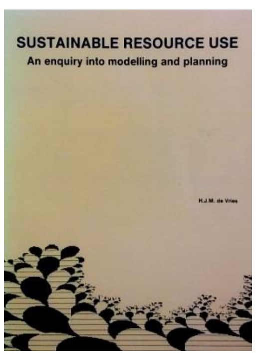
System dynamics in sustainability science
- an introduction -

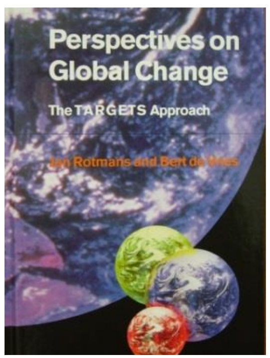
Prof. Dr. Bert de Vries
Utrecht University

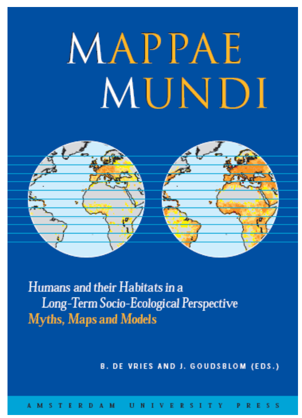
Copernicus Institute
Research Institute for Sustainable Development and Innovation

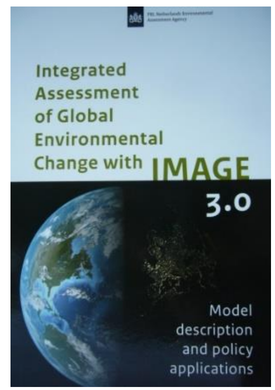
Universiteit Utrecht

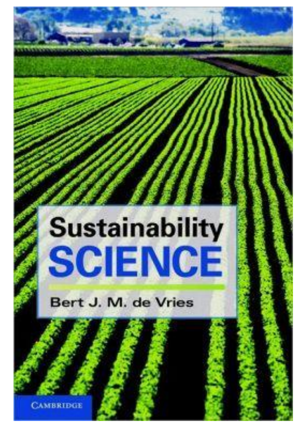
My background: natural science and philosophy, energy modelling and policy, global change and climate modelling and policy, teaching energy and sustainability science

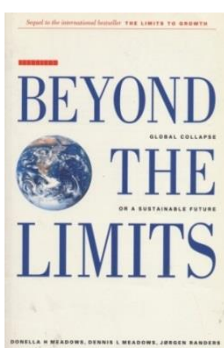


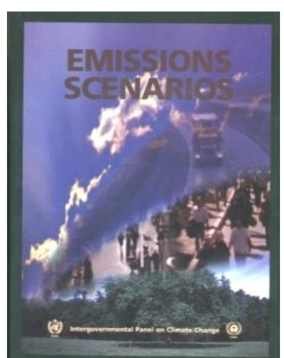








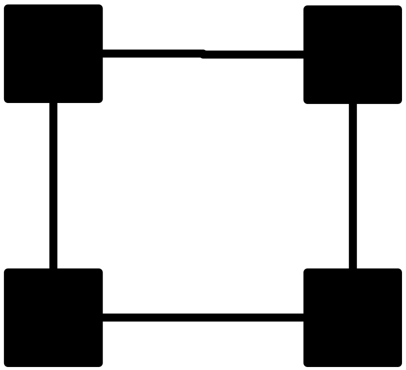


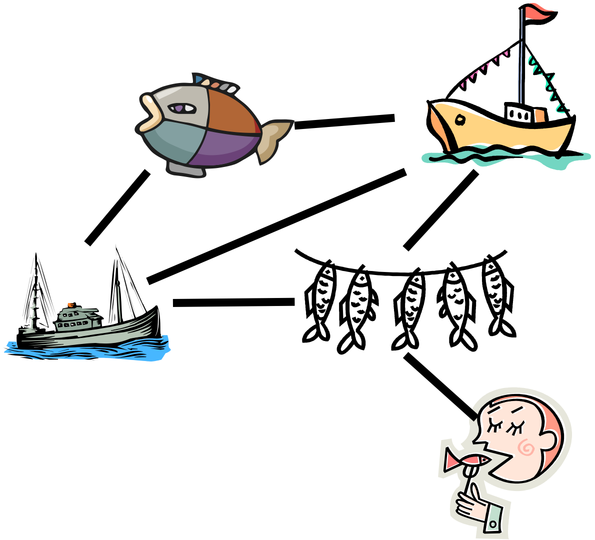


www.sustainabilityscience.eu

Strategies for sustainable development require an integrated systems approach. What is a system?

A *system* is an interconnected set of elements that is coherently organized [around some purpose].





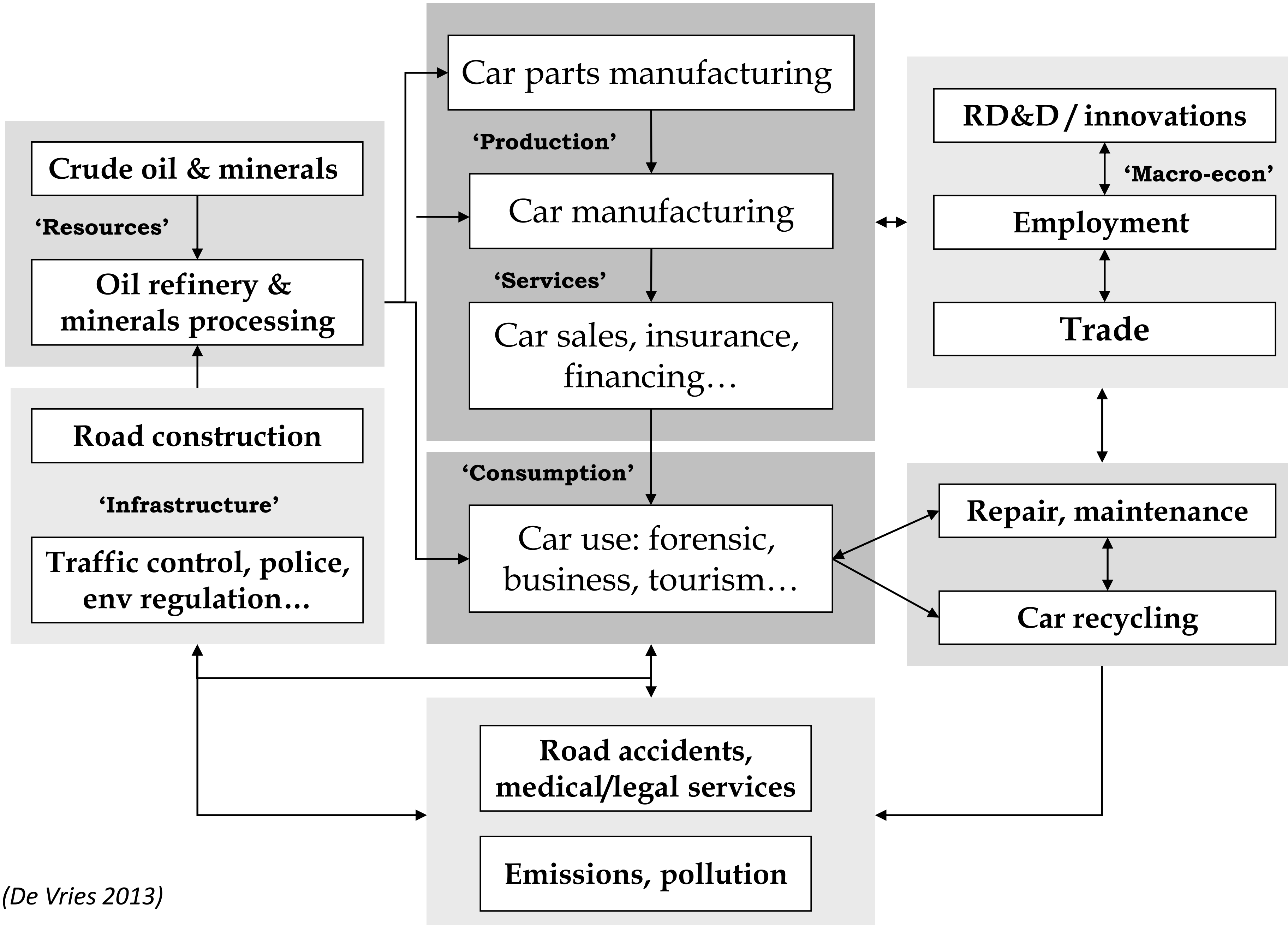
The **systems** approach is an abstract way of looking at what constitutes a part of reality (descriptive) and what determines its evolution in time (analysis, dynamics).

System dynamics (SD): Examples of systems

- a tree or wolves preying on deer, with its connected elements and the purpose to sustain their metabolism;
- a market place where vendors and buyers exchange fish, fruits and flowers according to a set of conventions and relationships;
- a football team or a school, with rules being the connections which permit to play the game or teach children;
- a house or an airplane, making up connected parts in order to provide shelter or movement.

An illustration: the (world) car system

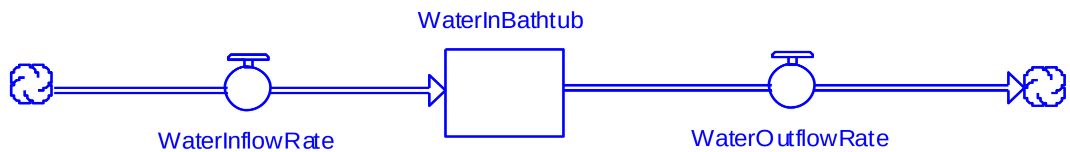
The importance of the system boundary: the car system



(De Vries 2013)

Perceiving the world in stocks and flows

(in differential-integral mathematics, it is about integrals and derivatives)



stocks...and flows

Stock variables are characterized by:

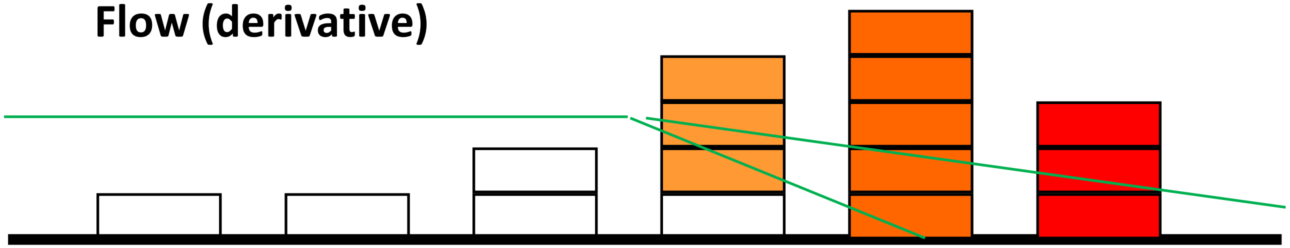
- A quantifiable size and a unit of measurement (if necessary: indexed)
- One or more particular features ('qualities')

In- and outflows are characterized by corresponding units per unit of time.

System dynamics (SD)
the difference between stocks and flows

and integrals and differentials

Flow (derivative)

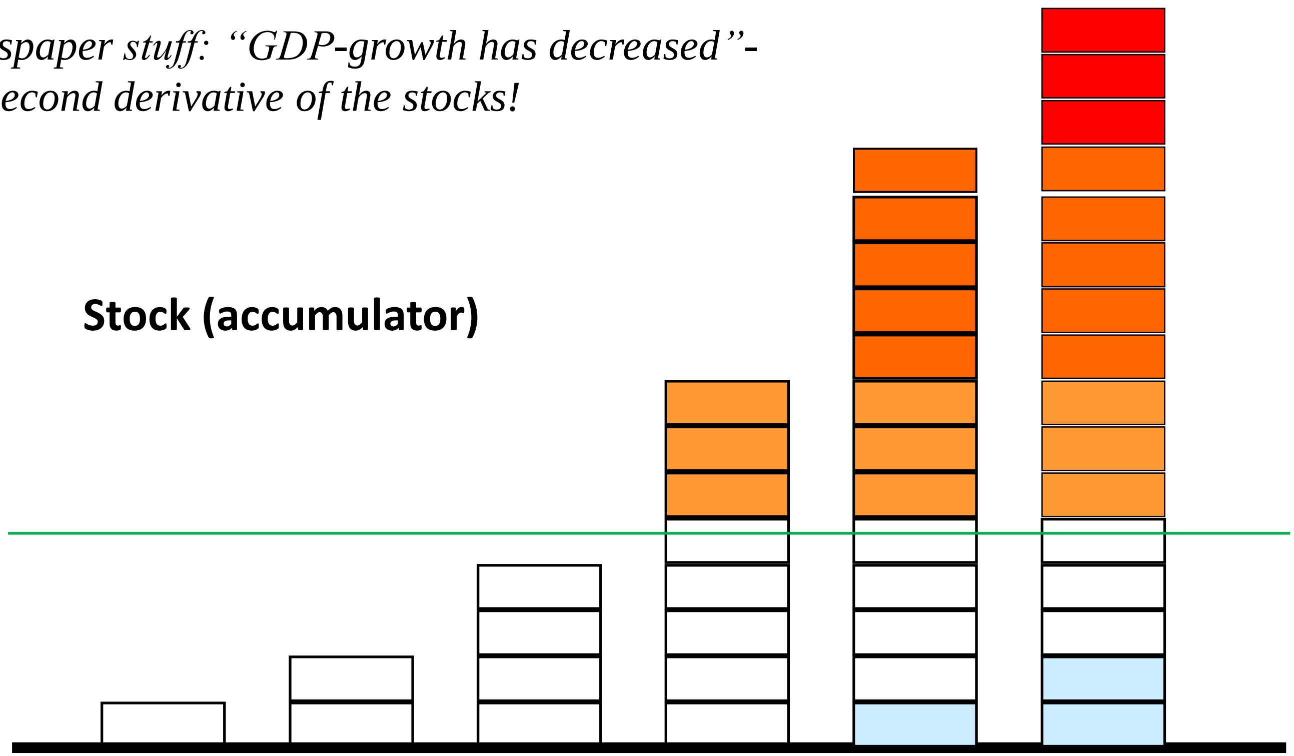


Eg.:
births
GDP
Investments
Fish catch
CO_2-emission

Units/yr

Newspaper stuff: "GDP-growth has decreased"- the second derivative of the stocks!

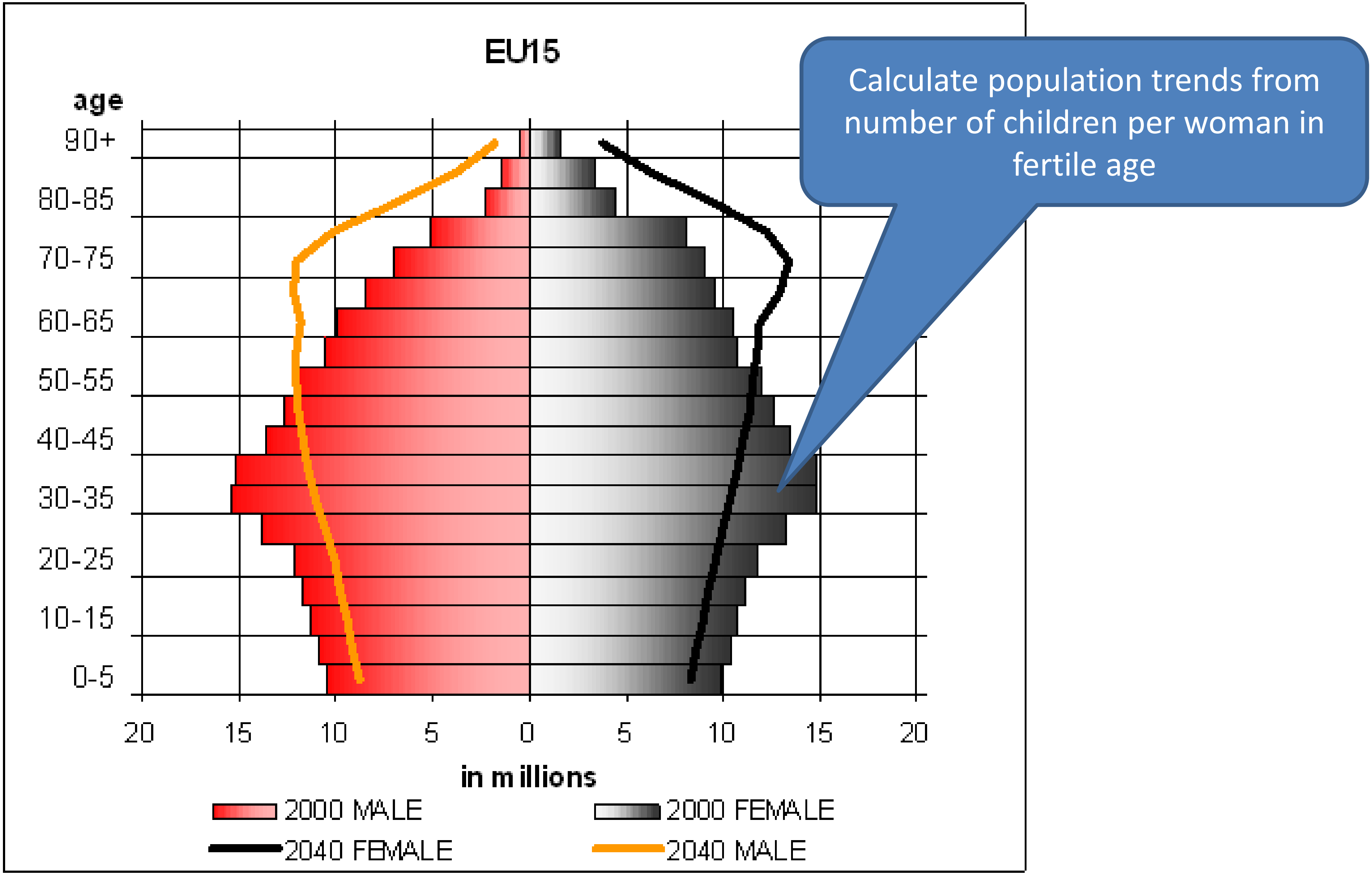
Stock (accumulator)



Eg.:
population
economic infrastr
capital stocks
fish population
CO_2-concentration

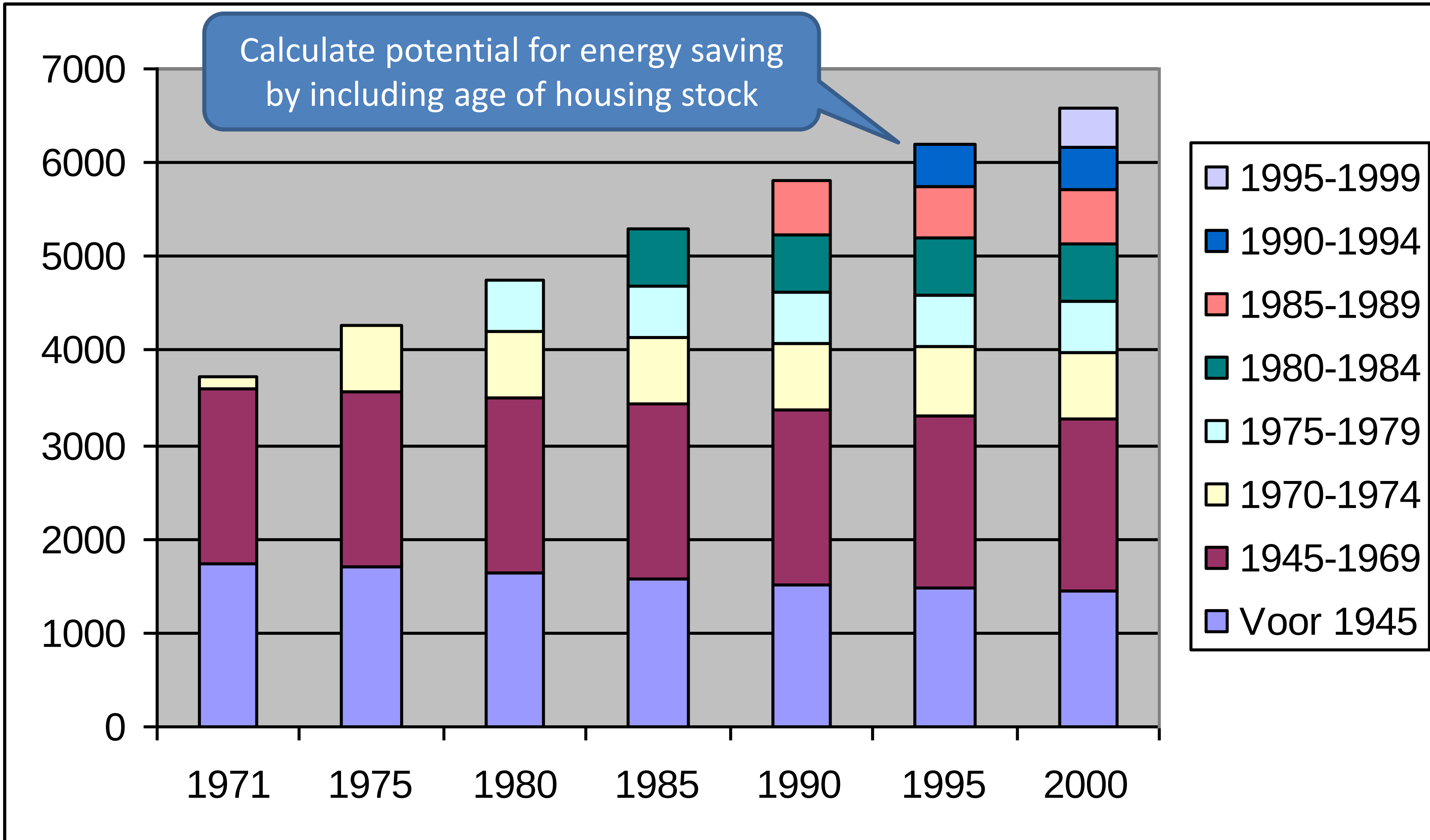
Units

Example of a stock [quality]:
Population of the EU-15 in 2000 and 2040: age and sex



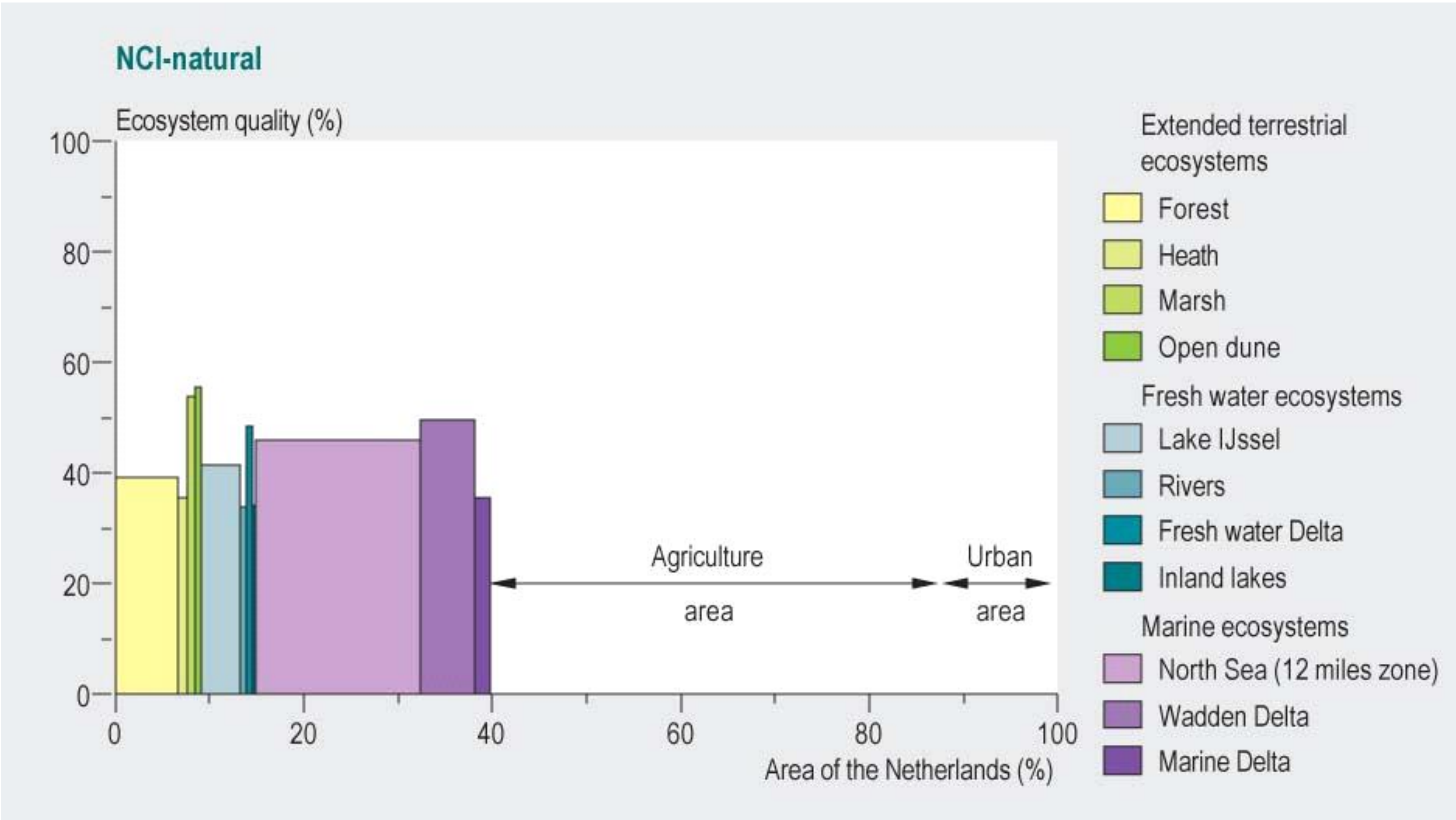
Example of a stock [quality]:

dwellings in The Netherlands in the period 1971-2000: age



Example of a stock [quality]:

Attempt to express natural capital as a stock, in numbers



Stocks and flows in various disciplines (based on: Sterman 2000:198)

Scientific discipline	*stocks*	*flows*
Mathematics and physics	**Integrals, states, state variables, stocks**	**Derivatives, rates of change, flows**
Chemistry	**Reactants and reaction products**	**Reaction rates**
Biology and physiology	**Compartments**	**Diffusion rates, flows**
Engineering	**Integrals, states, state variables, stocks (of machinery, capacity etc.)**	**Derivatives, rates of change, flows (of raw materials and products)**
Manufacturing	**Buffers, inventories**	**Throughput**
Demography	**Population**	**Birth/death and migration rate**
Medicine and epdimiology	**Prevalence, reservoirs**	**Incidence, infection, morbidity and mortality rate**
Economy	**Levels (of capital stocks etc.)**	**Rates (of production/consumption, savings, depreciation)**
Accounting	**Stocks, balance sheet items**	**Flows, cash flow or income statement items**

Modelling systems: positive and negative feedbacks, delays, causal loop diagrams (CLDs)

Why model? Epstein (JASSS 11(2008)1):

My favorite retort is, "You *are* a modeler." Anyone who ventures a projection, or imagines how a social dynamic—an epidemic, war, or migration—would unfold is running *some* model.

But typically, it is an *implicit* model in which the assumptions are hidden, their internal consistency is untested, their logical consequences are unknown, and their relation to data is unknown.

"Can you validate your model?" The appropriate retort, of course, is, "Can you validate yours?" At least I can write mine down so that it can, in principle, be calibrated to data, if that is what you mean by "validate“.

Sixteen Reasons Other Than Prediction to Build Models Epstein (JASSS 11(2008)1):

1. Explain (very distinct from predict)
2. Guide data collection
3. Illuminate core dynamics
4. Suggest dynamical analogies
5. Discover new questions
6. Promote a scientific habit of mind
7. Bound (bracket) outcomes to plausible ranges
8. Illuminate core uncertainties.
9. Offer crisis options in near-real time
10. Demonstrate tradeoffs / suggest efficiencies
11. Challenge the robustness of prevailing theory through perturbations
12. Expose prevailing wisdom as incompatible with available data
13. Train practitioners
14. Discipline the policy dialogue
15. Educate the general public
16. Reveal the apparently simple (complex) to be complex (simple)

Connecting stocks and flows: feedback dynamics

Simple exercise #1:

- A bowl contains 100 rice grains and is given to person #1.
- Give 10 participants a piece of paper.
- On the paper for the person #1 is the number 1.
- This person #1 takes from the bowl the number of units written on his paper (1)
- He gives the piece of paper and the bowl to his neighbour.

- The next person #2 multiplies the number on the paper received from person #1 with 2
- Person #2 writes this number on her piece of paper and takes this number of grains out of the bowl
- Person #2 gives her piece of paper and the bowl to her neighbour, person #3

- The next person #3 multiplies the number on the paper received from person #2 with 2
- Etc.

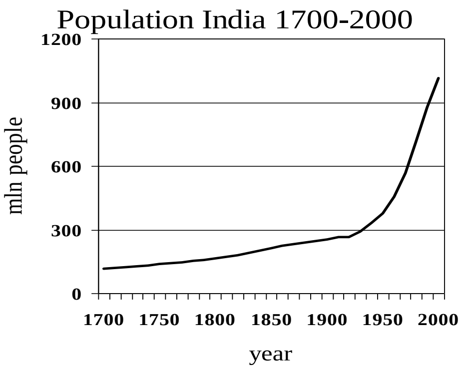
Make a graph of number of grains taken out (y-axis) for the person number (x-axis).
With which person are all grains taken out of the bowl?

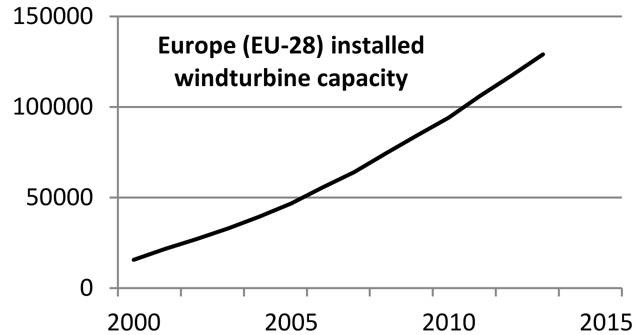
See e.g. www.calculusapplets.com/growthdecay.html

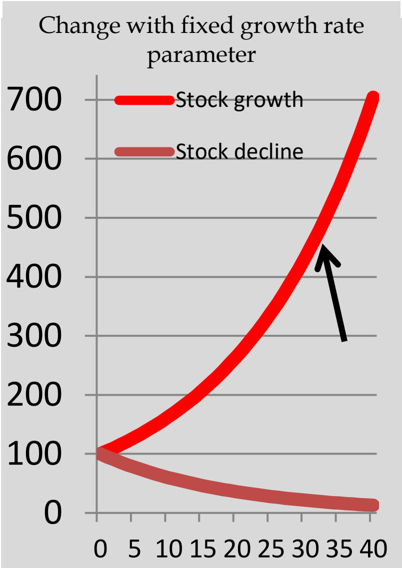
Exponential growth

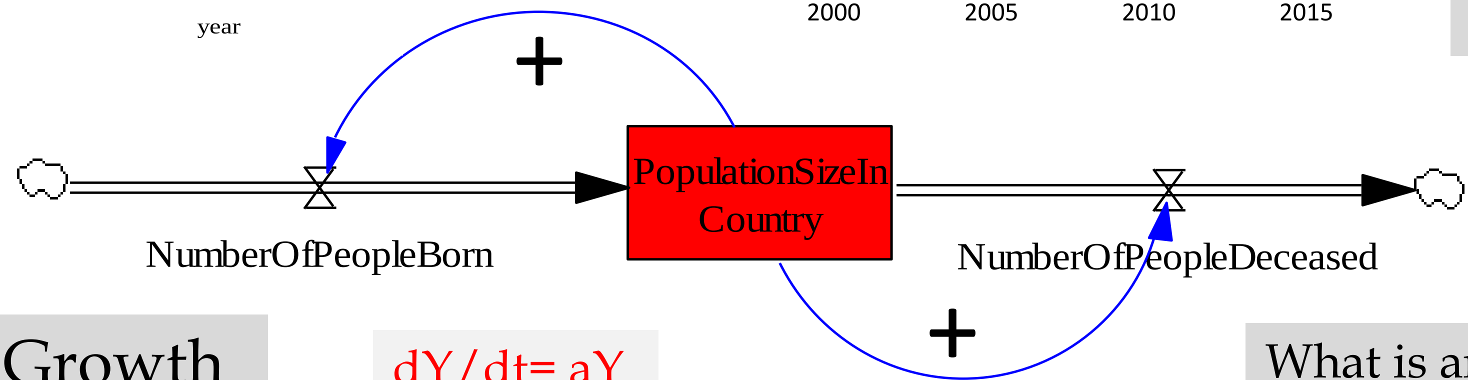
Positive feedback processes

Icons are from Vensim®





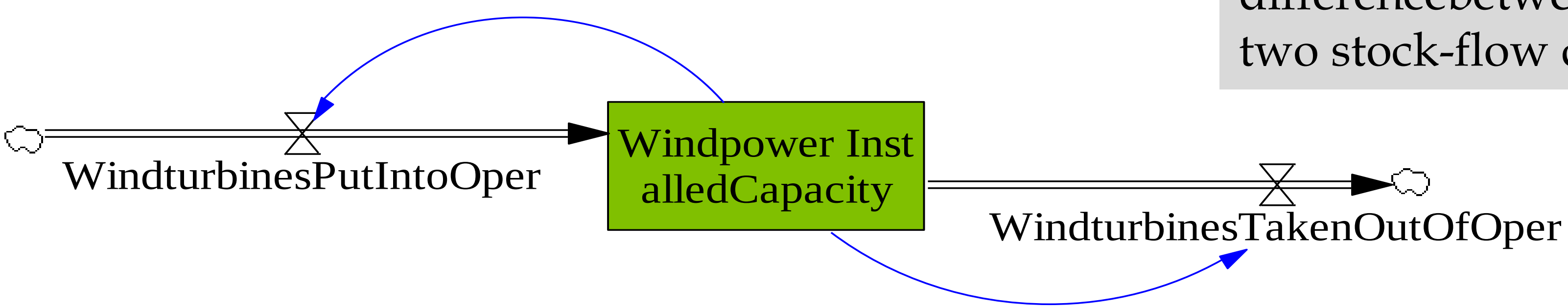




Growth

$dY/dt = aY$

What is an essential differencebetween these two stock-flow diagrams?



Connecting stocks and flows: feedback dynamics

Simple exercise #1:

- A bowl is filled with 100 rice grains and given to person #1.
- Give 10 participants a piece of paper.
- On the paper for the person #1 is the number 48.
- This person #1 takes from the bowl the number of units written on her paper (10)
- She gives the piece of paper and the bowl to her neighbour.

- The next person #2 multiplies the number on the paper received from person #1 with 0,5
- Person #2 writes this number on his piece of paper and takes this number of grains out of the bowl
- Person #2 gives his piece of paper and the bowl to his neighbour, person #3

- The next person #3 multiplies the number on the paper received from person #2 with 0.5
- Etc.

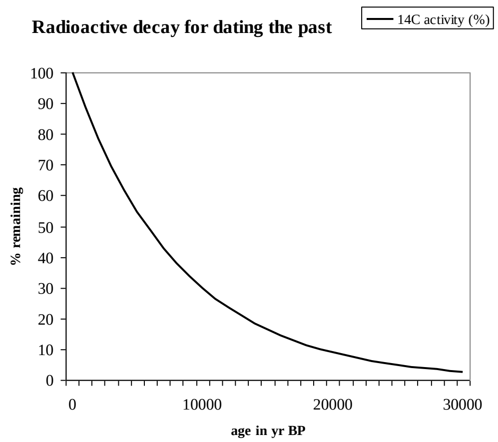
Make a graph of number of grains left in the bowl (y-axis) for the person number (x-axis).
When are all grains taken out of the bowl?

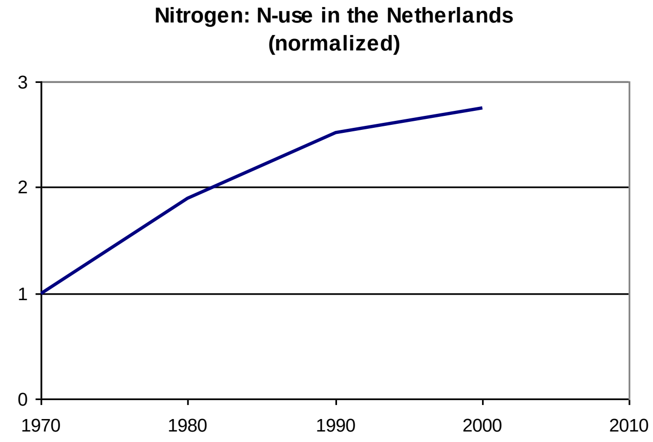
See e.g. www.calculusapplets.com/growthdecay.html

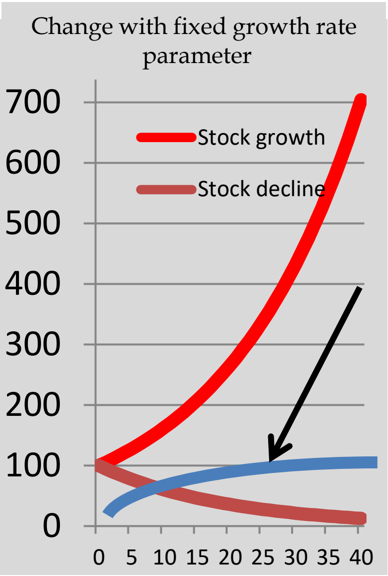
Exponential decline

Negative (or stabilizing) feedback processes

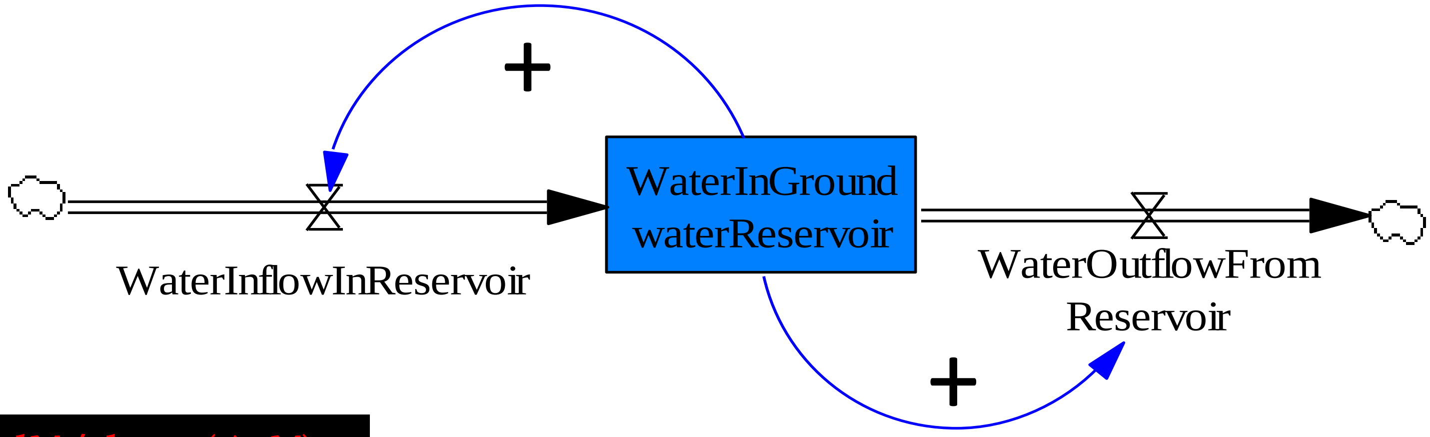
Icons are from Vensim®







Decline



$dX/dt = a(A-X)$

Combined growth and decline: **logistic growth**

A simple but characteristic dynamic process in which both a positive and a negative feedback loop operate, is the **logistic growth process**. This process can be formulated as the differential equation for exponential growth with the growth rate b* approaching zero for Y ≈ K:

$$\frac{dY}{dt} = bY = b(1 - \frac{Y}{K})Y$$

For Y << K, it is the formula for exponential growth. There are two attractors, i.e. Y-values for which dY/dt = 0, namely Y = 0 and Y = K. At Y = K there is a steady-state at which inflow cq. growth rate equals outflow cq. decline rate.

$$Y = \frac{K}{1 + e^{-b(t - t_0)}}$$

The functional solution is found by integrating and gives for the state variable Y as a function of time.

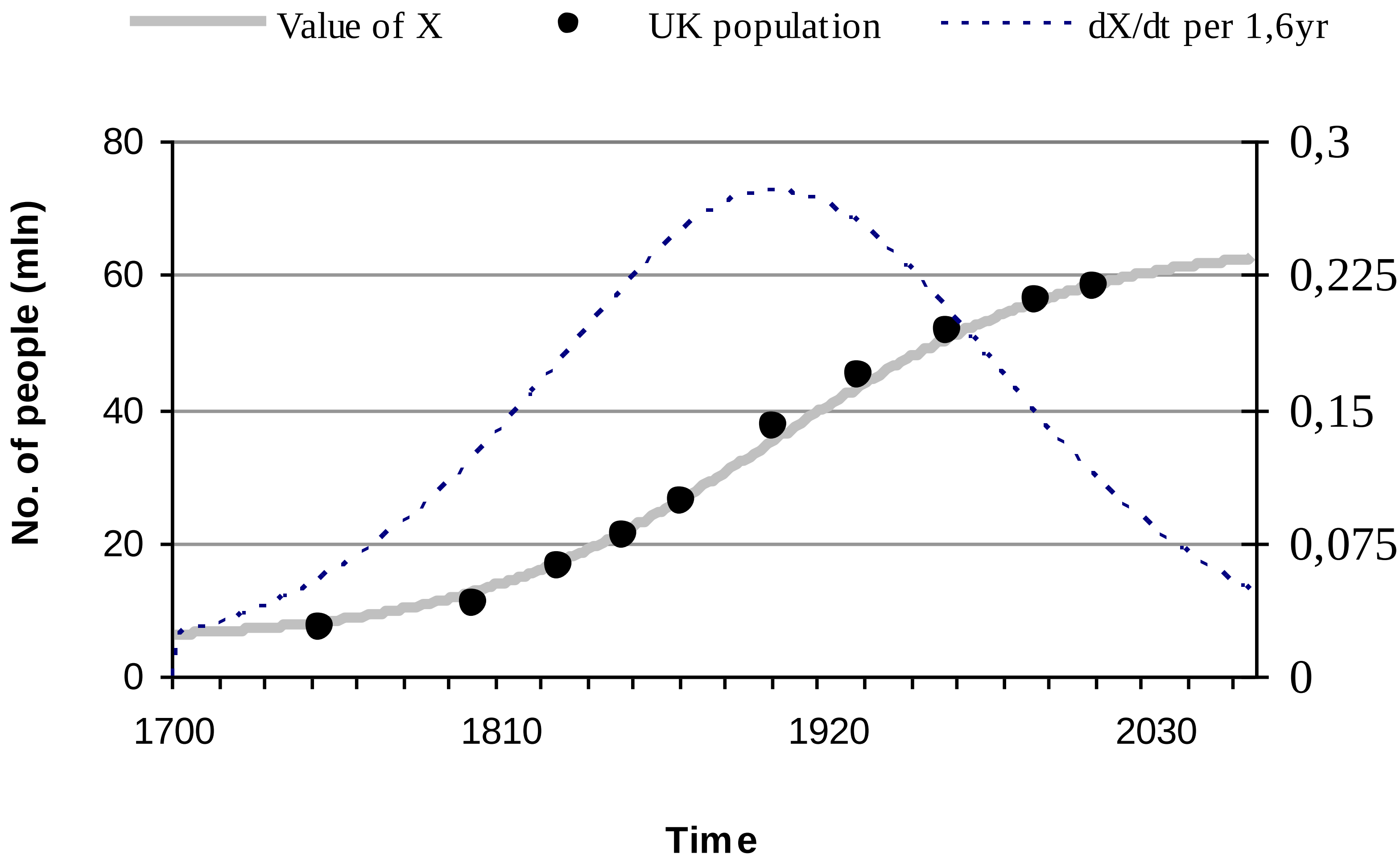


Figure 2-10 Example of a logistic growth process and estimates of the UK population since 1750 (source of data: Maddison 2006, Schandl and Krausmann 2007).

(De Vries 2013)

To remember about **positive and negative feedback loops**:

- The existence of a stock gives **inertia** to the system: change in the stock is limited by the change rates in in- and outflows

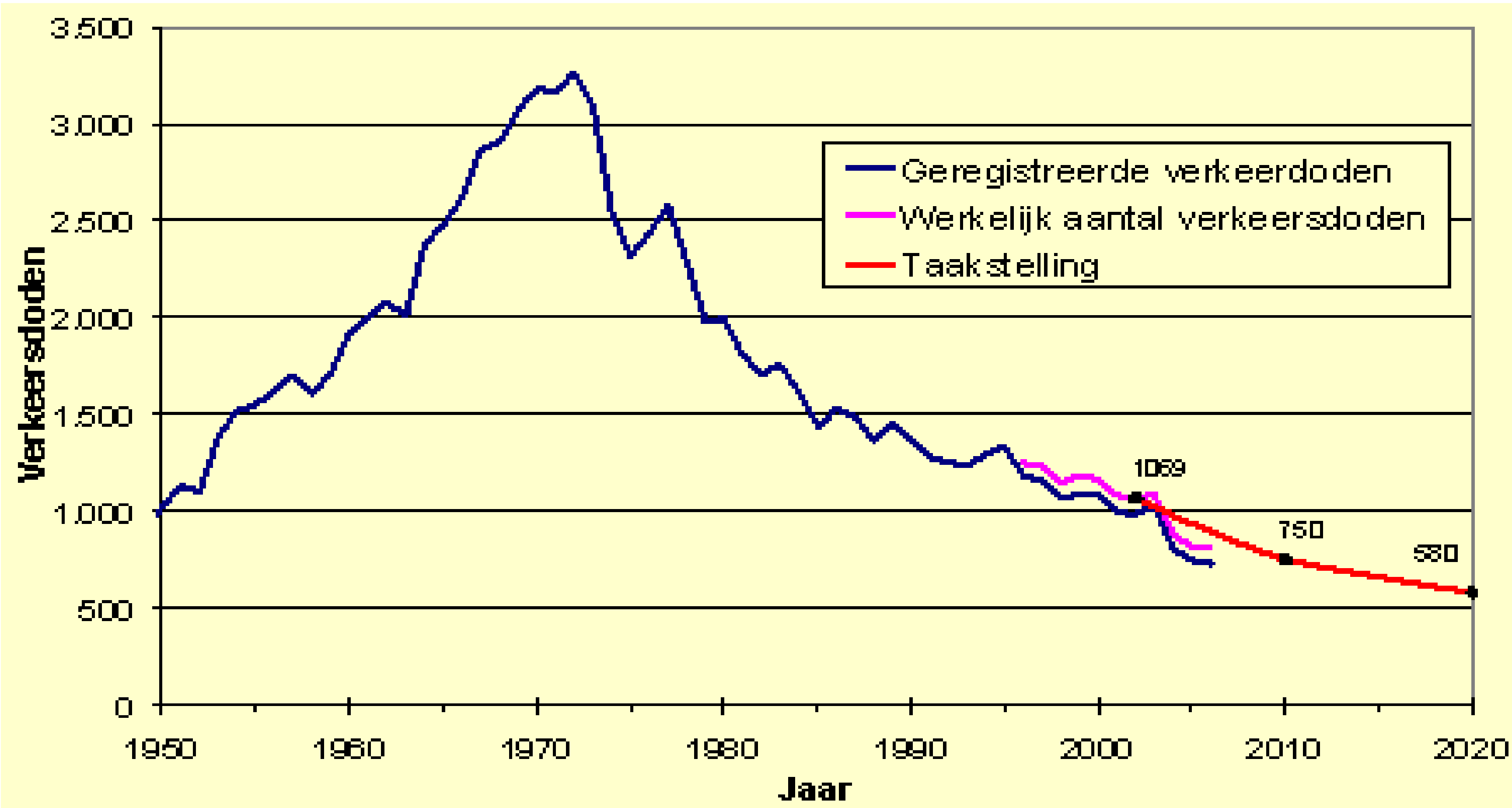
- Stock are characterized by (preferably measurable) units; flows are in units/time

- No real-world process exhibits perfect exponential growth or decline, because the change rate parameters are never constant (a possible exception: money on a bank account in times of constant interest rate)

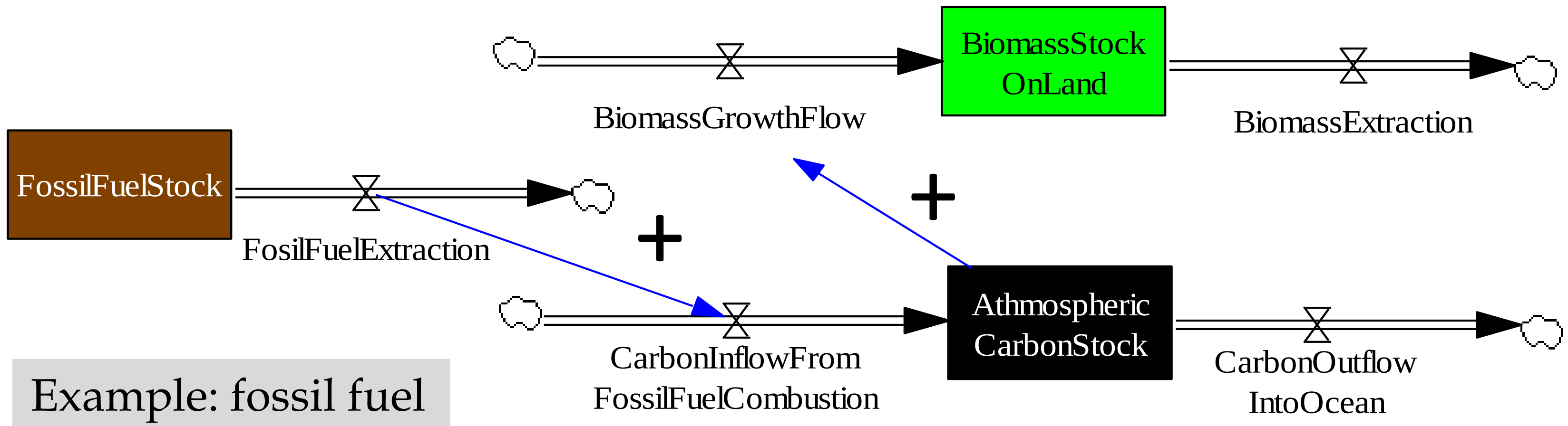
- Not every exponential growth or decline curve can be explained with the simple diagrams presented here.

Usually, combinations of processes occur over time e.g. first exponential growth then decline

Traffic death in the Netherlands



[Exponential] growth and decline processes never operate in isolation



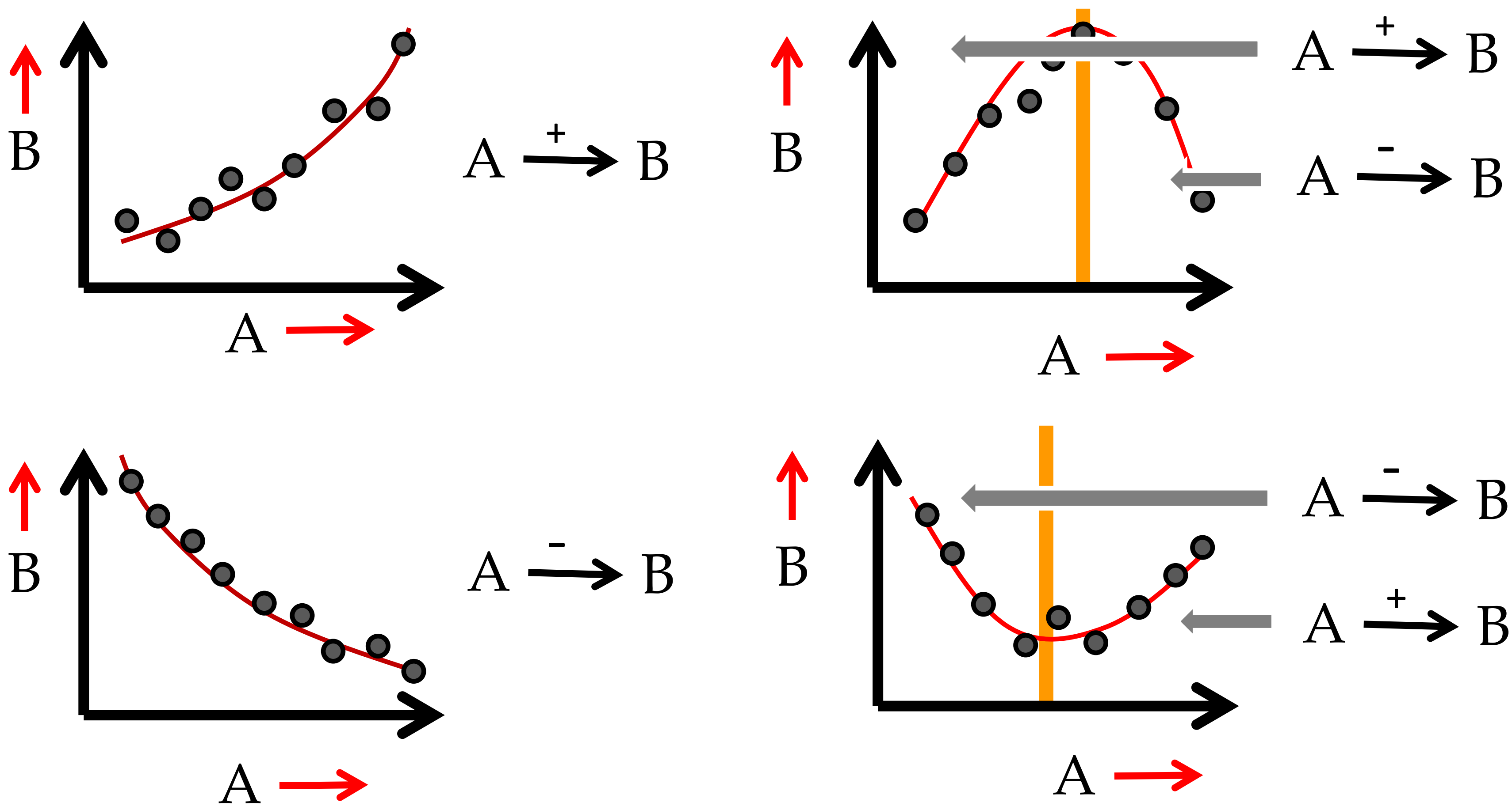
Example: fossil fuel combustion and biomass growth

Given the real-world complexity, it is best to start with a **causal loop diagram** (CLD):

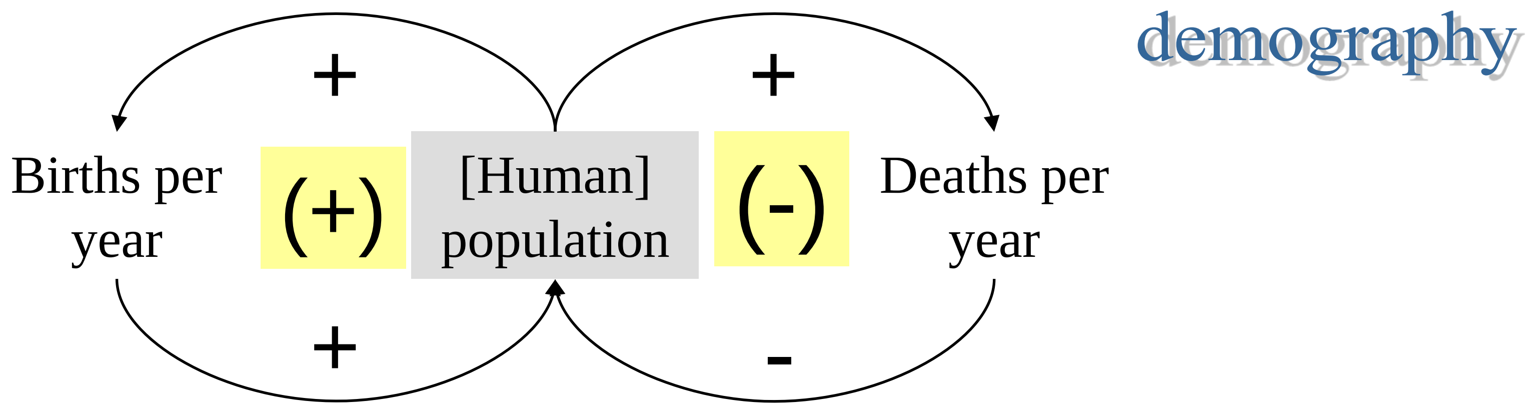
- Identifying relevant stock and flow variables
- Identifying the causal direction between them

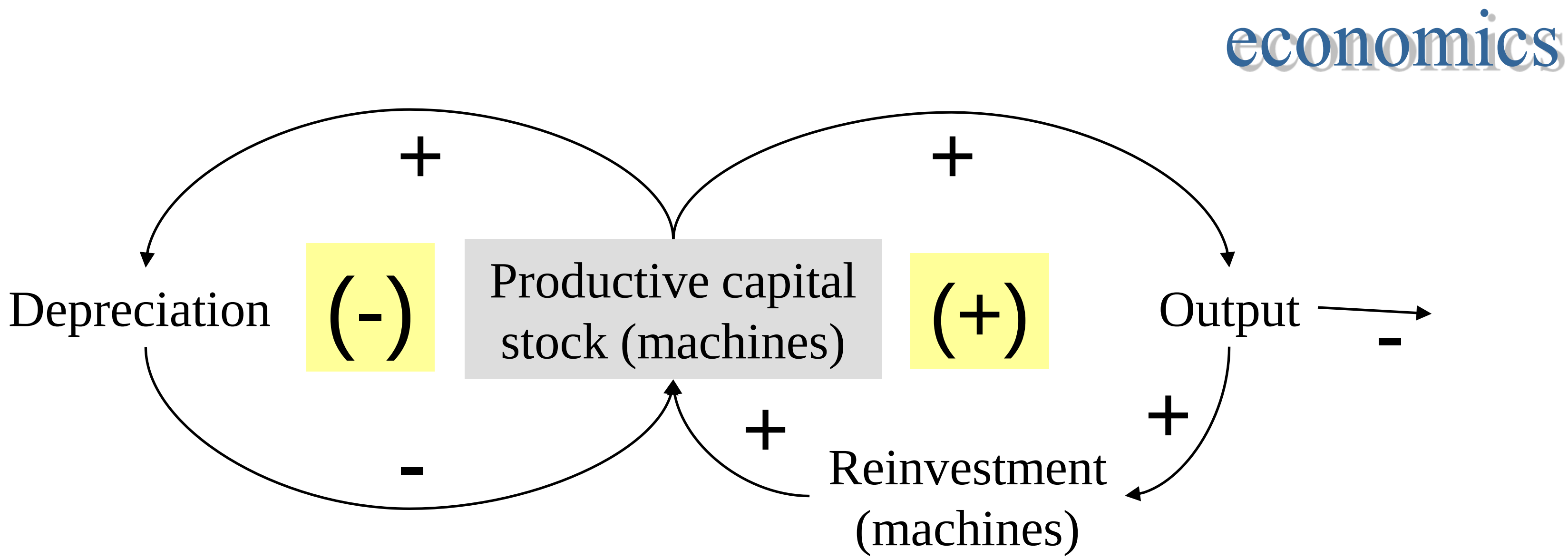
How to construct and read a CLD?

Observation and interpretation of causality



Examples of linked, positive and negative feedback loops





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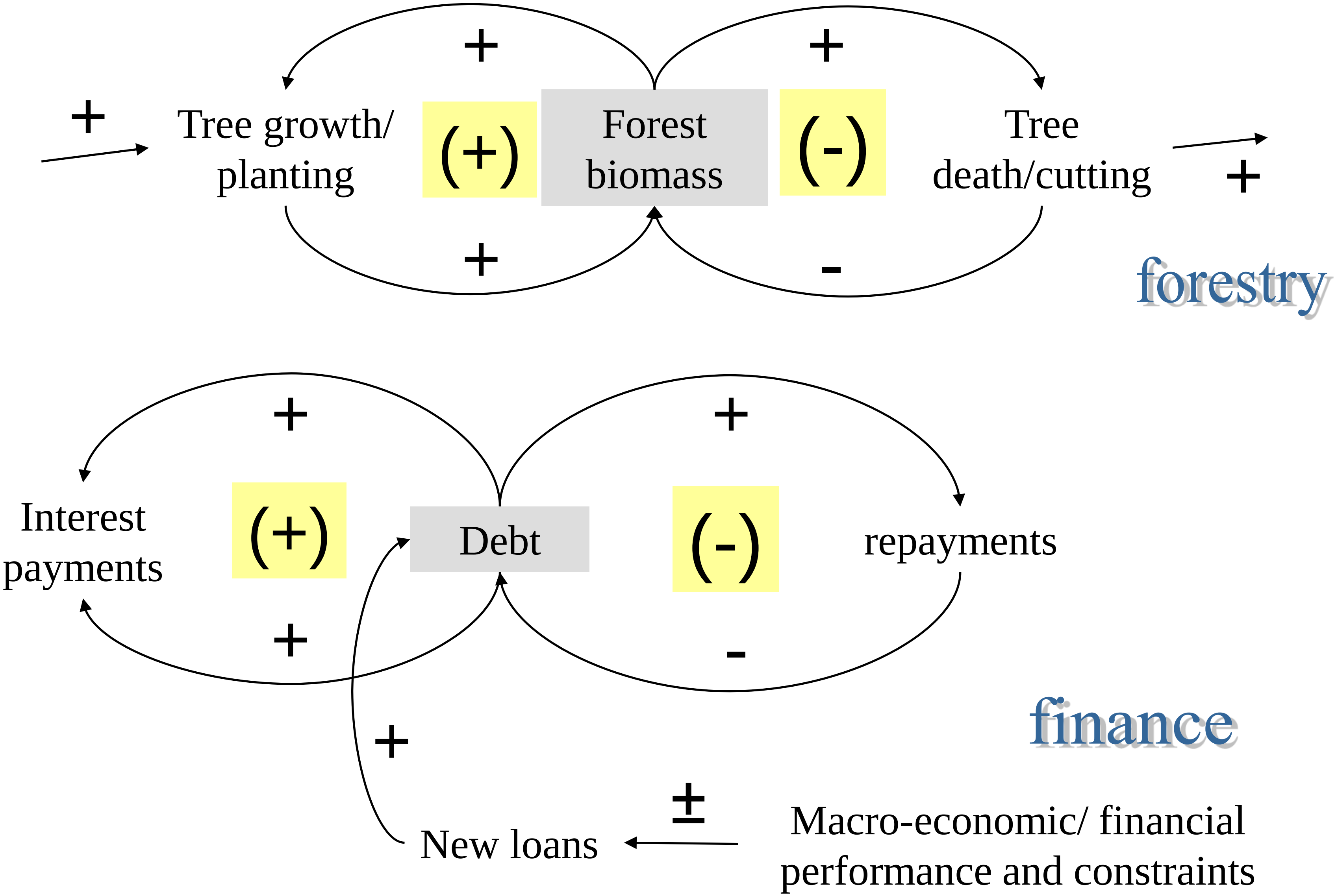
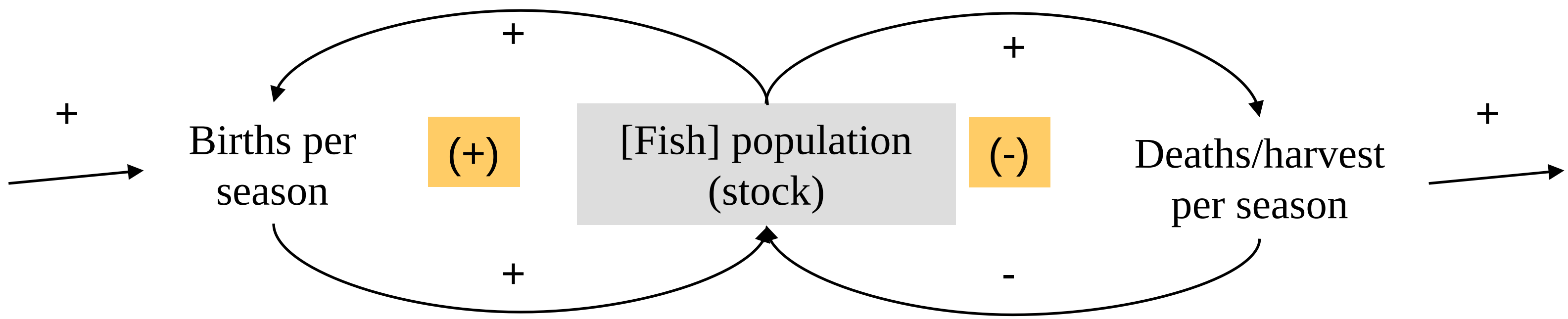
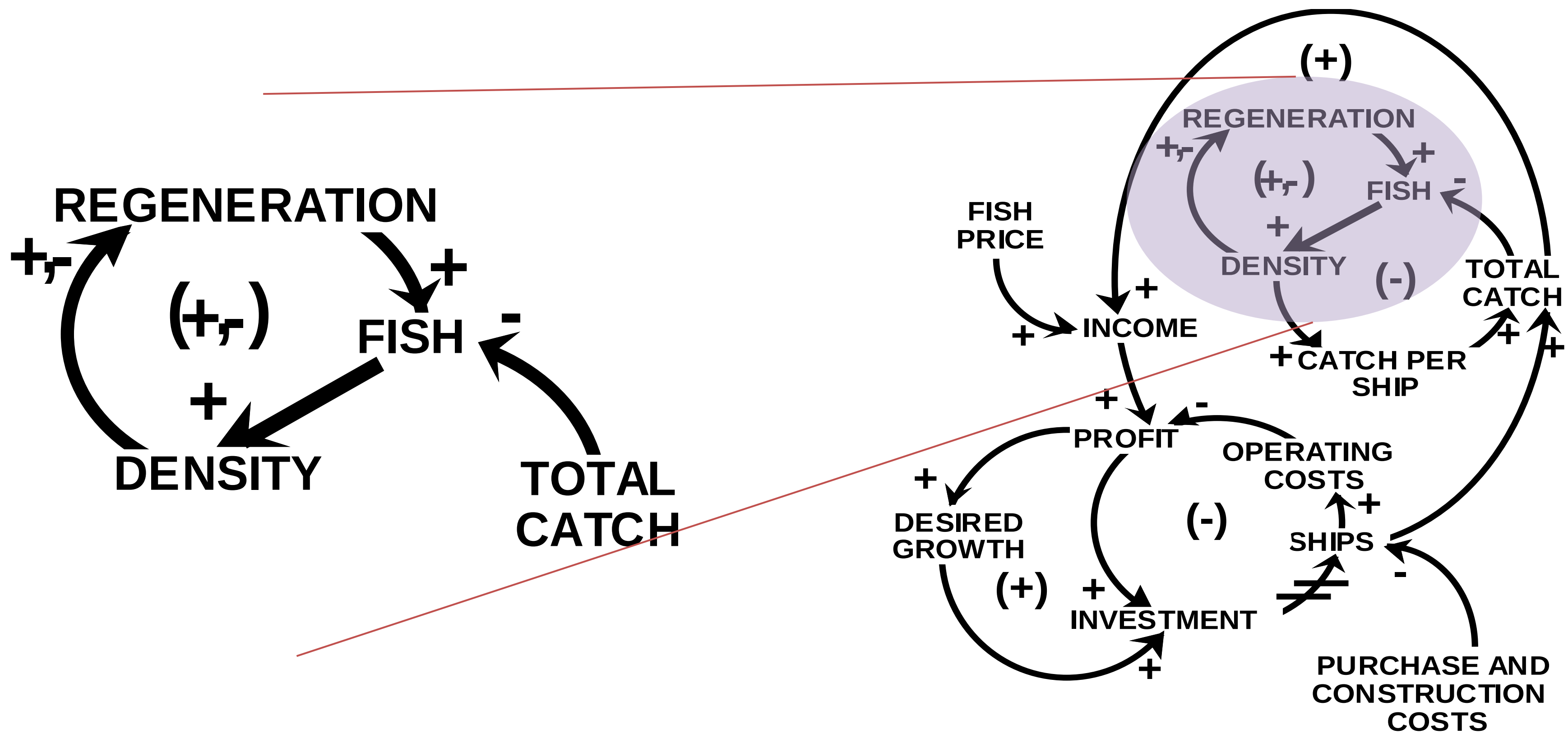


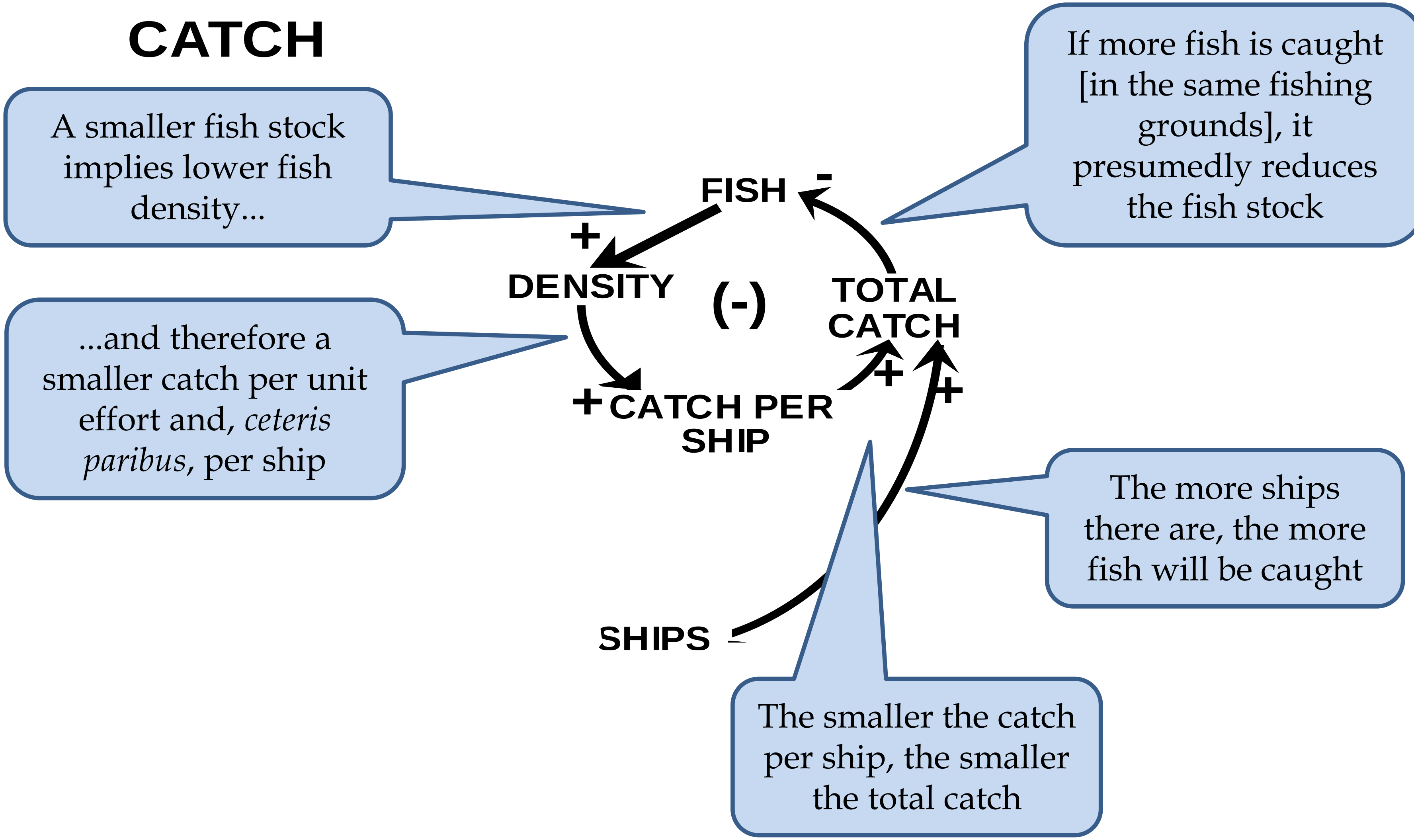
Example: exploiting fisheries





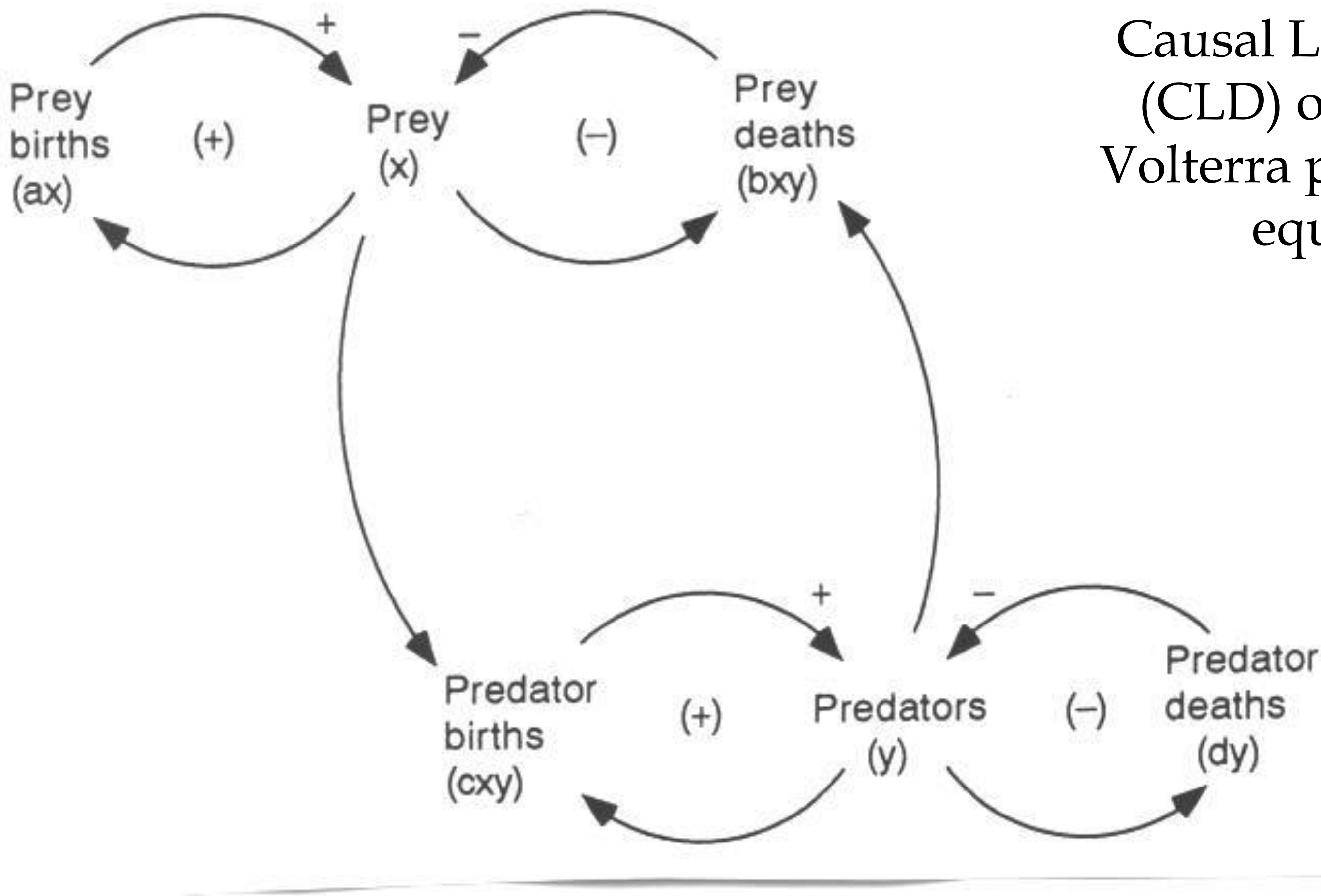
(Courtesy: Dennis Meadows)

How to read this fisheries CLD?



(Courtesy: Dennis Meadows)

Example: a prey-predator model



Causal LoopDiagram (CLD) of the Lotka-Volterra predator-prey equations

Analog descriptions: arms race, consumer culture, performance archetype

(Richardson 1991)

Empirical data on prey-predator oscillations and adaptive ecosystem management

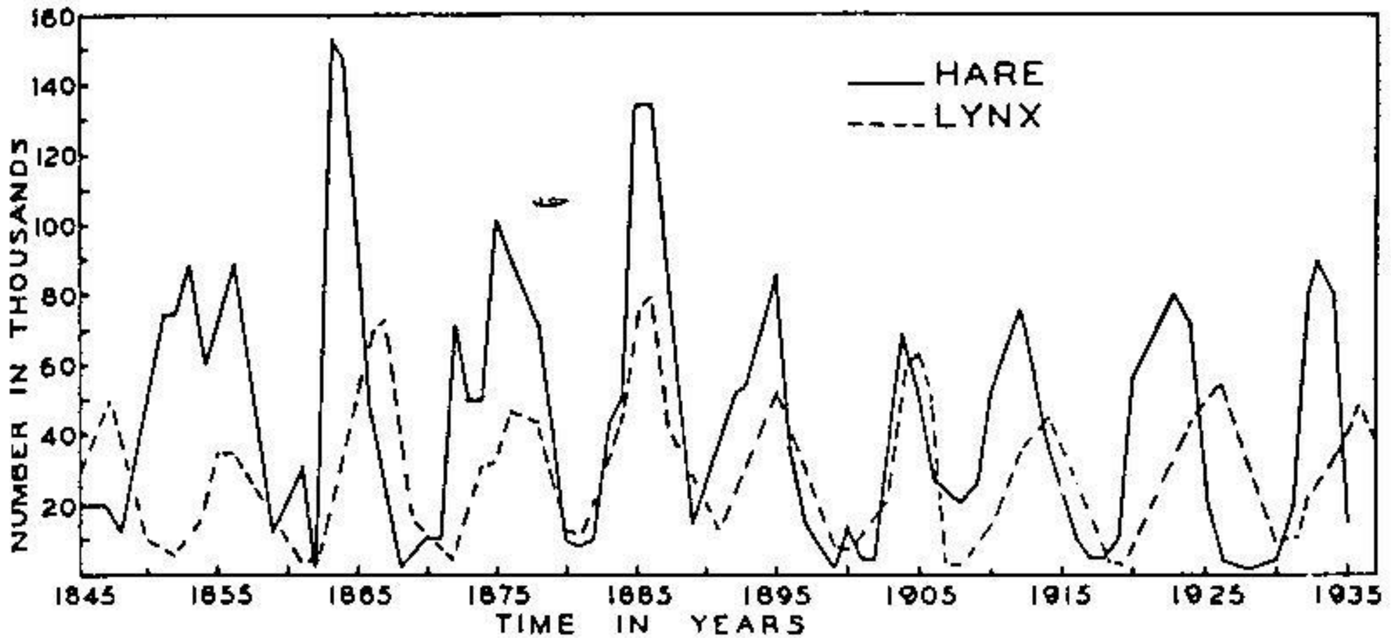


Figure 6.3 *Records dating back to the 1840s kept by the Hudson Bay Company. Their trade in pelts of the snowshoe hare and its predator the lynx reveals that the relative abundance of the two species undergoes dramatic cycles. The period these cycles is roughly 10 years. [From E.P. Odum (1953), fig. 39.]*

(see also https://www.sustainabilityscience.eu/the-kaibab-narrative-management-on-ill-understood-systems/)

(from: Edelstein-Kesset 1988)

Prey-predator model in space (NetLogo): wolfs and sheep

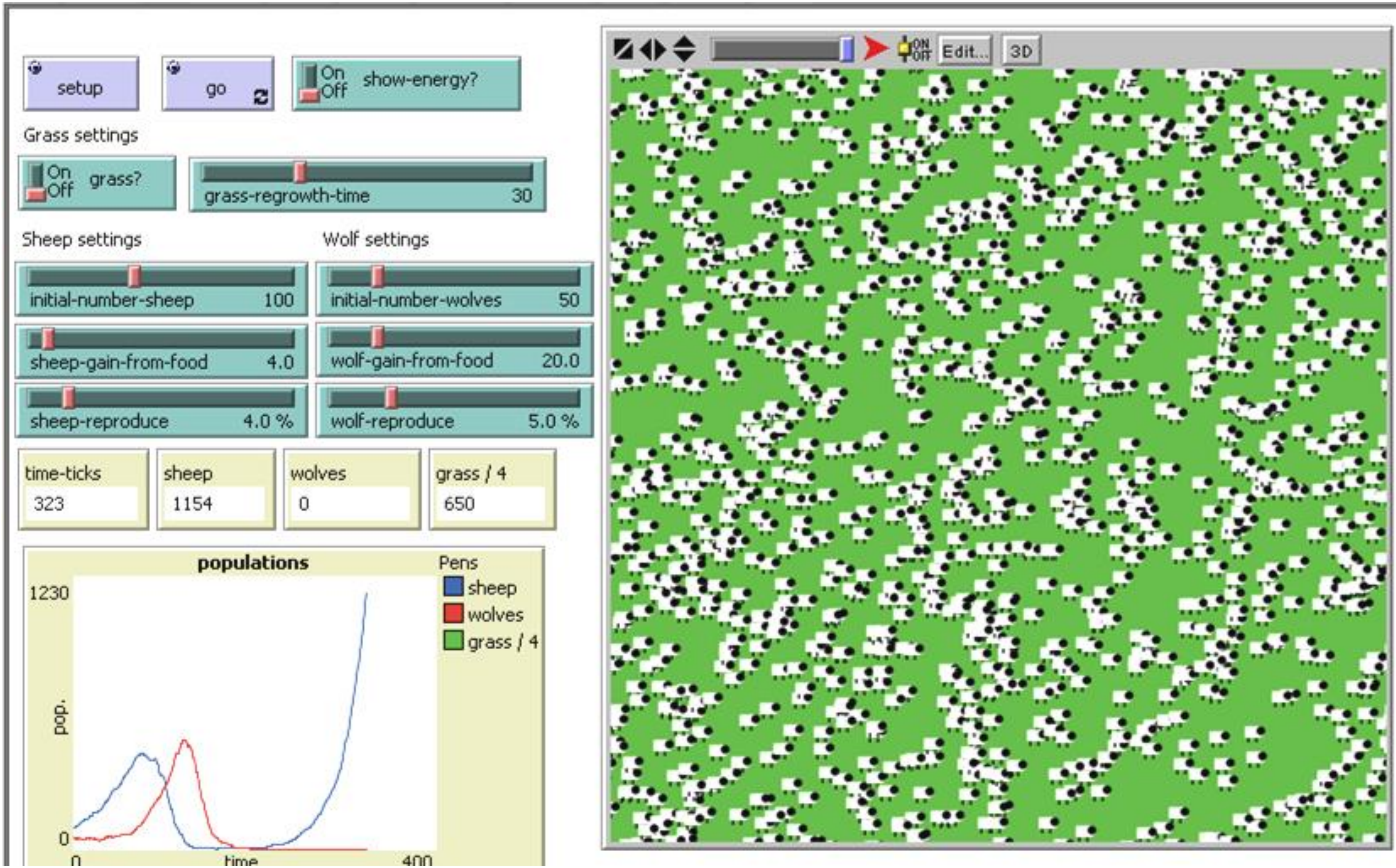


Figure 9.14a Spatial dynamics of a simple, CA-based wolf-sheep predation model, with grass 'off'. It is almost impossible to find a limit cycle path.

Prey-predator model in space (NetLogo): wolfs, sheep and grass

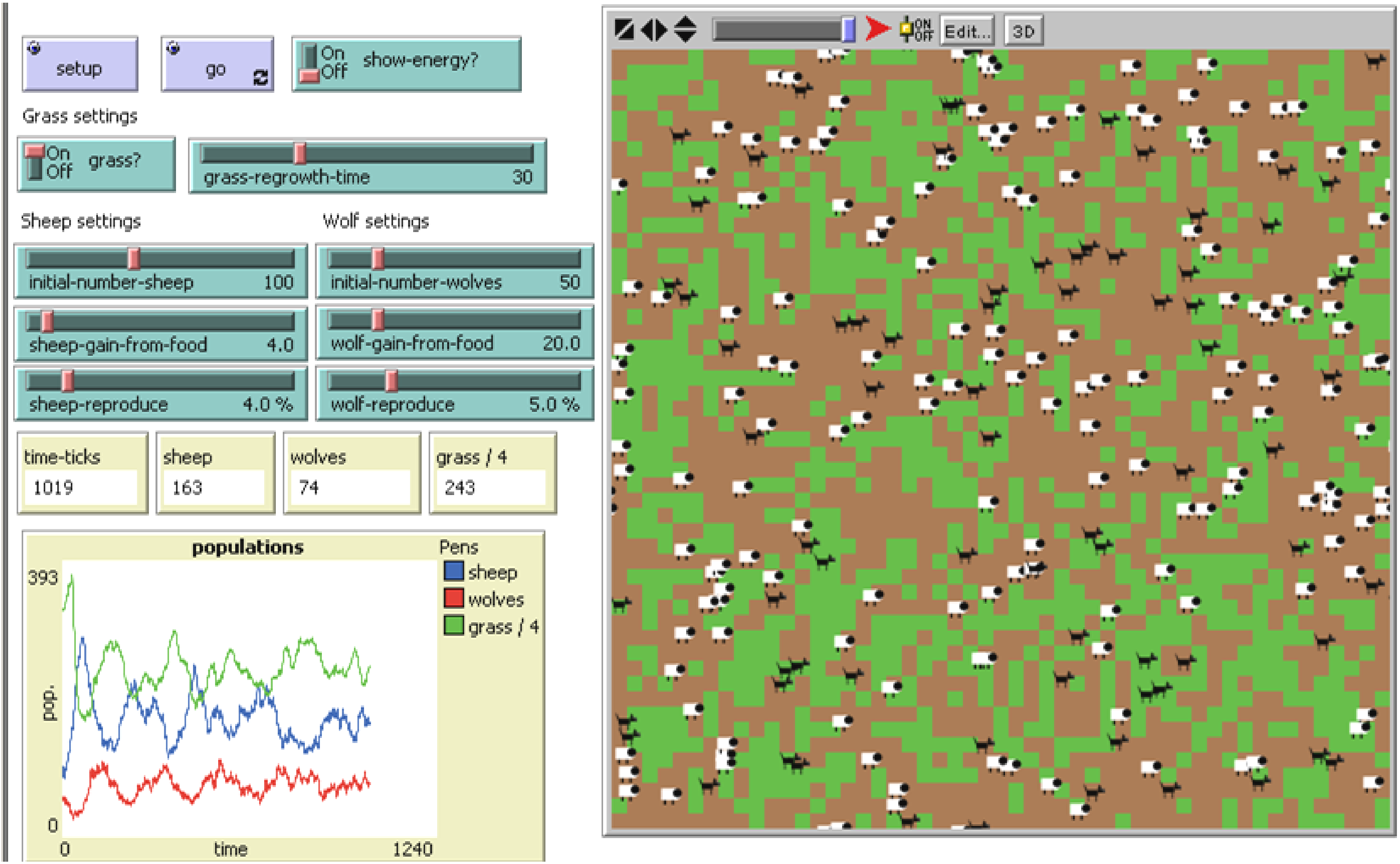
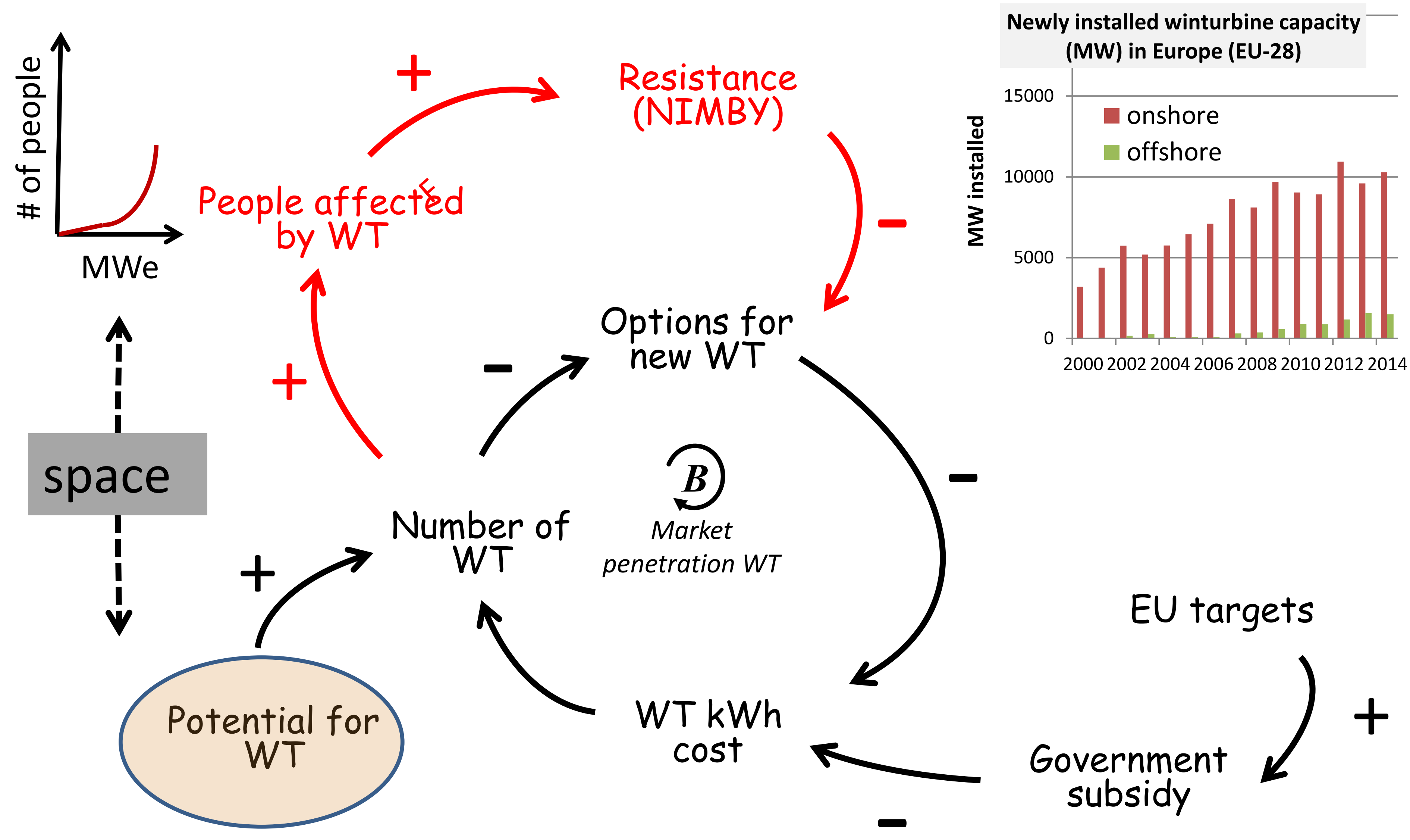


Figure 9.14b Spatial dynamics of a simple, CA-based wolf-sheep predation model, with grass regenerating at a 30%/yr rate (grass 'on') (Courtesy: Net-logo 3.1.3). The lower left graph shows the population trajectories.

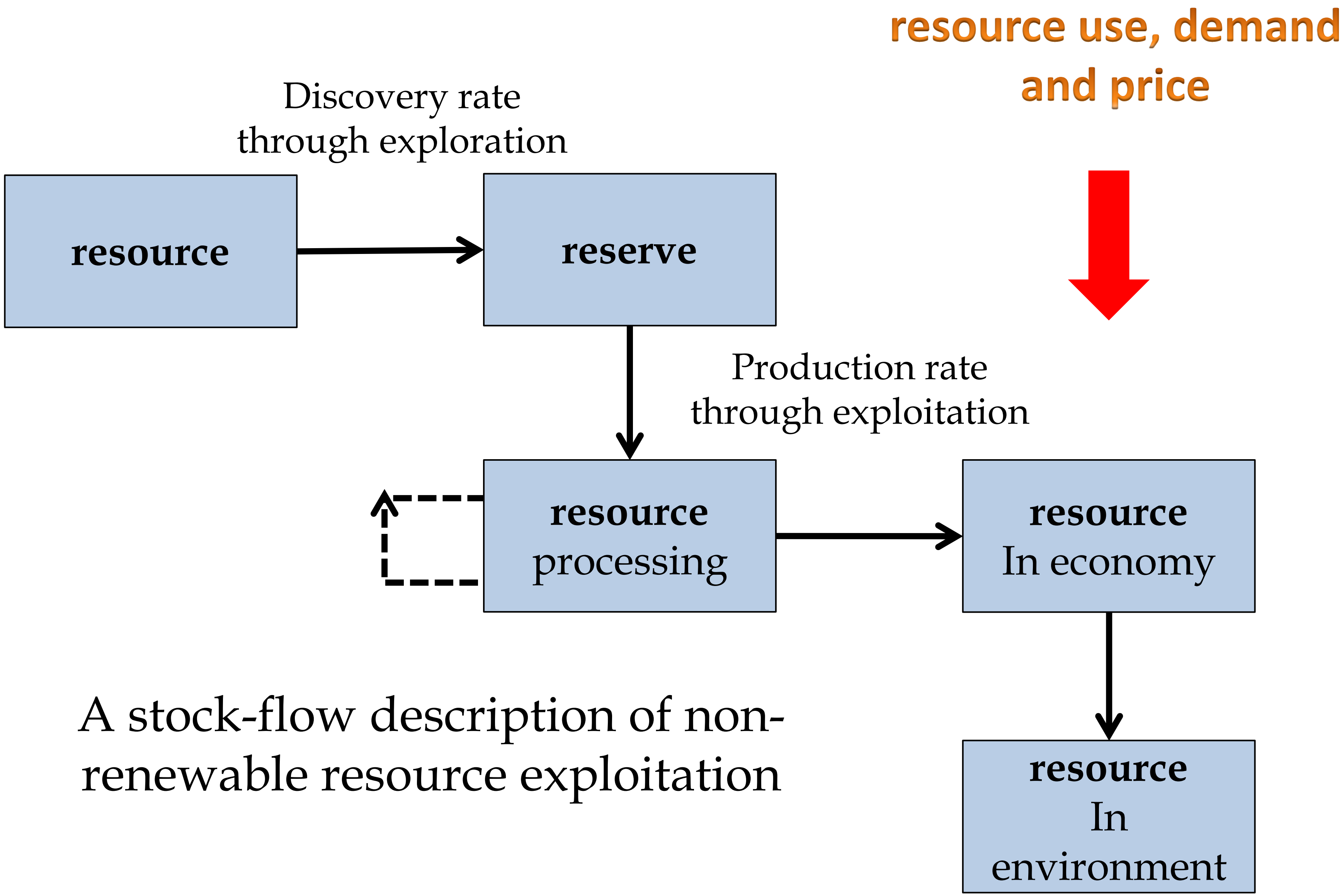
Example: story-based modelling of market penetration of windturbines (WT)



Energy policy: stimulating windturbines and its pitfalls

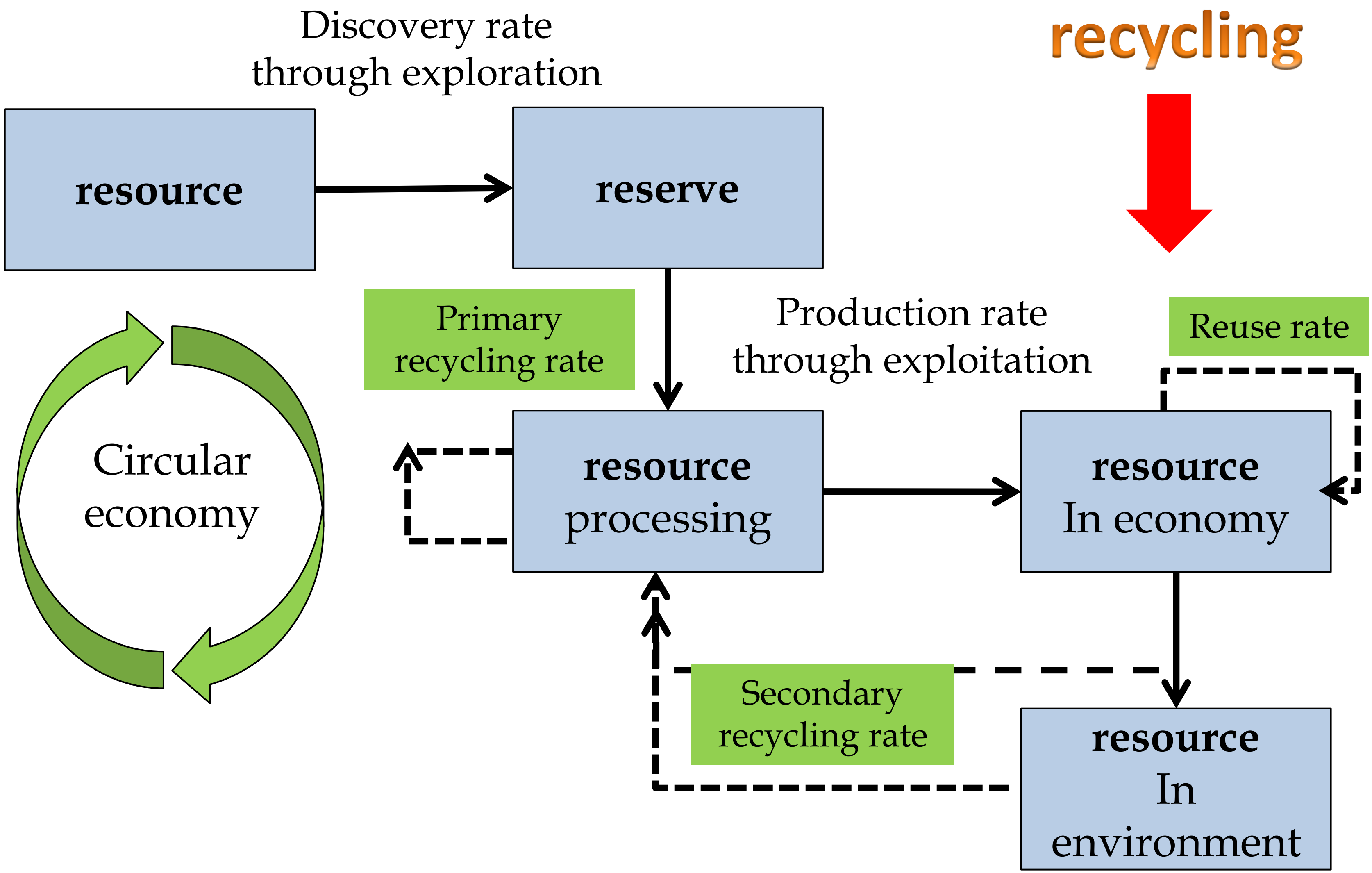
(De Vries 2013)

Example: exploration and exploitation of finite [fuel] resources



A stock-flow description of non-renewable resource exploitation

resource reuse, and recycling



Mechanisms behind fossil fuel exploitation and use

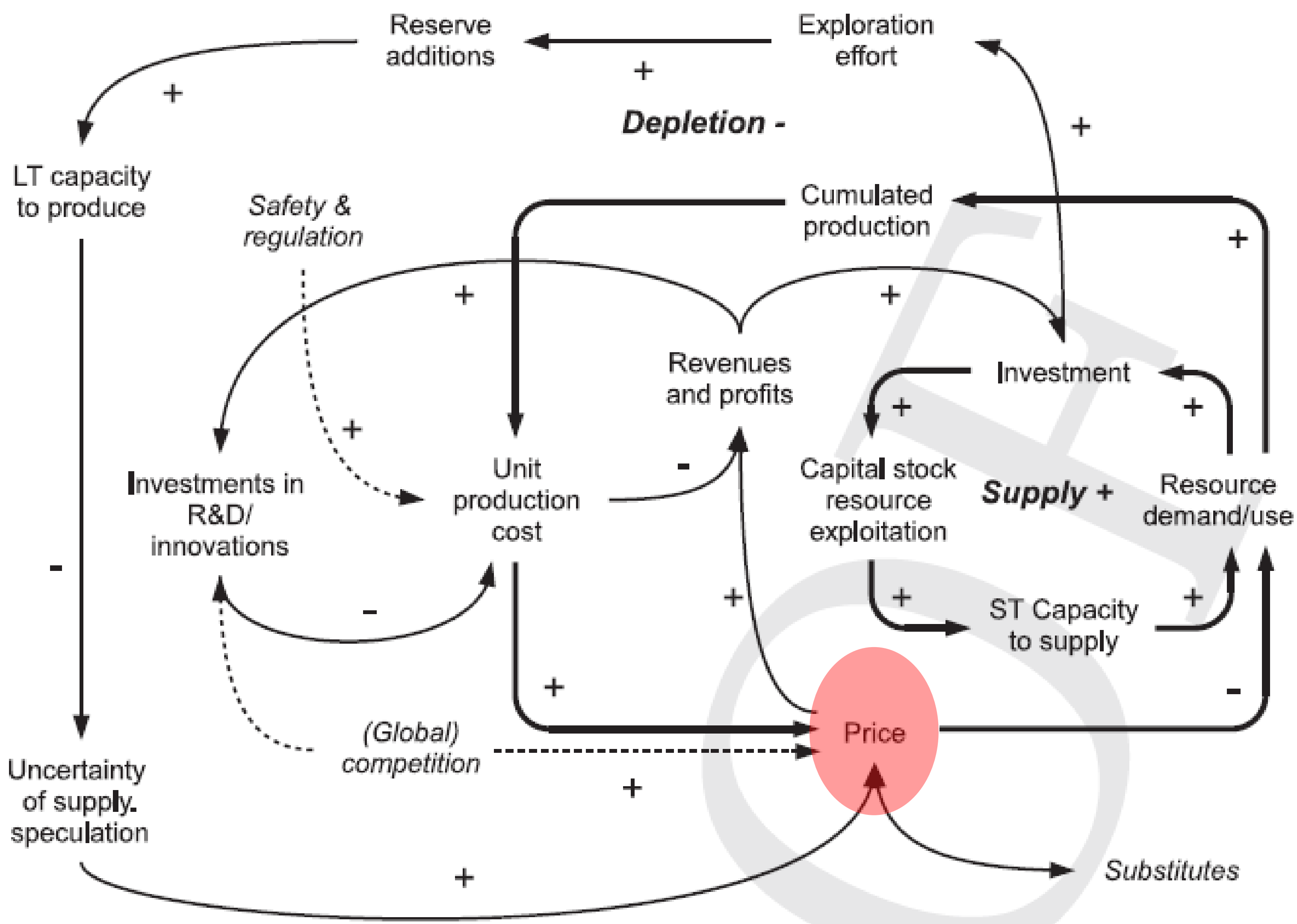


Figure 13.7. The most important dynamic mechanisms that determine long-term trends in resource supply, costs and prices. The items in italic are influences from other subsystems.

(De Vries 2013)

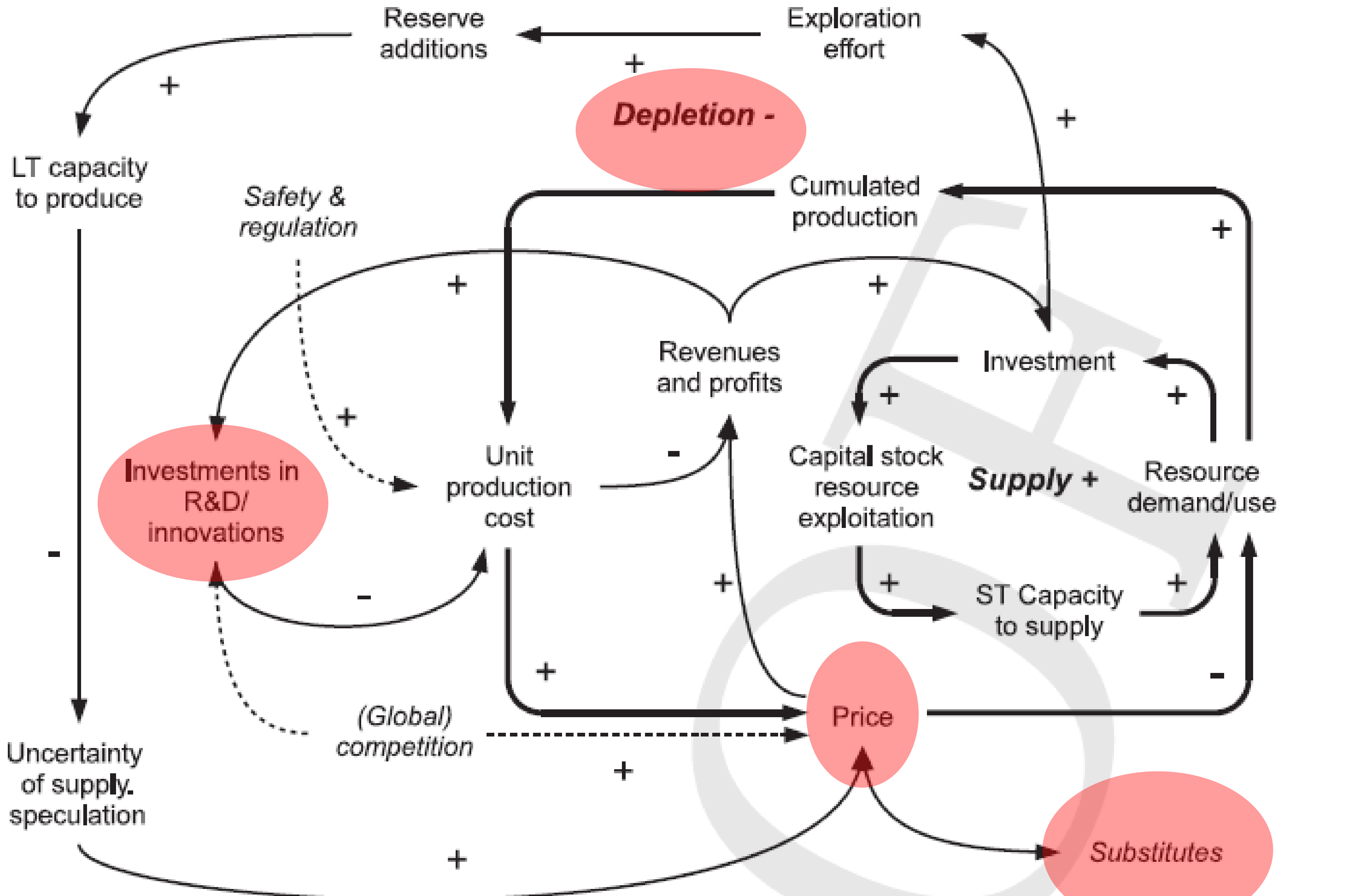
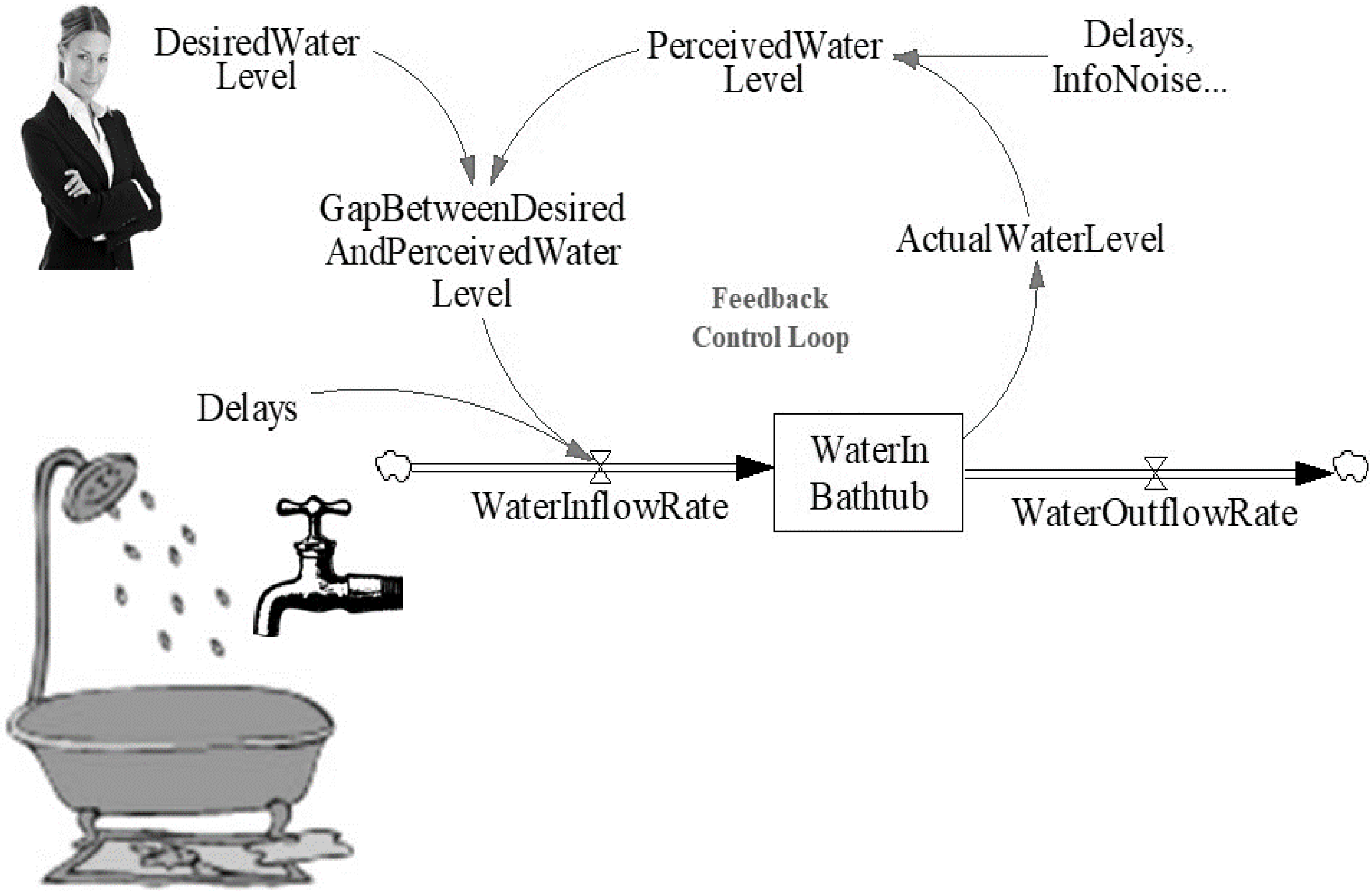


Figure 13.7. The most important dynamic mechanisms that determine long-term trends in resource supply, costs and prices. The items in italic are influences from other subsystems.

(De Vries 2013)

Managing systems: interference based on observed and desired

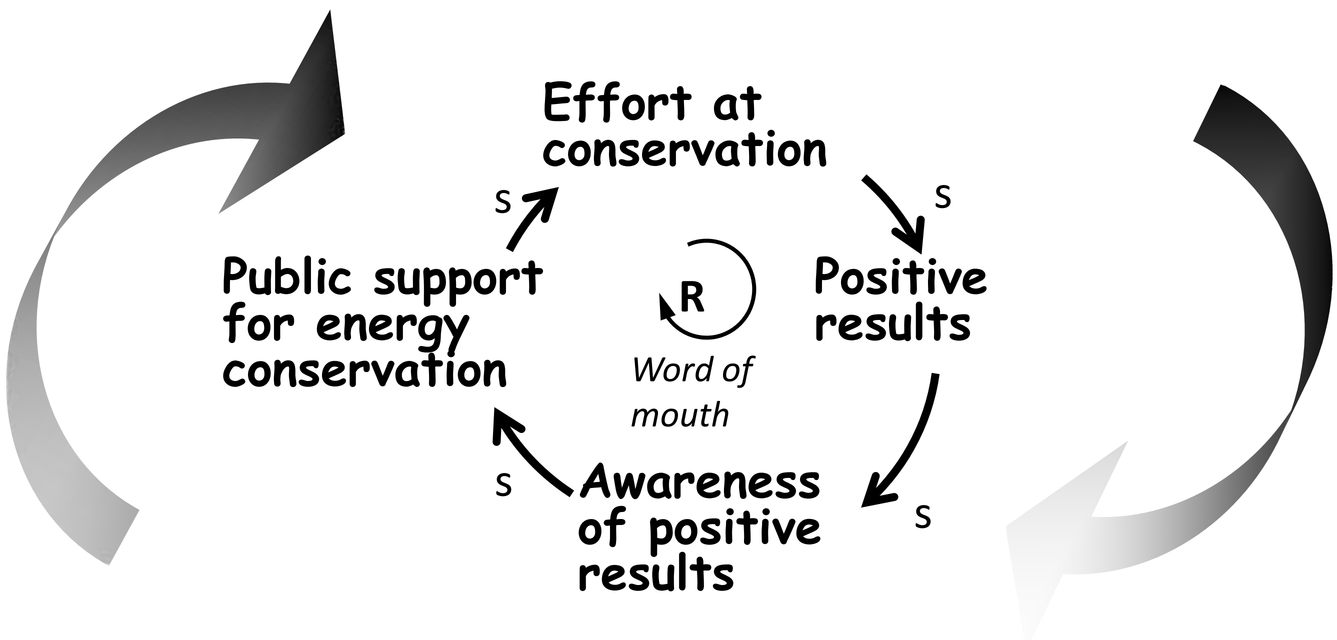


(De Vries 2023)

Example: energy conservation policy

In words:

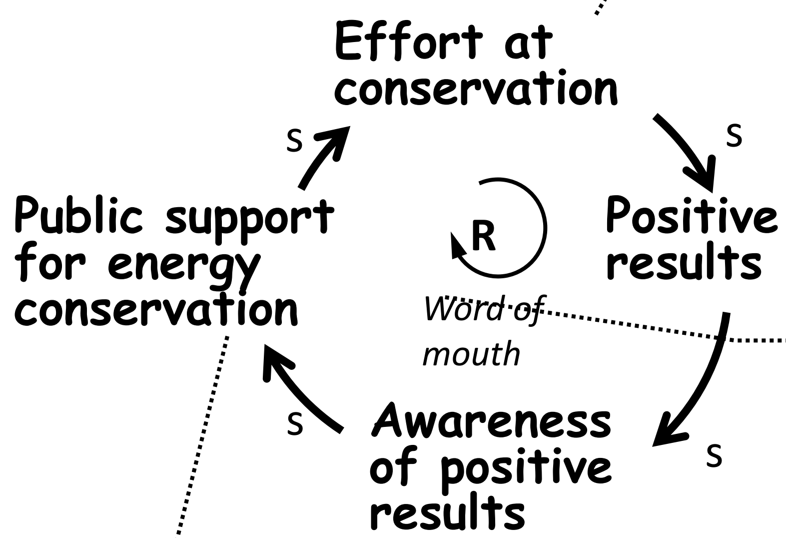
A local effort at water conservation produced ***positive results***. Over time, there was general ***awareness of positive results***. Awareness boosted overall ***public support for water conservation*** in the community. Community support lead to additional ***effort at conservation*** which produced even more ***positive results***, leading to even greater ***awareness of positive results*** … and so on...



Example: energy conservation policy

2. Arrow -- Means one variable affects the next one in some direction, all else being equal.

3. Sign -- “S” or “+”means the second variable changes in the <u>S</u>ame direction as the first. “O” or “-” would mean the <u>O</u>pposite direction



4. Type of loop -- R for reinforcing. B for balancing

1. Variable -- Important factors in the systems. Can get bigger or smaller.

How to read a Causal Loop Diagram (CLD)?

Example: groundwater exploitation for agriculture in South-Eastern Spain

case-study:

Groundwater use in Spain

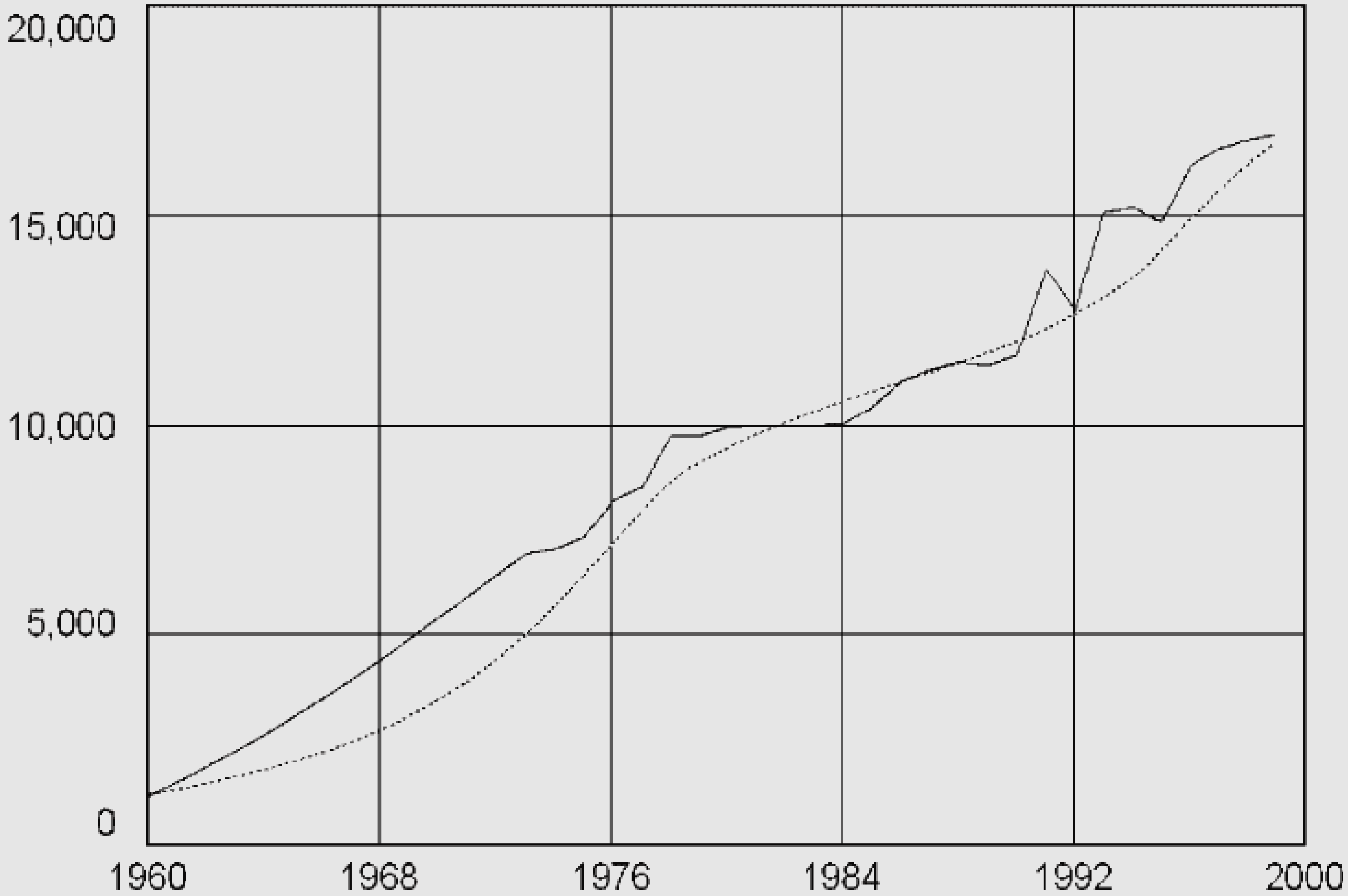


Fig. 4. Simulated values (dashed line) and historical values (solid line) for hectares of irrigated lands

Observed development: **irrigated area** in ha

Observations on Mazillon and Aguirras irrigated lands: **groundwater level and salinity**

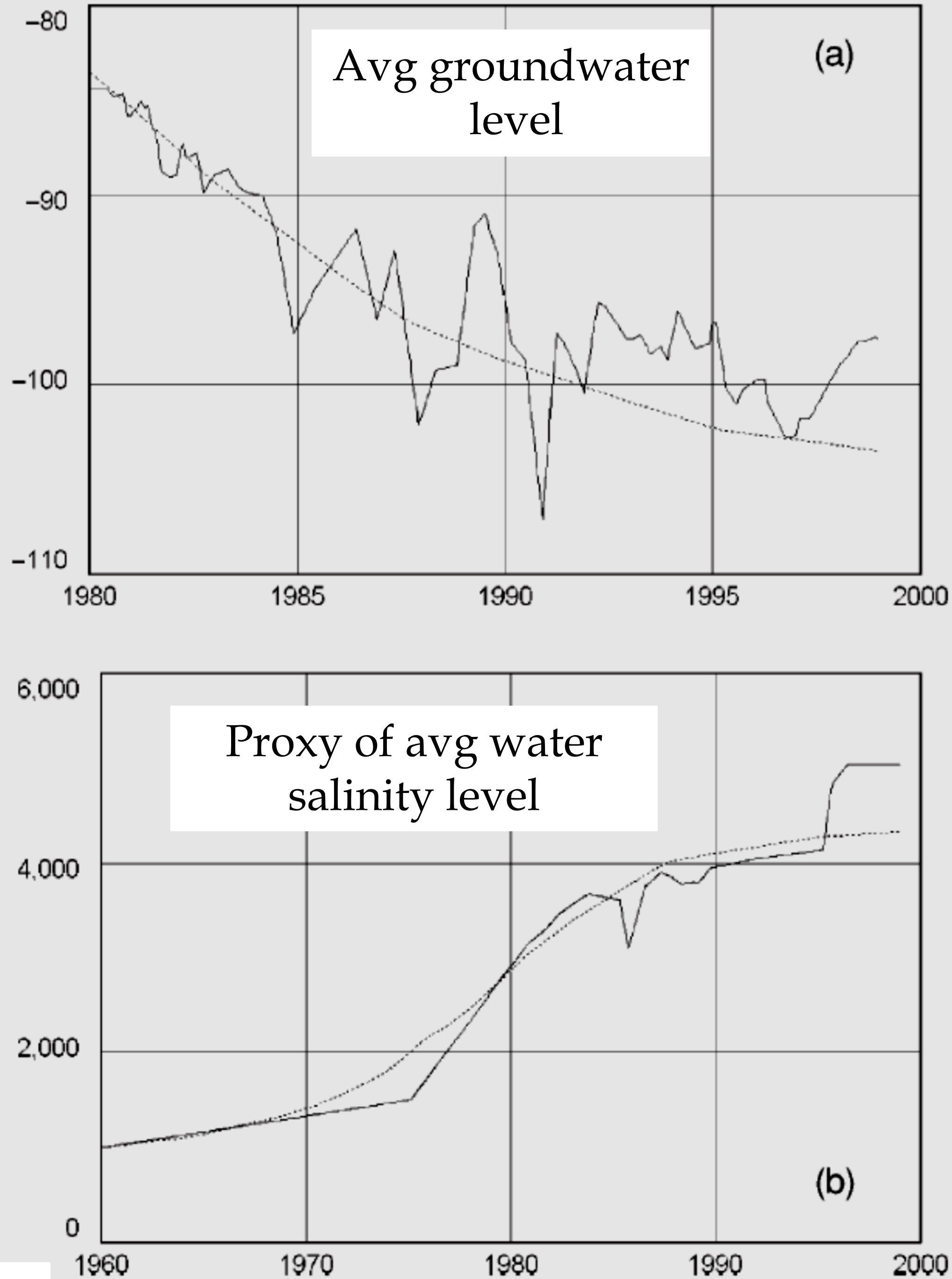
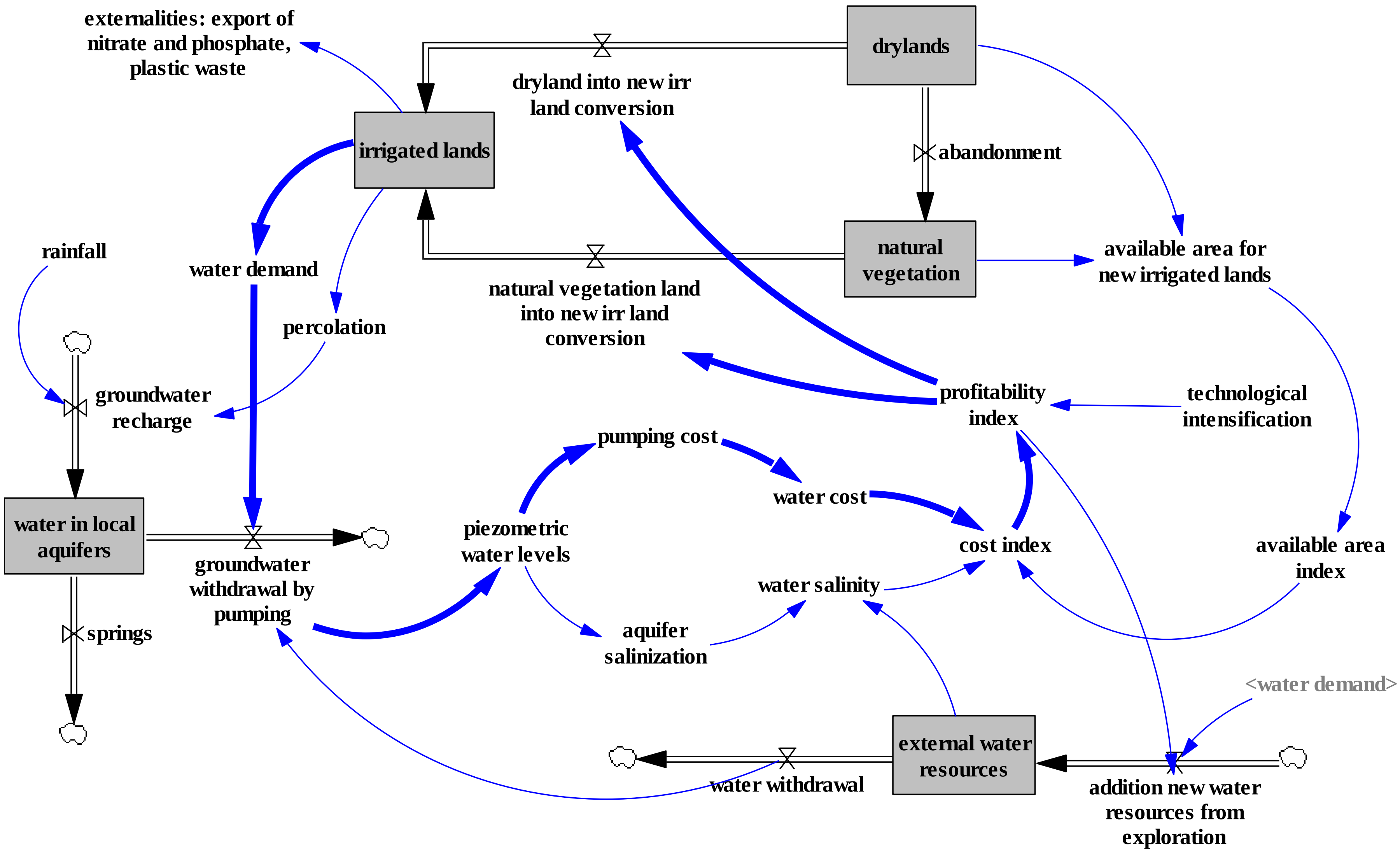


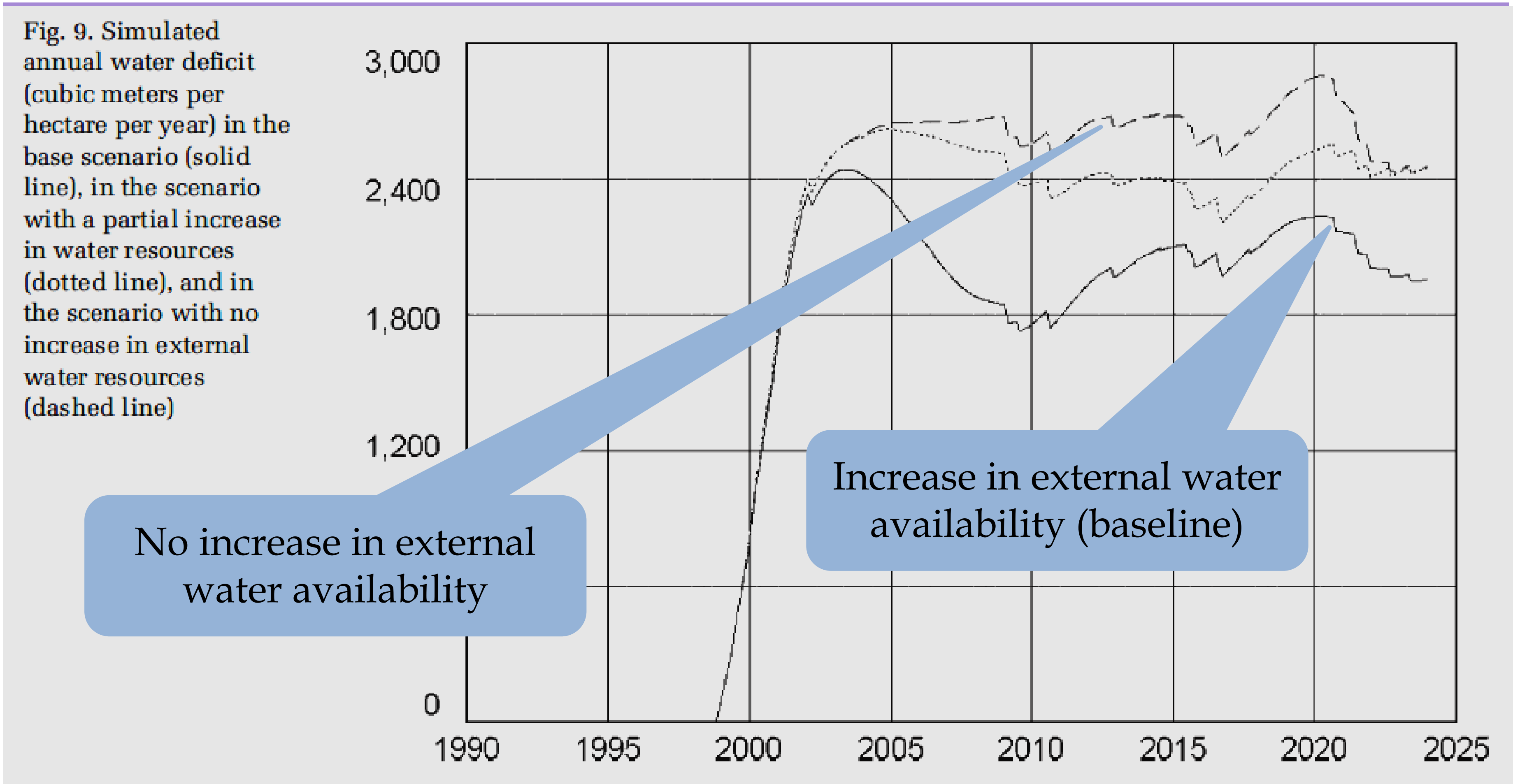
Fig. 5. (a) Historical (solid line) and simulated (dashed line) decline in average piezometric level (in meters). (b) Historical (solid line) and simulated (dashed line) increase in aquifer water conductivity (in microsiemens/cm), a measure of salinity

Fernandez et al. 2004



Case-study: CLD of (ground)water use in south-eastern Spain

Based on: Fernandez et al. 2004



Model simulation of **water deficit**

Model-based narratives (or scenarios):
different prospects for water deficiency and profitability

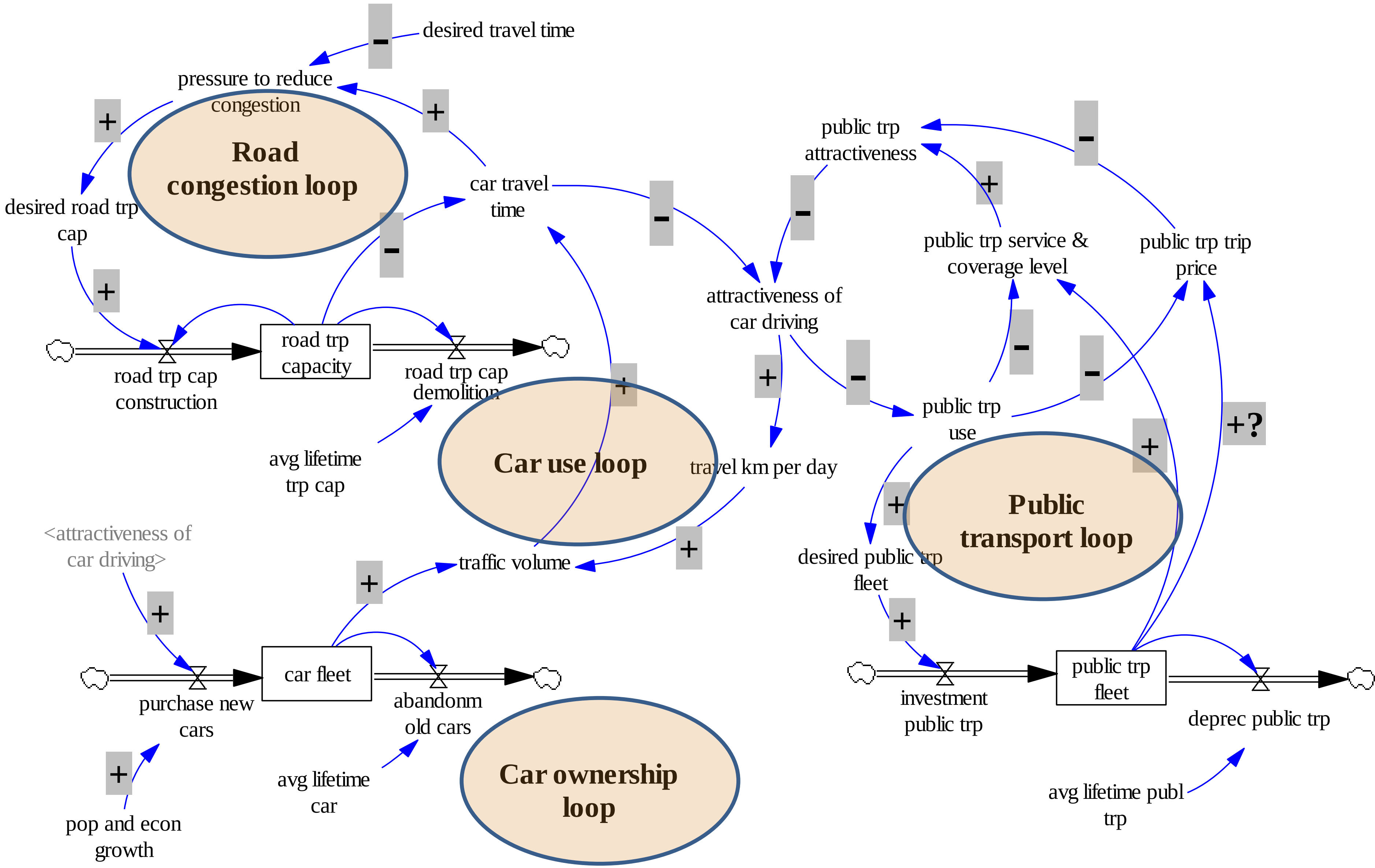
Fernandez et al. 2004

Example: basic model of transport modal split dynamics

STOCKS	FLOWS	FEED BACKS?	DELAYS?
# of cars	Purchase Discarding	from fuel cost, safety, pollution. Congestion, status	sales
# of bicycles	Purchase Discarding	from safety, congestion, status	sales
Road -km	Road building	noise, civil resistance	building, permits
Bicyclepath-km	B-path building		building

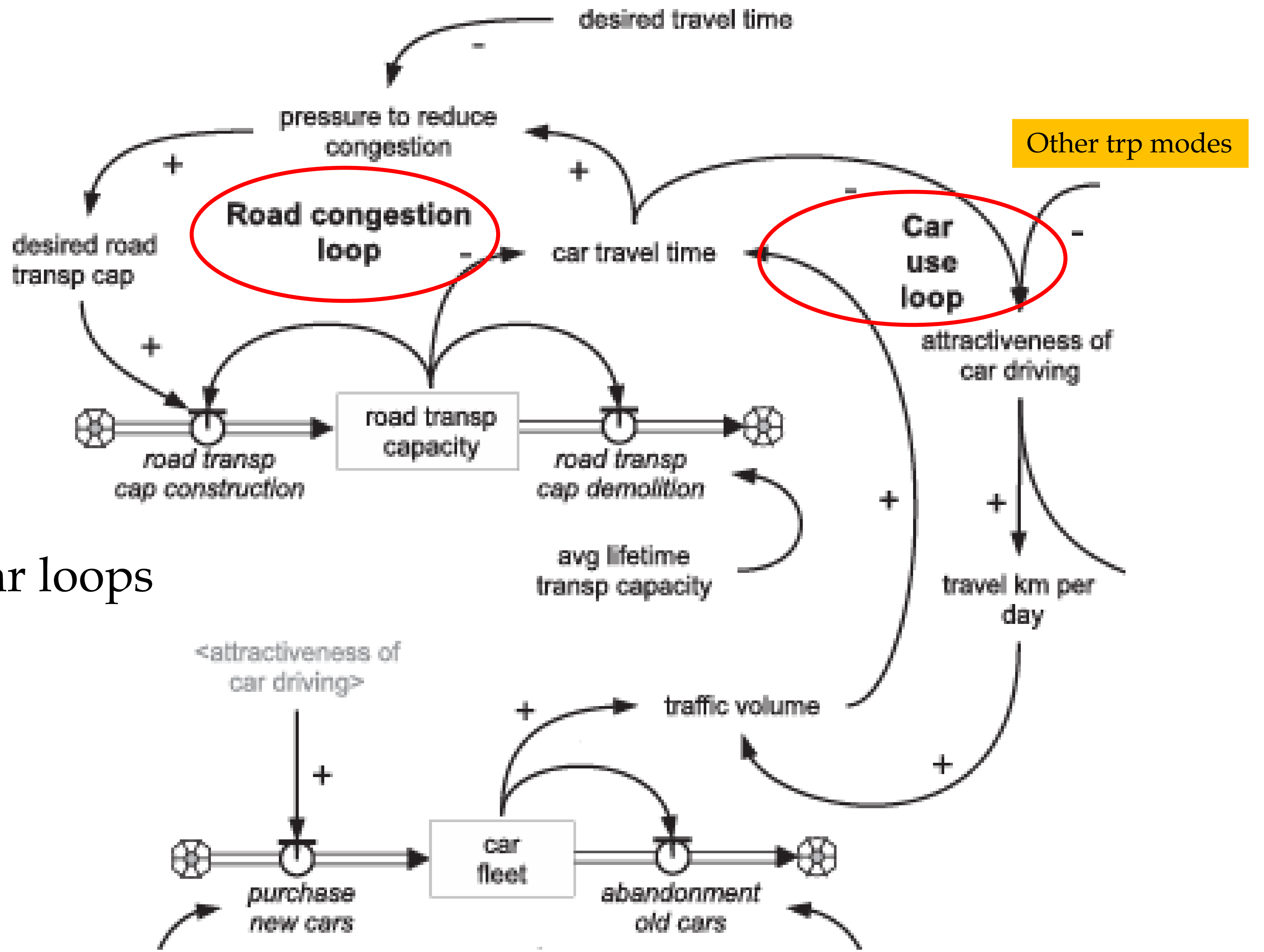
Can you fill in the table, from your own experiences?

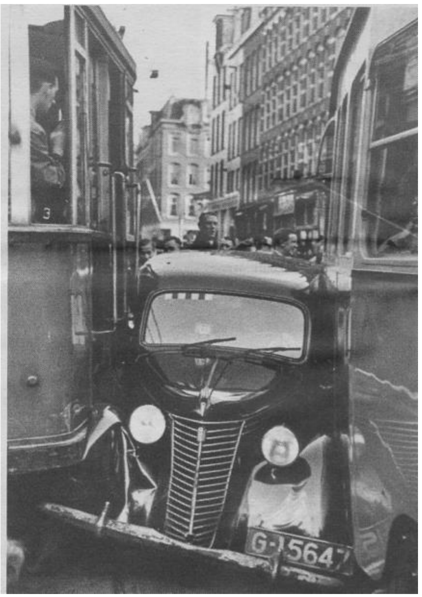
What follows; two more examples

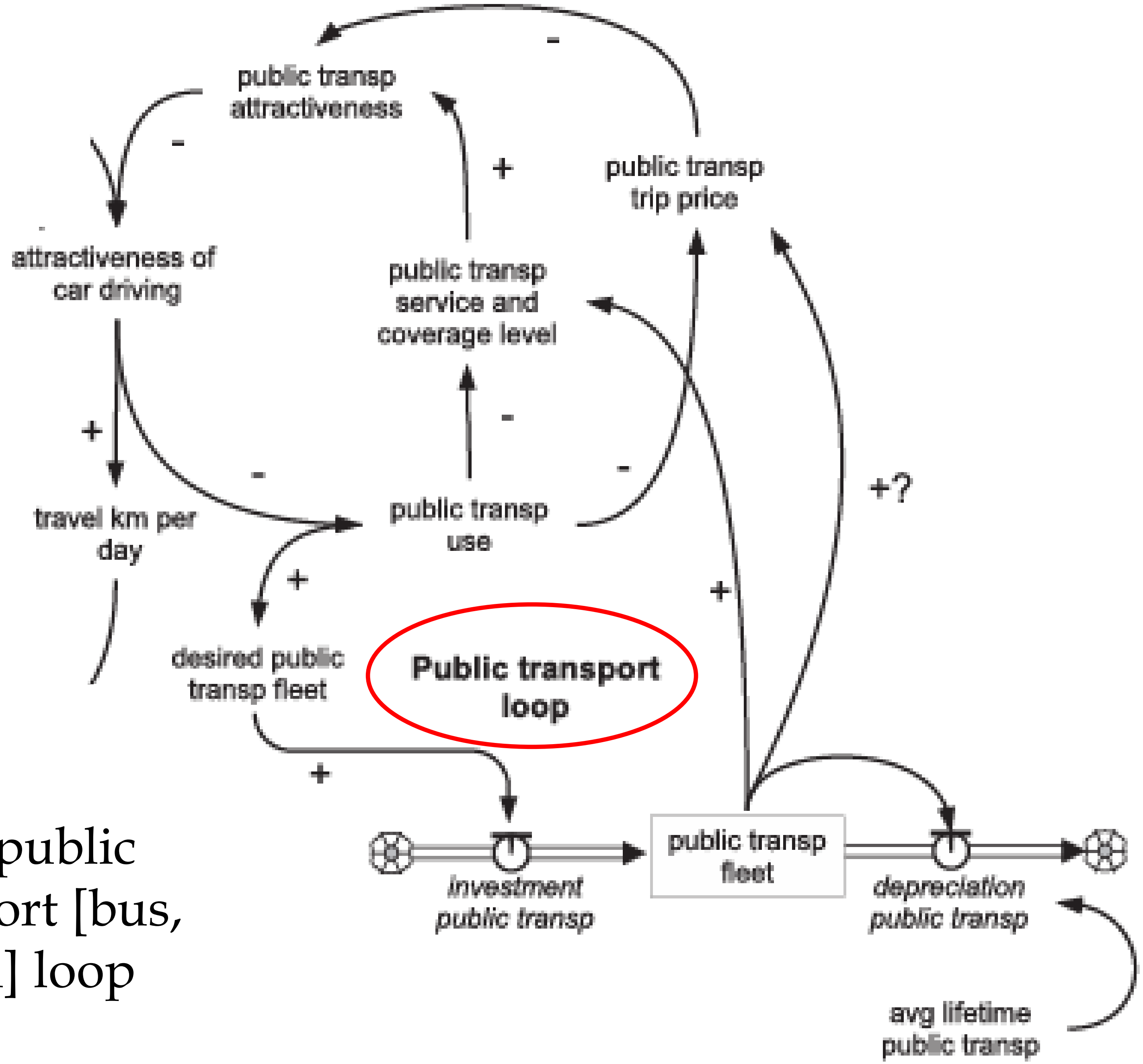


A causal loop diagram (CLD) of parts of the transport system
(based on Sterman 2000)

The car loops







The public transport [bus, tram] loop

Steps in making a [good] system dynamics model:

1. Carefully **analyse** statistical data (time-series, cross-country, material flux chains etc.)
2. **Talk** with people involved (‘stakeholders’) to understand their perception of the situation and their motives for their behaviour
3. **Construct** in an interactive way a first ‘causal loop diagram’ (CLD) to represent a common representation of the system [and the problem]
4. **Organize** a number of simulation rounds to implement the model and reproduce the available observations/data (‘model validation’)
5. **Organize** a number of presentation and discussion rounds which are used to improve the model and increase its legitimacy
6. **Set up** some model experiments to explore possible policy interventions

(Sterman, Business Dynamics 2000)

A **definition of sustainability** in the vein of system dynamics is the one proposed by the ecological economist Daly, in the form of three rules:

- *"Its rate of use of renewable resources do not exceed their rates of regeneration;*

- *its rates of use of nonrenewable resources do not exceed the rate at which sustainable renewable substitutes are developed; and*

- *its rates of pollution emission do not exceed the assimilative capacity of the environment."*

(Daly, in Meadows *et al*. 1991 pp. 209).

Sustainability ↔ Stability (i.e. Attractors)

www.sustainabilityscience.eu