K(t)$.

$$\text{Let } \frac{dK(t)}{dt} = c \cdot \frac{dP(t)}{dt}.$$

If $c < 1$, $P(t)$ follows logistic curve.

If $c = 1$, $P(t)$ follows exponential curve.

If $c > 1$, $P(t)$ follows "doomsday" curve & goes to infinity in finite time.

Malthus Condorcet Mill model

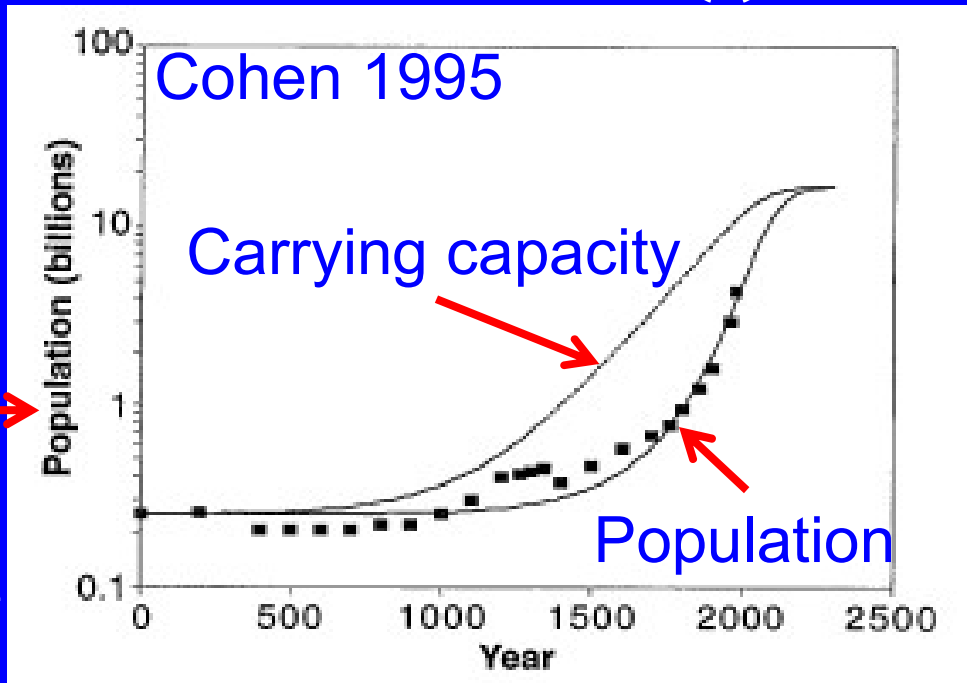
Cohen *Science* 269:341-346, 1995

$$\frac{dP(t)}{dt} = rP(t)\big(K - P(t)\big), \qquad \frac{dK(t)}{dt} = c \cdot \frac{dP(t)}{dt}$$

If c depends on the amount of resource per person & the total resource is L, then $c = \frac{L}{P(t)}$ &

$$\frac{dK(t)}{dt} = \frac{L}{P(t)} \cdot \frac{dP(t)}{dt}.$$

Then $\log P(t)$ grows sigmoidally. Log scale!



Methods of estimating human carrying capacity

1. Assertion
2. Maximum density (by latitude)
3. Logistic curve
4. Single limiting factor:
   estimate total supply,
   estimate minimum requirement per person.

Single limiting factor: food

G. H. Knibbs 1912, Albrecht Penck 1925:
maximum population =
maximal food supply divided by minimal individual food requirement.

$$\frac{\text{Food supply}}{\text{Requirement}}$$

G. H. Knibbs
statistician
1858-1929

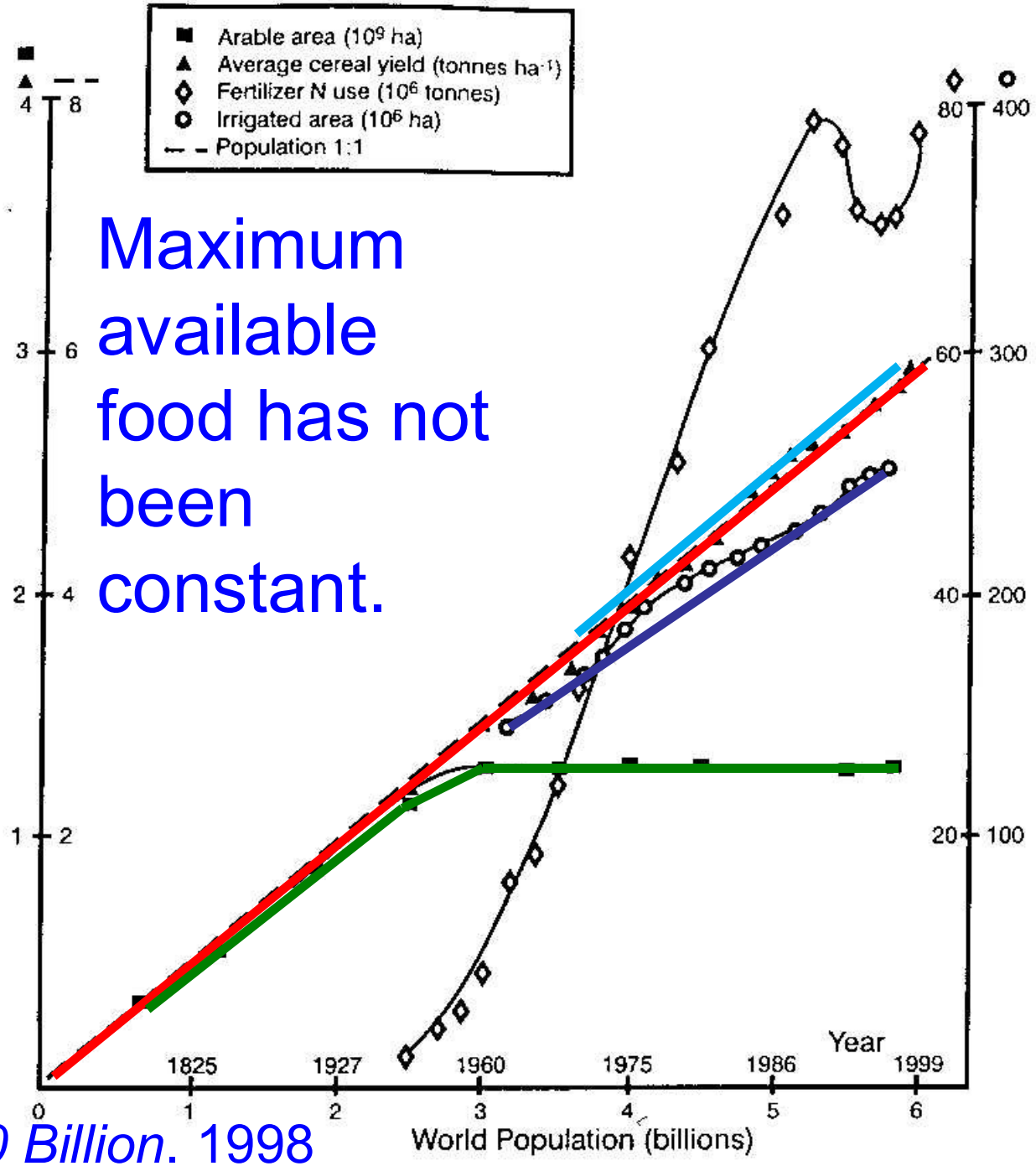
Albrecht Penck
geomorphologist
1858-1945

Food supply & demand are not constants of nature.

Maximal food supply depends on prices, subsidies, credit, cultivars, transport, refrigeration, storage, water, soil maintenance, control of biological competitors, climate, farmer education, fertilizers, irrigation, …

Food requirement per person depends on diet, activity, temperature (culture & environment), age, infectious disease, education, religion, …

As population surpassed 3 billion in 1960, arable area leveled off, but average cereal yield rose with increasing fertilizer nitrogen use and irrigation.



Evans, *Feeding the 10 Billion*. 1998

Urban & rural people have different food habits in developing countries

Rural residents eat more cereals, tubers, & roots.
Urban residents eat more meat, fruits, & vegetables.
Urbanization will increase average meat, fruit, vegetable consumption/person, reduce average cereal, root, tuber consumption/person.
Diets rich in meats require feedgrains & meals, so demand more cereal than diets based on direct cereal consumption.
Changes in consumption patterns brought about by urbanization can significantly affect global food supply, markets, & trade.

What is food?

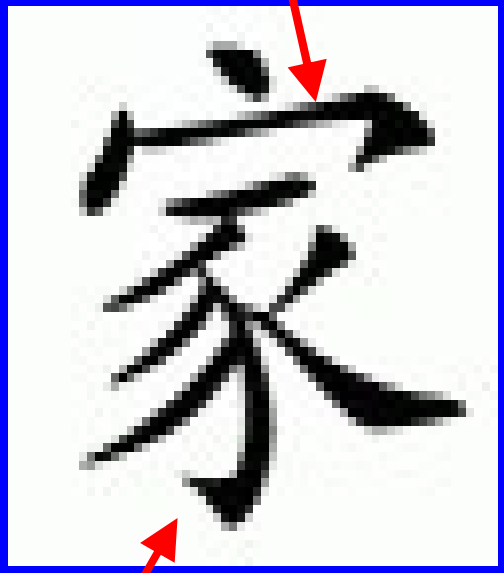
"… natural species are chosen not because they are 'good to eat' but because they are 'good to think.' "

Claude Levi-Strauss

(1962, *Le Totémisme aujourd'hui*)

“Home” in Chinese

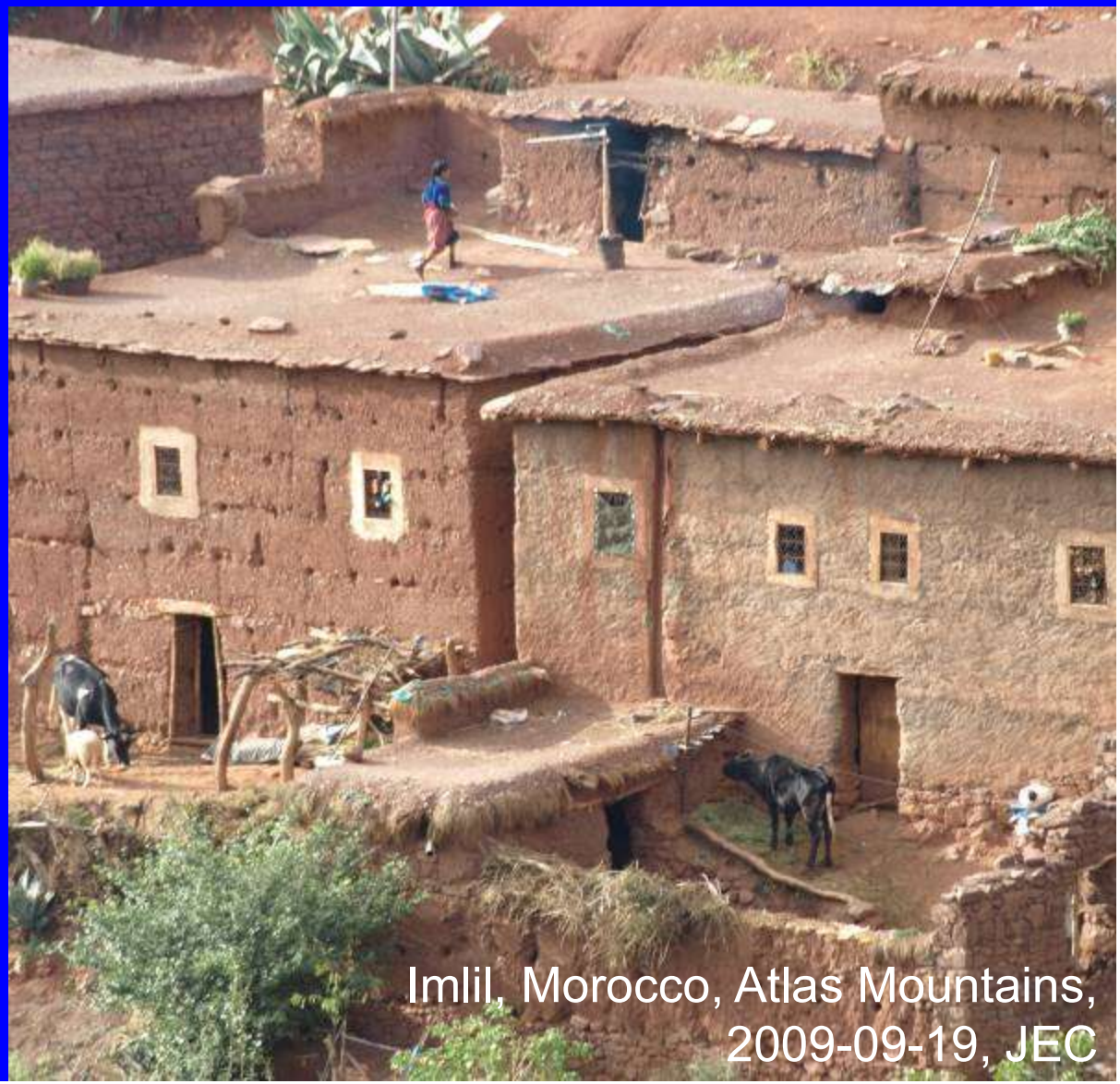
roof



pig

For >1 billion people, pig is part of home.

For >1 billion people, pig is forbidden.

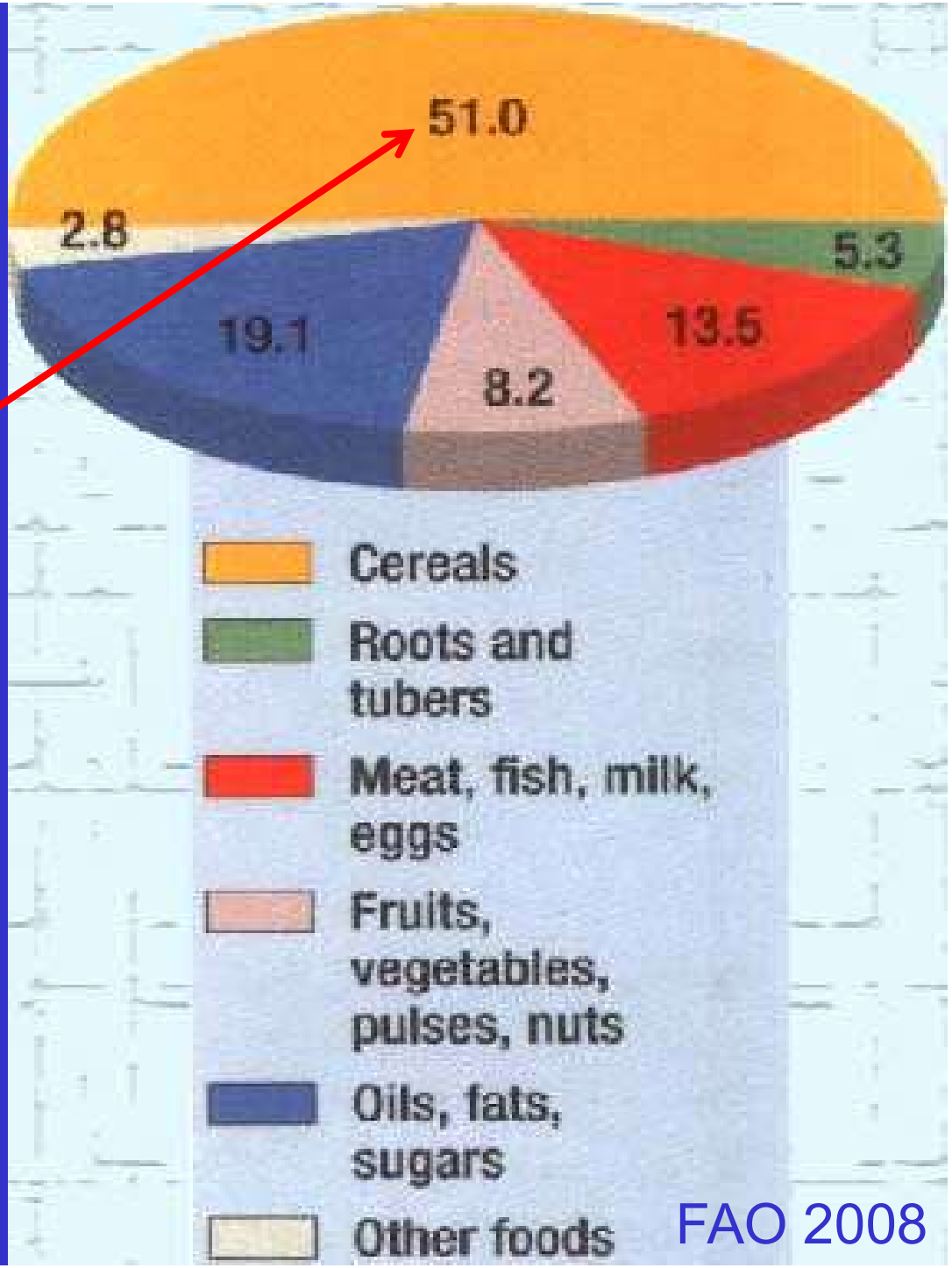


Imlil, Morocco, Atlas Mountains, 2009-09-19, JEC

Photo credit: Peter Halasz

50,000 plant species are edible.

Rice, maize, wheat provide 60% of world's food energy intake. FAO 2008



Is food the single limiting factor for human population?

Population growth is most rapid in some areas where food is scarcest.

Population growth is slowest in many areas where food is most abundant.

How can food be the single limiting factor for human population?

Single “limiting factors" for human population?

Water: ‘More than any other factor, availability of water determines the ultimate population capacity of a geographic province.’ Brian J. Skinner

1969, geologist at Yale University

Same claim for: food, land, energy, biologically accessible nitrogen, phosphorus, light, soil, space, diseases, waste disposal, nonfuel minerals, forests, biological diversity, & climatic change.

Many unsupported claims are in conflict!

Methods of estimating human carrying capacity

1. Assertion
2. Maximum density (by latitude)
3. Logistic curves
4. Single limiting factor
5. Single currency for multiple factors (e.g. land, energy, “ecological footprint”)

“Ecological footprint”

Wackernagel *et al. PNAS* 2002 assumed that most resources humans consume & wastes humans generate "can be measured in terms of the biologically productive [land] area necessary to maintain these flows (those resource and waste flows that cannot are excluded from the assessment)."

Human needs are multidimensional.

If all energy production were nuclear, no "biologically productive land" would be needed to draw down emitted CO_2. But no amount of "biologically productive land" will dispose of spent nuclear fuels.

No amount of "biologically productive land" will restore lost biological species & habitat types.

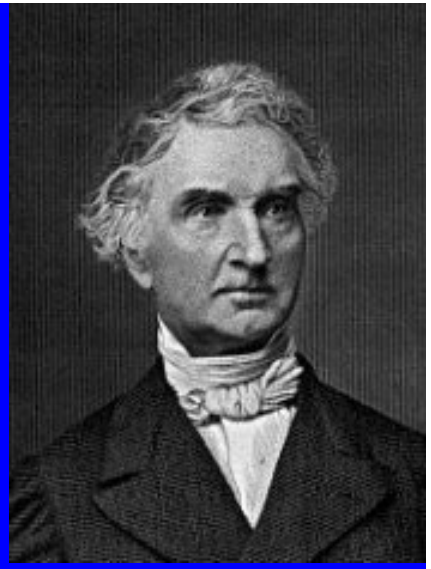
No amount of "biologically productive land" will provide ores & rare earths, discover new prevention or cures for diseases, generate technology, lead institutions for public order, or create art.

Methods of estimating human carrying capacity

1. Assertion
2. Maximum density (by latitude)
3. Logistic curves
4. Single limiting factor
5. Single currency for multiple factors
6. Law of the minimum for independent limiting factors

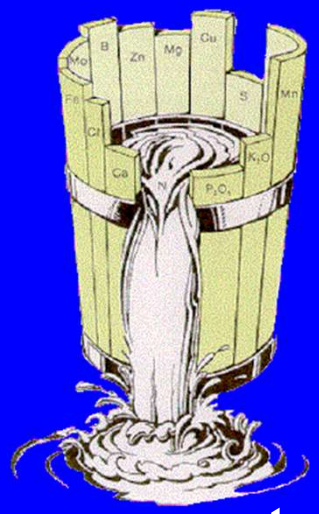
Karl Sprengel
1787-1859
stated it in
1828.

Justus von
Liebig
1803-1873
popularized it
~1855.



Law of the minimum for independent limiting factors

Suppose people need food, wood, & water.



Maximum human population

= minimum of

{

Max food supply / min food requirement,

Max wood supply / min wood requirement,

Max water supply / min water requirement

}

If use of water affects amounts of food & wood, independent constraints fail.

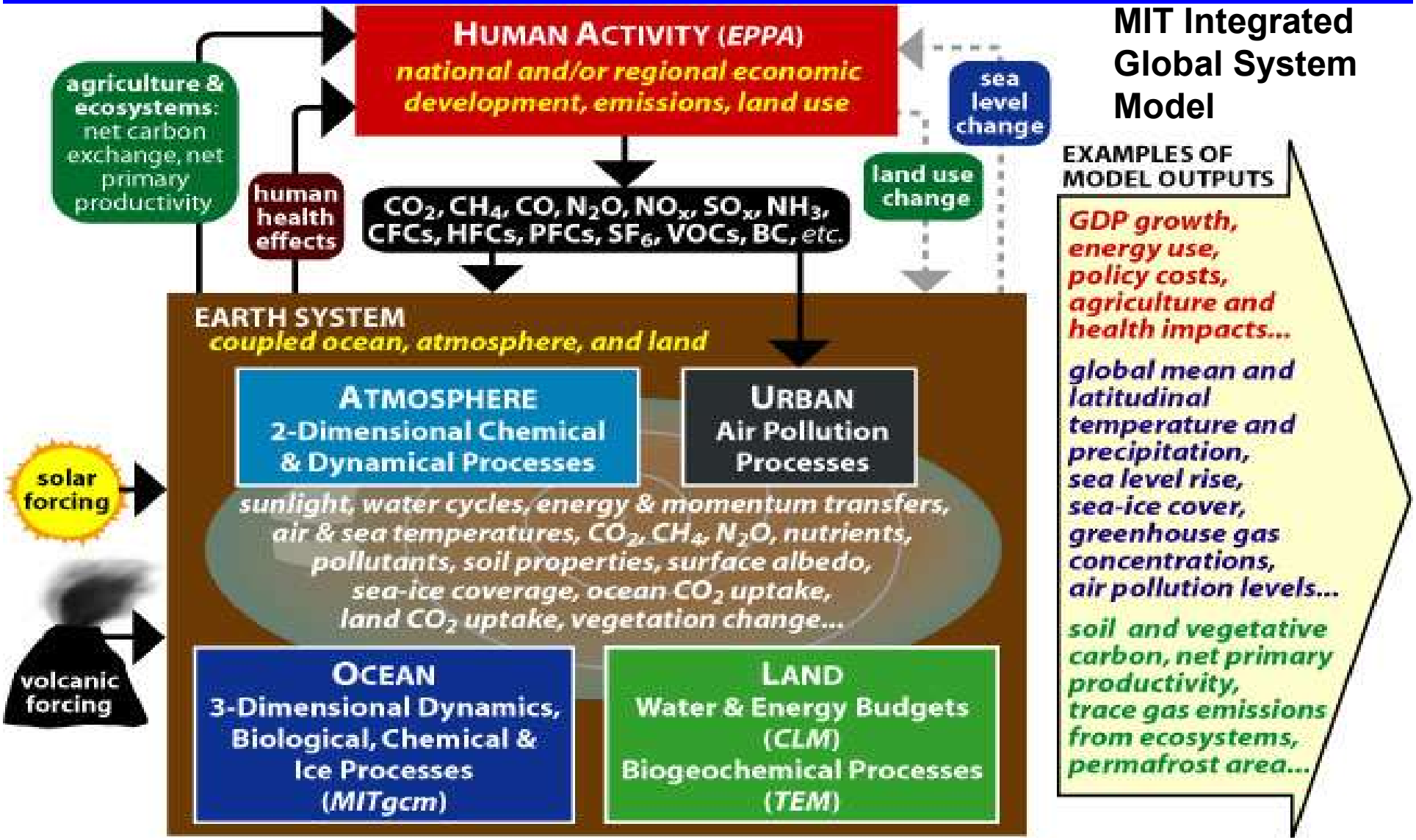
What if human carrying capacity depends on the right mix (proportions) of non-substitutable factors?

E.g., what if there are trade-offs in use of water for forests & food?

Methods of estimating human carrying capacity

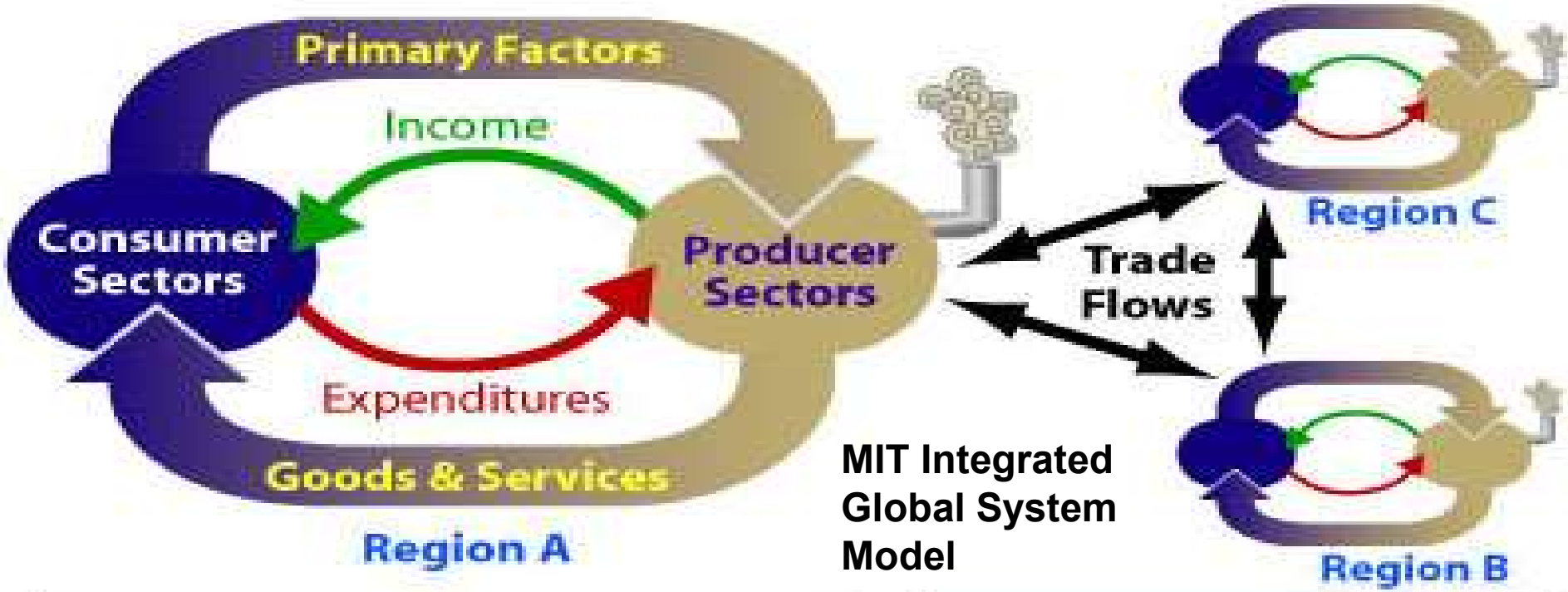
1. Assertion
2. Maximum density (by latitude)
3. Logistic curves
4. Single limiting factor
5. Single currency for multiple factors
6. Independent limiting factors
7. Multiple interacting limiting factors

Multiple interacting limiting factors: system models



Human activity submodel

MIT Emissions Prediction and Policy Analysis (EPPA) Model



MIT Integrated Global System Model

Model Features

- All greenhouse-relevant gases
- Flexible regions
- Flexible producer sectors
- Energy sector detail
- Welfare costs of policies

Mitigation Policies

- Emissions limits
- Carbon taxes
- Energy taxes
- Tradeable permits
- Technology regulation

Human carrying capacity has not been defined & measured in a clear, persuasive way.

How many people Earth can support depends on answers to additional questions.

How many people Earth can support depends on:

1. Average level of material & cultural well being

(food, fiber, water, housing, industrial output, health, sanitation, energy, education, travel)

2. Distribution of material & cultural well being

How to measure global inequality?

Milanovic, *Global Policy* 2013

Inequality 1: country averages, all countries weighted equally

Inequality 2: country averages, countries are weighted by population size

Inequality 3: individual observations

#3 is best, but data on top of pyramid are missing or unreliable!

Measure income, wealth, "happiness," or ?

Inequality of what?

Income

World Income Inequality Database (WIID) presents information on income inequality for developed, developing, and transition countries. https://www.wider.unu.edu/project/wiid-world-income-inequality-database

"Happiness"

https://worldhappiness.report/ed/2019/

Patents

https://www.wipo.int/portal/en/index.html

Wealth

How does Credit Suisse measure wealth?

Credit Suisse, Global Wealth Report 2016

"Net worth, or 'wealth', is defined as the value of financial assets plus real assets (principally housing) owned by households, minus their debts. Private pension fund assets are included, but not entitlements to state pensions. Human capital is excluded …, along with assets and debts owned by the state (which cannot easily be assigned to individuals). … we disregard the relatively small amount of wealth owned by children …"

Wealth inequality in 2018

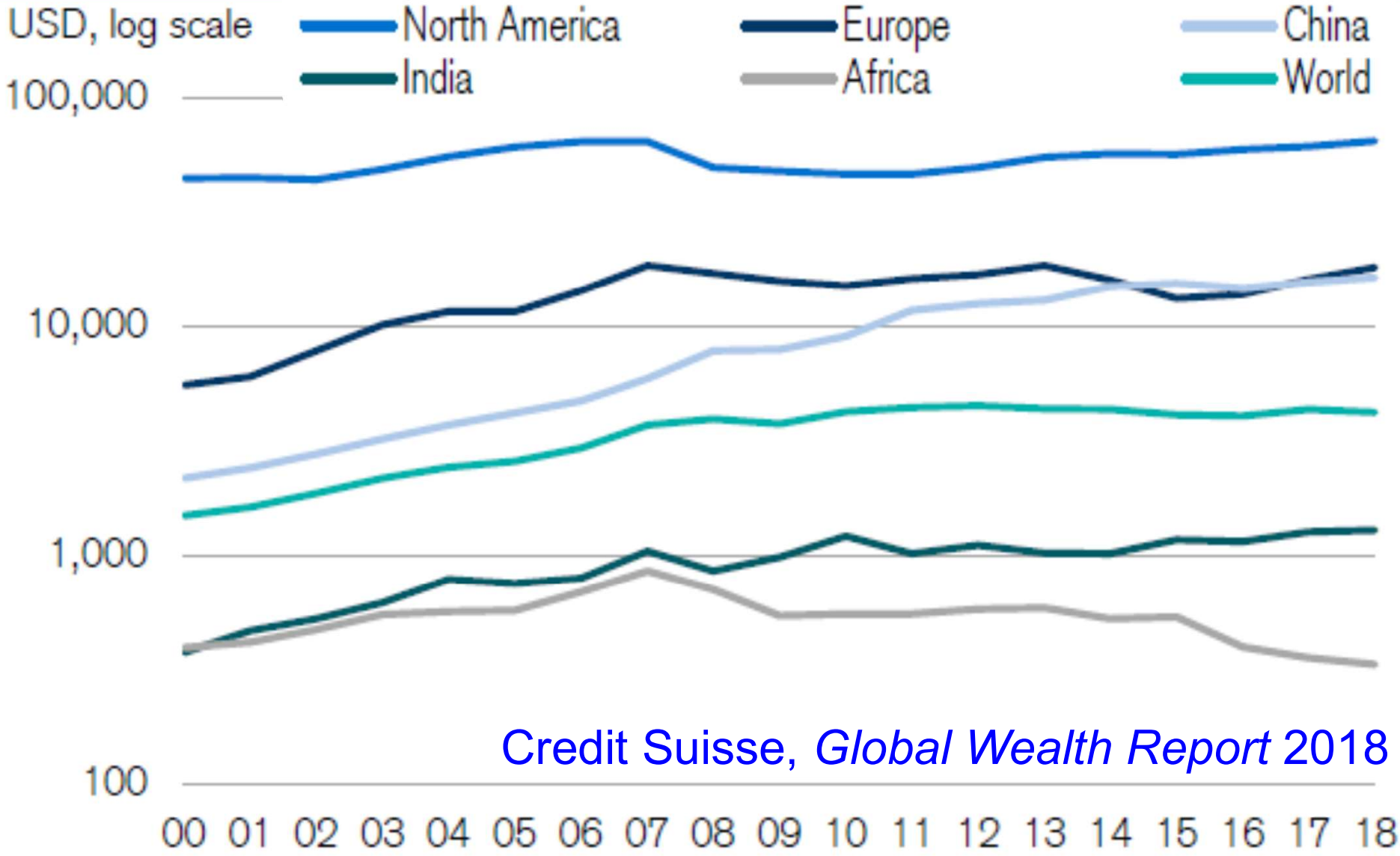
The poorest half of adults own <1% of global wealth.

The richest 10% own 85% of global wealth.

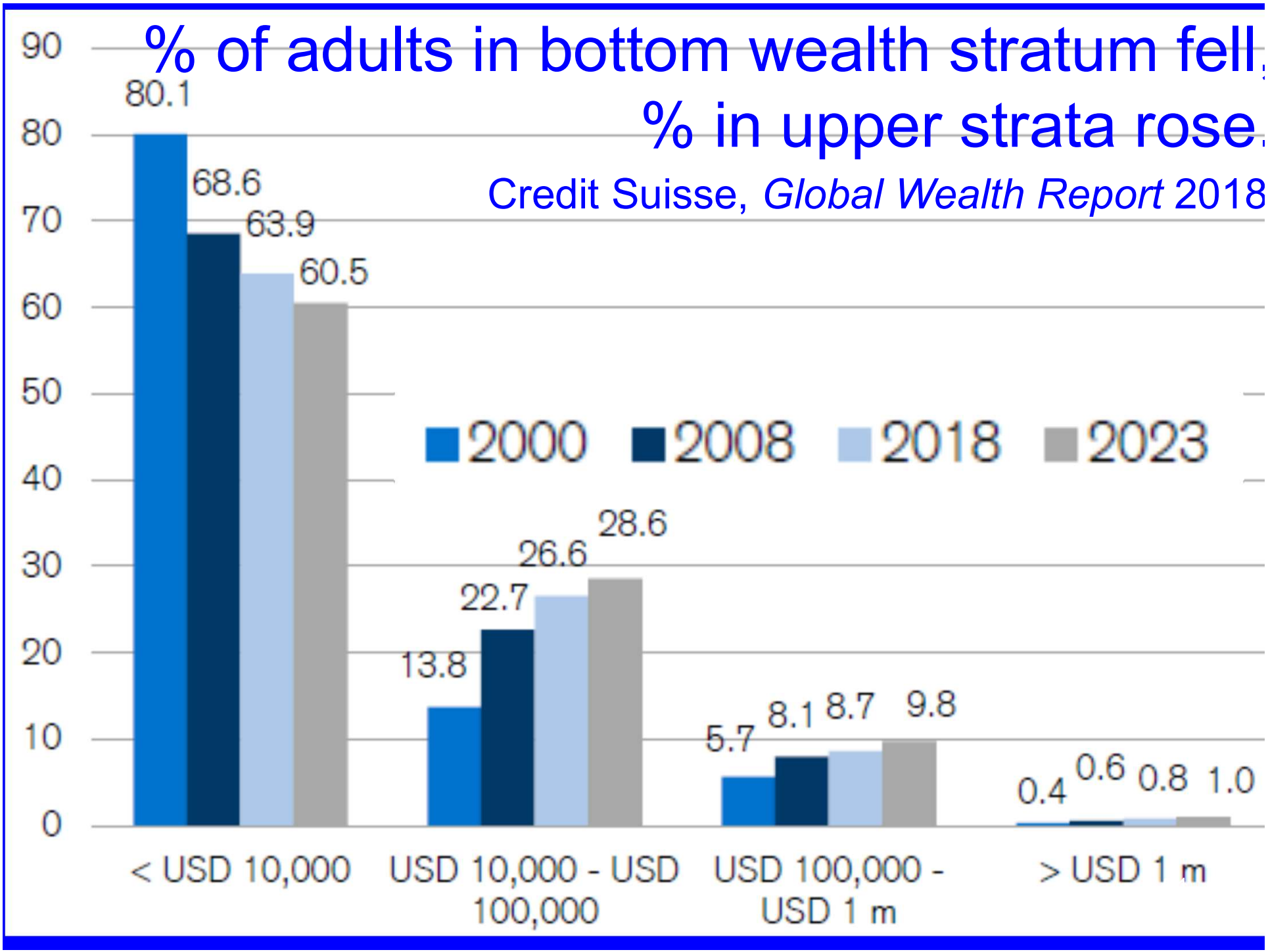
The top 1% own 47% of global wealth.

Credit Suisse, Global Wealth Report 2018

Median wealth differs 100-fold between regions, 2000-2018.

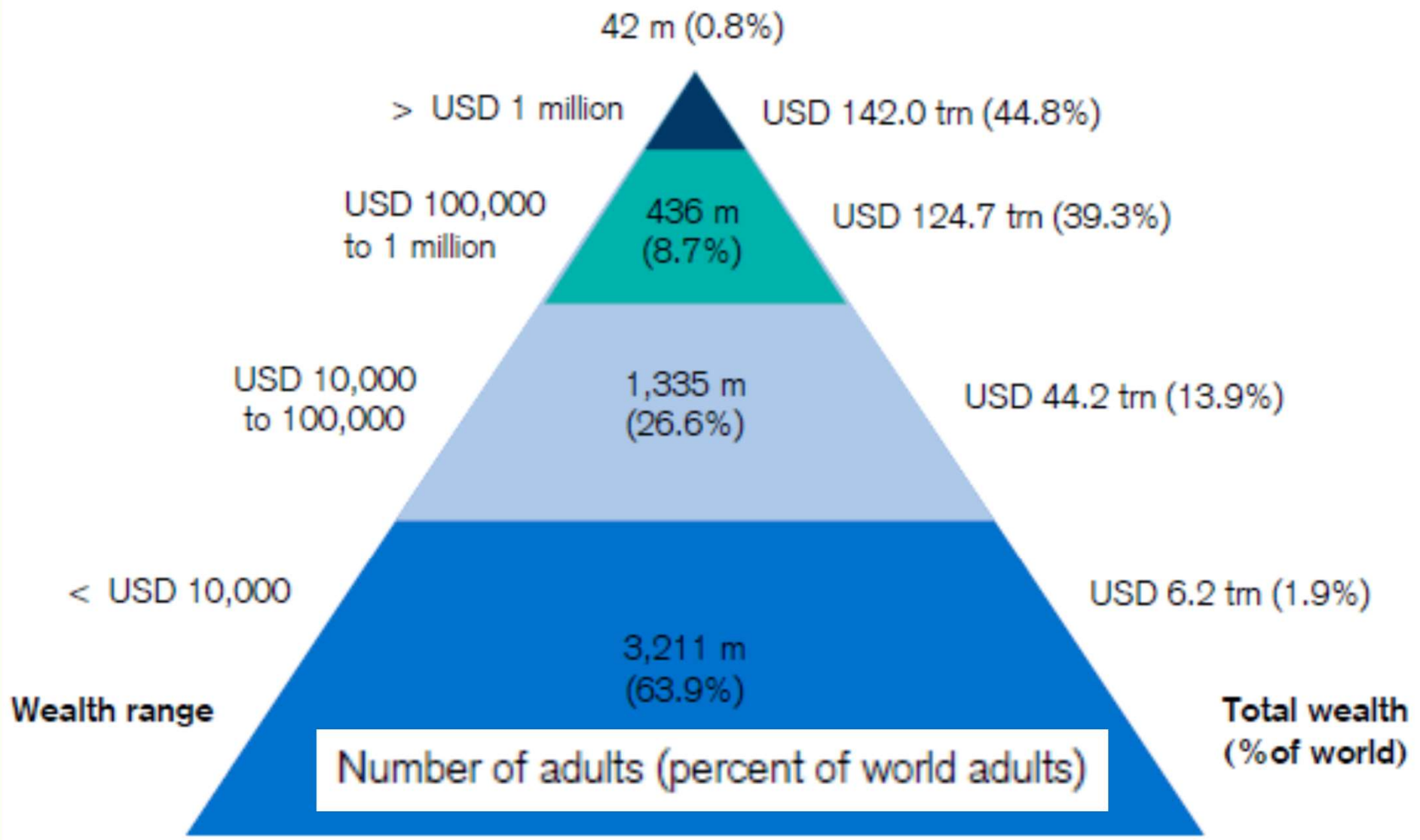


Credit Suisse, *Global Wealth Report* 2018


% of adults in bottom wealth stratum fell
% in upper strata rose
Credit Suisse, *Global Wealth Report* 2018
90
80
70
60
50
40
30
20
10
0
2000
2008
2018
2023
80.1
68.6
63.9
60.5
13.8
22.7
26.6
28.6
5.7
8.1
8.7
9.8
0.4
0.6
0.8
1.0
< USD 10,000
USD 10,000 - USD 100,000
USD 100,000 - USD 1 m
> USD 1 m

Global wealth pyramid 2018

Credit Suisse *Global Wealth Report* 2018



Exercise

Construct the Lorenz curve of wealth based on this pyramid.

Calculate the Gini coefficient of wealth based on this pyramid.

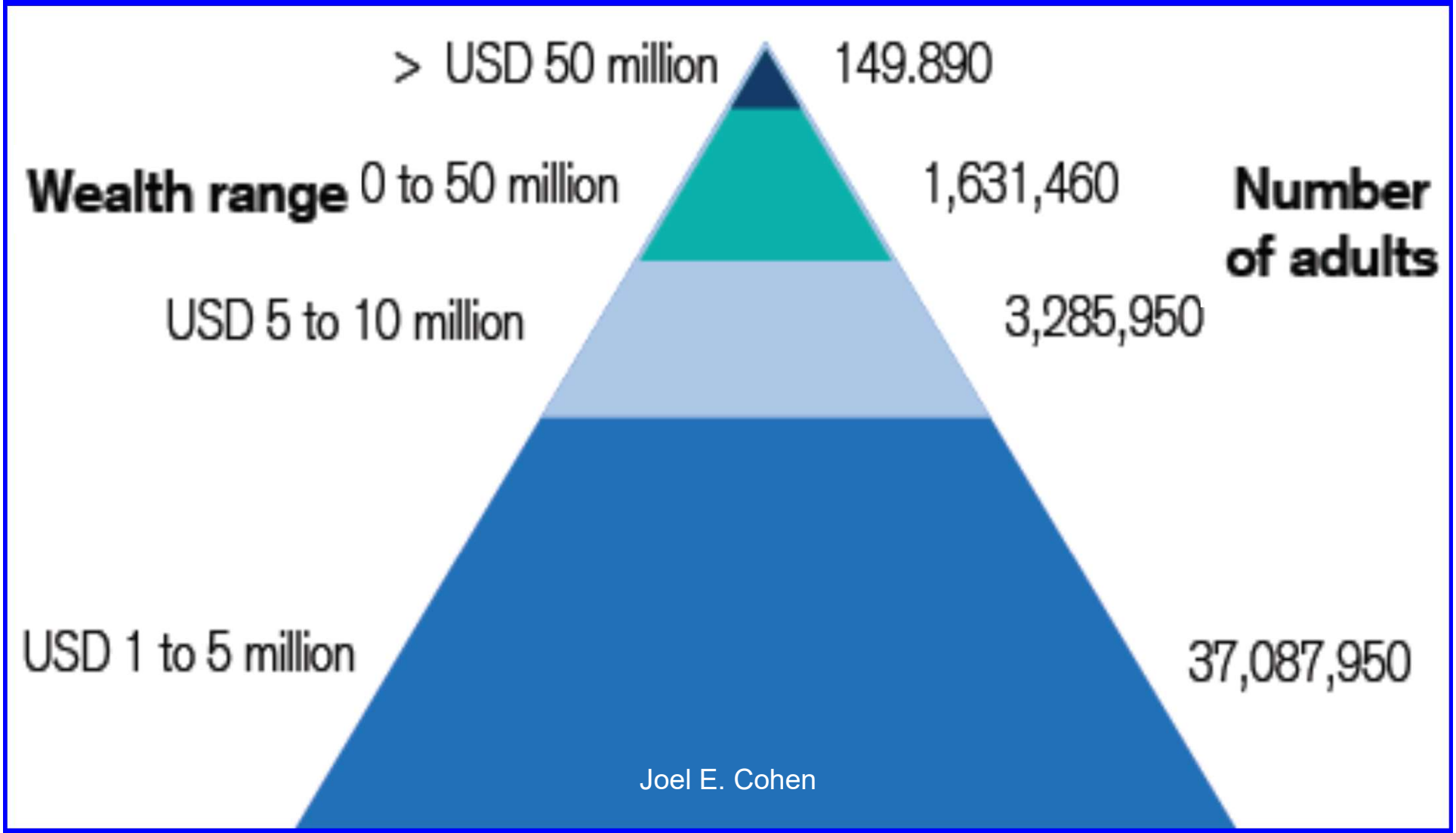
Gini coefficient of wealth based on this pyramid is ~0.87.

Credit Suisse estimate of Gini coefficient of wealth for globe is 0.904.

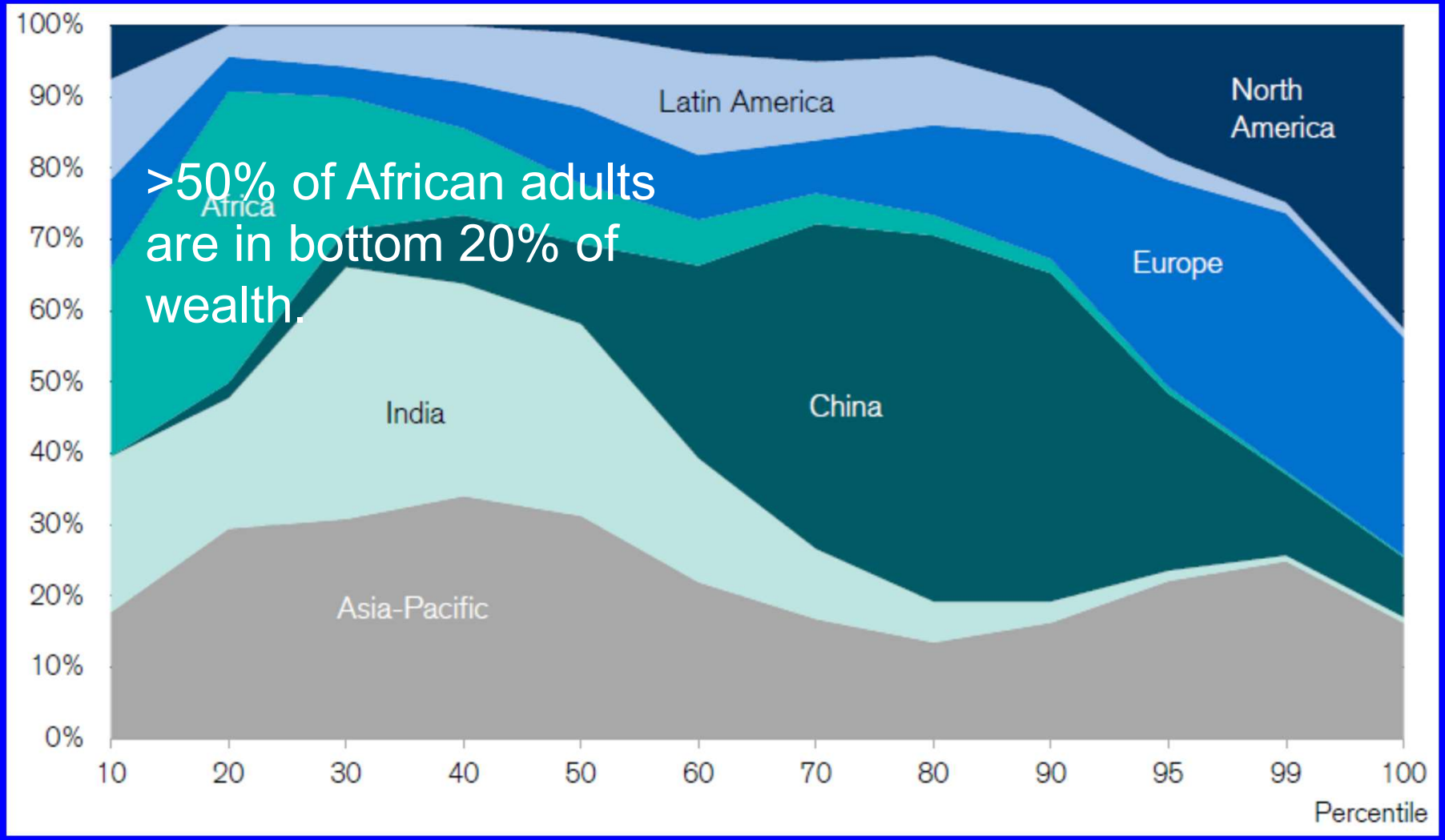
Credit Suisse *Global Wealth Databook* October 2018, p. 117

Global wealth at the top 2018

Credit Suisse, *Global Wealth Report* 2018



Regional composition of global wealth distribution, 2018



>50% of African adults are in bottom 20% of wealth.

James Davies, Rodrigo Lluberas, Anthony Shorrocks, Credit Suisse, Global Wealth Databook 2018

The sinking bottom

"… the past 20 years have seen an increasing incidence of low wealth in high income countries [and] the increasing likelihood that low wealth holdings involve negative net worth, with debts exceeding the value of assets."

Credit Suisse Global Wealth Report 2016

>420 million adults (~1 in 11) were net in debt, 2016.

Bottom half (2.4 billion) of adults owned ≤USD 2,222, with average wealth USD 159.

"80% of adults in Africa & India belong to the bottom half of the global wealth distribution."

Bottom fifth (~1 billion) of adults owned ≤USD 248, had average net debt USD -1,079.

USA had 21 million adults in lowest **global** wealth quintile.

In bottom wealth quintile, 44% were debtors with average net debt of USD -2,628.

Credit Suisse, Global Wealth Report 2016

How many people Earth can support depends on

3. Technology

How many people Earth can support depends on

4. Domestic & international political institutions (means of resolving conflicts, individual freedoms, procedures for change)

How many people Earth can support depends on

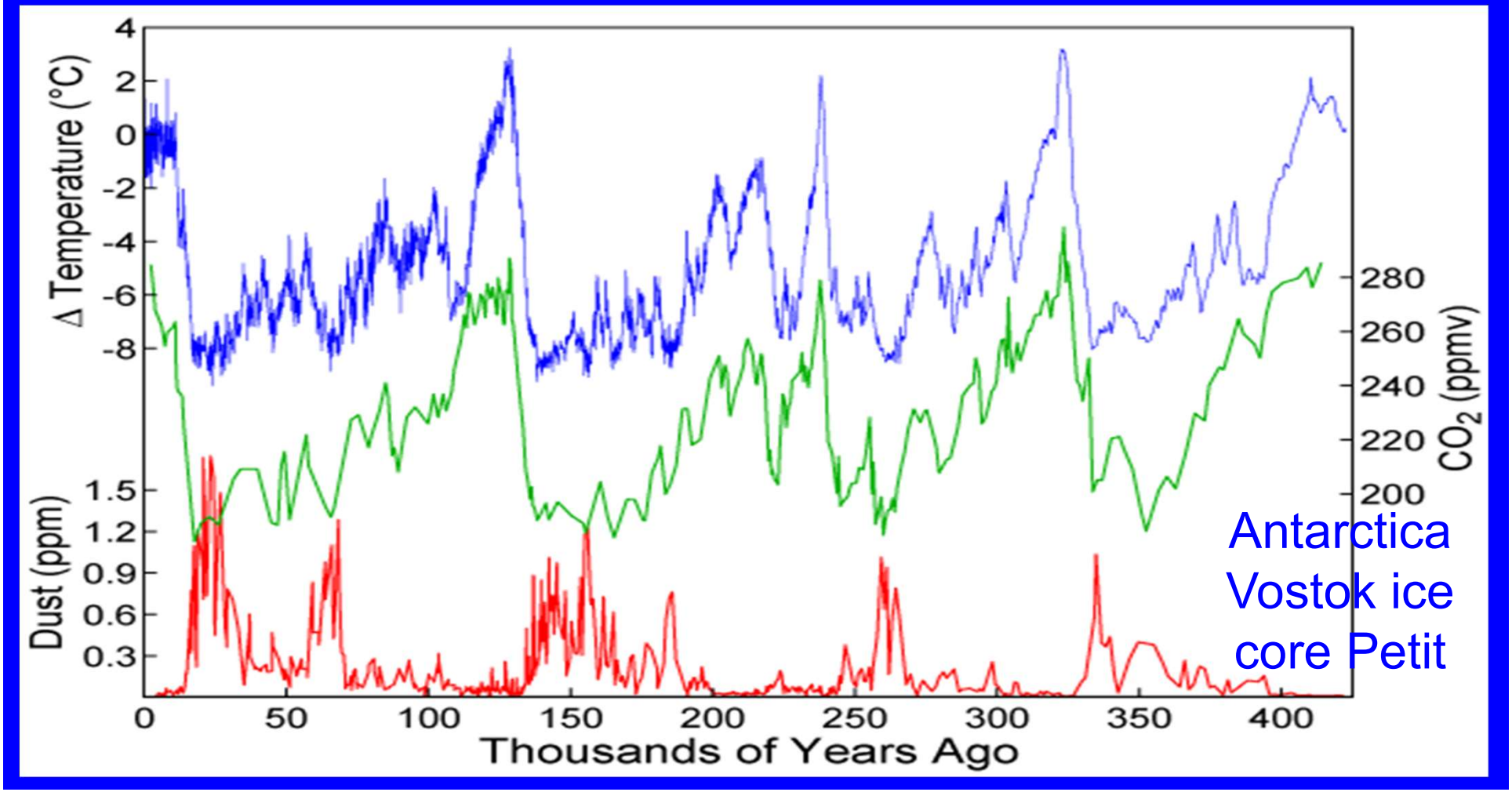
5. Domestic & international economic arrangements (incentives, production, trade or tariffs, regulation)
6. Domestic & international demographic arrangements (marriage, family, birth, death, migration, age structure, cities)

How many people Earth can support depends on

7. Physical, chemical & biological environment

How many people Earth can support depends on

8. Variability or stability



How many people Earth can support depends on

9. Risk or robustness
10. Time horizon
11. Values, tastes & fashions

Parks?

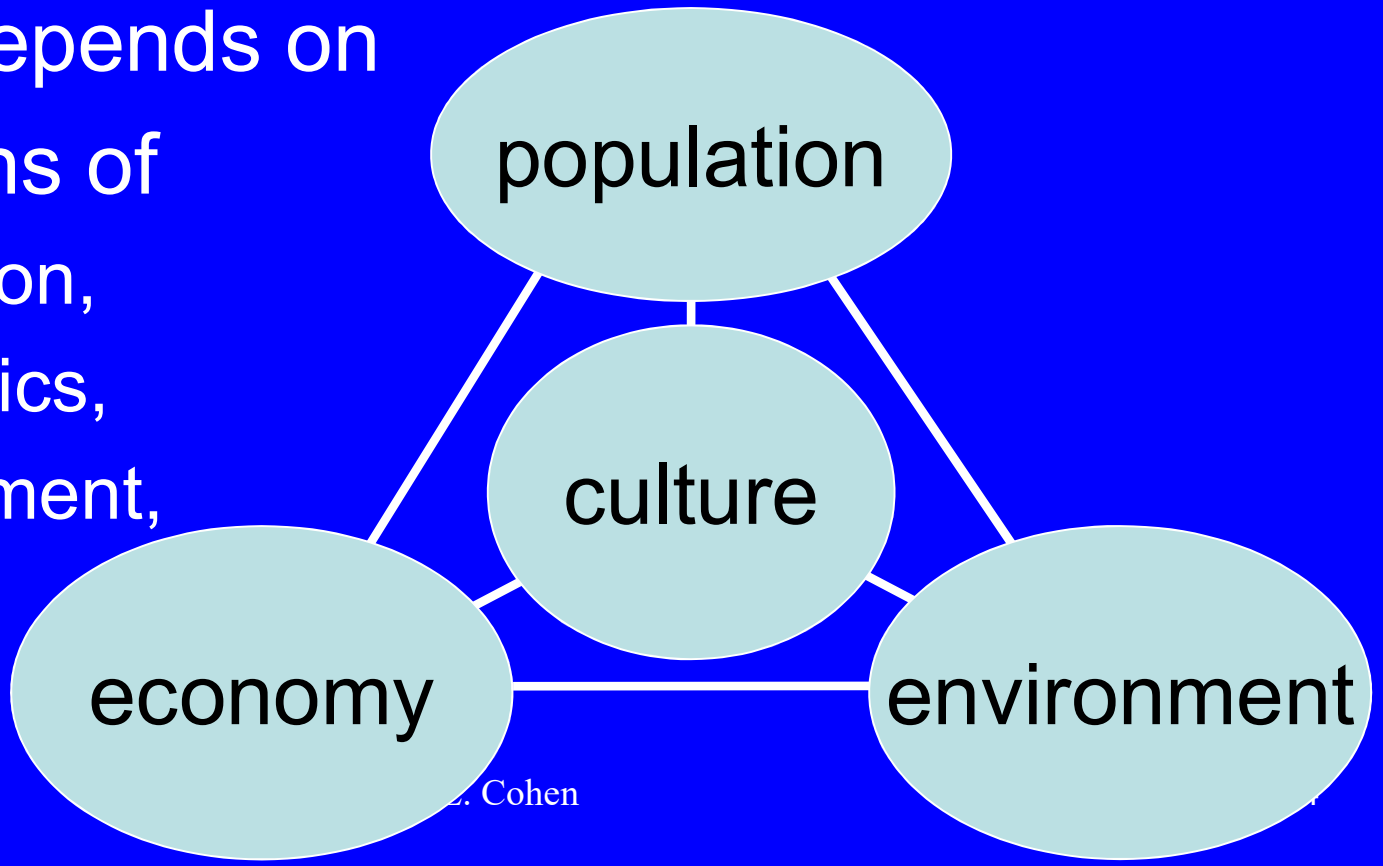
Parking lots?

How many people can Earth support?

Answer depends on natural constraints & human choices.

Answer depends on interactions of

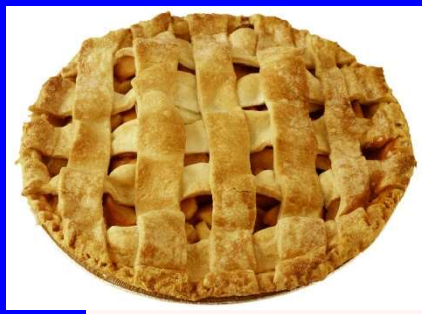
- Population,
- Economics,
- Environment,
- Culture.



Increasing population size makes difficult trade-offs more difficult long before population size approaches "hard limits."

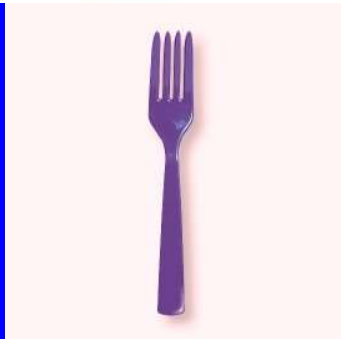
Rapid population growth continues in poor countries. It poses serious challenges to them & to the rest of the world.

Proposed panaceas



Bigger pie

increase productive capacity



Fewer forks

slow population growth through voluntary reductions in fertility

reduce unwanted material by-products of consumption & production

Better manners

reduce violence, corruption, inequities, barriers to efficiency

Cohen, *How Many People Can the Earth Support?* 1995

Outline

How many people can Earth support? (1995)

Lessons since then

→ Education

Nutrition

Proposal:
Educating all children well for 10-12 years could support
Bigger pie,
Fewer forks,
Better manners.

Universal Basic & Secondary Education (UBASE) Project

American Academy of Arts & Sciences, 1998-2007

What would the world be like if all children had 10-12 years of high-quality education?

(not only primary or basic)

What would it take to achieve such a world by 2050 or sooner?

EDUCATING ALL CHILDREN
A GLOBAL AGENDA

edited by
Joel E. Cohen, David E. Bloom,
and Martin B. Malin

American Academy of Arts and Sciences

MIT Press, 2006

International Perspectives on the Goals of Universal Basic and Secondary Education

Edited by Joel E. Cohen
and Martin B. Malin

AMERICAN ACADEMY
OF ARTS & SCIENCES

ROUTLEDGE

Routledge, 2010

Conclusion:

Educating all children well with high-quality primary & secondary education is a worthwhile, affordable, & achievable strategy to develop people who can cope with future problems.

Lutz, "Towards a world of 2-6 billion well-educated and therefore healthy and wealthy people." JRSS-A 2009

"… educational attainment is the key driver of economic growth. Moreover, … universal primary education is not enough, and only when combined with broadly based secondary education will the poorest countries be able to come out of their poverty traps. … for industrialized countries, tertiary education matters most."

Lutz, "Towards a world of 2-6 billion well-educated and therefore healthy and wealthy people." JRSS-A 2009

"…progress in female [& male] education together with access to family planning services are the key determinants of future population growth in the less developed countries."

Universal Basic & Secondary Education studies raised 3 additional questions:

Costs

Goals

Nutrition

Costing universal education is hard.

- The cost per child who is NOT in school now probably differs from the cost per child ALREADY in school.
  - more remote, poorer, minority, disadvantaged
- Access to schooling at present level of quality may not suffice to induce parents to send children.
  - costs of quality improvements, food incentives
- Means of education may not be conventional school.
  - information centers, homes, work & school

Melissa Binder, Department of Economics, University of New Mexico

Enrollment data

- Gross Enrollment Rate (GER) provided by 90% of countries in sample

$$GER = \frac{All\ Students}{School\ \ Age\ Population}$$

- Net Enrollment Rate (NER) provided by 2/3 of countries in sample

$$NER = \frac{School\ \ Age\ Students}{School\ \ Age\ Population}$$

Average annual costs over 25 years for achieving 90% NER (NER = net enrollment ratio)

Melissa Binder	Repetition unchanged	Repetition reduced to 7%
90% NER in 15 years	$44.6 bln	$29.4 bln
90% NER in 25 years	$28.2 bln	$24.3 bln

Why so much repetition?

What is the opportunity cost of having hundreds of millions of children *not* get secondary education of high quality—
costs
to those children & their families?
to their countries?
to the world's economy & society?

Cost is not the only obstacle.

Economic disincentives. Families value more the time children spend working for income or handling chores so other household members can work for pay.

Competing demands. Education competes for scarce national resources with roads, medical care, & defense. Returns on investment in education are difficult to measure.

Lack of information. Internationally comparable, useful data on quality of 1^{o} & 2^{o} education are lacking.

Political obstacles. Benefits of schooling accrue too slowly to benefit political incumbents. Violence.

Cultural barriers. Discrimination inhibits schooling for girls, linguistic, religious, & ethnic minorities.

Historical context. History of education in a country affects success of externally imposed solutions.

What are goals of 2^{o} education?

UNESCO was supposed to address goals but focused on universal access to school.

Goals of education influence

- priorities for how educational funds are used,
- assessments of how successfully children are learning.

Universal *secondary* education is important because:

It is a source of new teachers for countries with rapidly expanding access to primary schools.

It provides an opportunity & an incentive for students who complete primary school.

It has demographic impacts: delayed & reduced fertility, improved survival of children & adults.

Why is education important?

Gustavo Bell Lemus. Vice-President & Defense Minister of Colombia (1998-2002),
David E. Bloom, Harvard, & Patricia Craig, IBM Latin America

	Society	Individual
Social	Equity	Human Development/ Human Rights
Political	Democracy	Access to Political Process
Economic	Income Growth	Earnings/ Poverty

4. Demographic: fertility, health, child & adult survival
5. Environmental: respecting nature, coping with change
6. Cultural: tradition, religion, manners, values (re change, skepticism, independence, diversity, equity, justice, mercy)
7. Personal: self-understanding (biological, psychological & cultural), self-expression, & self-control

Content of education matters.

Will children learn:

the workings of their own bodies & minds & the bodies & minds of others?

the history, strengths & limits of their own culture & at least one other culture?

the skills to cope with intra- & inter-national, religious & cultural diversity?

to love people, nature, understanding (natural & social sciences) & beauty (the arts)?

Outline

How many people can Earth support? (1995)

Lessons since then

- Education
- → Nutrition

Camer Vellani MD: children cannot learn if their brains do not work.

In Sindh, among urban & rural children under 3 years old, 40% were stunted, 37% had “delayed psychomotor development” by age 3.

B.I. Avan, B.Kirkwood, *Soc. Sci. & Med.* 71:102-109 (2010)

Age	N	Normal (%)	Delayed (%)
First Year	454	86	14
Second Year	454	78	22
Third Year	336	63	37
Overall	1,244	77	23

Avan 2007

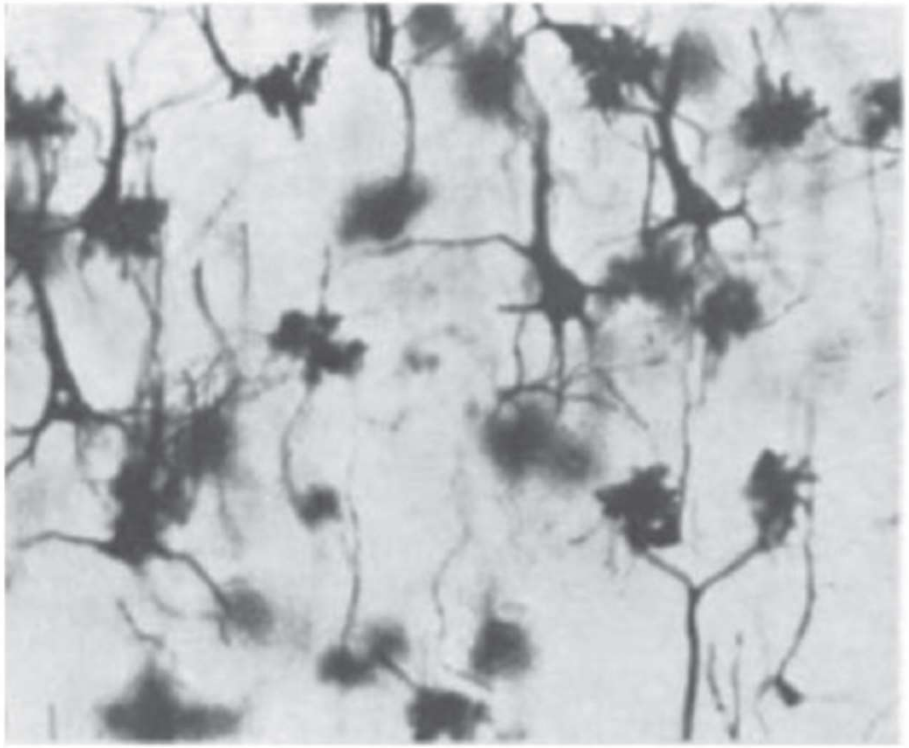
Undernourishment alters brain.

M. de Onis & F. Branca 2016 from Cordero et al. 1993

Well-nourished infant

Typical brain cells
Extensive branching

Undernourished infant



Impaired brain cells
Limited branching
Abnormal, shorter branches

Remember the high repetition rates?

Educating all children well for 10-12 years could support:

Bigger pie
Fewer forks
Better manners

Educate all the children.
Feed all the children
(& their mothers).

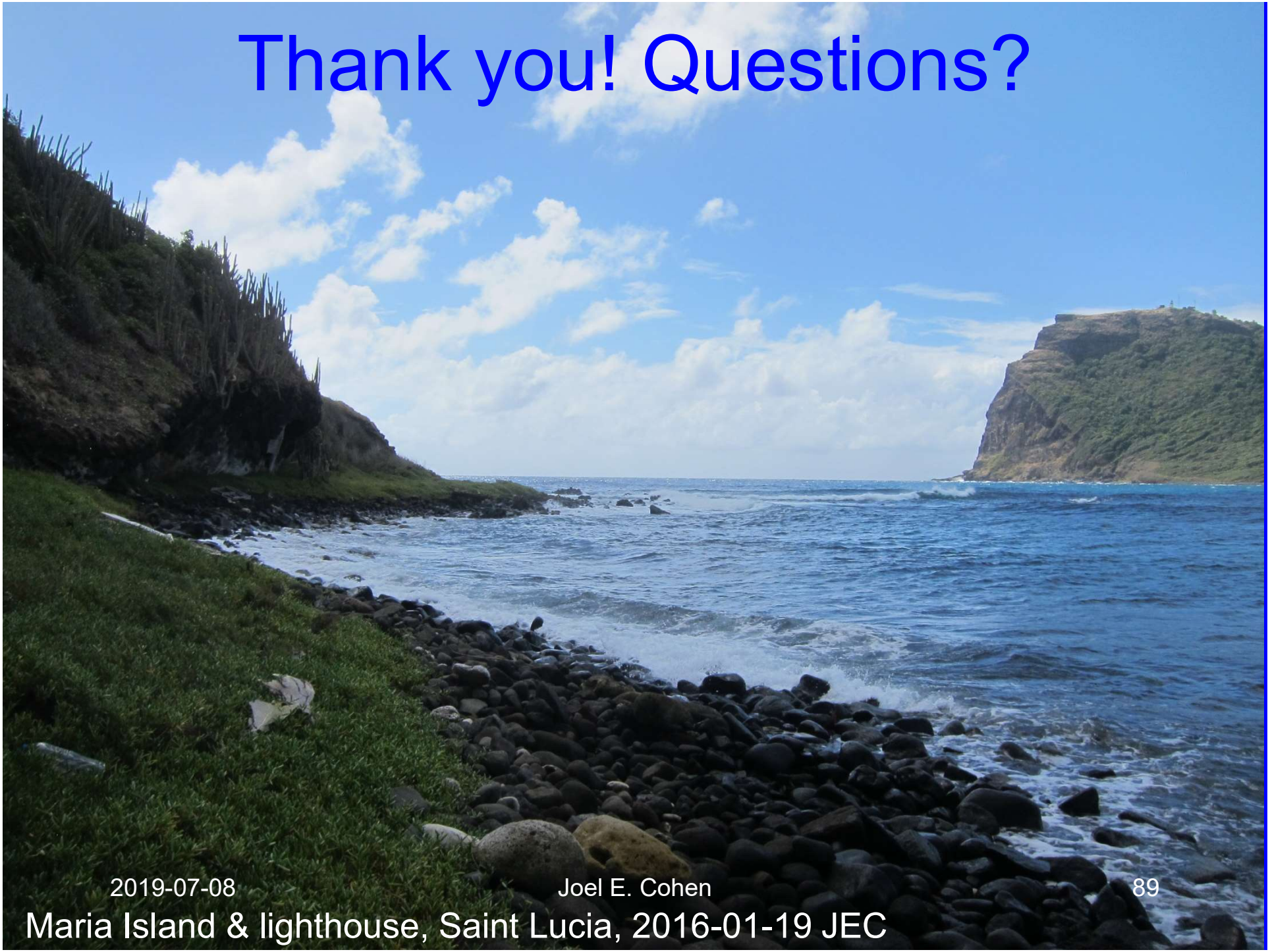
Multiple choice test

1. How many people can the Earth support?
<10 billion; ≥10 billion; don't know

2. The human population of the Earth is now and will in the future be limited by food.
T, F

3. Rapid population growth helps human well-being because it creates more people to solve problems.
T, F

Thank you! Questions?



Maria Island & lighthouse, Saint Lucia, 2016-01-19 JEC