Human and Nature Dynamics (HANDY): Modeling Inequality and Sustainability

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Numerical Analysis and Predictability

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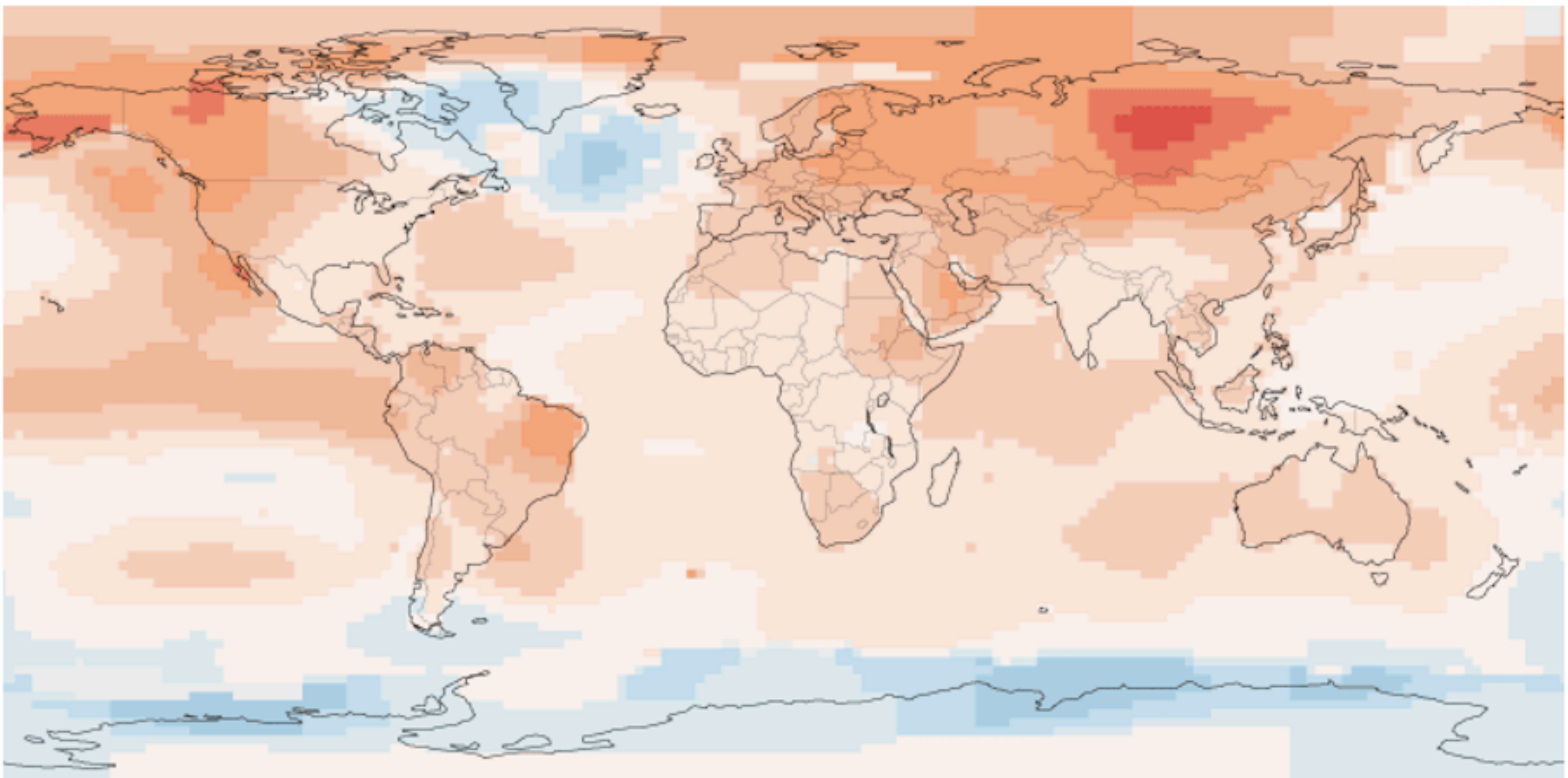
Is climate change really happening?

The Hottest Year on Record

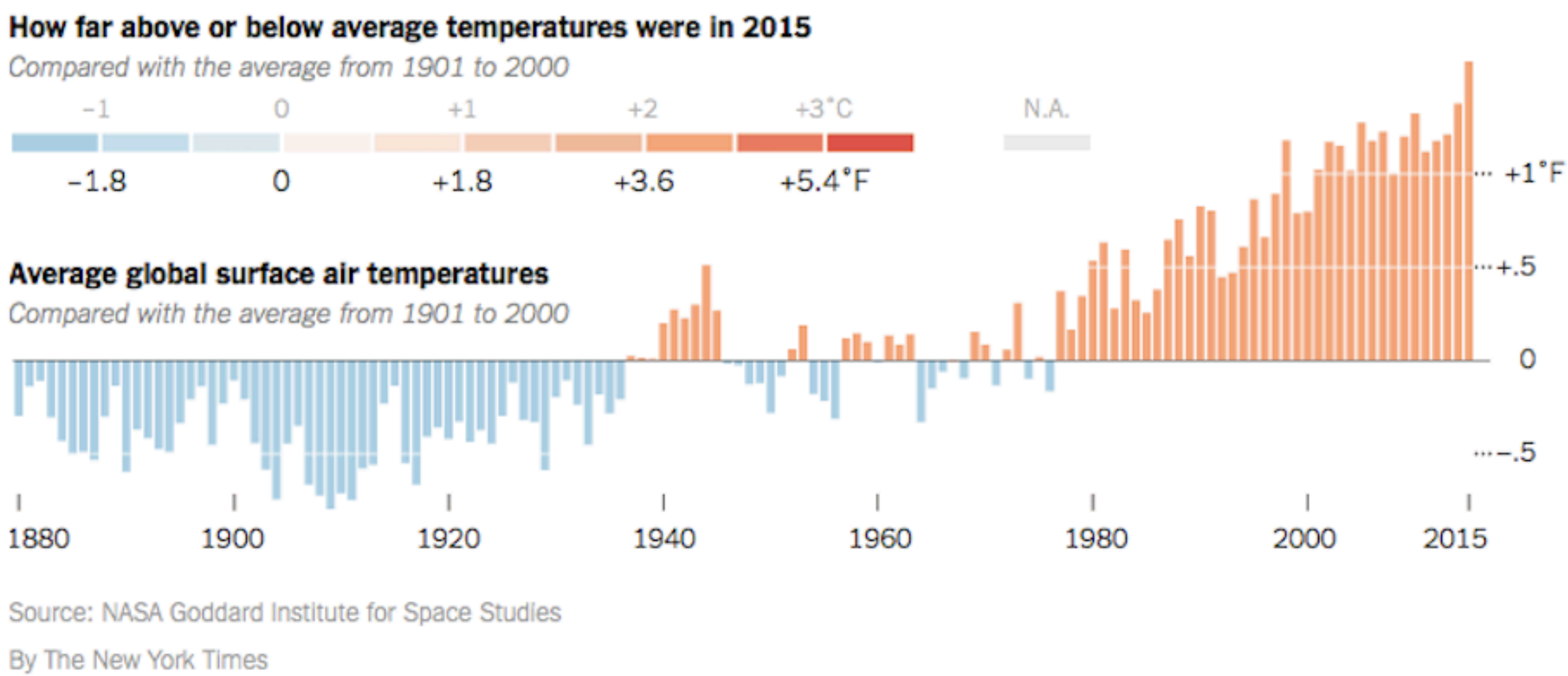
Globally, 2015 was the warmest year in recorded history.

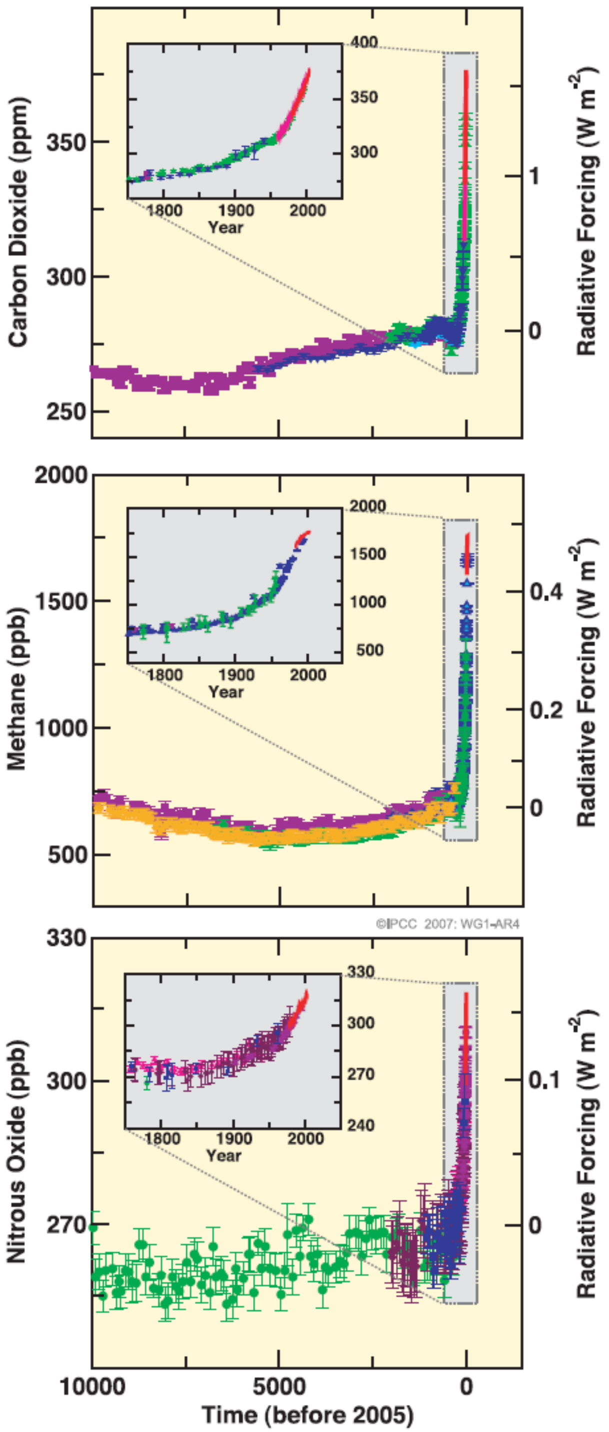


How far above or below average temperatures were in 2015

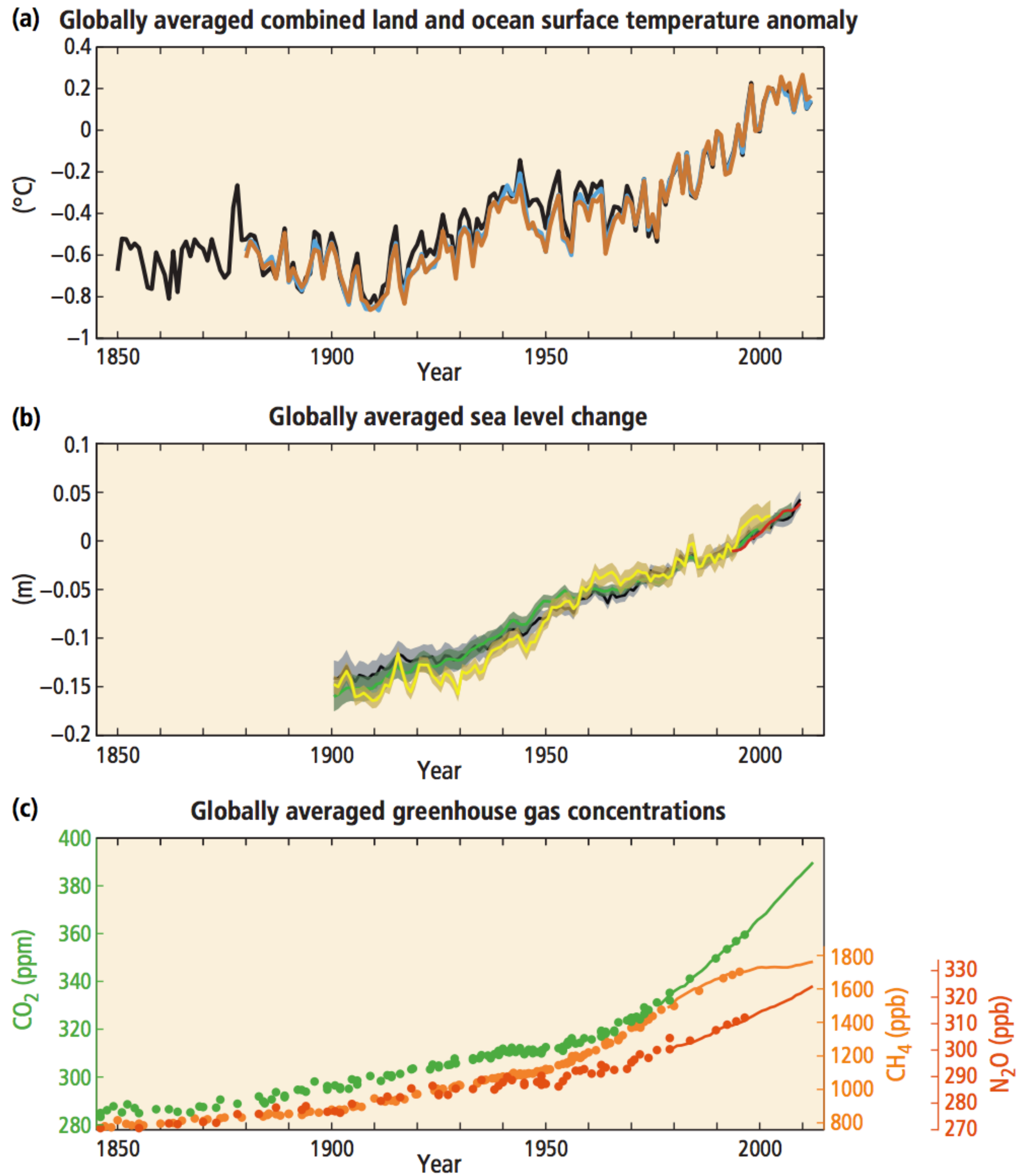
Compared with the average from 1901 to 2000

Is climate change really happening?

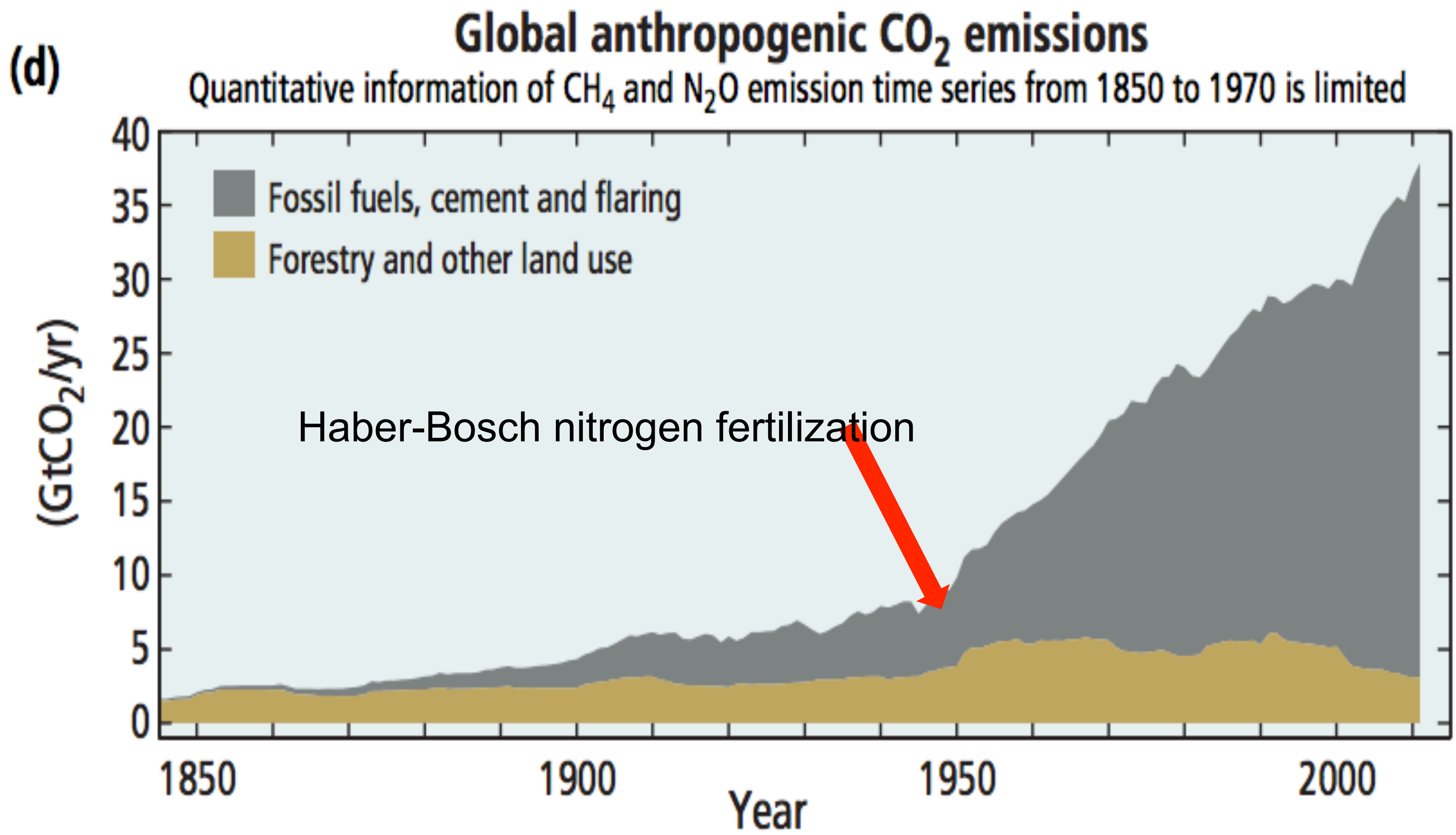




Carbon Dioxide (ppm)
Radiative Forcing (W m-2)
Methane (ppb)
Nitrous Oxide (ppb)
Year
©IPCC 2007: WG1-AR4
Time (before 2005)



(a) Globally averaged combined land and ocean surface temperature anomaly
(°C)
Year
(b) Globally averaged sea level change
(m)
Year
(c) Globally averaged greenhouse gas concentrations
CO2 (ppm)
CH4 (ppb)
N2O (ppb)
Year


(d)
Global anthropogenic CO_2 emissions
Quantitative information of CH_4 and N_2O emission time series from 1850 to 1970 is limited
Fossil fuels, cement and flaring
Forestry and other land use
Haber-Bosch nitrogen fertilization
($GtCO_2$/yr)
40
35
30
25
20
15
10
5
0
1850
1900
1950
2000
Year

Climate change

Since 1800 we are burning the fossil fuels that Nature accumulated during millions of years.

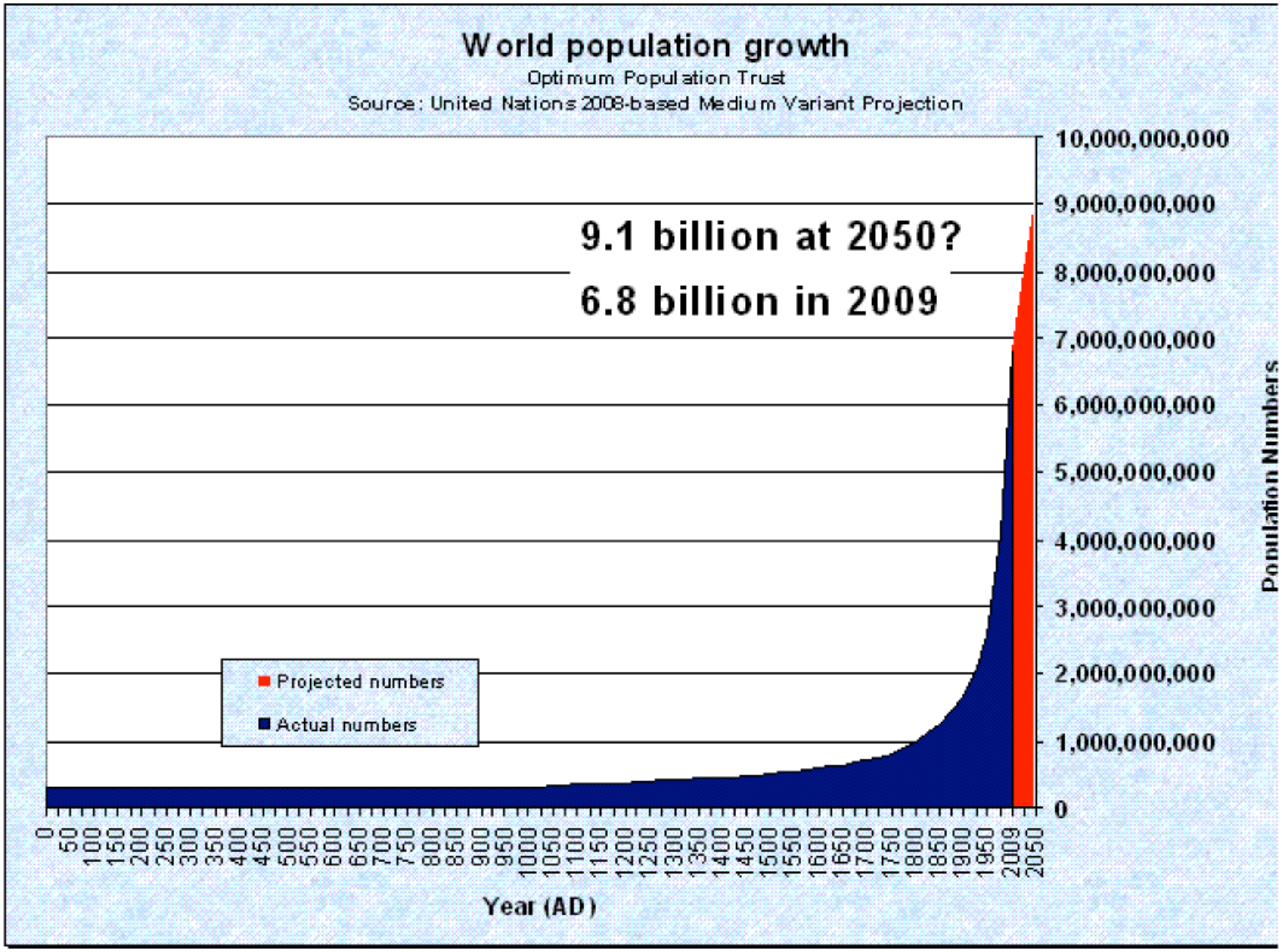
By burning the accumulated carbon we **emit** CO_2 into the atmosphere.

The CO2 acts like a blanket (greenhouse effect). So, the atmosphere is warming up:

Total emission=population x emission per person

Population growth

1AD	0.3b
1650	0.5b
1800	1.0b
1927	2.0b
1960	3.0b
1975	4.0b
1987	5.0b
1998	6.0b
2011	7.0b



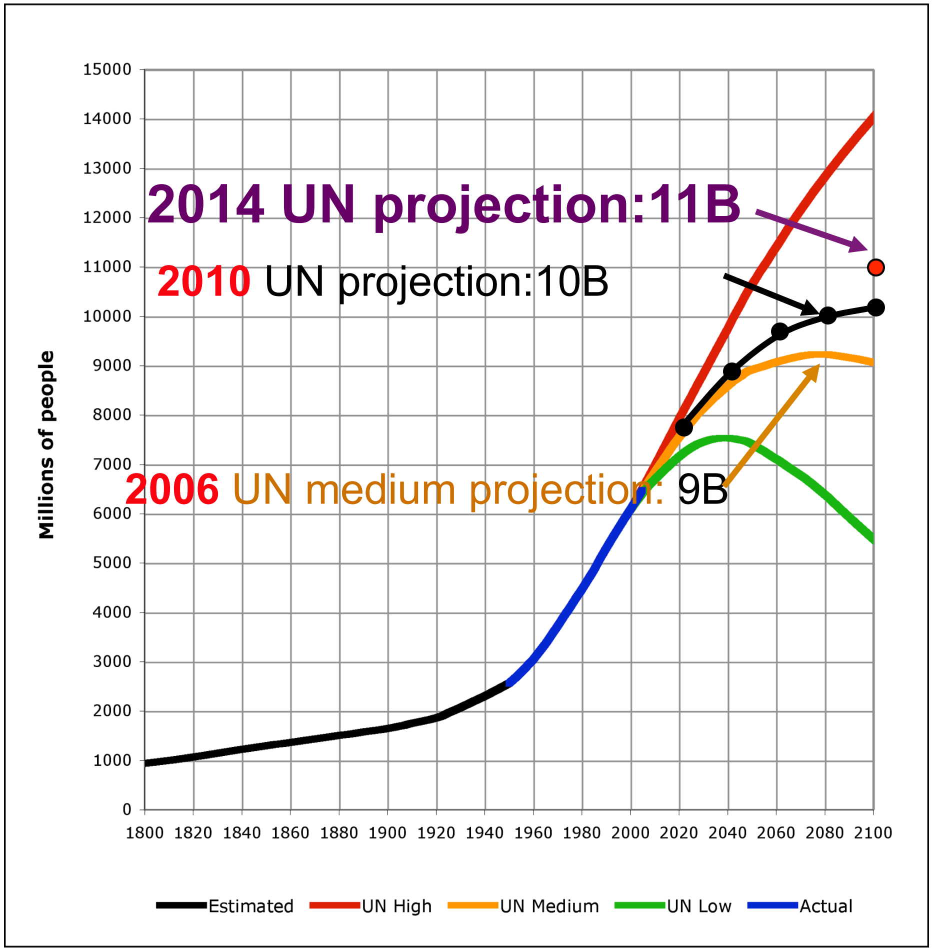
Population and climate: a study at the London School of Economics

Total emission=population x
emission per person

Per dollar spent,

family planning reduces **four times** as much carbon over the next 40 years as

adopting **low-carbon technologies**



Why was the population able to grow so fast since the 1950's?

Two reasons:

1) Sanitation and antibiotics (living longer)

2) Use of fossil fuels in agriculture starting in the 1950's:

- fertilizers, pesticides, irrigation, mechanization (Green Revolution).

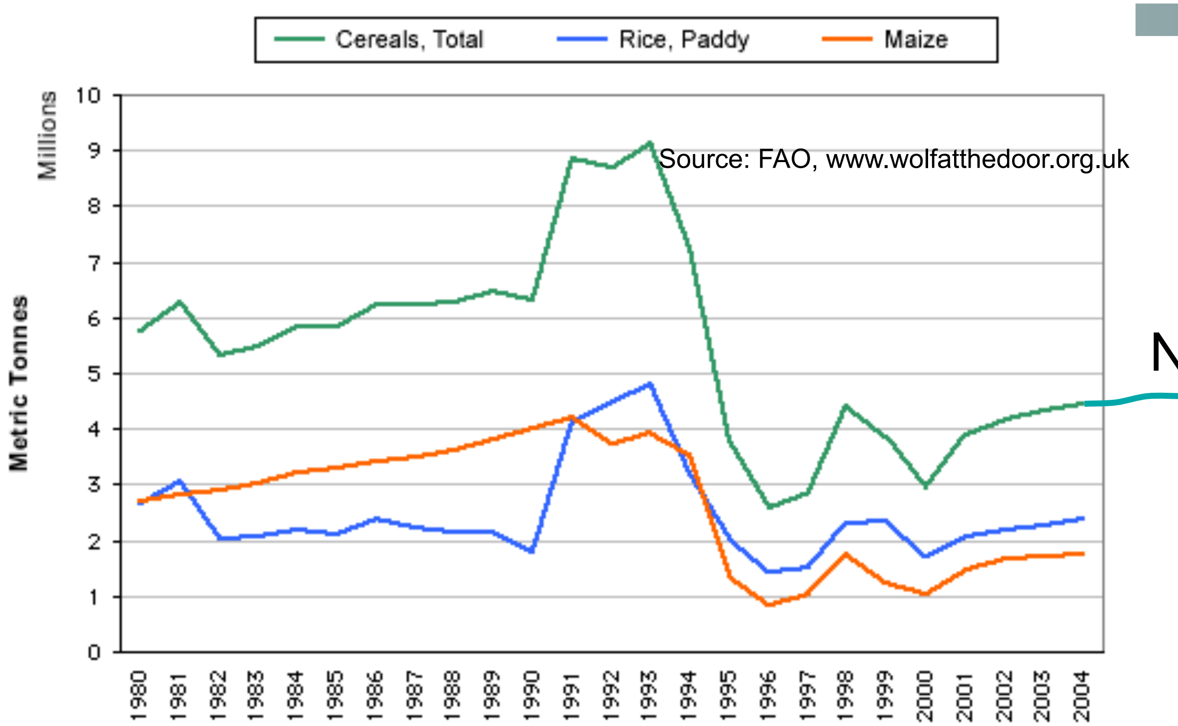
1950 to 1984: production of grains increased by 250% and the population doubled

Without fossil fuels population would be much smaller!

- Growth in grain production is now flattening out
- Industrial farming is destroying forests, soil
- Urban and suburban sprawl is overrunning best farmland

This is not sustainable: "We are drawing down the stock of natural capital as if it was infinite" (Herman Daly)

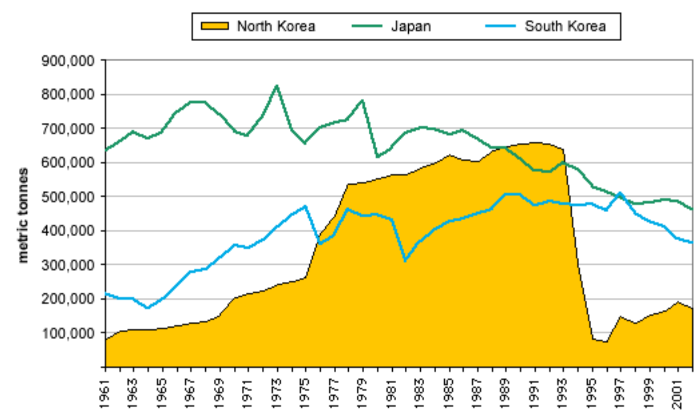
Example: North Korea, got cheap oil from the former Soviet Union until early 1990s



Production of grain in North Korea, updated to 2008

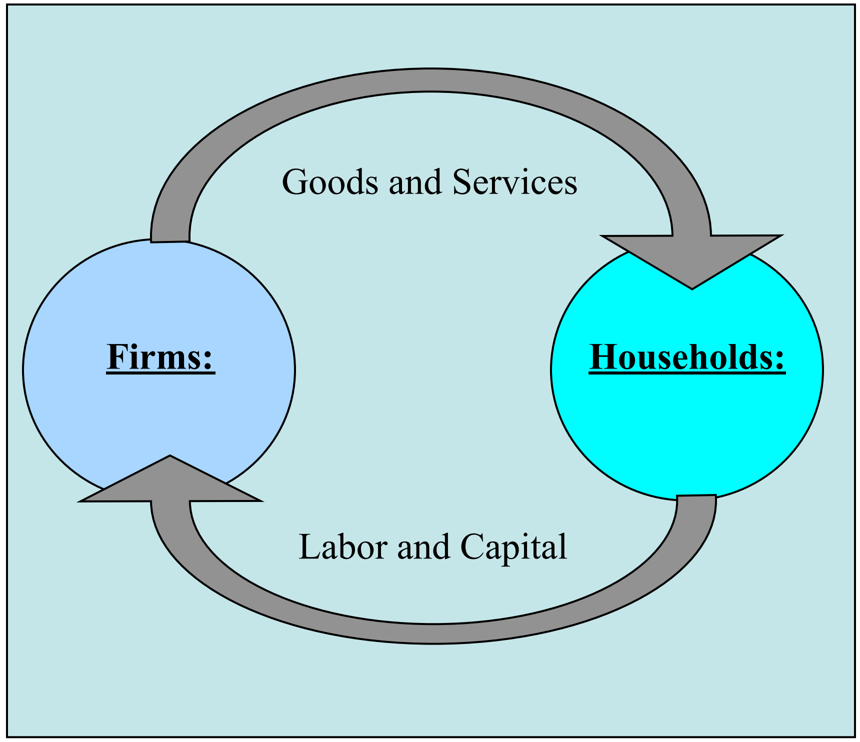
The famines in North Korea are the result of the sudden loss of access to abundant fossil fuel

G2. Fertiliser Use (Nitrogenous) - Far East



Standard Neoclassical Economic Model

As Herman Daly, Robert Costanza, and other scholars in the field of Ecological Economics describe,



The standard Neoclassical Economic Model does not account for:

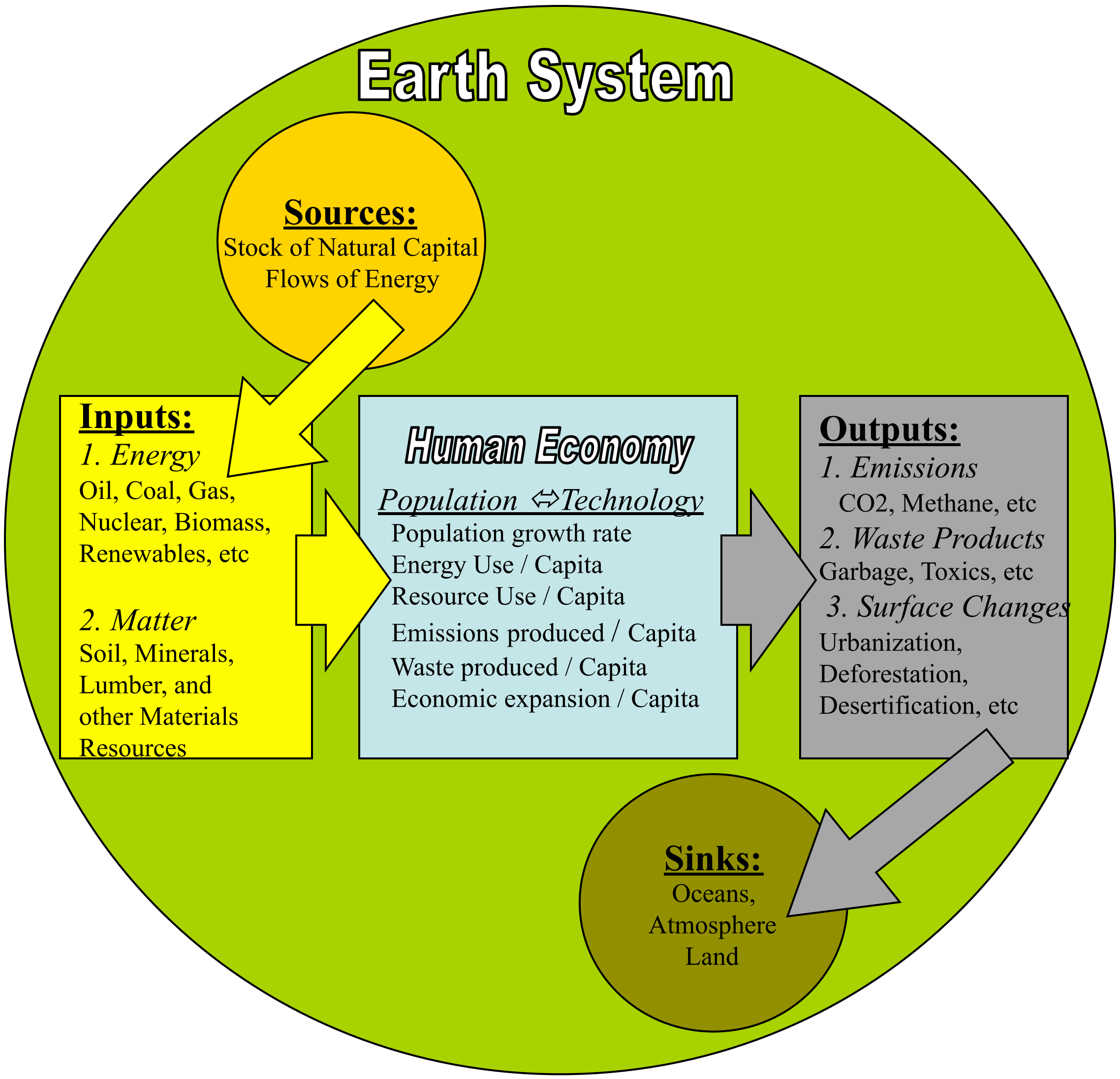
- Inputs (resources), Outputs (pollution), Stocks of Natural Capital
- Dissipation of Energy (i.e., a Perpetual Motion Machine)
- Depletion, Destruction or Transformation of Matter

Therefore, no *effects on the Earth System*, and *No Limits to Growth*.

Herman Daly (UMD) introduced **Ecological Economics**, **within** the **Earth System**

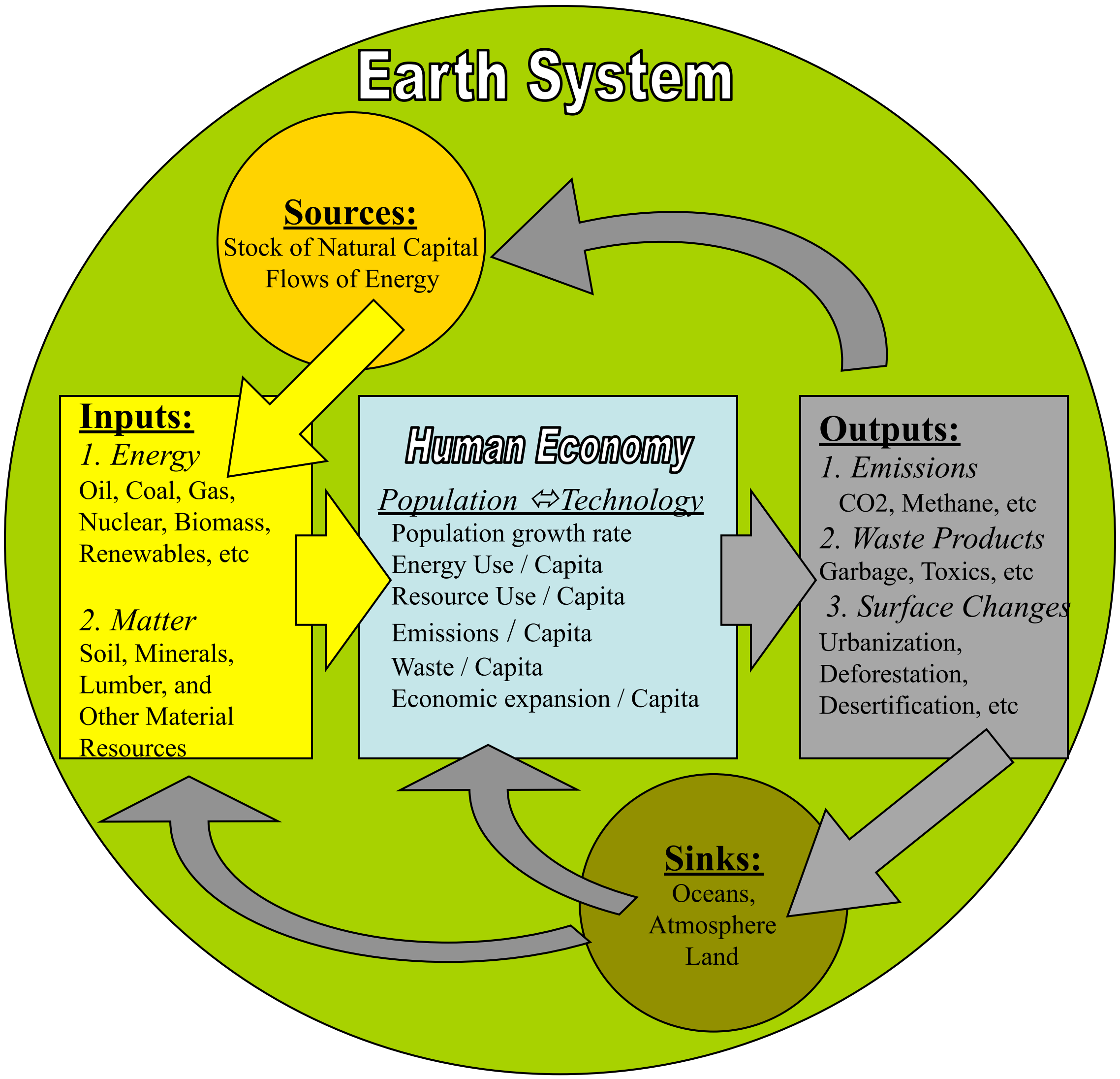
Realistic **Ecological** Economic Model (Herman Daly)

- Incorporates INPUTS, including **DEPLETION** of **SOURCES**
- Incorporates OUTPUTS, including **POLLUTION** of **SINKS**



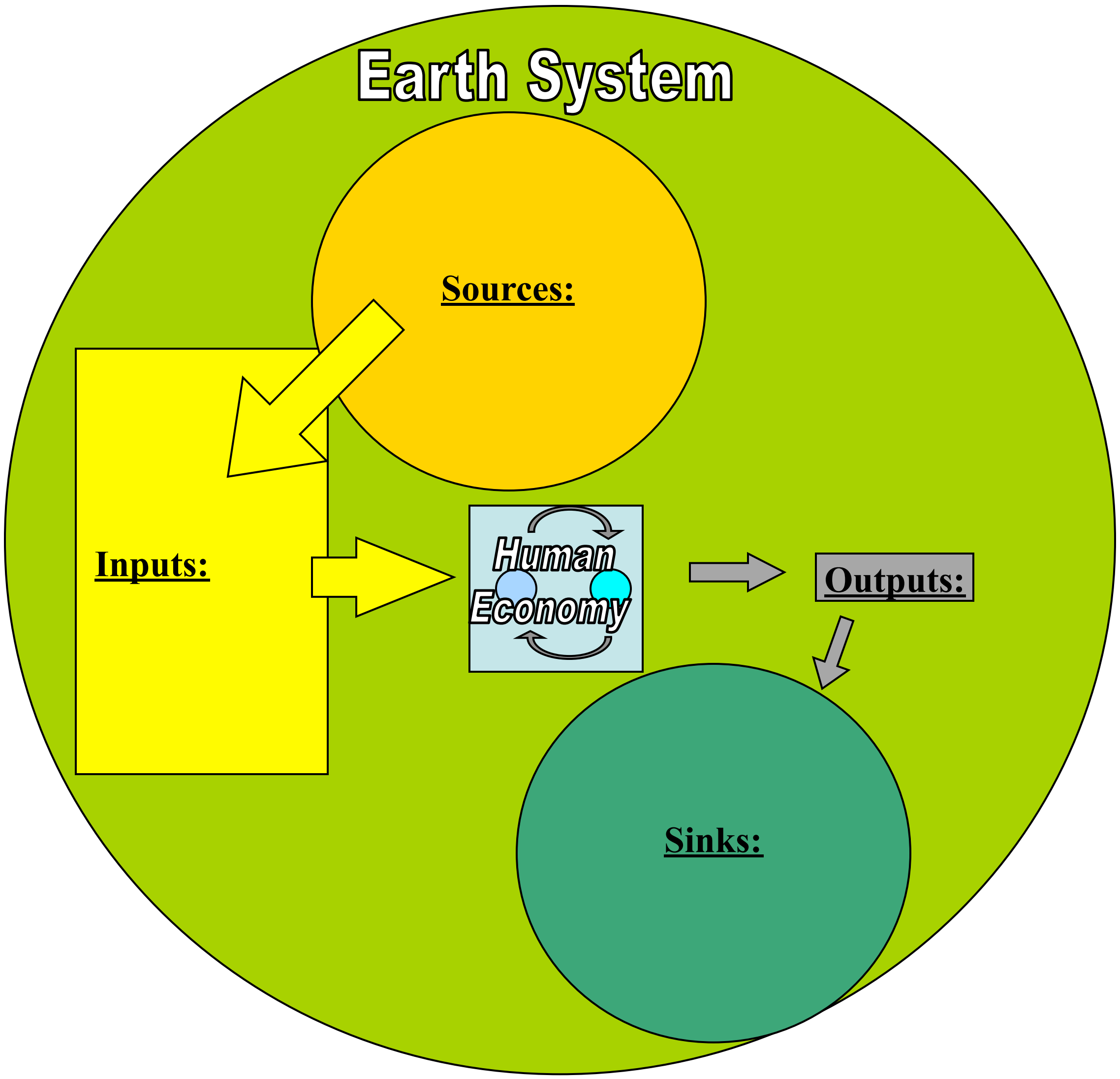
Feedbacks in an Ecological Economic Model

Of course, the OUTPUTS and the **filling up** of **SINKS,** have **feedbacks** on the **Human Economy**, the Quantity and Quality of the INPUTS, and the **depletion of SOURCES** :

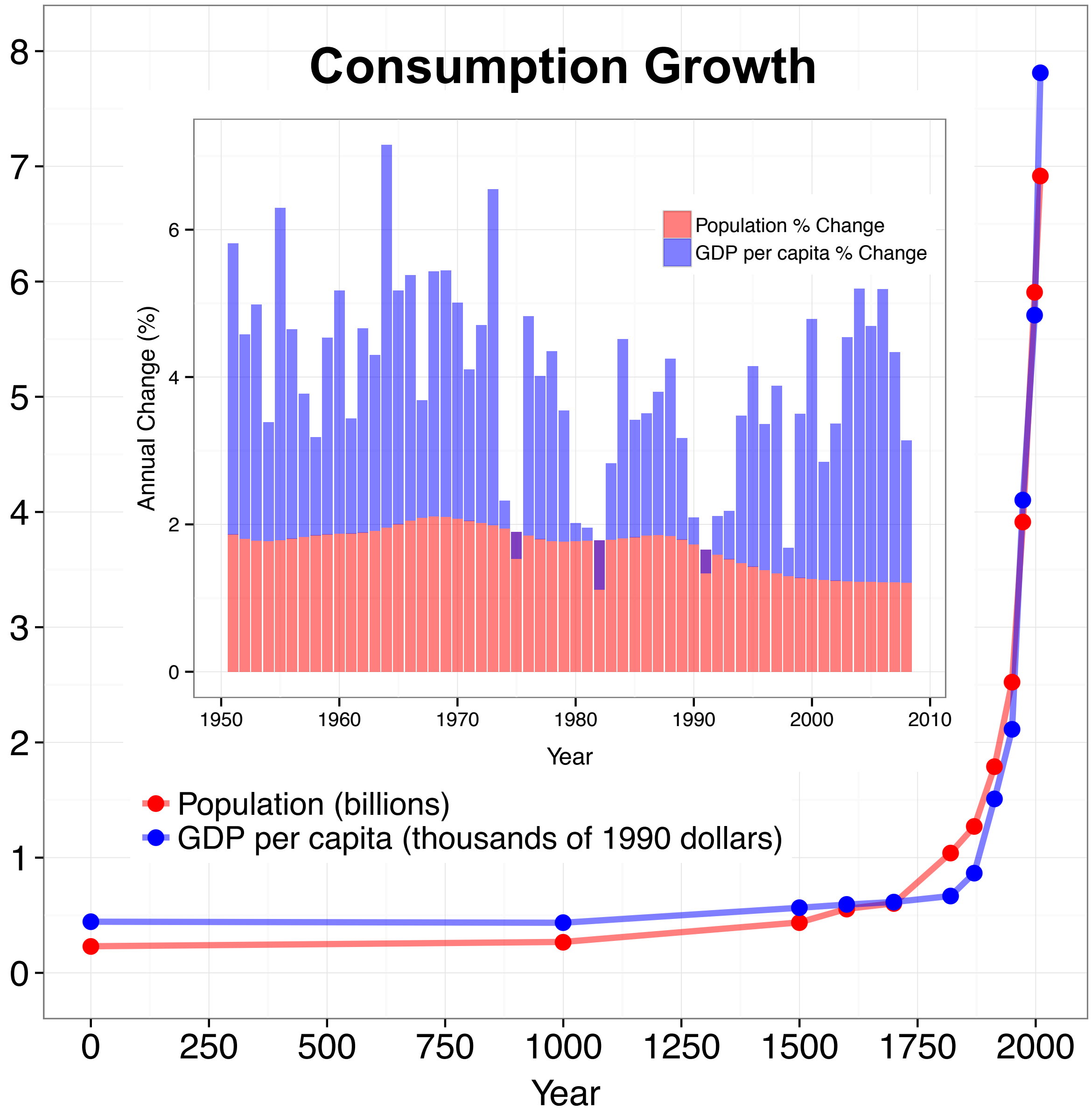


“Empty World” Model

- Throughout most of human history, the **Human Economy** was so small relative to the **Earth System**, that it had little impact on the **Sources** and **Sinks**.
- In this scenario, the standard isolated economic model might have made sense.



Population and GDP per capita: explosion is very recent (1950)



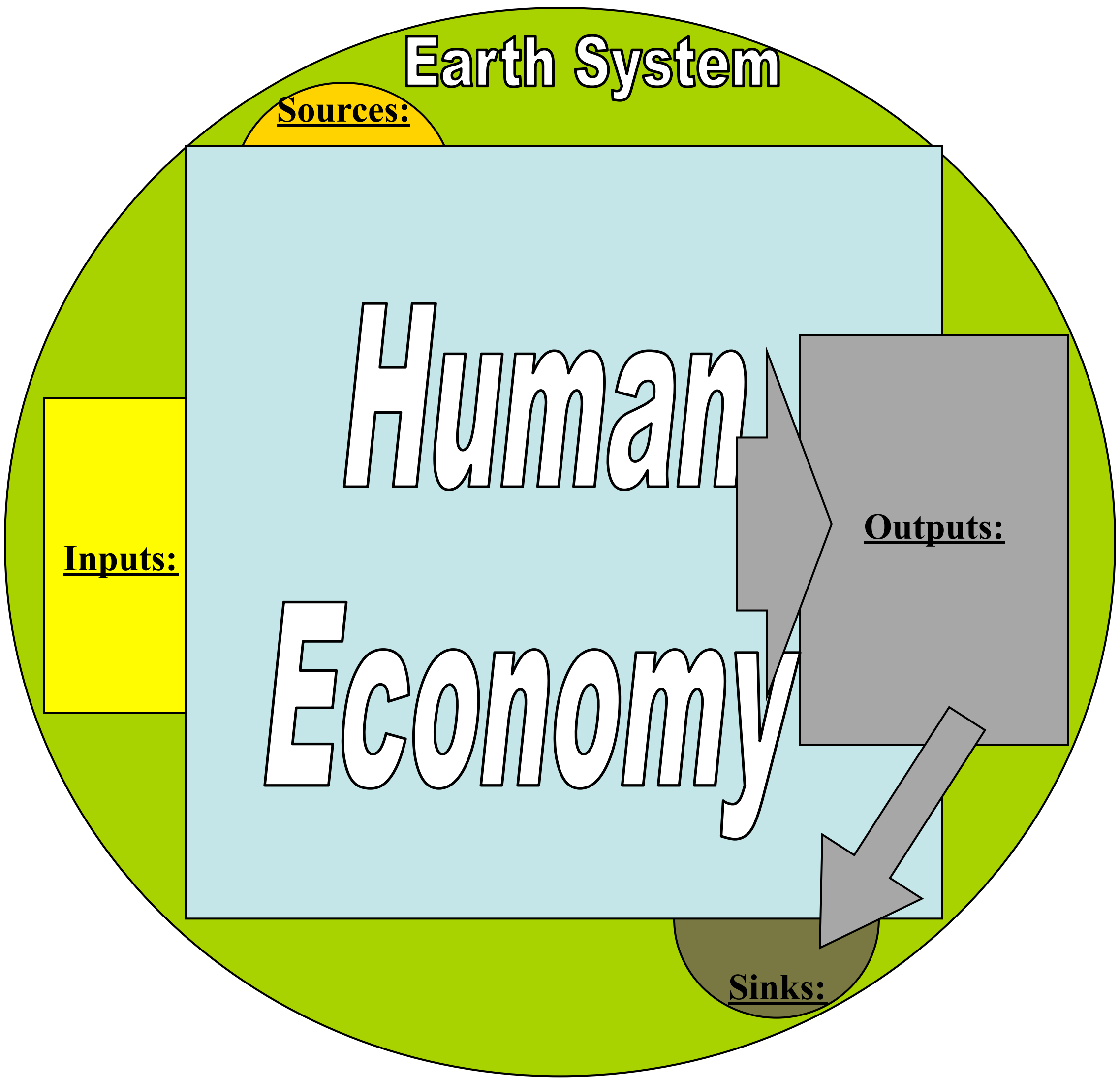
Consumption is growing
~2% population
~2% GDP/cap

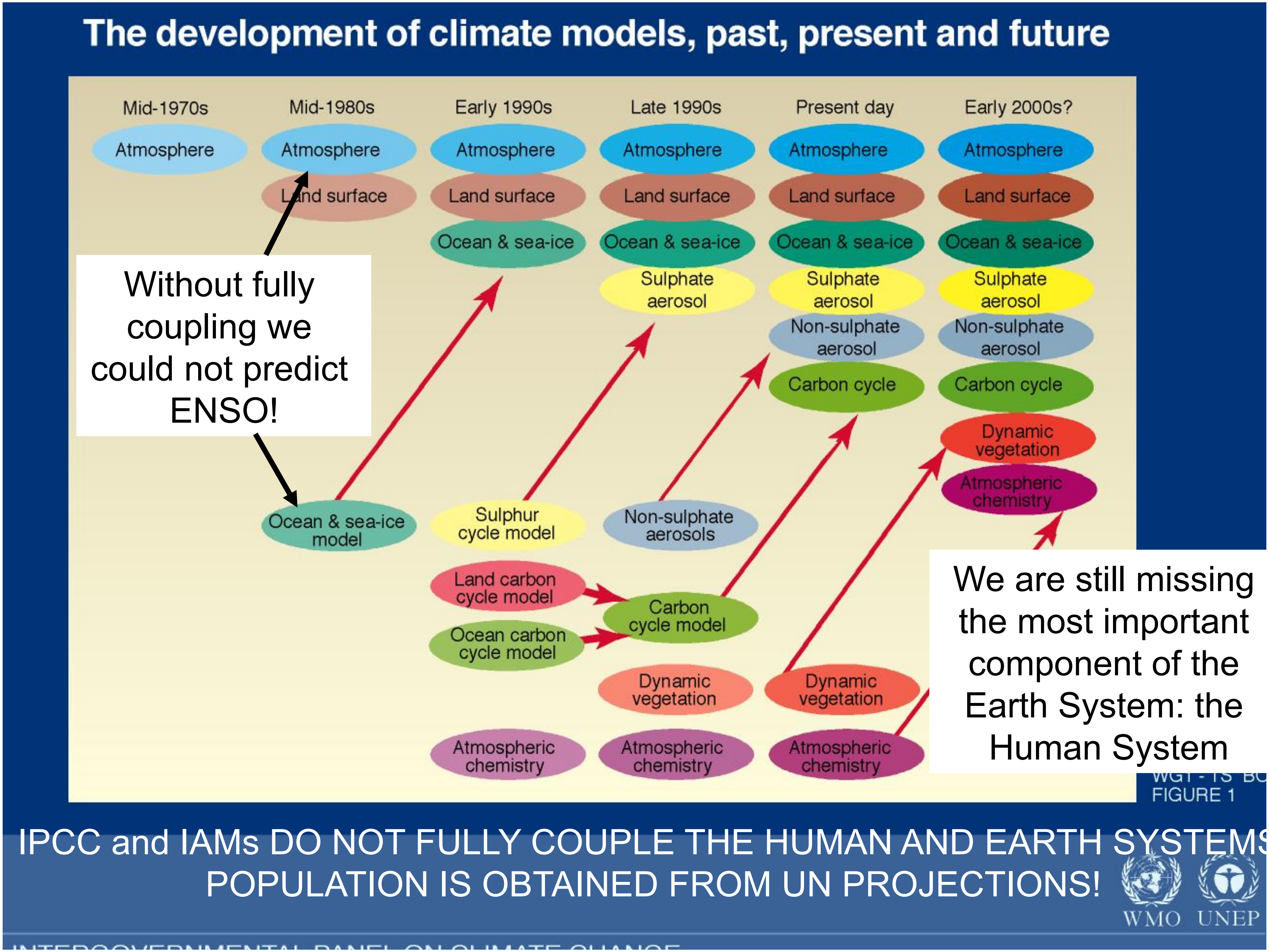
~4% per year!

Since 1950,
<u>we double our total consumption</u>
every 17-20 years!

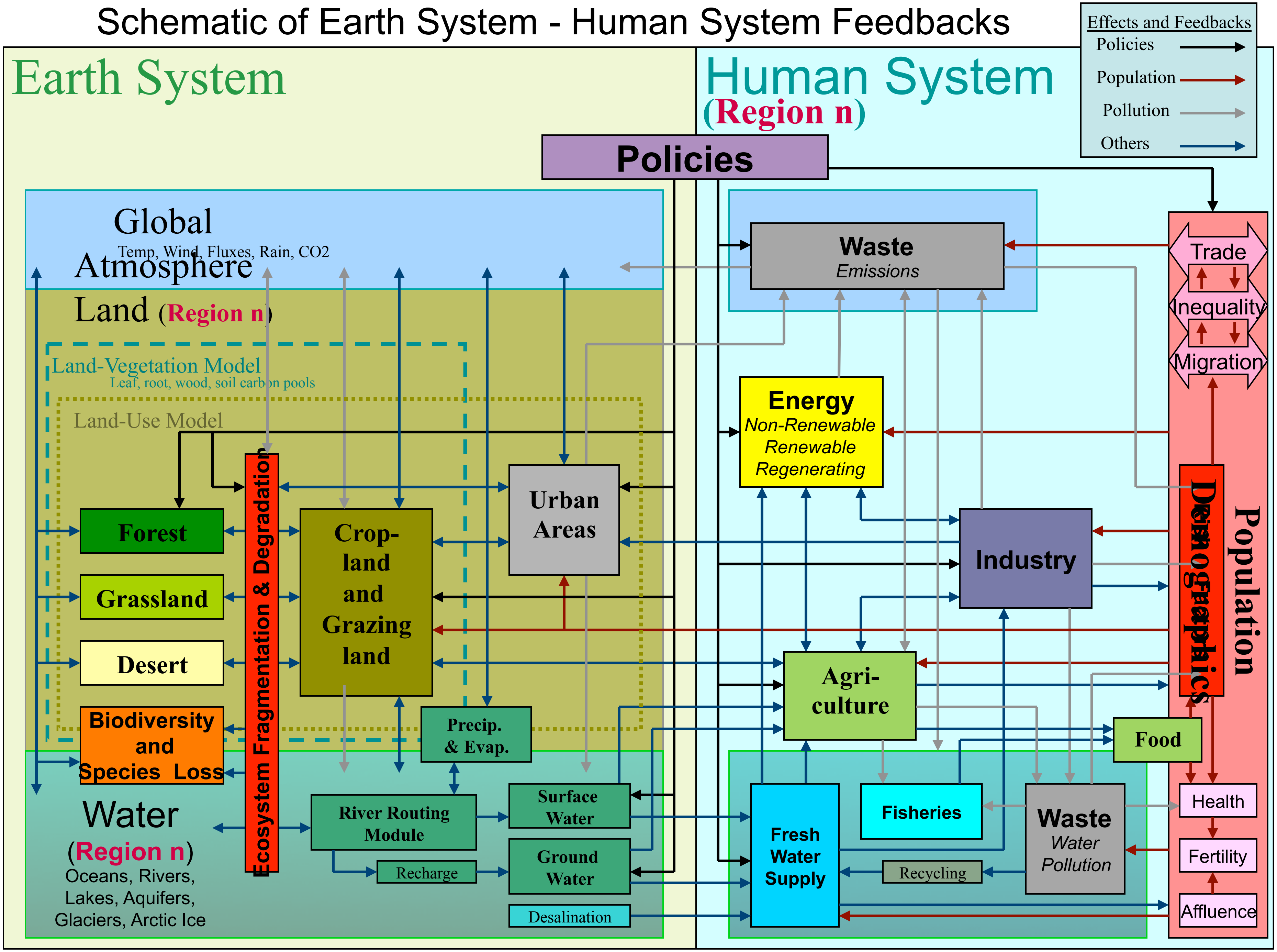
"Full World" Ecological Economic Model

- Today, the **Human Economy** has grown so large, it has very large **Effects** on the **Earth System**, ***Depleting*** the **Sources** and ***Filling*** the **Sinks**. It is clear that ***growth cannot continue forever***.

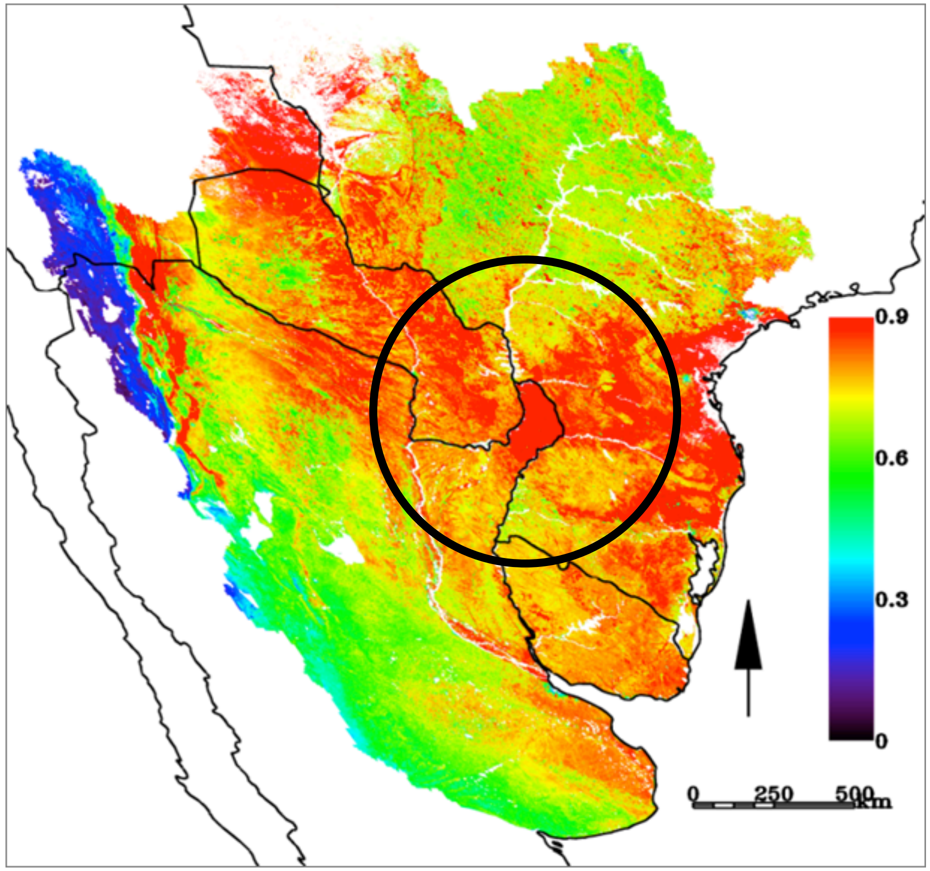



The development of climate models, past, present and future
Mid-1970s
Mid-1980s
Early 1990s
Late 1990s
Present day
Early 2000s?
Atmosphere
Atmosphere
Land surface
Atmosphere
Land surface
Ocean & sea-ice
Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol
Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol
Non-sulphate aerosol
Carbon cycle
Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol
Non-sulphate aerosol
Carbon cycle
Dynamic vegetation
Atmospheric chemistry
Without fully coupling we could not predict ENSO!
Ocean & sea-ice model
Sulphur cycle model
Non-sulphate aerosols
Land carbon cycle model
Ocean carbon cycle model
Carbon cycle model
Dynamic vegetation
Dynamic vegetation
Atmospheric chemistry
Atmospheric chemistry
Atmospheric chemistry
We are still missing the most important component of the Earth System: the Human System
FIGURE 1
IPCC and IAMs DO NOT FULLY COUPLE THE HUMAN AND EARTH SYSTEMS
POPULATION IS OBTAINED FROM UN PROJECTIONS!
WMO
UNEP

Schematic of Earth System - Human System Feedbacks



Policies: Can we use nature sustainably?



The red (highest NDVI **vegetation index**) is in the province of Misiones, Argentina, that protects the forest.
Compare Misiones with Brazil, Paraguay and the rest of Argentina!

Could an advanced society like ours **collapse**?

- **Collapses of many advanced societies have taken place in the last 5000 years!**
- A recent study of the many collapses that took place in Europe (Neolithic, -10K to -4K) has excluded climate forcing, war, and disease as the root cause of such collapses, so that it concluded:
- The collapses were due to overrunning the Carrying Capacity
- We developed a “Human and Nature Dynamical model” (**HANDY**) to start understanding the nonlinear feedbacks between the Earth and the Human System.

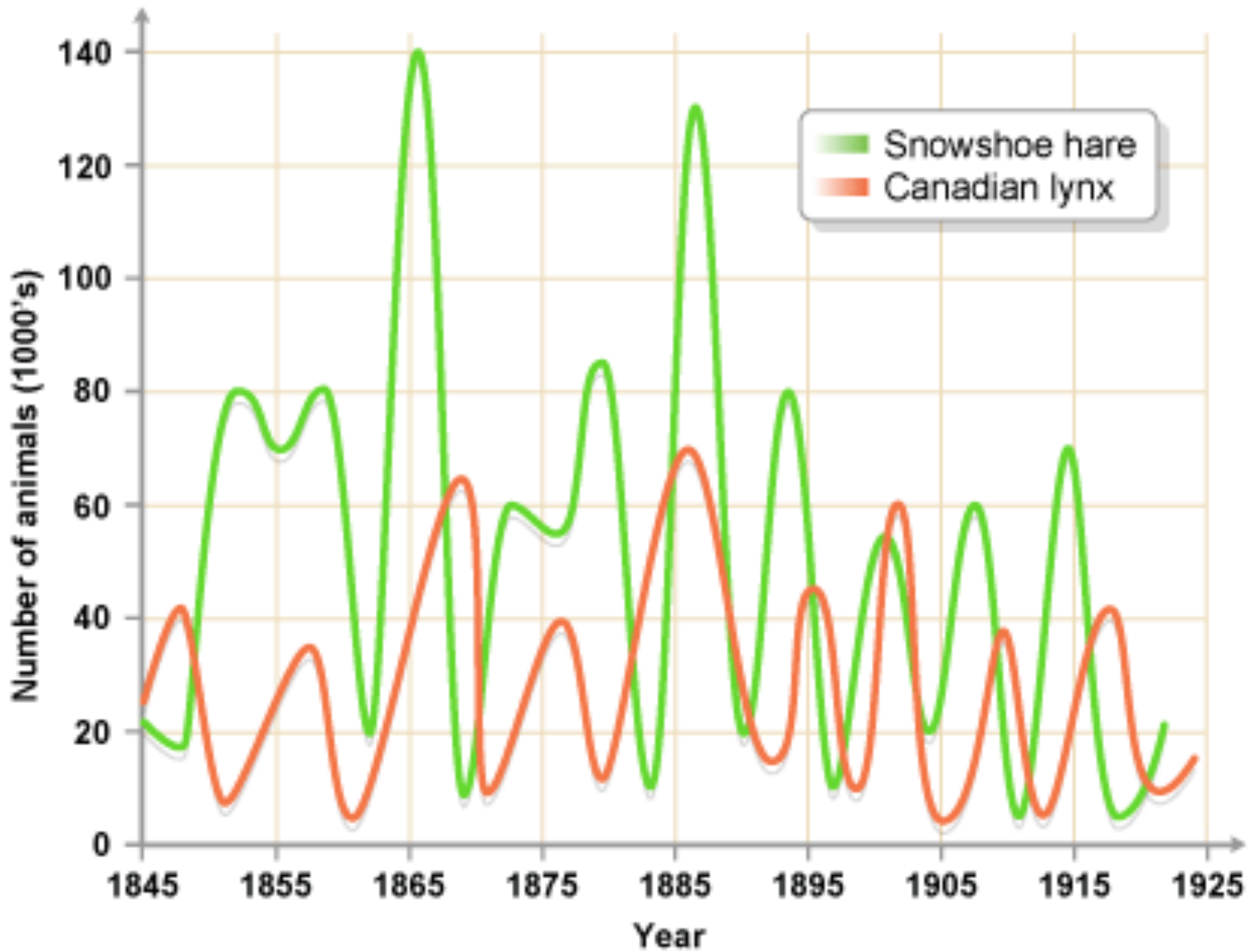
Exploring the Dynamics producing Historical Cycles of Rise and Collapse

- There are widespread concerns that current trends in resource-use (growth in <u>depletion</u> *and* <u>pollution</u>) are unsustainable.

- But our understandings of
  - **<u>Long-Term Sustainability</u>**

    and of
  - **<u>Overshoot and Collapse</u>**
- Remain under-theorized *AND* controversial

Oscillations with Overshoots and Collapses are common in Natural Systems (like the Predator and Prey model)



But do they occur in Human Systems?

- It is popularly believed that Human History has been a continuous and inevitable upward trend in levels of
  - population and
  - prosperity.
- However, the **Historical Record** is closer to the **Oscillations found in Nature**.
- **Cycles of Rise and Collapse** occurred **frequently in history**,
- often involving centuries of decline (population, economic, and intellectual).

Review of Some Historical Collapses

- **Collapse of the Roman Empire**
  - **Well known, but not the first rise and collapse in Europe.**
- **Minoan Civilization**
- **Mycenaean Civilization** – Complete and Total Collapse (in Greece, 2K BC)
  - Population dropped by an order of magnitude,
  - Urban areas abandoned,
  - Literacy completely lost
  - Recovery took **4 to 5 centuries**

History is also full of *Cycles* of Rise and Decline

- **Mesopotamian History:**
  - the Sumerians, the Akkadians, Assyrians, Babylonians, Achaemenids, Seleucids, Parthians, Sassanids, Umayyads, and Abbasids.
- **Egyptian History**,
  - Three distinct cycles of Rise And Collapse in Ancient Egypt:
  - More Cycles after Egypt was conquered by the Persians, Greeks, Romans, Arabs, Turks, and British
- **Chinese History**
  - Zhou, Han, Song, Ming, & Ching Empires
  - all were followed by a decline or a collapse.

Indian History:

- Indus Valley Civilization, Mauryan Empire, Gupta Empire, A Dark Ages, Empire under Harsha. Finally by many Foreign Conquests by Arabs, Moguls, British

Collapses Not Restricted to the "Old World"

- Collapse of **Maya Civilization** in the Yucatan
  - One of the best-known cases
  - Partly because of the Depth of the Collapse
    - As Diamond [2005] puts it,

    "the disappearance of between 90 and 99% of the Maya population after A.D.800."

- **Other Rise and Collapse Cycles in Mesoamerica:**
- **Central Mexico**:
  - The Olmecs, The Toltecs, Teotihuacan (the sixth largest city in the world in the 7th C), Monte Alban

Many others examples from around the World:

- **Mississippi Valley Cultures** such as:
  - Cahokia,
  - The Hopewell Complex
- **South West US Cultures** such as
  - The Pueblo and
  - The Hohokam,
- **Andean Civilizations** such as
  - Huari, Tiwanaku,
- **Sub-Saharan African Civilizations** such as Great Zimbabwe, and
- Collapses in **the Pacific Islands**,
  - Easter Island is the most well known.

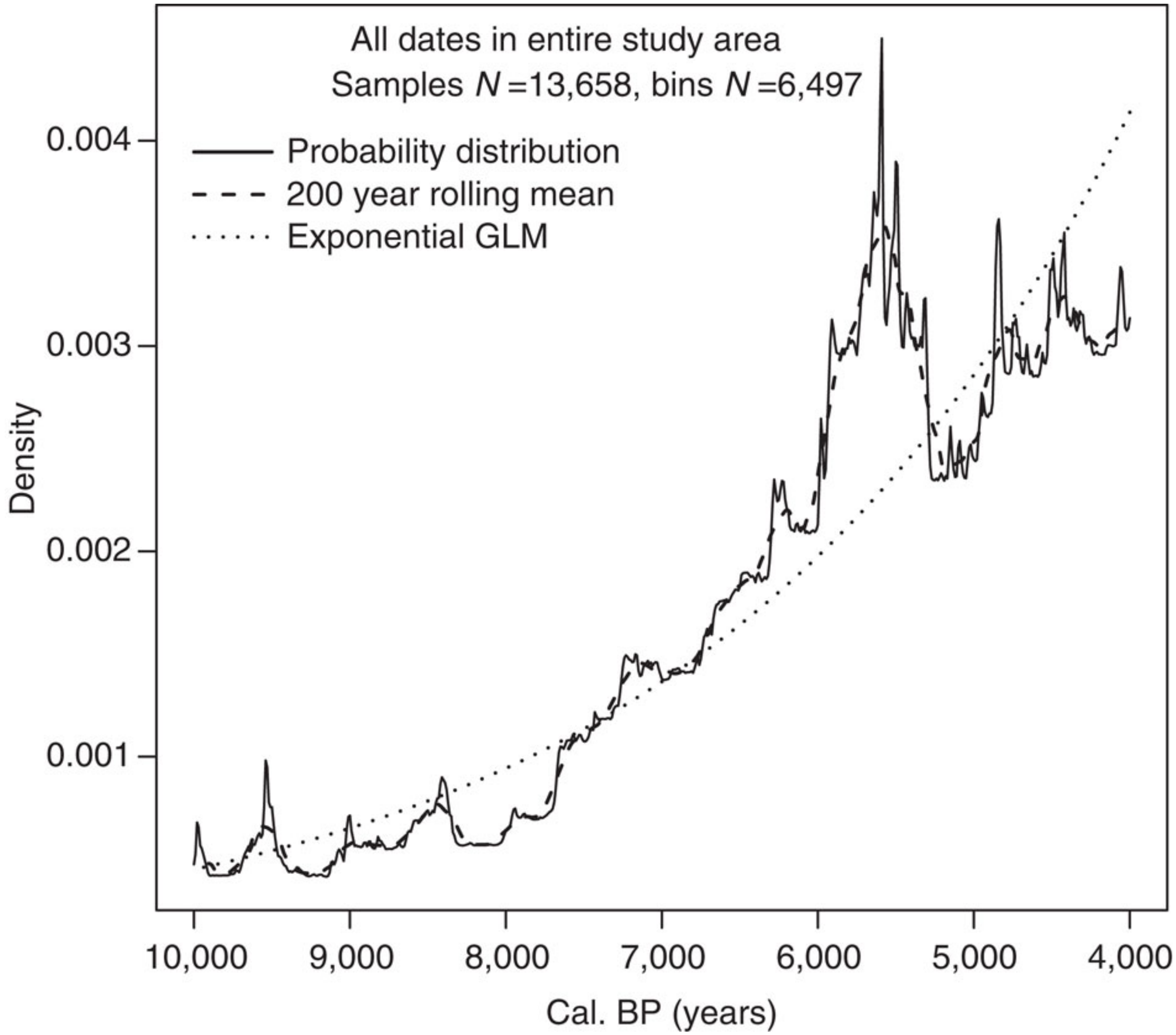
Cycles also occurred in early non-stratified Neolithic Societies

- A recent study [Shennan et al., 2013] of **<u>Neolithic Europe</u>** found:
  - "in contrast to the steady population growth usually assumed,

  the introduction of agriculture into Europe was followed by

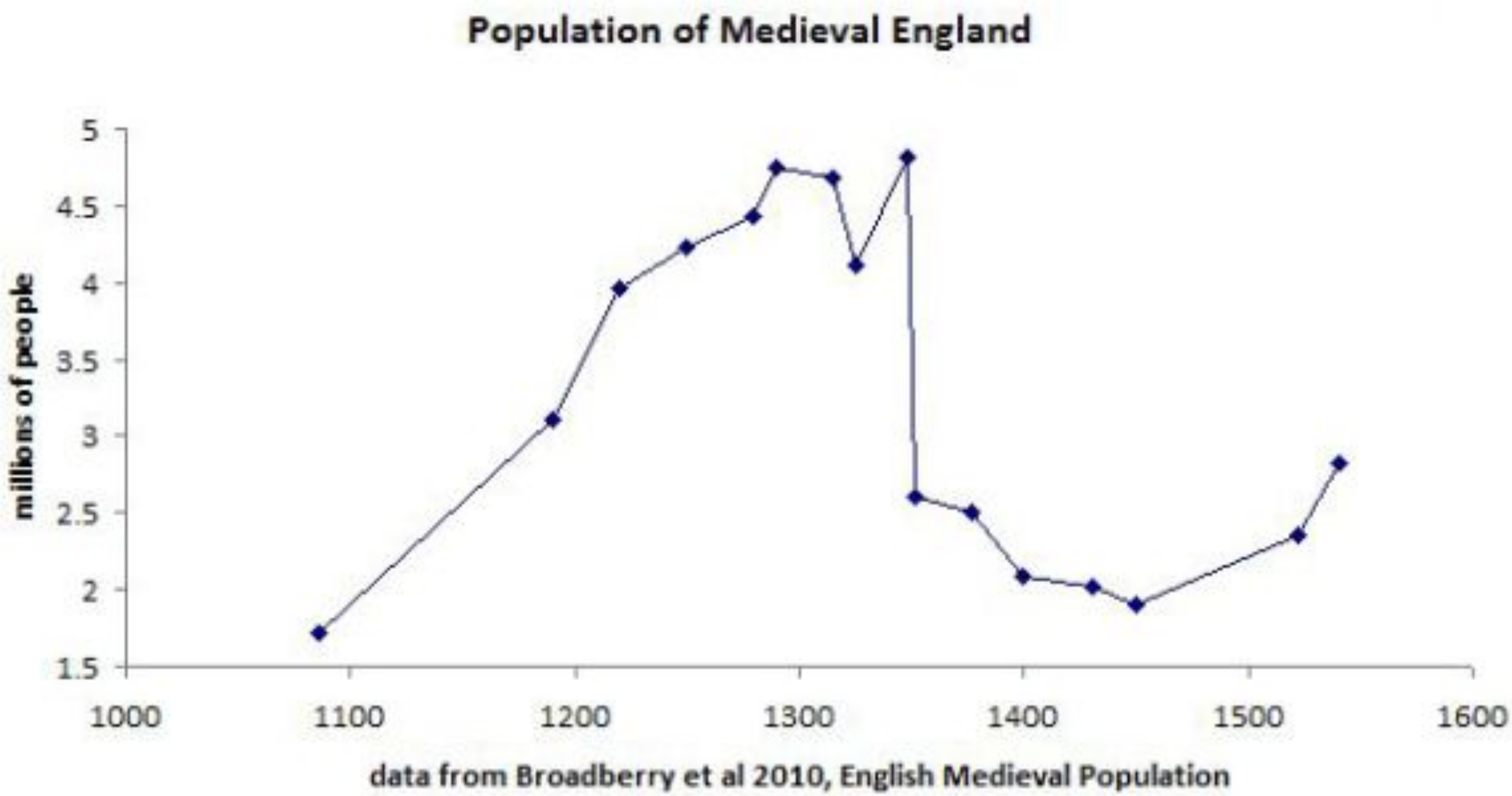
  - **<u>a boom-and-bust pattern in the density of regional populations</u>**".
- Multiple Cycles:
  - "most regions show **<u>more than one boom-bust pattern</u>**"

Neolithic Population (all of Western Europe)

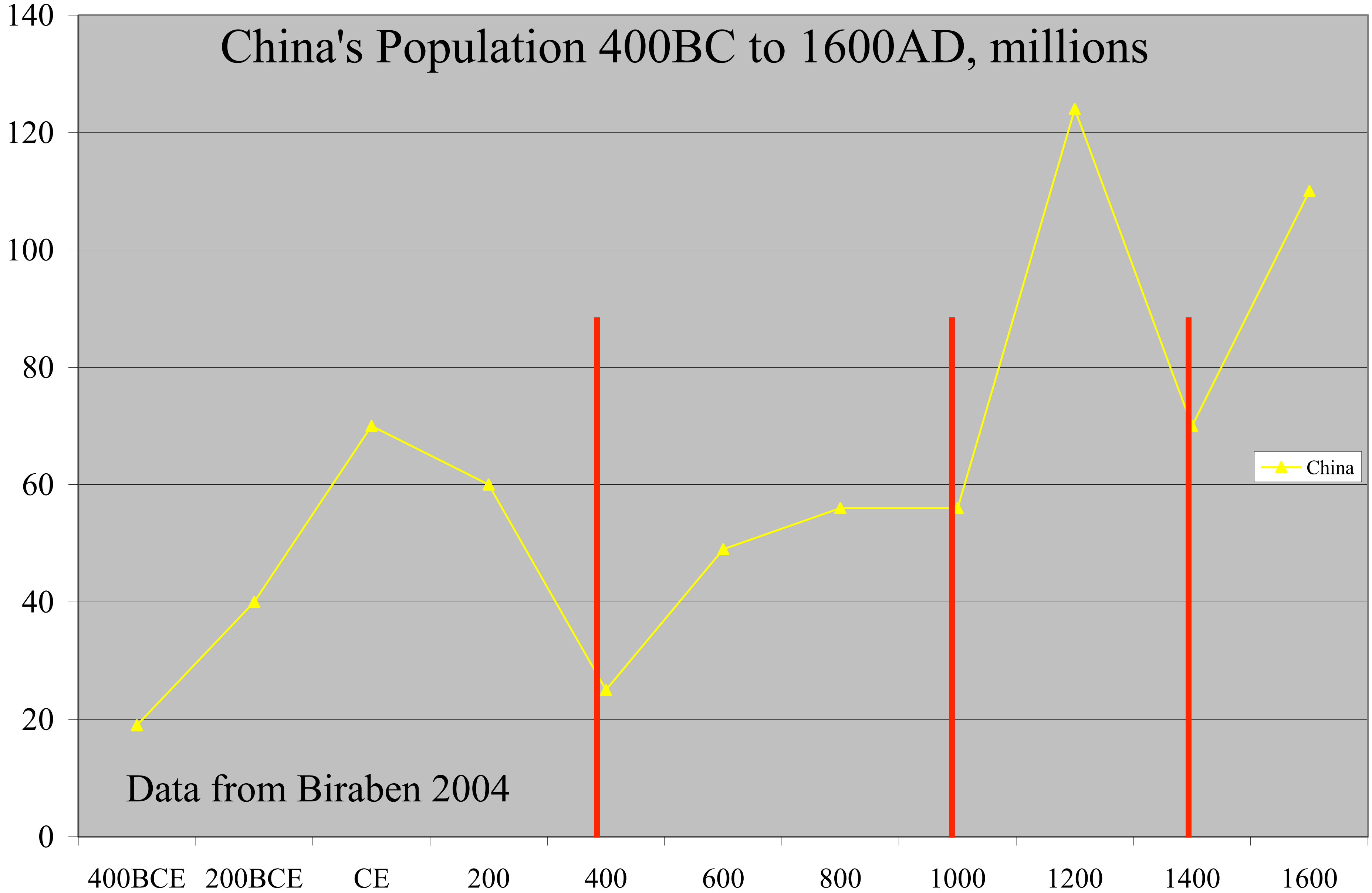


Population Density change 10,000–4,000 BP
using all radiocarbon dates in the western Europe
(SCRPD) summed calibrated radiocarbon date density

The European Medieval Demographic Collapse:



These relatively precise estimates provides us with a good example of a rise and collapse cycle.



China's Population 400BC to 1600AD, millions
140
120
100
80
60
40
20
0
400BCE
200BCE
CE
200
400
600
800
1000
1200
1400
1600
China
Data from Biraben 2004

In sum:

Cycles of rise and collapse are common across different Regions, Time Periods, and levels of Technological Development

- Tainter [1988]
  - The "picture that emerges is of a process recurrent in history, and global in its distribution"
- Turchin and Nefedov [2009]:
  - "demographic-social-political oscillations of a very long period (centuries long) are the rule, rather than an exception...."

Human and Nature Dynamics Model (HANDY)

We built a **Human Population Dynamics Model** by starting with a **Standard Population Model In Biology** ("predator–prey"),

And adding two **Properties** found in **Human Populations**:

(1) Accumulated Surplus (wealth) and

(2) Economic Inequality

to **investigate Potential Mechanisms** that can **explain these cycles** found in the historical record.

Human **a**nd **N**ature **Dy**namical model (HANDY) with Rich and Poor: for thought experiments

Just 4 equations!

Total population: Elite + Commoners $x = x_E + x_C$

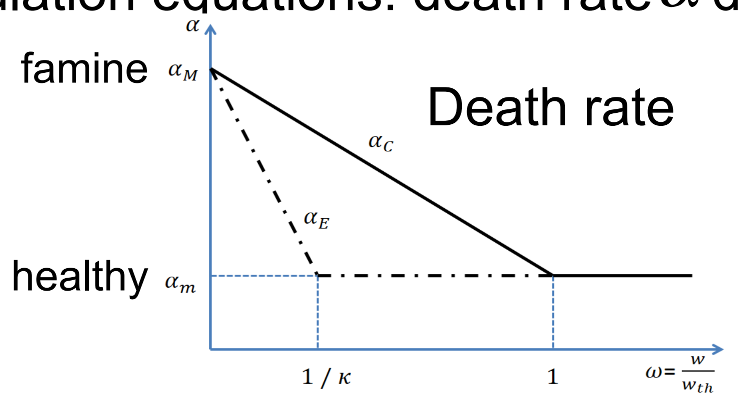
Nature equation: Logistic Regeneration – Production by Commoners:

$$\dot{y} = \text{Regeneration } \gamma y(\lambda - y) - \text{Production } \delta x_C y$$

Wealth is managed by the Elites. Inequality factor $\kappa \sim 100$

$$\dot{W} = \text{Production-Commoner consumption-Elite consumption} = \delta x_C y - s x_C - \kappa s x_E$$

Population equations: death rate α depends on whether there is enough food:

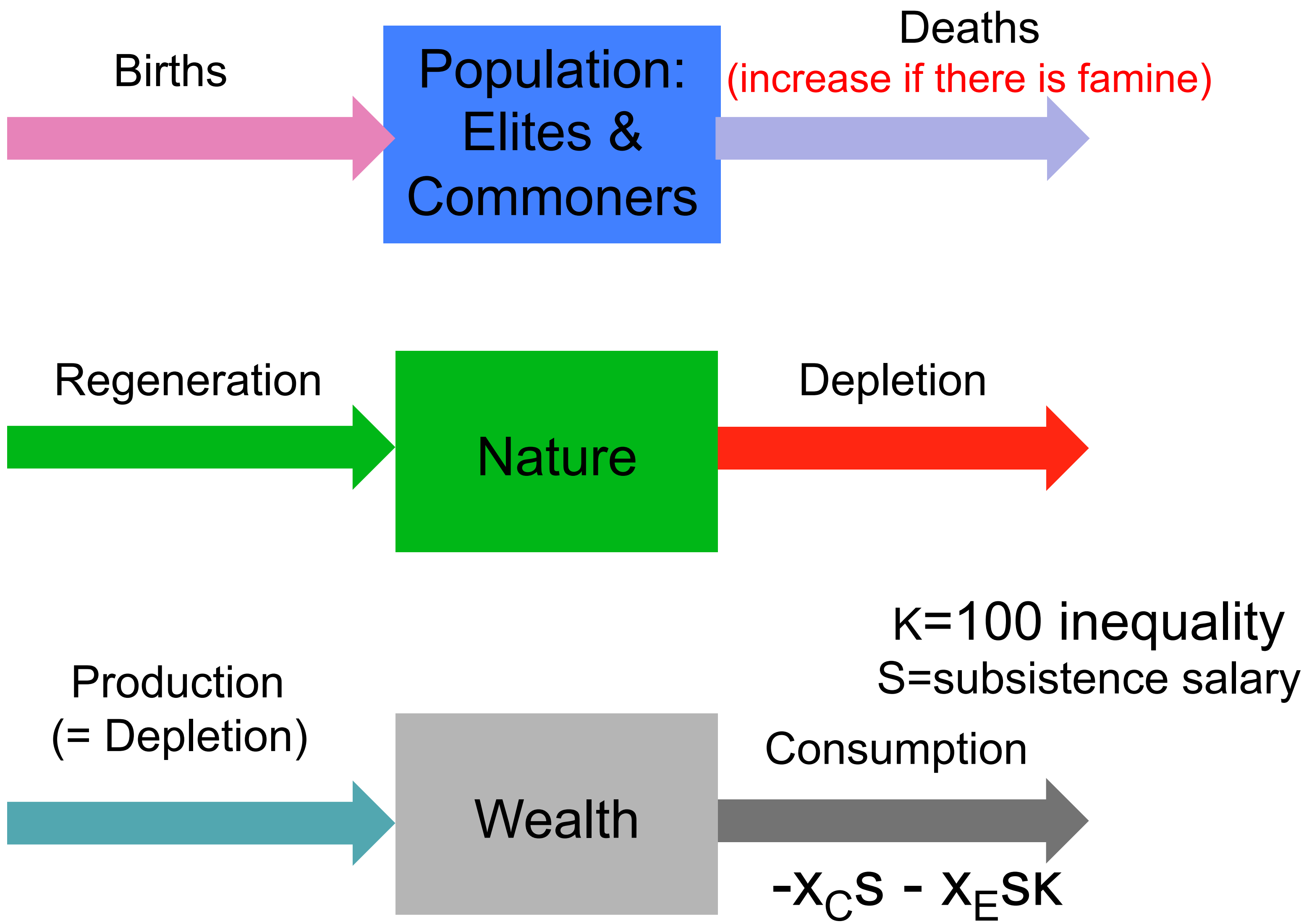


$$\dot{x}_C = -\alpha_C x_C + \beta_C x_C$$

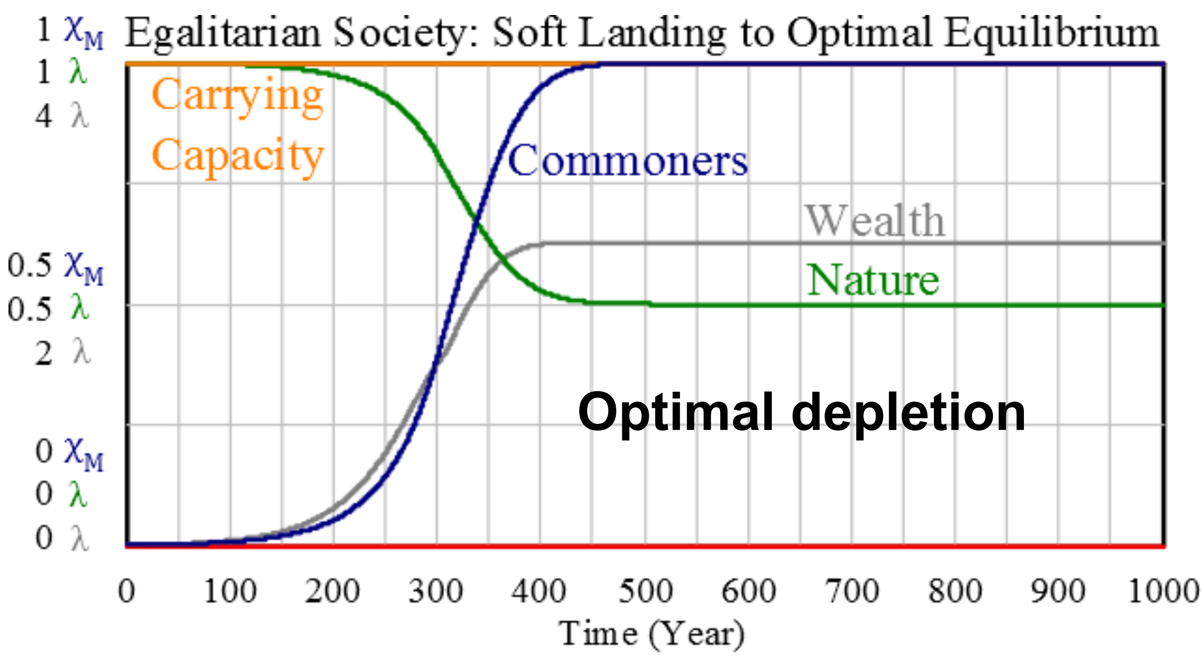
$$\dot{x}_E = -\alpha_E x_E + \beta_E x_E$$

The **rich Elite** accumulates wealth from the work of everyone else (here referred to as the **Commoners**). When there is a crisis (e.g., famine) the Elite can spend the accumulated wealth to buy food and survive longer.

State Variables (Stocks) and Flows in HANDY1



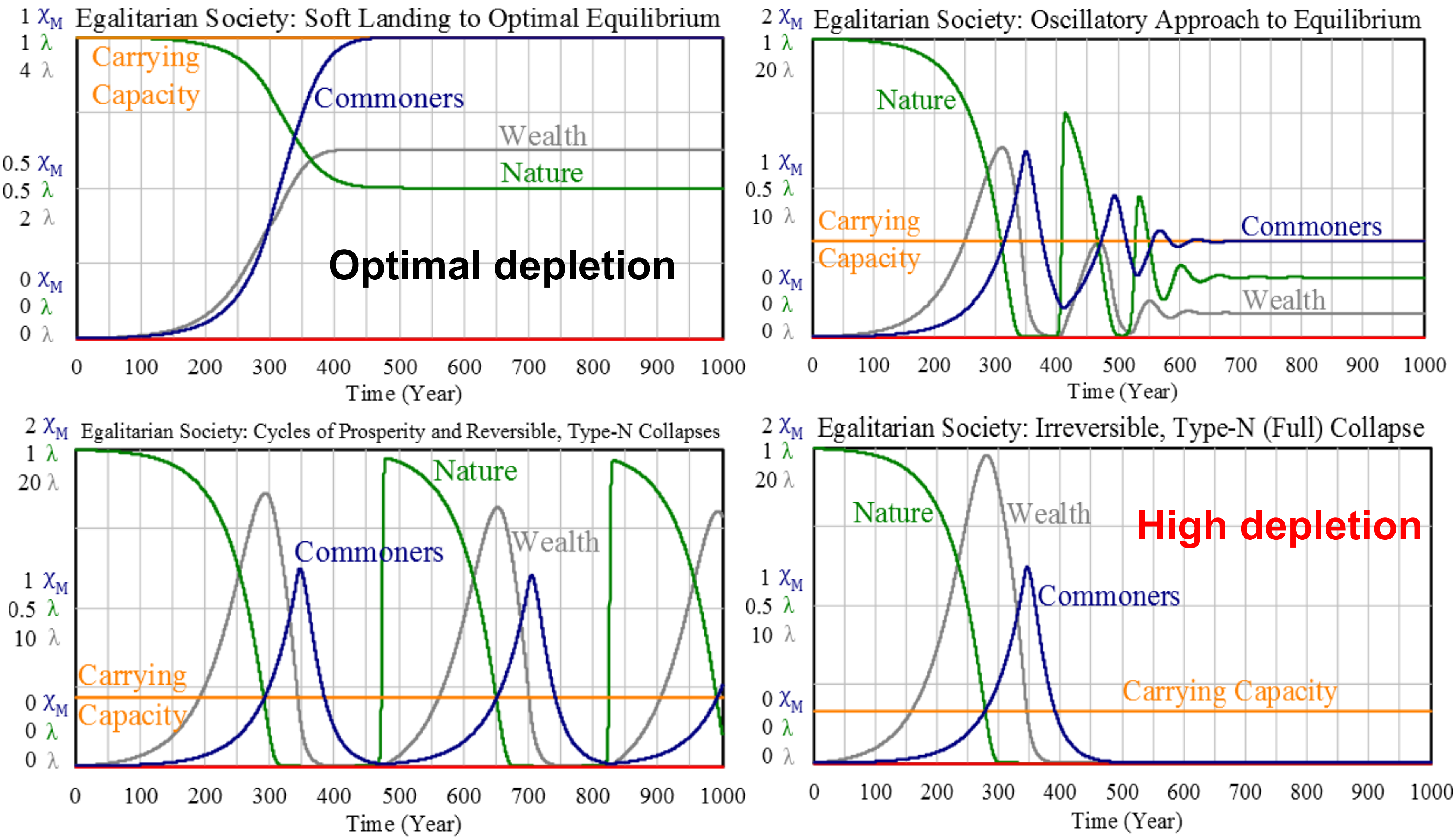
Experiments for an Egalitarian Society (K=1)



With optimal depletion an egalitarian society reaches equilibrium at the maximum Carrying Capacity

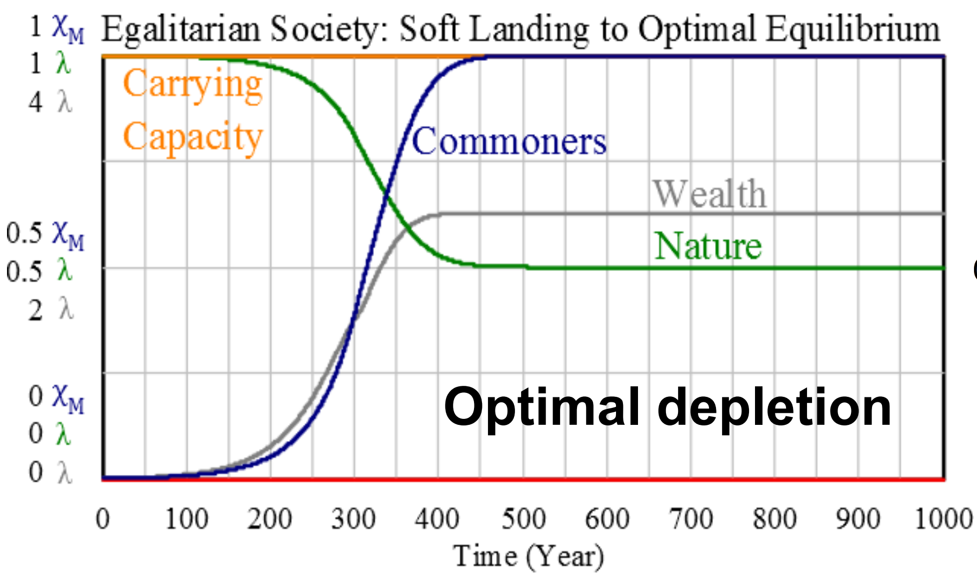
What happens if we increase the depletion per capita?

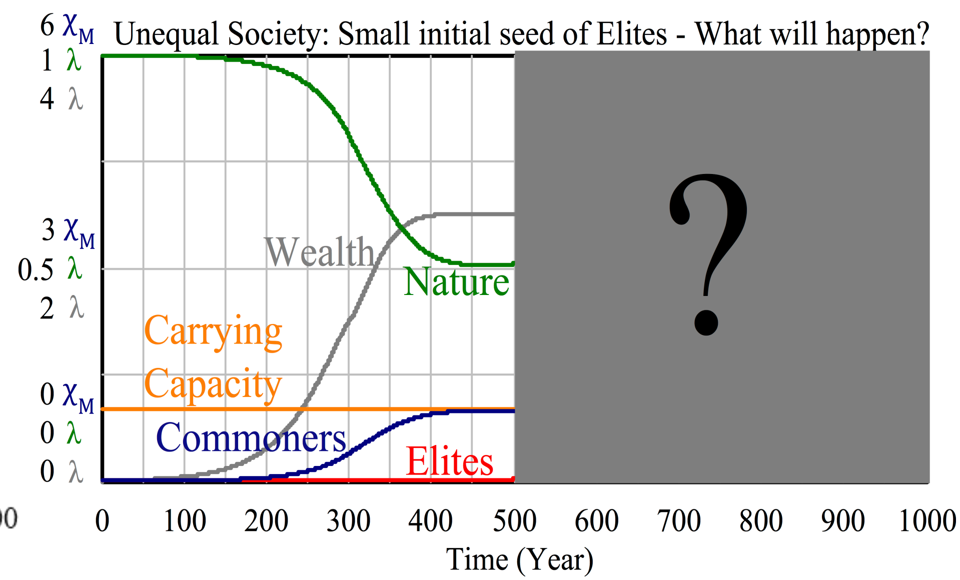
Experiments for an Egalitarian Society (K=1)



High depletion rate leads to collapse: nature cannot regrow

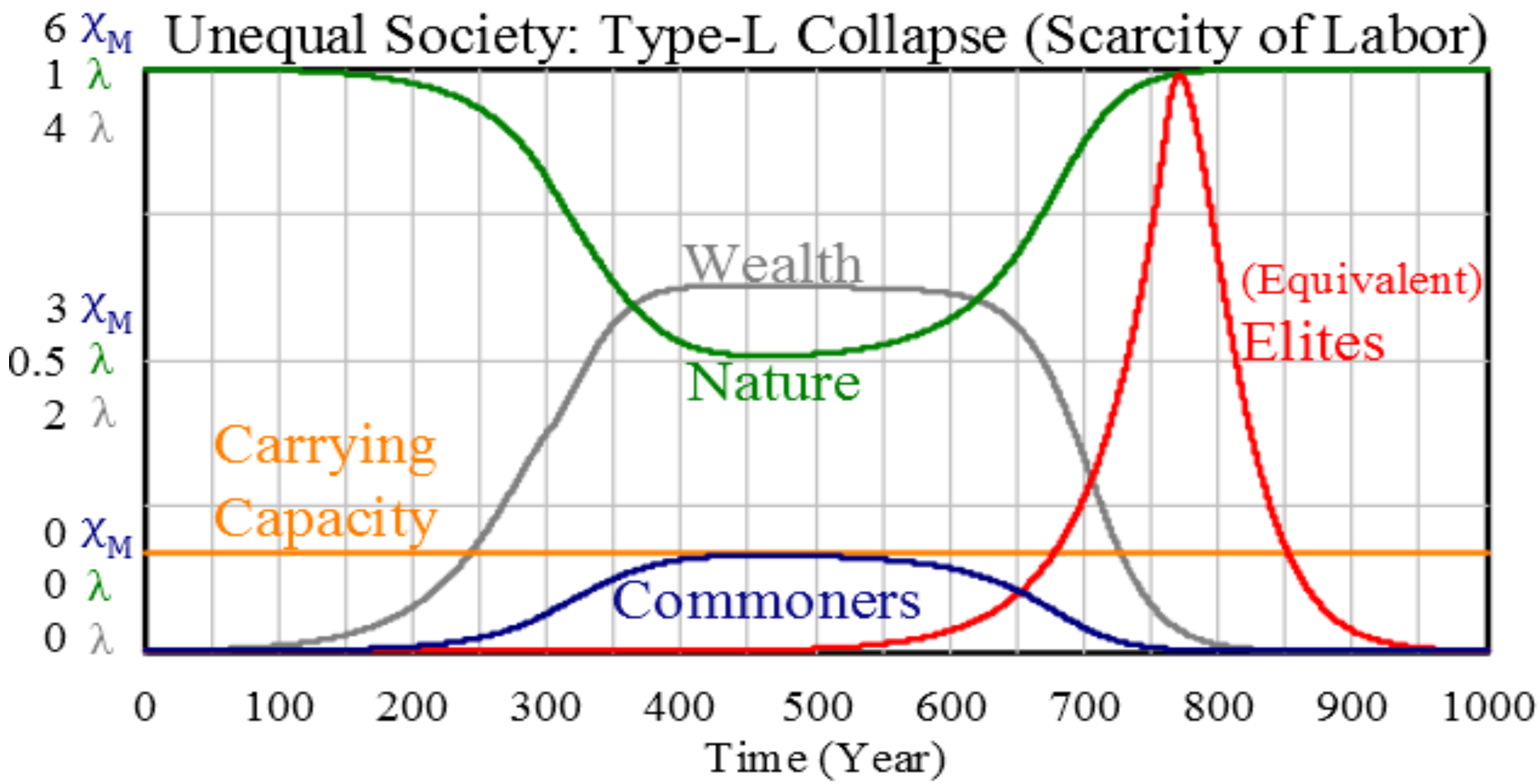
What happens if we introduce Inequality?
Optimal depletion, but K=100





Up until t = 500,
both scenarios show the exact same evolution

An otherwise *sustainable* society will collapse if there is high inequality (κ = 100).



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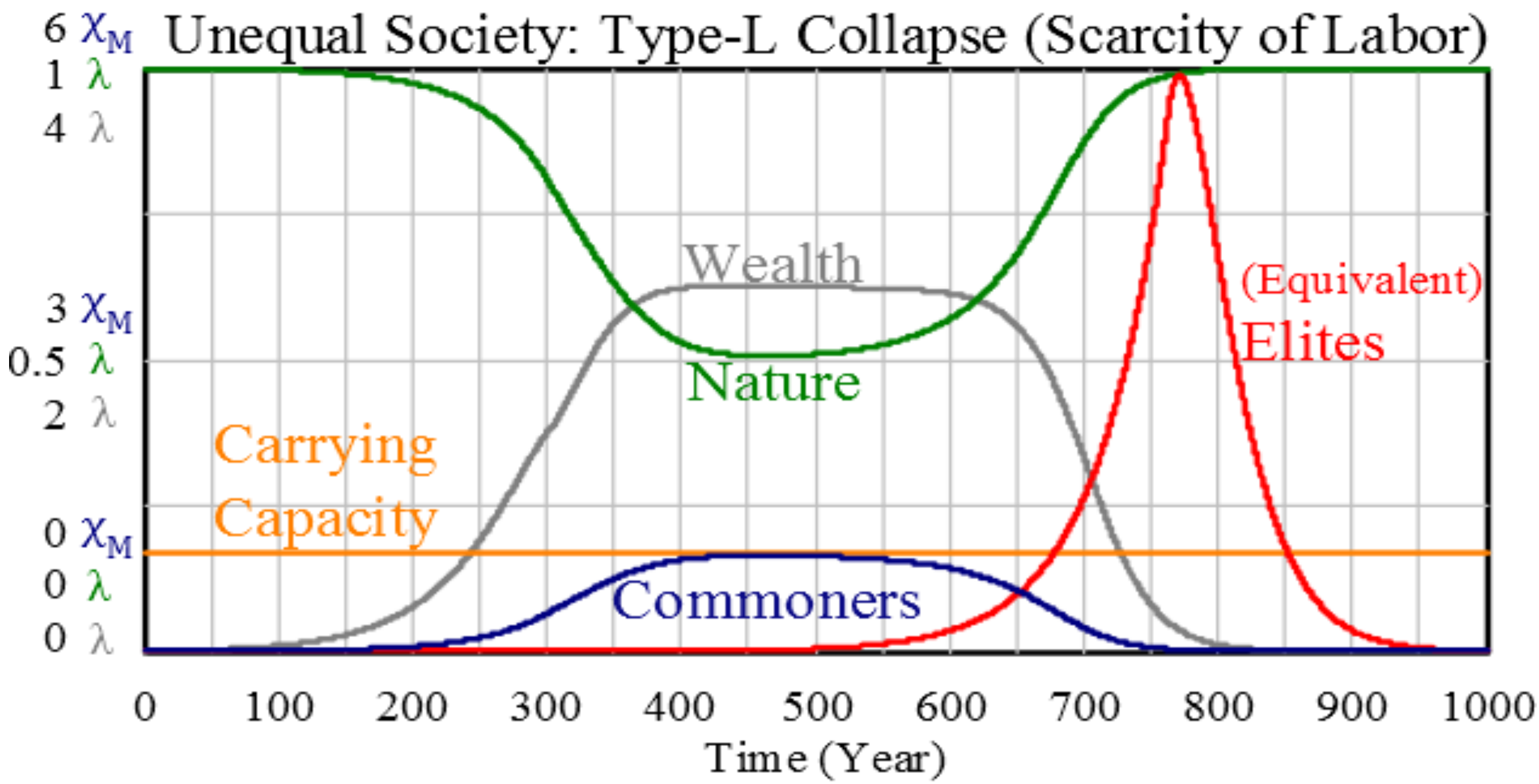
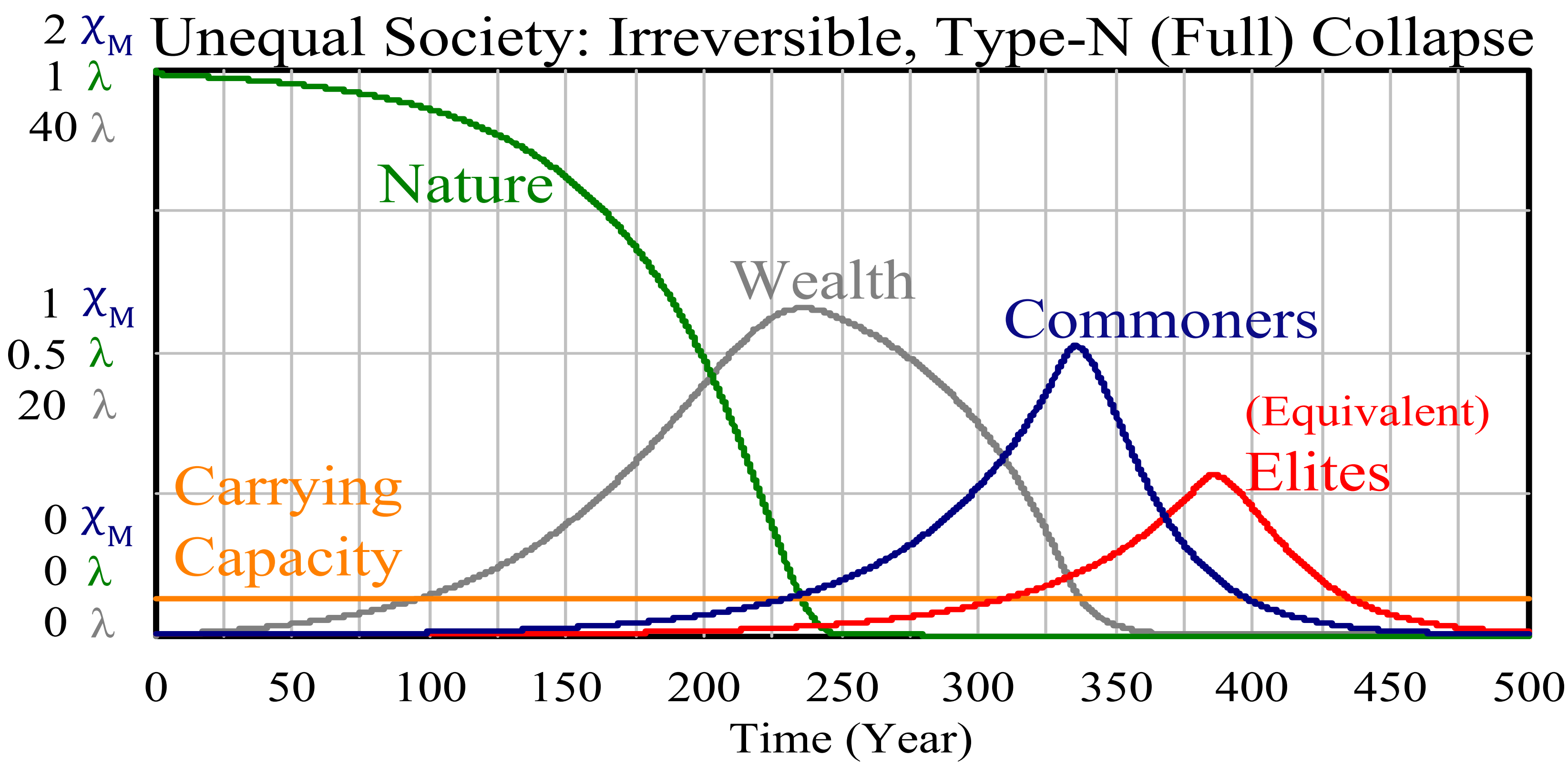


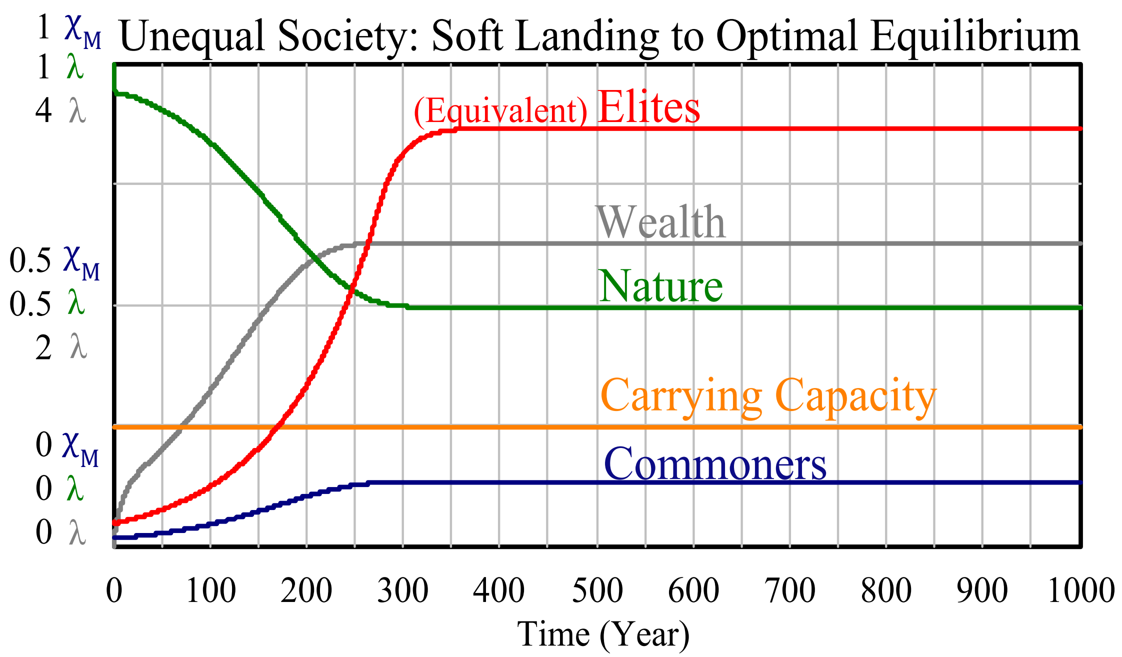
What happens if we have *both* high inequality and high depletion rate?

Typical Collapse: High Depletion Rates and High Inequality at the same time



Is there any hope for an unequal society to survive?

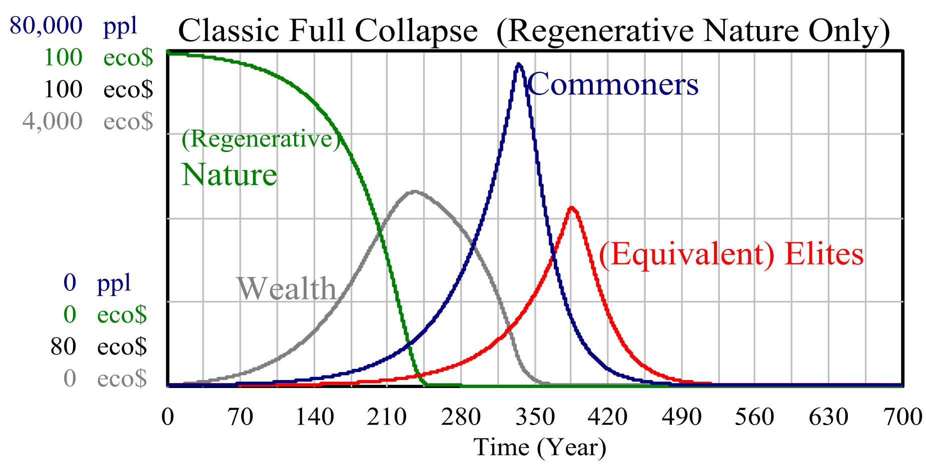
If we reduce the *depletion per capita* and *inequality*, and slow down the *population growth*, it is possible to reach a steady state and survive well.



Reaching this equilibrium requires **changes in policies**:

- Reduce depletion per capita
- Reduce inequality ($\kappa = 10$) (as estimated by Daly)
- Reduce birth rates

Could a collapse be prevented if we "find" large stocks of Nonrenewable Energy?



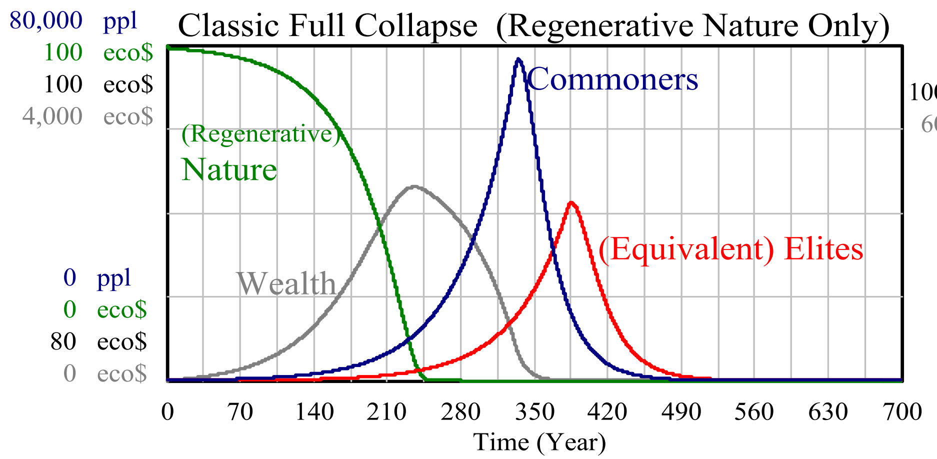
What happens when we add fossil fuels?

This is the classic HANDY1 full collapse scenario, with only regenerating Nature

We then add to the regenerating Nature a **nonrenewable Nature**

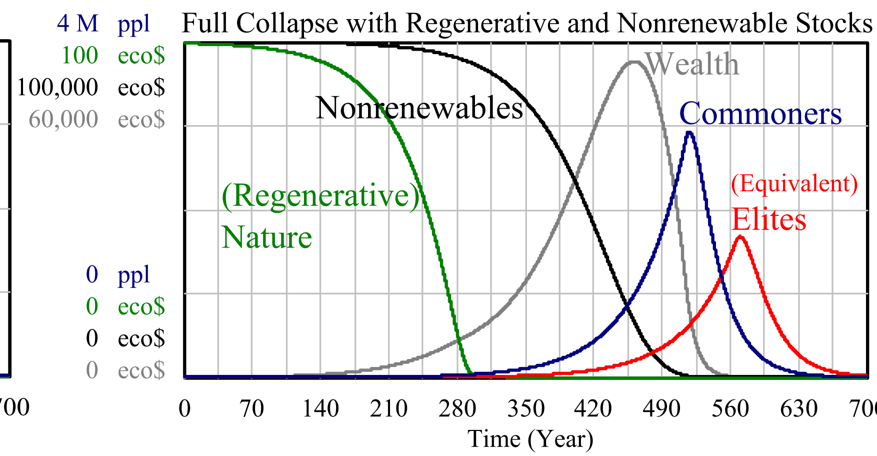
Impact of adding fossil fuels (nonrenewable energy resources)

80K



Regenerating Nature Only

4Million

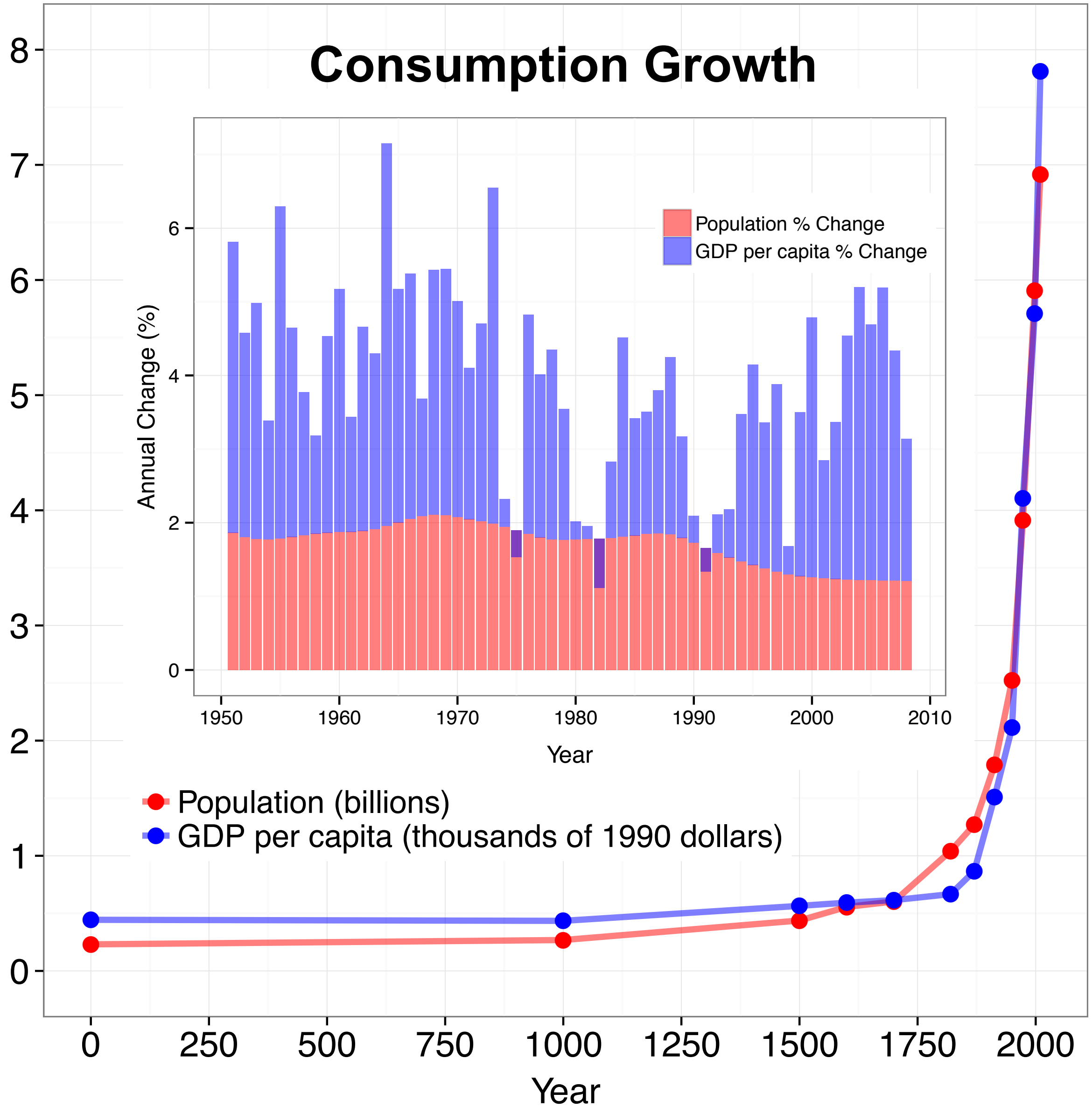


Both Regenerating and **Nonrenewable** Resources

The collapse is postponed by ~200 years and the peak population increases by a factor of ~20!

Reminiscent of the Industrial Revolution!

Population and GDP per capita: explosion is very recent (1950)



Consumption is growing
~ 2% population
~ 2% GDP/cap

~ 4% per year!

Since 1950,
<u>we double our total consumption</u>
every 17 years!

Non-Renewables Expanded the Carrying Capacity:

- Fossil Fuels are Stocks of Energy *and* Material Resources accumulated
- *over several hundreds of millions years*.
- We are *consuming those stocks in ~ 3 centuries*.
- A similar dynamic is taking place with **Aquifer Water**. In just a few decades, we are drawing down vast stores of fresh water from *aquifers that take centuries or millennia* to recharge.

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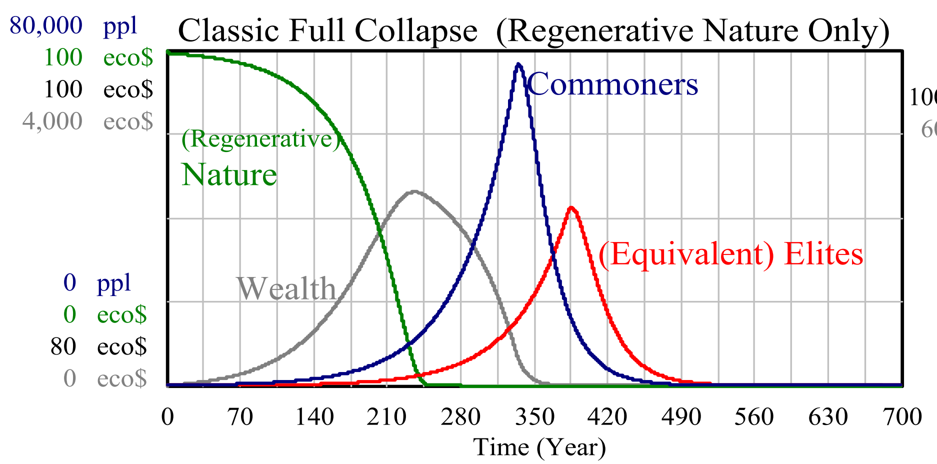
80K



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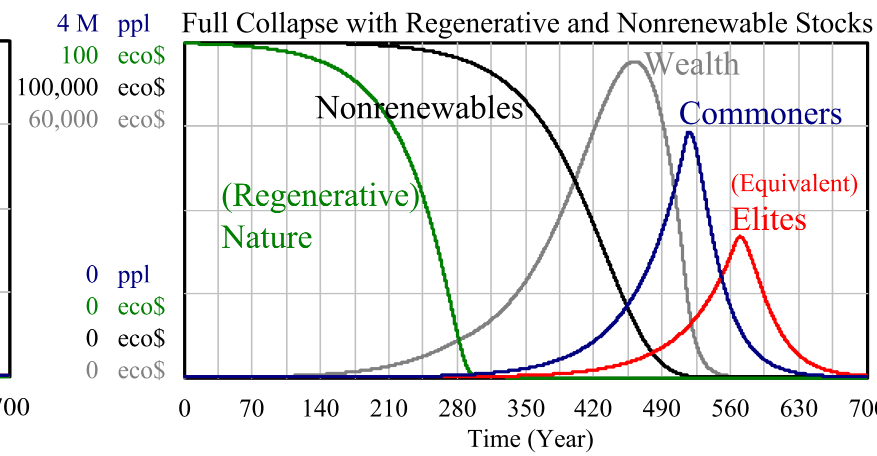

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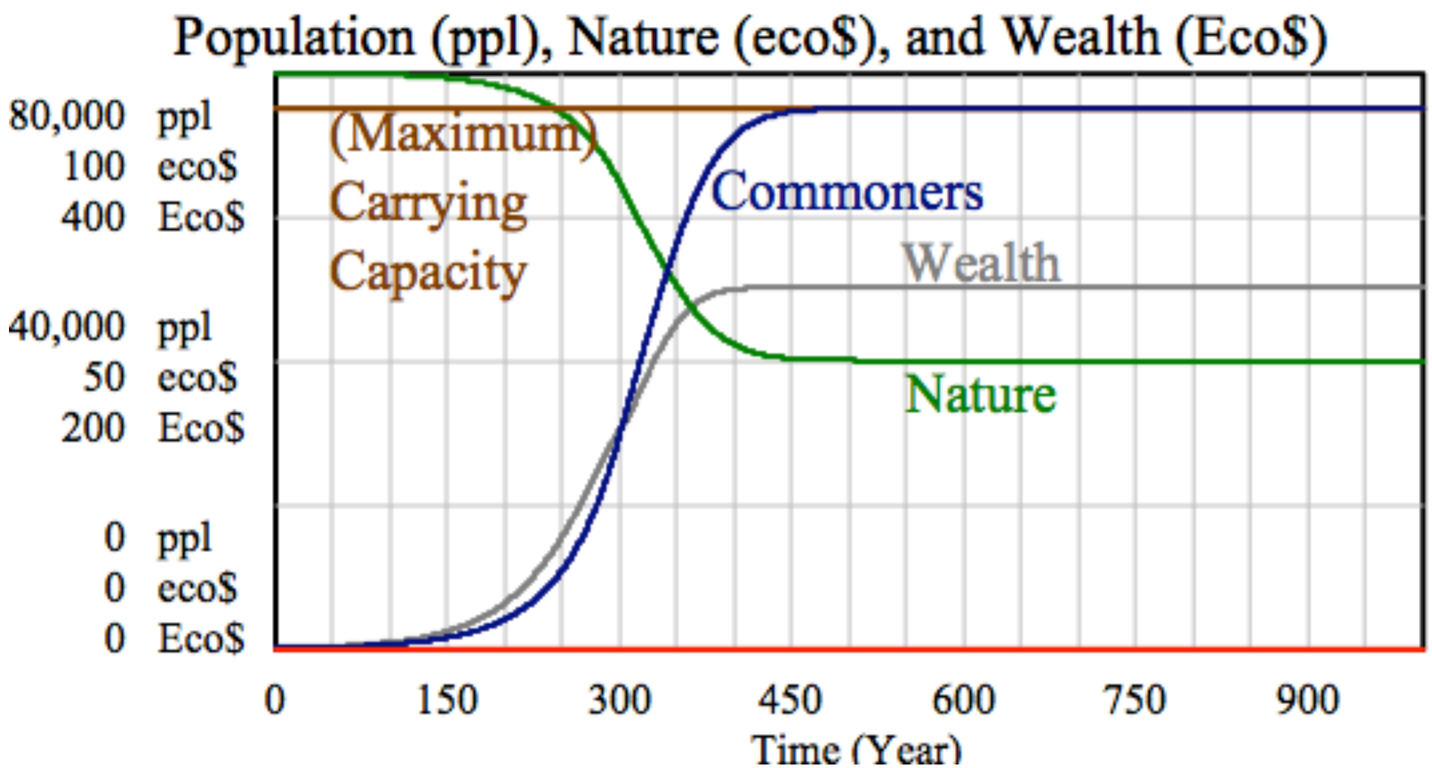
Reminiscent of the Industrial Revolution!

Can we survive? **Yes!** (but only if we live sustainably!)



Carrying capacity: the population that nature can sustain forever.

If we use nature in a sustainable way, and consume only as much as nature can regrow, we can reach a good state of equilibrium

Summary

- We are using up in 200+ years the fossil fuels that nature accumulated over millions of years. Same with fossil water.
- The use of fossil fuels for agriculture increased food production and population after 1950.
- HANDY I "thought experiments" show that reducing:
  1. Social inequality
  2. Population growth
  3. Depletion per capita allow society to become sustainable.
- HANDY II: Adding non-renewables
  1. Increases maximum population by ~20 times.
  2. Postpones collapse by about 200-300 years
  3. If the transition from fossil to renewables (solar and winds) is done early enough, it is possible to avoid the collapse.

We are NOT modeling the coupled Earth-Human System!

- We need to couple them to provide feedbacks!
- Data assimilation can help tune the coupled models

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Thanks!

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