Sustainability Modeling with System Dynamics and Modelica

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MODPROD Workshop February 5, 2020

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SUSTAINABLE DEVELOPMENT GOALS
17 GOALS TO TRANSFORM OUR WORLD
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Watch and Listen
1 NO POVERTY
2 ZERO HUNGER
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4 QUALITY EDUCATION
5 GENDER EQUALITY
6 CLEAN WATER AND SANITATION
7 AFFORDABLE AND CLEAN ENERGY
8 DECENT WORK AND ECONOMIC GROWTH
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
10 REDUCED INEQUALITIES
11 SUSTAINABLE CITIES AND COMMUNITIES
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION
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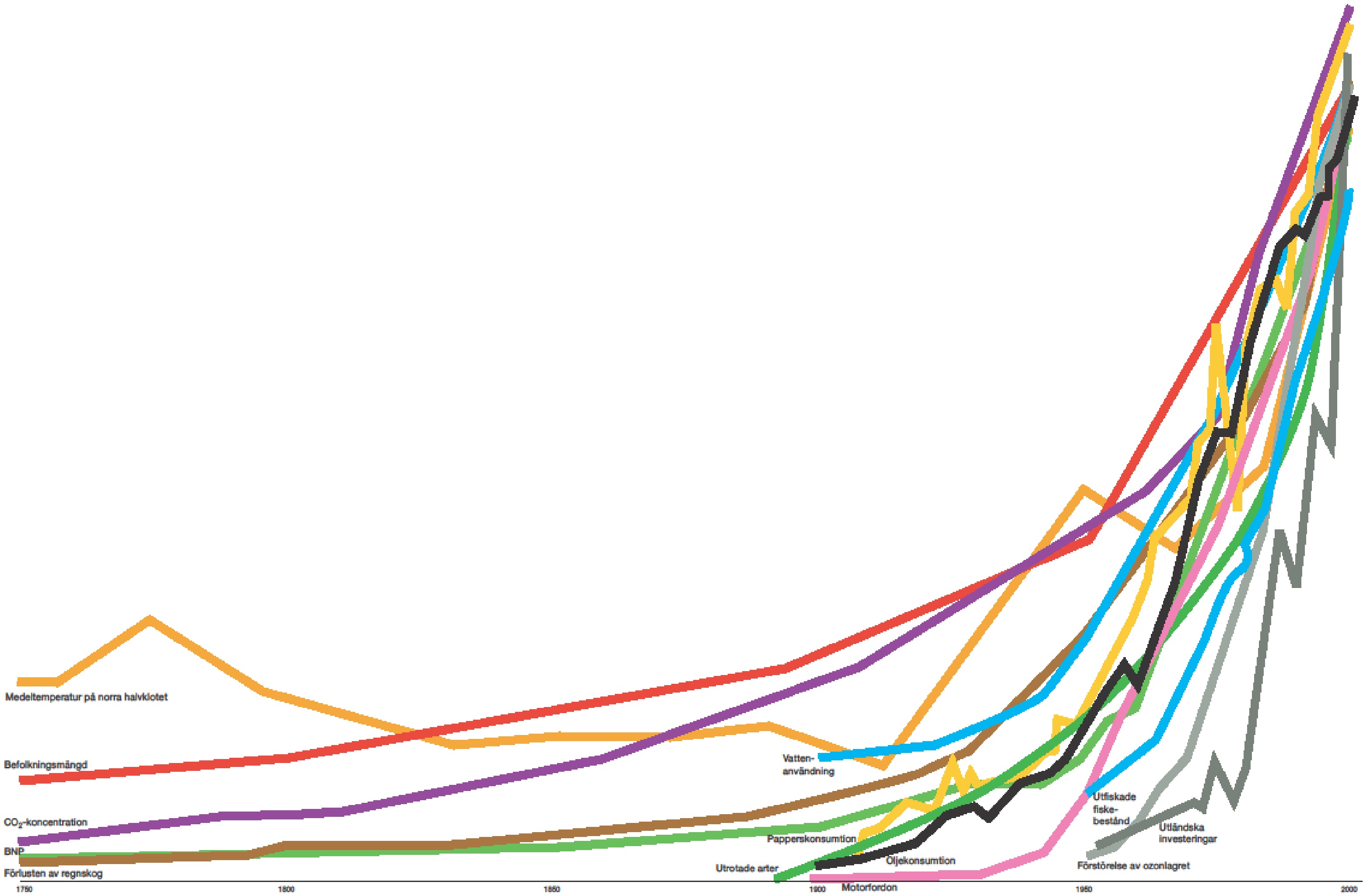
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
17 PARTNERSHIPS FOR THE GOALS
SUSTAINABLE DEVELOPMENT GOALS

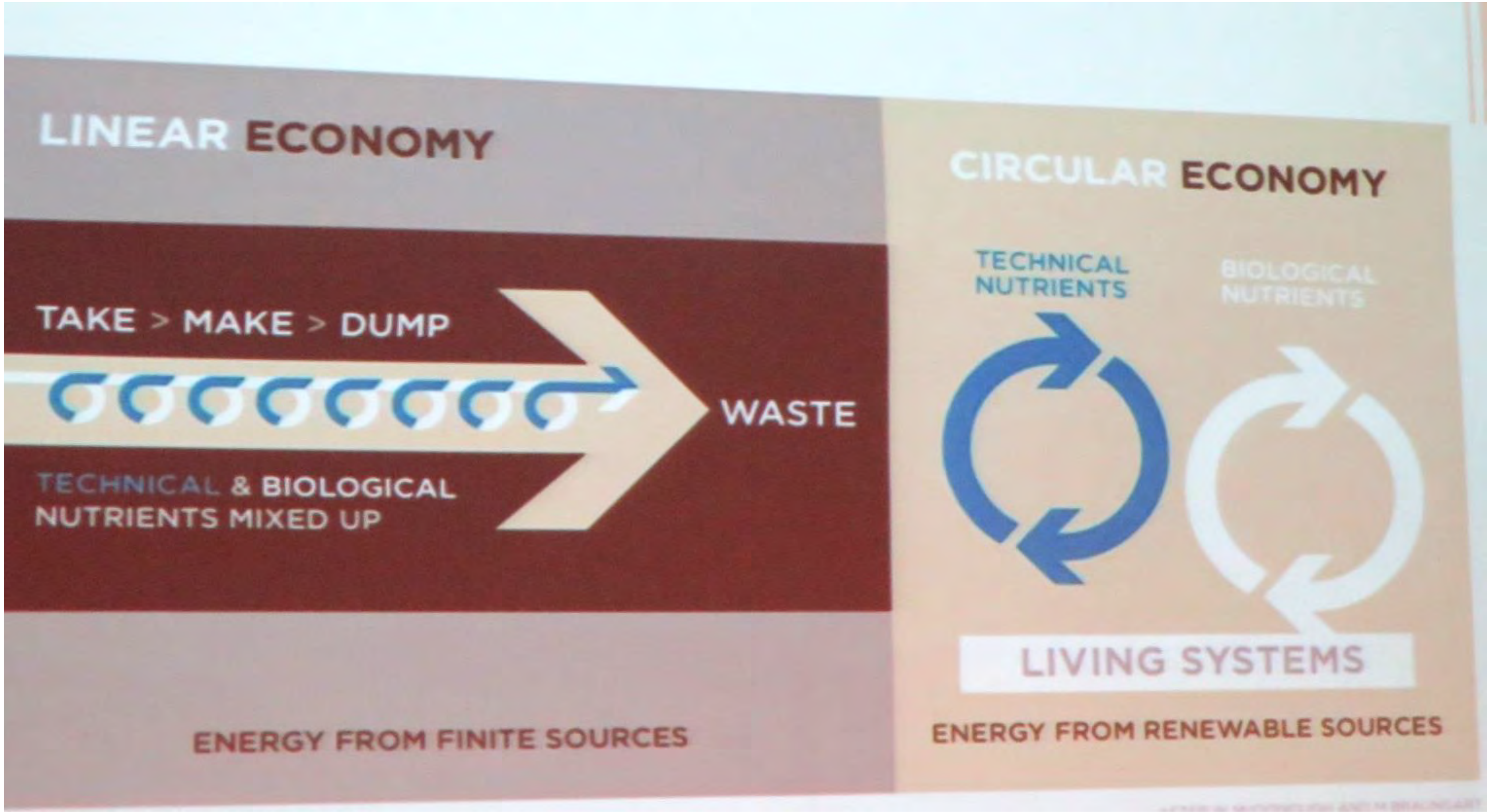
A Unique Point in History - Exponential Trends Approaches Planet Earth Boundaries

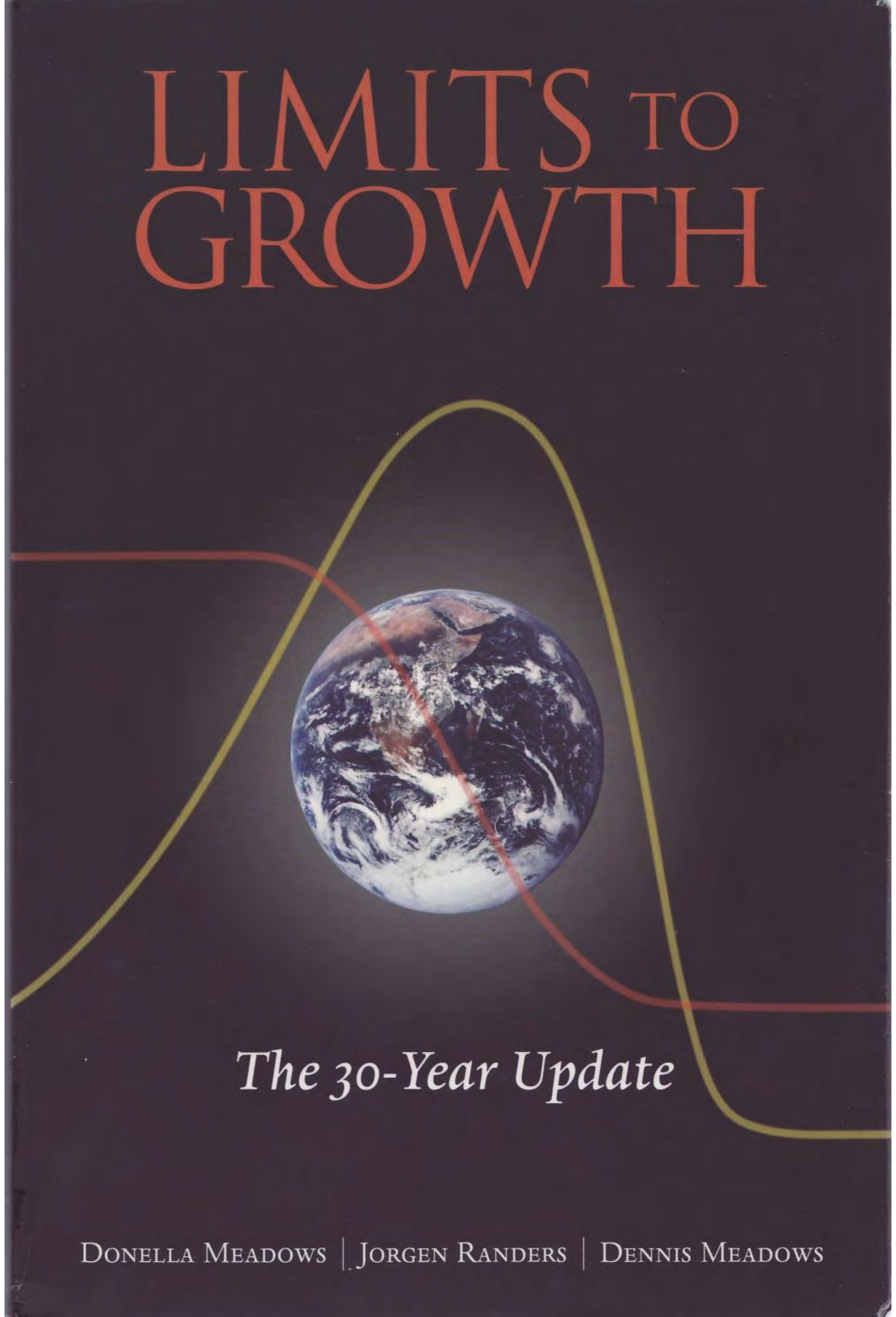


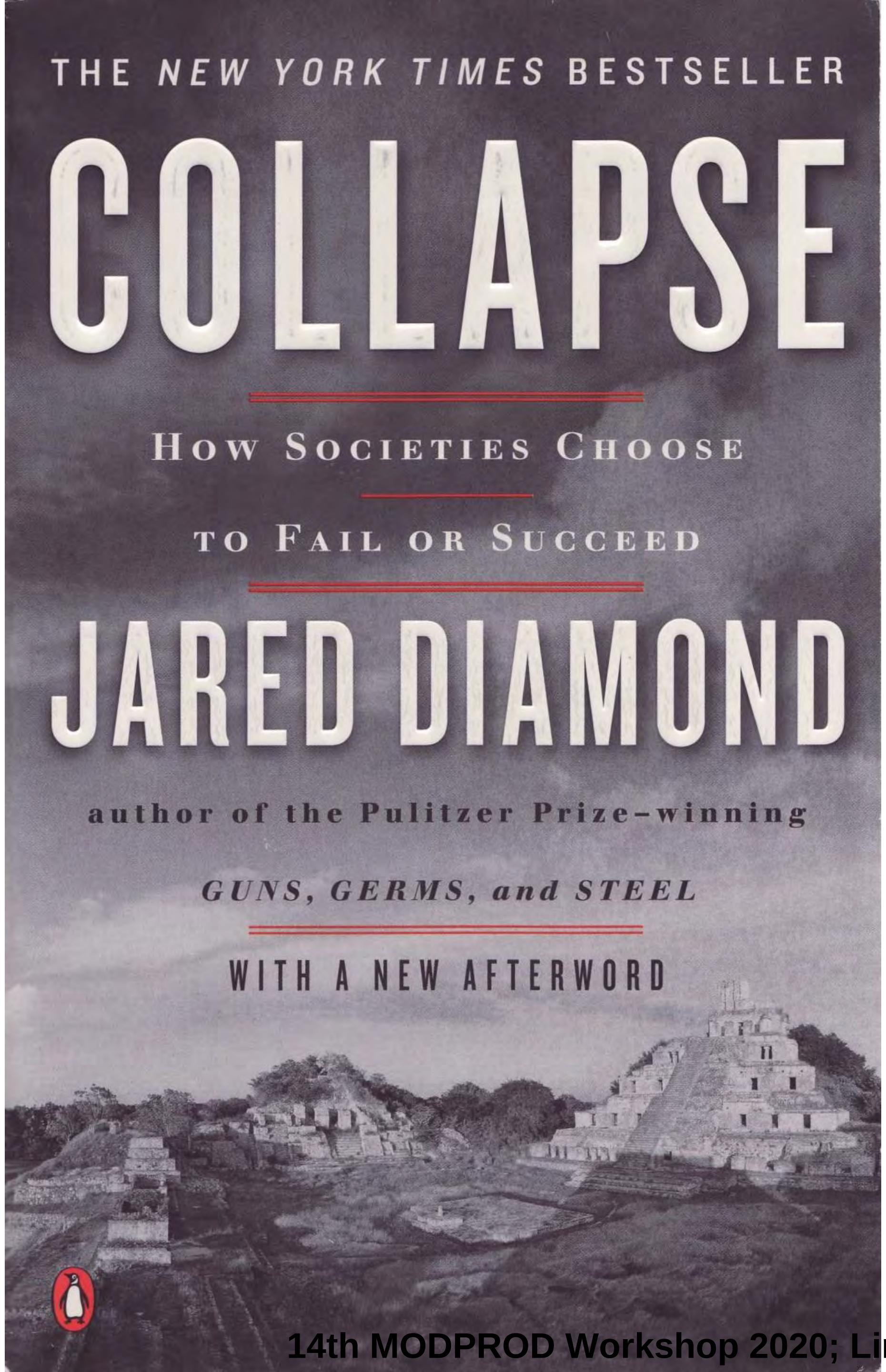
Year 1750-2000:

- Mean temperature north hemisphere,
- Population,
- CO_2-concentration,
- BNP,
- Loss av rain forest,
- Water usage
- Paper consumption,
- Exterminated species
- Oil consumtion,
- Motor vehicles
- Destroyed fish populations
- Destruction of ozon layer
- Foreign investments

Challenge: Use Modeling and Simulation Technology to Support Circular Economy - for a Sustainable World

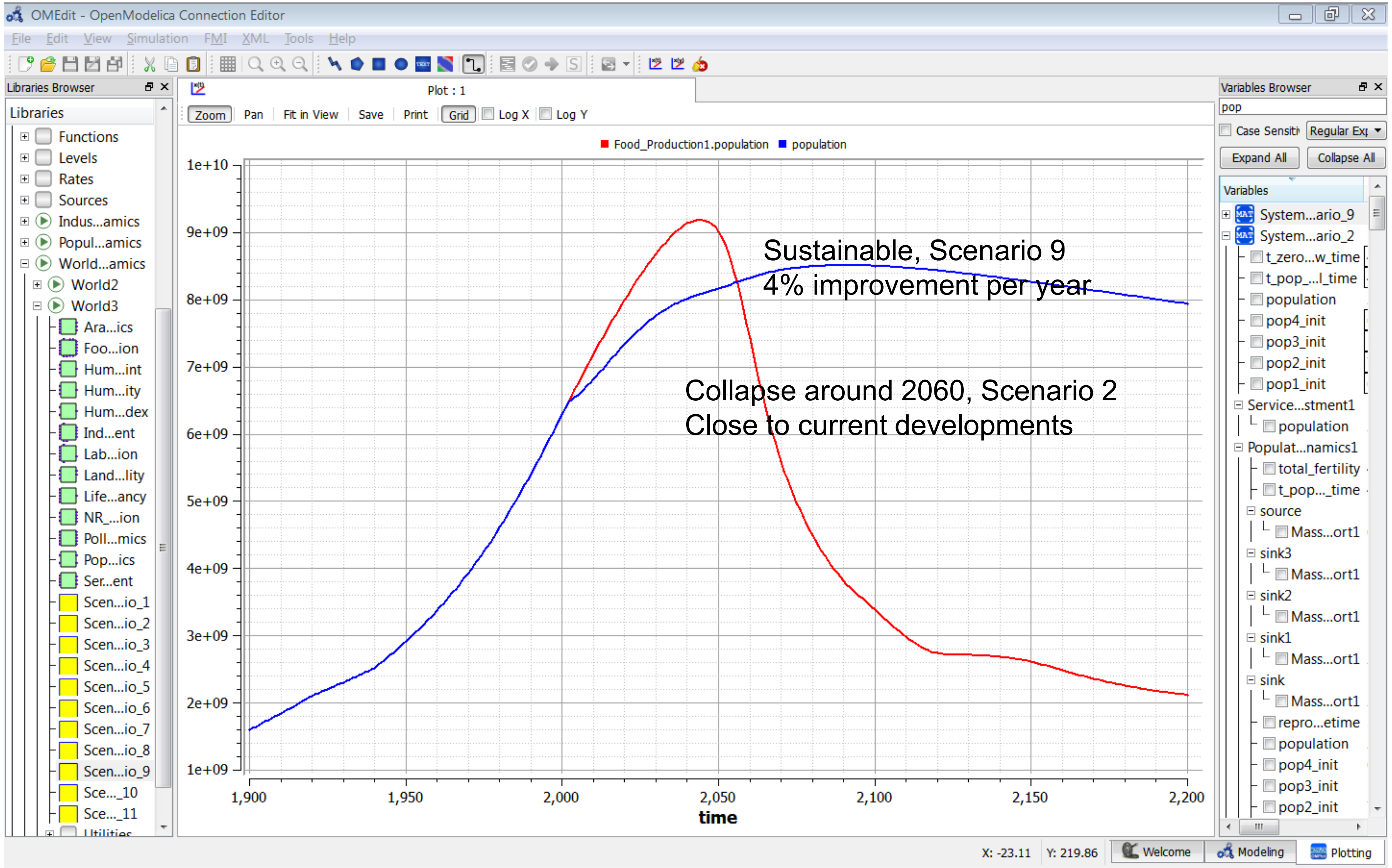



LIMITS TO GROWTH
The 30-Year Update
DONELLA MEADOWS | JORGEN RANDERS | DENNIS MEADOWS


THE NEW YORK TIMES BESTSELLER
COLLAPSE
HOW SOCIETIES CHOOSE
TO FAIL OR SUCCEED
JARED DIAMOND
author of the Pulitzer Prize-winning
GUNS, GERMS, and STEEL
WITH A NEW AFTERWORD

The Biggest Challenge of All -

Sustainable society - Avoid Global Collapse in 50 years



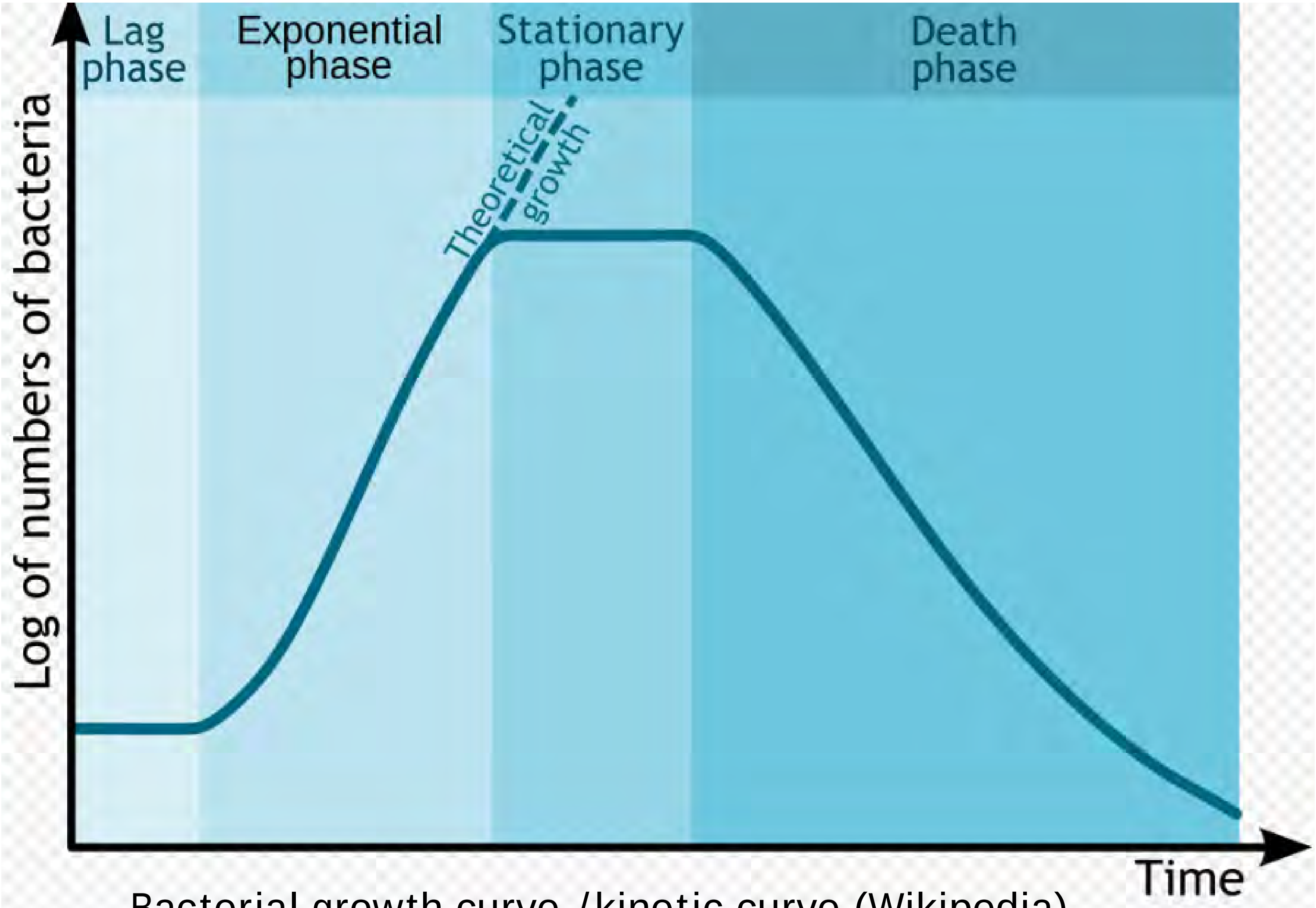
System Dynamics Simulation with OpenModelica – World3 Model, Meadows et al

Are Humans More Intelligent than Bacteria?
Not yet evident!

Humans
on a
finite
Earth

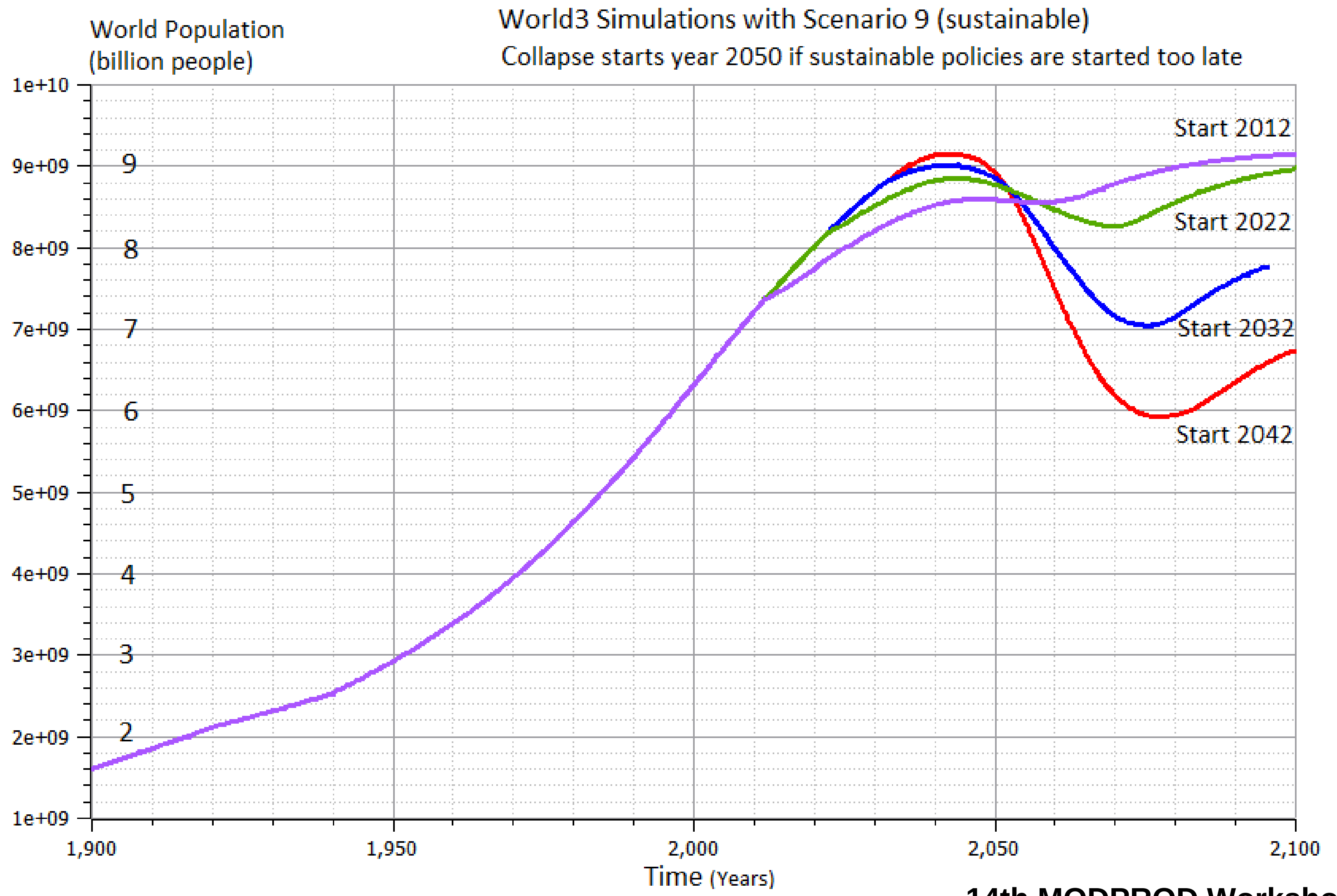
vs

Bacteria
on a
finite
substrate



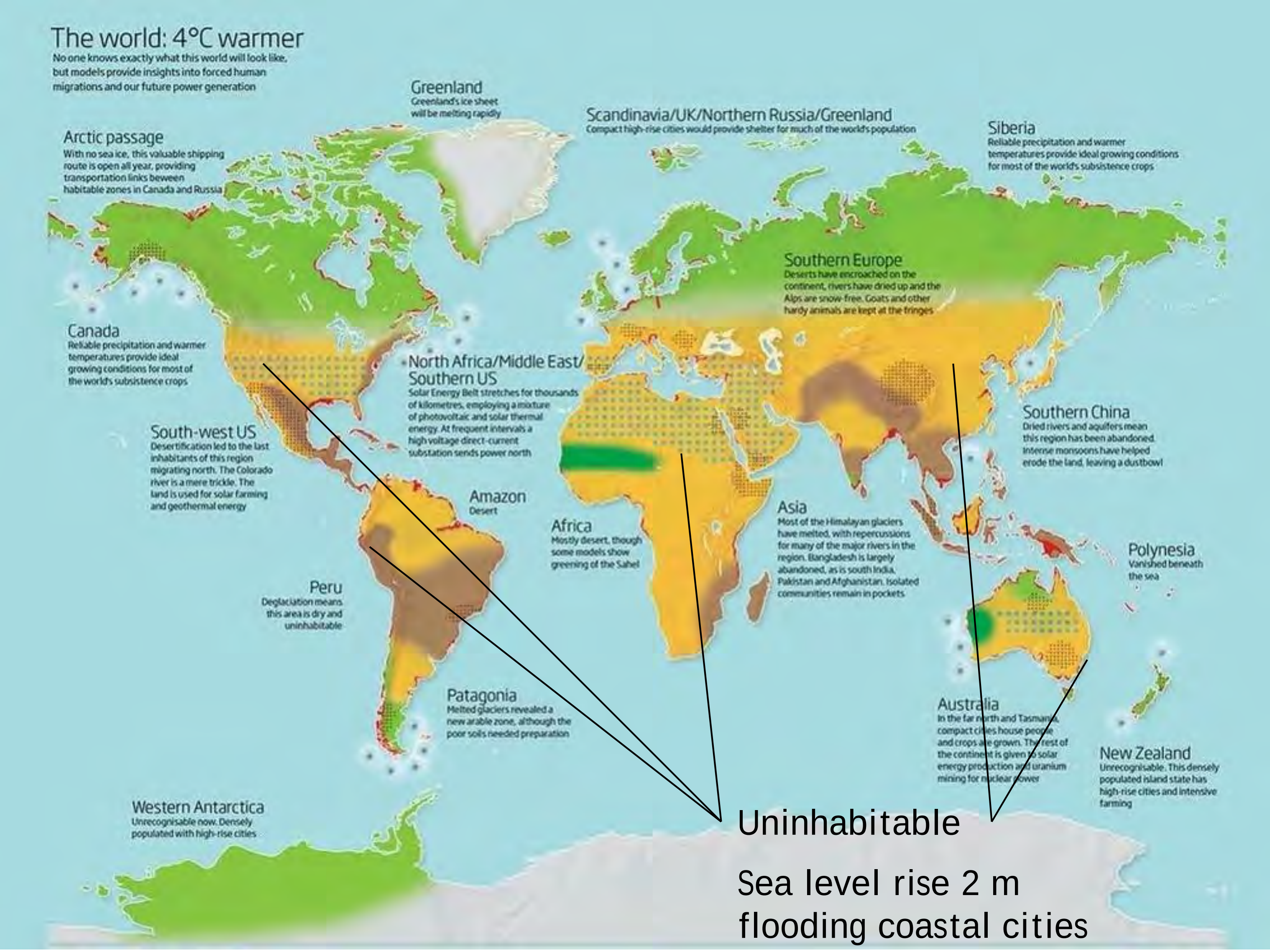
Bacterial growth curve /kinetic curve (Wikipedia)

World3 Simulations with Different Start Years for Sustainable Policies - Collapse if starting too late



How the world could be in 80-100 years at a global warming of 4 degrees

Business-as-usual scenario, IPCC



- Cities, agriculture
- Uninhabitable desert
- Uninhabitable due to extreme weather
- Flooded

Massive migration to to northern Europe, Russia, and Canada

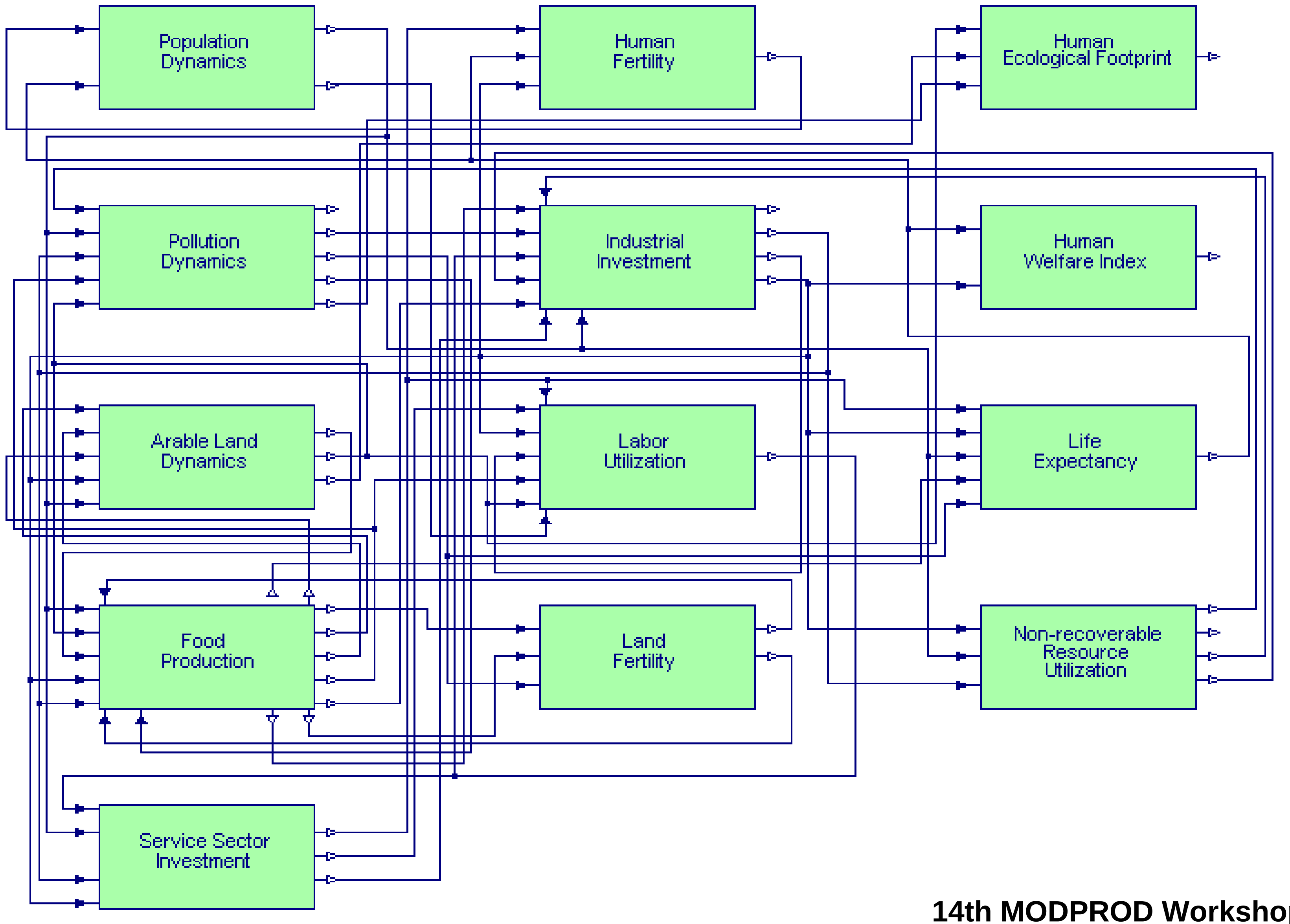
Example Emissions
CO_2e / person
- Earth can handle 2 ton/yr
- Flight Spain - 1 ton
- Flight Canaryisl - 2 ton
- Flight Thailand - 4 ton

References

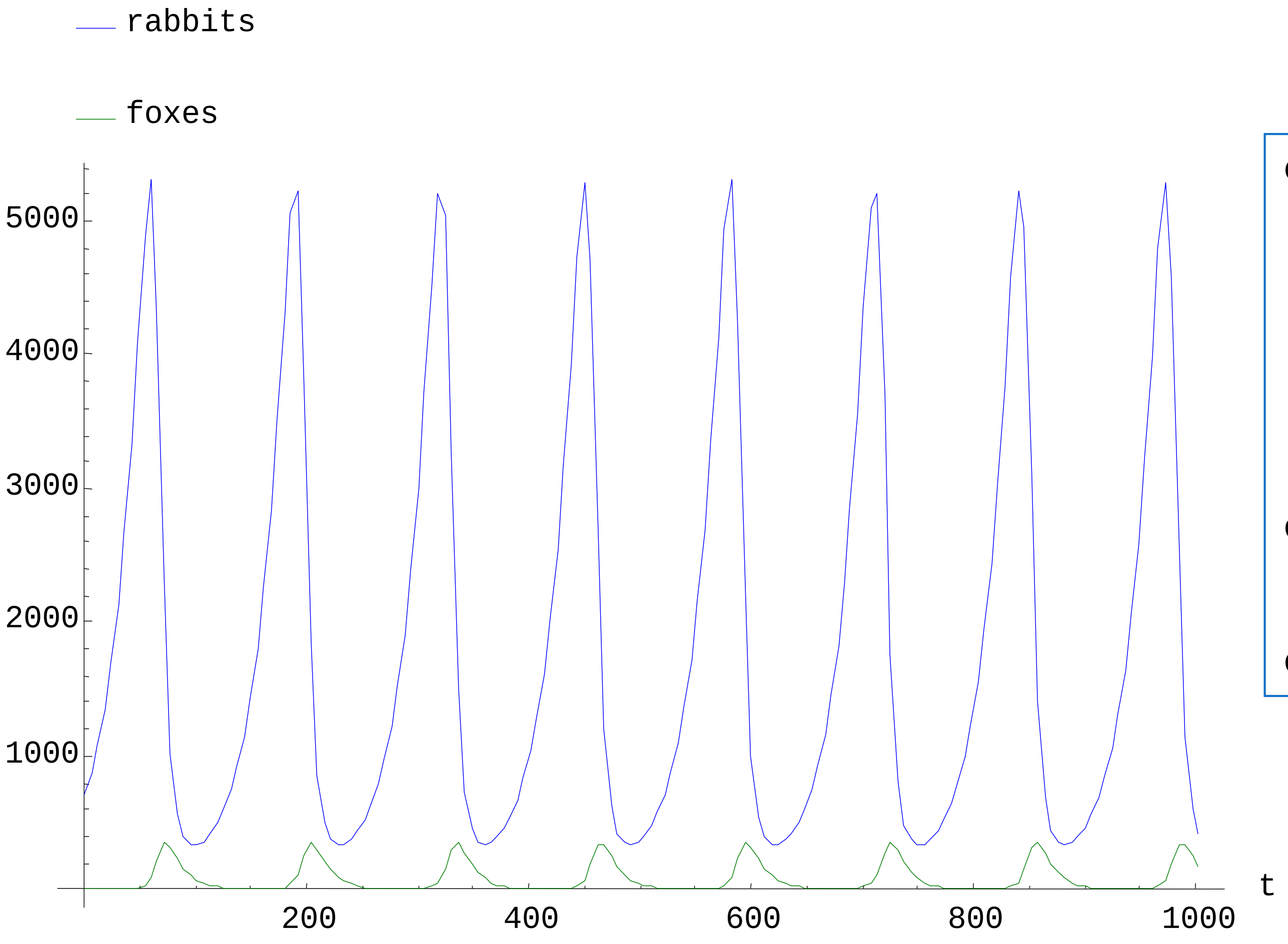
New Scientist, 28 february 2009
IPCC, business as usual scenario
www.climate-lab-book.ac.uk
www.atmosfair.de

World3 Model in Modelica, Meadows et al, Cellier

Comprehensive model - 13 areas



The Lotka Volterra Model




```
class LotkaVolterra
  parameter Real g_r =0.04     "Rabbit growth rate";
  parameter Real d_rf=0.0005  "Death rate due to foxes";
  parameter Real d_f =0.09    "Foxes deathrate";
  parameter Real g_fr=0.1     "Efficency
                                    in growing foxes from rabbits";
  Real rabbits(start=700) "Rabbits,(R)";
  Real foxes(start=10)    "Foxes,(F)";
equation
  der(rabbits) = g_r*rabbits – d_rf*rabbits*foxes;
  der(foxes)   = g_fr*d_rf*rabbits*foxes – d_f*foxes;
end LotkaVolterra;
```

Consider exponential growth of a population with unlimited food supply. Planetary limits?

Cyclic behavior – growth/collapse;   Nature/food/rabbits vs humans/foxes

The System Dynamics Methodology

- Introduced in the late sixties by J.W.Forrester
  - A tool for visually organizing partial knowledge about models of poorly understood systems in phenomenological sciences
    - Biology, Ecology, Macro economy, Sociology, etc.
- Low-level modeling paradigm: “Stocks and Flows”
  - Stock elements connected by material or non-material (e.g., information) Flows
  - Flows regulated by input-output Rates
  - A simplified way of dealing with differential equations
    - Shuns traditional calculus

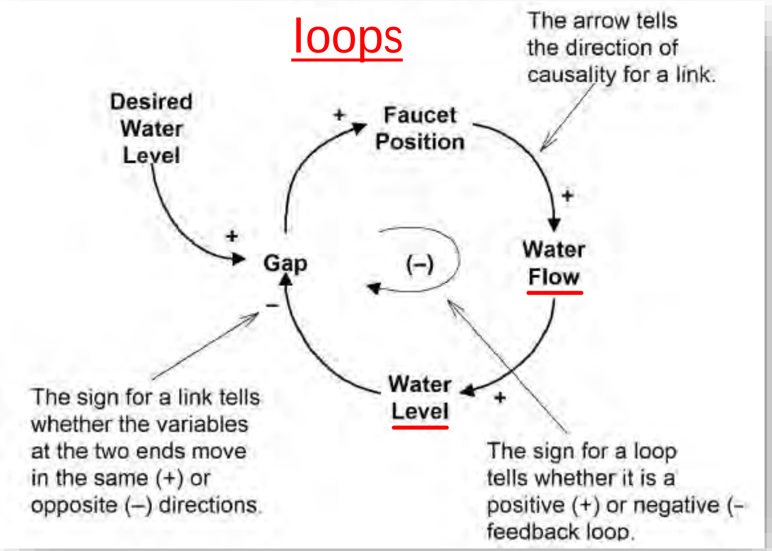
The System Dynamics Methodology

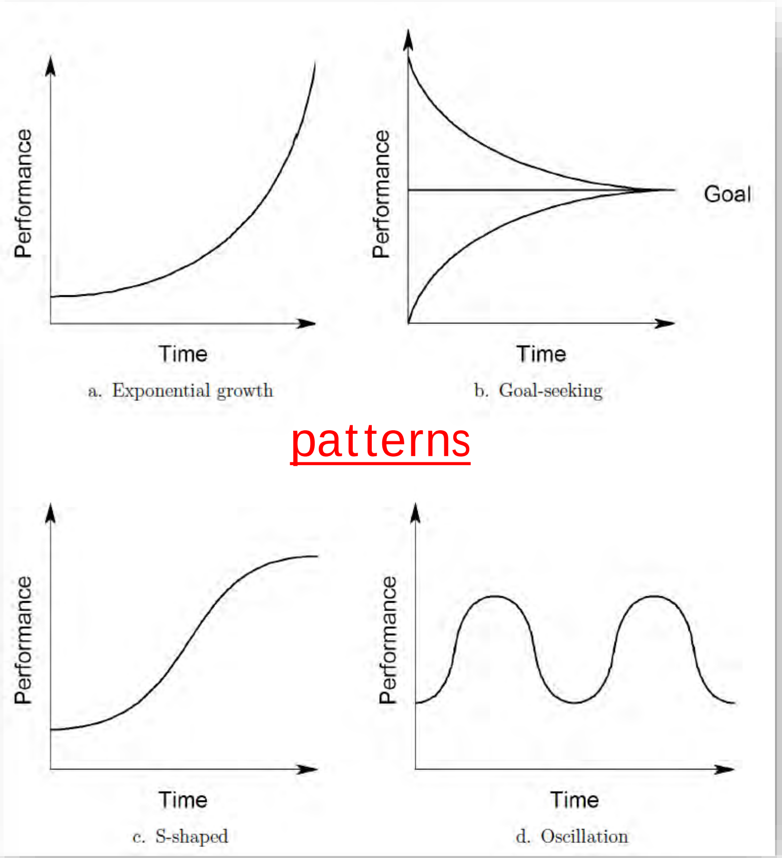
- Physical systems call for deductive modeling
  - Well established meta laws exist. These are preserved:
    - across a wide range of spatio-temporal scales
    - under system composition/decomposition procedures
  - Very reliably modeled
  - *Example: a car (mechanical-electro-computerized system)*
- Ill-defined systems call for inductive modeling
  - Much more complex to model in a reliable way
  - Very weak, narrowly applicable, or totally inexistent meta laws
  - Difficult decomposability into subsystems (densely connected)
    - Submodel parameters are influenced by many system’s variables in similar orders of magnitude
  - *Example: an ecosystem (bio-geo-chemical system)*
- System Dynamics
  - Applicable in both deductive and inductive modeling
  - Useful only when used carefully (avoid to incur in a “modern reductionism”)

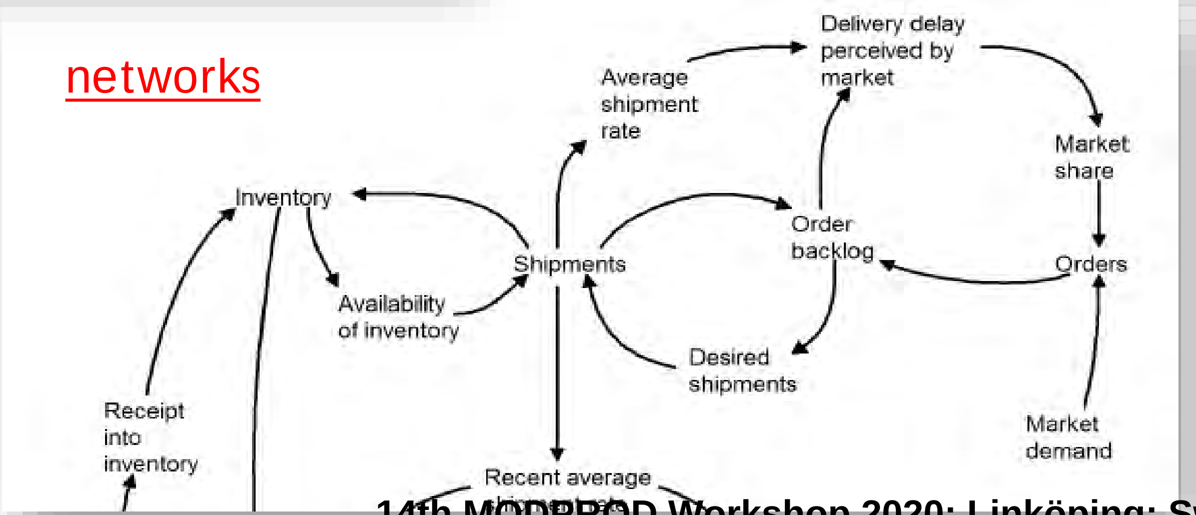
The System Dynamics Methodology

- Explore dynamic behavior of systems lacking universal laws
- Think visually in terms of:
  - Basic system structures as positive and negative feedback loops
  - Patterns of behavior
- Loops forming complex interdependent networks
  - Opposed to simplistic independent unidirectional cause-effect relations
- Also accounts for:
  - Time delays in internal system flows
  - Nonlinear effects

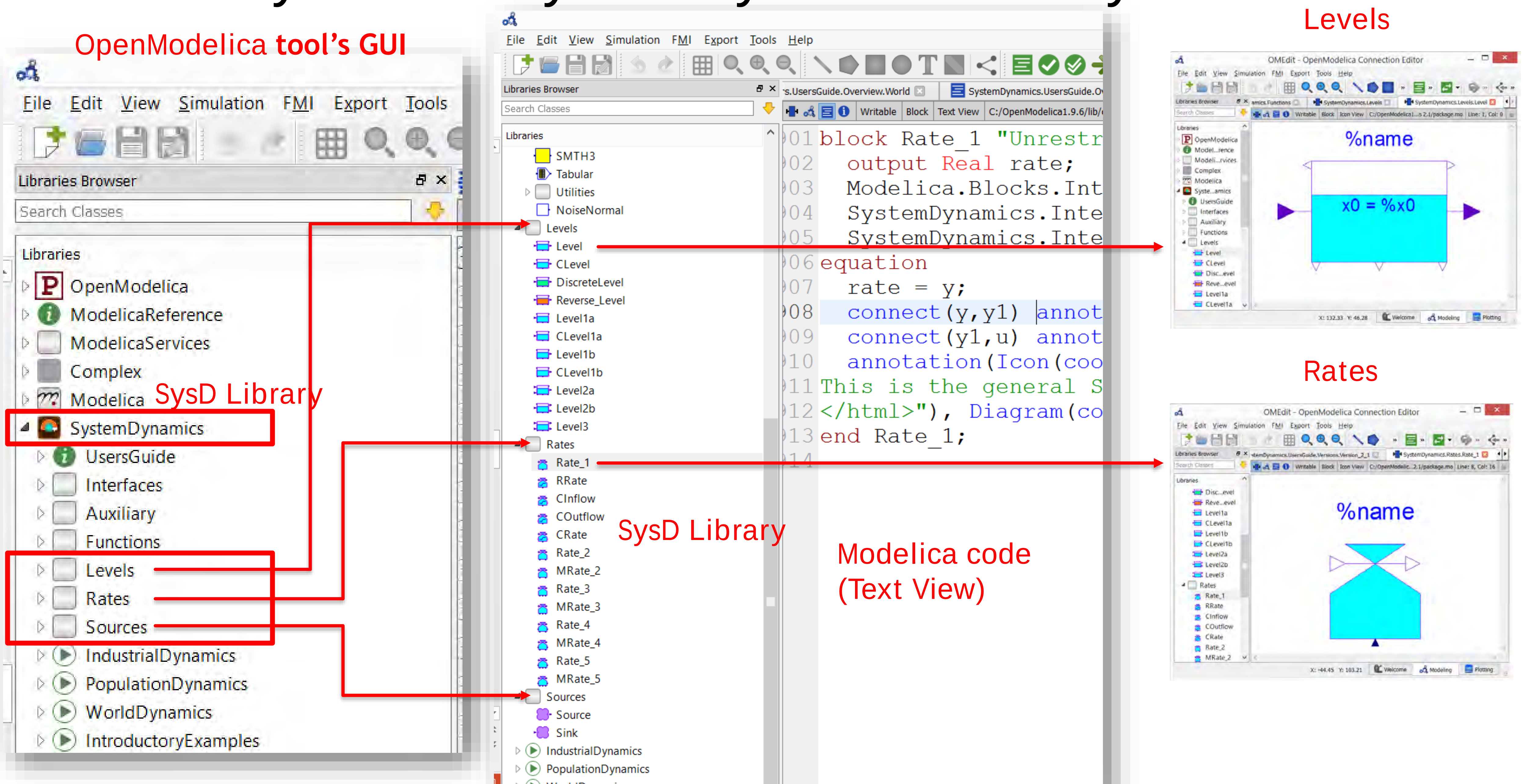
from System Dynamics Methods: A Quick Introduction, C. Kirkwood





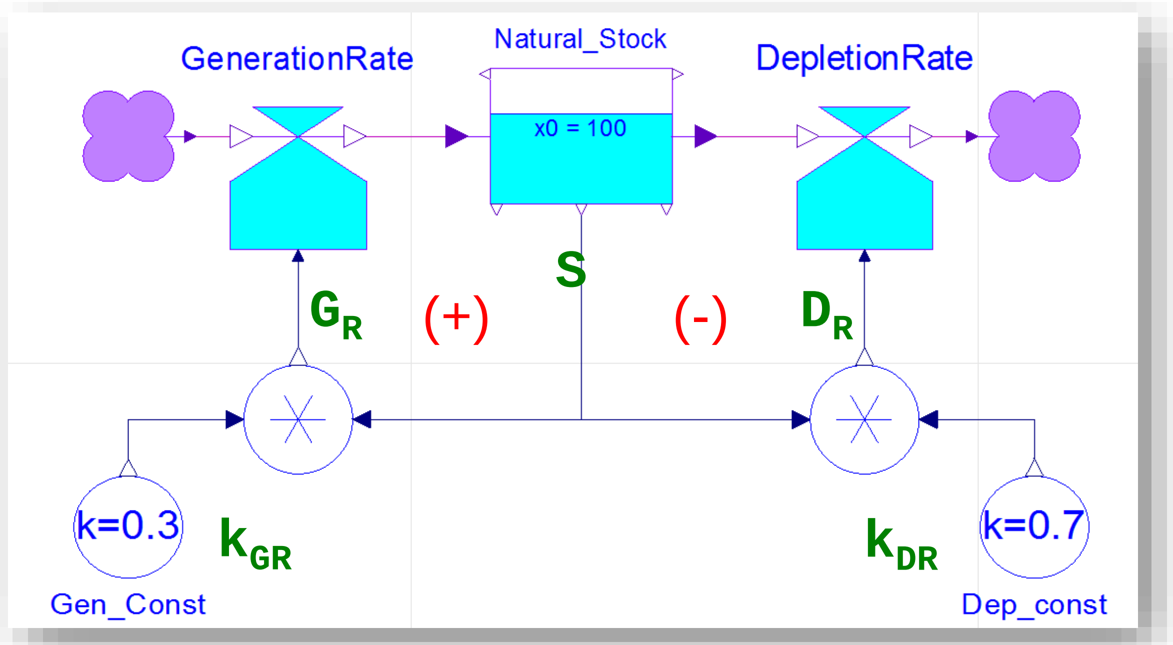


Modelica-SysD: The SystemDynamics library for Modelica



Simple Exponential Generation/Depletion model

- Required model parameters:
  - Level: initial condition
  - Rates: constant coefficients
- Required simulation parameters:
  - Initial and final simulation time
  - Numerical accuracy desired



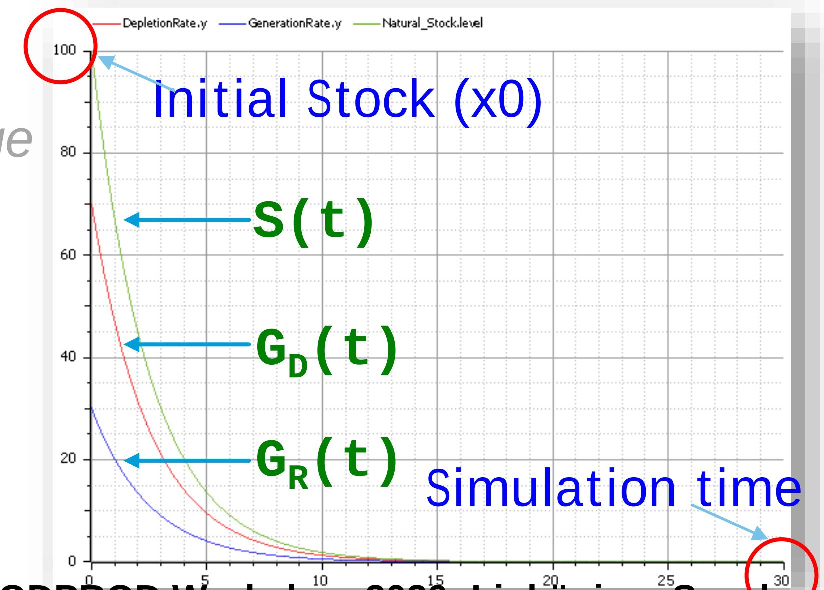
Rate of Level change

$$\dot{S} = + G_R - D_R$$

$$S(t=0) = x0$$

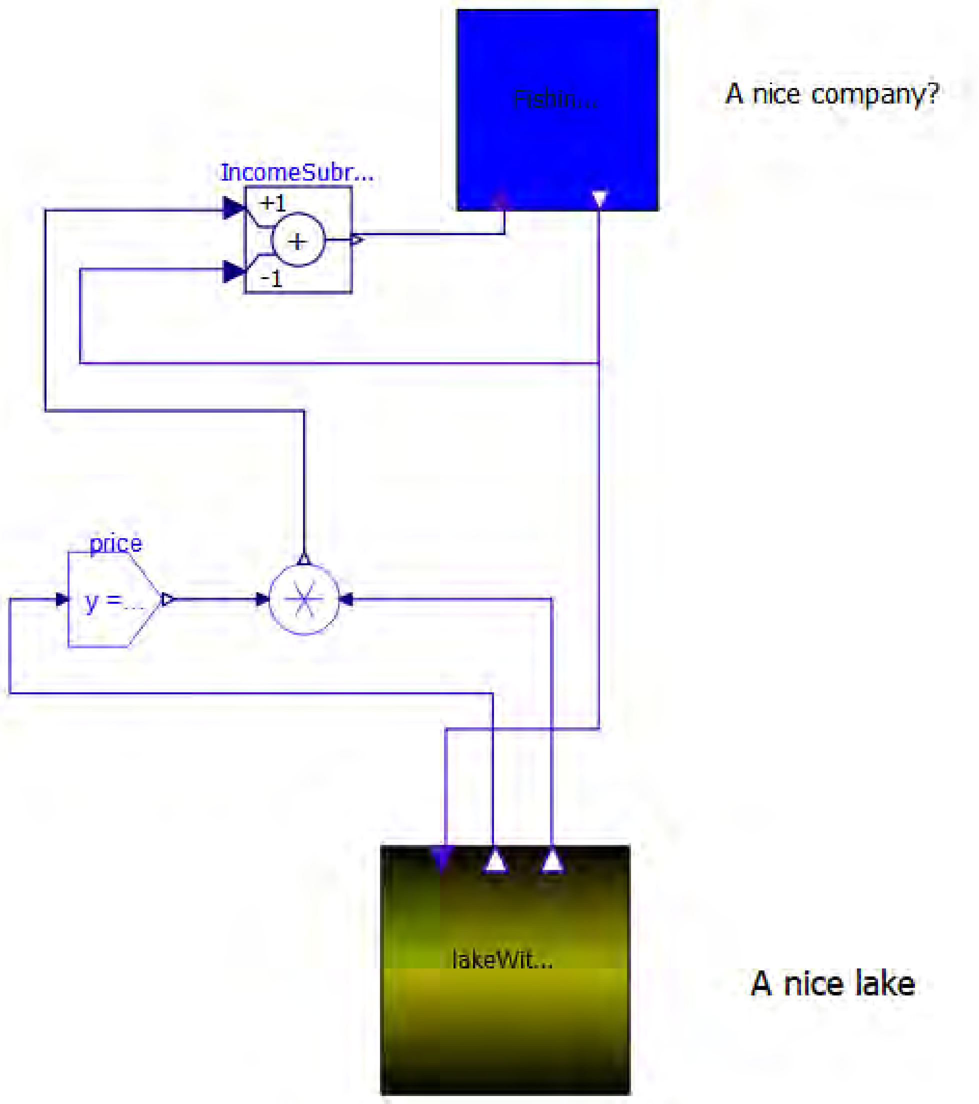
$$G_R = k_{GR} \cdot S$$

$$D_R = k_{DR} \cdot S$$

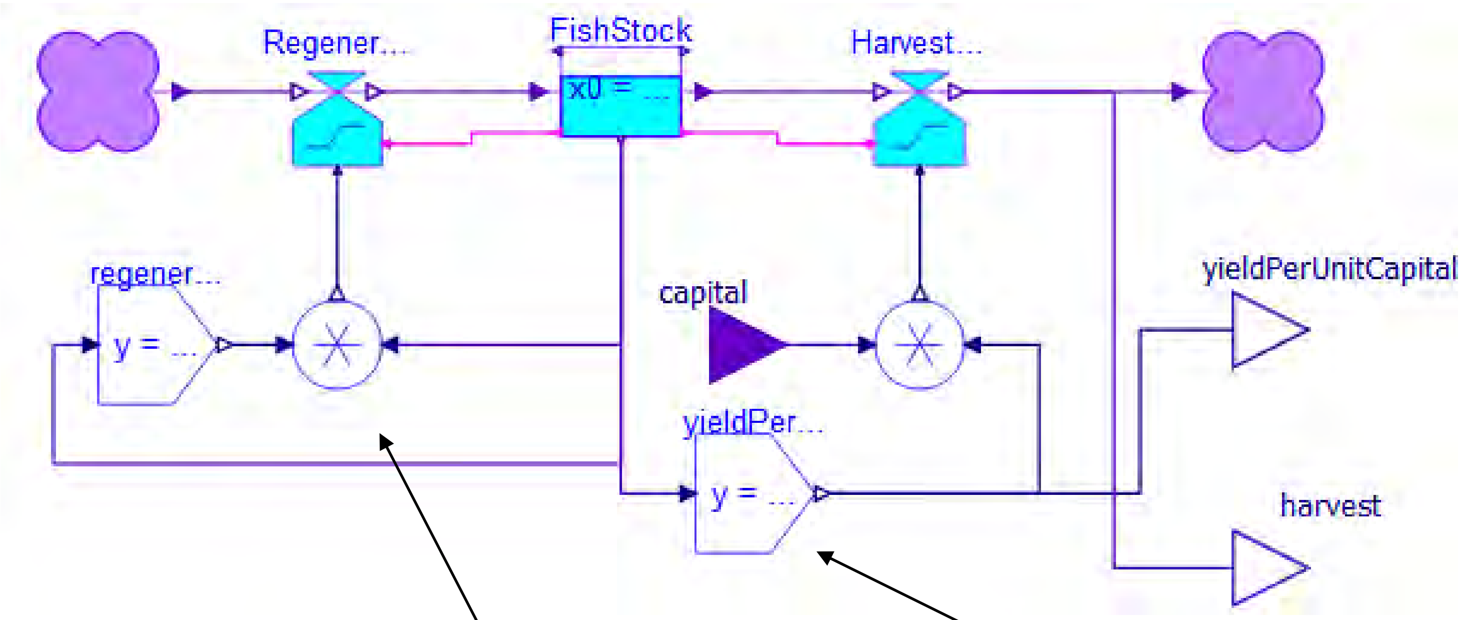


Modeling a Fishing economy with a renewable resource

- Classic System dynamics model by Donella Meadows:
- Models a company extracting a renewable resource, fish consisting of :
  - Company model
  - Lake model
- Here we use the compositional facilities of Modelica to compose our model, in this way the Fishing Company and Lake can be modeled and tested in separation



The Lake model



Regeneration function

- You need to provide data or a function representing the generation rate of the renewable fish resource.

Yield per unit capital

- Specify the yield per unit of capital the company has invested in fishing boats

Main Model Aspects

Fish Stock

- SystemDynamics.Levels.Clevel
- General System Dynamics controlling level
- Initial stock = 1000

Regeneration

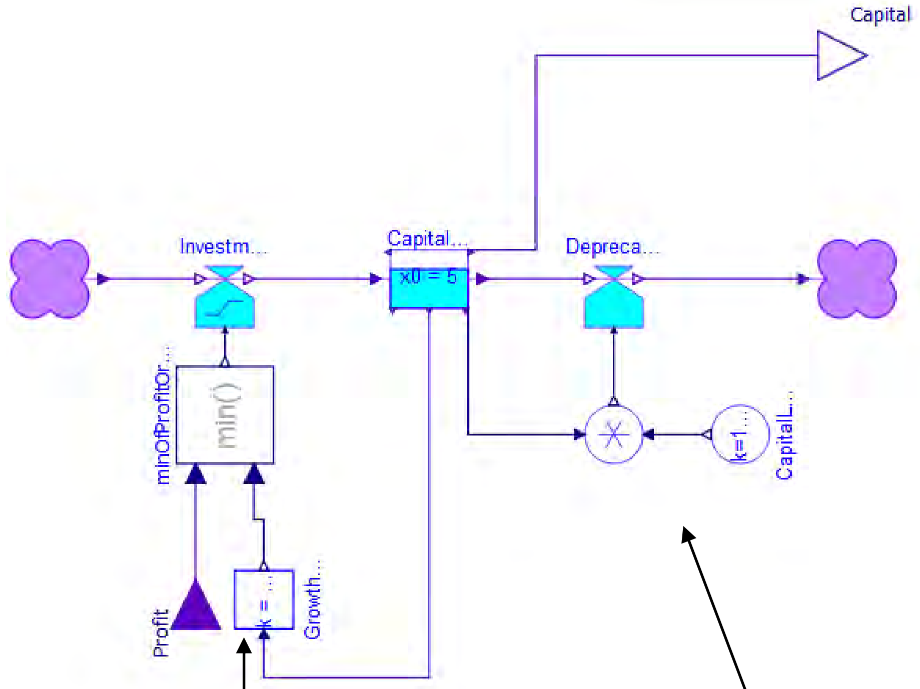
- SystemDynamics.Rates.CInflow
- Minimal flow = 0

Harvest rate

- SystemDynamics.Rates.Coutflow
- Controlled outflow element
- Minimal outflow = 0

- Input
  - Capital, the amount of capital invested by the company
- Outputs
  - The yield per unit capital
  - The harvest, e.g fish extracted from the lake

The Company model



Capital Stock

- SystemDynamics.Levels.Level
- Initial stock = 5

Investment rate

- SystemDynamics.Rates.Rrate
- Minimal flow = 0

Deprecation of Capital

- SystemDynamics.Rates.Rate_1
- Unrestricted rate element with one influencing variable
- Minimal outflow = inf

- Input
  - Profit, the profit the company is currently generating from its fishing endevours.
- Outputs
  - Capital, capital to invest into new activities

Growth goal

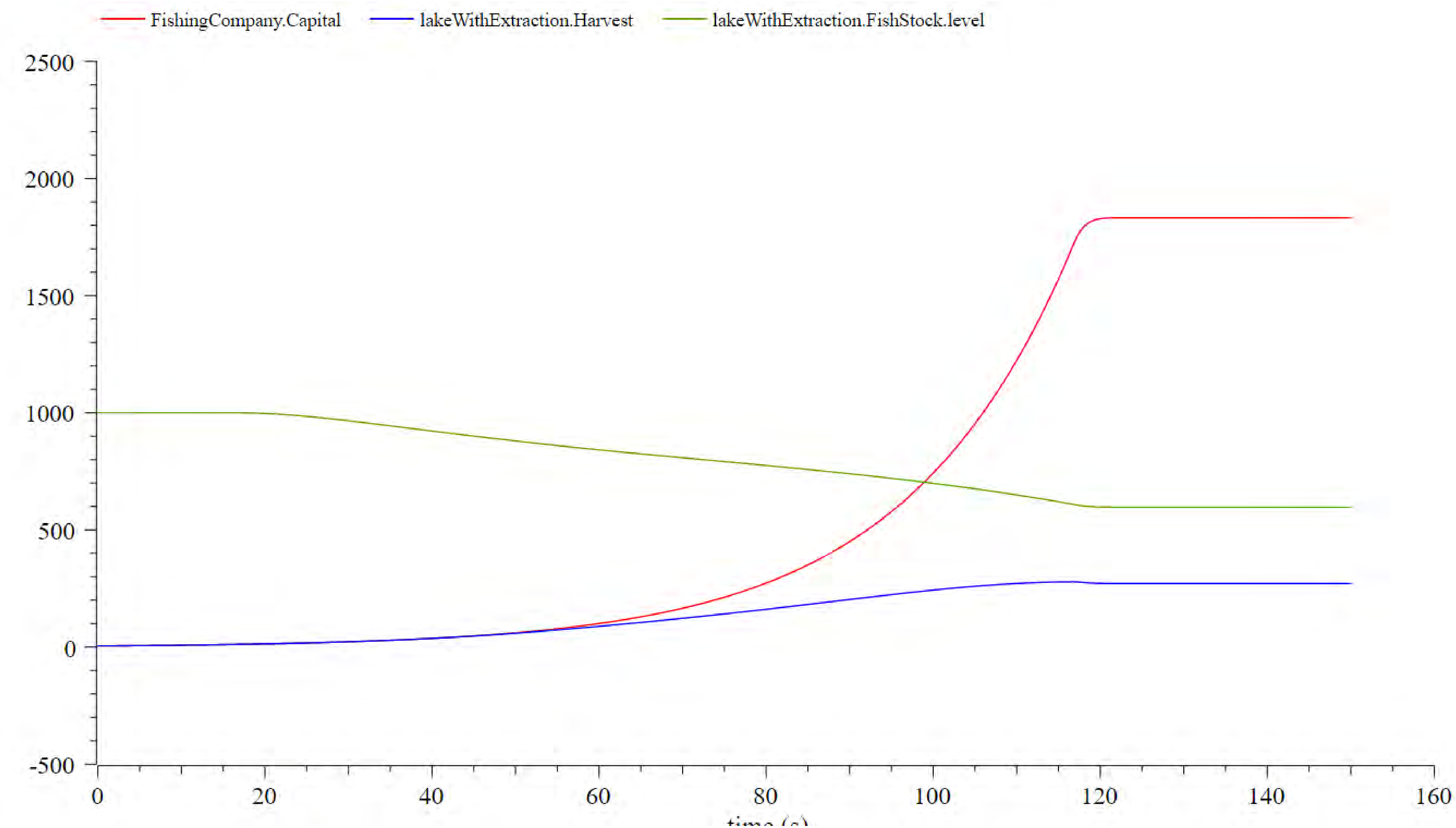
- Representation how the company plans for the future.

Capital lifetime

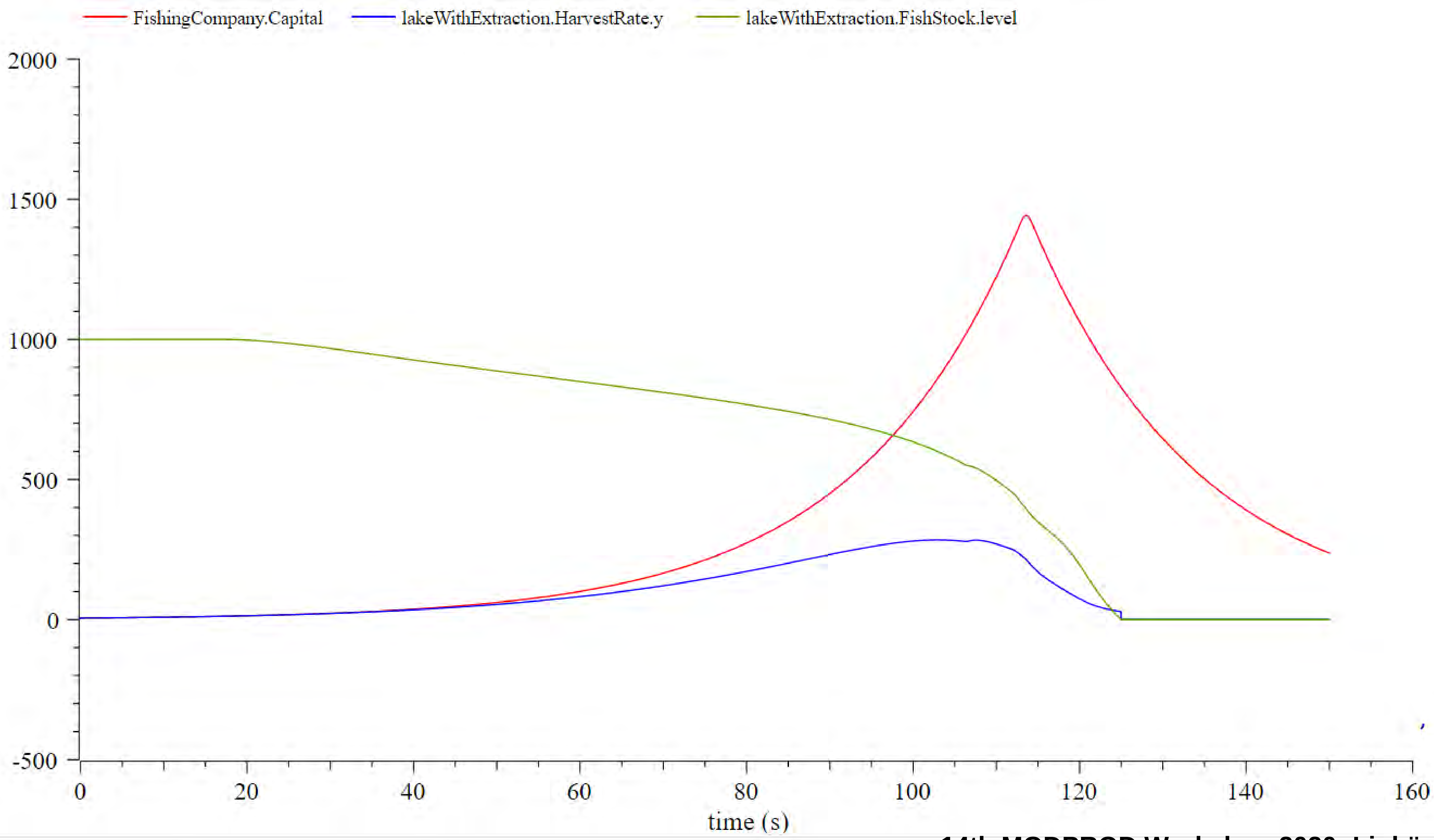
- Lifetime of capital, used to model deprecation

DEMO

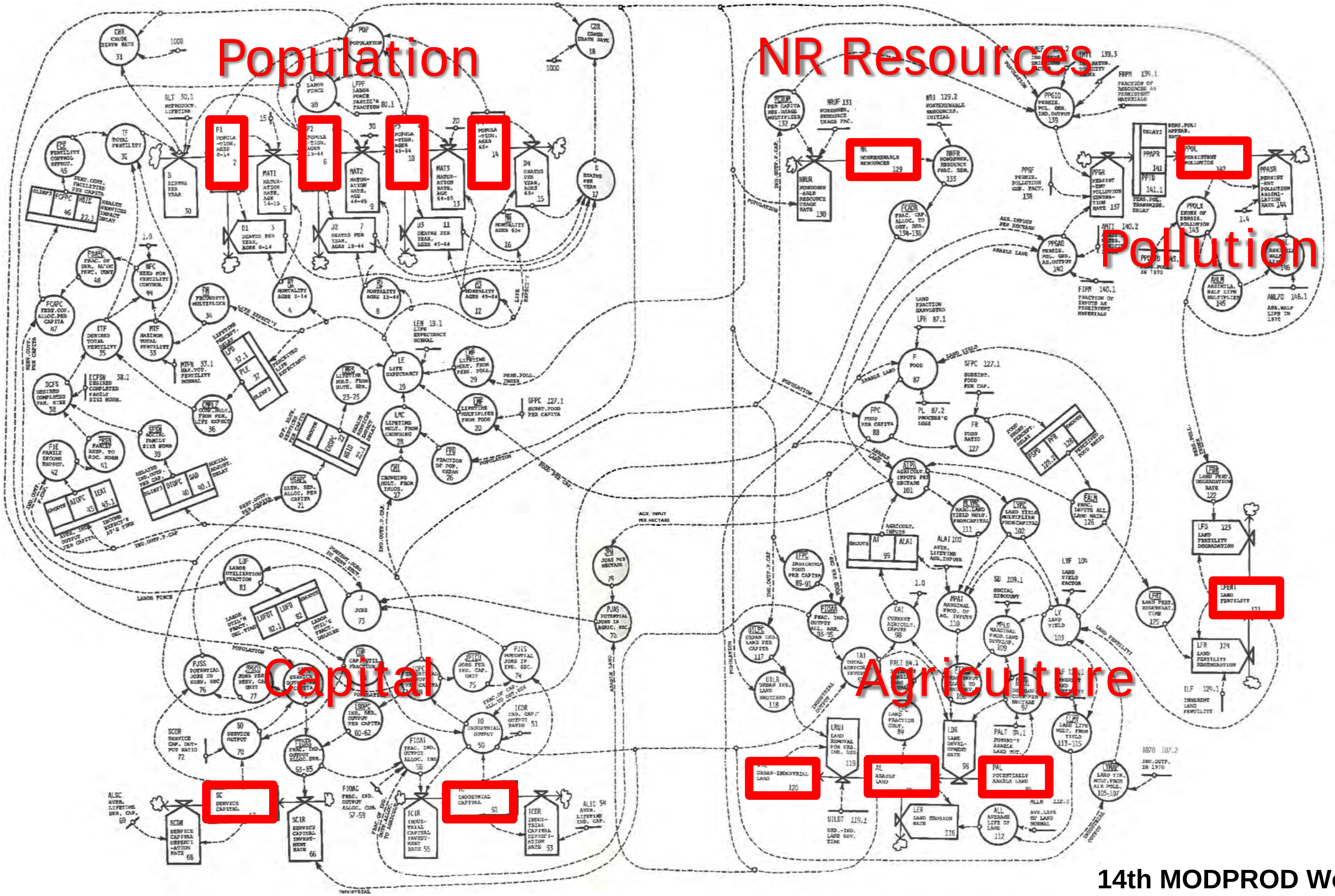
Fishing Scenario 1 - Letting the system balance itself, stable fish stock



Fishing Scenario 2 - Maximizing short-term profit leads to collapse of fish population



A Complex World Model with System Dynamics: World3



Conclusions

- Based on the Modelica ecosystem of technologies, we can leverage the pre-existing knowledge base of System Dynamics to cope with the requirements of the next generation of global models
- System dynamics was introduced as a methodology that allows us to formulate and capture partial knowledge about any soft-science application, knowledge that can be refined as more information becomes available
- Systems dynamics is the most widely used modeling methodology in all soft sciences. Tens of thousands of scientists have embraced and used this methodology in their modeling endeavors