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

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Is climate change really happening?

Source: NASA Goddard Institute for Space Studies
By The New York Times
Climate change 101

Since ~1800 we are burning the fossil fuels that Nature accumulated during 100’s of 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 $\times$ emission/person
Global anthropogenic CO₂ emissions

Quantitative information of CH₄ and N₂O emission time series from 1850 to 1970 is limited

- Fossil fuels, cement and flaring
- Forestry and other land use

Haber-Bosch nitrogen fertilization
### Population Growth

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<tr>
<th>Year</th>
<th>Population (b)</th>
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<td>0.3</td>
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<tr>
<td>1650</td>
<td>0.5</td>
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<tr>
<td>1800</td>
<td>1.0</td>
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<tr>
<td>1927</td>
<td>2.0</td>
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<td>1960</td>
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<td>1975</td>
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<td>1987</td>
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<td>1998</td>
<td>6.0</td>
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<td>2011</td>
<td>7.0</td>
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**World Population Growth**

Source: United Nations 2008-based Medium Variant Projection

- 9.1 billion at 2050?
- 6.8 billion in 2009

![Graph showing world population growth](image)
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

**Sources:**
- Stock of Natural Capital
- Flows of Energy

**Inputs:**
1. Energy
   - Oil, Coal, Gas, Nuclear, Biomass, Renewables, etc
2. Matter
   - Soil, Minerals, Lumber, and other Materials Resources

**Human Economy**
- Population \(\leftrightarrow\) Technology
  - Population growth rate
  - Energy Use / Capita
  - Resource Use / Capita
  - Emissions produced / Capita
  - Waste produced / Capita
  - Economic expansion / Capita

**Outputs:**
1. Emissions
   - CO2, Methane, etc
2. Waste Products
   - Garbage, Toxics, etc
3. Surface Changes
   - Urbanization, Deforestation, Desertification, etc

**Sinks:**
- Oceans, Atmosphere
- Land
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:

**Inputs:**
1. Energy
   - Oil, Coal, Gas, Nuclear, Biomass, Renewables, etc
2. Matter
   - Soil, Minerals, Lumber, and Other Material Resources

**Sources:**
- Stock of Natural Capital
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**Sinks:**
- Oceans
- Atmosphere
- Land
“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, we double our total consumption every 17-20 years!

UNSUSTAINABLE!
“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**.
Without fully coupling we could not predict ENSO!

IPCC and IAMs DO NOT FULLY COUPLE THE HUMAN AND EARTH SYSTEMS! POPULATION IS OBTAINED FROM UN PROJECTIONS!
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!
There are widespread concerns that current trends in resource-use (growth in depletion and pollution) are unsustainable.

But our understandings of Long-Term Sustainability and of Overshoot and Collapse 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
Many others examples from around the World:

- Collapse of **Maya Civilization** in the Yucatan
- Central Mexico Cultures
- Mississippi Valley Cultures
- South West US Cultures
- Andean Civilizations
- Sub-Saharan African Civilizations
- Collapses in **the Pacific Islands**,  
  – Easter Island is the best known.
- Multiple “Boom and Bust” Cycles also in early non-stratified **Neolithic Societies**
Cycles also occurred in early non-stratified Neolithic Societies

• A recent study [Shennan et al., 2013] of Neolithic Europe found:
  – “in contrast to the steady population growth usually assumed,
    the introduction of agriculture into Europe was followed by
    – a boom-and-bust pattern in the density of regional populations”.

• Multiple Cycles:
  – “most regions show multiple boom-bust cycles”
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 provide us with a good example of a rise and collapse cycle.
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 (population)–prey (nature)"),

But, we added 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 and Nature Dynamical 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 \[ \kappa \sim 100 \]

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

Population equations: death rate \( \alpha \) 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

Births → \text{Population: Elites \\& Commoners} → Deaths (increase rate if there is famine)

Regeneration → \text{Nature} → Depletion

Production (= Depletion) → \text{Wealth} → Consumption

\( k=100 \) inequality
\( S=\text{subsistence salary} \)

\( -x_C S - x_E S K \)
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 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 ($\kappa = 100$).
An otherwise *sustainable* society will collapse if there is high inequality ($\kappa = 100$).

What happens if we have *both* high inequality and high depletion rate?
Typical Collapse: High **Depletion Rates** and High **Inequality** at the same time

![Graph showing collapse]

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)

Regenerating Nature Only

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

Reminiscent of the Industrial Revolution!
**Population and GDP per capita: explosion is very recent (1950)**

Consumption Growth

- Consumption is growing
  - ~ 2% population
  - ~ 2% GDP/cap
  - ~ 4% per year!

Since 1950, we double our total consumption 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.
- And *polluting* the water (e.g., fracking)
Impact of adding fossil fuels (nonrenewable energy resources)

Regenerating Nature Only

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!
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
- We developed a coupled Water-Population model for Phoenix
Extra Slides
Coupled Water-Population model for Phoenix watershed.
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?

How far above or below average temperatures were in 2015

Compared with the average from 1901 to 2000

Average global surface air temperatures

Compared with the average from 1901 to 2000

Source: NASA Goddard Institute for Space Studies
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Global anthropogenic CO₂ emissions

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- Fossil fuels, cement and flaring
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Haber-Bosch nitrogen fertilization
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

2014 UN projection: 11B
2010 UN projection: 10B
2006 UN medium projection: 9B
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.
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
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Collapses Not Restricted to the “Old World”

• Collapse of **Maya Civilization** in the Yucatan

• **Central Mexico:**
  – The Olmecs, The Toltecs, Teotihuacan (the sixth largest city in the world in the 7th C), Monte Alban
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China's Population 400BC to 1600AD, millions

Data from Biraben 2004