Population and Climate Change: Coupling Population Models with Earth System Models

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MIT Seminar: 28 April 2011

My research at the U. of Maryland

1) Data assimilation, Ensemble Kalman Filter and the LETKF, CO2, AIRS data and Mars data assimilation

2) Impact of land use and land-use change on climate (Observations minus Reanalysis): over the last 30 years, changes of land cover have significantly increased surface temperature: "Green is cool".

But today I will talk about something very different:
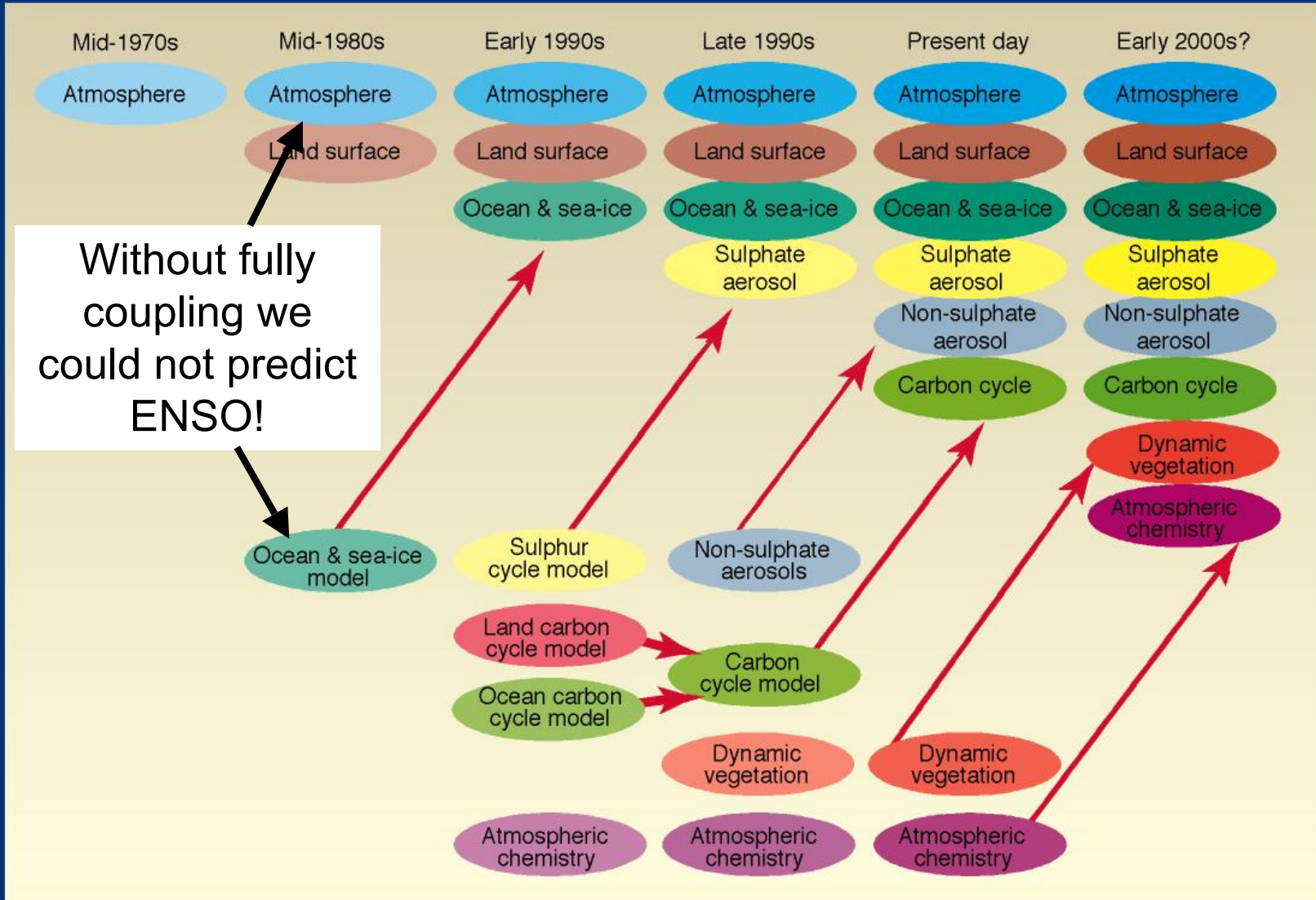
"Population and Climate Change:

Fully Coupling Population and Earth System Models"

The development of climate models, past, present and future
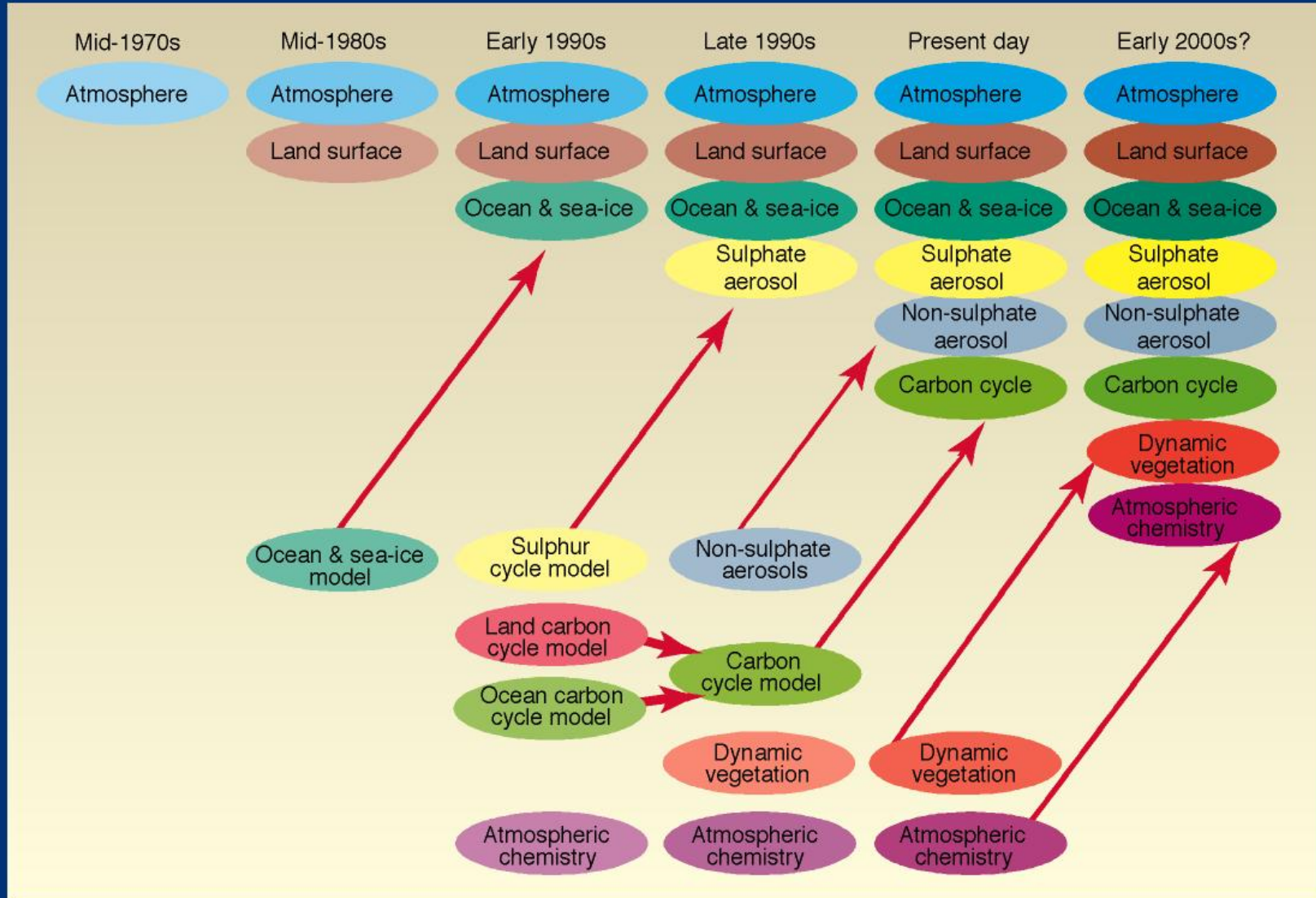
The development of climate models, past, present and future

The development of climate models, past, present and future

Population growth

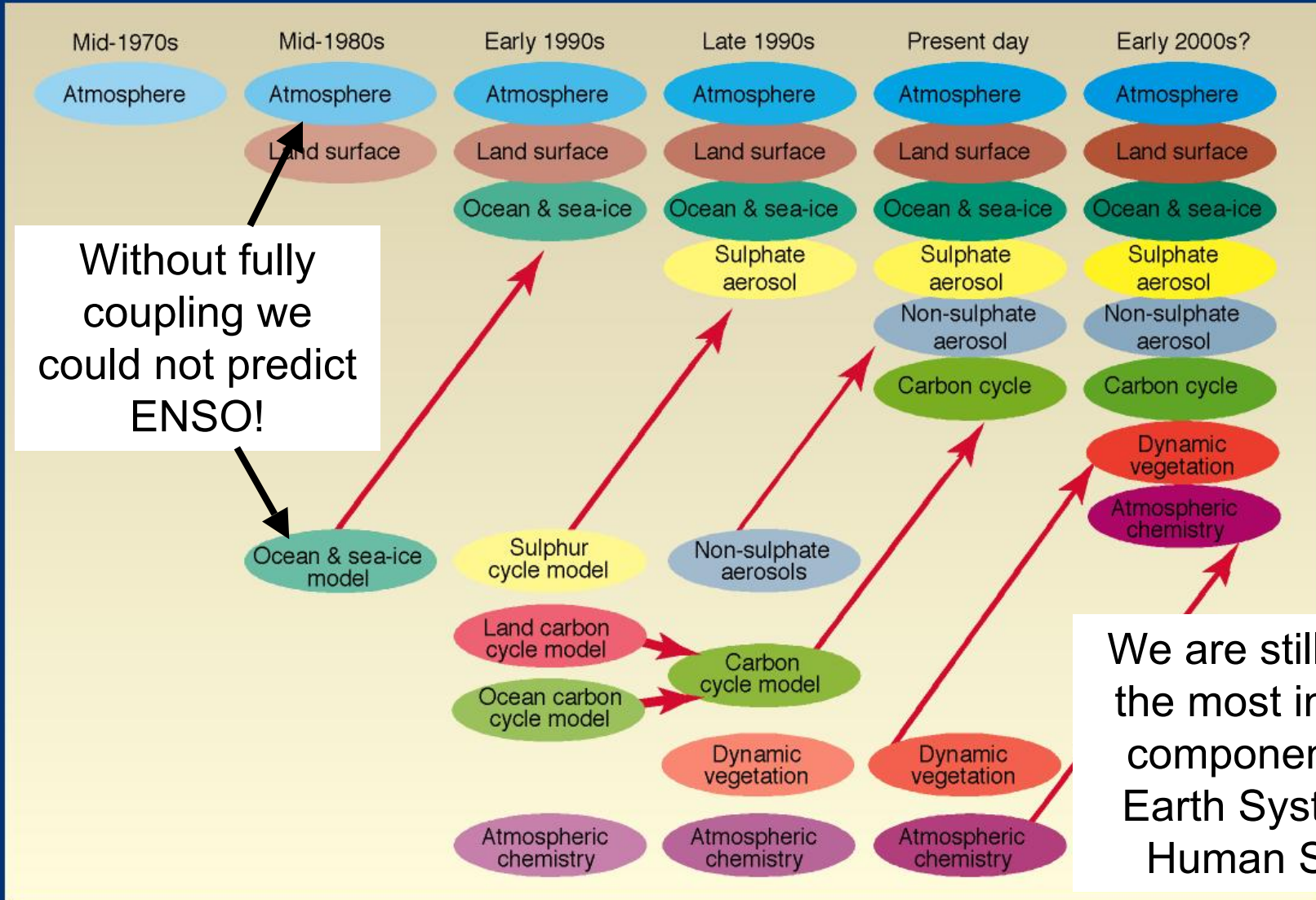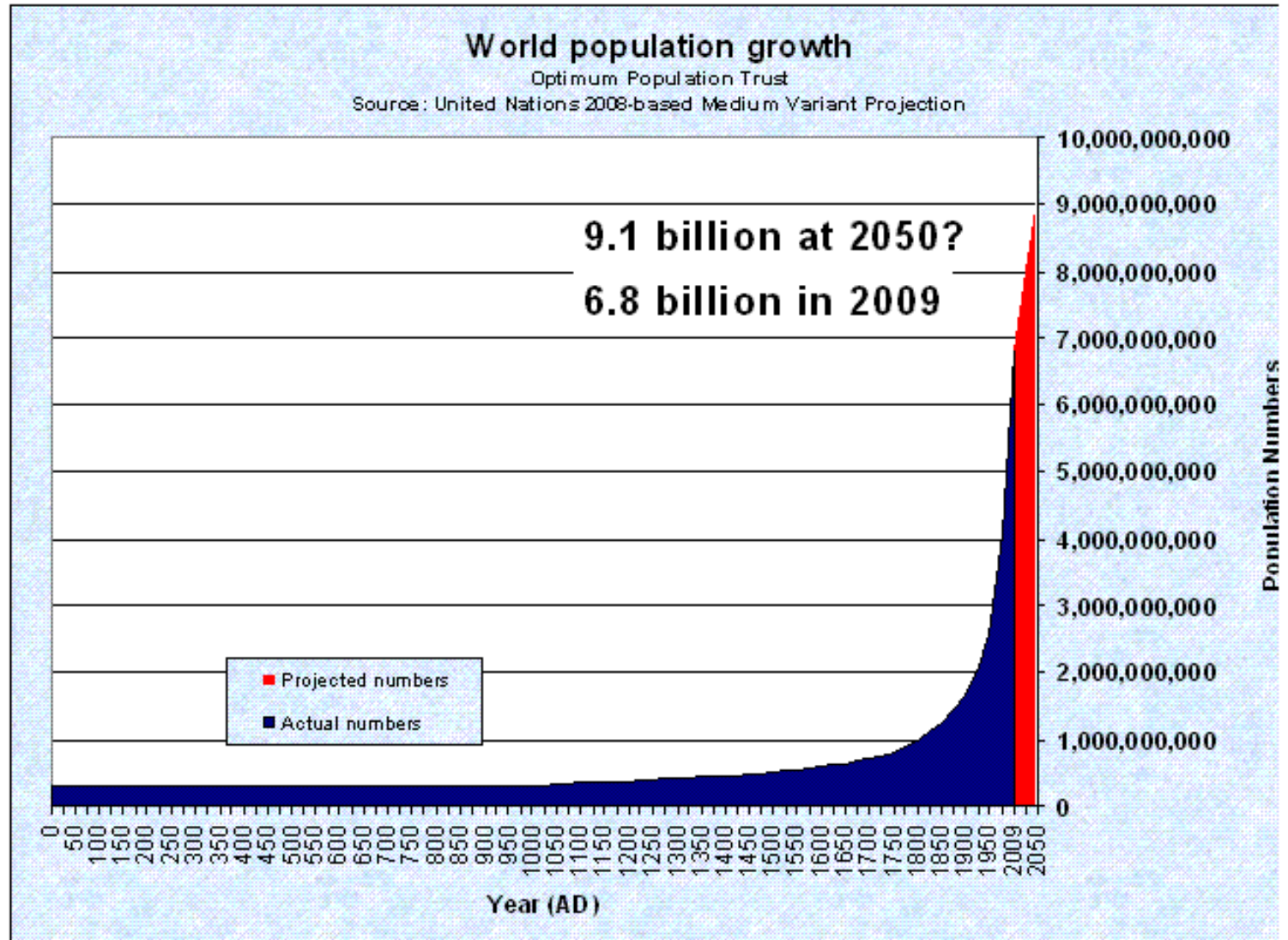|	
1AD	**0.3b**
1650	**0.5b**
1800	**1.0b**
1927	**2.0b**
1960	**3.0b**
1975	**4.0b**
1987	**5.0b**
1998	**6.0b**
2011	**7.0b**

World population growth
Optimum Population Trust
Source: United Nations 2008-based Medium Variant Projection

9.1 billion at 2050?
6.8 billion in 2009

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

Per dollar spent,

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

adopting **low-carbon technologies**

Concluded: Family planning is cost effective and should be a primary method to reduce emissions

Copenhagen: no discussion on population or family planning: it is a **taboo** subject

UK Royal Soc: New population study underway!
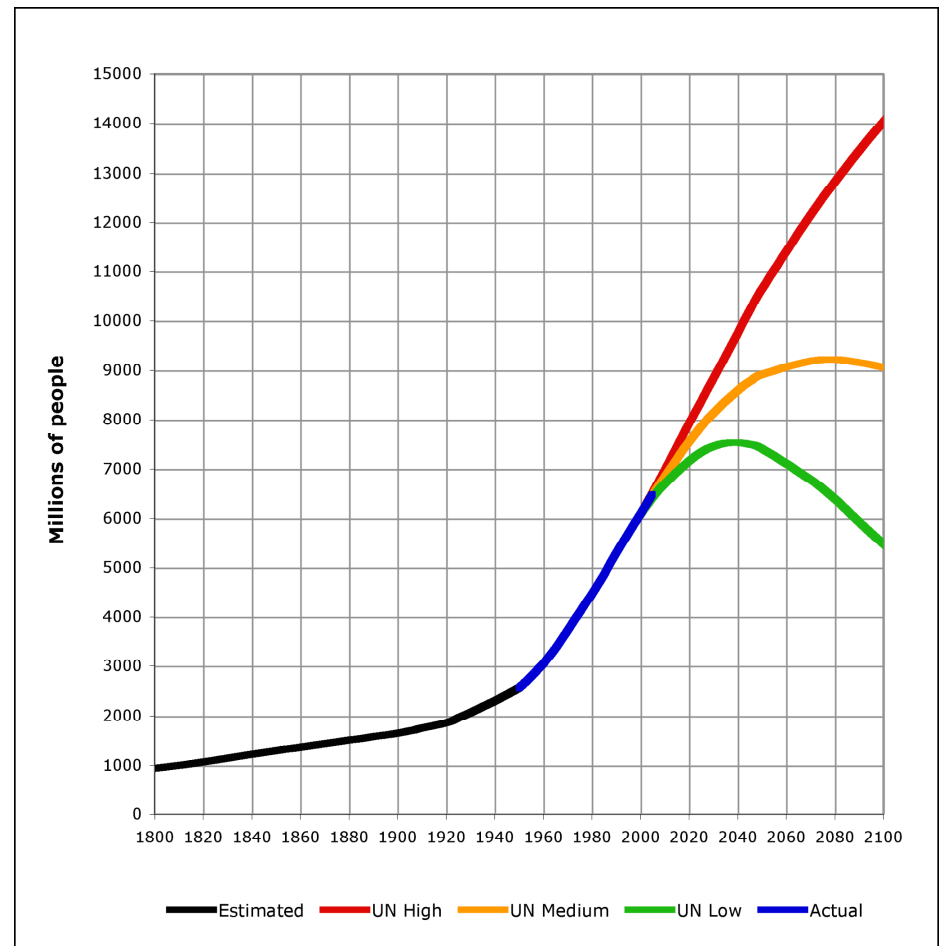
Population growth affects every environmental challenge we face:

- Generation of GHG, other pollutants and toxic waste
- Resource depletion: water, oil, fisheries, topsoil, etc.
- Resource wars and civil conflicts
- Malnutrition and world hunger
- Lack of resources for education and health care, especially in poor countries
- Best farmland converted to urban and suburban sprawl
- Garbage disposal and need to find more landfill space
- Species extinction…

Feedbacks between coupled human and natural systems exhibit nonlinear dynamics, time lags,…, and surprises… (Liu,…, Lubchenko,…Science, 2010)

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

Is this population sustainable?

We spend orders of magnitude more calories to grow food than the calories we get from it!!!

This is only possible because **we are using non-renewable resources**. Herman Daly (UMD, founder of Ecological Economics): "We are drawing down the stock of natural capital as if it was infinite"
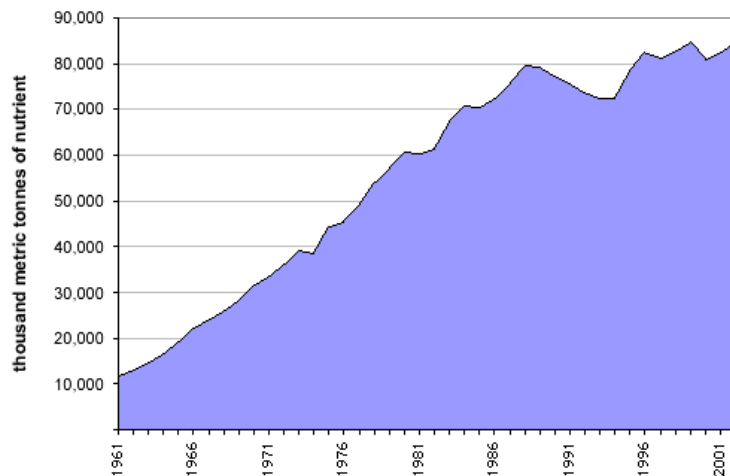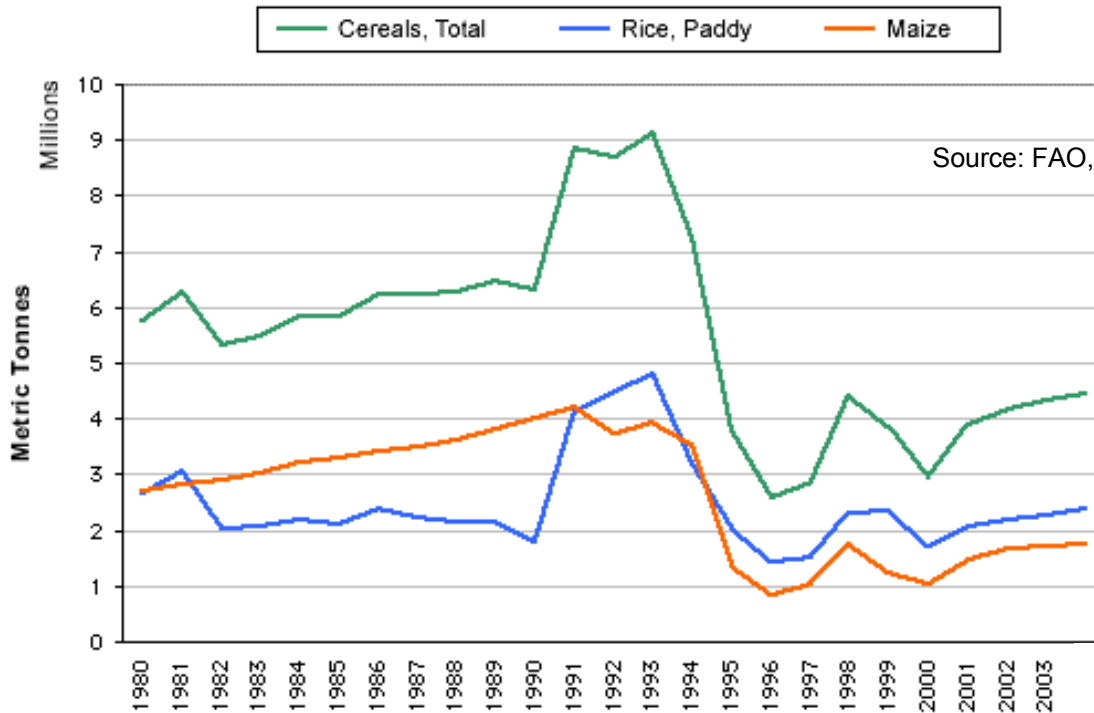

Fertilizer Use (Nitrogenous) - World (FAO)
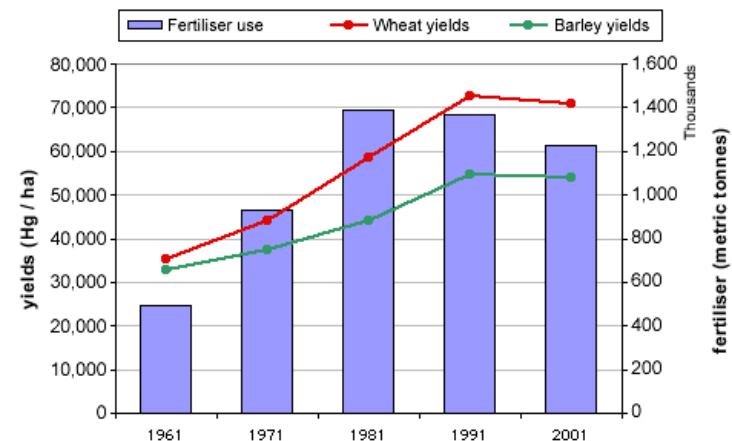
Fertilizer use and crop yields (UK)

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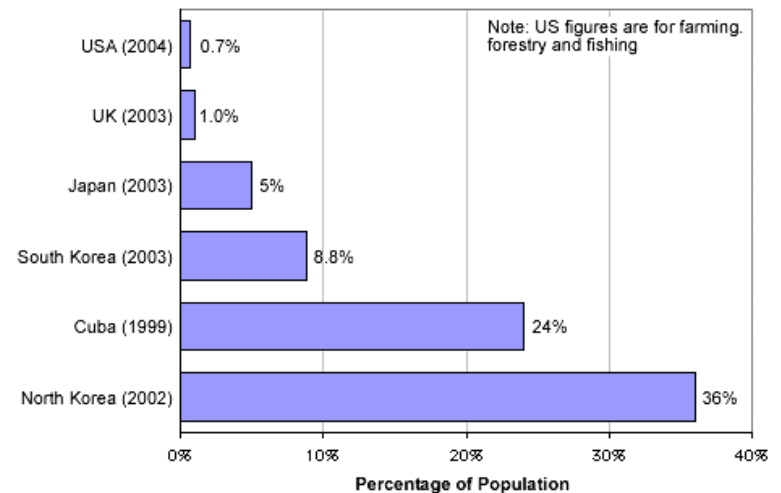

Source: FAO, www.wolfatthedoor.org.uk

Production of grain in North Korea.
Also, without oil, they burn biomass, increasing loss of soil.

Source: CIA, www.wolfatthedoor.org.uk
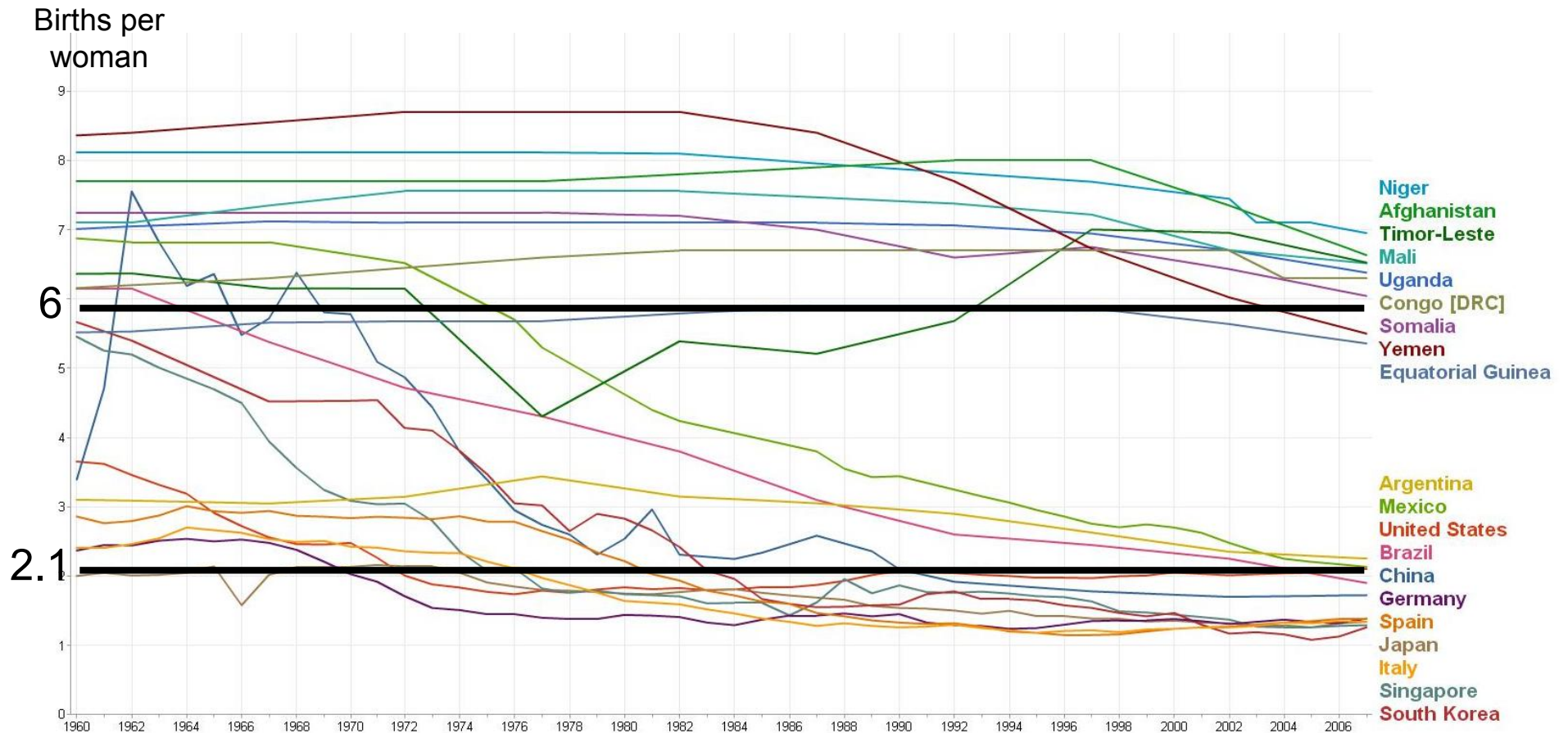
Percentage of workers in the agricultural sector

Births per woman

There are many countries that are still at the level of 6 or more births per woman. Many countries are close to or below replacement level. China is at 1.7 b/w

Births per woman

Niger
Afghanistan
Timor-Leste
Mali
Uganda
Congo [DRC]
Somalia
Yemen
Equatorial Guinea

Argentina
Mexico
United States
Brazil
China
Germany
Spain
Japan
Italy
Singapore
South Korea

Data source: World Bank, World Development Indicators - Last updated November 20, 2009

Are we past the problem of population growth?

Conventional wisdom is that population growth is no longer a problem because the rate of growth is going down

The population explosion took place in the second half of the 20th century.

Although the rate of growth is going down,

in absolute terms we are still adding about 75m every year.

This is more than during most of the population explosion period!
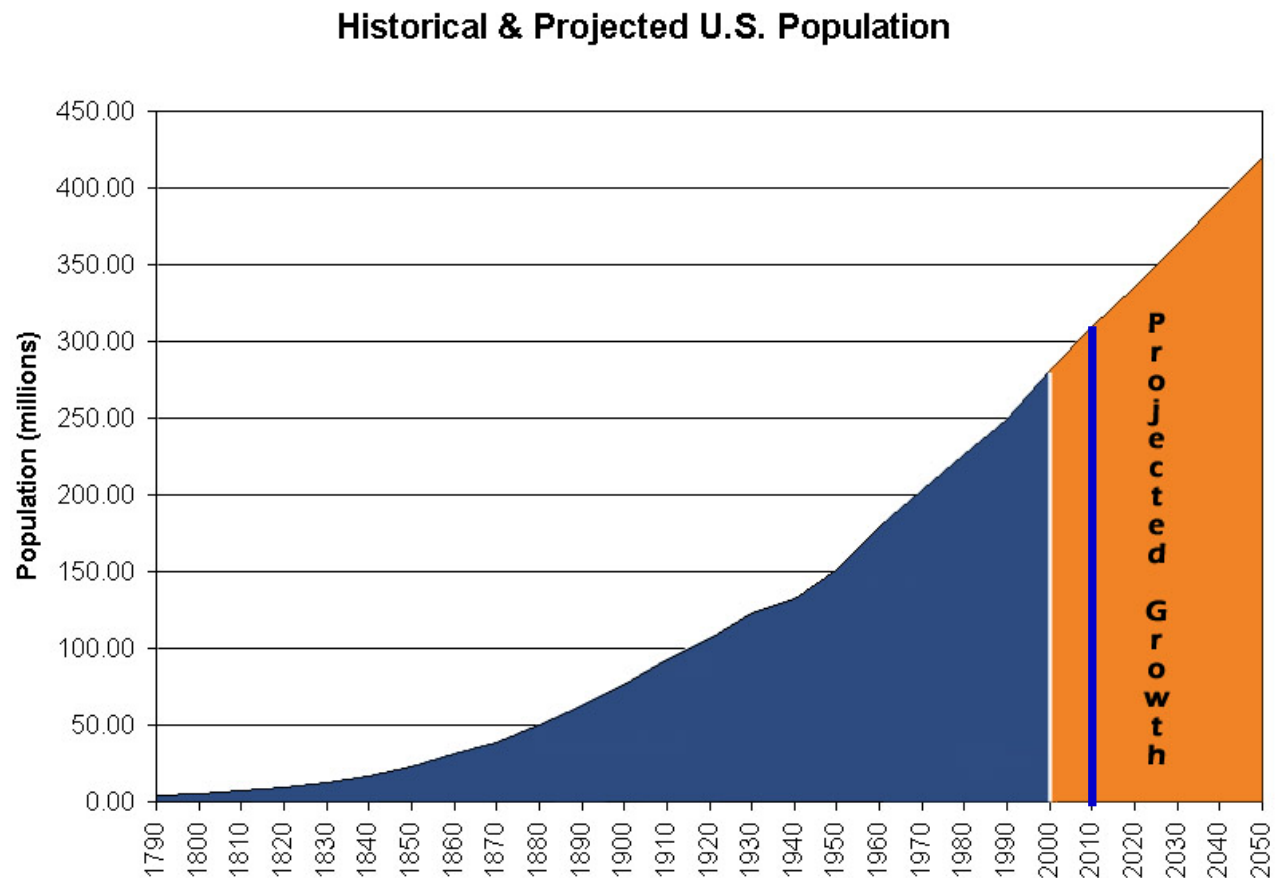
Annual Increase in World Population

Millions
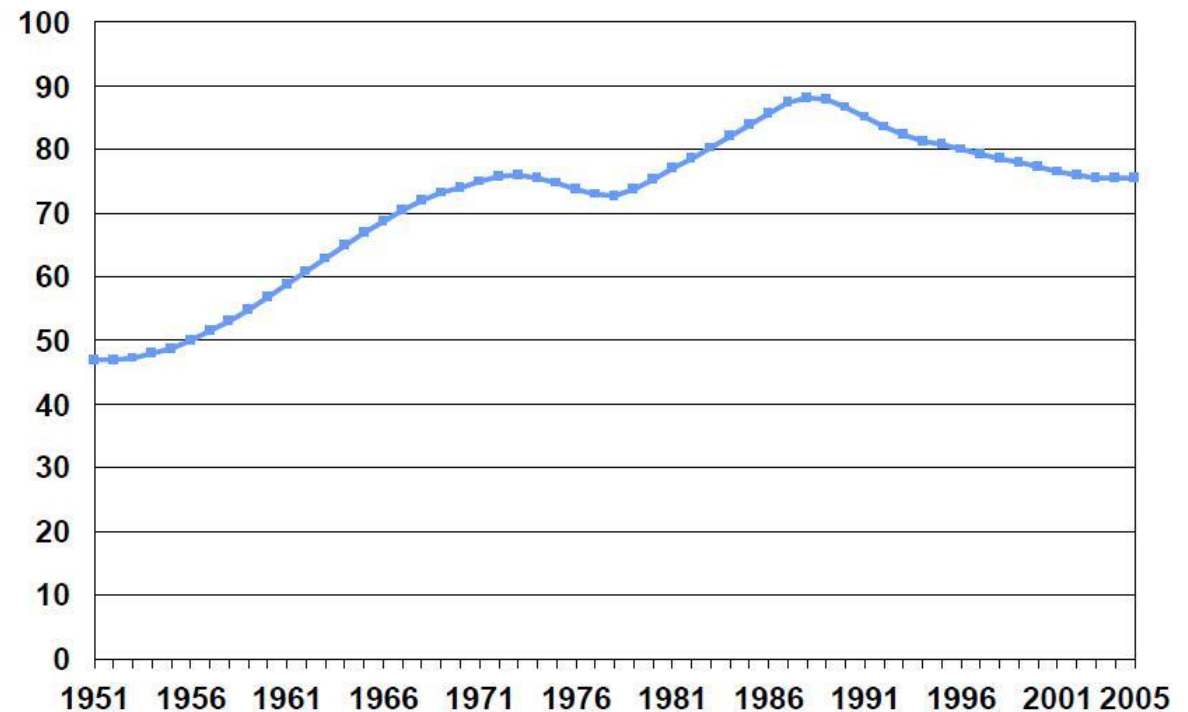
Still growing…

Most population growth takes place in underdeveloped countries, but

Some developed countries are still growing fast:

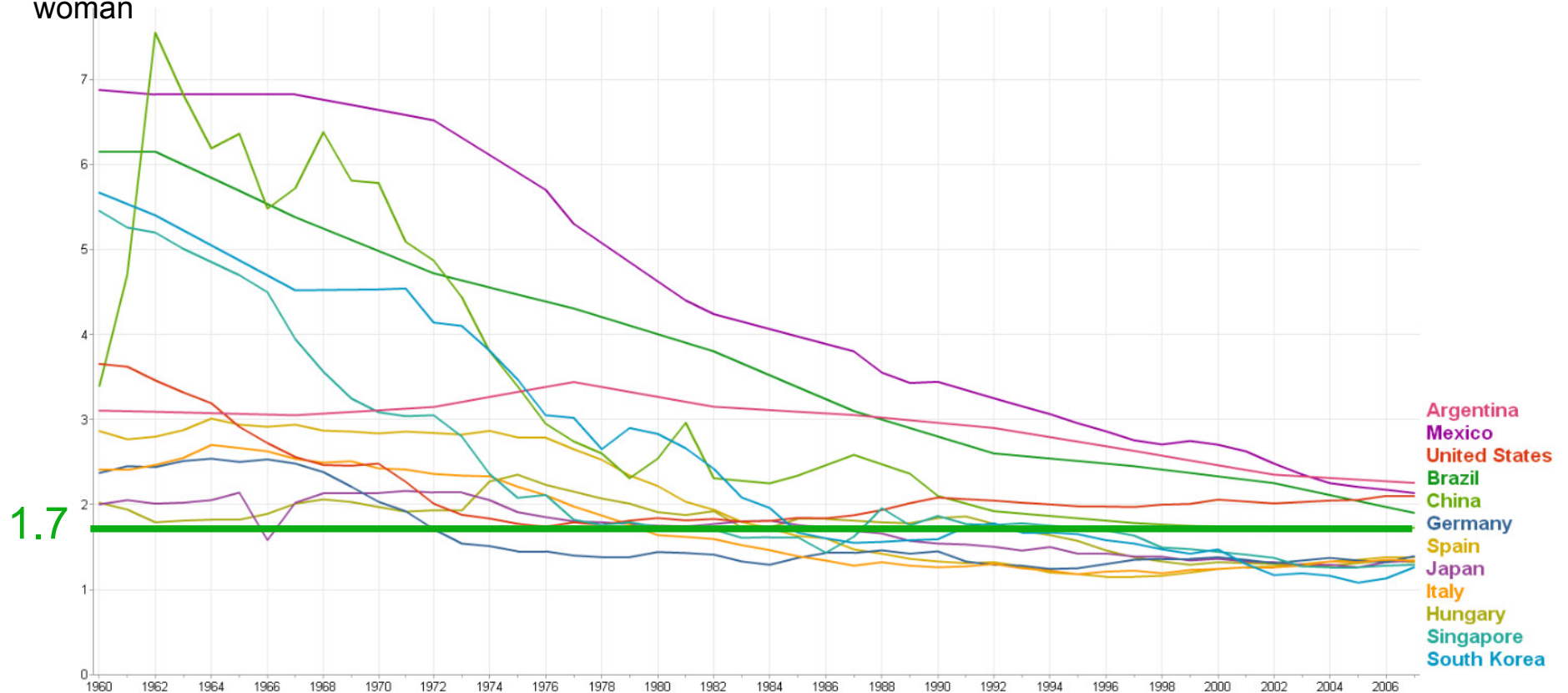UK grew more in 2008 than in the previous 50 years despite lower immigration

US fertility rate is increasing: 1.7 in the 1970s, now it is 2.13.

Historical & Projected U.S. Population

The good news!

~40 countries (Canada, most of Europe, South Korea, Taiwan, Cyprus, etc.) have reached a birth/woman rate
Births per lower than China's 1.7 without coercive measures!
woman

1.7

Argentina
Mexico
United States
Brazil
China
Germany
Spain
Japan
Italy
Hungary
Singapore
South Korea

Data source: World Bank, World Development Indicators - Last updated November 20, 2009

What about human rights?

When people think of reducing population growth, they think of coercive measures: the one-child target in China, forced sterilizations in India.

This misses the fact that *most women are forced to have more children than they want*.

It is a human rights issue indeed but in the opposite direction. International UN polls show in many countries more than 80% of married women of reproductive age with 2 children, do **not** want to have more children.

A nurse I know was asked by a Somali patient why she had no children, and she responded she had not wanted any yet. The response of the Somali woman was: "Wow! You are so lucky to have that choice. I have 6 children already and I have no choice in the matter. I wish **I** had that choice!".

Non-coercive methods to reduce growth

The UN estimates that 40% of all pregnancies worldwide are unintended. Just helping women to avoid unintended pregnancies would have a huge impact.

Non-coercive ways to drastically reduce fertility:

- Education,

- access to birth-control and

- equal economic opportunity for women

Population control is both feasible and effective.

In stark terms,

if every woman of bearing age had only one child, the population would be reduced to a level between 1 and 2 billions in about 150 years.

Supportive government policies (national and international) to **empower women** are essential for reducing growth.

What about the economics of reducing population?

We hear a lot about the dire problems that reducing the population will bring… Let's look at the evidence:

China has had the strictest population control policies since the 1970's: b/w went down from more than 6 to 1.7. It is estimated that 300-400 million births have been avoided (more than the population of the US!)

At the same time China has had the highest rate ever of sustained economic growth in the human history.

Similarly Japan, South Korea, Taiwan have had extremely high sustained economic growth with lower birth rates.

A counter example is the Philippines, with higher population growth and lower economic growth.

Will we face a shortage of workers?

We are repeatedly told that in Europe, Japan, the US, and China, lower birth rates will create a huge demographic crisis due to a shortage of workers.

However, as Dean Baker, of the Center for Economic and Policy Research, explains:

Prices reflect supply and demand. A shortage of labor means workers' wages will rise and higher wages shift the labor force from low to high productivity work. So, we may have fewer greeters at Wal-Mart, valet parking or all-night convenience stores. And dangerous or unpopular work would be mechanized.

(*has this "crisis" scared you yet?*)

This alleged "demographic horror story" would actually be good: today these economies suffer from labor surpluses and high unemployment rates.
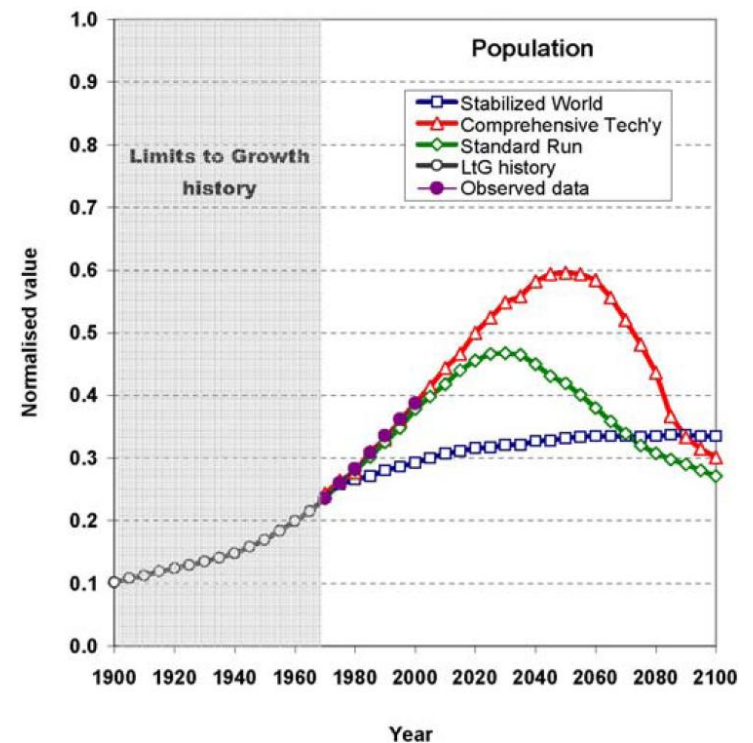
1972: Club of Rome "Limits to Growth"

The Club of Rome commissioned a group at the MIT Sloan School of Management to study:

"Are current policies leading to a sustainable future or to collapse?"

When the results appeared in 1972, the conclusion that with **finite** natural resources growth would overshoot and collapse was dismissed as **absurd** by many economists. ("discredited")

35 years later the "standard run" model compares well with reality for all variables.
(Graham Turner, G.E.C., 2008)

Population

- Stabilized World
- Comprehensive Tech'y
- Standard Run
- LtG history
- Observed data

Limits to Growth history

Normalised value

Year

The "World3" model they used:

The model is relatively simple:

There are "stock" variables [boxes]: population, cultivated land, industrial capital, non-renewable resources, pollution, etc.

There are interactions (arrows) with positive or negative feedbacks.

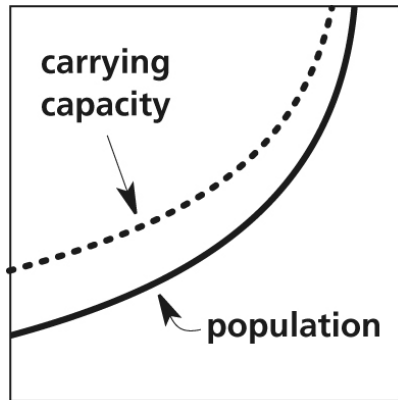The model is then integrated from 1900 to 2100 (model tuned using 1900-1970).
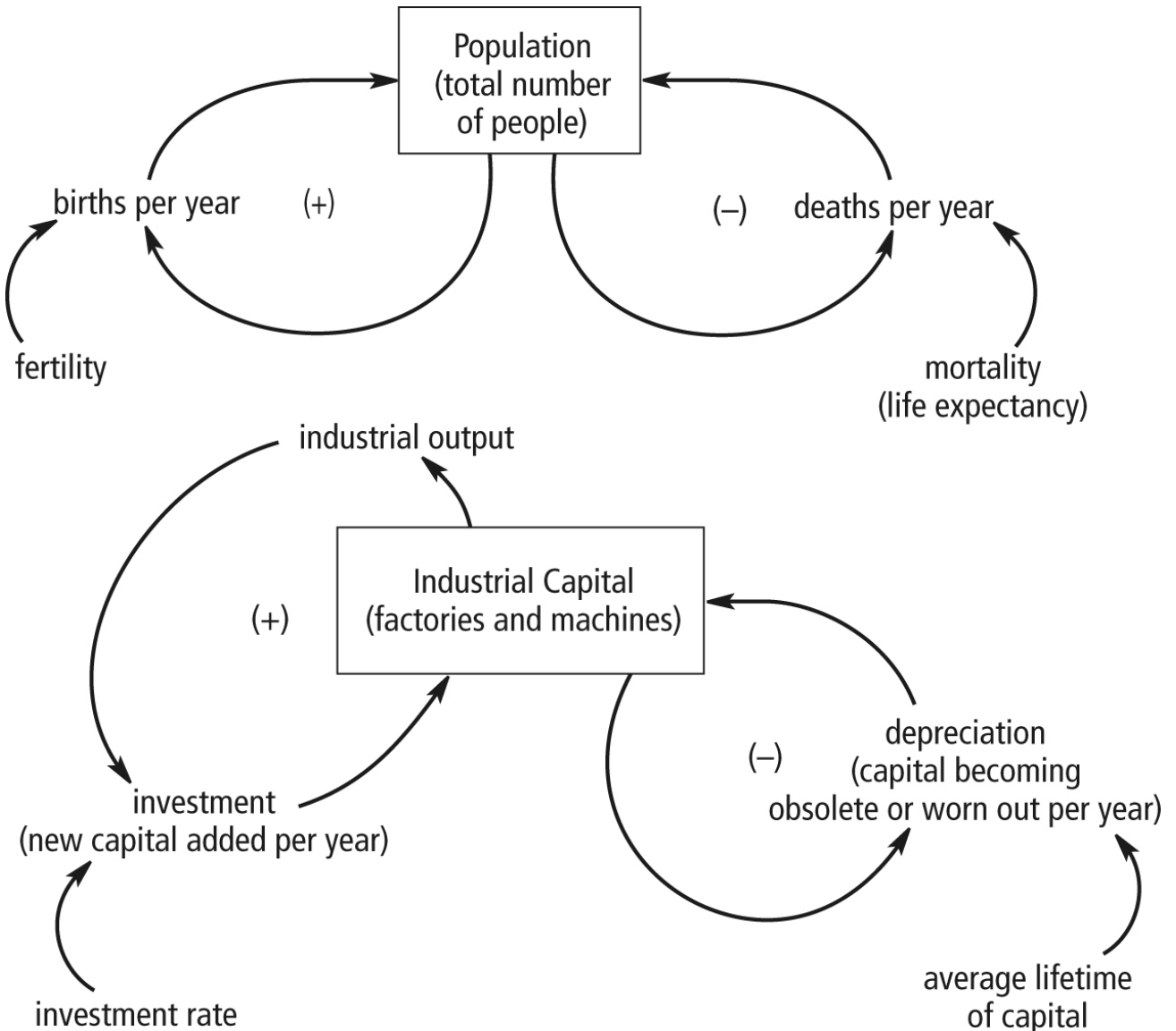
Feedbacks of Population, Capital, Agriculture and Pollution (left) and Population, Capital, Services and Resources (right)
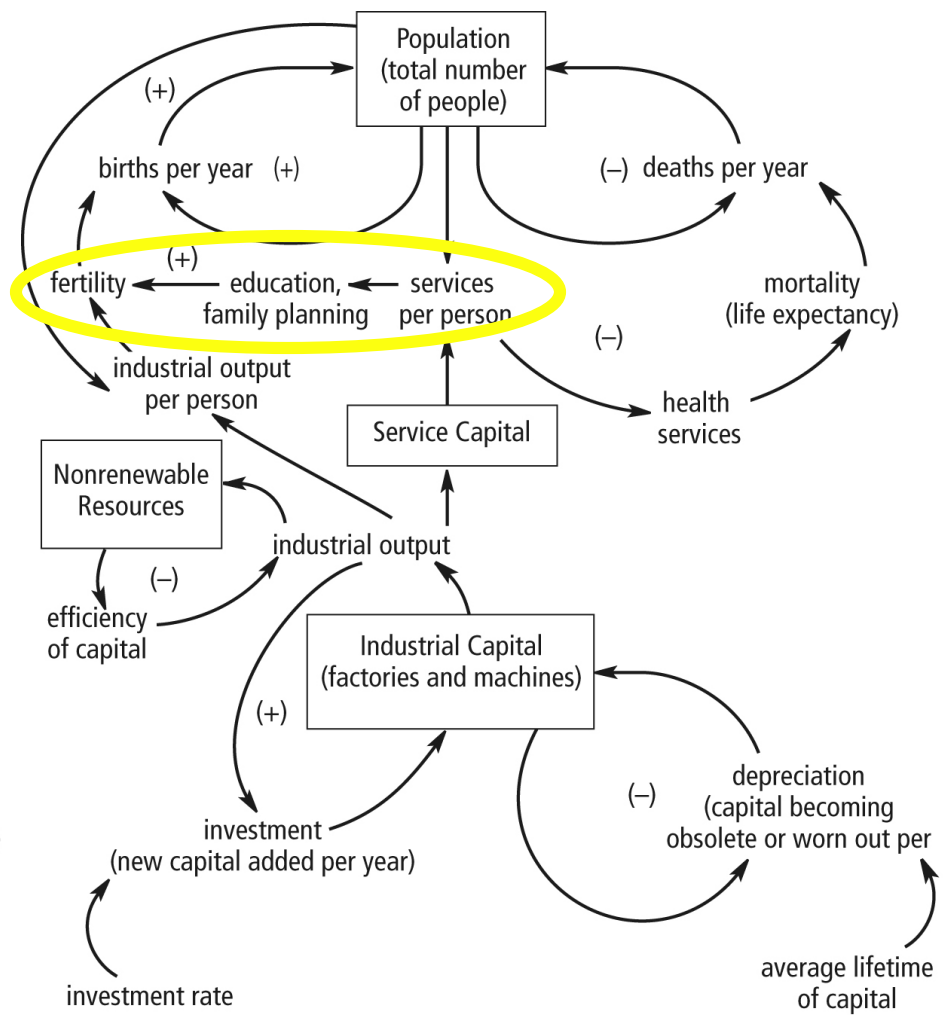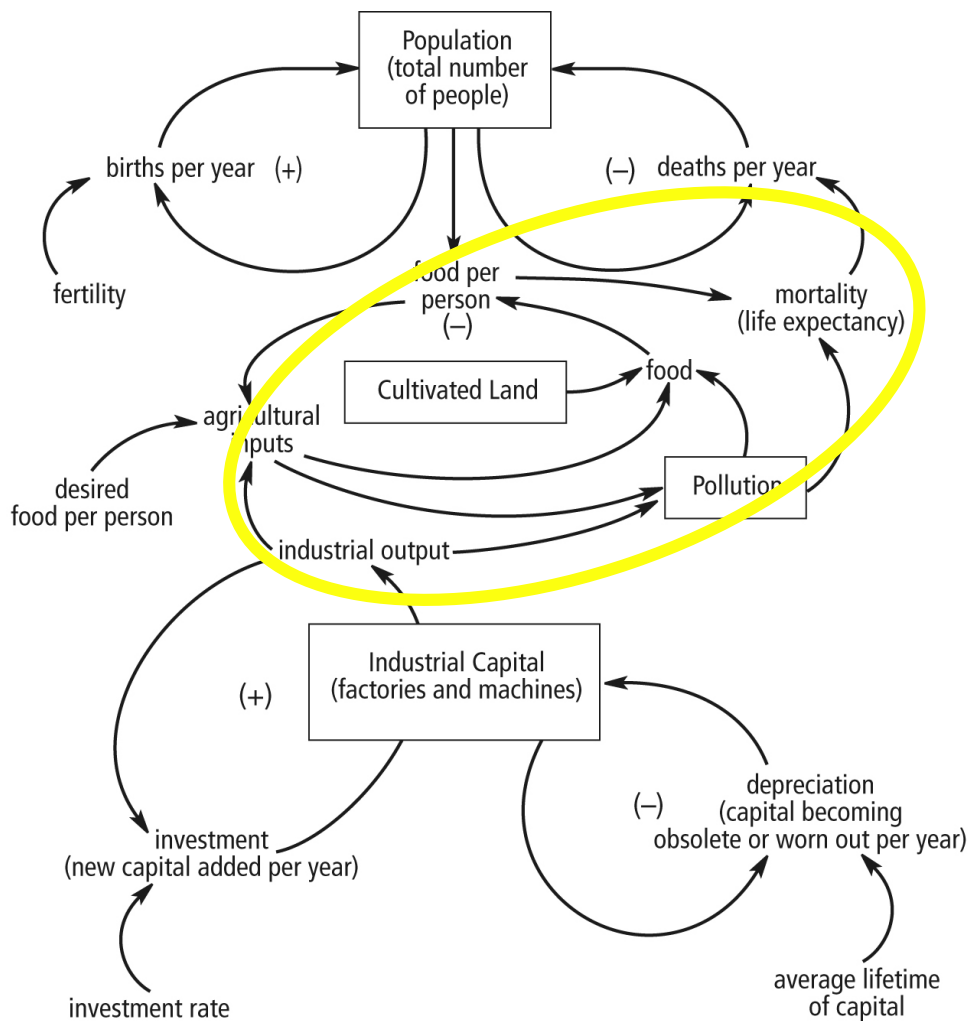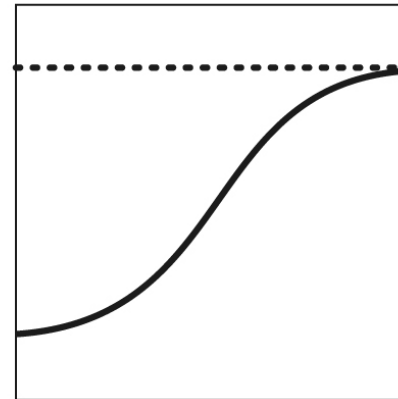
The model could have
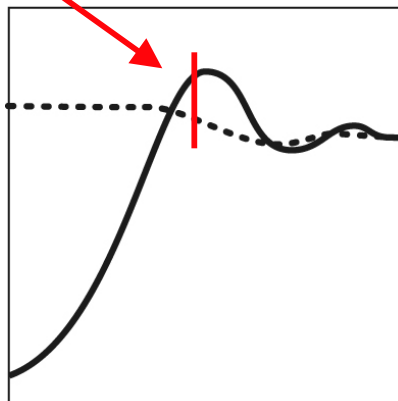# four possible types of outcomes

Infinite World

carrying
capacity

population

time ⟶

a) Continuous Growth

Ideal
(no overshoot)
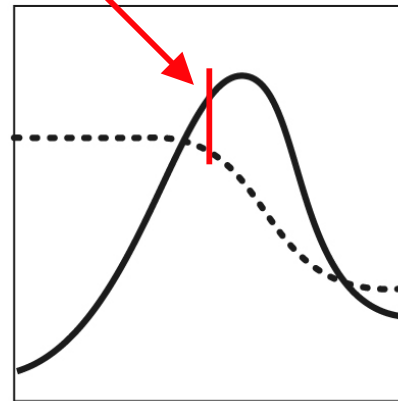
b) Sigmoid Approach to Equilibrium

You are here…   Or here…

Hopefully…

Disaster

c) Overshoot and Oscillation   d) Overshoot and Collapse

The results are sobering:
most scenarios collapse

Even if resources are doubled,
collapse is only postponed ~20 years

In order to avoid collapse
policies are needed to:
- Stabilize population and
- Stabilize industrial production per person
- Adopt technologies to
  - abate pollution
  - conserve resources
  - increase land yield
  - protect agricultural land

We proposed to develop regional population models and to couple them to an ESM.

The Limits to Growth model aggregates the whole world into a single model. Therefore it **cannot** include:

- Rich vs. poor (differential consumption rates)
- Resource wars
- International migration
- Government policies
- …

To include these important factors we need to develop regional population models.

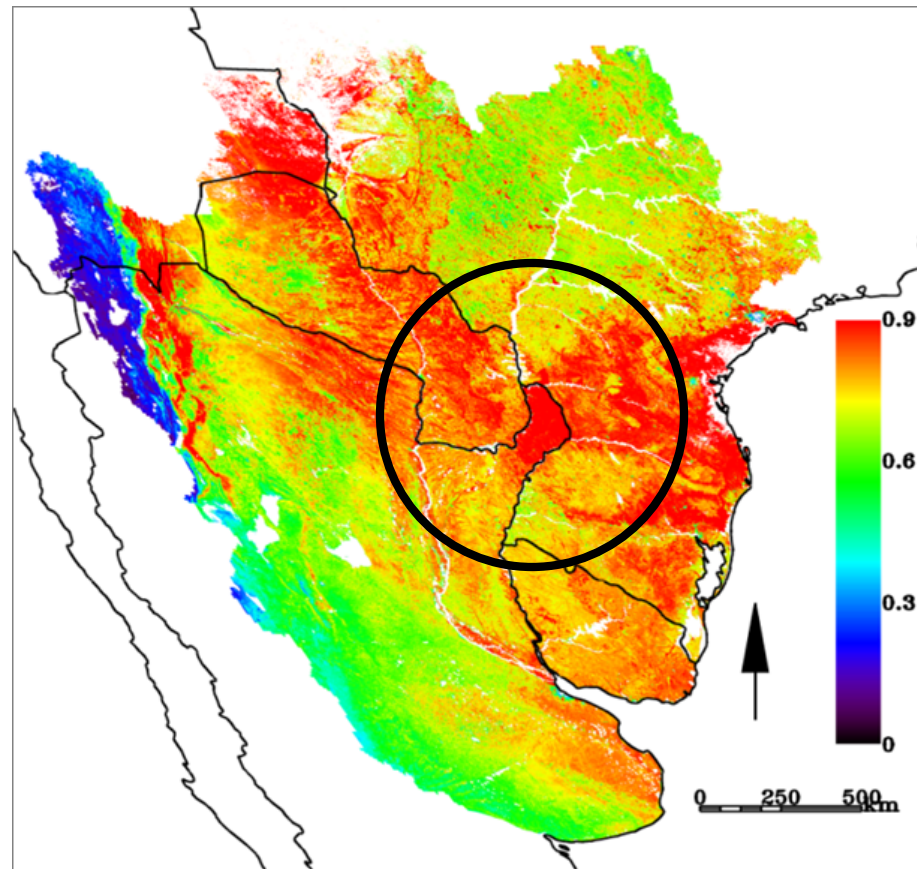We will start with ~6 - 10 regions, e.g., North America, South America, Africa, Europe, China, Rest of Asia

This is computationally very feasible (about 10 stocks and 1000 parameters per region)

Can government policies be effective?
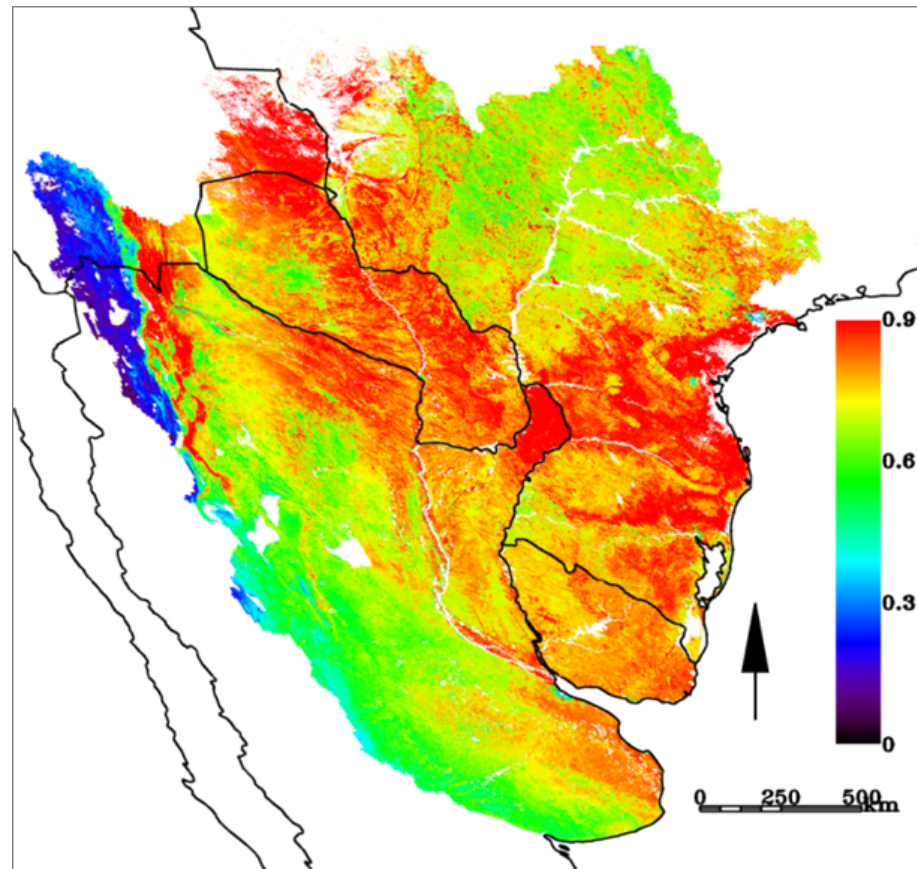
Vegetation productivity (NDVI) in South America:
red is maximum primary (vegetation) productivity
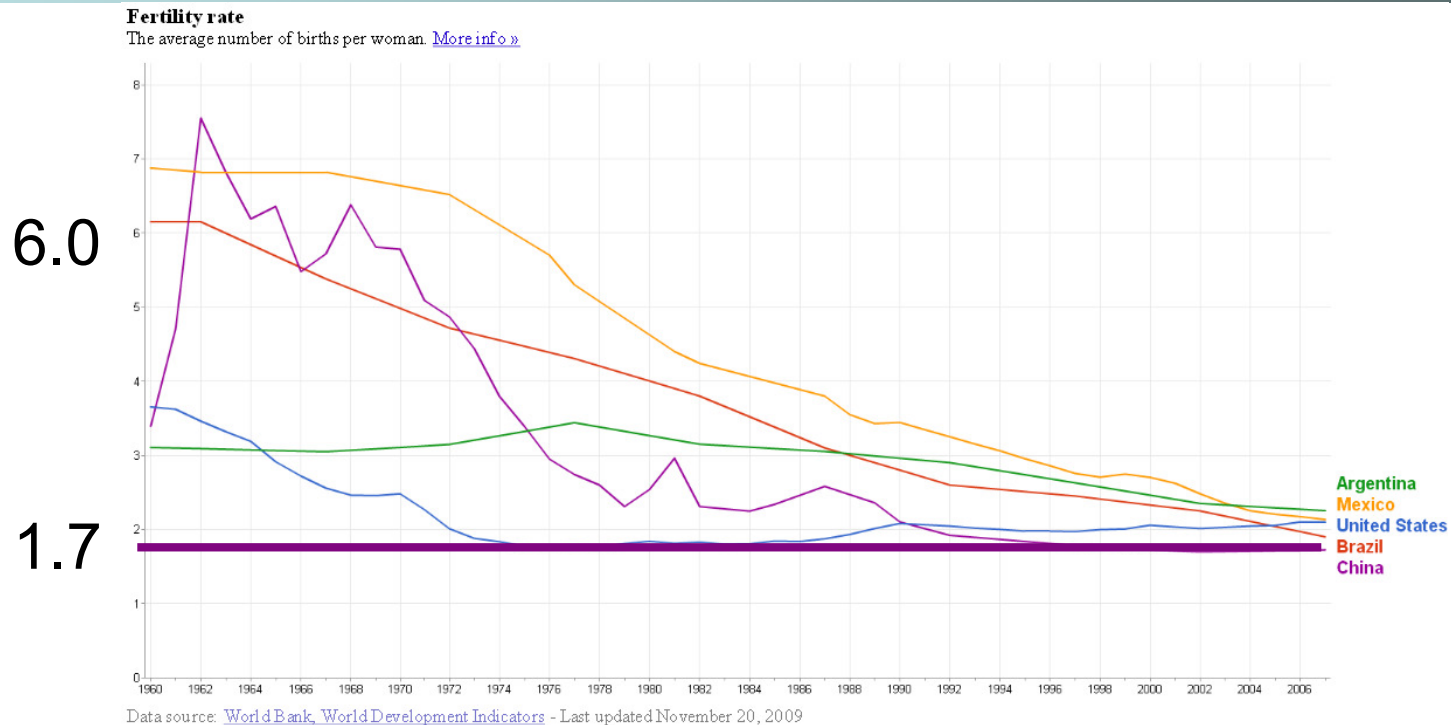
Government policies are important!

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

Another example of government policies: Forest policy in Japan (Edo period)

- During the Edo period (17th and 18th centuries) the Tokugawa shoguns in Japan developed an advanced forest management policy.
- Increased demand for timber resources for construction, shipbuilding and fuel had led to widespread deforestation, which resulted in forest fires, floods and soil erosion.
- In response, the shogun, beginning around 1666, instituted a policy to reduce logging and increase the planting of trees.
- The policy mandated that only the shogun and daimyo could authorize the use of wood. By the 18th century, Japan had developed detailed scientific knowledge about silviculture and plantation forestry.
- They stopped and reversed the deforestation of the preceding centuries through substituting timber by other products and more efficient use of land that had been farmed for many centuries.
- **With these policies, Japan averted a deforestation collapse.**

Example: impact of government support for family planning

Fertility rate
The average number of births per woman. More info »

6.0

1.7

Argentina
Mexico
United States
Brazil
China

Data source: World Bank, World Development Indicators - Last updated November 20, 2009

In the 1960's Argentina's fertility rate was less than half of Brazil and Mexico. Brazil and Mexico enacted strong policies on family planning. Argentina did not.

Brazil and Mexico have now much lower fertility rates than Argentina.
Government policies matter!

Example: Kerala, a low-wealth state in India, with high social development and welfare

- Life expectancy in Kerala at birth is 75 years compared to 64 in India and 77 in the US (and Cuba!).

- Literacy rate is 91%, the highest in India, compared to India's 65%.

- Kerala's Human Development Index rating is the highest in India.

- How did they do it?

  - Building a statewide infrastructure of primary health centers, with over 2,700 government medical institutions in the state, and 330 beds per 100,000 population, the highest in India.

  - Building a statewide infrastructure for education:

  - More than 94% of the rural population has access to primary school within 1 km, 98% benefit from a facility for secondary education within 8 km.

- With the right government policies, population growth can be reduced and quality of life increased.

A proposal to NSF, DOE, NASA, NOAA, State Department

Call for Earth System modelers and social scientists to develop coupled scenarios for climate change with regional modules for population:

This would achieve two major goals:

1) Study different scenarios for world development and population policies.
2) Force us to look at the population problem from a scientific point of view.

A proposal to NSF, DOE, NASA, NOAA, State Department

Call for Earth System modelers and social scientists to develop coupled scenarios for climate change with regional modules for population:

This would achieve two major goals:

1) Study different scenarios for world development and population policies.
2) Force us to look at the population problem from a scientific point of view.

It would eliminate "the elephant in the room"

Standard Neoclassical Economic Model

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

Goods and Services

Firms:

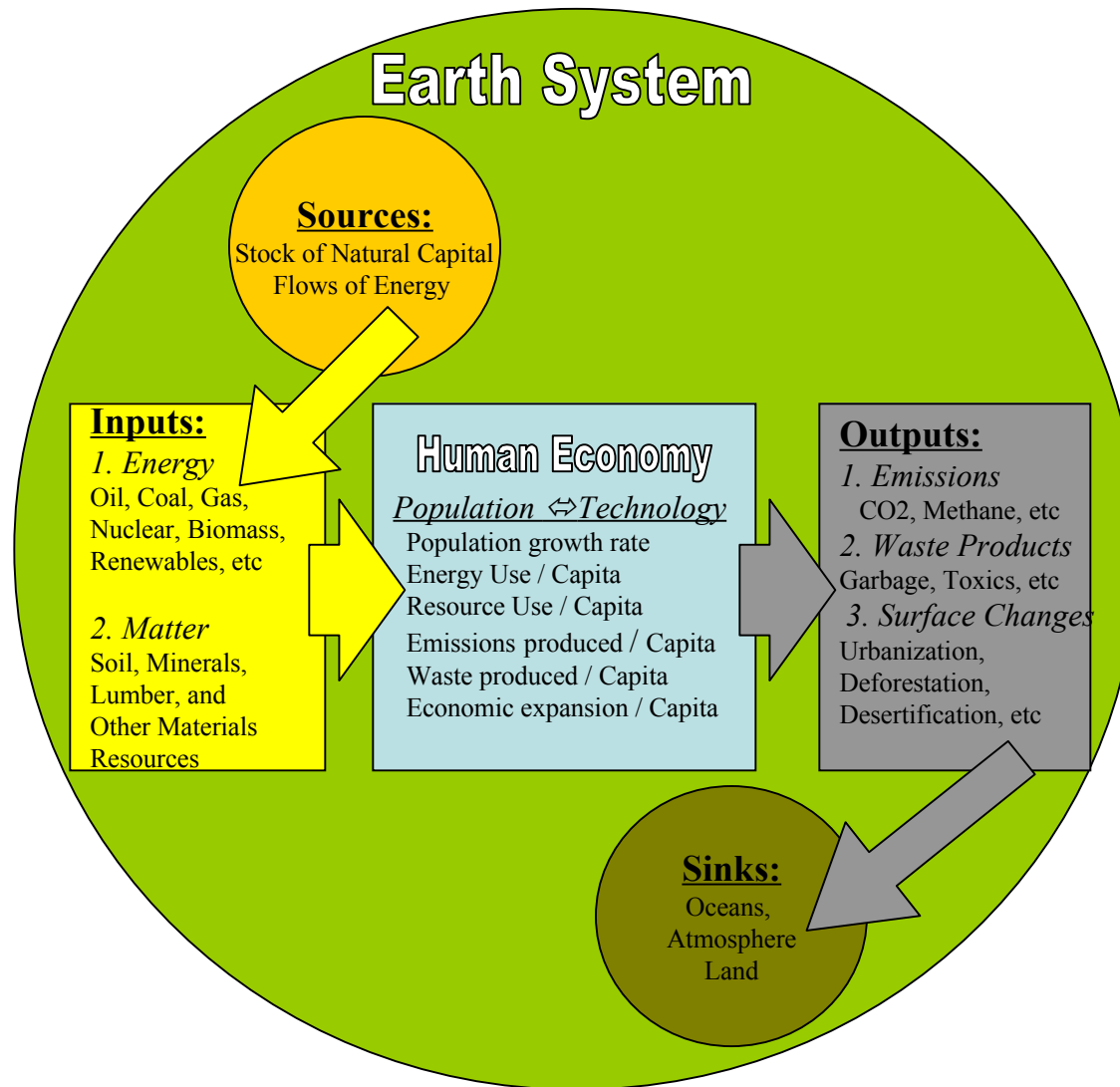**Households:**

Labor and Capital
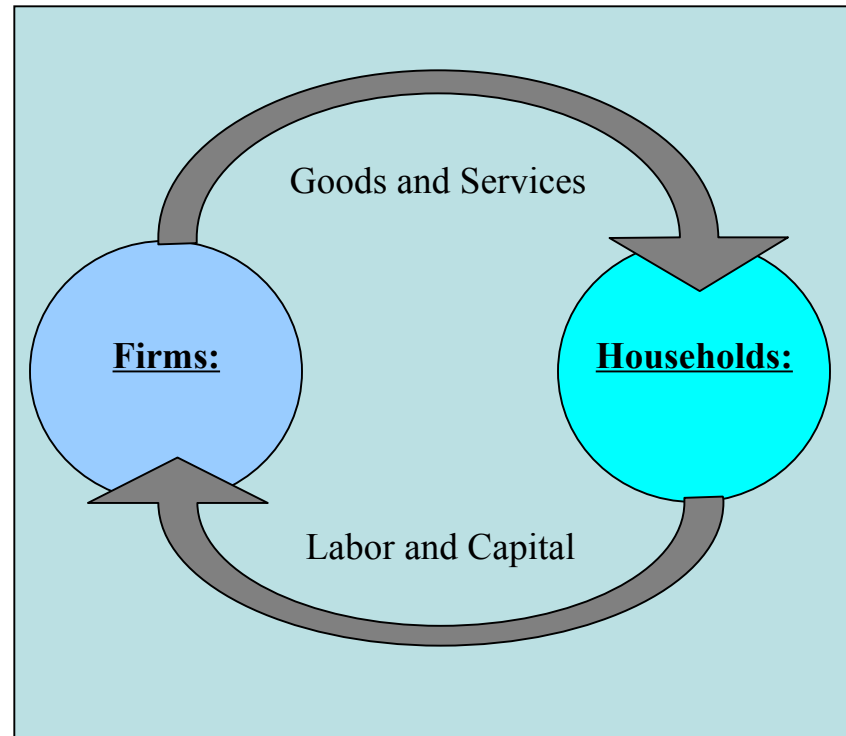
The standard Neoclassical Economic Model does not account for:
- Inputs (resources)
- Outputs (pollution)
- Stocks of Natural Capital
- Dissipation of Energy (i.e., a Perpetual Motion Machine)
- Depletion, Destruction or Transformation of Matter

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

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

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

Earth System

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 ⇔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** :
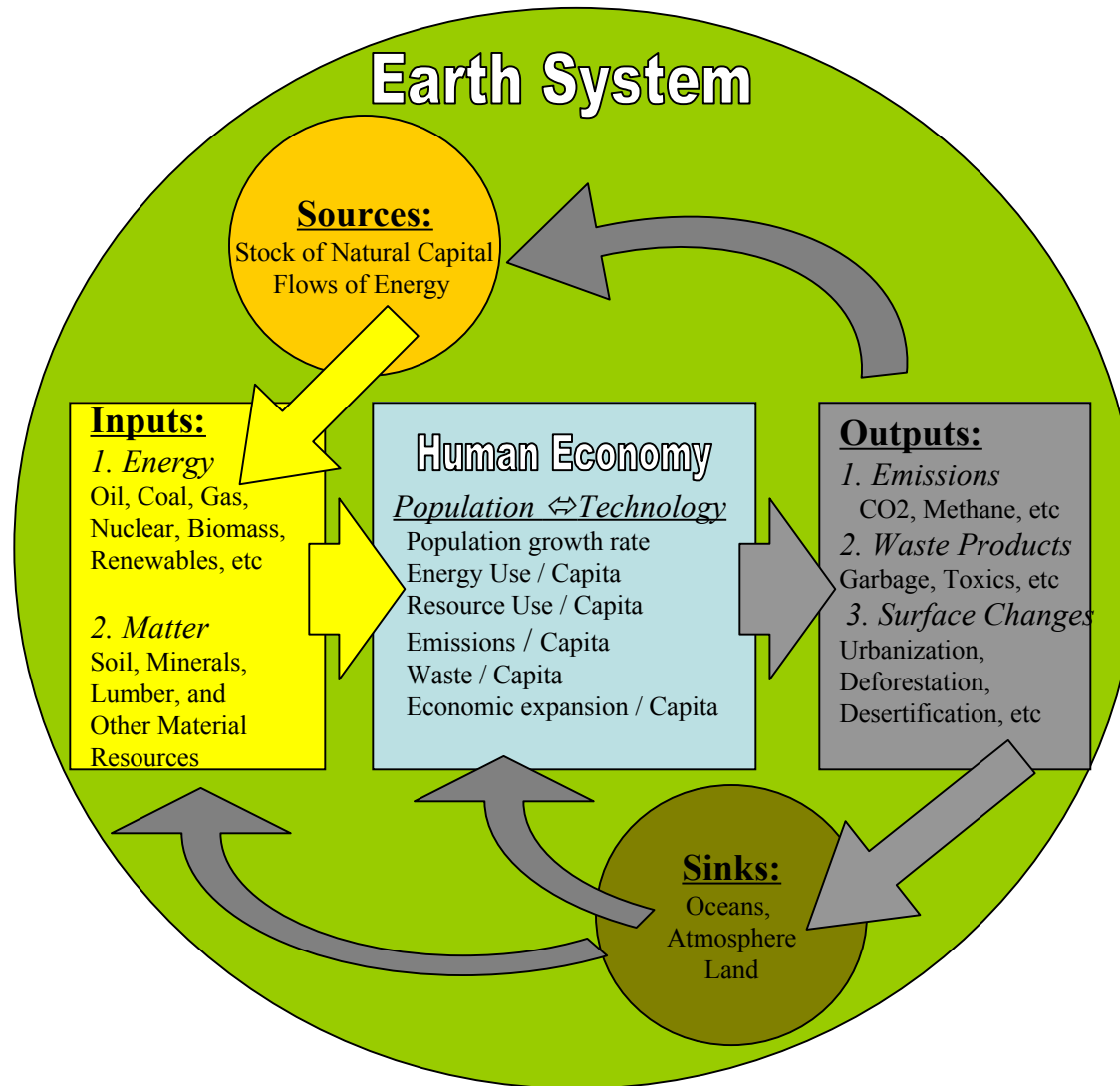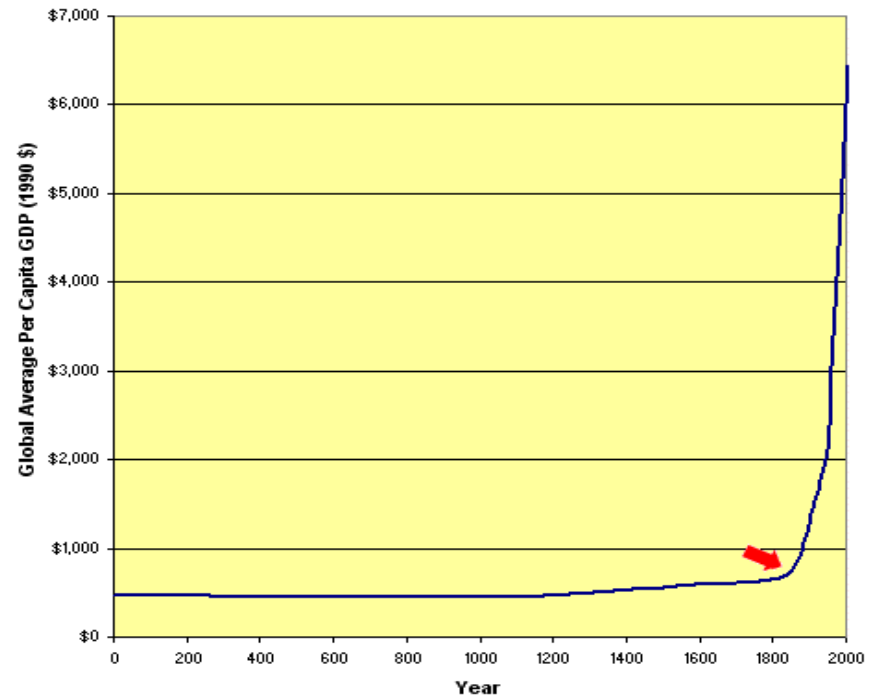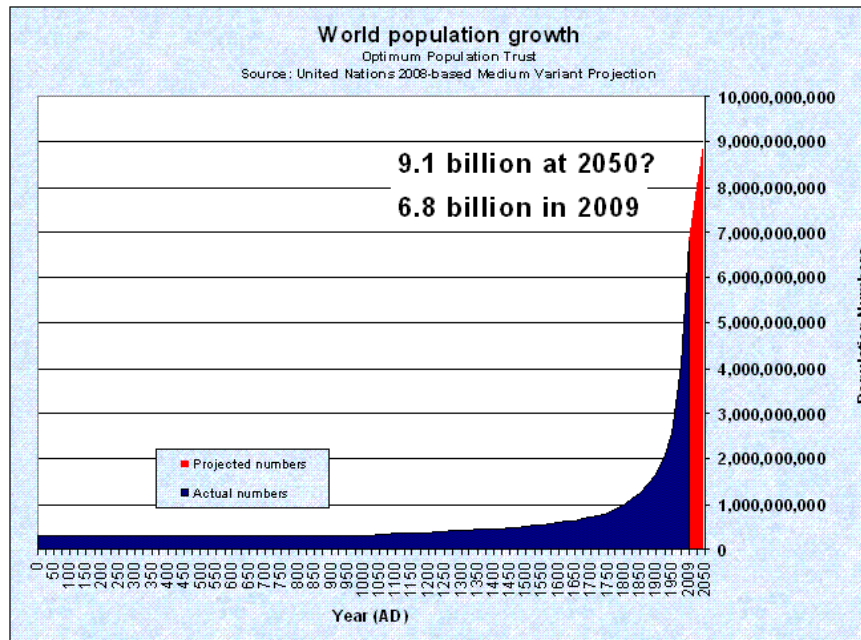
"Empty World" Model

- 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.
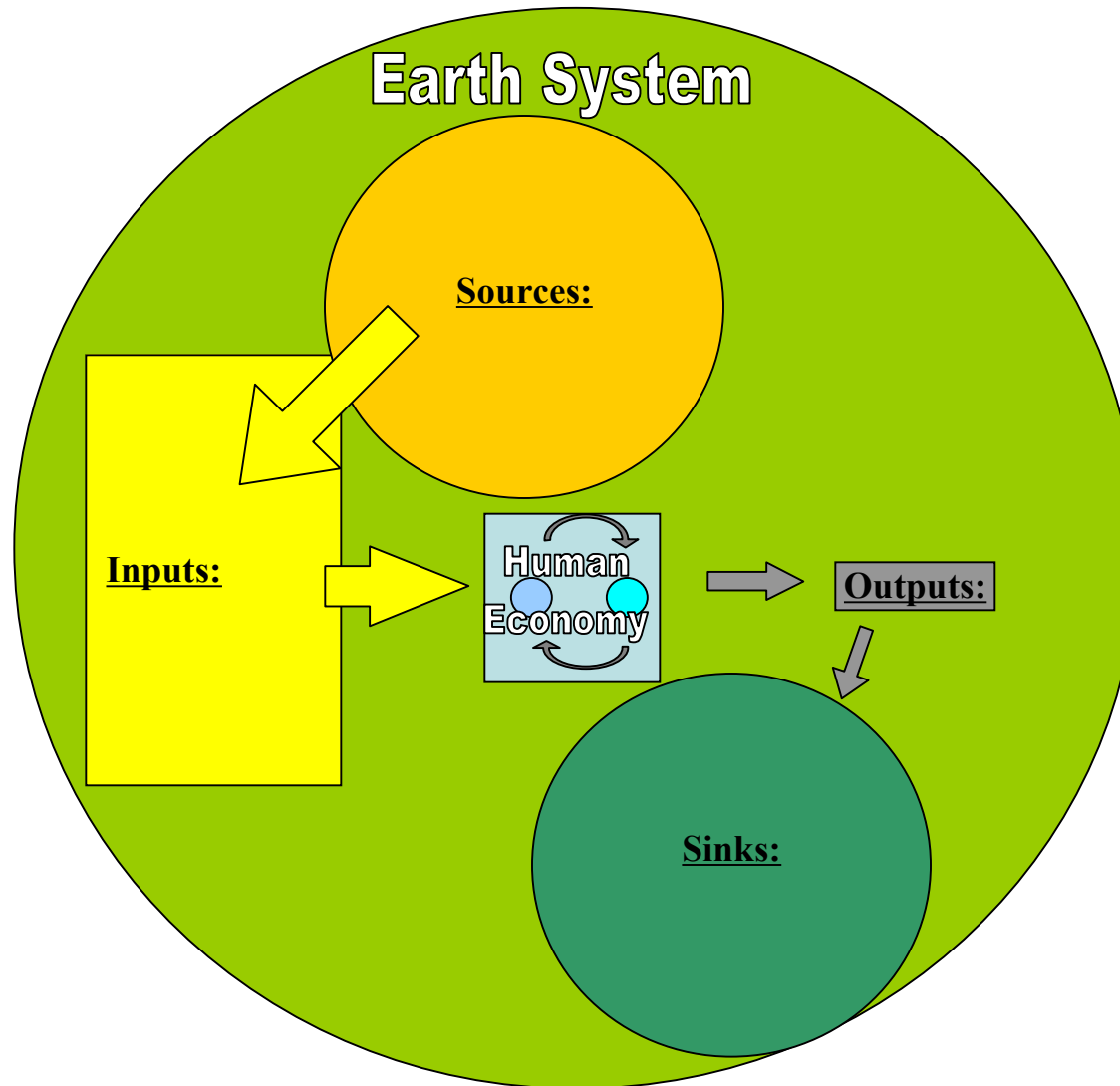
But Population and Economic Output *per Capita* have grown, and the net impact is their product!

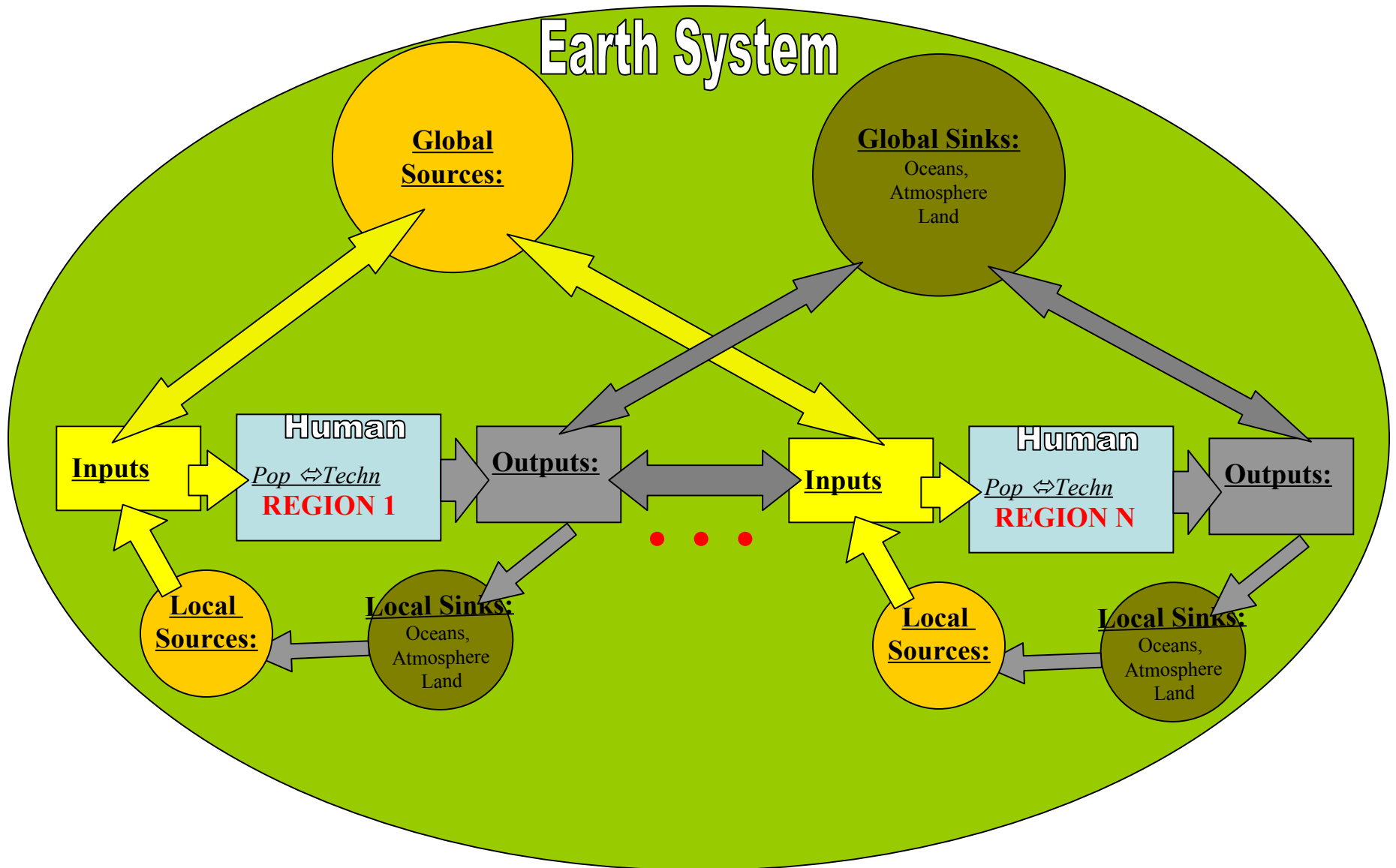Technology allows more efficient production, but also much faster consumption!

"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*.
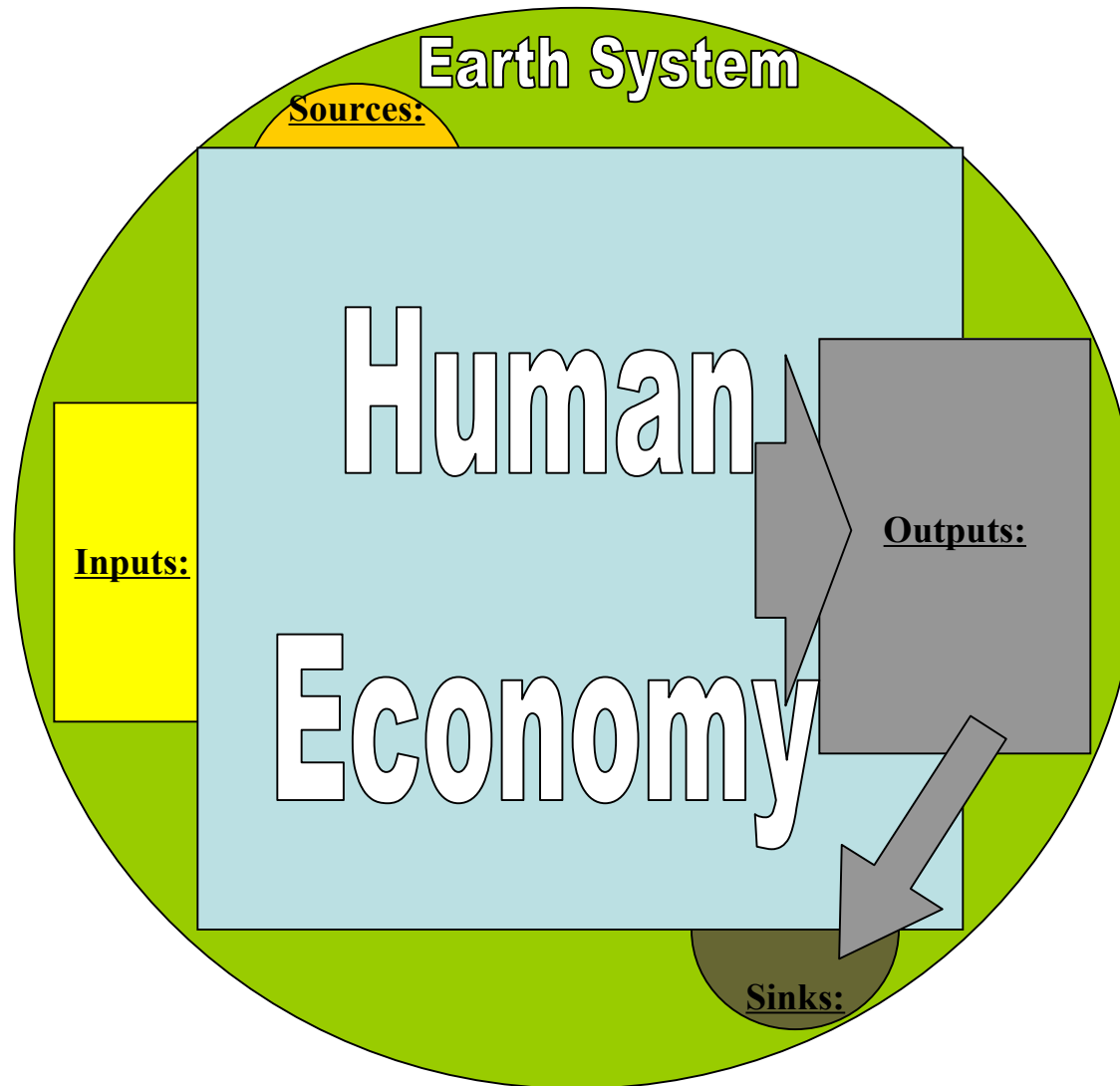
Regional Population Models

with two-way coupling is needed!

Some of the Essential Feedbacks needed

- Vegetation <=> albedo (climate change)
- CO_2 emissions <=> climate change <=> vegetation
- Vegetation <=> water use, fossil fuel use <=> crops
- Population <=> crops, food/capita <=> mortality
- Population <=> food/capita <=> fisheries
- Population <=> CO_2 emission, pollution <=> atmosphere, land
- Population <=> urban sprawl <=> loss of cultivated land
- Technology <=> non-renewable resources <=> alternative resources
- Policies <=> education, birth rate, pollution, emissions
- Resource depletion <=> trade, resource conflicts
- Population <=> CO_2 emissions <=> climate change <=> vulnerability

We proposed to experiment first using an intermediate model (UMD-ICTP ESM). Then we would use the NCAR CCSM with more realistic population/economic feedbacks

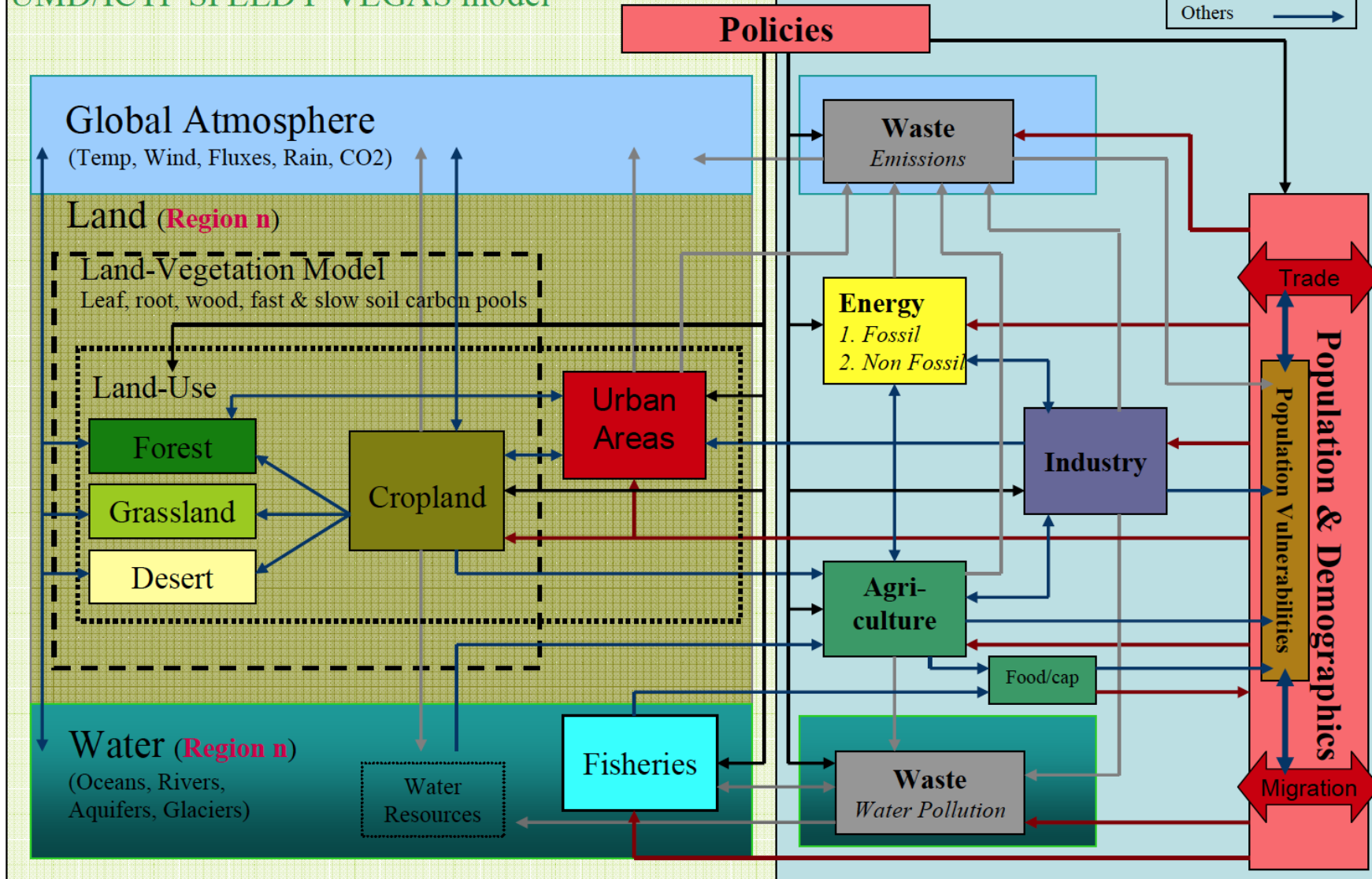# Prototype Earth System - Human System Feedbacks

Effects and Feedbacks
Policies →
Population →
Waste →
Others →

Earth System
UMD/ICTP SPEEDY-VEGAS model

Human System
(Region n)

Policies

Global Atmosphere
(Temp, Wind, Fluxes, Rain, CO2)

Land (Region n)

Land-Vegetation Model
Leaf, root, wood, fast & slow soil carbon pools

Land-Use

Forest

Grassland

Desert

Cropland

Urban Areas

Waste *Emissions*

Energy
1. Fossil
2. Non Fossil

Industry

Agri-culture

Food/cap

Water (Region n)
(Oceans, Rivers, Aquifers, Glaciers)

Water Resources

Fisheries

Waste *Water Pollution*

Trade

Population & Demographics

Population Vulnerabilities

Migration

Agriculture and fisheries (food) prototype submodel and feedbacks
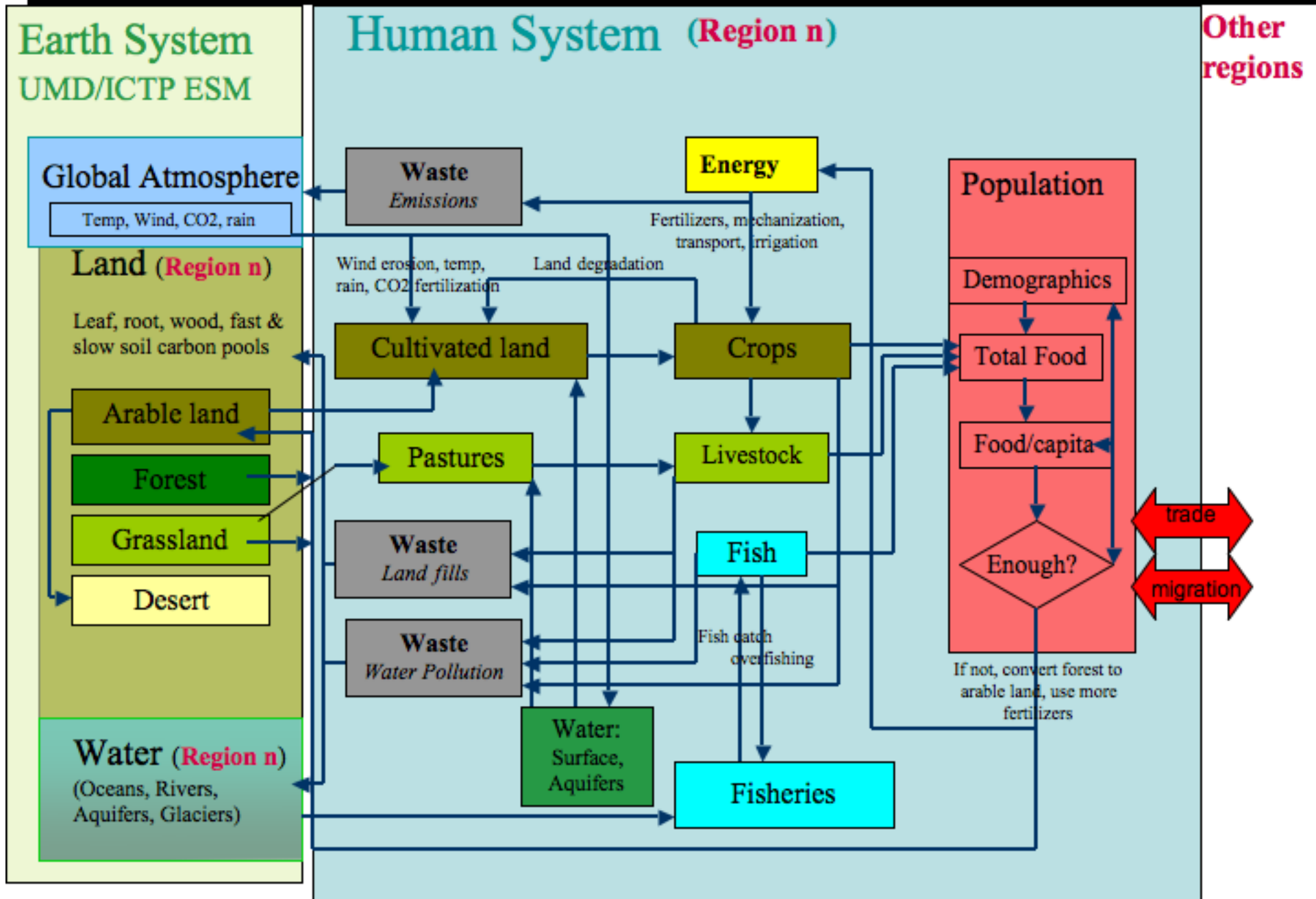
Water prototype submodel and feedbacks

Earth System
UMD/ICTP ESM

Human System (Region n)

Other regions

Global Atmosphere
Temp, Wind, CO2, rain

Land (Region n)

Leaf, root, wood, fast & slow soil carbon pools

Arable land
Forest
Grassland
Desert

desertification and soil regeneration

Water (Region n)
(Oceans, Rivers, Aquifers, Glaciers)

Sea-Level Rise

Precipitation, snow melt

Precipitation by Land type

recharge

Surface Water:
(Rivers, Lakes, etc)

Runoff

Aquifers

Depletion of Aquifers

Collection Efficiency

Fresh Water Supply

Use Efficiency

irrigation

Households
Industry
Energy
Pastures
Cropland

Loss of Cropland

Water Pollution

Waste
Water Pollution

Coastal Flooding

Population:
urban/rural

Demographics

Water/capita
Water/industry
Water/crops

Enough?

Internal Migration

If not, increase use

trade

migration

Energy prototype submodel and feedbacks
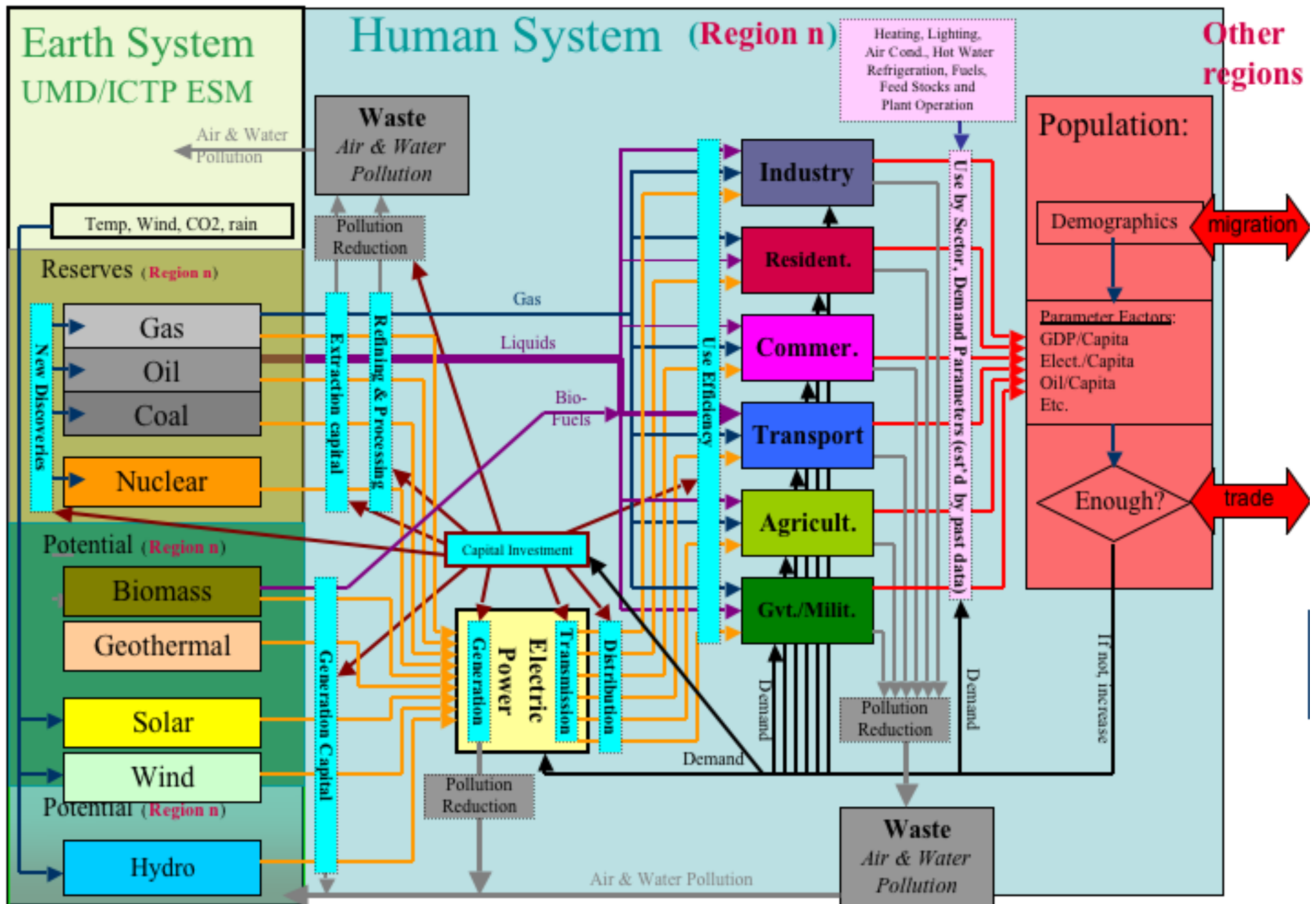
Demographic module: impact of education delaying age of birth
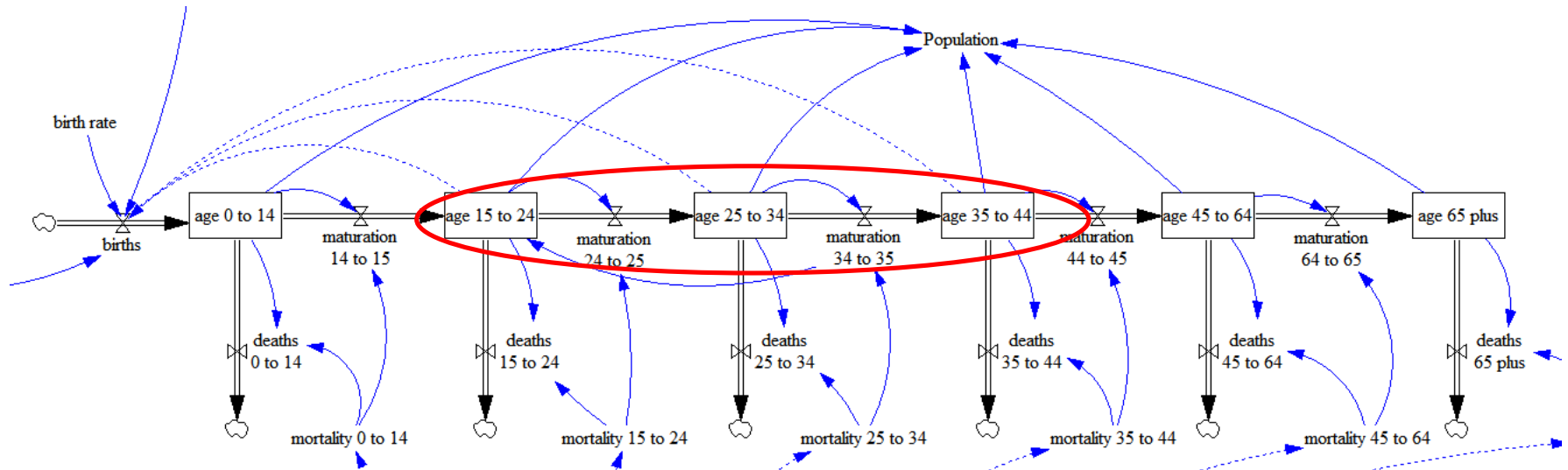
For simplicity, Limits to Growth grouped ages 15 to 44 into a single cohort. We separate then into 3.

Experiment: women have an average of 2.6 births, either young (15 to 24 yrs cohort) or older (25 to 34 yrs or 35 to 44 yrs). Postponing birth results in half the population after 150 years.
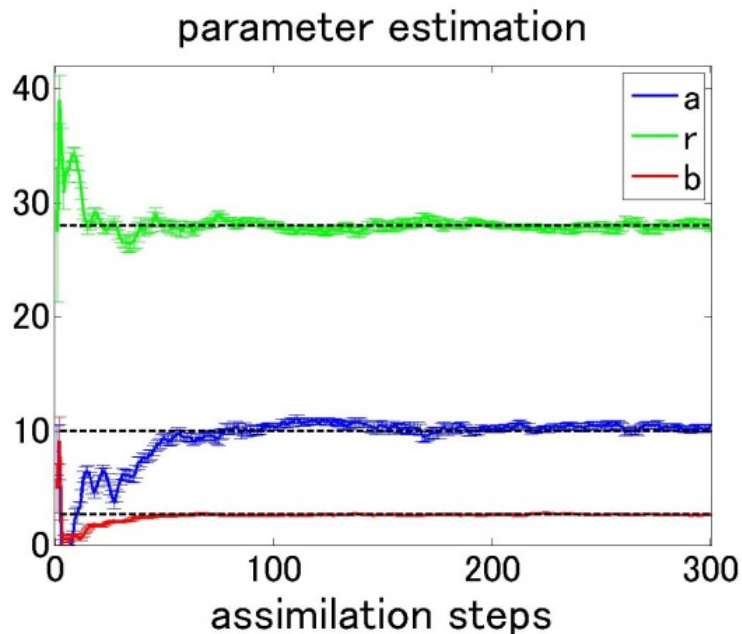
Time (Year)	2000	2050	2100	2150
Exp1 ("young")	6.19b	11.8b	19.5b	31.7b
Exp2 ("older")	6.19b	10.0b	13.5b	17.8b

Impact of maternal age

How to calibrate the model?

We plan to use the Ensemble Kalman Filter parameter estimation approach to obtain estimates of parameters that are not measured.

Example: Lorenz 1963 model.

Left: LETKF calibration;
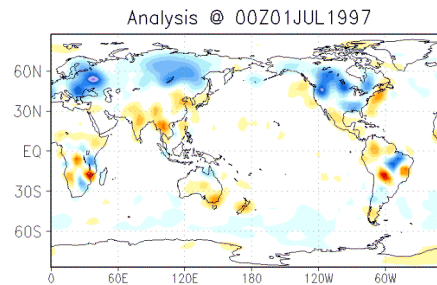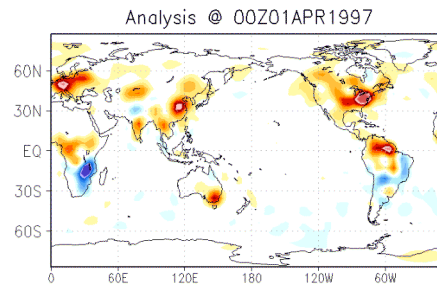
Right: standard regression approach
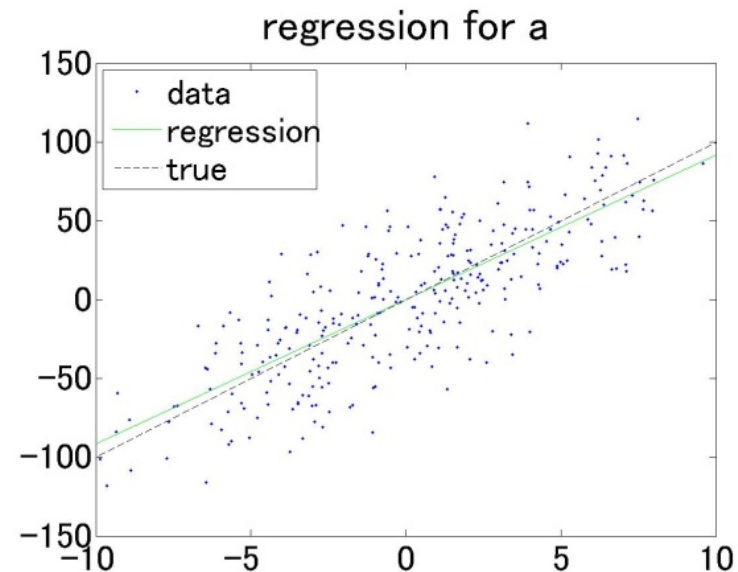
Example: Estimation of unmeasured surface carbon fluxes with LETKF. Impact of inflation methods

True fluxes
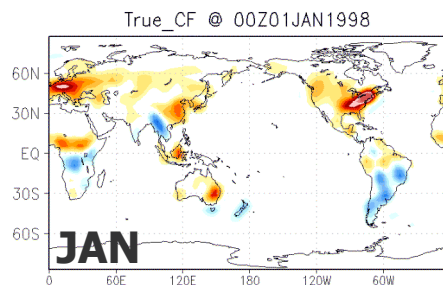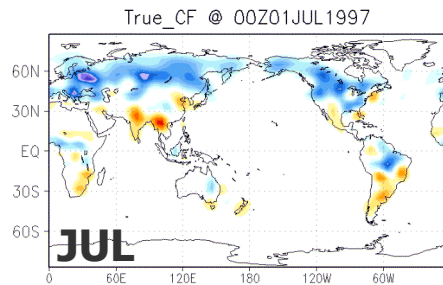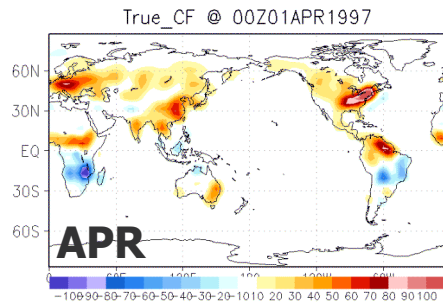
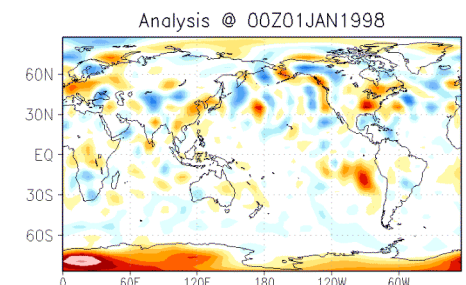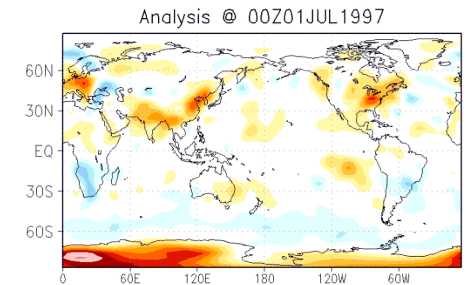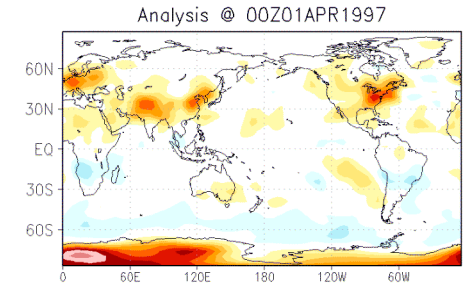**adaptive multiplicative** **+additive**
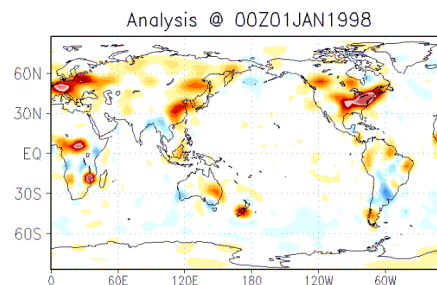
fixed multiplicative **+additive**
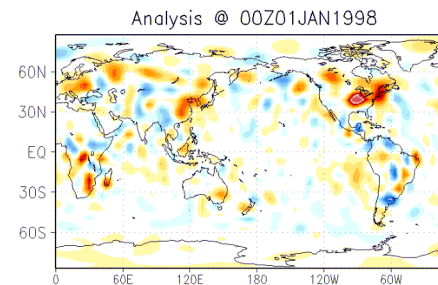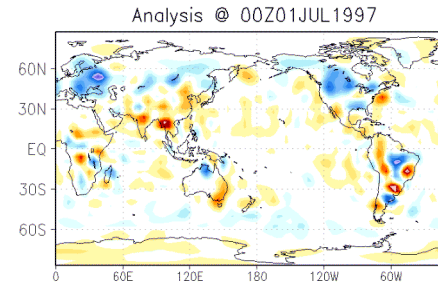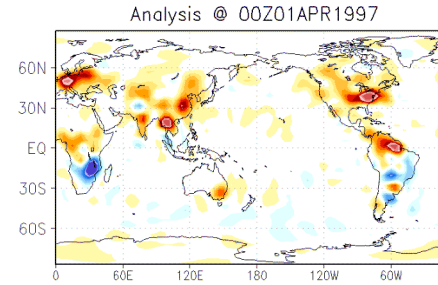
standard: fixed multiplicative

Adaptive inflation by Miyoshi (2011, Mon. Wea. Rev.)

Human and Nature Dynamical model (HANDY) with Rich and Poor: a thought experiment

Nature equation:

$$\dot{y} = \text{Regeneration} \, \gamma \, y(\lambda - y) - \text{Production} \, \delta x_P y$$
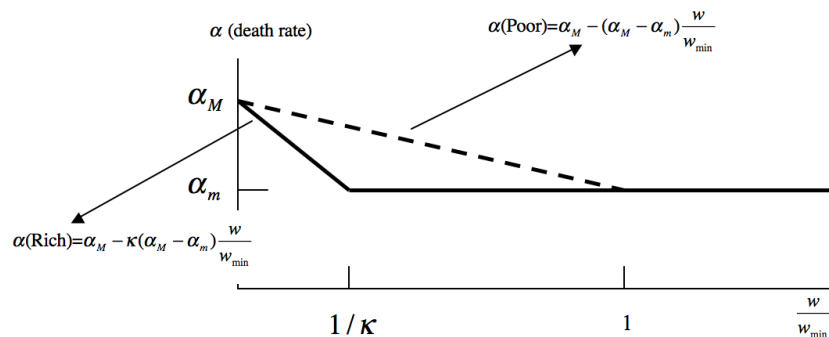
Total population: Rich +Poor, only the poor work. $x = x_R + x_P$

The Wealth belongs to the Rich:

Added Wealth=Production -Consumption of the Rich -Consumption of the Poor

$$\dot{W} = \delta x_P y - C_R - C_P = \delta x_P y - \kappa s x_R - s x_P$$

s: subsistence salary

κ: inequality factor~100

α (death rate)

$\alpha(\text{Poor}) = \alpha_M - (\alpha_M - \alpha_m)\dfrac{w}{w_{min}}$

α_M

α_m

$\alpha(\text{Rich}) = \alpha_M - \kappa(\alpha_M - \alpha_m)\dfrac{w}{w_{min}}$
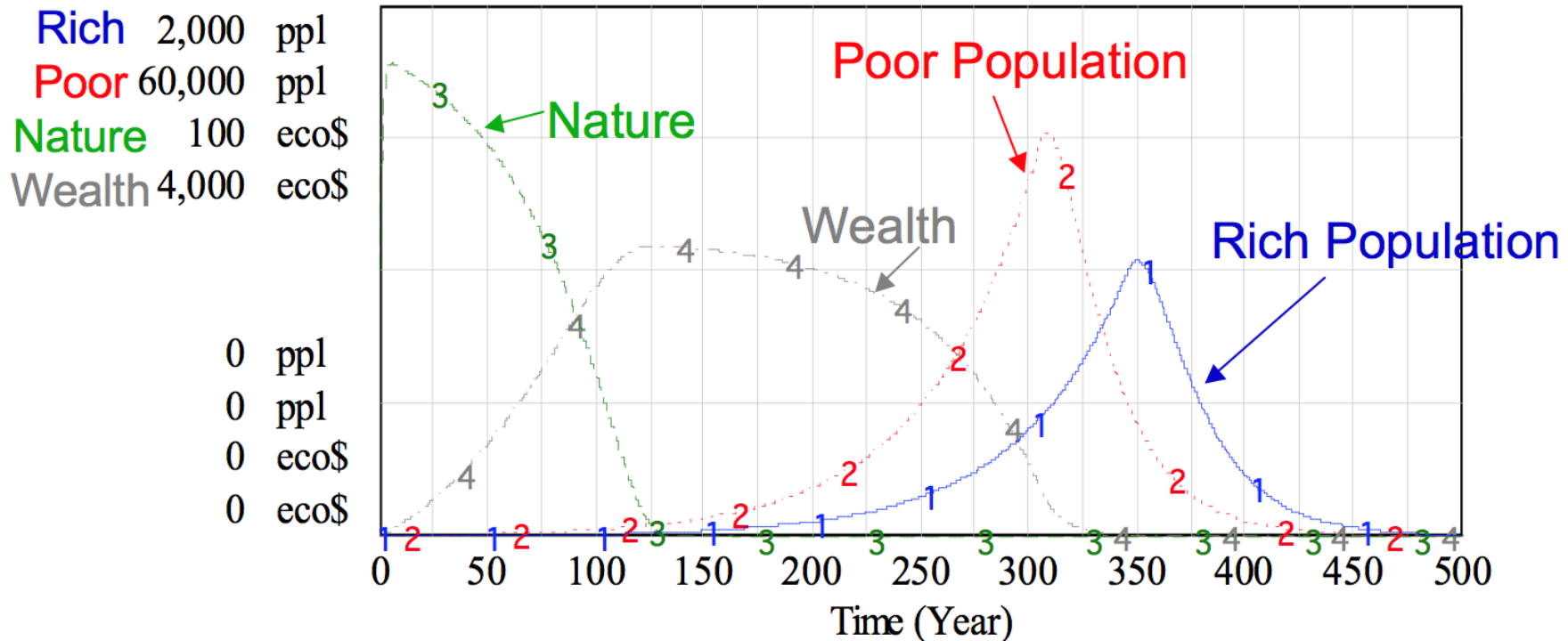
$1/\kappa$ 1 $\dfrac{w}{w_{min}}$

Death rate depends on whether there is enough wealth. Birth rate is the same for Rich and Poor

The **rich elite** accumulates wealth from the work of everyone else (here referred to as the **poor**). When there is a crisis (e.g., famine) the elite can spend the accumulated wealth on food.

Human and Nature Dynamical model (HANDY) with Rich and Poor: a thought experiment

Population, Nature, and Wealth

Rich 2,000 ppl
Poor 60,000 ppl
Nature 100 eco$
Wealth 4,000 eco$

0 ppl
0 ppl
0 eco$
0 eco$

Nature

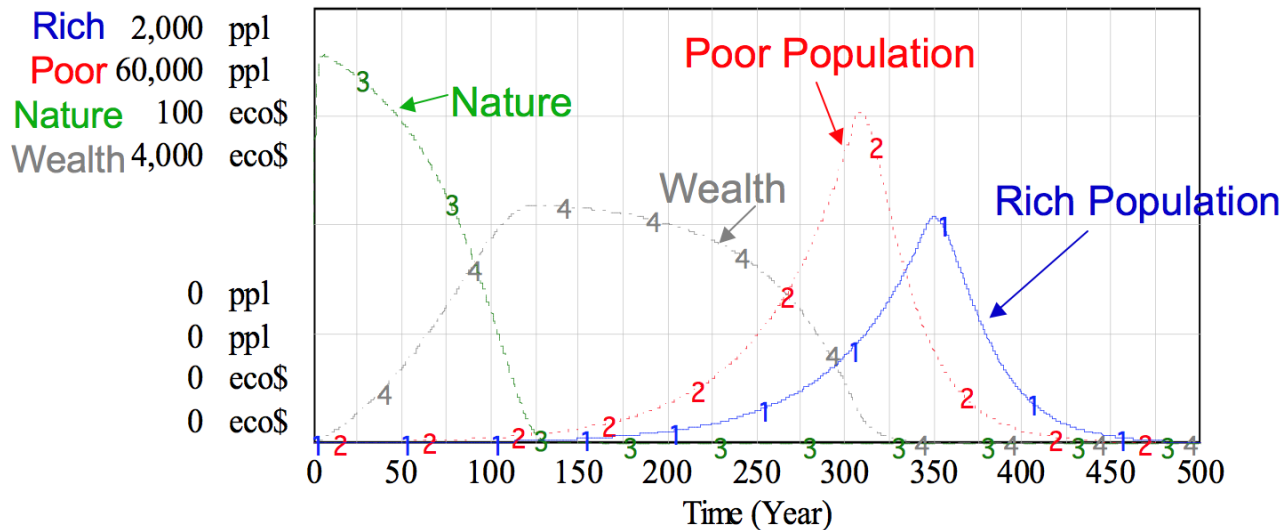Poor Population

Wealth

Rich Population

Time (Year)

- Nature declines with population growth

- Using their wealth, the rich class can shield itself for a while from environmental degradation, which first affects the poor, but eventually it reaches the upper class as well at a delayed time, when it is too late to take preventive measures.

Human **a**nd **N**ature **Dy**namical model (HANDY) with Rich and Poor: <u>a thought experiment</u>

Population, Nature, and Wealth

Rich 2,000 ppl
Poor 60,000 ppl
Nature 100 eco$
Wealth 4,000 eco$

0 ppl
0 ppl
0 eco$
0 eco$

Poor Population

Nature

Wealth

Rich Population

Time (Year)

• Nature declines with population growth

• Using their wealth, the rich class can shield itself for a while from environmental degradation, which first affects the poor, but eventually it reaches the upper class as well at a delayed time, when it is too late to take preventive measures.

This thought experiment shows how a crisis can happen rapidly, even though it appears that population is rising steadily without any problems, and that the wealthy would not feel the effects of the collapse until it is too late for the poor (and then it is too late for the rich as well!).

Thanks…, we welcome your feedback

AND THE VILLAIN STILL PURSUES HER.

Parameter Estimation in EnKF

- Example of carbon cycle data assimilation
  - Surface CO_2 fluxes (CF): a forcing for atmospheric CO_2
- State vector augmentation
  - State vector is augmented by CF which is updated by error covariance between the variables in the state vector
- Variable localization
  - In a multivariate analysis of EnKF, error covariance is zeroed out when there is no significant physical relationship between variables, in order to reduce a sampling error
- Inflation
  - It helps represent background uncertainty more accurately
- Vertical localization of satellite column data
  - Averaging kernel is nearly uniform in the vertical, although a forcing term (our ultimate estimate) is at the surface. Then…?
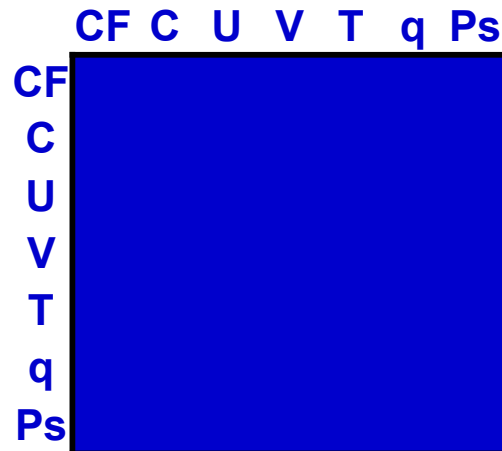
Kang et al. (2011, JGR)

Variable localization

- Analysis of surface CO_2 fluxes assimilating atmospheric CO_2 observations
  - A case with a constant forcing

True fluxes
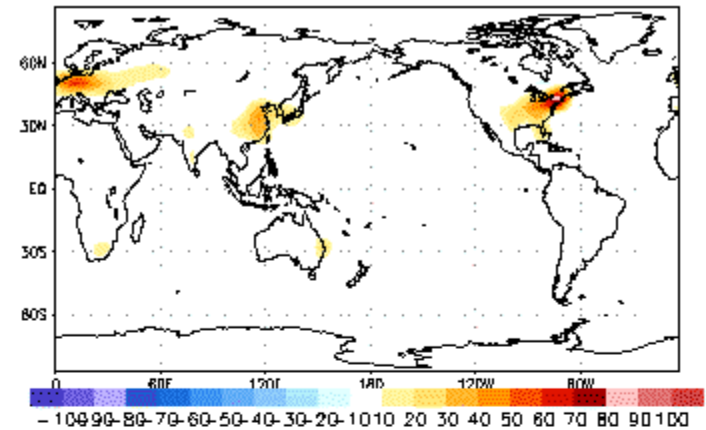

1-way multivariate analysis with a variable localization ➔
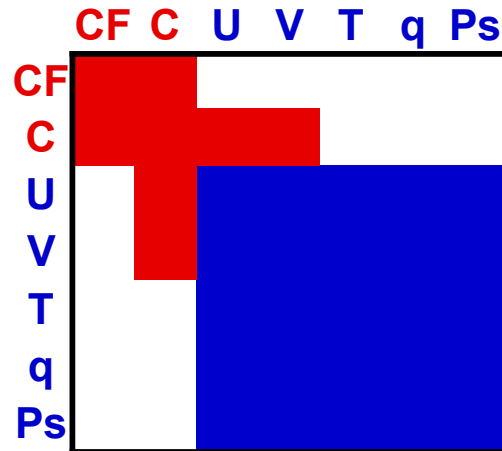
Fully multivariate analysis ➔

CF estimation w/ varloc
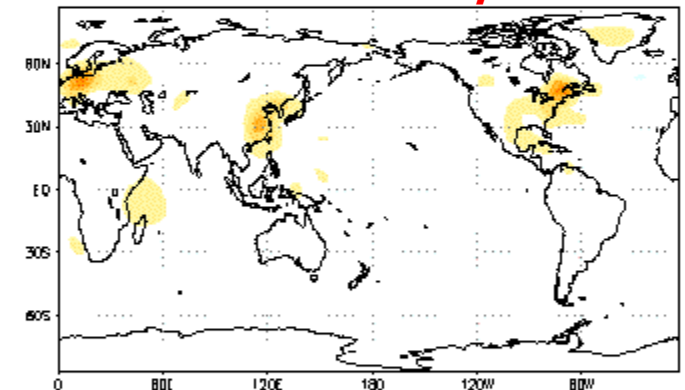
CF estimation w/o varloc

Kang et al. (2011, JGR)
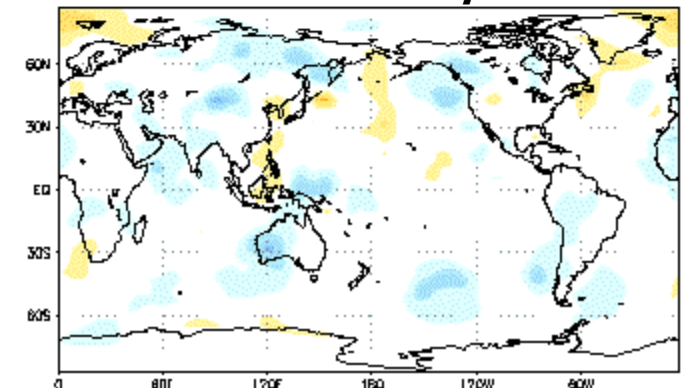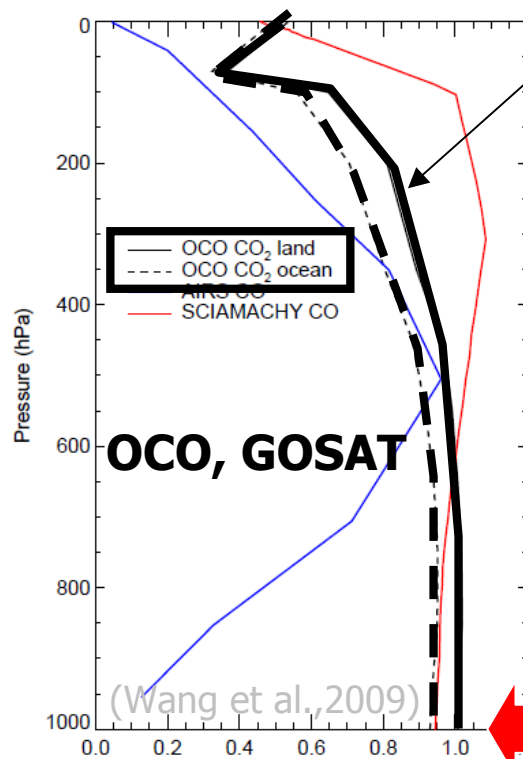
Vertical localization of CO$_2$ column data

- **OCO** (Orbiting Carbon Observatory) & **GOSAT** (Greenhouse gases Observing Satellite)
  - Satellites dedicated to mapping Earth's CO$_2$ levels

Averaging kernel is quite flat from the surface to the middle troposphere

In order to estimate surface CO$_2$ fluxes with those satellite data, we have **localized the column CO$_2$ data, updating only lower atmospheric CO$_2$** rather than a full column of CO$_2$.
(the vertical localizing function is broad in the lower troposphere but zero in the upper layers)

Forcing of CO$_2$ is at the surface!!!

Vertical localization improves results

- Time series of CF for one year

(a) CF over N Equatorial Africa

(b) CF over S Equatorial Africa
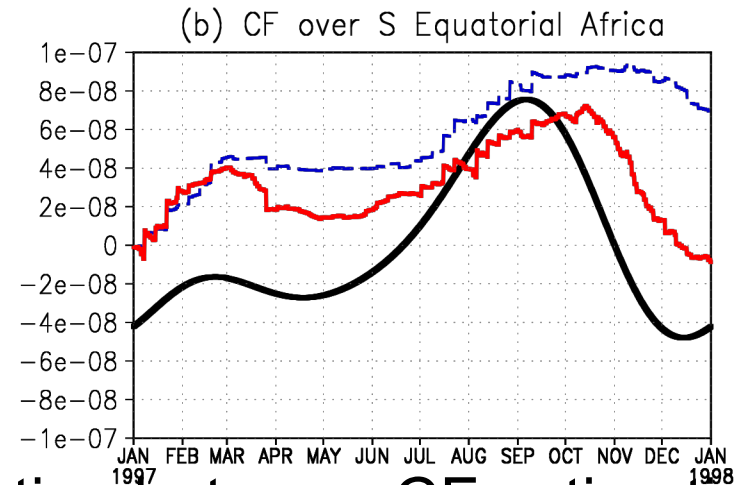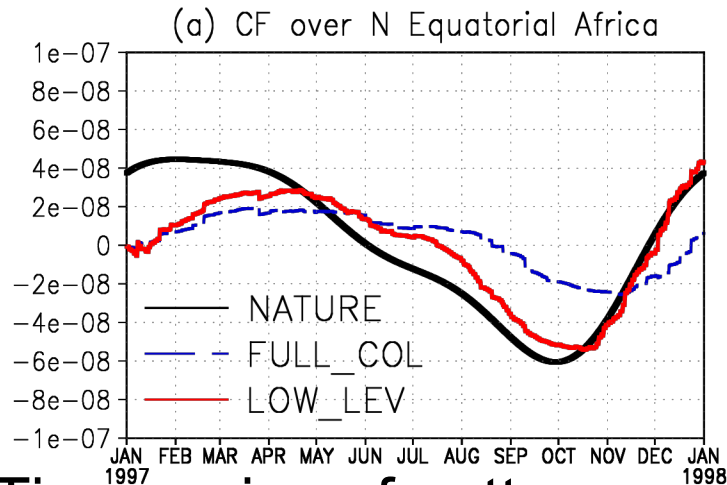
- Time series of pattern correlation between CF estimation and its true state

CF_Pattern_Correlation [LAND]