Lecture 03
Systems Thinking 2

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CIVIL 534: Computational systems thinking for sustainable engineering

5 March 2025

Housekeeping

- **Assignment 1: updates to part 3!**
- Course project: Milestone 1 document posted to Moodle

Outline

- **Course project introduction**
- Predator-prey example and simulation details
- Delays
- Multi stock system example
- How to assess model dynamics
  - Varying parameters and understanding impacts

Course project - logistics

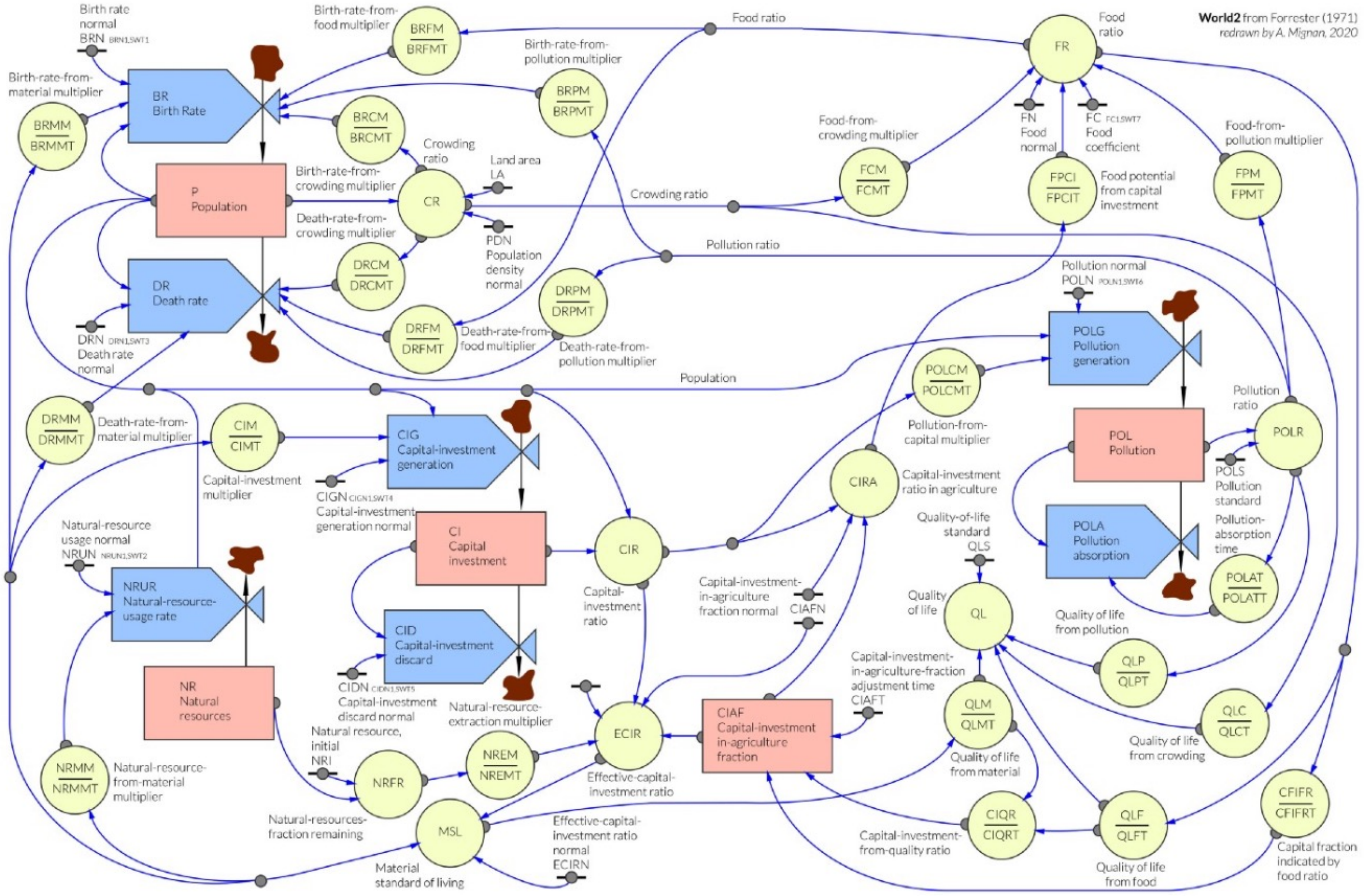
- 2 Milestones
  - Milestone 1 due April 04
  - Focuses on system characterization and sustainable policy development
  - More information on Moodle and course information sheet
- Form groups of 3 or 4
  - Propose group by Friday - if I don’t hear from you, I will assign groups
  - Email both Prof. Sonta and Vasantha

Course project - content

- We will work with the World2 and World3 models
  - The `world2` model was developed by Jay Forrester and presented in his book *World Dynamics*.
  - The `world3` model was developed by Dennis Meadows and a large team of collaborators. The results were presented in the book *The Limits to Growth* and the model was published in the book *Dynamics of Growth in a Finite World*.
- Both models can be installed with python packages
- They model the same thing with different complexity
- Milestone 1 works with World2

Model	Stocks	Flows	Variables	Total connections
world2	5	8	82	121
world3	15	23	156	336

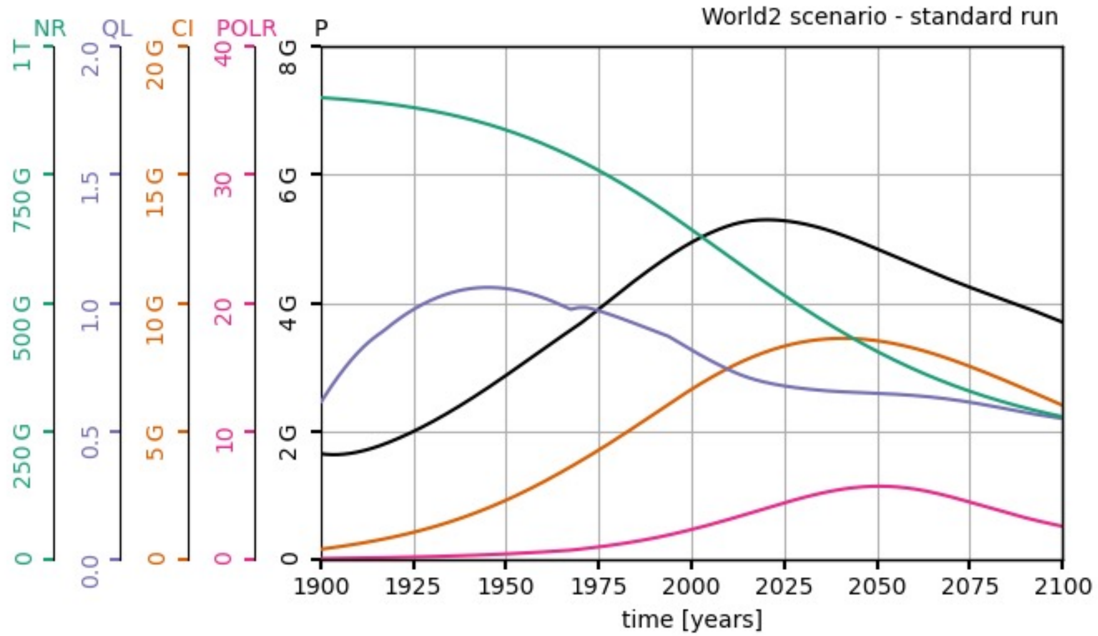
World2


World2 from Forrester (1971)
redrawn by A. Mignan, 2020
Birth rate
normal
BRN BRN1,SWT1
Birth-rate-from-
material multiplier
BRMM
BRMMT
BR
Birth Rate
Birth-rate-from-
food multiplier
BRFM
BRFMT
Birth-rate-from-
pollution multiplier
BRPM
BRPMT
BRCM
BRCMT
Food ratio
FR
Food
ratio
FN
Food
normal
FC FC1,SWT7
Food
coefficient
Food-from-
crowding multiplier
FCM
FCMT
FPCI
FPCIT
Food potential
from capital
investment
Food-from-
pollution multiplier
FPM
FPMT
P
Population
Birth-rate-from-
crowding multiplier
Crowding
ratio
CR
Land area
LA
Crowding ratio
Death-rate-from-
crowding multiplier
PDN
Population
density
normal
Pollution ratio
DR
Death rate
DRCM
DRCMT
DRFM
DRFMT
Death-rate-from-
food multiplier
DRPM
DRPMT
Death-rate-from-
pollution multiplier
DRN DRN1,SWT3
Death rate
normal
Pollution normal
POLN POLN1,SWT6
POLG
Pollution
generation
POLCM
POLCMT
Population
Pollution-from-
capital multiplier
Pollution
ratio
POLR
DRMM
DRMMT
Death-rate-from-
material multiplier
CIM
CIMT
Capital-investment
multiplier
CIG
Capital-investment
generation
CIGN CIGN1,SWT4
Capital-investment
generation normal
POL
Pollution
POLS
Pollution
standard
Pollution-
absorption
time
CIRA
Capital-investment
ratio in agriculture
Quality-of-life
standard
QLS
Natural-resource
usage normal
NRUN NRUN1,SWT2
NRUR
Natural-resource-
usage rate
CI
Capital
investment
CIR
Capital-
investment
ratio
Capital-investment-
in-agriculture
fraction normal
CIAFN
POLA
Pollution
absorption
POLAT
POLATT
Quality
of life
QL
Quality of life
from pollution
CID
Capital-investment
discard
CIDN CIDN1,SWT5
Capital-investment
discard normal
Natural-resource-
extraction multiplier
NR
Natural
resources
Natural resource,
initial
NRI
ECIR
CIAF
Capital-investment
in-agriculture
fraction
Capital-investment-
in-agriculture-fraction
adjustment time
CIAFT
QLM
QLMT
QLP
QLPT
QLC
QLCT
Quality of life
from material
Quality of life
from crowding
NRMM
NRMMT
Natural-resource-
from-material
multiplier
NRFR
NREM
NREMT
Effective-capital-
investment ratio
Natural-resources-
fraction remaining
MSL
Material
standard of living
Effective-capital-
investment ratio
normal
ECIRN
Capital-investment-
from-quality ratio
CIQR
CIQRT
QLF
QLFT
Quality of life
from food
CFIFR
CFIFRT
Capital fraction
indicated by
food ratio

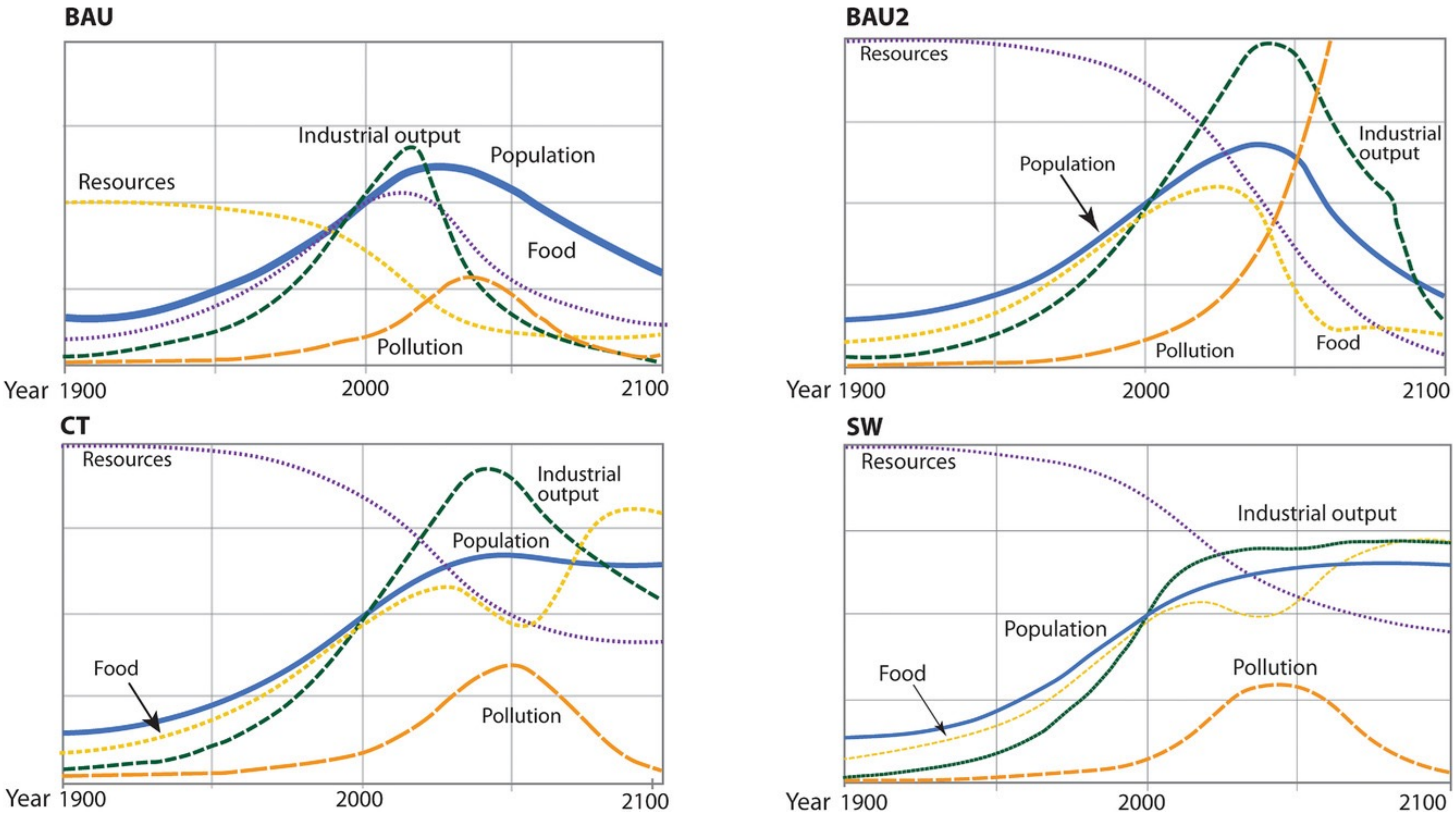
What are the world2 and world3 models?

- Primarily focuses on the following stocks:
  - Population
  - Natural resources
  - Capital investment
  - Pollution
- Defines a key variable of interest:
  - Quality of life
- Seeks to model feedback loops and dynamics among these different stocks at a global scale

pyworld2 “standard run”

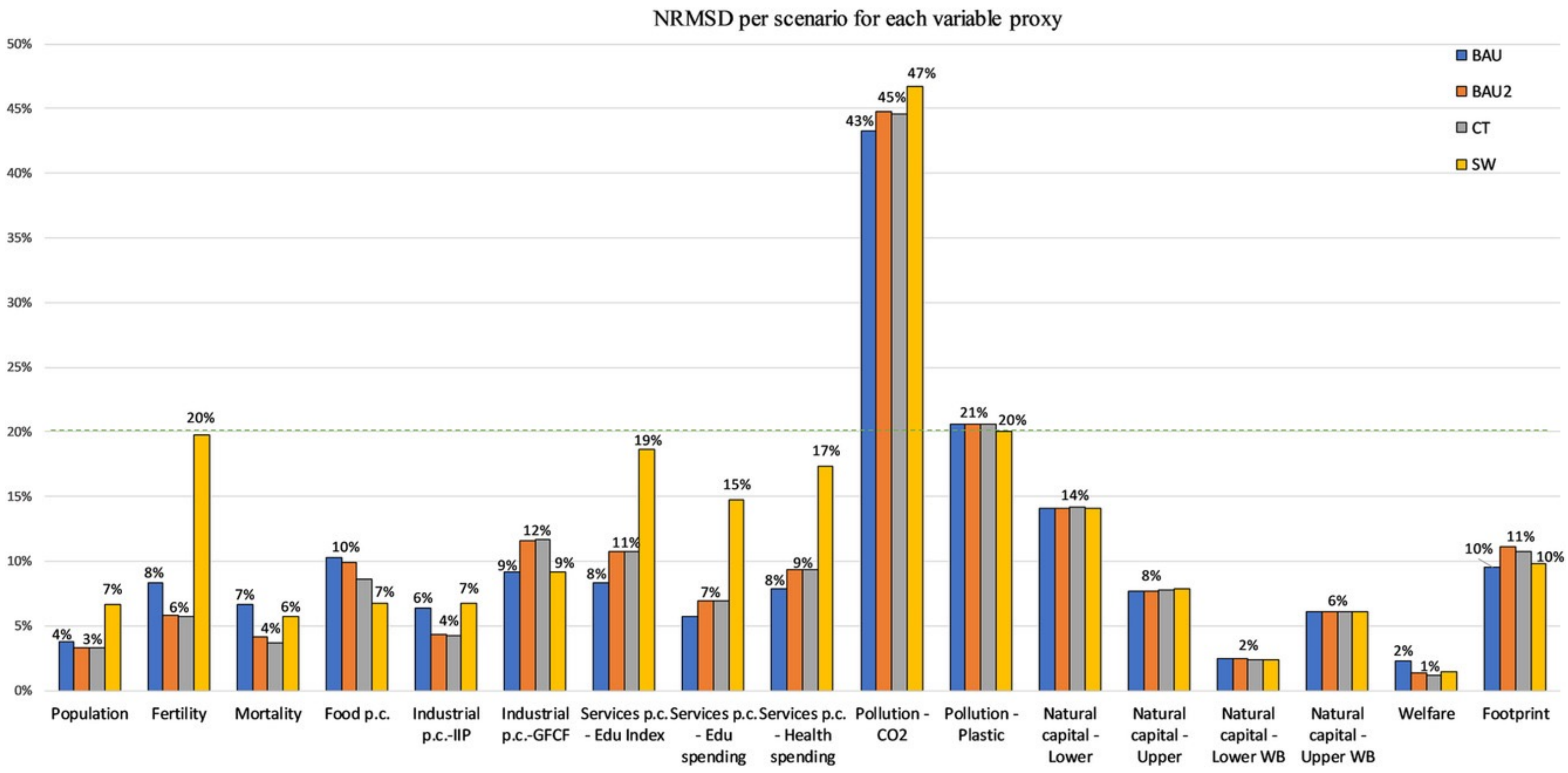


Different scenarios of world3

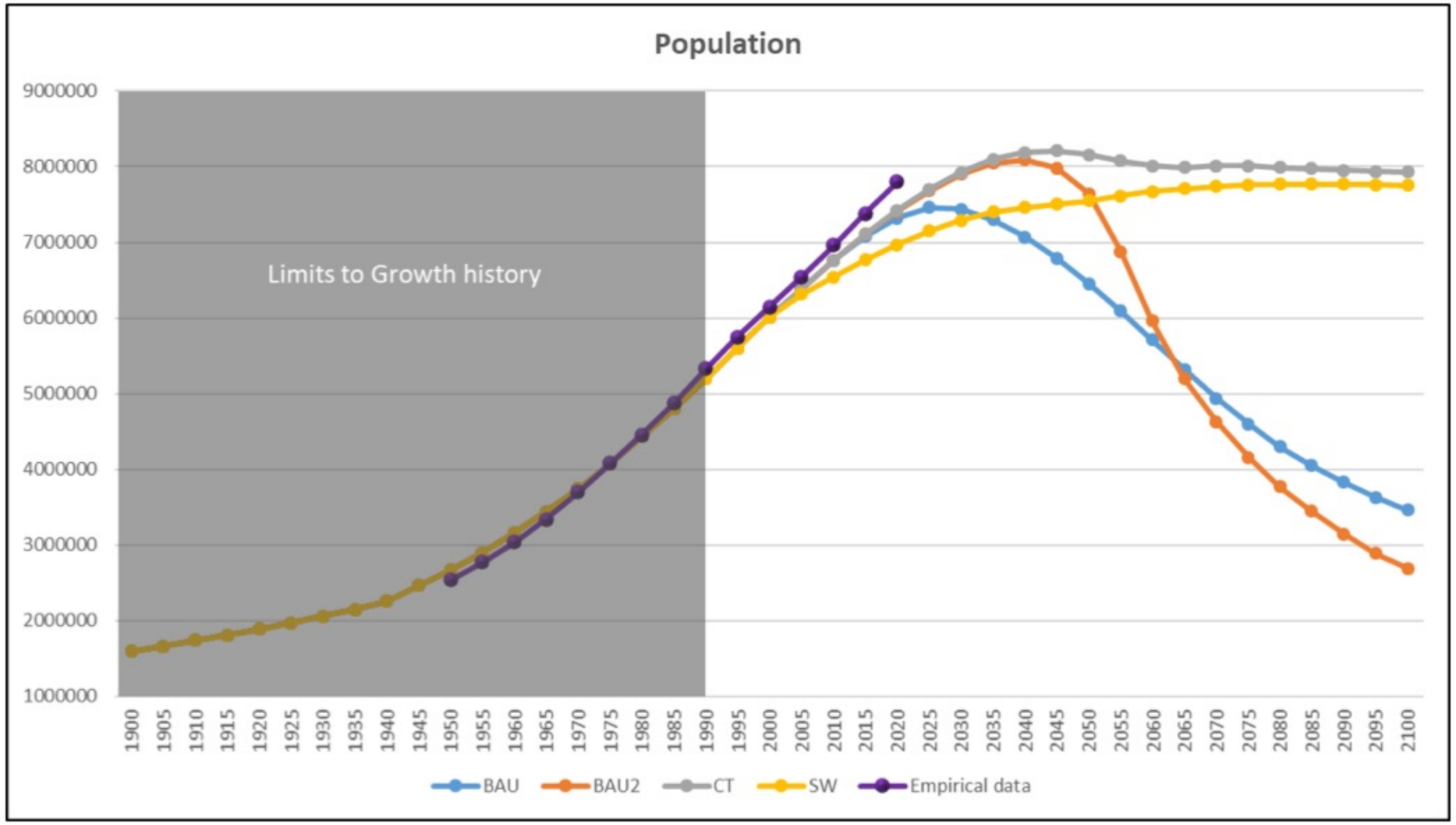


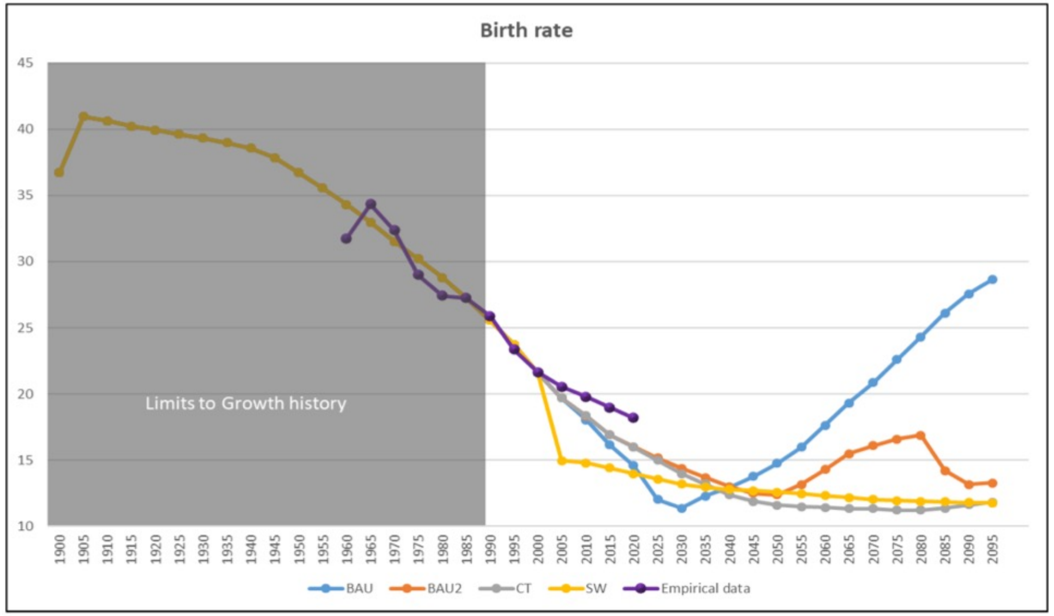
Herrington G. Update to limits to growth: Comparing the world3 model with empirical data. *J Ind Ecol*. 2021; 25: 614–626. https://doi.org/10.1111/jiec.13084

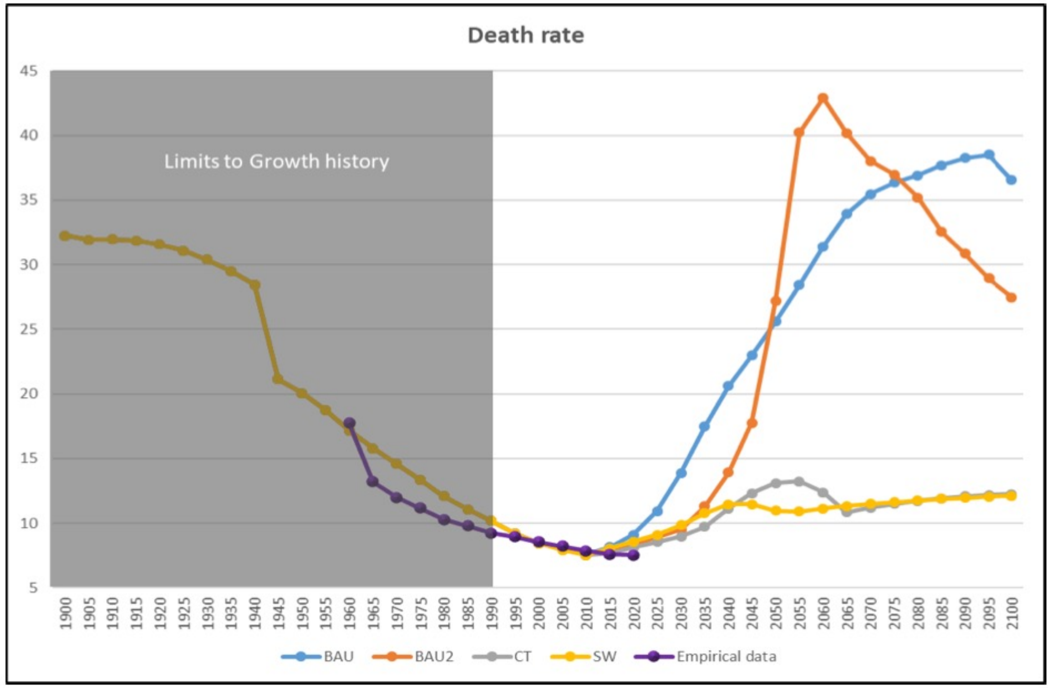
Accuracy of world3

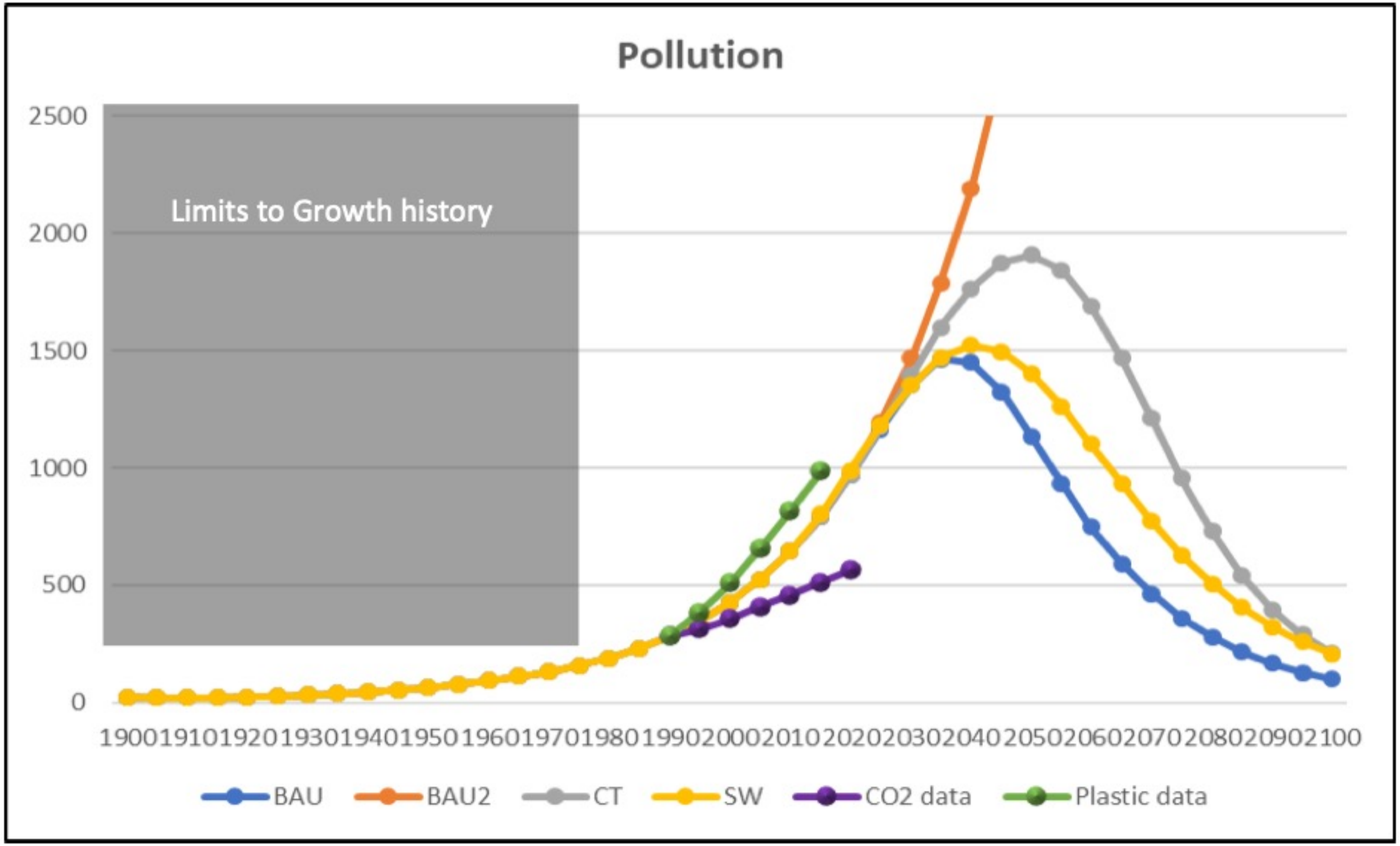


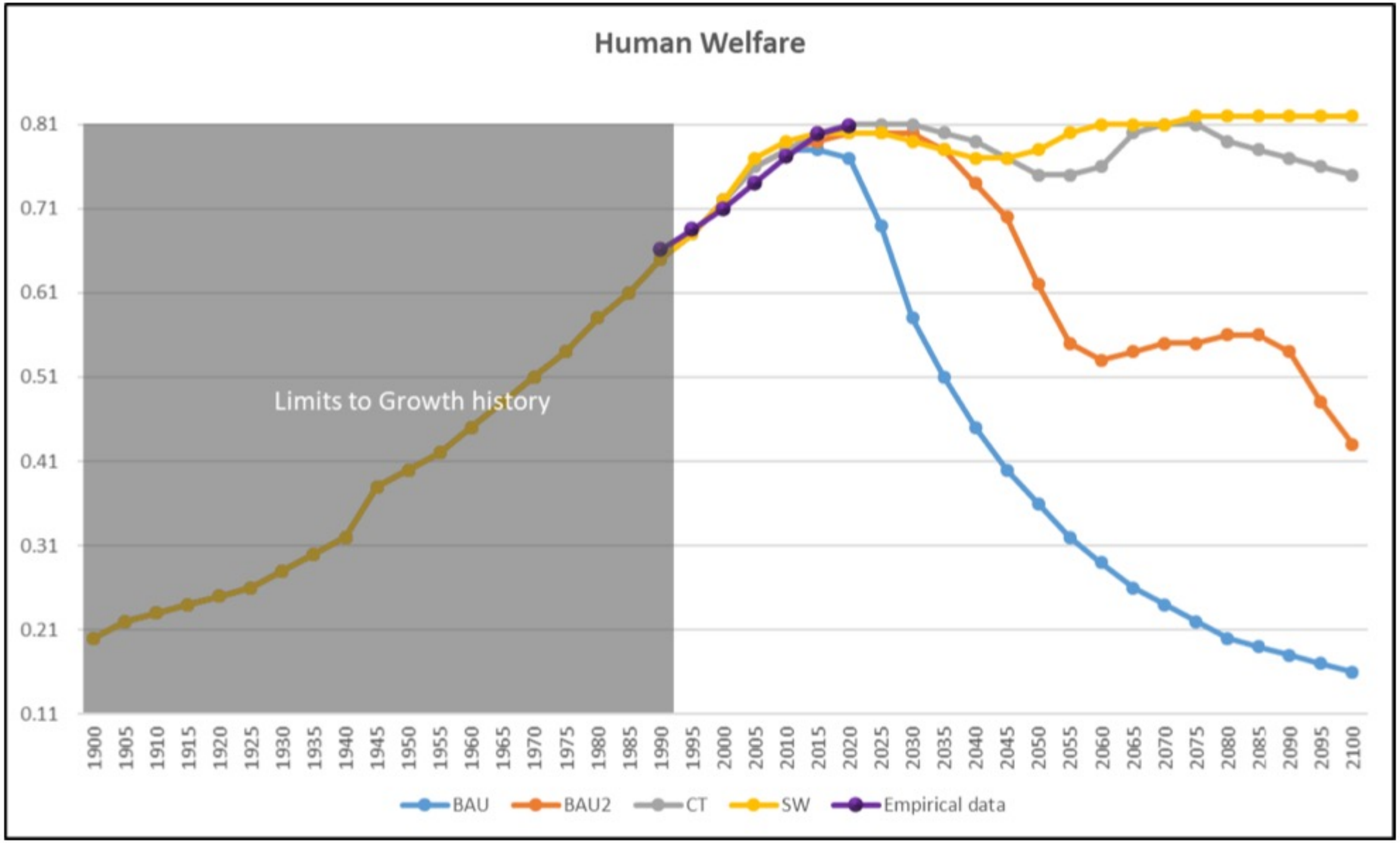
Herrington G. Update to limits to growth: Comparing the world3 model with empirical data. *J Ind Ecol*. 2021; 25: 614–626. https://doi.org/10.1111/jiec.13084


Population
Limits to Growth history
9000000
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
1900 1905 1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
BAU
BAU2
CT
SW
Empirical data


Birth rate
Limits to Growth history
45
40
35
30
25
20
15
10
BAU
BAU2
CT
SW
Empirical data


Death rate
Limits to Growth history
45
40
35
30
25
20
15
10
5
BAU
BAU2
CT
SW
Empirical data


Pollution
Limits to Growth history
2500
2000
1500
1000
500
0
1900191019201930194019501960197019801990200020102020203020402050206020702080209021 00
BAU
BAU2
CT
SW
CO2 data
Plastic data


Human Welfare
0.81
0.71
0.61
0.51
0.41
0.31
0.21
0.11
Limits to Growth history
1900 1905 1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
BAU
BAU2
CT
SW
Empirical data

Your task in Milestone 1

- Become familiar with the model
- Understand how different parameters can be varied
- Characterize the impact of different parameters
- Use Python computing tools to automate a process for finding a sustainable development policy
- Deliverable: written narrative (8 pages, including figures)
    - More details in “Milestone 1” document

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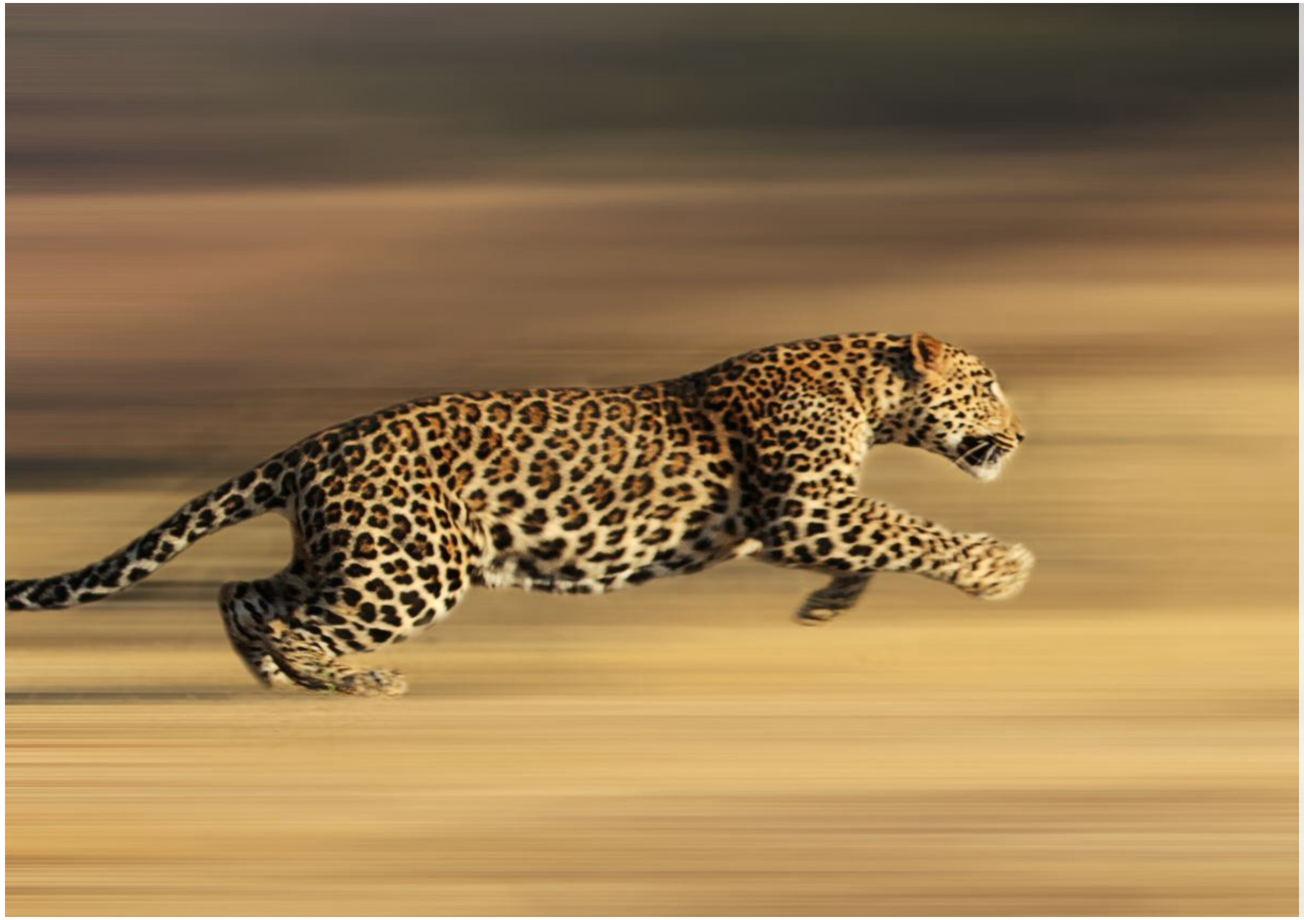
Your turn
Predator-prey cycle

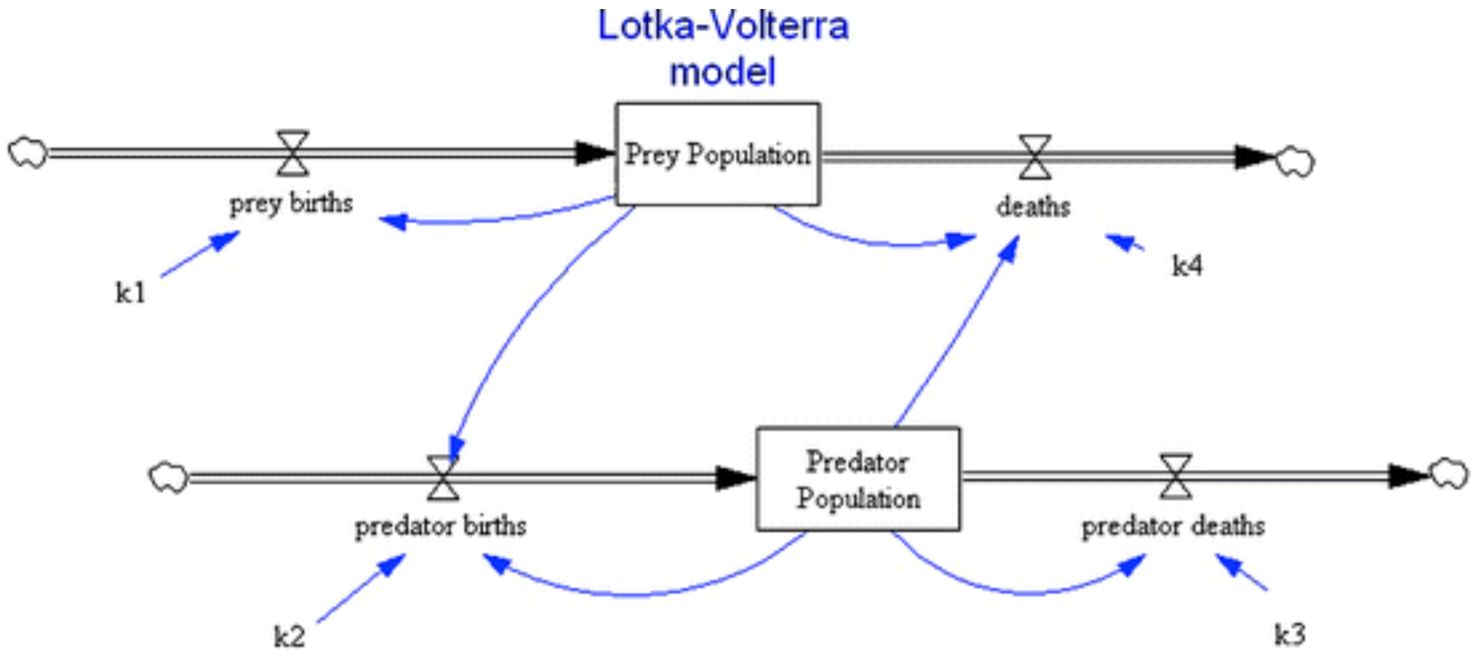


Stocks:
- Number of predators
- Number of prey

Feedback loops:
- 4 simple
- 1 complex

Also known as the Lotka-Volterra model

- This is a standard system of coupled differential equations

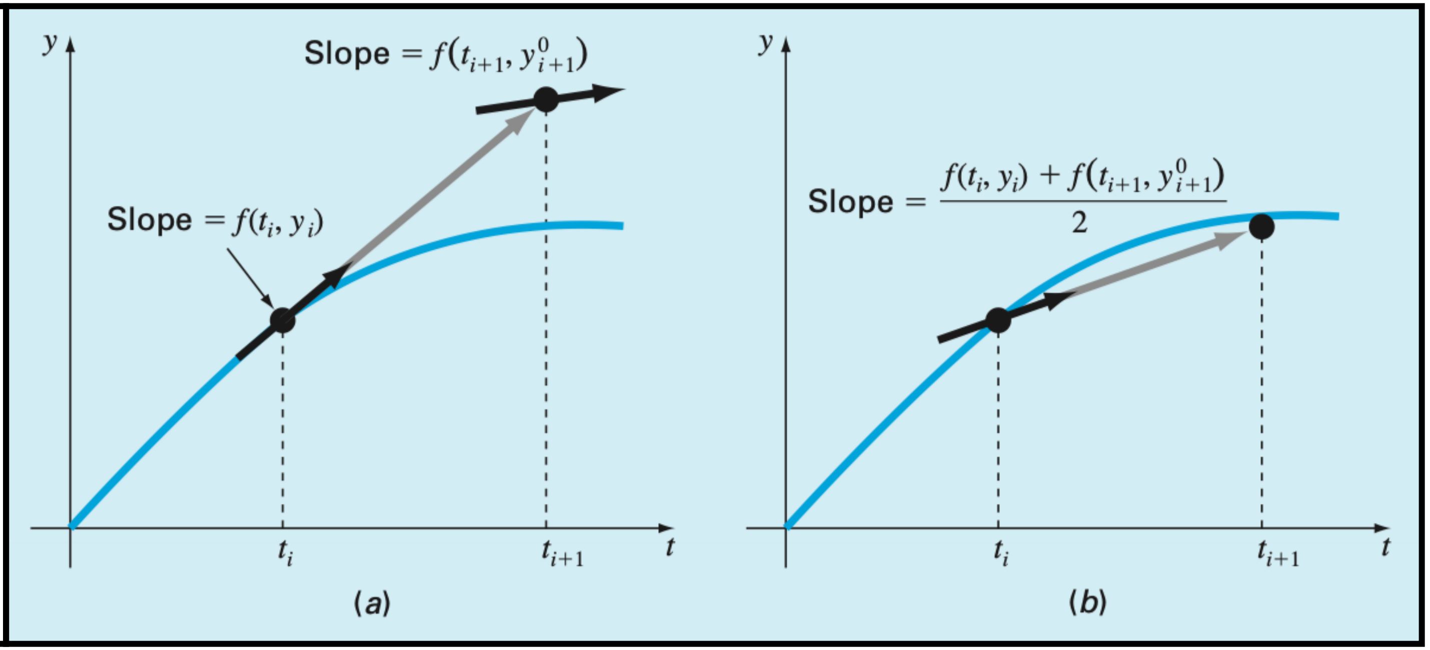


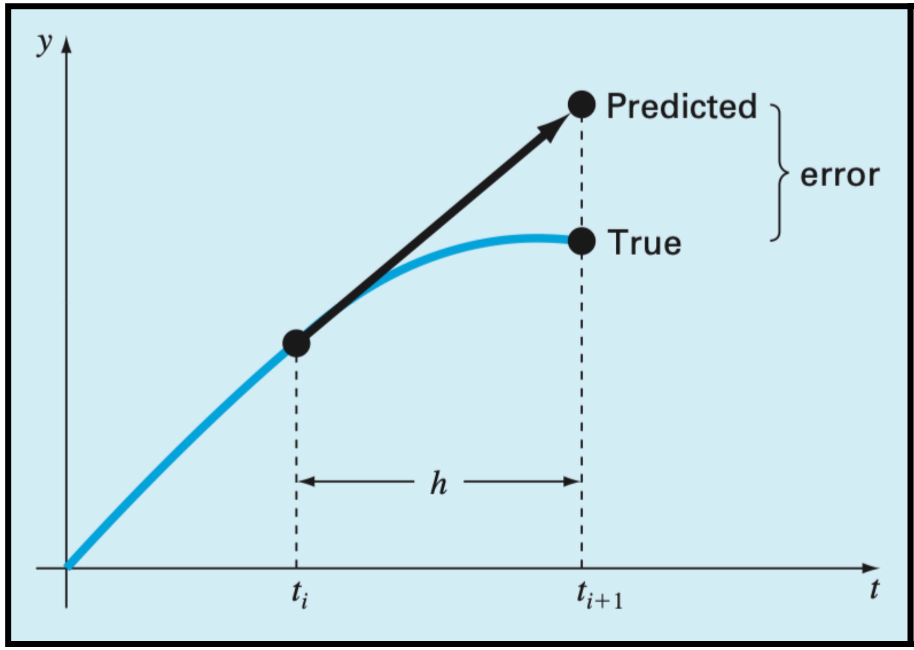
Solving coupled differential equations

- When systems are complex (multiple stocks and multiple feedback loops), we cannot solve these systems analytically
- In this class, the stepwise calculations we have implemented is the "Euler method"
- More complex numerical procedures exist, e.g.
  - Runge-Kutta Methods (RK)
  - Adaptive step-size methods
  - These are outside the scope of this class

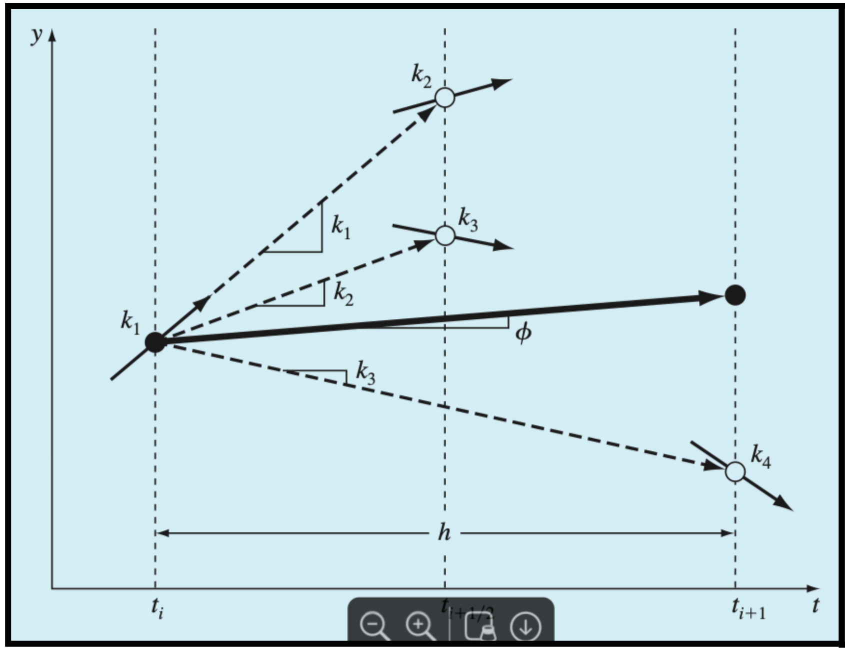
Method illustrations

Second-order Runge-Kutta method





Euler's method



Fourth-order Runge-Kutta method

Chapra, S. C. *Applied Numerical Methods with MATLAB for Engineers and Scientists*

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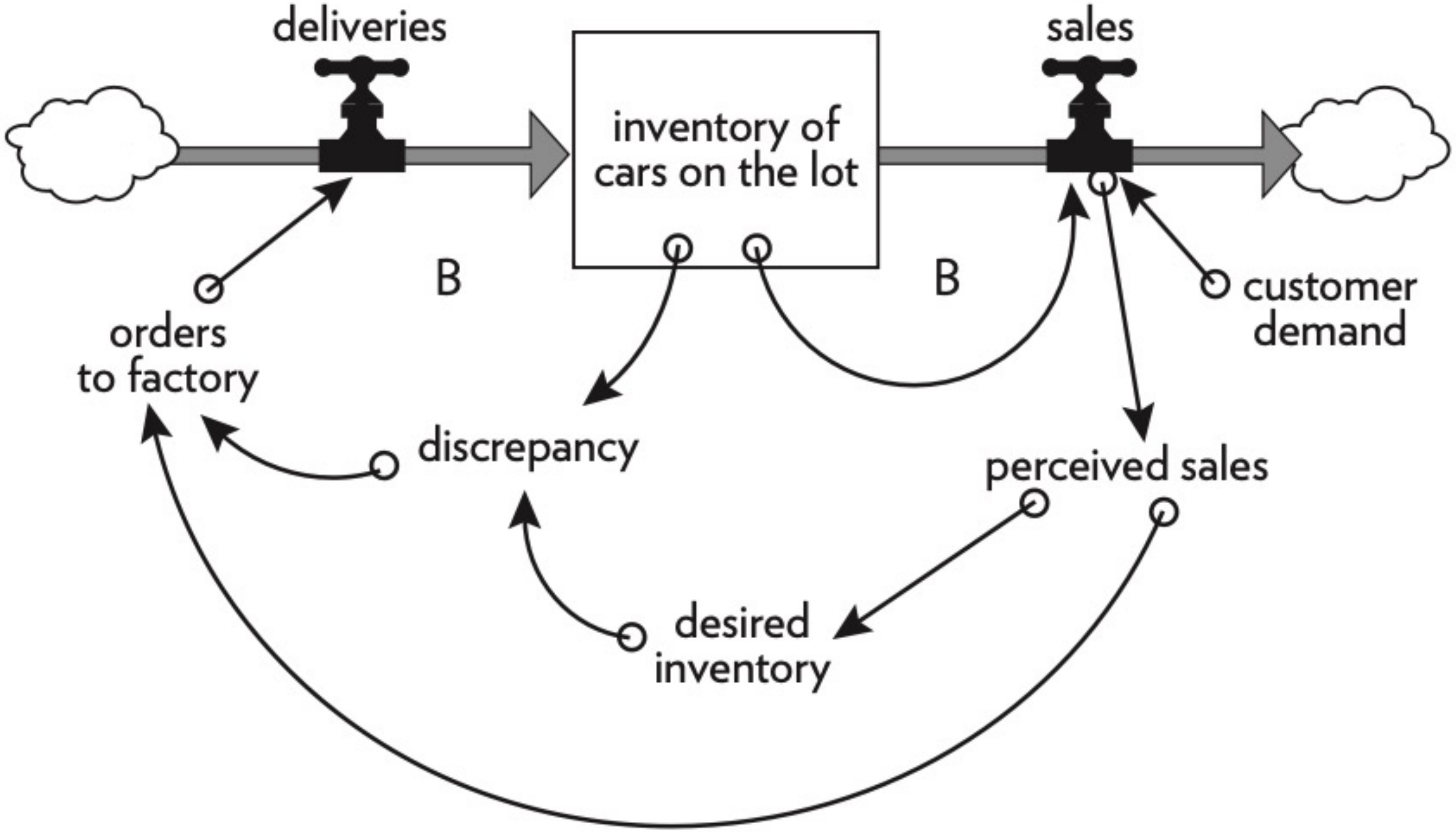
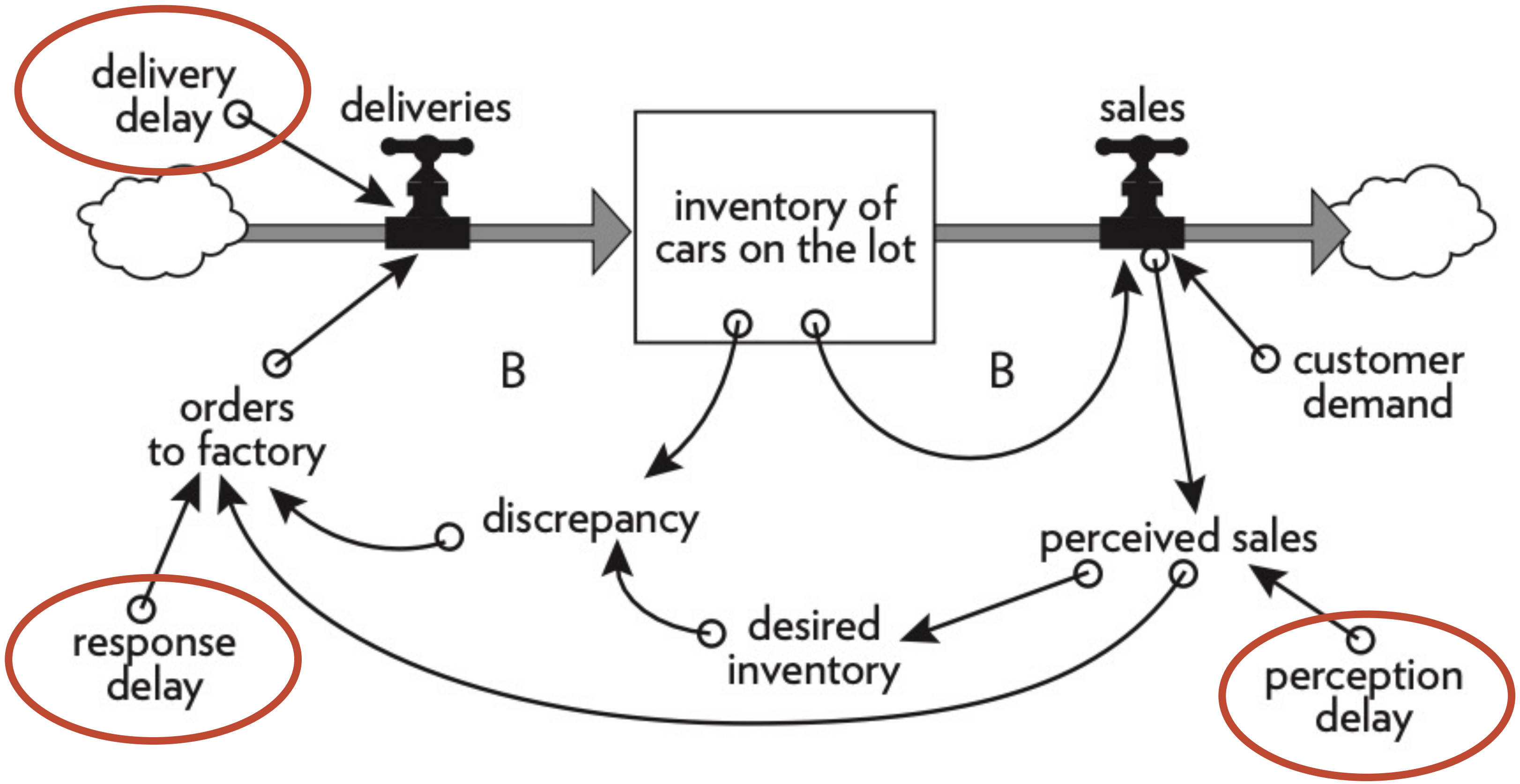
Car dealership system



Delays in systems

- Real systems have delays
- **Perception delay**: information about changes to the system take time to measure/perceive
- **Response delay**: system does not correct itself in a single iteration
- **Delivery delay**: It takes time for corrective measures to be implemented

Car dealership delays



Delays in urban systems

- Do you have to be smart if you are fast?
- “The engineering approach conveniently bypasses the complexities that always arise in these systems at longer temporal or larger spatial scales, such as the need to develop models of human behavior**. In this way, a difficult and important problem can be solved essentially without theory; this is the (potential) miracle of big data in cities**.”
- But “it has remained difficult to create engineering solutions to problems of education, public housing, economic development, poverty, or sustainability at the city level.”

TABLE 1. URBAN ISSUES, THEIR TEMPORAL AND SPATIAL SCALES, AND THE CHARACTER OF THEIR ASSOCIATED METRICS

Problem	*Timescale*	*Spatial scale*	*Outcome metric*
Transportation (buses, subway)	Minutes	Meters	Simple
Fire	Minutes	Meters	Simple
Epidemics (HIV, influenza)	Years, days	Citywide	Simple
Chronic diseases	Decades	Citywide	Simple
Sanitation	Years	Citywide	Simple
Crime	Minutes	Meters	Simple
Infrastructure (roads, pipes, cables)	Days	Meters	Simple
Traffic	Minutes	Meters to km	Simple
Trash collection	Days	Meters	Simple
Education	Decades	Citywide	Complex
Economic development	Decades	Citywide	Complex
Employment	Years	Citywide	Complex
Poverty	Decades	Neighborhood	Complex
Energy and sustainability	Years	Citywide	Complex
Public housing	Years to decades	Neighborhood	Complex

Luís M.A. Bettencourt. The Uses of Big Data in Cities. Big Data. Mar 2014. 12-22.

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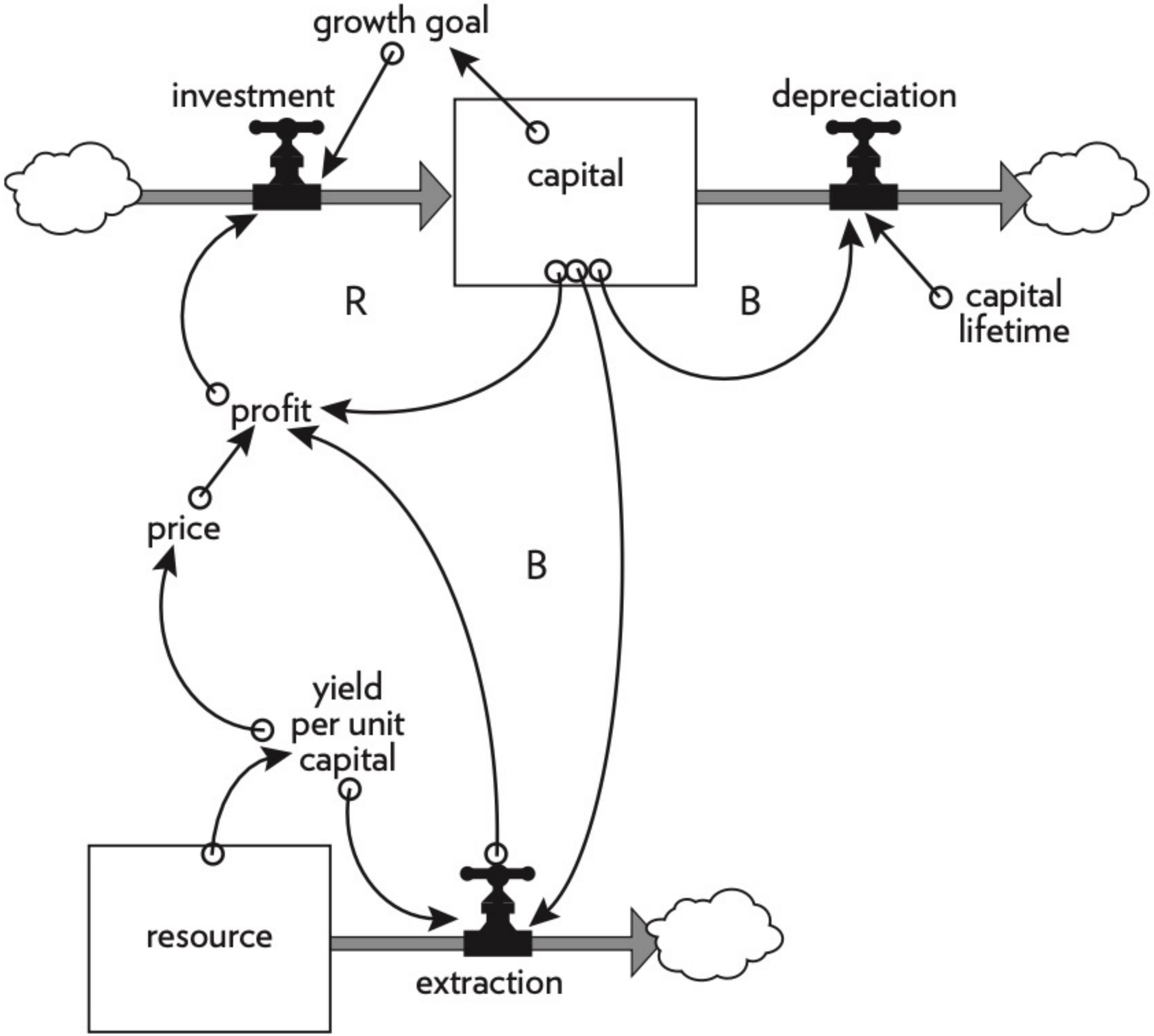
Multi-stock system

- Connecting internal system behavior (e.g., population, heat pump in a house) to its surroundings
- “Limits to growth” archetype
- Example 1: population growth constrained by natural resources
- Example 2: nonrenewable resource and business capital (think oil company)

Example 1: Population growth constrained by natural resources

- Stock 1: population
- Stock 2: natural resources
- Multiple feedback loops
- How to model?
- Systems thinking models are systems of coupled differential equations
  - Simple models can be solved analytically
  - As we add more stocks and flows, it is more likely that we will need numerical simulations

Multi-stock system: Oil company



Oil company dynamics

- Stock 1: Capital (renewable)
- Stock 2: Oil (nonrenewable)
- Balancing loop: More capital stock, more machines break down (5% of stock removed each year)
- Reinforcing loop: More capital enables more resource extraction and more profits for reinvestment (10% growth goal per year)
- Net income: Price*Extraction – Capital Costs
- Extraction: Yield per Capital
- Yield: function of the amount of stock remaining (harder to harvest)

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Building the “correct” model

- Balance between details and interpretability
  - Are the driving forces likely to unfold in this way?
    e.g. what will happen to flows?
  - If they did how would the system react?
    e.g. do changes in flows really cause stocks to behave as we think?
  - What drives the driving forces?
    e.g. what affects the changes in flows?
- What is the purpose of the system analysis?
  - Are we hoping to inform policies? Prices? Design?
- The biggest power comes from asking “what if” questions!

Assessing model dynamics

- What happens when you change parameters?
- Are the parameter changes reasonable?
  - Physically
  - With respect to policies
- Which parameters have the largest impact?

Next time

- Read Meadows chapters 3 and 4
- Resilience, self-organization, hierarchy
  Structure vs. behavior