Global biophysical constraints on urban systems

James H. Brown
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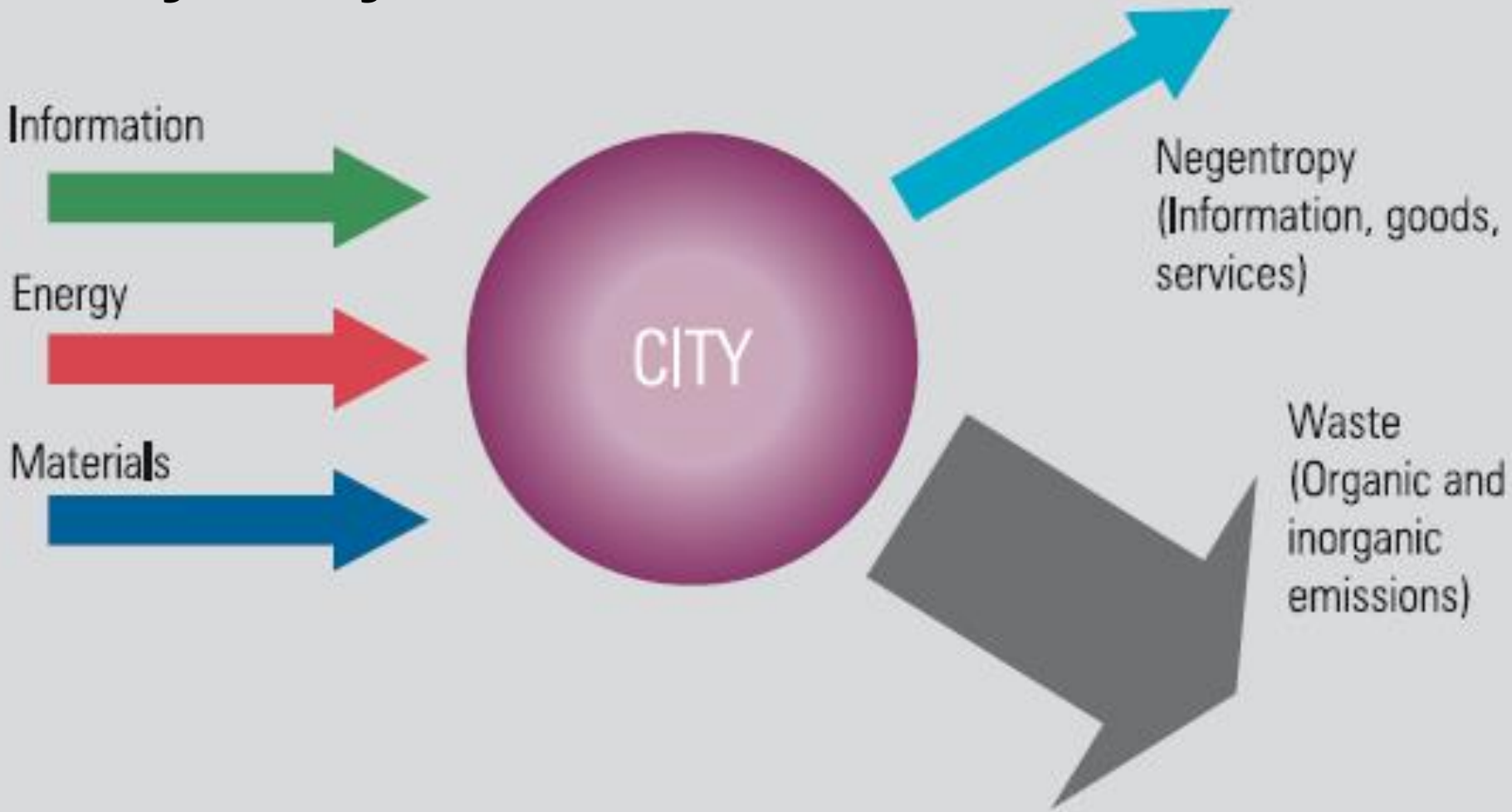
University of New Mexico

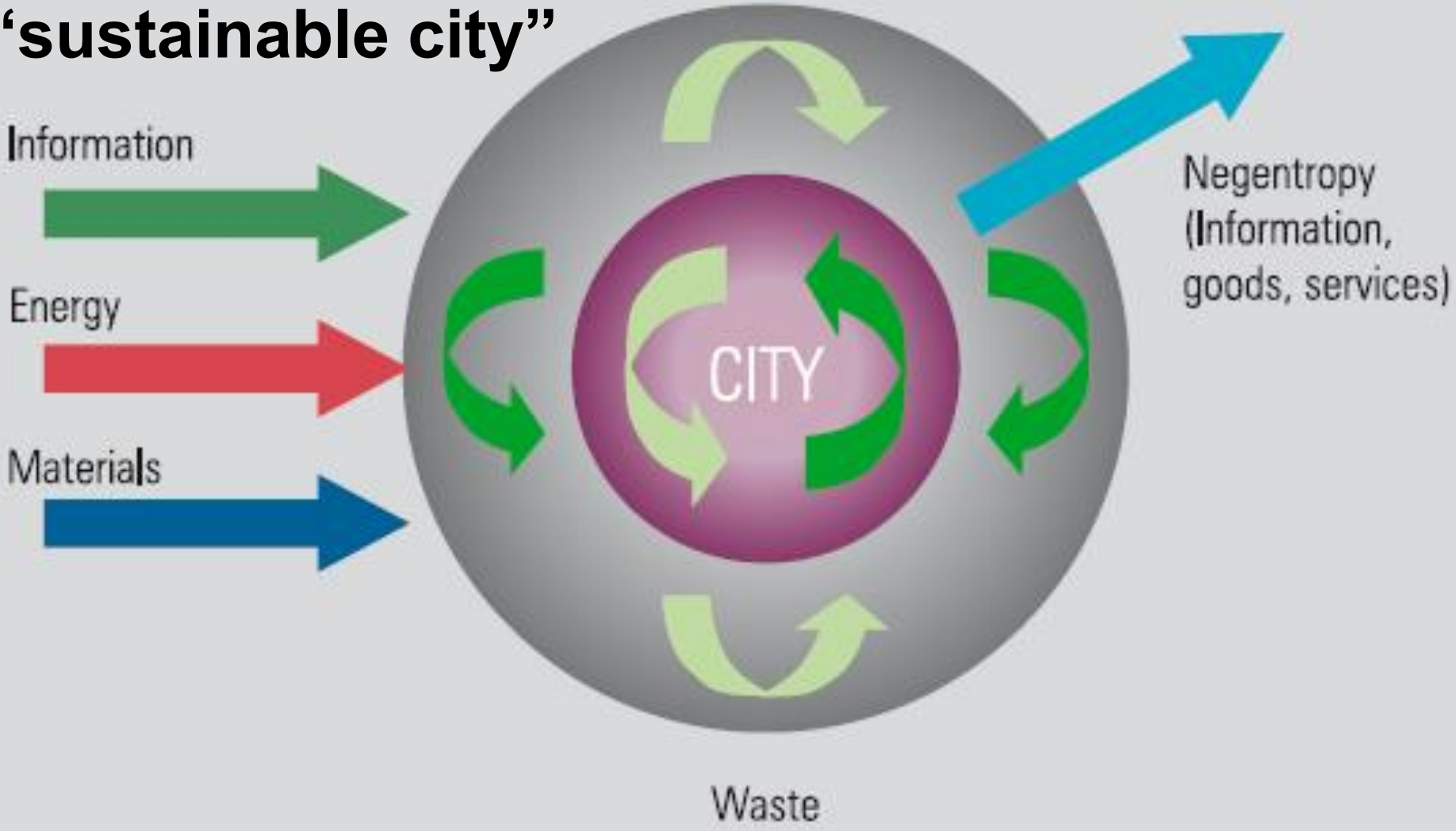
“today’s city”



From: State of the World's Cities 2008/9: Harmonious Cities By Un-Habitat

THIS PICTURE IS OK

“sustainable city”



From: State of the World's Cities 2008/9: Harmonious Cities By Un-Habitat

WHAT IS WRONG WITH THIS PICTURE?

THREE POINTS:

1. PHYSICS AND BIOLOGY CONSTRAIN THE "SUSTAINABILITY" OF ALL HUMAN SYSTEMS

CITIES MUST OBEY ALL SCIENTIFIC LAWS

2. CITIES ARE OPEN SYSTEMS, EMBEDDED IN LARGER REGIONAL AND GLOBAL SYSTEMS

ENERGY AND MATERIALS FLOW IN AND OUT

NO CITY CAN BE SELF-SUSTAINABLE

3. "SUSTAINABILITY" OF A CITY DEPENDS ON GLOBAL BIOPHYSICAL CONSTRAINTS

HUMAN WELL-BEING AND SOCIOECONOMIC ACTIVITY DEPEND ON BOTH THE GLOBAL ENVIRONMENT AND INTERNAL CONDITIONS

NEED TO DO A BIOPHYSICAL ANALYSIS

1. INVIOLATE LAWS OF NATURE

- Laws of thermodynamics and conservation of mass, energy, and stoichiometry govern the stocks and flows of energy and materials
- Humans transform energy and materials to "create" goods and services, and produce wastes (e.g., CO_2, toxins, sewage)
- Principles of biology govern human physiology and behavior
  - Metabolism: food, water, clothing, shelter
  - Malthusian-Darwinian Dynamic: use resources and creativity selfishly to grow population and economy
- Cannot "innovate" around these laws

2. NO CITY IS AN ISLAND

All cities are open systems, embedded in regional and global systems

They depend for their existence on flows across the boundaries:

Biological:

Input of food (2,000 kCal/day), water, etc.

Output of “sewage”

Physical:

Input of energy and raw materials

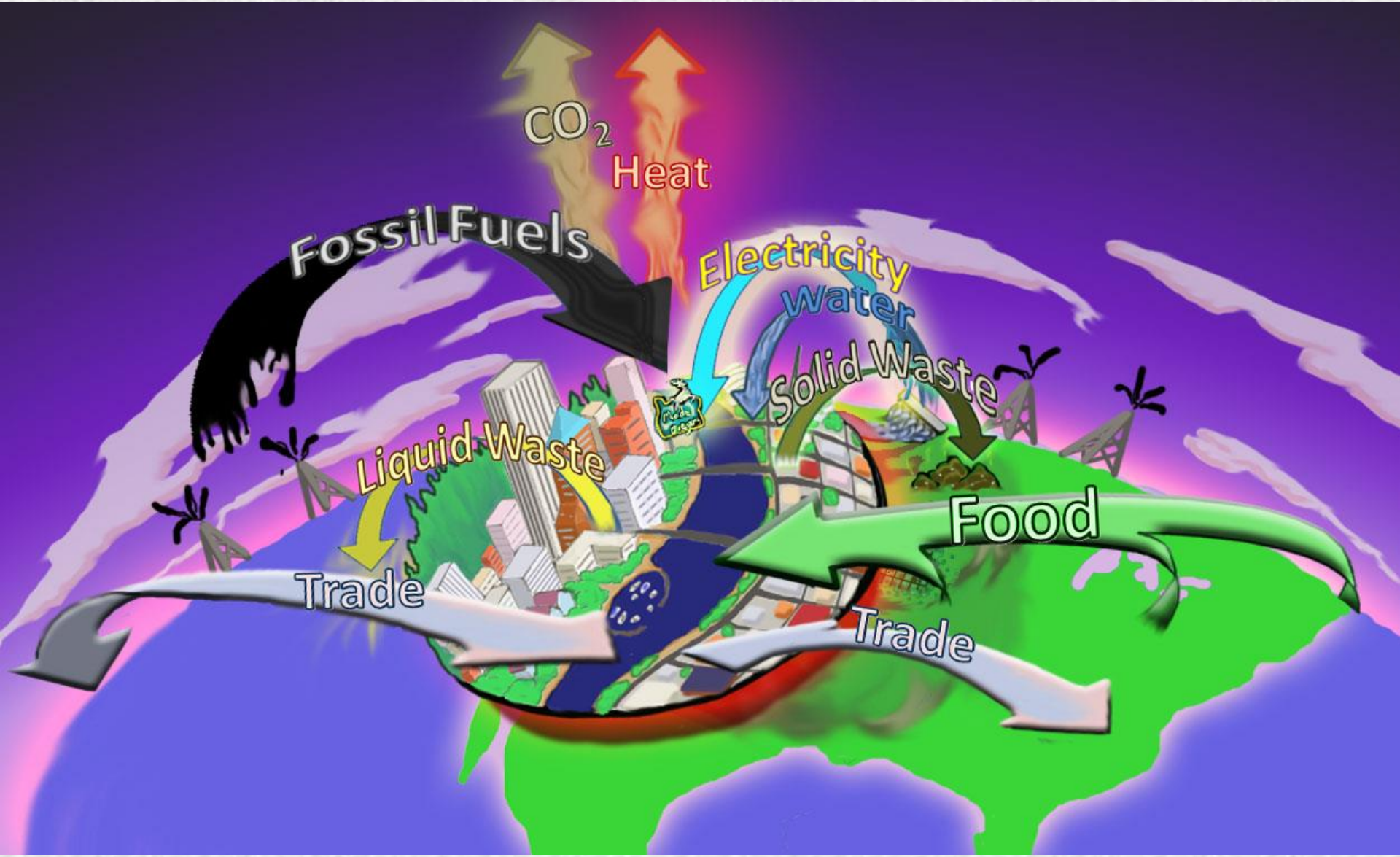
Output of wastes: CO_2, toxins, heat

Malthusian-Darwinian Dynamic governs human behavior and drives consumption

Portland, Oregon

“The most sustainable city in America”

Portland, Oregon



Source: Burger, Joseph R. et al. "The macroecology of sustainability." PLoS biology 10, no. 6 (2012): e1001345.

Portland, Oregon

- **Portland and Multnomah County:**
  population 715,000, median income $51,000
- **Imports and consumes:**
  1.25 billion liters of gasoline
  28.8 billion megajoules of natural gas
  31.1 billion megajoules of electricity
  136 billion liters of water
  0.5 million tonnes of food
- **Exports and releases:**
  8.5 million tonnes of carbon as CO_2
  99 billion liters of liquid sewage
  1 million tonnes of solid waste

A SELF-SUSTAINABLE CITY IS BIOPHYSICALLY IMPOSSIBLE

- No city can survive without
  - Importing food, energy, and raw materials
  - Exporting wastes and manufactured goods
- Flows determine the "ecological footprint": foodshed, watershed, energy network, sources of raw materials, pollution sink
- Magnitudes of flows depend on population and socioeconomic development
  - Orders-of magnitude higher consumption in rich developed economies than poor developing economies (London vs. Lagos)

AGRICULTURE: CAN A CITY FEED ITSELF? LET'S DO THE ARITHMETIC

36 cities have densities:

>200,000/km^2 or <0.5 m^2 ground area per person

Most productive agriculture:

10 tonnes/ha/yr for Green Revolution rice

Caloric value of rice:

1.5 kcal/g

Human metabolic requirement is 2,000 kcal/day

730,000 kcal/yr

480 kg of rice per person

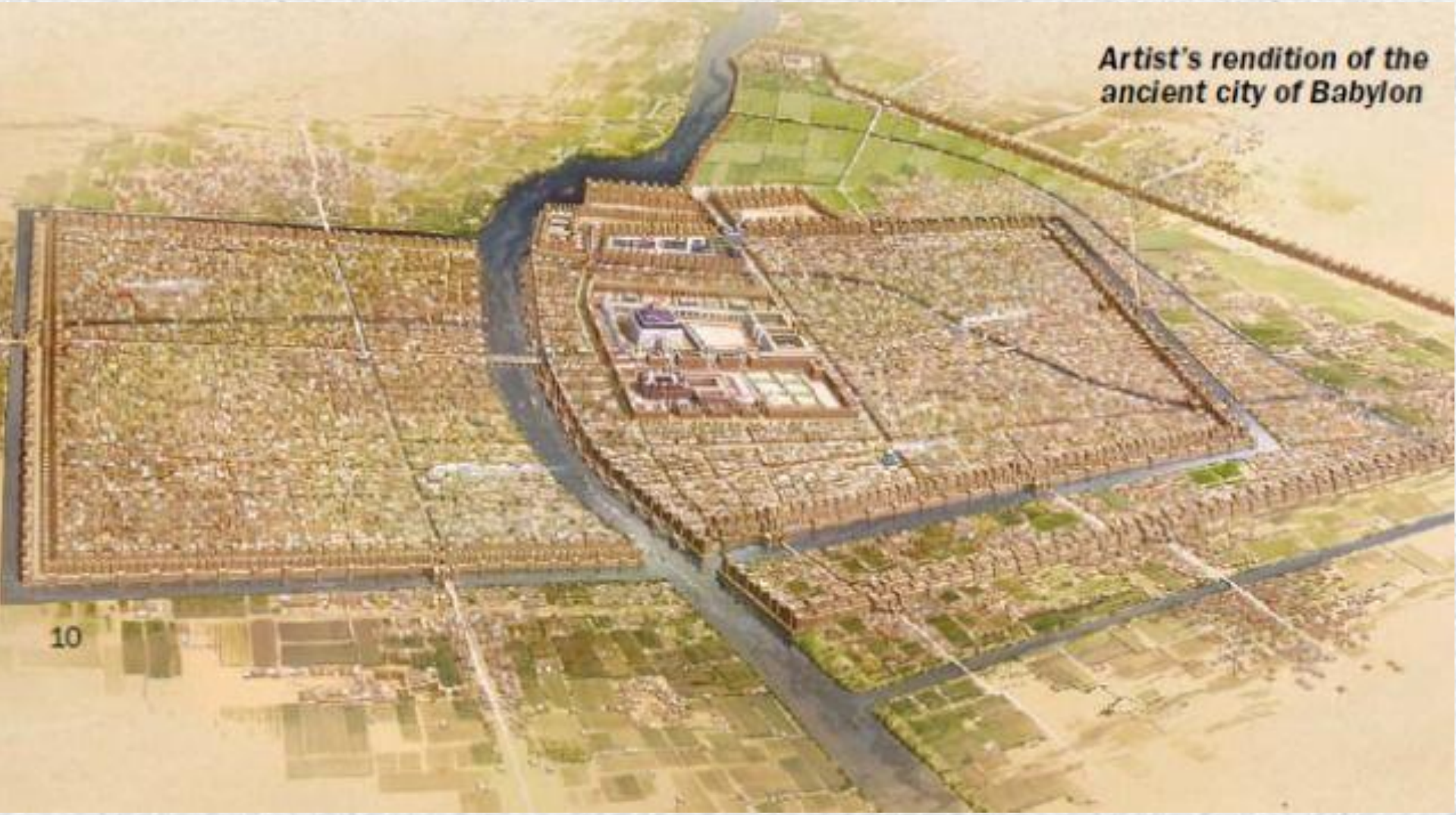
Agricultural area required per person:

0.05 ha or 500 m^2

So you need 1,000 times more land area/person

NO CITY CAN FEED ITSELF!

ANCIENT BABYLON SURROUNDED BY PART OF ITS FOODSHED



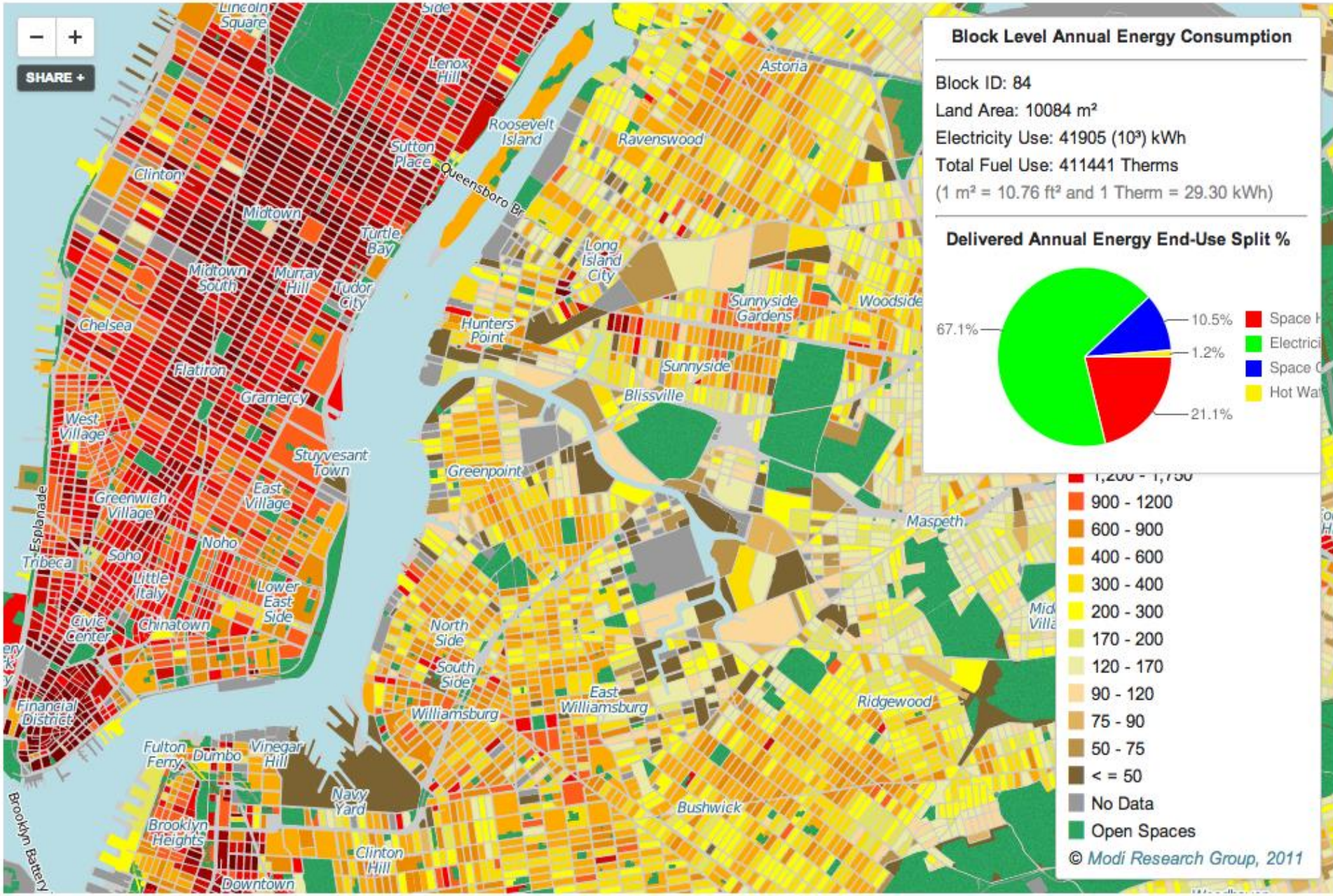
Source: http://zoroastrianheritage.blogspot.com

ENERGY: CAN A CITY POWER ITSELF?
LET'S DO THE ARITHMETIC

36 cities have densities:
>200,000/km^2 or <0.5 m^2 ground area per person
Solar energy input (insolation):
150 to 300 W/m^2 or 3.5 to 7.0 kWh/m^2/day
Efficiency of solar energy capture:
30% for CSP-Stirling, 15% for photovoltaic
Human extra-metabolic energy use:
2,000 W global average, 100,000 W for US
Area required:
22 to 1,100 m^2 per person
So you need 44 to 550 times more area/person

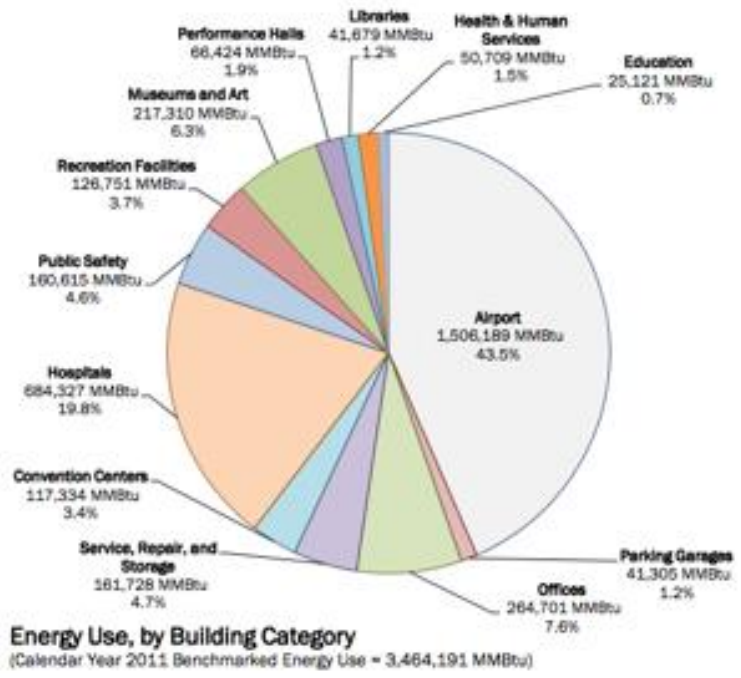
NO CITY CAN POWER ITS ECONOMY!

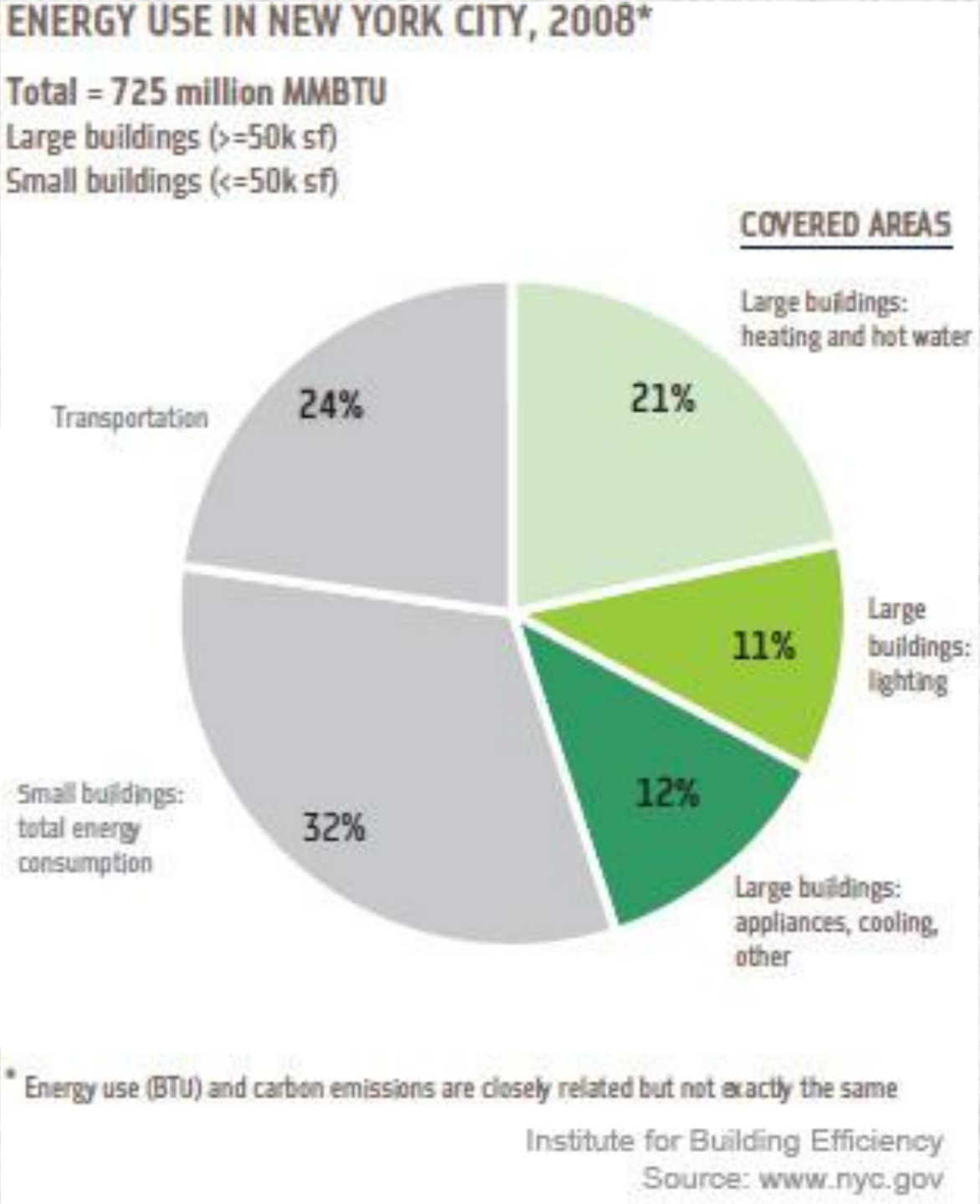
Total Annual Building Energy Consumption for New York City



Data Source: Spatial distribution of urban building energy consumption by end use
B. Howard, L. Parshall, J. Thompson, S. Hammer, J. Dickinson, V. Modi

EXTRA-METABOLIC ENERGY USE IN CITIES

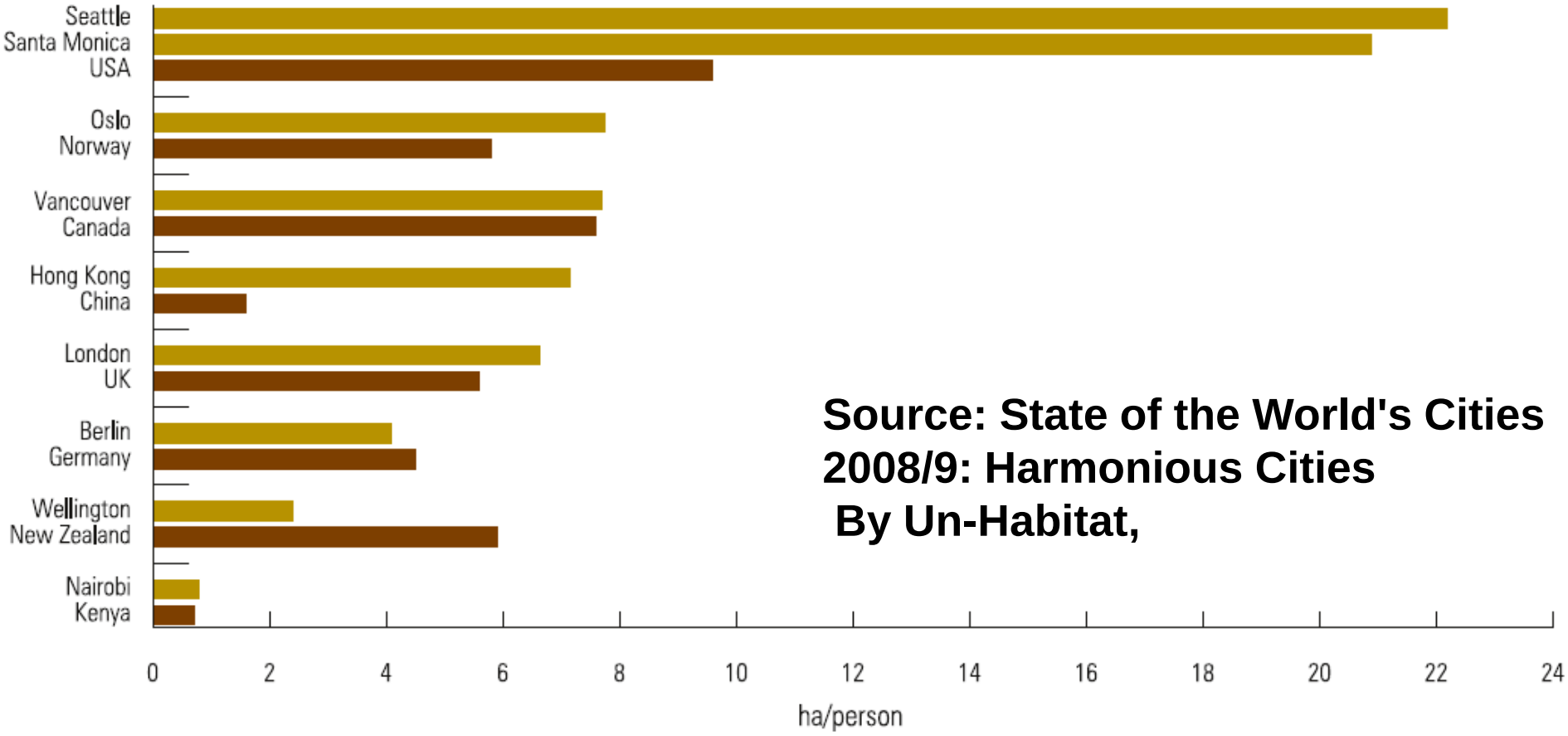




Source: State of the World's Cities 2008/9: Harmonious Cities By Un-Habitat

ECOLOGICAL FOOTPRINTS OF CITIES ARE COMPARABLE TO AVERAGE FOR COUNTRIES

FIGURE 3.4.9: **ECOLOGICAL FOOTPRINT OF SELECTED CITIES AND OF THE COUNTRIES WHERE THEY ARE LOCATED**



Source: State of the World's Cities 2008/9: Harmonious Cities By Un-Habitat,

Source: UN-HABITAT Global Urban Observatory 2008

3. “SUSTAINABILITY” DEPENDS ON GLOBAL BIOPHYSICAL CONSTRAINTS

Cities are not ecologically efficient

With increasing population and development

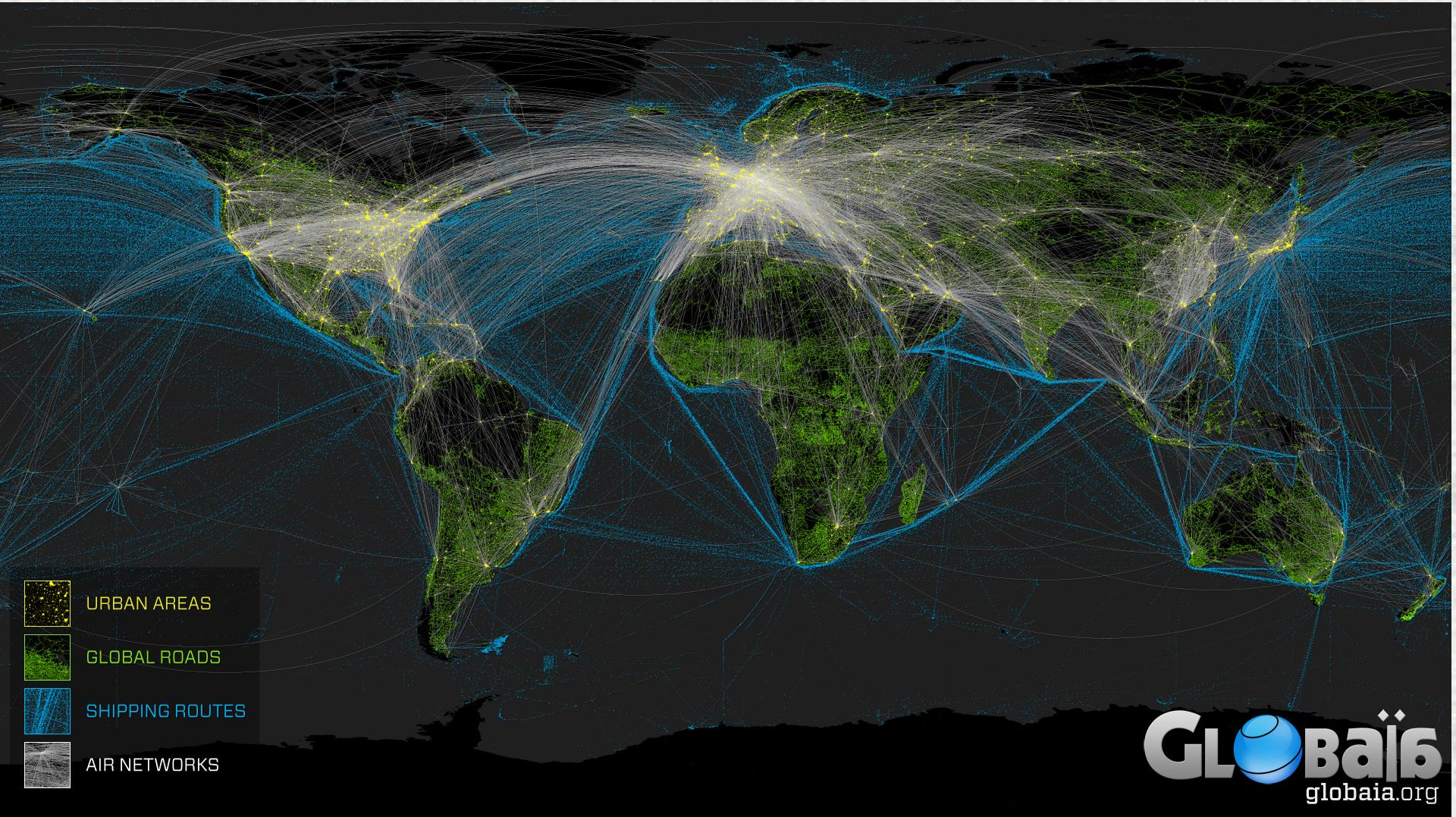
i) the ecological footprint increases

ii) more energy and infrastructure are required to supply resources and remove wastes, to provide goods and services

Global constraints on agriculture and fossil fuels will determine the future of humankind

There is not enough food and fossil fuel for 10 billion people living Chinese lifestyles

GLOBAL FLOWS SUSTAIN MODERN ECONOMIES AND CITIES



GLOBAL CONSTRAINTS: FOOD

Metabolic energy use:

- **Food energy used by global population**
  - **100 W/capita x 7.2 billion = 0.72 TW**
- **Terrestrial net primary production = 63.4 TW**
- **Humans consume about 1% of global photosynthetic production as food**

Extra-metabolic energy use (mostly fossil fuels) for agriculture = 2.3 TW :

- **Total global energy use = 15 TW**
- **About 15 % of total energy is used to grow, harvest, preserve, transport food**
- **This is more than three times the energy content of the food**

GLOBAL CONSTRAINTS: ENERGY AND ECONOMICS

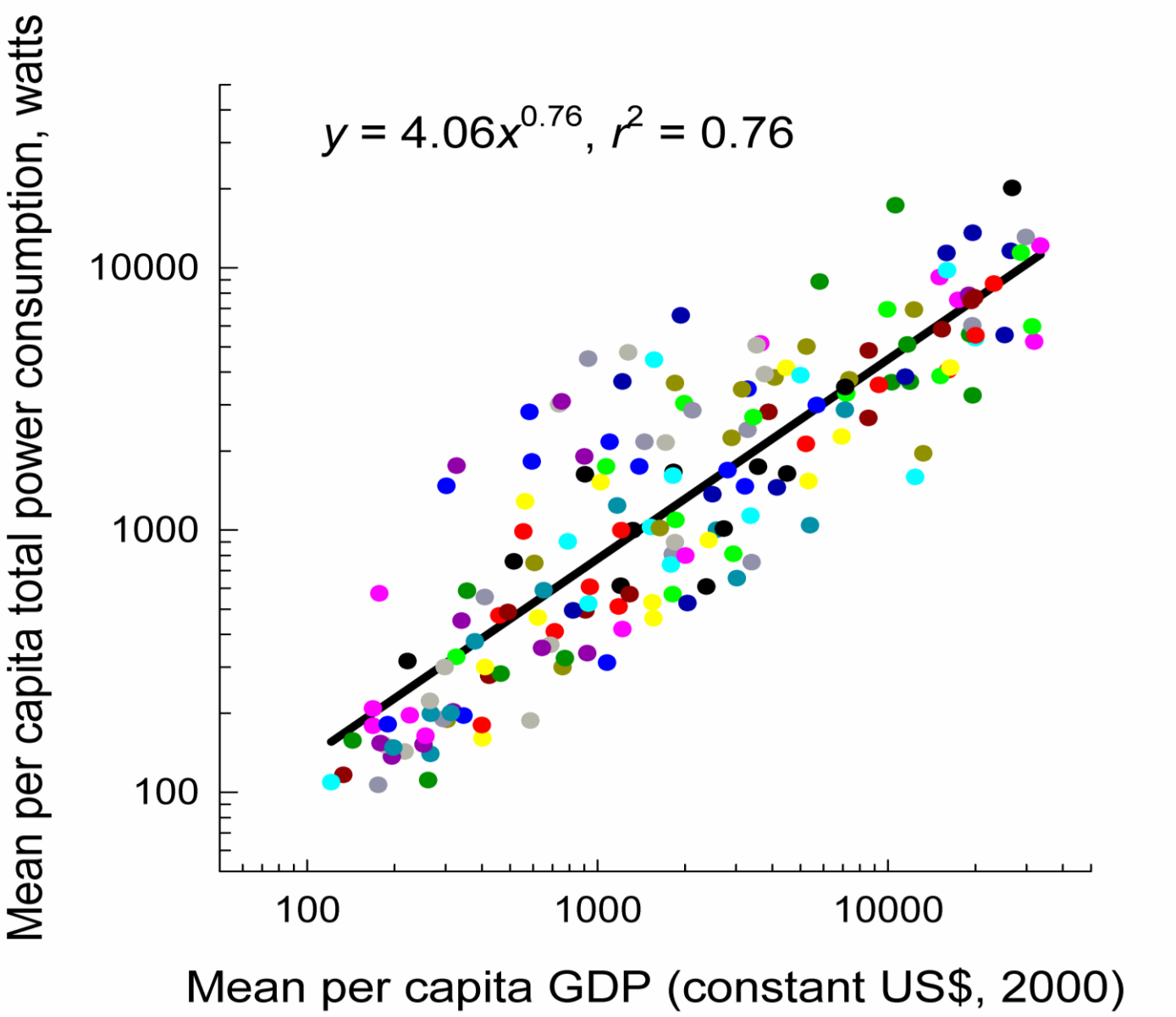
Human population and economy are sustained by consuming energy

Most energy (85%) comes from fossil fuels

Per capita GDP tracks per capita energy use across nations and cities

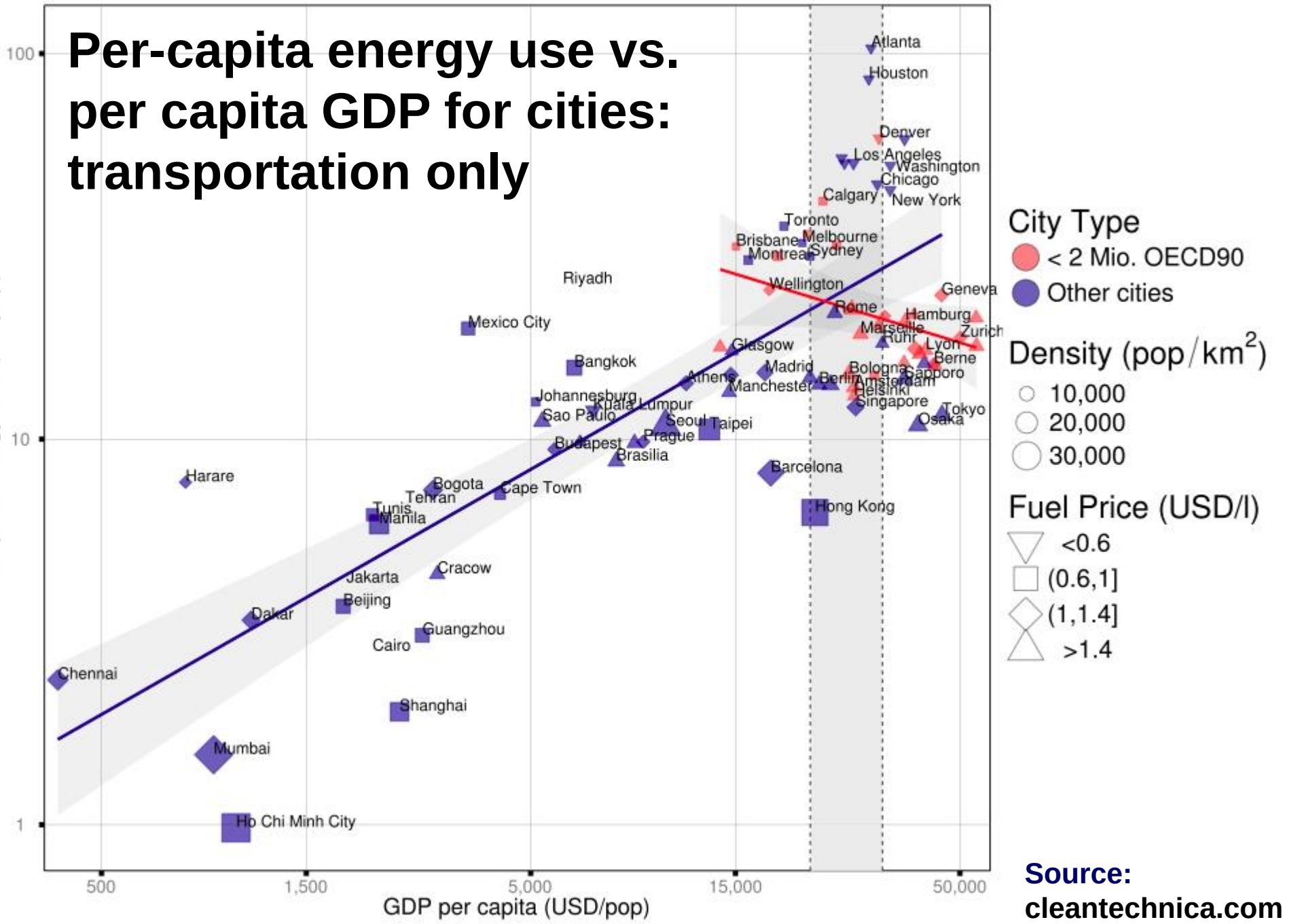
There is not enough energy to fuel optimistic projections for growth of population and economy, and increased standard of living

Per-capita energy use vs. per capita GDP for countries: 25-year averages



Source: Brown, J. H. et al. (2014). Macroecology meets macroeconomics: Resource scarcity and global sustainability. Ecological engineering, 65, 24-32.

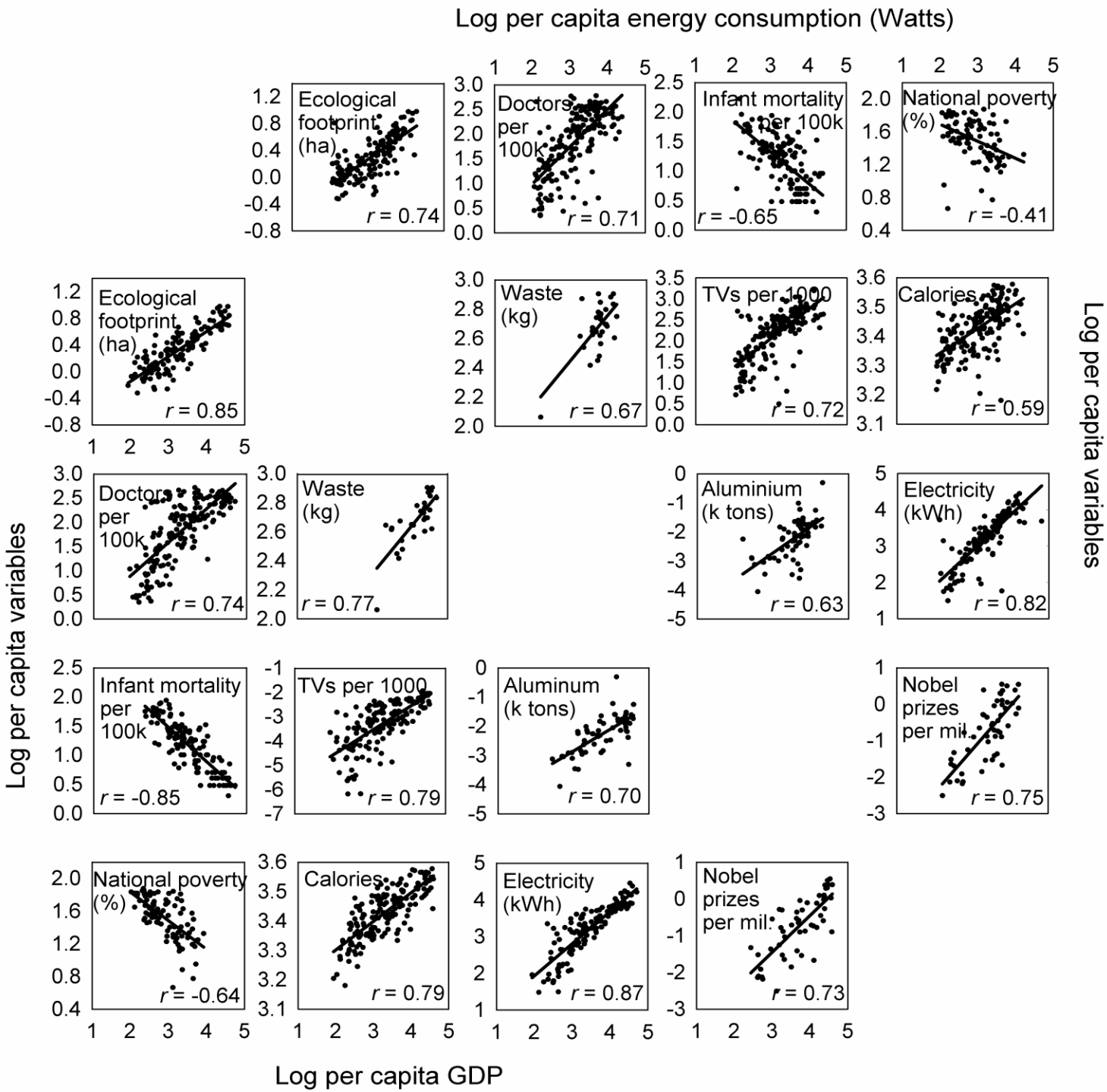
Per-capita energy use vs. per capita GDP for cities: transportation only



Source:
cleantechnica.com

QUALITY OF LIFE

All metrics are correlated with GDP and energy use

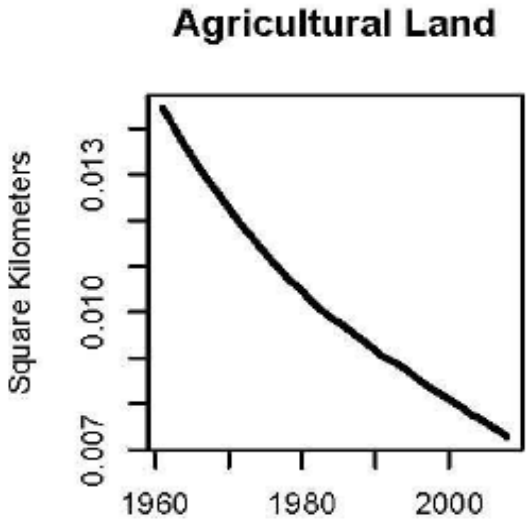


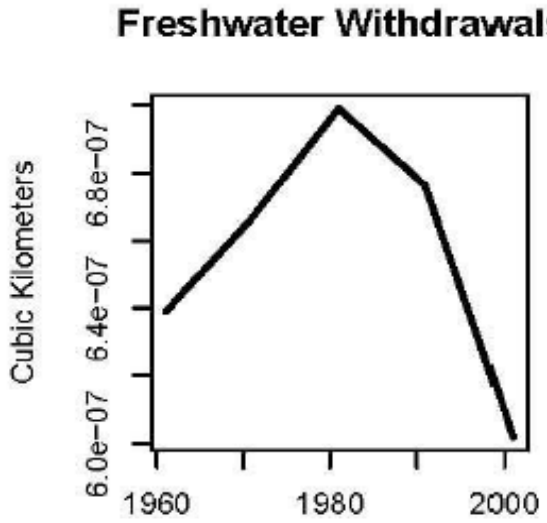
Source:
Brown, J. H., et al. (2011). Energetic limits to economic growth. BioScience, 61:19-26.

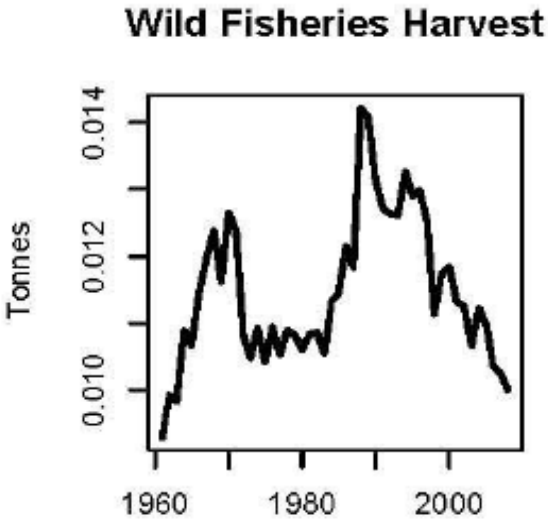
INCREASING RESOURCE SCARCITY

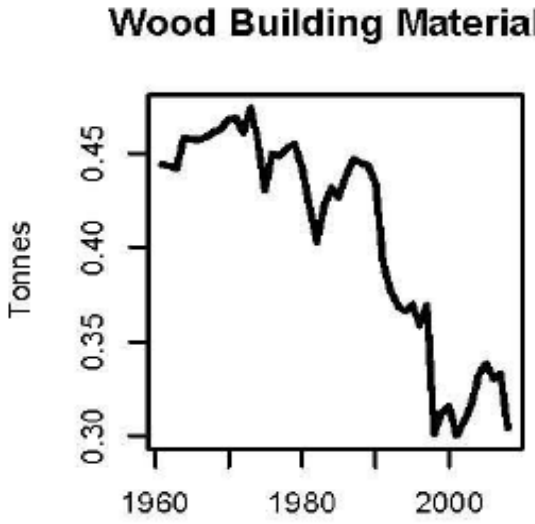
Per capita consumption of critical resources is decreasing

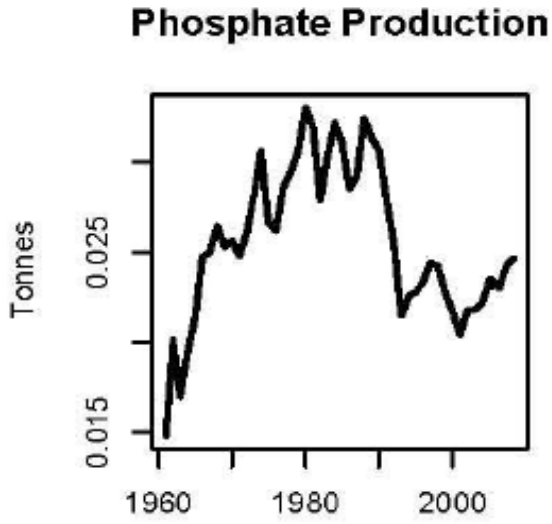
Burger et al. 2012

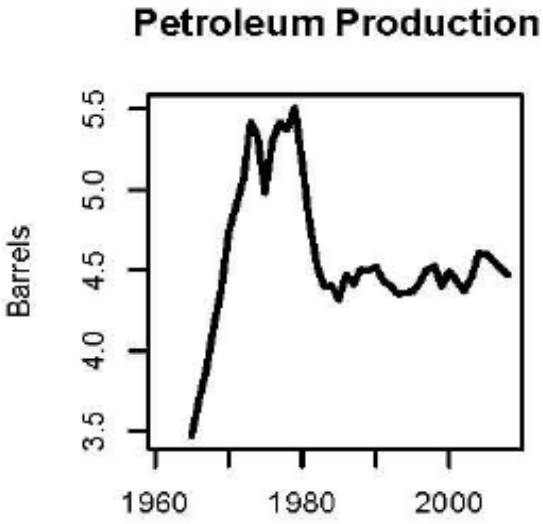










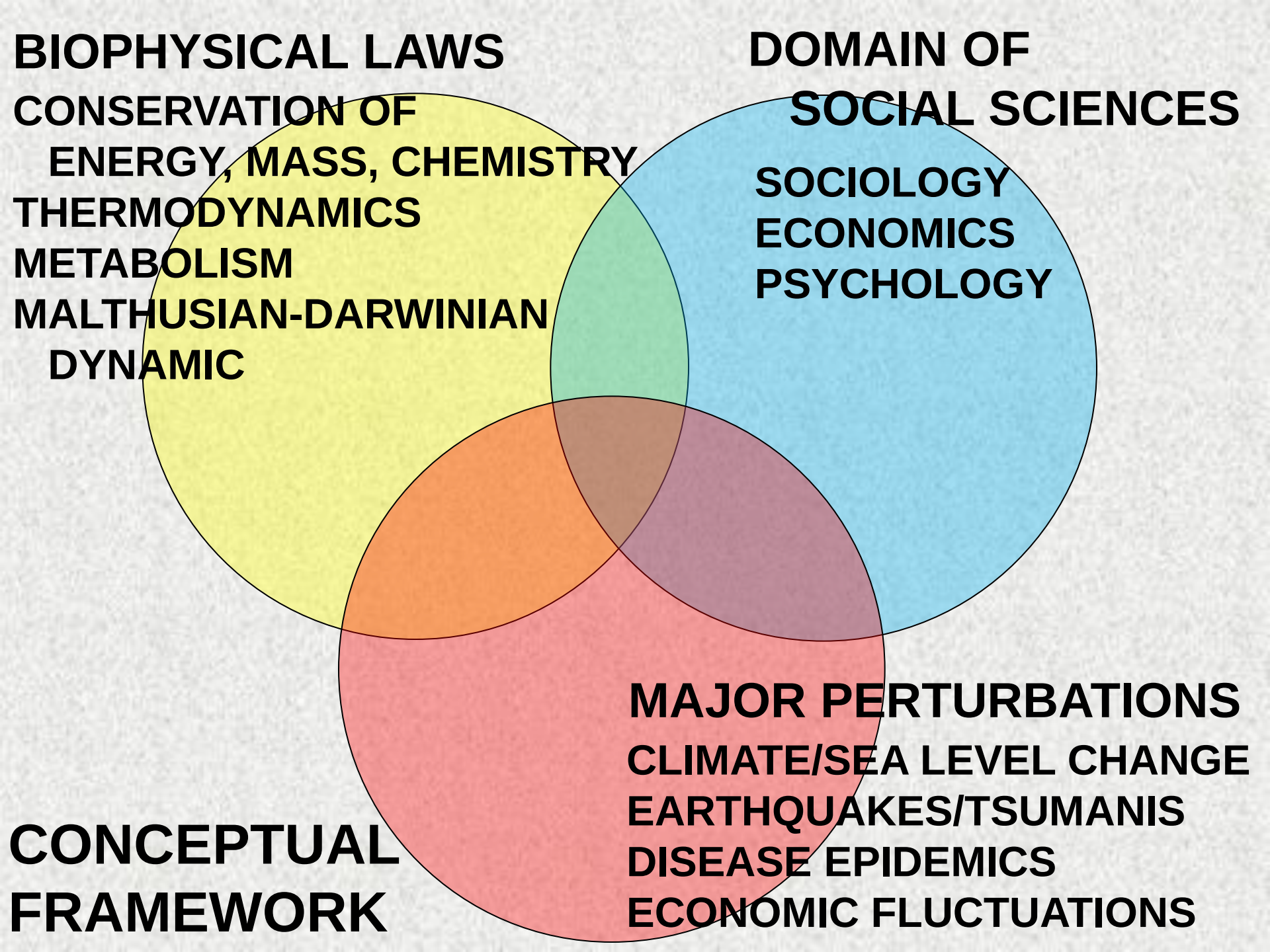


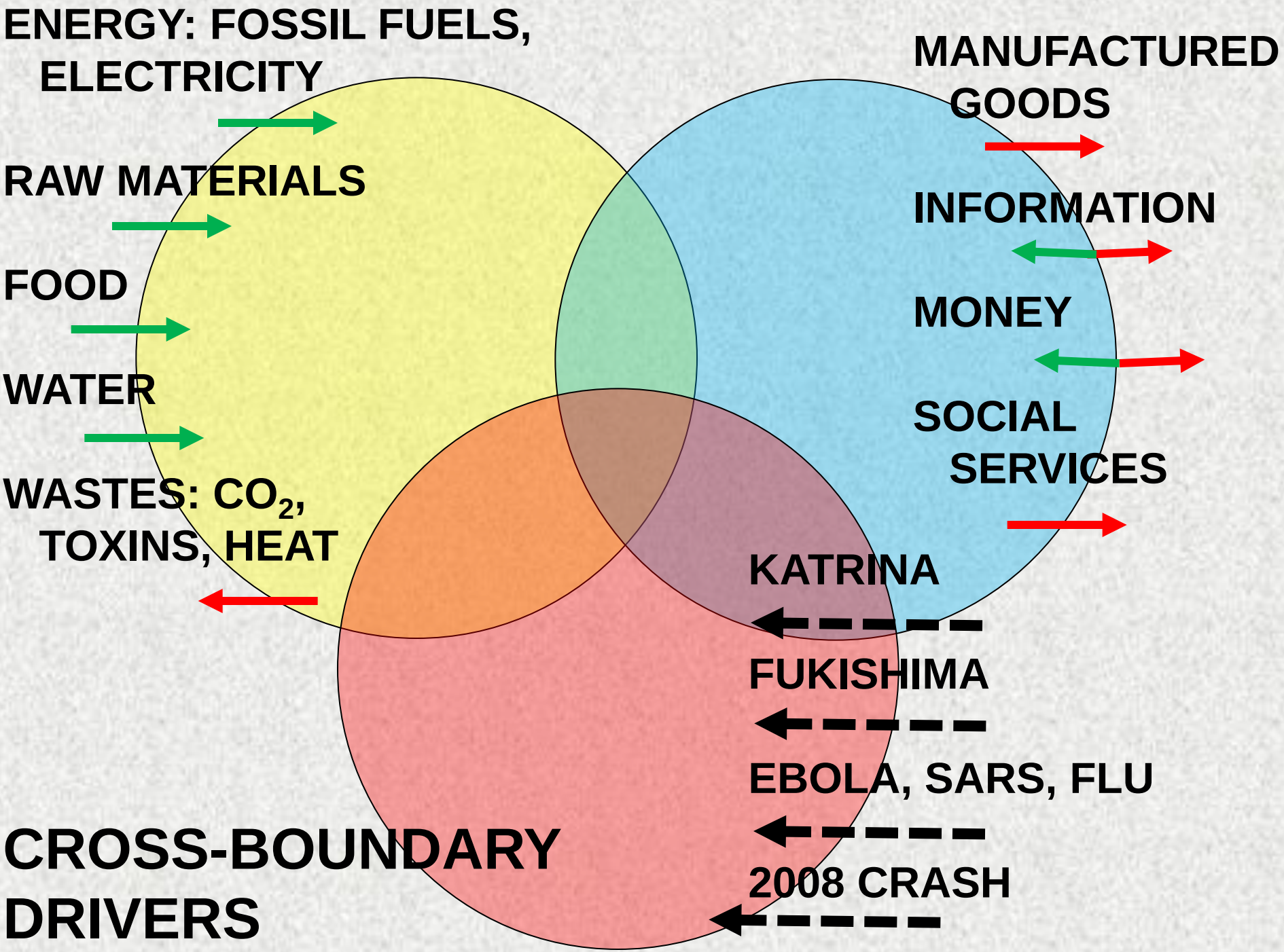
BIOPHYSICALLY IMPOSSIBLE CITY

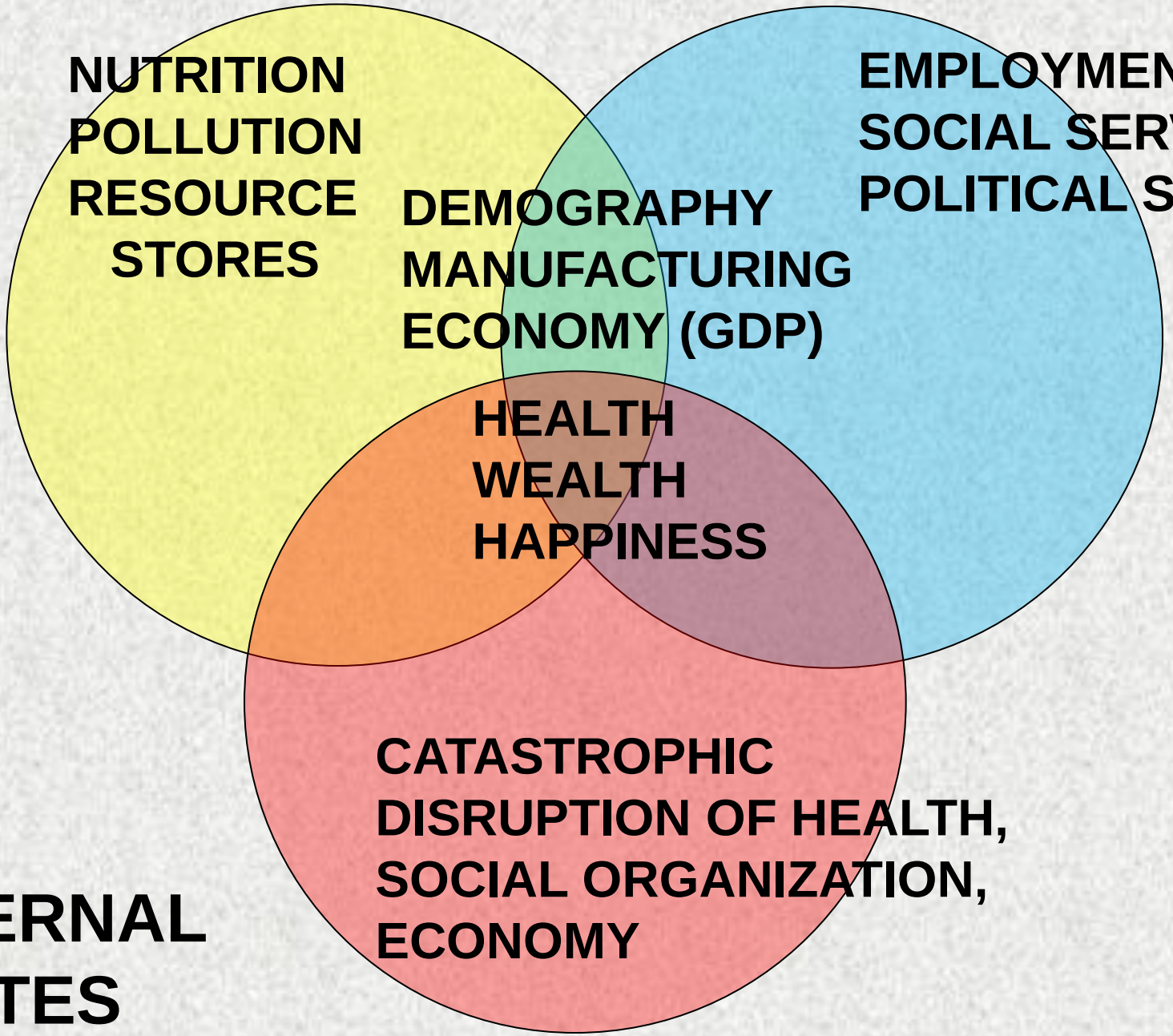
GLOBAL BIOPHYSICAL CONSTRAINTS ON RESOURCE SUPPLY

CONSERVATION LAWS CONSTRAIN OUTPUTS: ENERGY (HEAT) MATERIALS (TOXINS) CHEMISTRY (CARBON)

THERMODYNAMIC CONSTRAINTS ON RECYCLING


BIOPHYSICAL LAWS
CONSERVATION OF
ENERGY, MASS, CHEMISTRY
THERMODYNAMICS
METABOLISM
MALTHUSIAN-DARWINIAN
DYNAMIC
DOMAIN OF
SOCIAL SCIENCES
SOCIOLOGY
ECONOMICS
PSYCHOLOGY
MAJOR PERTURBATIONS
CLIMATE/SEA LEVEL CHANGE
EARTHQUAKES/TSUMANIS
DISEASE EPIDEMICS
ECONOMIC FLUCTUATIONS
CONCEPTUAL
FRAMEWORK


ENERGY: FOSSIL FUELS, ELECTRICITY
RAW MATERIALS
FOOD
WATER
WASTES: CO_2, TOXINS, HEAT
MANUFACTURED GOODS
INFORMATION
MONEY
SOCIAL SERVICES
KATRINA
FUKISHIMA
EBOLA, SARS, FLU
2008 CRASH
CROSS-BOUNDARY DRIVERS


NUTRITION
POLLUTION
RESOURCE
STORES
DEMOGRAPHY
MANUFACTURING
ECONOMY (GDP)
EMPLOYMENT
SOCIAL SERVICES
POLITICAL SYSTEM
HEALTH
WEALTH
HAPPINESS
CATASTROPHIC
DISRUPTION OF HEALTH,
SOCIAL ORGANIZATION,
ECONOMY
INTERNAL
STATES

"SUSTAINABILITY" DEPENDS ON GLOBAL BIOPHYSICAL CONSTRAINTS

All human systems are subject to the laws of physics and biology

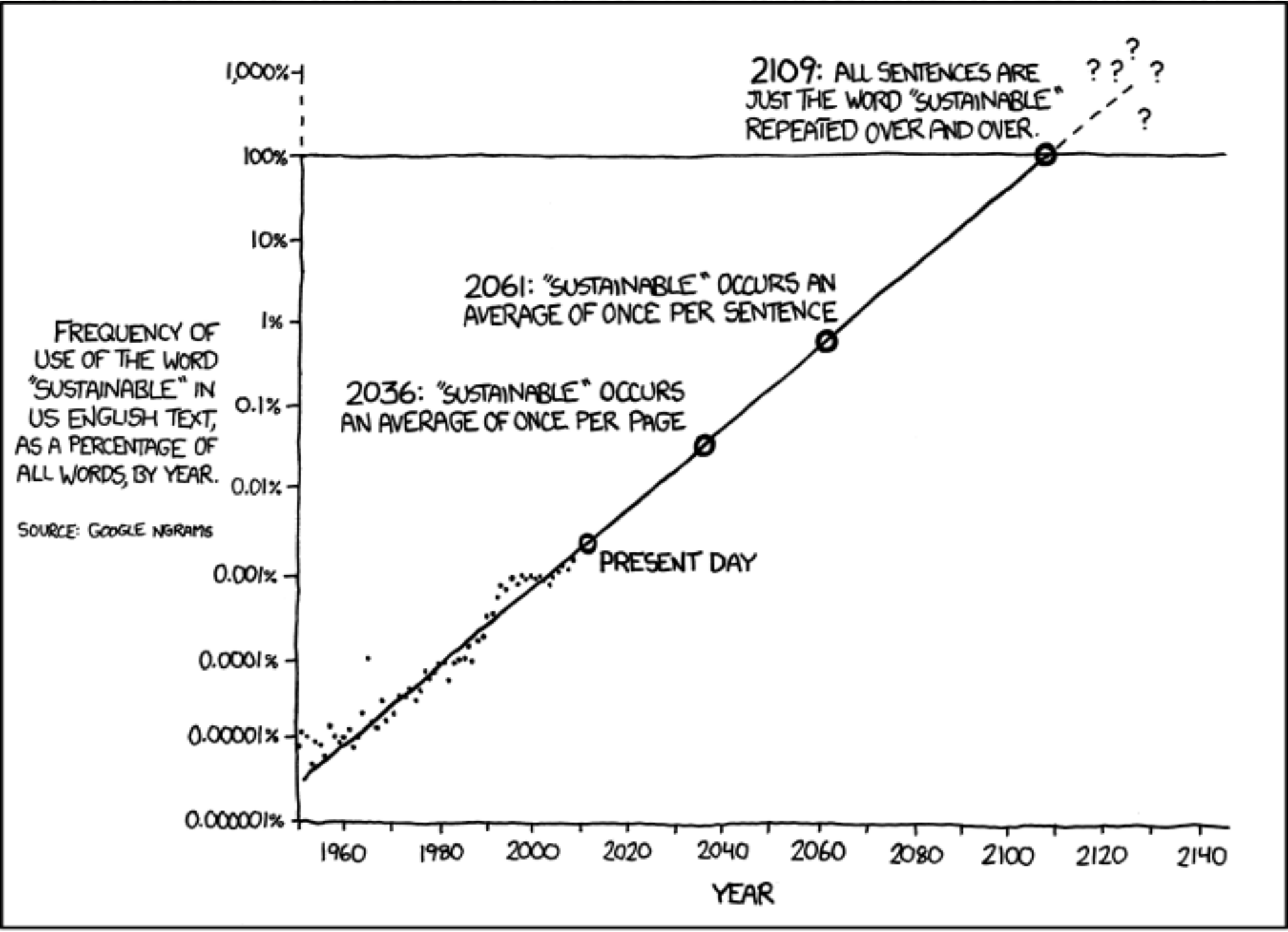
A city is an open system, embedded in regional and global systems

No city is self-sustainable; it requires flows of energy and materials across its boundaries

Global limits on agriculture constrain food supply

Global limits on energy constrain standard of living and economic development

Do a biophysical analysis: get the data, do the arithmetic, draw logical conclusions

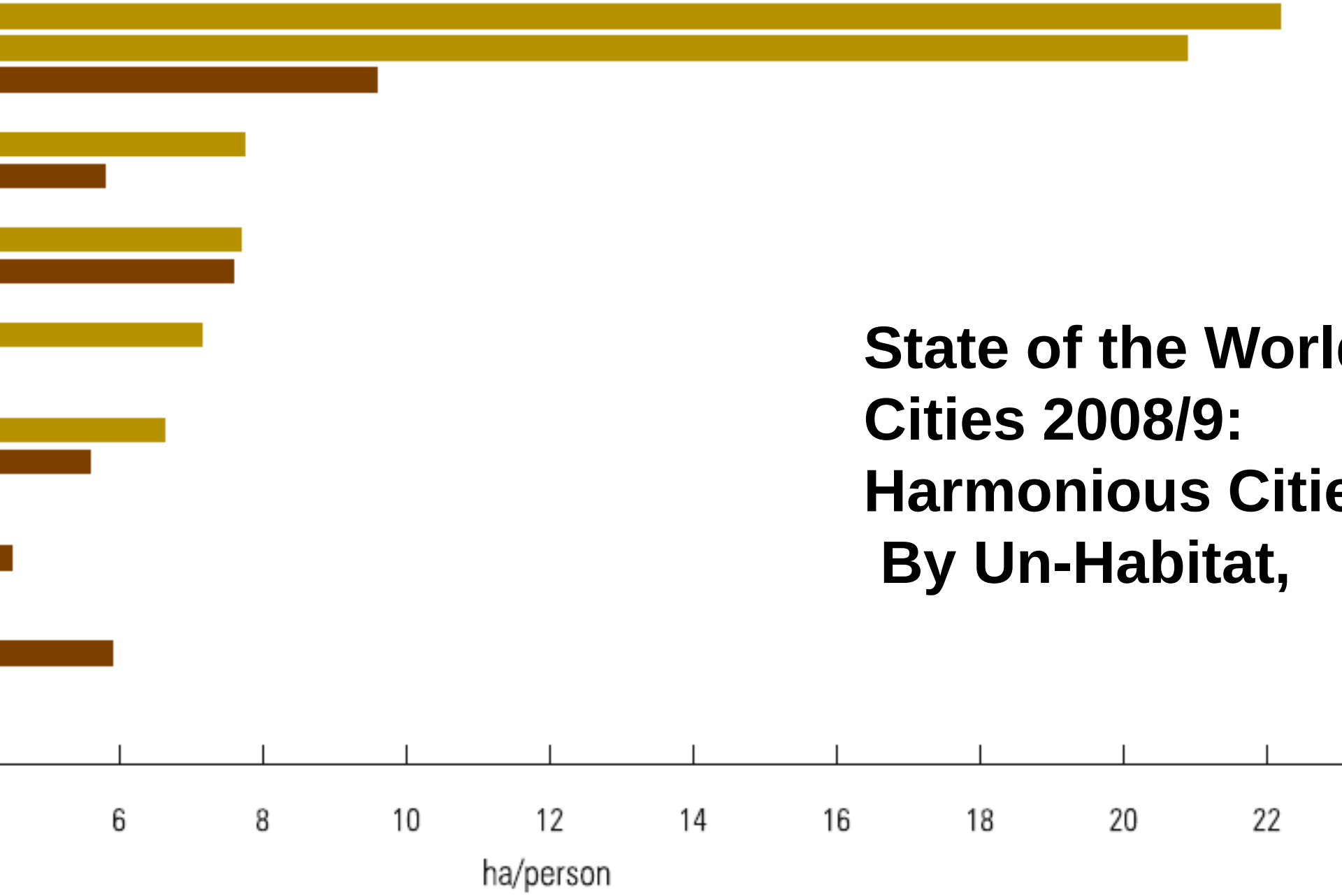


THE WORD "SUSTAINABLE" IS UNSUSTAINABLE.

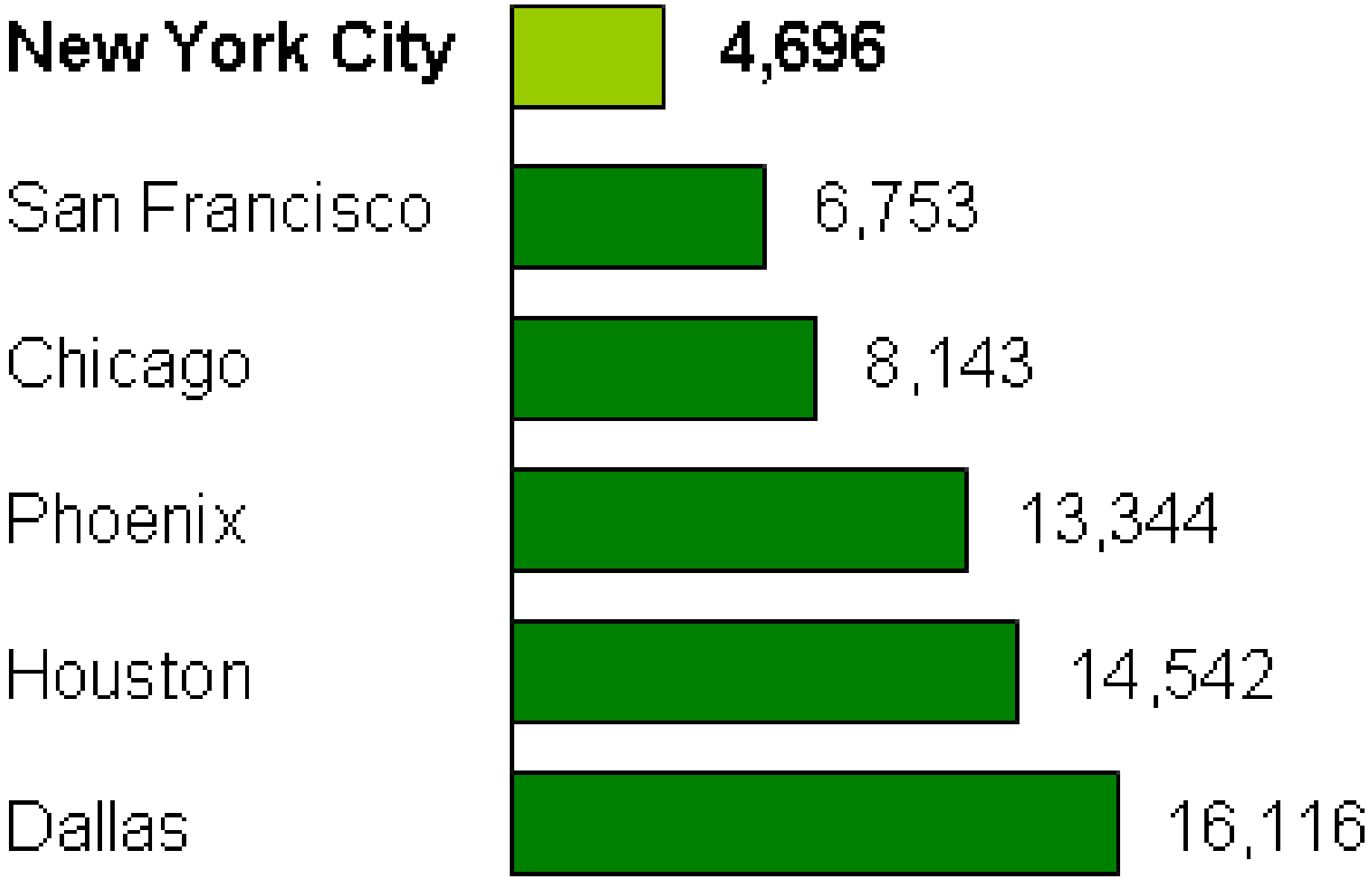
Collaborators:
UNM Human Macroecology group:
Robbie Burger, Trevor Fristoe, Marcus Hamilton, Astrid Kodric-Brown, Norman Mercado-Silva, Jeff Nekola, Jordan Okie
and:
John Day, Eric Roy, John Schramski

Supported by:
UNM Program in Interdisciplinary Biological and Biomedical Science (PiBBs) with grants from the Howard Hughes Medical Institute and the National Institutes of Health

RINT OF SELECTED CITIES AND OF THE COUNTRIES WHERE THEY ARE LOCATED

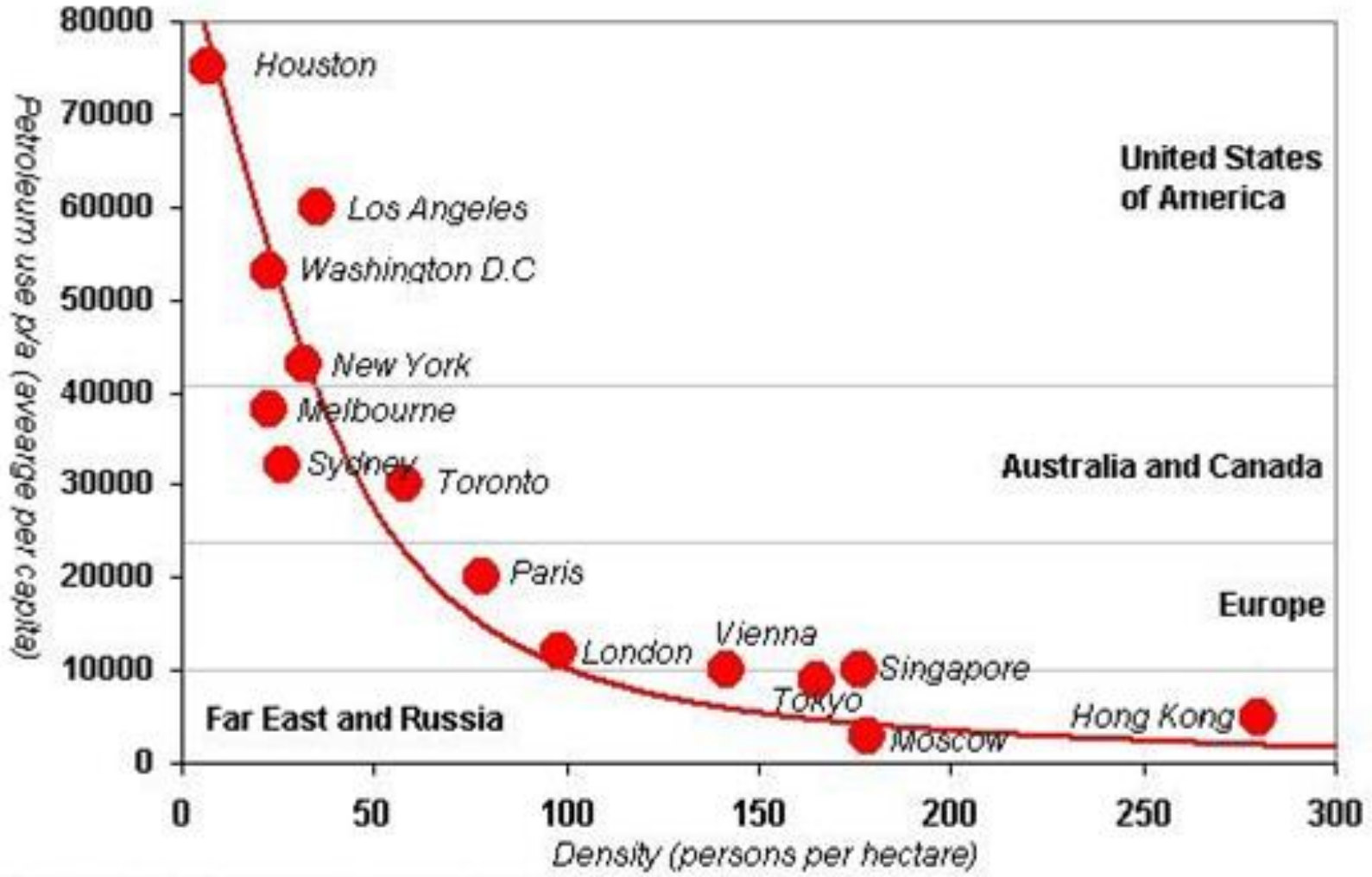


State of the Worl
Cities 2008/9:
Harmonious Citie
By Un-Habitat,


New York City
4,696
San Francisco
6,753
Chicago
8,143
Phoenix
13,344
Houston
14,542
Dallas
16,116

Relationship between Transport and Land Use

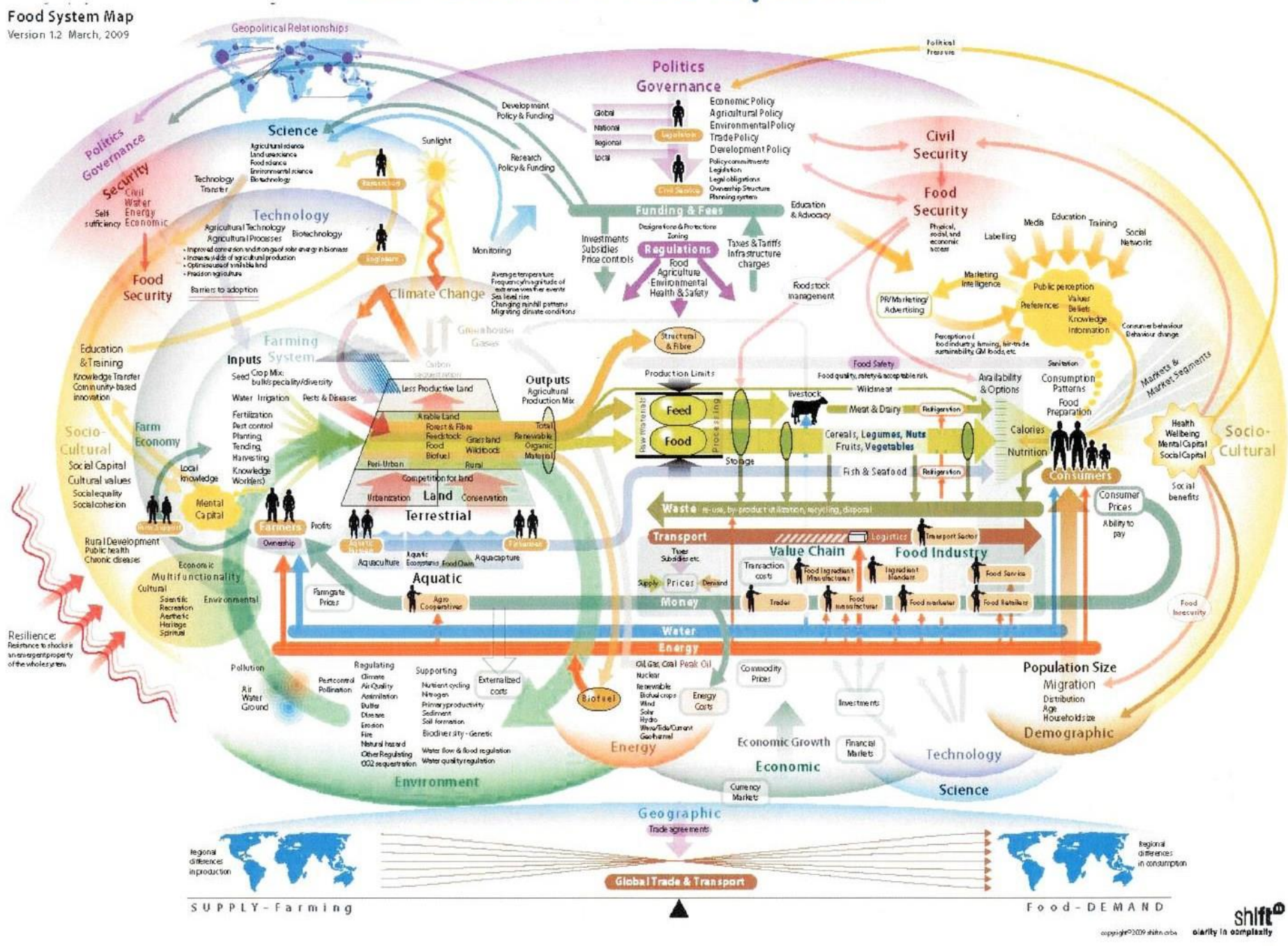
A commonly used study of 32 cities by Newman & Kenworthy in 1989 concluded that there was a strong link between urban development densities and petroleum consumption.



Annual petroleum use per capita adjusted to US MJ (1980)
After Andrew Wright Associates, small section taken from 'Towards an Urban Renaissance', Urban Task Force Partnership, 1999, (c) DETR, 1999.

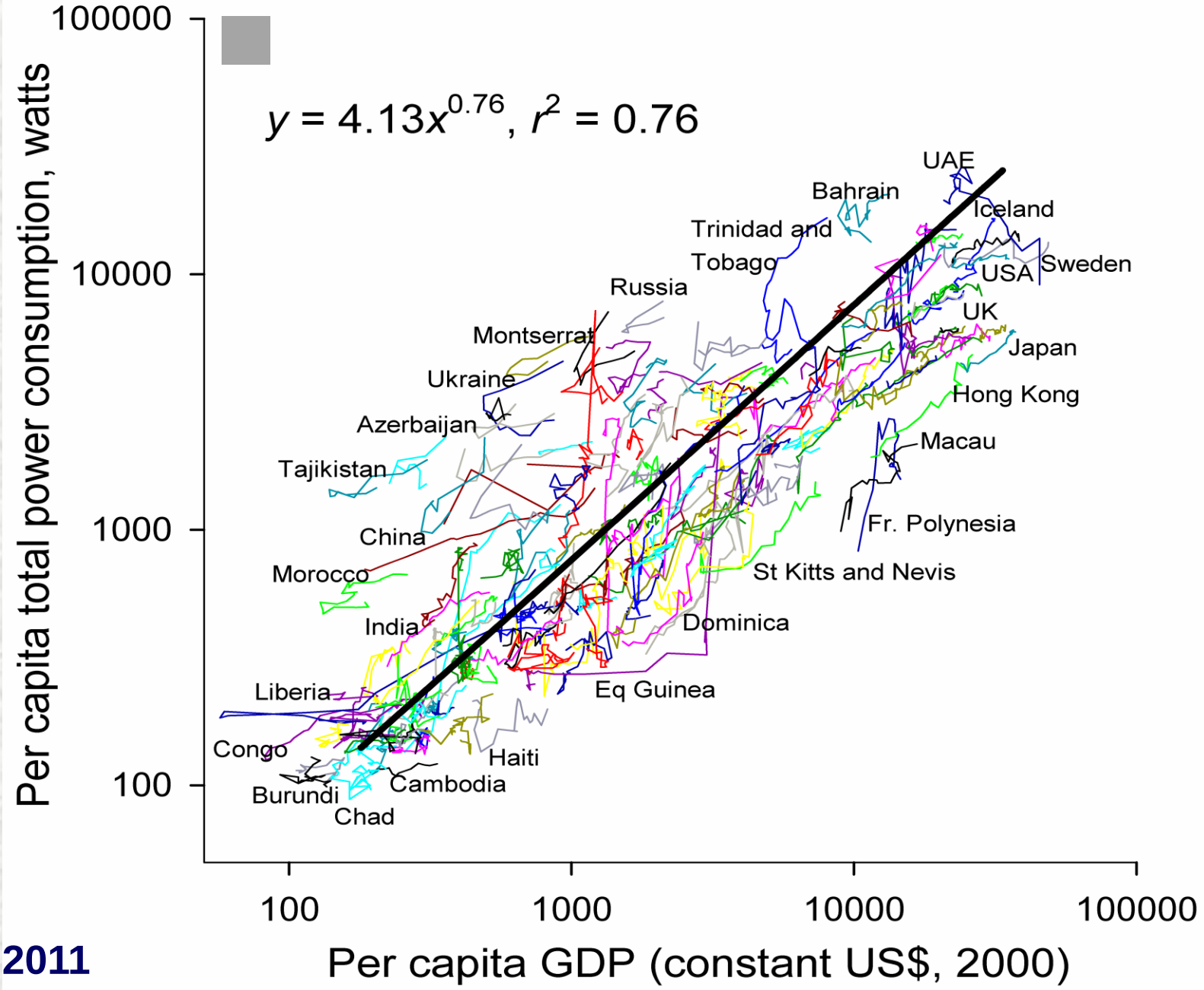
WikiUser[robbison -
Under GDPL

The Global Food System




e!Sankey
Trial Version
www.e-sankey.com

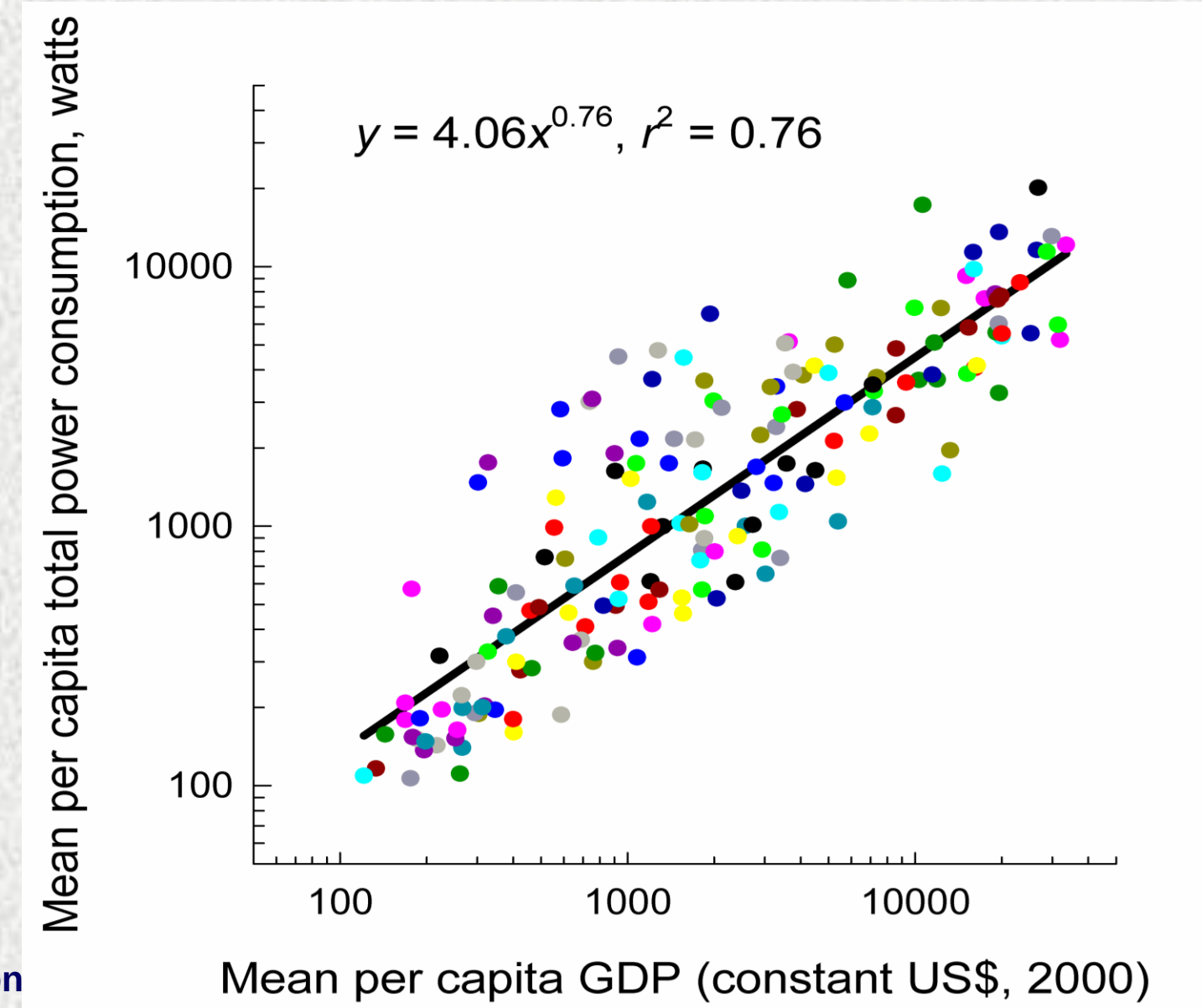
Per-capita energy use vs. per capita GDP



Brown et al. 2011


GONE WITH THE WIND
“I can't think about that right now. If I do, I'll go crazy. I'll think about that tomorrow.”
Scarlet O’Hara

Per-capita energy use vs. per capita GDP
25-year averages for alternative scenarios



Data compiled and analyzed by M. Hamilton