EPFL

ENV 501 / GR A3 30

Material Flow Analysis and resource management

Prof. Dr. Claudia R. Binder claudia.binder@epfl.ch
Dr. Francisco Xavier Felix Martin Del Campo francisco.felixmartindelcampo@epfl.ch
Teaching Assistant :Jaïr Campfens jair.campfens@epfl.ch
Teaching Assistant : Leonard Léchot leonard.lechot@epfl.ch
Student Assistant: Alicia Pérez Domouso alicia.perezdomouso@epfl.ch

Fall 2025

- Laboratory on Human-Environment Relations in Urban Systems

Last week

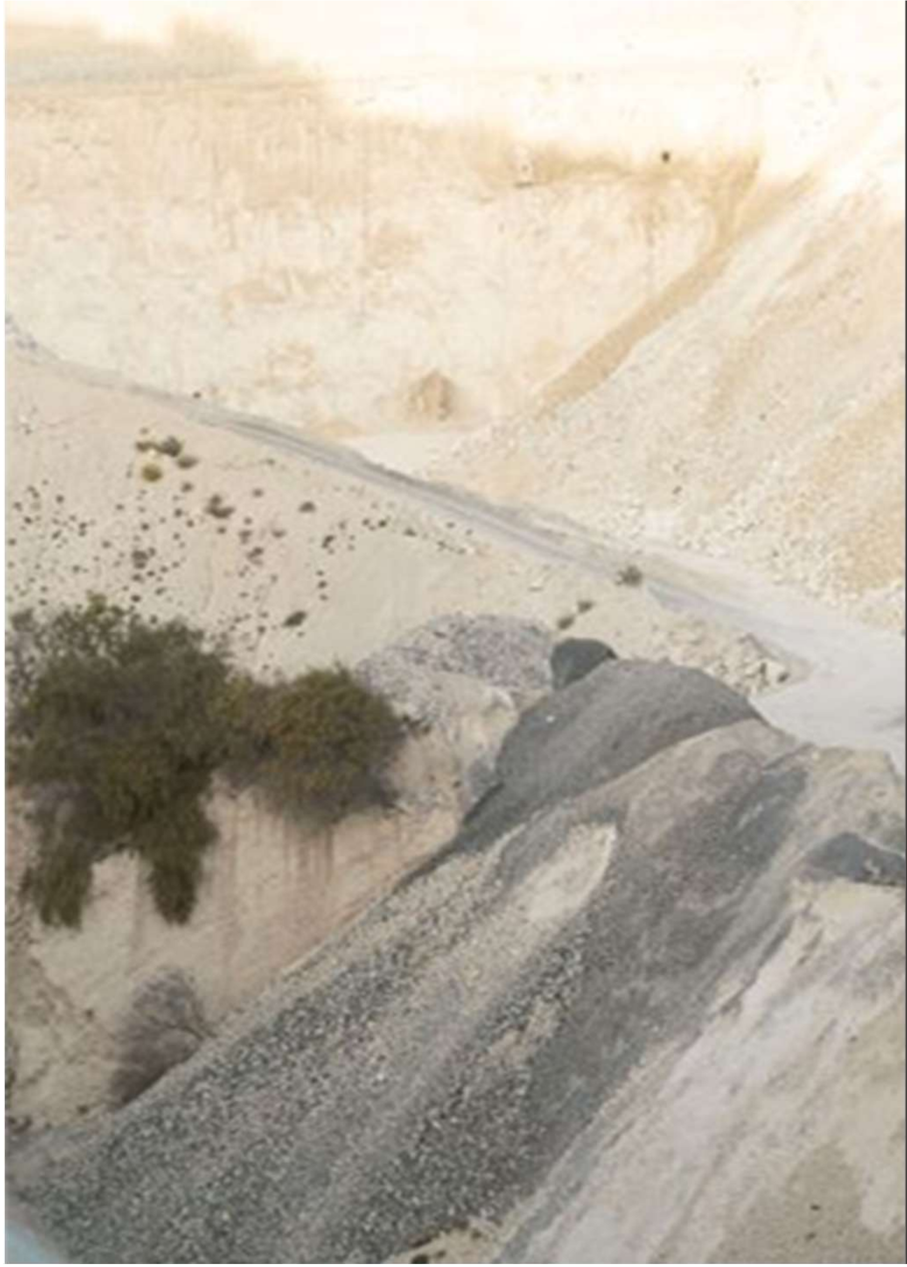
- Urban Metabolism vs. Urban MFA
- System boundaries of cities
- Accounting approaches
- Where to find data
- Urban metabolism examples
- Circular economy and MFA
- Circular economy policies and insights

Course outline

Block	Week	8:15 - 9:00 and 9:15 - 10:00		13:15 - 14:00	14:15 - 15:00
Block I: EW-MFA global / national	W1 - Sep 11	Introduction to the course and general concepts	All	Exercise	Project
	W2 - Sep 18	EW – MFA and EW – MFA in the Swiss context	External Guest – Florian Kohler	Exercise	Project
	W3 – Sep 25	Examples of EW – MFA. Scaling EW-MFA to Cantons	FMC	Exercise	Project
	W4 - Oct 02	Urban Metabolism and Circular Economy	FMC	Exercise	Project
Block II: MFA regional / urban	W5 - Oct 09	MFA method and the Stock-Flows-Service Nexus	CRB	Exercise	Project
	W6 - Oct 16	Dynamic MFA	External Guest – Stefan Pauliuk	Exercise	Project
	Oct 23	Autumn break			
	W7 - Oct 30	Applications of MFA – case study	External Guest – Guillaume Massard	Exercise	Project
	W8 - Nov 06	Input-Output Analysis and Material Flow Cost Accounting	External Guest – Vincent Moreau	Exercise	Project
	W9 - Nov 13	Spatial MFA	FMC	Exercise	Project
	W10 - Nov 20	Combined approaches: MFA + LCA; MFA + sociodemographics.	AS & FMC	Exercise	Project
Block III: Social sciences and public policy	W11 - Nov 27	Combined approaches: MFA + surveys; Quasi-dynamic MFA	GF & FMC	Exercise	Project
	W12 - Dec 04	Social metabolism and dynamic MFA in industrial systems	CRB – Martyn Wakeman	Past exam	Project
	W13 - Dec 11	Agent-based model	CRB, FMC, MAH, SLC	Project	Project
	W14 - Dec 18	Group Project Presentation	All	Project	Project

Content of lecture

- Opening the box: regional MFA
- Main components of MFA systems
- MFA and mathematical system definition
- The Stock-Flow-Service Nexus: Definitions and relevance
- System’s linkages in society’s metabolism



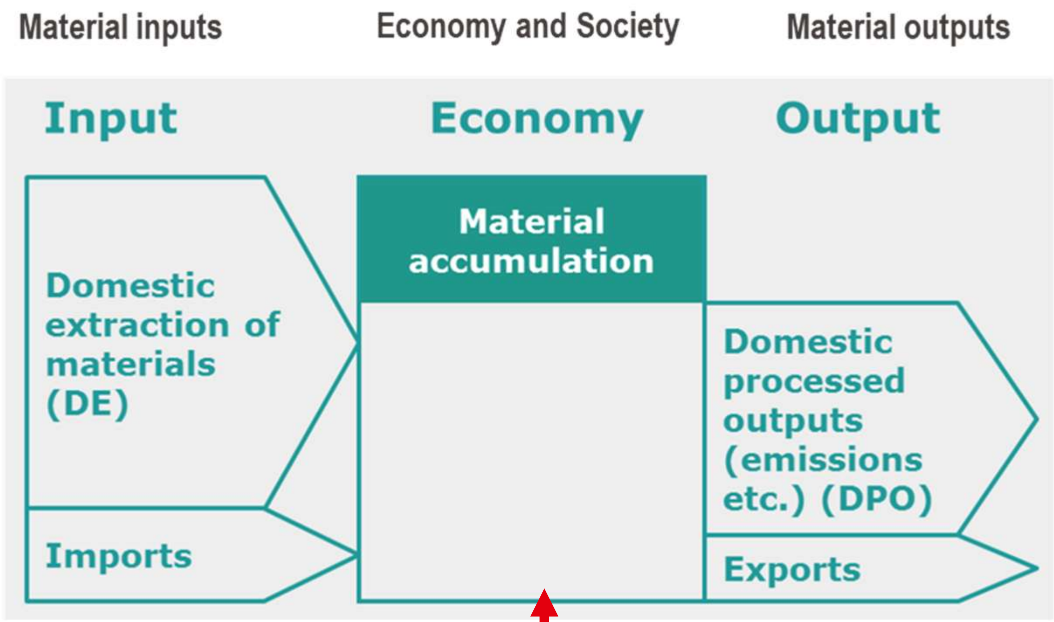
Binder, Félix Martín del Campo

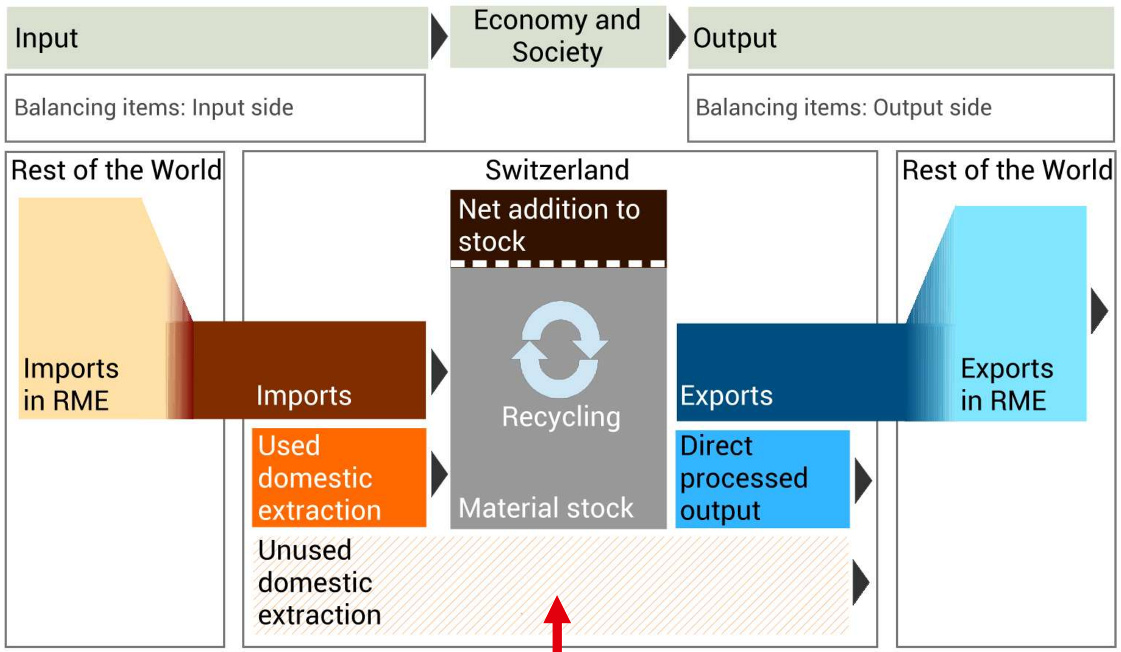
Opening the box

• Laboratory on Human-Environment Relations in Urban Systems

EPFL

Switzerland EW-MFA indicators





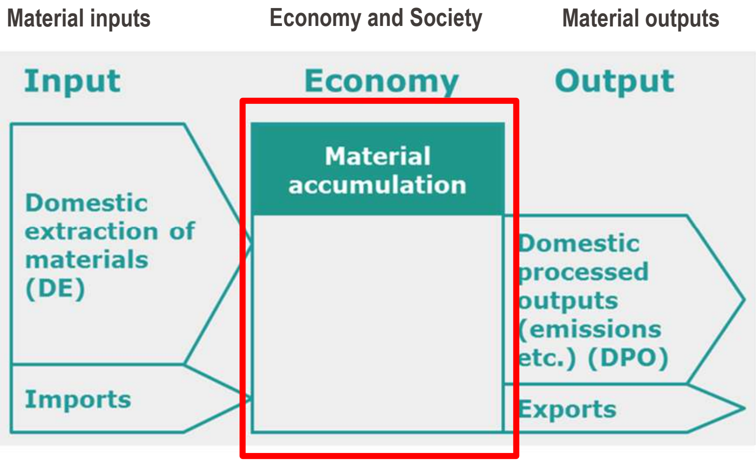
RME: Raw Material Equivalents

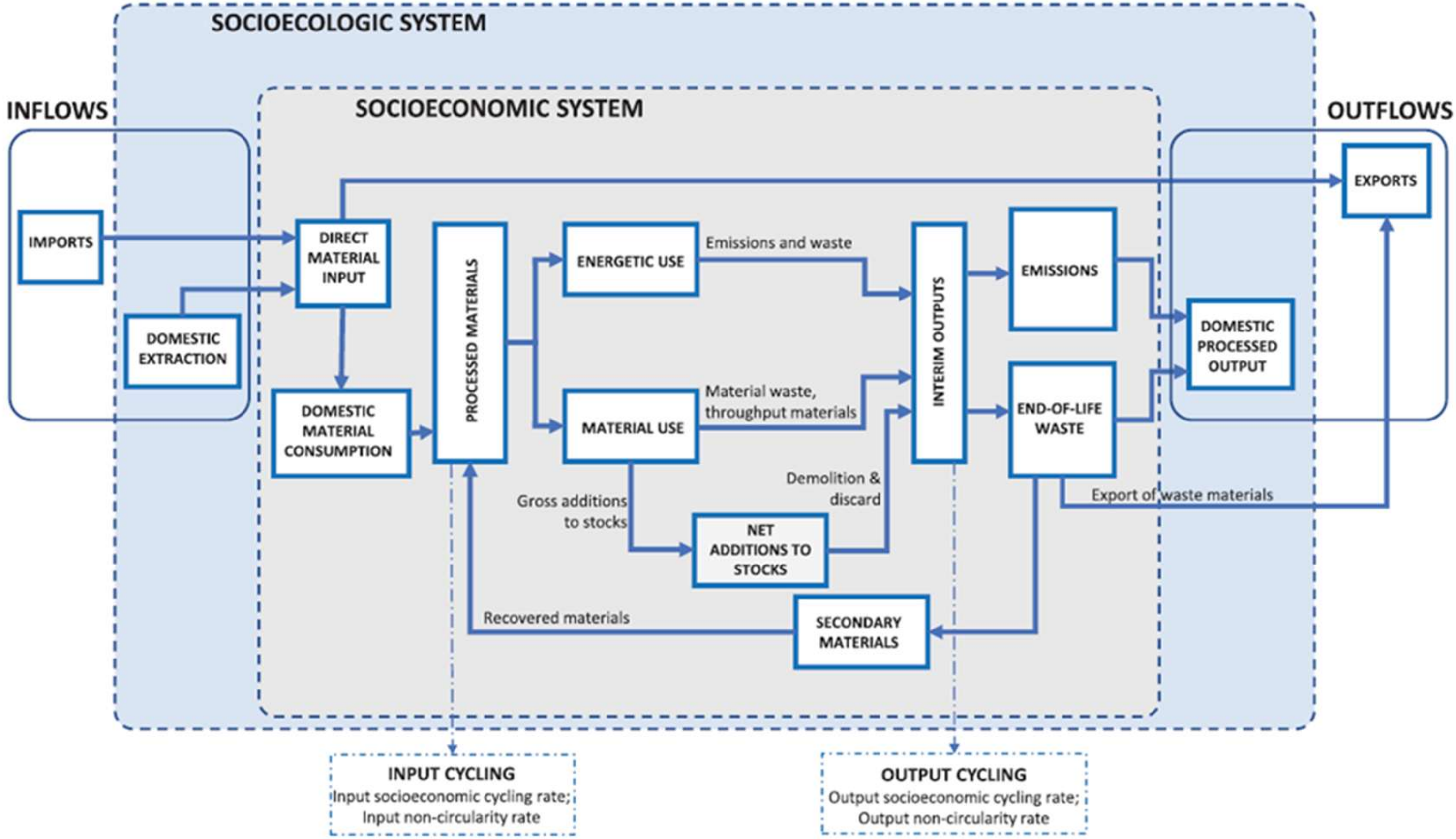
What happens inside the box?

Who consumes what?
Who recycles ?
What are the recycling processes?

Source: Swiss Federal Statistical Office, 2018; Eurostat, 2018

Economy-wide MFA (EW-MFA)

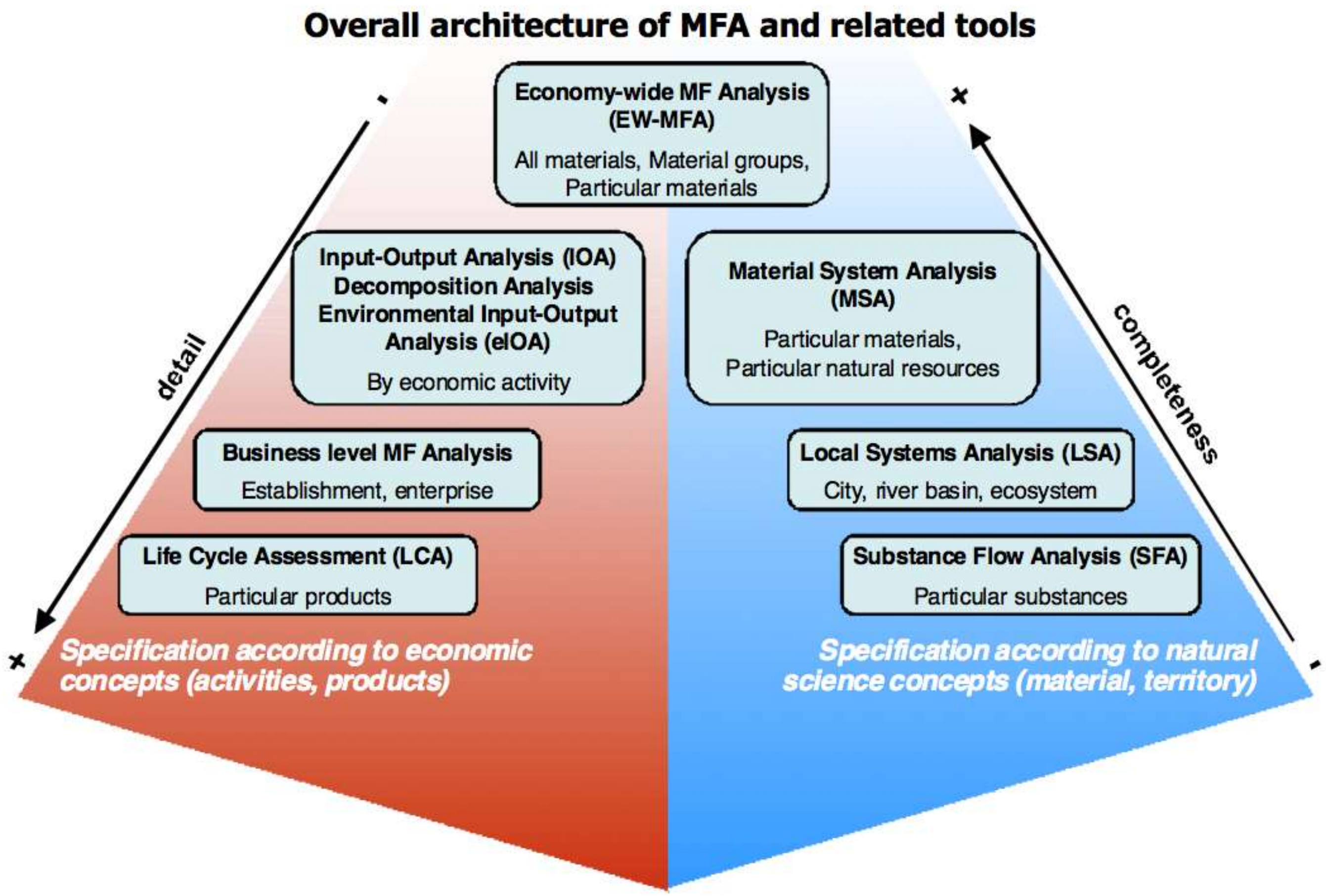




Note: Calculations also possible in **Raw Material Equivalents** = domestic extraction of natural material inputs that were necessary to produce the respective traded goods

Source: Martin del Campo et al., 2023

Hierarchy of MFA tools



OECD, 2008

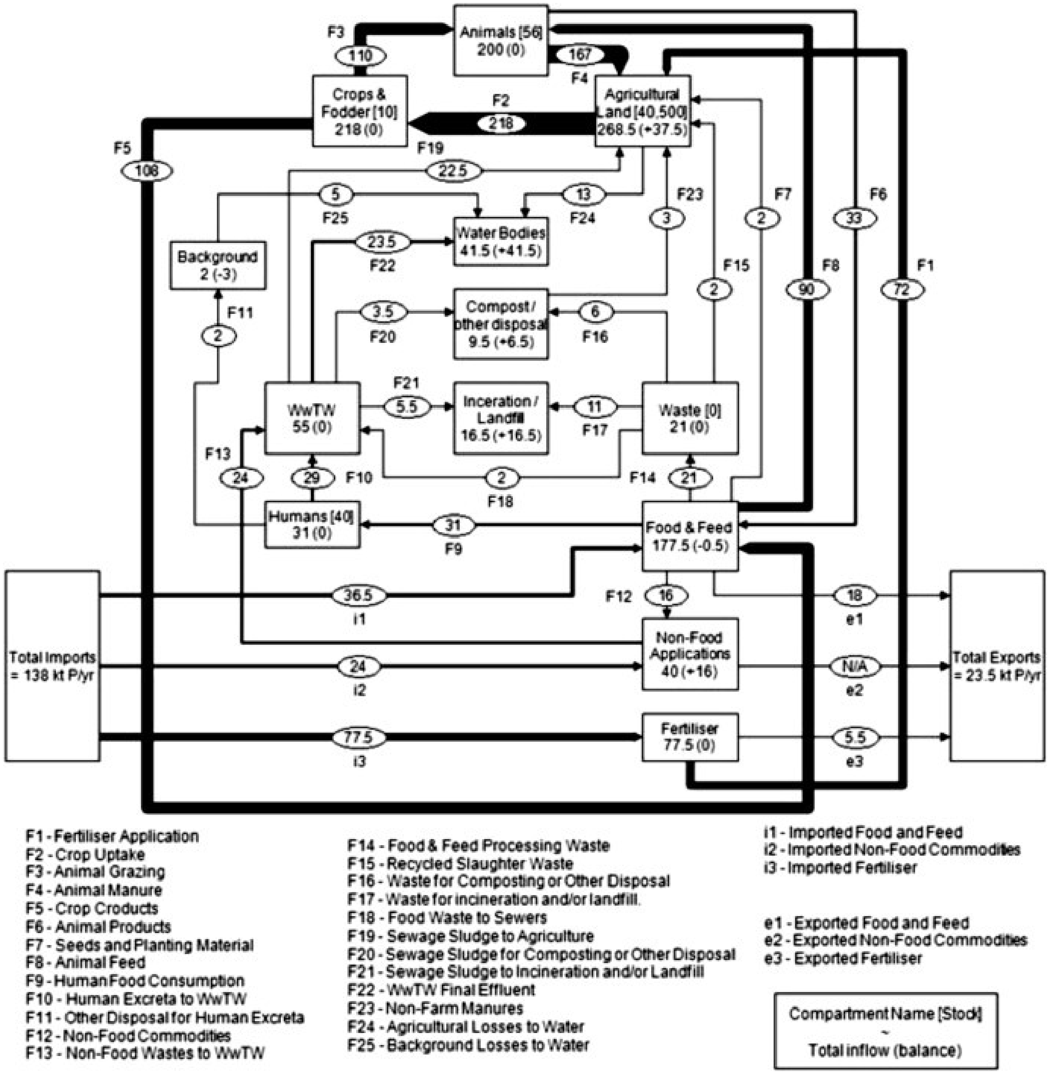
IE approaches in this course

Main objective	Substances	Materials	Products, Goods and Services		Businesses		Economic activities	Countries, Regions
	e.g., chemical elements or compounds (Cd, Cl, Pb, Zn, Hg, N, P, C, CO_2, CFC)	e.g., raw materials and semi-finished goods, energy carriers, metals (ferrous and nonferrous), sand and gravel, timber, plastics	e.g., batteries, transportation, packaging		e.g., offices, plants, small and medium sized entreprises, multi-national entreprises		e.g., mining, construction, chemical industry, iron and steel industry	e.g., aggregated mass of materials and related mixed or selected materials
Type of analysis	**Substance Flow Analysis**	**Material Flow Analysis**	**Life Cycle Assessment**		**Business level Material Flow Analysis**		**Input–Output Analysis**	**Economy-wide Material Flow Analysis**
Type of analytical tools	Substance Flow Accounts	Material Flow Accounts, Industrial, Urban or Regional Metabolism	Life-Cycle Inventory, Impact Assessment (ISO 14040)	Lif-Cycle Costing	Material Flow Cost Accounting (ISO 14051)	Business Material Flow Accounting	Physical Input-Output Tables, NAMEA approaches	Economy-wide Material Flow Accounts

Source: Moreau and Massard, 2017

Phosphorous flows in UK

Binder, Félix Martín del Campo



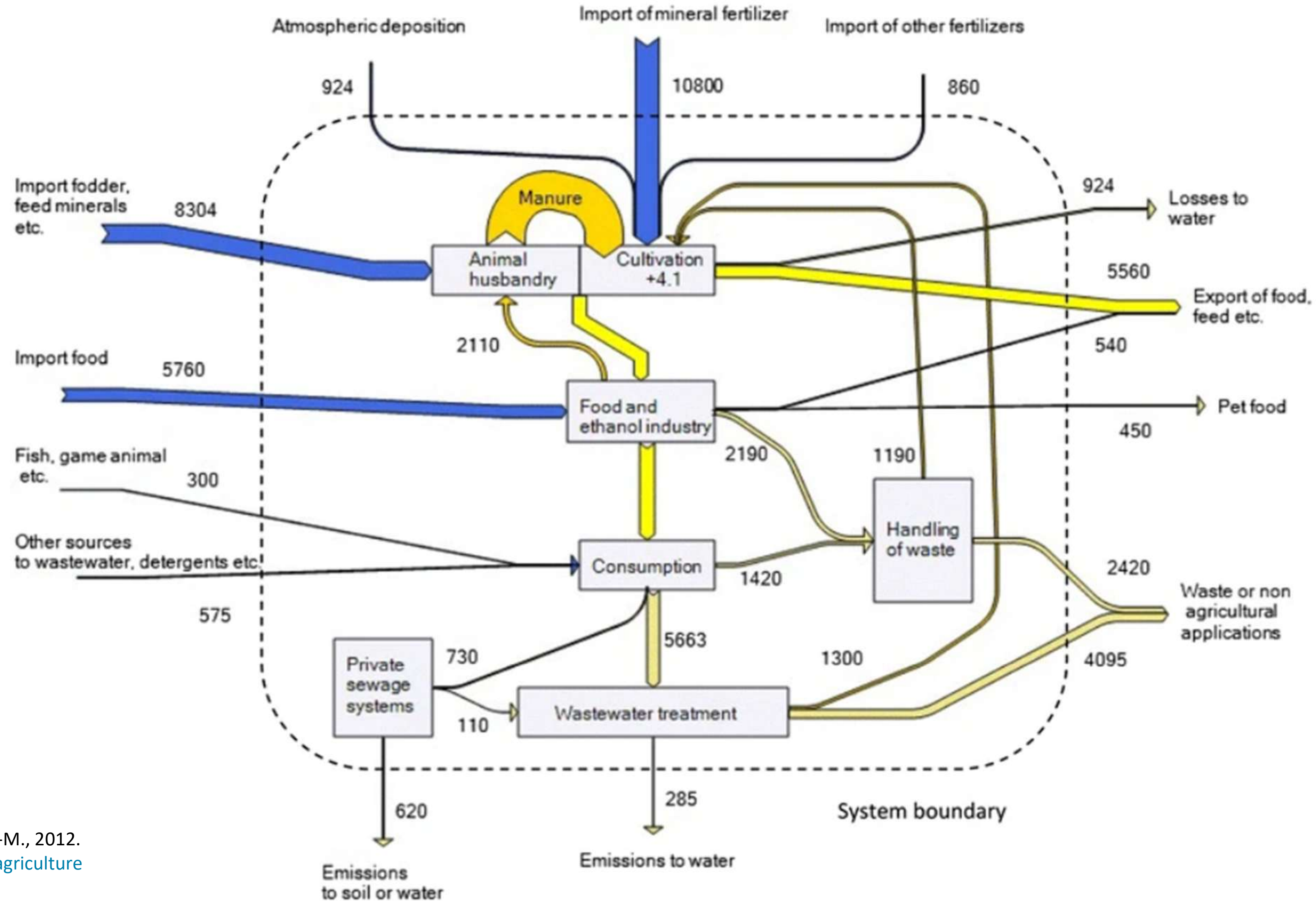
SFA for the UK food production and consumption system. Diagram produced using the STAN program All values are expressed in kt P/yr. The calculations, assumptions and uncertainties for each flow are detailed in Table 1. The existing stock, inputs and accumulations for each process are presented in Table 2.
Cooper and Carliell, 2013

Phosphorous flows in UK

Flow number and name	Description	Calculations, assumptions and references.	Estimated amount (kt P/yr)	Average amount[a] [±2 s] (kt P/yr)	Average confidence interval[b] [range] (kt P/yr)	Final value[c] [95% confidence limits] (kt P/yr)
F1) Fertiliser application	The quantity of p within fertiliser applied to arable and grassland in the UK.	FAOSTAT (2011) estimate of consumption in 2009.	73.8	68.0 [±20.0]	*/1.1 [±9.5]	72.0 [±20.0]
		FAOSTAT (2012) estimate of consumption in 2009.	80.3			
		British Survey of Fertiliser Practice (BSFP) 2010 land areas and application rates for 2009 (Defra, 2011b). British application = 70.5 kt P/yr (45.7 kt P/yr to arable land (4.55 million hectares (Mha) at 10.0 kg P/ha) and 24.8 kt P/yr to grassland (6.3 Mha at 3.9 kg P/ha)). Northern Ireland total = 2.3 kt P/yr (DARD, 2010b).	72.8			
		BSFP total fertiliser nutrient consumption for UK (Defra, 2011b).	56.3			
		Defra's soil nutrient balance for 2009, inorganic fertilisers (Clothier, 2010).	56.0			
F2) Crop uptake	The quantity of P removed from agricultural land in crops and grasses.	Estimates for UK crop production obtained from Agriculture in the UK 2010 (Defra, 2011a), average nutrient contents taken from the Fertiliser Manual (RB209) (Defra, 2010d), gives UK crop production of 107.3 kt P. Uptake of P from pasture of 110 kt P from Clothier (2010).	217.3	217.0 [±0.3]	*/1.2 [±48.0]	218.0 [±48.0]
		Defra's soil nutrient balance for 2009, total phosphorus outputs, including total harvested crops, forage and crop residues (Clothier, 2010).	217.0			

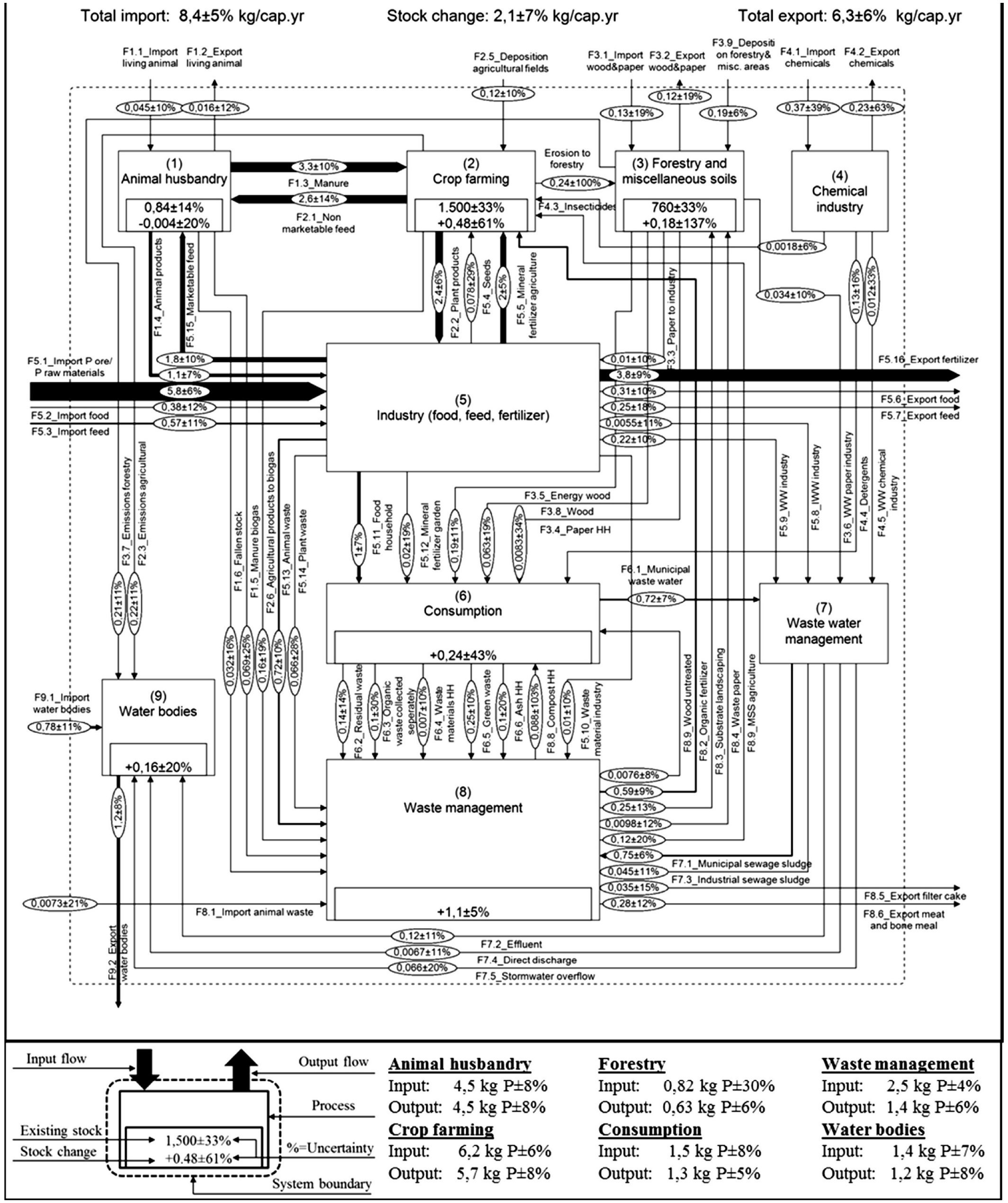
Cooper and Carliell, 2013

From: Phosphorus Flows to and from Swedish Agriculture and Food Chain



Linderholm, K., Mattsson, J., Tillman, A.-M., 2012.
Phosphorus flows to and fromSwedish agriculture and food chain. AMBIO 41, 883–893.

Binder, Félix Martín del Campo



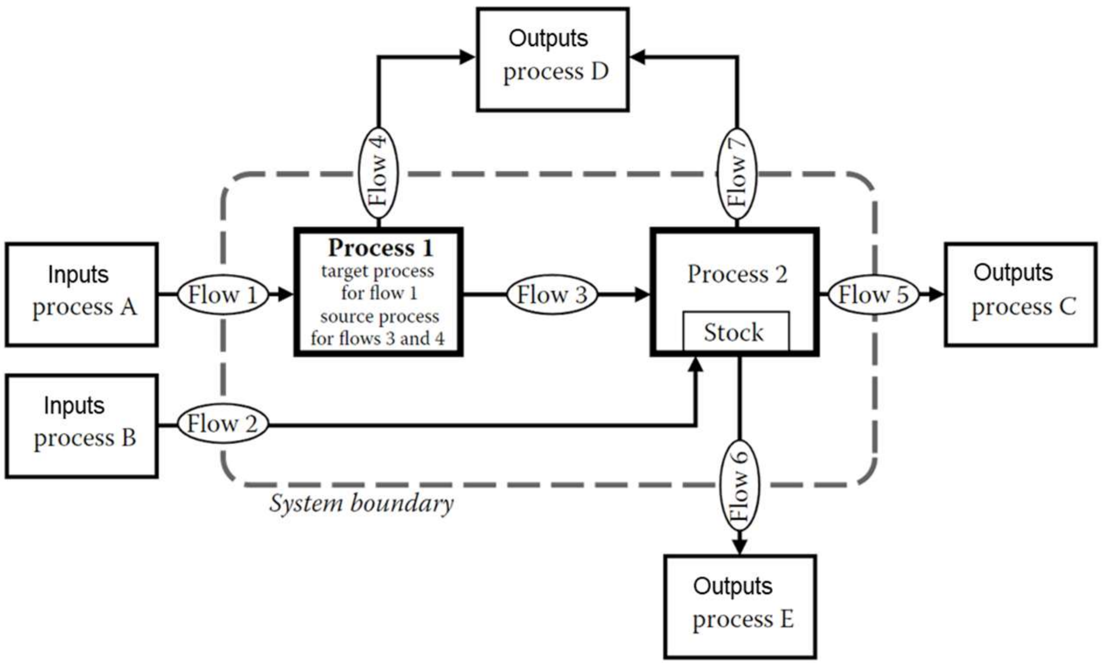
Austrian national phosphorus budget with reconciled data in kg P cap−1 yr−1.
Egle et al., 2014

Observations

- No clear standardized representations
- Each country uses different set of processes
- Difficult to compare countries

- What do they have in common?

EPFL



- Laboratory on Human-Environment Relations in Urban Systems

Binder, Félix Martín del Campo

Main components of MFA systems

Material Flow Analysis (MFA) – Definition (recap)

- Material Flow Analysis (MFA) is the systematic study of **physical flows of natural resources and materials** into, through and out of a given system (usually the economy).
- It is based on accounts in **physical units,** and uses the **principle of mass balancing** to analyze the **relationships between material flows** (including energy), **human activities** (including economic and trade developments) and **environmental changes.**
- The system is defined in **space** and **time**.
- **Connects** the sources, pathways and sinks of a **material**.

MFA system

- **MFA system:** comprises a set of material **flows**, **stocks**, and **processes** within a defined **boundary**.
- **System boundary** is defined in space and time.
- **Temporal boundary:** time period over which the material balance is calculated (e.g. 1 hour for waste incineration process, 1000 years for landfills, 1 year for a city).
- **Spatial boundary:** geographical area (e.g. municipality, region, city) or virtual limits (e.g. private households, company).

EPFL

MFA system (I)

Binder, Félix Martín del Campo

What is a **process**?

- A **process** is any **transformation**, **operation**, or **activity** within a system where materials or energy are **converted**, **stored**, or **utilized** to produce **goods**, **services**, or **emissions**.
- Processes interact with flows by receiving inputs, transforming these into products or services, and generating outputs like emissions or waste.
- Analyzing processes is crucial for identifying efficiencies in production systems, and optimizing resource use.

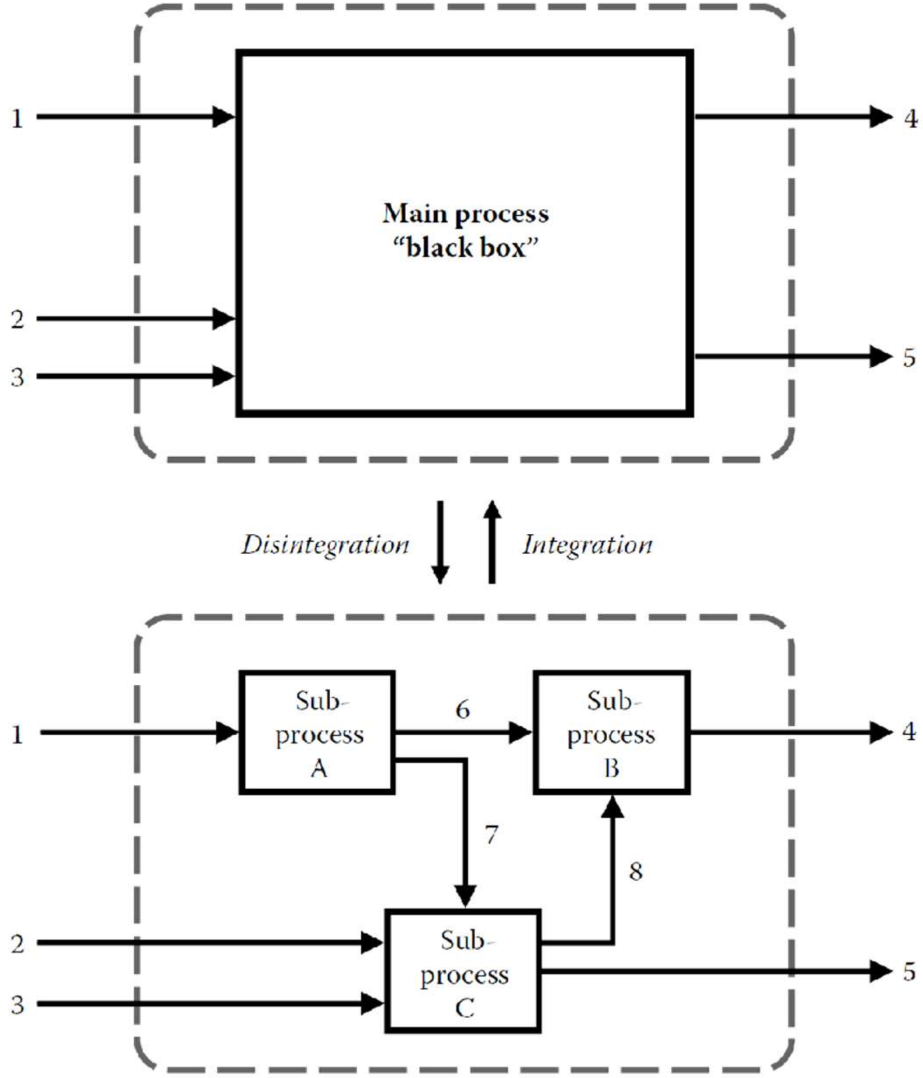
MFA system

Process

System understanding

Opening the “black box”

- Waste incineration process
- Wastewater treatment plant
- Energy production
- Recycling
- Landfill

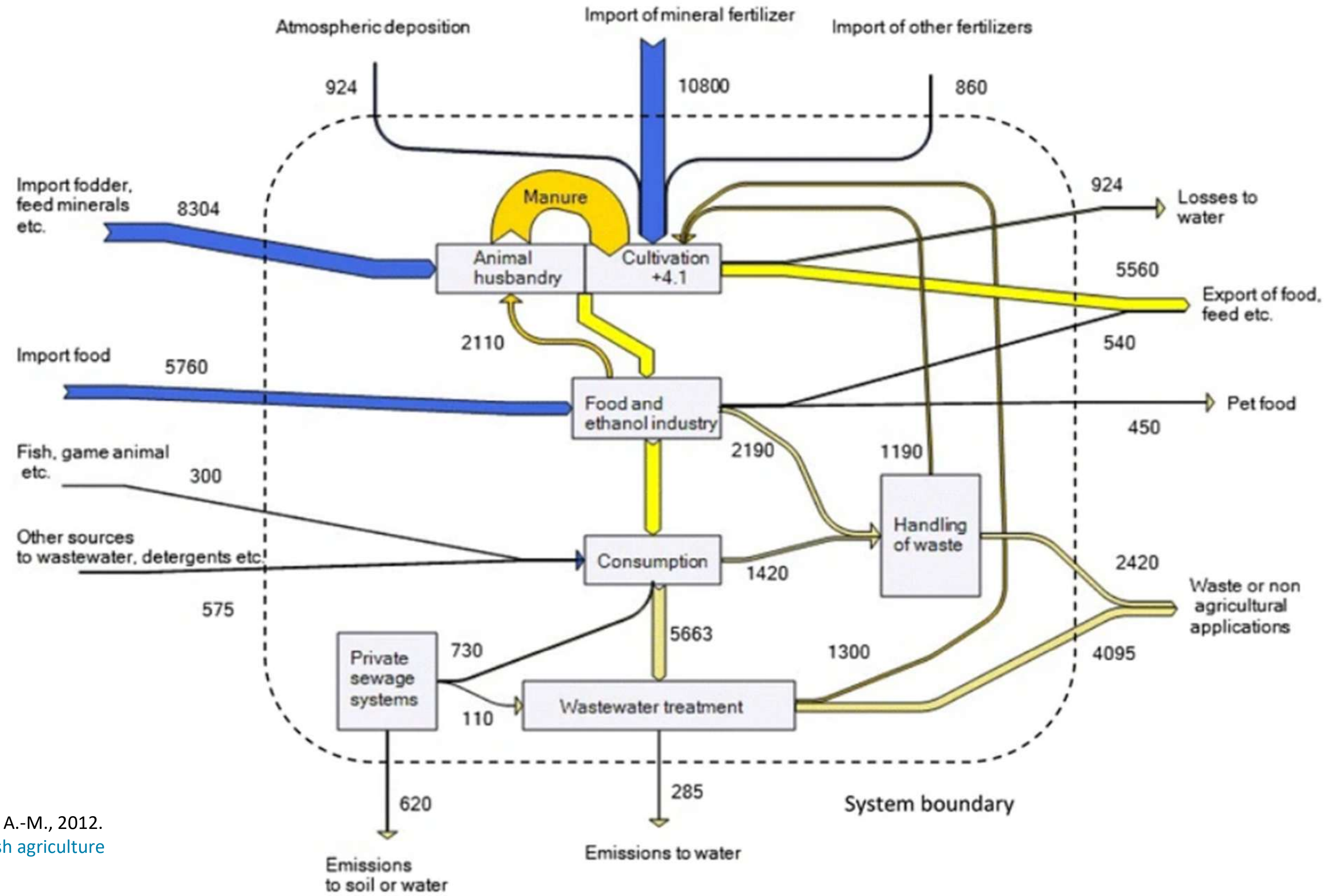


Binder, Félix Martin del Campo

From: Phosphorus Flows to and from Swedish Agriculture and Food Chain

How are processes labelled?

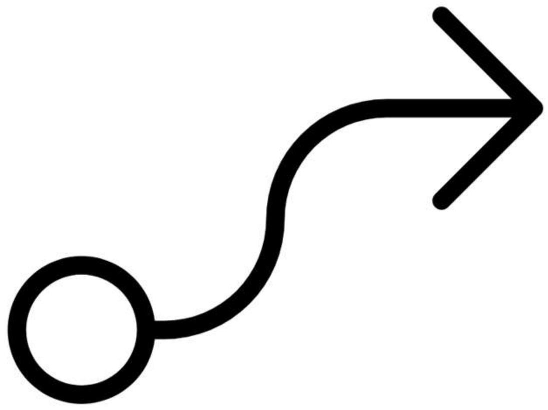
How would you define efficiency indicators?



Linderholm, K., Mattsson, J., Tillman, A.-M., 2012. Phosphorus flows to and fromSwedish agriculture and food chain. AMBIO 41, 883–893.

MFA system (II)

What is a **flow**?



- A **flow** refers to the **movement** or **transfer** of materials, resources, or energy **through a system** over a specific period of **time**.
- **Inflows** (inputs), **throughputs** (flows within the system), and **outflows** (outputs e.g., emissions, waste, or products).
- Tracking flows is essential to monitoring resource efficiency, consumption patterns, and environmental impacts associated with production and use.

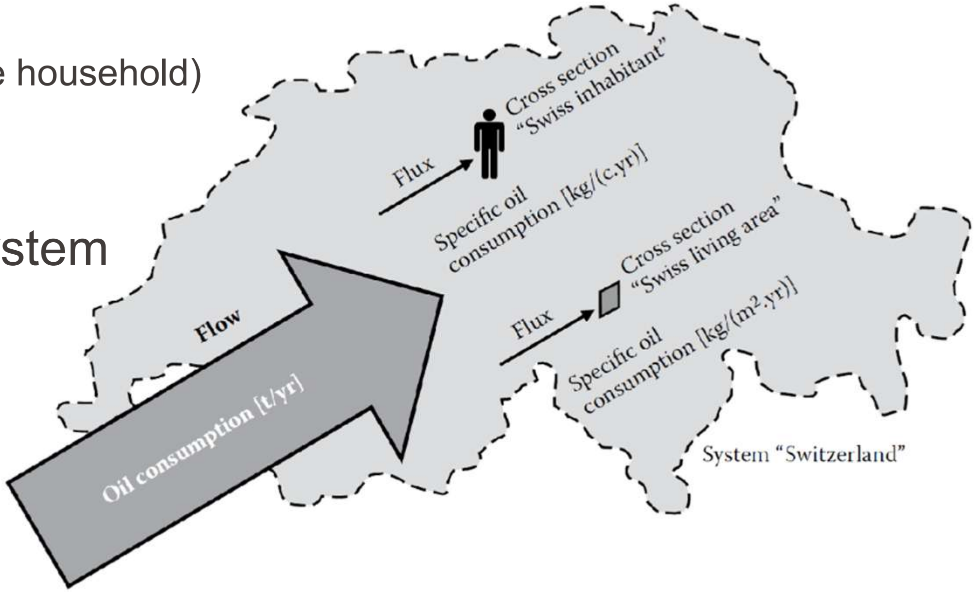
Binder, Félix Martín del Campo

MFA system (III)

Flows

<u>Materials flowing from one process to another</u>

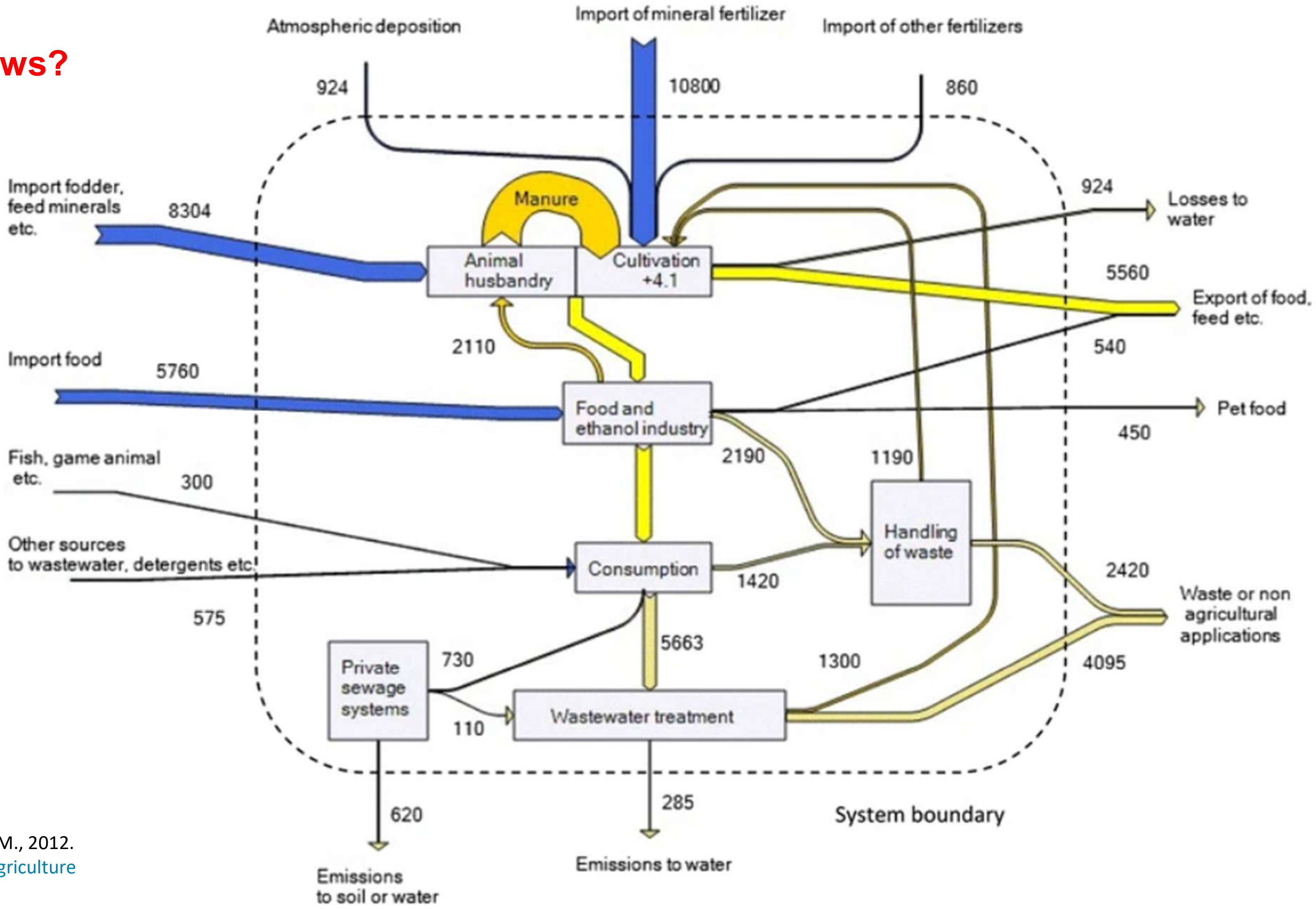
- **Flows:** ratio of mass per time (e.g. t/y)
- **Fluxes:** flow per cross section (e.g. person, private household)
- **Inputs**: Flows/fluxes entering a process
- **Outputs:** Flows/fluxes exiting a process
- **Imports and exports:** Flows/fluxes across system boundaries:



Source: Brunner & Rechberger, 2016

From: Phosphorus Flows to and from Swedish Agriculture and Food Chain

What are the key flows?



Linderholm, K., Mattsson, J., Tillman, A.-M., 2012. Phosphorus flows to and fromSwedish agriculture and food chain. AMBIO 41, 883–893.

Importance of flows

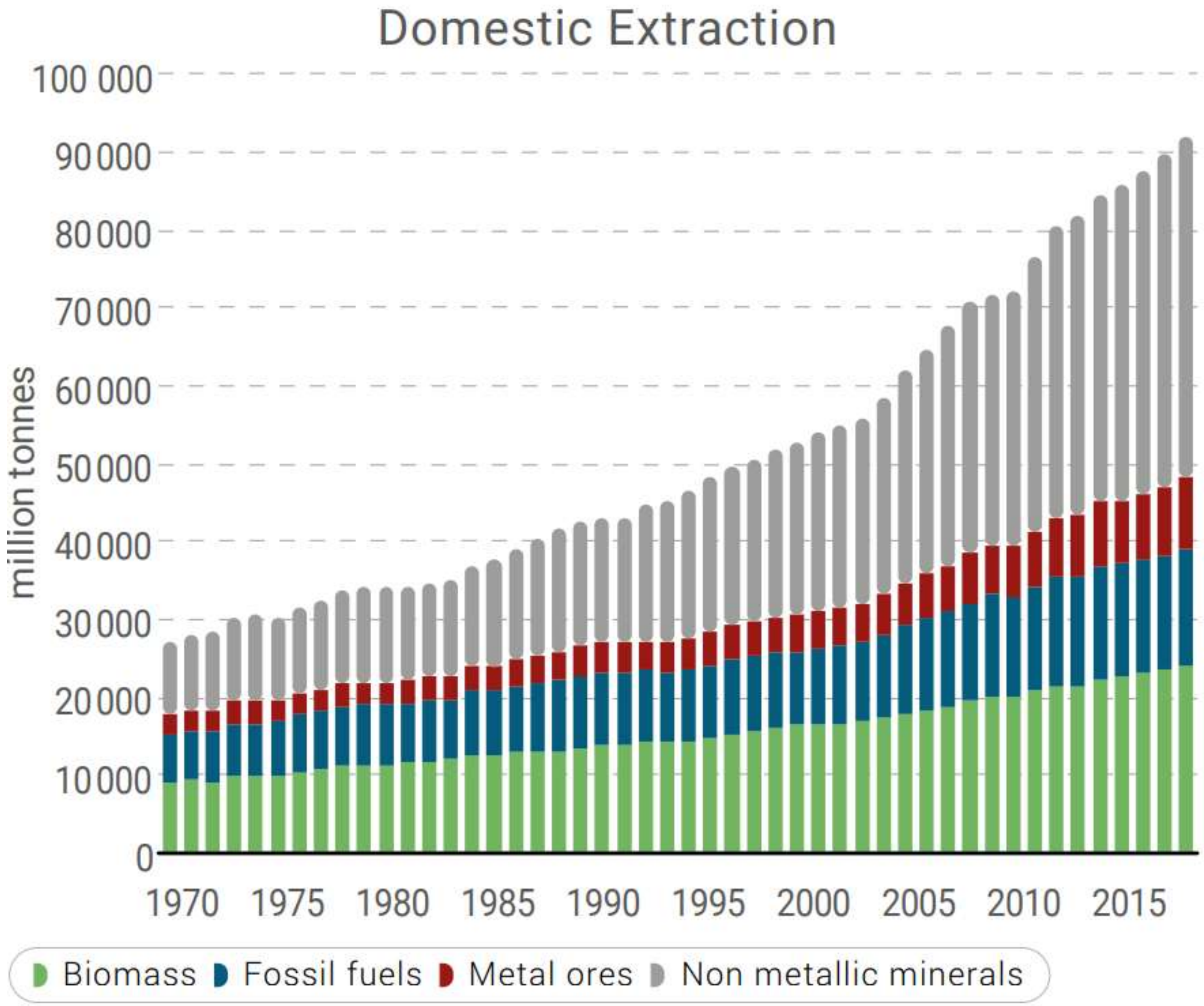
The growth in resource use has caused a sharp increase in global material extraction, particularly of non-renewable materials.

Extraction in **1970**:
+**20** billion tonnes

Extraction in **2020**:
+**100** billion tonnes

Projections by **2050**:
+**180** billion tonnes

Recycling rates in **2020**:
8.6%



Source: UNEP & IRP, 2018

Binder, Félix Martín del Campo

MFA system (IV)

What is a **stock**?

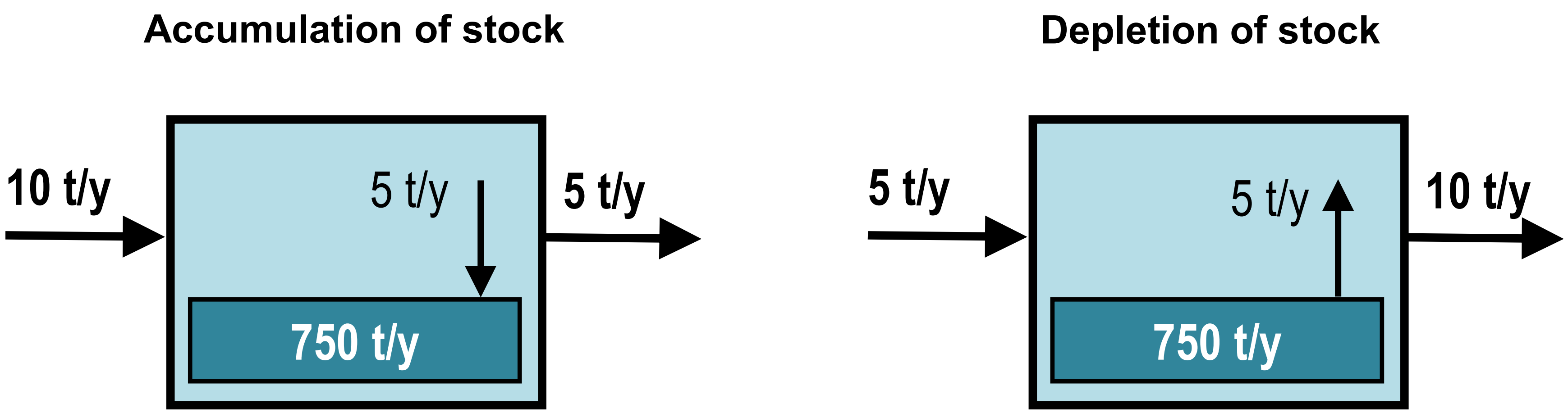
- A **stock** represents the **accumulated quantity** of a material, resource, or product present in a **defined system or boundary** at a given point in **time**.
- Stocks can refer to **physical assets** such as buildings, infrastructure, machinery, or the amount of a resource stored within a particular environment (e.g., metal stock in urban buildings).
- Stocks are crucial because they store materials, need materials for maintenance, and eventually release them back into the environment.

MFA system: Stocks

Binder, Félix Martín del Campo

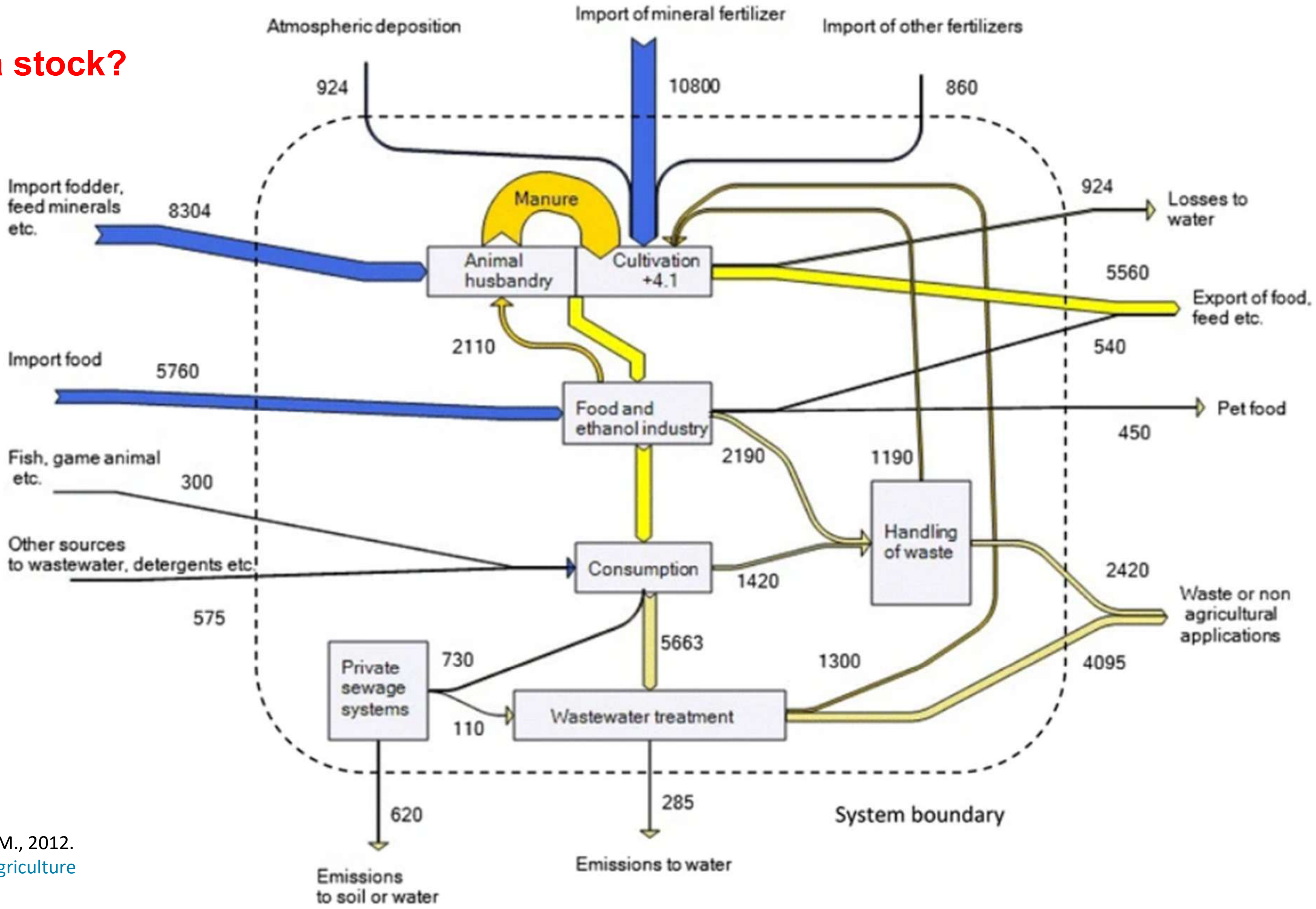
- <u>Material reservoirs or material quantity **within a process**</u>

- Stocks can stay constant, increase or decrease in size
- Accumulation/depletion of stock: difference between process inputs and outputs between two time steps



From: Phosphorus Flows to and from Swedish Agriculture and Food Chain

Where do we have a stock?

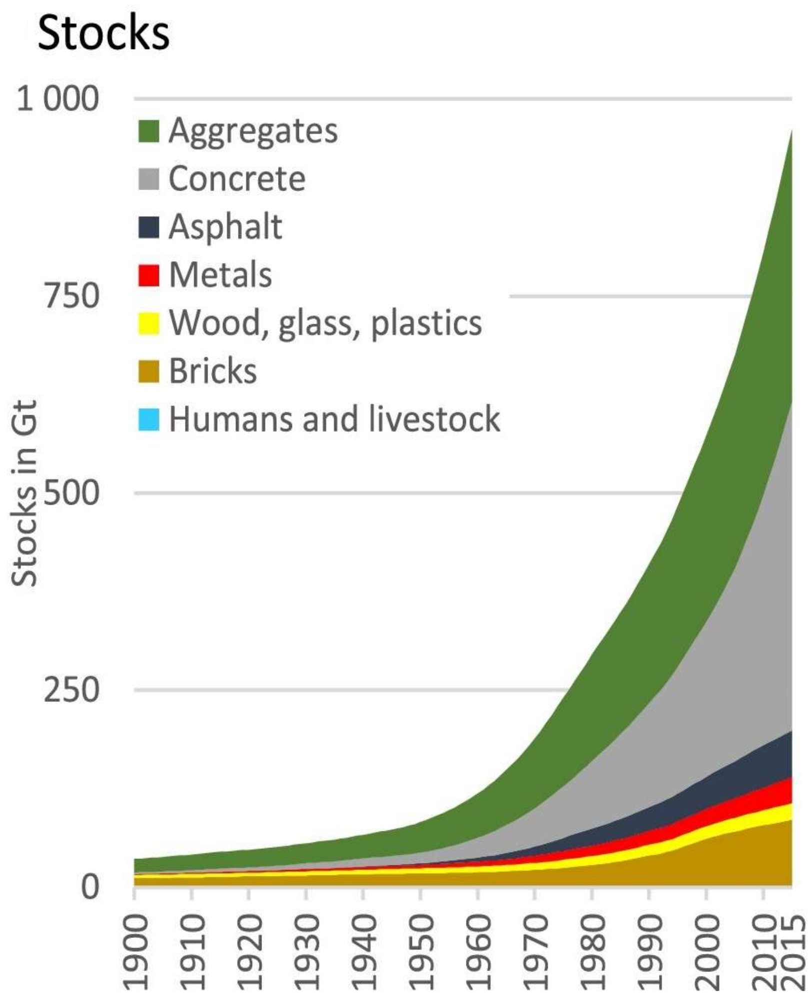


Linderholm, K., Mattsson, J., Tillman, A.-M., 2012.
Phosphorus flows to and fromSwedish agriculture and food chain. AMBIO 41, 883–893.

EPFL

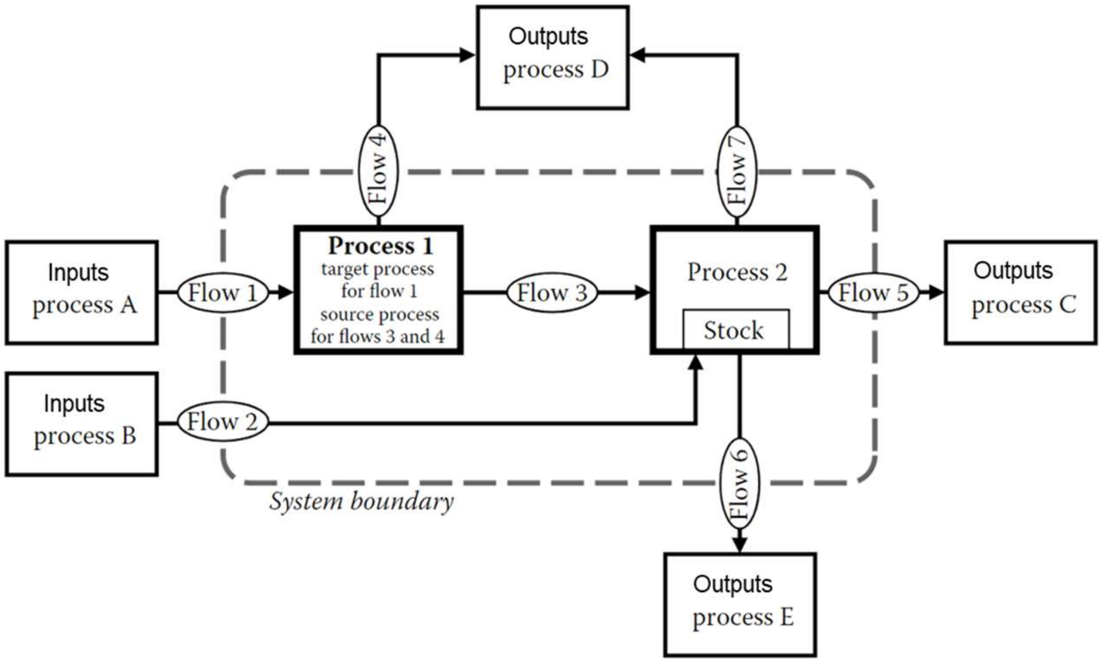
Importance of stocks

- In 2015**, 75%** of all **extracted materials** were linked to increasing or replacing **material stocks**
  - Buildings
  - Infrastructures
  - Machinery, etc.
- Utilized for **building** and **maintaining** these, or for **operating** them and **providing services**
- **When they are obsolete – they become waste**



Krausmann et al. 2018

Binder, Félix Martin del Campo



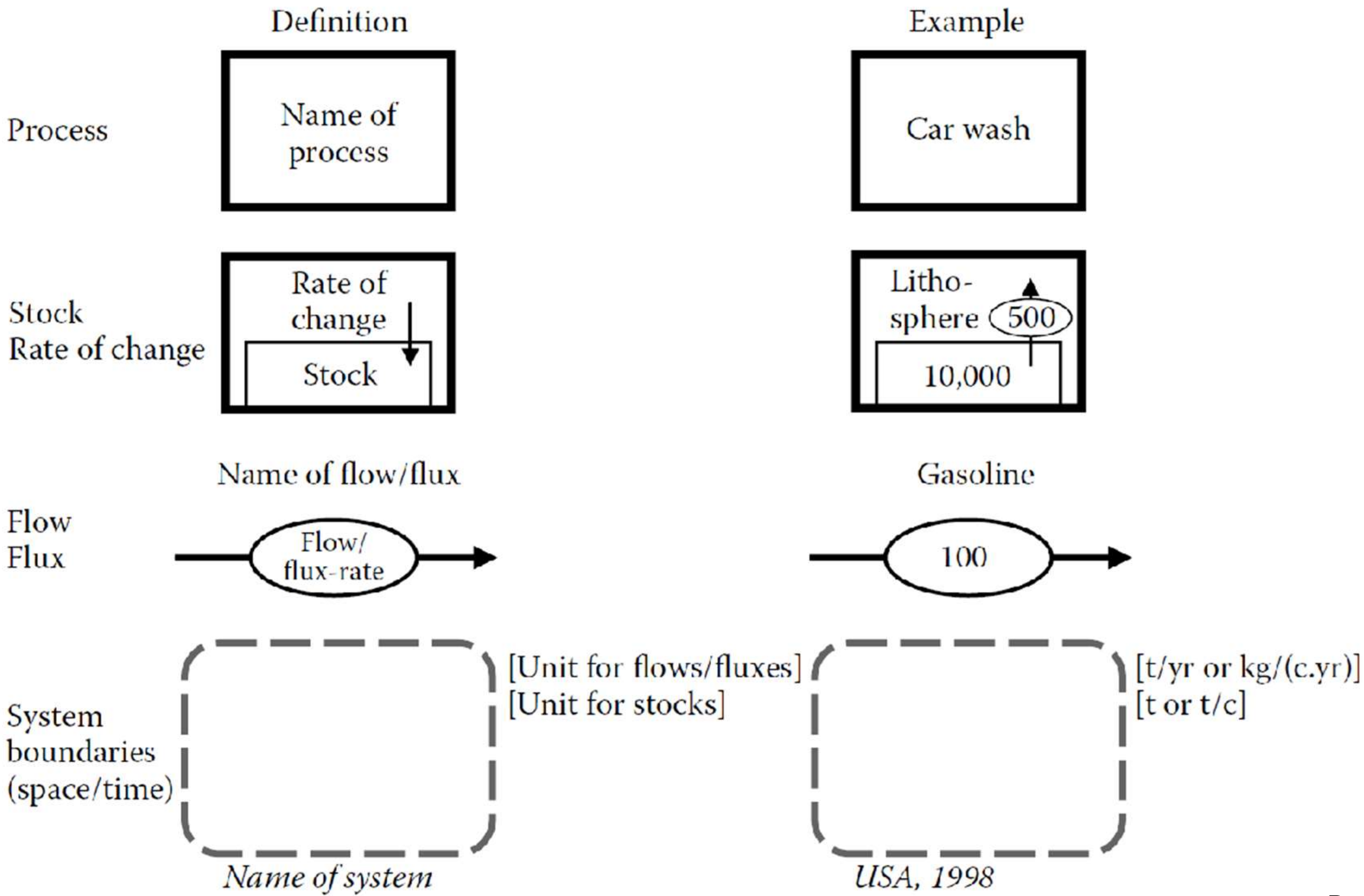
Material Flow Analysis

MFA notation, transfer coefficients and the time aspect in MFA

Binder, Félix Martín del Campo

Symbols used in MFA diagrams

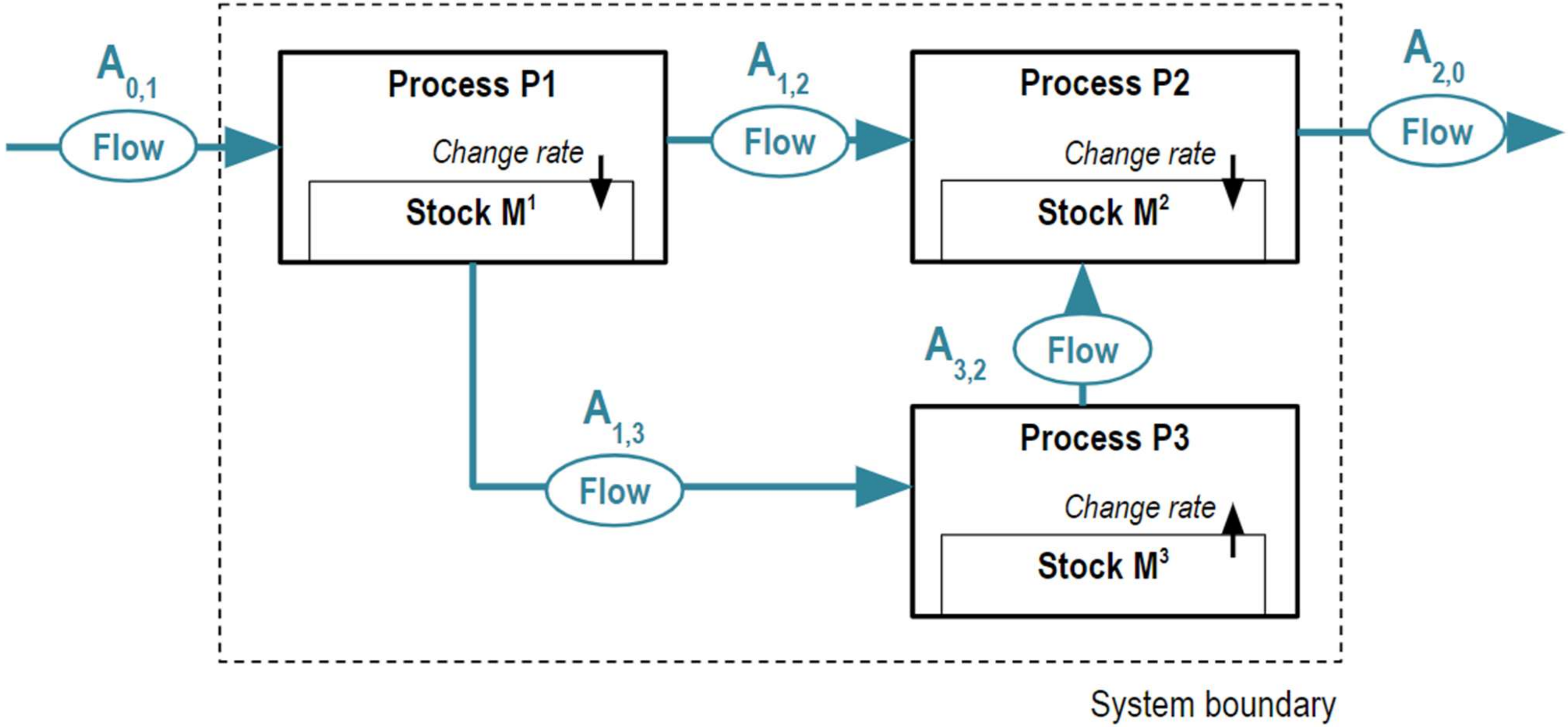
Binder, Félix Martín del Campo



Brunner & Rechberger, 2016

MFA notation

Binder, Félix Martín del Campo



Brunner & Rechberger, 2016

MFA notation

Binder, Félix Martín del Campo

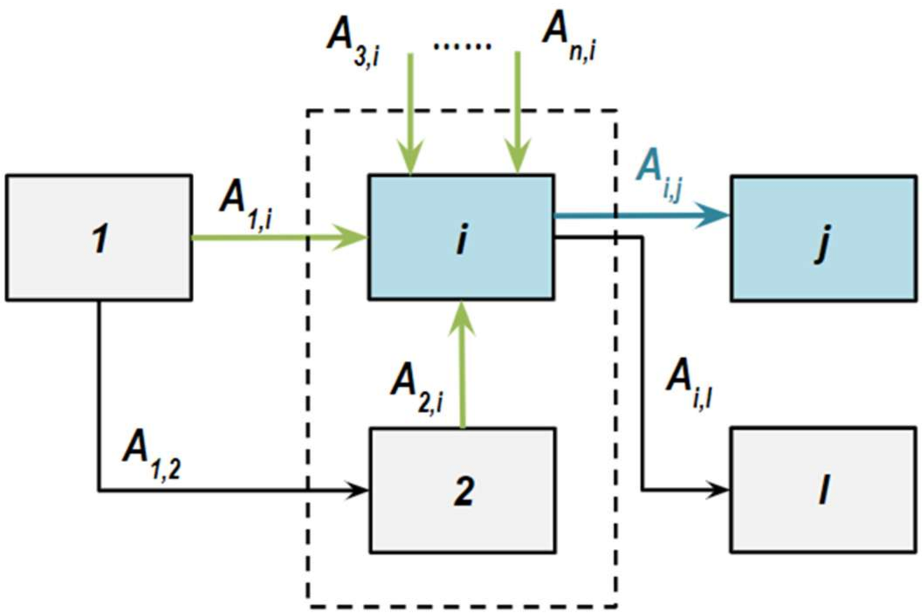
- **Mass** [t] $\mathbf{M}_{\text{salt, stock}}$
- Material **flow** [t/yr] $\mathbf{A}_{\text{salt, flow}}$
- **Substance** flow [kg/yr] $\mathbf{A}_{\text{Cl, salt, flow}}$
- Substance **concentration** [kg/t] $\mathbf{C}_{\text{Cl, salt}}$

Transfer coefficients (I)

Binder, Félix Martín del Campo

Transfer coefficients describe the **division** of a **material/substance leaving a process** (output) for a single input or the sum of all inputs.

Transfer coefficient ($k_{i,j}$) indicates the relative proportion of the total input to process *i* that flows into process *j*.



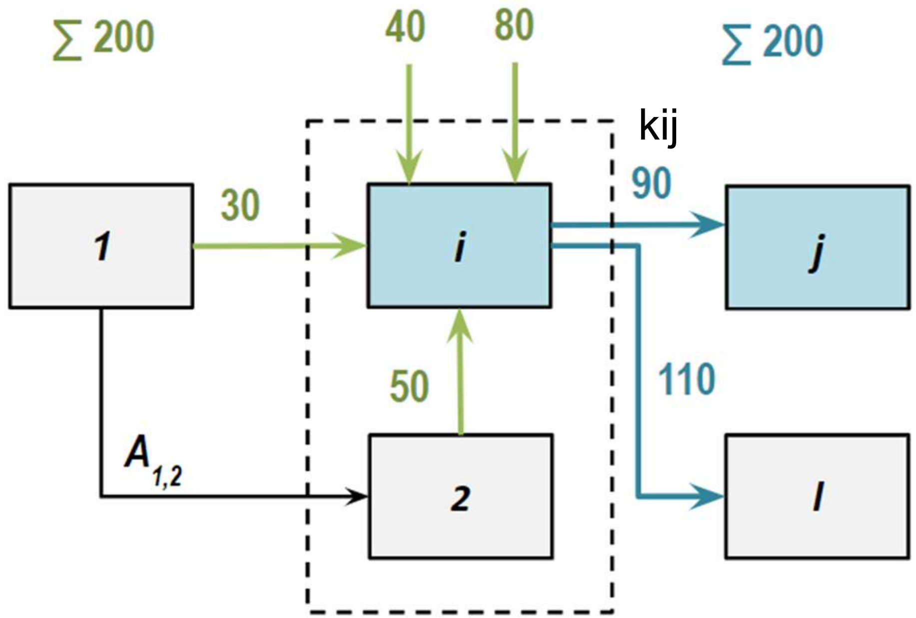
$$k_{i,j} = \frac{A_{i,j}}{\sum_n A_{n,i}}$$

$$k_{i,j} + k_{i,l} = 1$$

Transfer coefficients (II)

Transfer coefficients describe the **division** of a **material/substance leaving a process** (output) for a single input or the sum of all inputs.

Transfer coefficient ($k_{i,j}$) indicates the relative proportion of the total input to process *i* that flows into process *j*.



$k_{i,j} = 90 / (50+30+40+80) = 0.45$

$k_{i,l} = 110 / (50+30+40+80) = 0.55$

$k_{i,j} + k_{i,l} = 0.45 + 0.55 = 1$

Transfer coefficients (III)

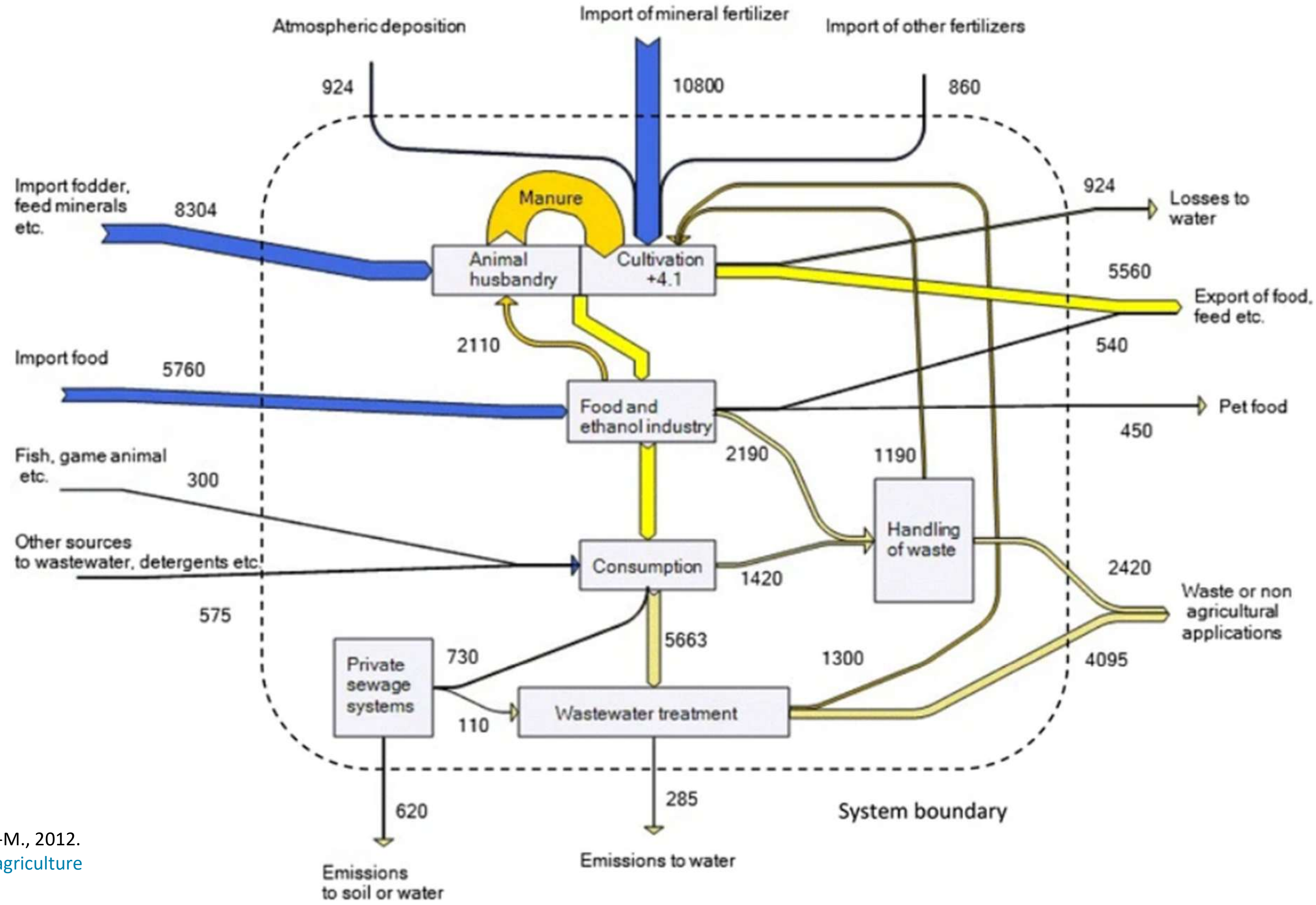
Binder, Félix Martín del Campo

Benefits

- Quantifying resource allocation and efficiency
- Supporting system optimization
- Enabling modeling and predictive analysis

From: Phosphorus Flows to and from Swedish Agriculture and Food Chain

Which transfer coefficients could be optimized?



Linderholm, K., Mattsson, J., Tillman, A.-M., 2012. Phosphorus flows to and fromSwedish agriculture and food chain. AMBIO 41, 883–893.

The time aspect in MFA

- **Steady state:** constant flows and stocks
- **Quasi-stationary:** constant flows and linear (de)growth of stocks
- **Dynamic:** system state at "*t*" is a function of the state a "*t-1*"
- **Time dependent:** parameters external to the model are function of time (e.g. extraction or disposal costs)

Steady state

- Material and energy are conserved for each individual process and for the overall system.
- **Steady state of a process *i*:**

$$\frac{\partial A}{\partial t} = 0$$

$$\frac{\partial M^i}{\partial t} = A_{1,i} + A_{2,i} + \ldots + A_{n,i} - (A_{i,1} + A_{i2} + \ldots + A_{i,l}) = \sum_n A_{n,i} - \sum_l A_{i,l} = 0$$

- **Steady state of the overall system *j*:**

$$\frac{\partial M^{tot}}{\partial t} = A_{in} - A_{out} = 0$$

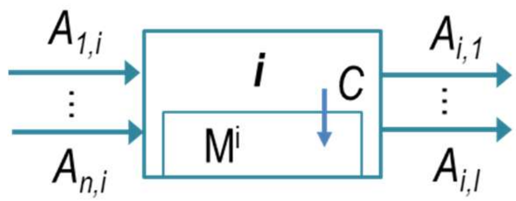
Quasi-stationary

- **Quasi-stationary case of a process *i*:**

$$\frac{\partial A}{\partial t} = 0$$

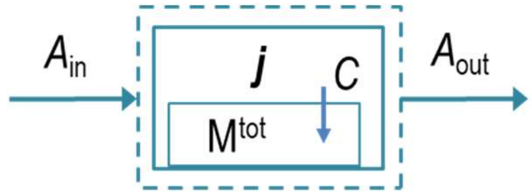
$$\frac{\partial M^i}{\partial t} = A_{1,i} + A_{2,i} + \ldots + A_{n,i} - (A_{i,1} + A_{i2} + \ldots + A_{i,l}) = \sum_n A_{n,i} - \sum_l A_{i,l} = C$$

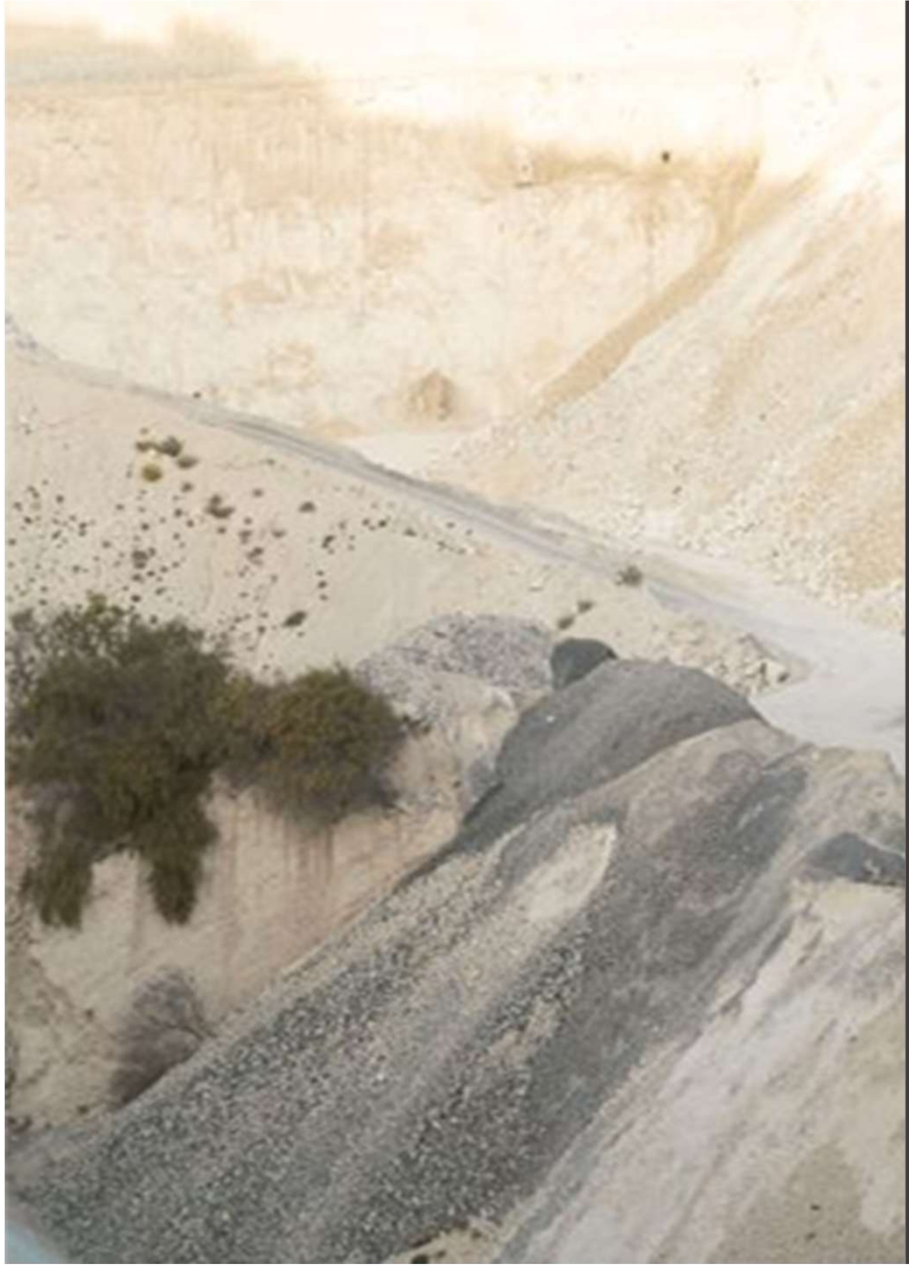
$$\frac{\partial C}{\partial t} = 0$$



- **Quasi-stationary case of the overall system *j*:**

$$\frac{\partial M^{tot}}{\partial t} = A_{in} - A_{out} = C$$





Example of MFA and mathematical system definition

Steps of MFA

Step I: System definition
Problem definition, definition of system boundaries, selection of processes and flows of materials/substances (qualitative model)

Step II: Measurement
Data collection of flows and stocks of materials/substances and characterization of uncertainties (measurements, literature data, estimations)

Step III: Calculation
Calculation of unknown quantities by balancing of materials based on the principle of mass conservation (MFA software)

Step IV: Illustration and interpretation
Sources, stocks, flows and sinks

Step V: Recommendations
How can the system be optimized?

System definition

Binder, Félix Martín del Campo

- **Research question for glass bottle management in CH:**

  How does glass recycling change the system?
  a. How much glass needs to be imported?
  b. How much energy can be saved?

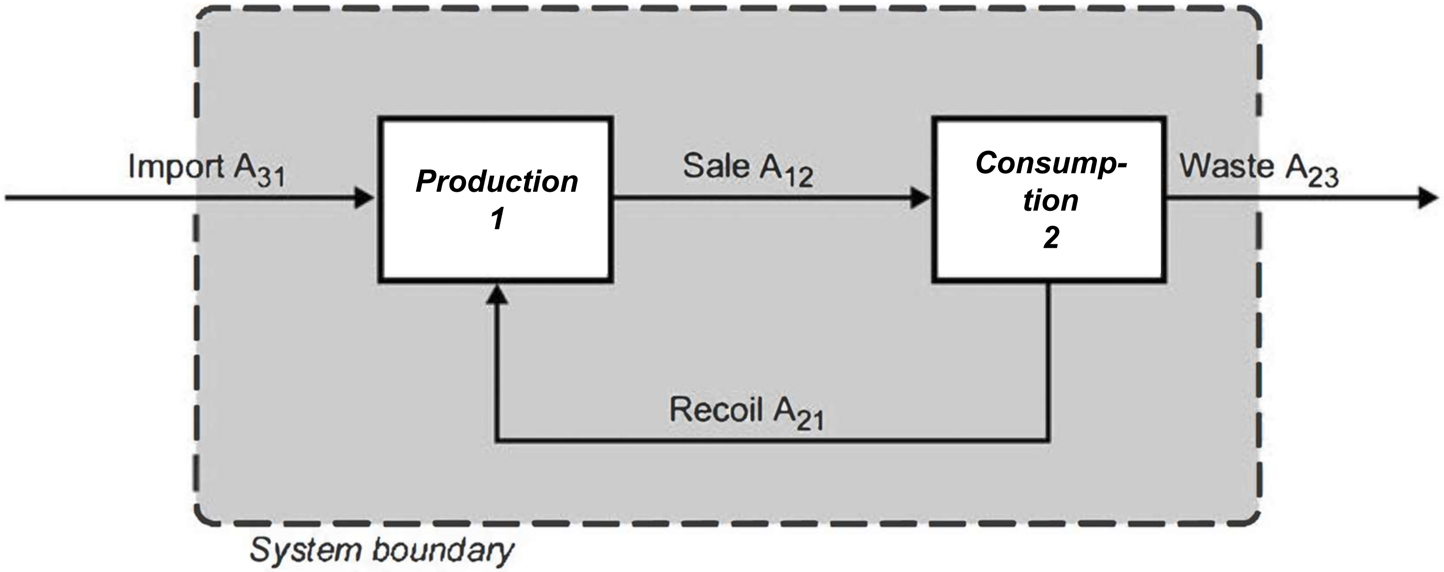
- **System boundary:** Switzerland, 1 year
- **Unit for flows:** kg/cap*yr
- **Unit for stocks:** kg/cap
- **Processes:** glass production, glass consumption
- **Material flows:** glass, waste glass
- **Indicators:** glass import rate, energy use

Laboratory on Human-Environment Relations in Urban Systems

System definition

Simplified material system for glass bottle management in Switzerland

Material flow: glass, waste glass



Baccini & Brunner, 2012

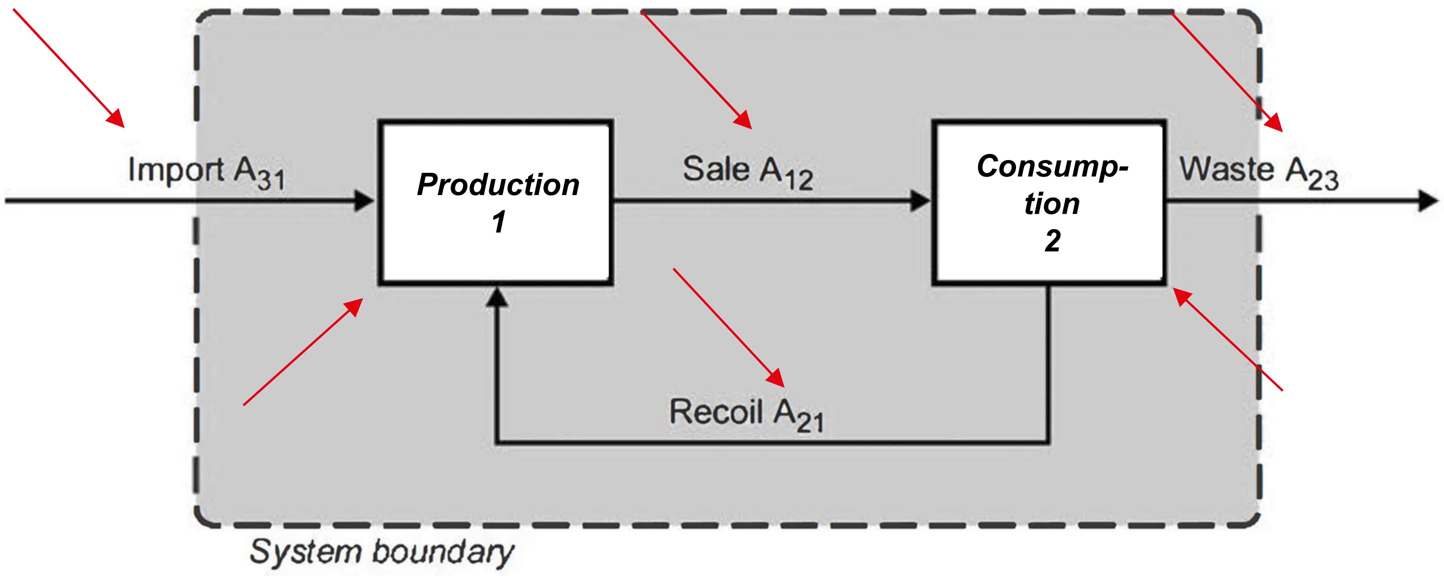
System definition

Procedure for mathematical system definition:

- Define the system unknowns
- Setup the system of equations
- Complete the system of equations with specific relationships
- Solve the system of equations
- Analyze the results and check for errors

System unknowns (steady state)

What are the system unknowns?



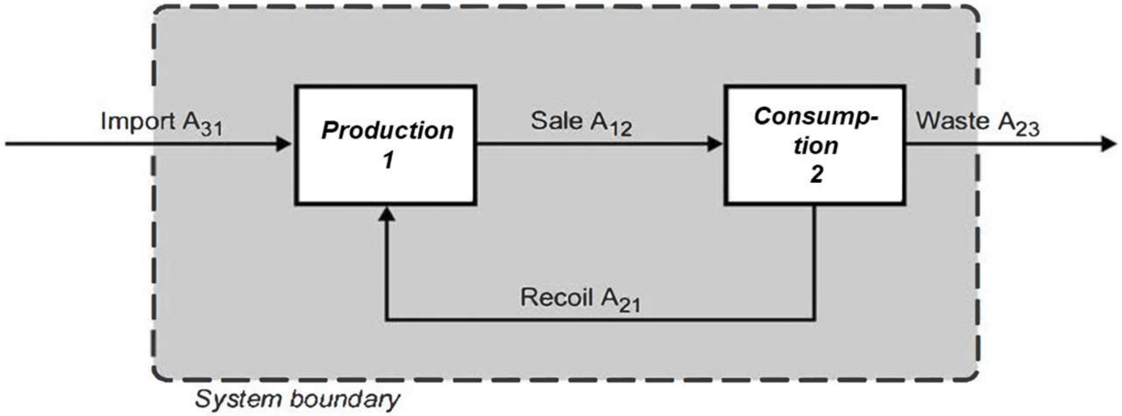
4 flows
2 stocks

Baccini & Brunner, 2012

System unknowns

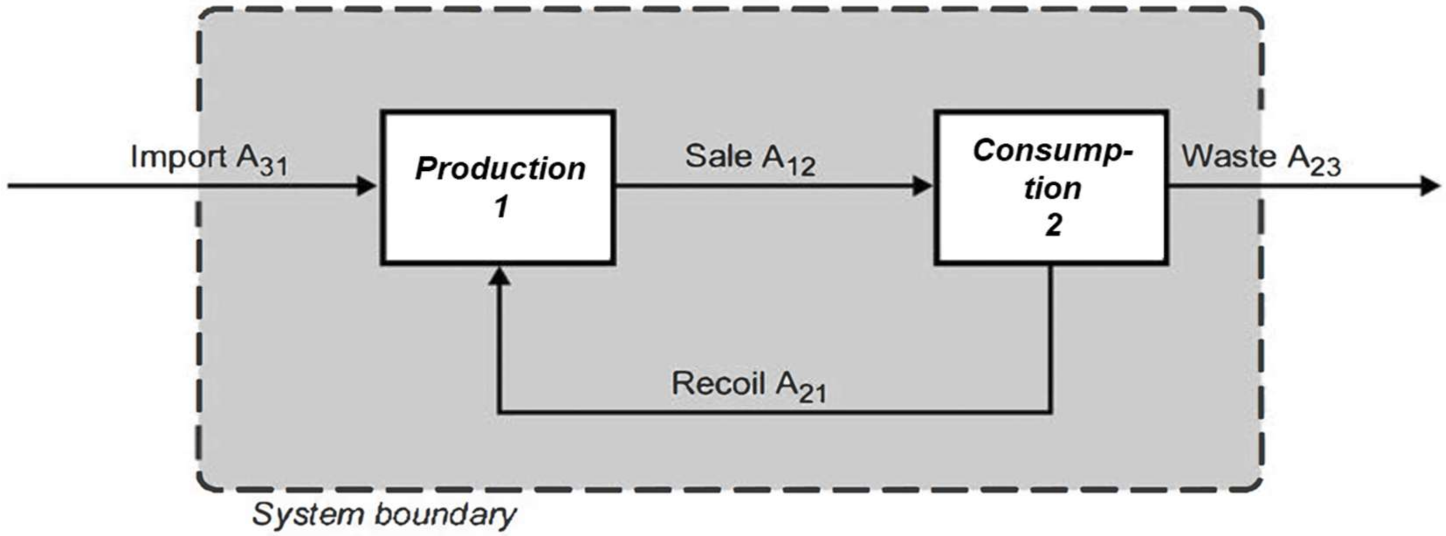
Binder, Félix Martín del Campo

Steady state: 6 system unknowns (stocks, flows)
Quasi-stationary state: 8 system unknowns (stocks, stock changes, flows)



Baccini & Brunner, 2012

2 balance equations (steady state)



$M^{(1)} =$

$M^{(2)} =$

$A_{31} =$

$A_{12} =$

$A_{21} =$

$A_{23} =$

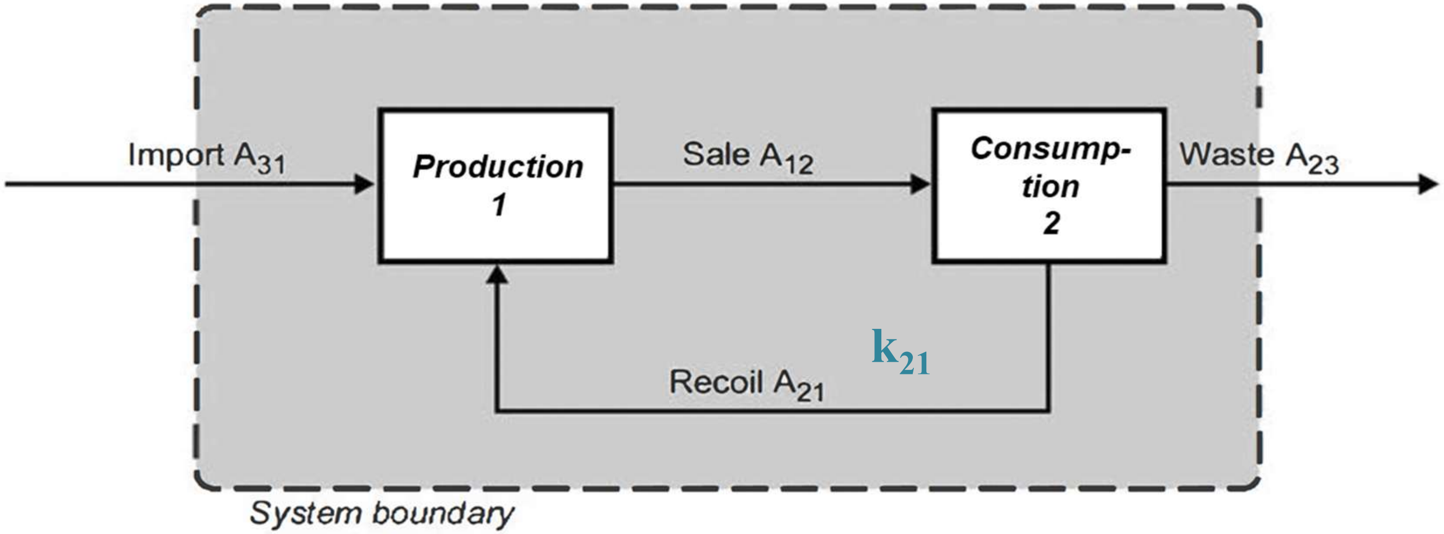
$$\frac{dM^{(1)}}{dt} = 0$$

$$\frac{dM^{(2)}}{dt} = 0$$

Binder, Félix Martín del Campo

• Laboratory on Human-Environment Relations in Urban Systems

6 parameter equations (steady state)



Assumptions / available data

$$M^{(1)} = 0$$

$$M^{(2)} = 0$$

$$A_{31} = \text{given input}$$

$$A_{12} =$$

$$A_{21} =$$

$$A_{23} =$$

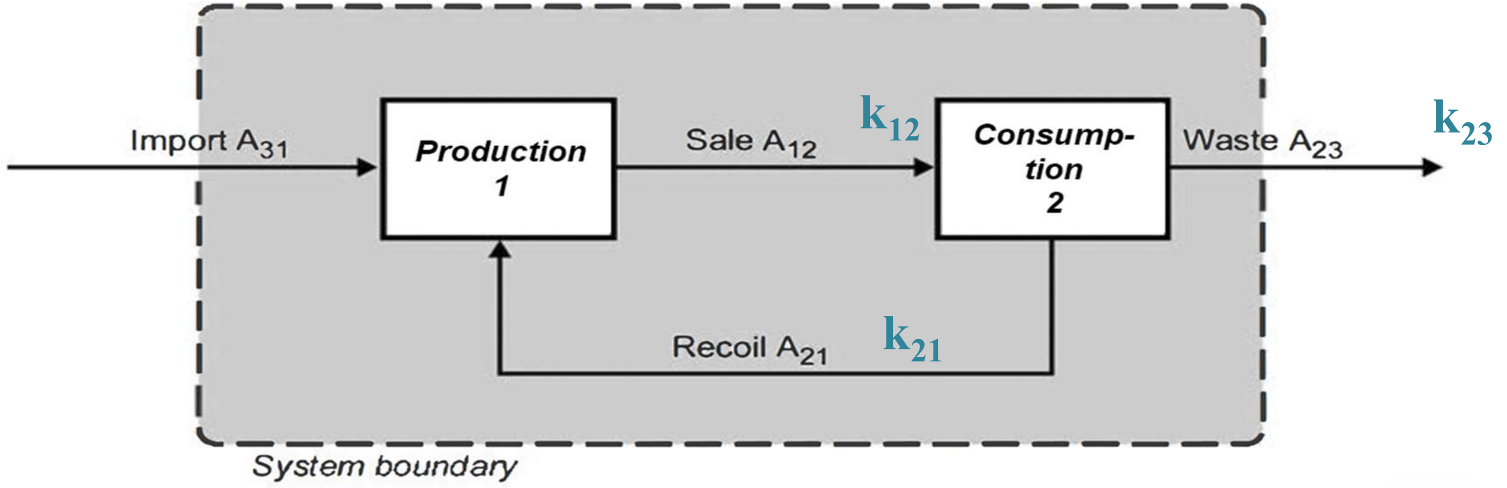
$$A_{31} = \text{given input}$$

$$k_{21} = \text{given input}$$

EPFL

6 parameter equations

Transfer coefficients



$$k_{i,j} = \frac{A_{i,j}}{\sum_n A_{n,i}}$$

$$k_{i,j} + k_{i,l} = 1$$

$$M^{(1)} = 0$$

$$M^{(2)} = 0$$

$$A_{31} = \text{given input}$$

$$A_{12} = k_{12}(A_{21} + A_{31})$$

$$A_{21} = \underline{k_{21}}A_{12}$$

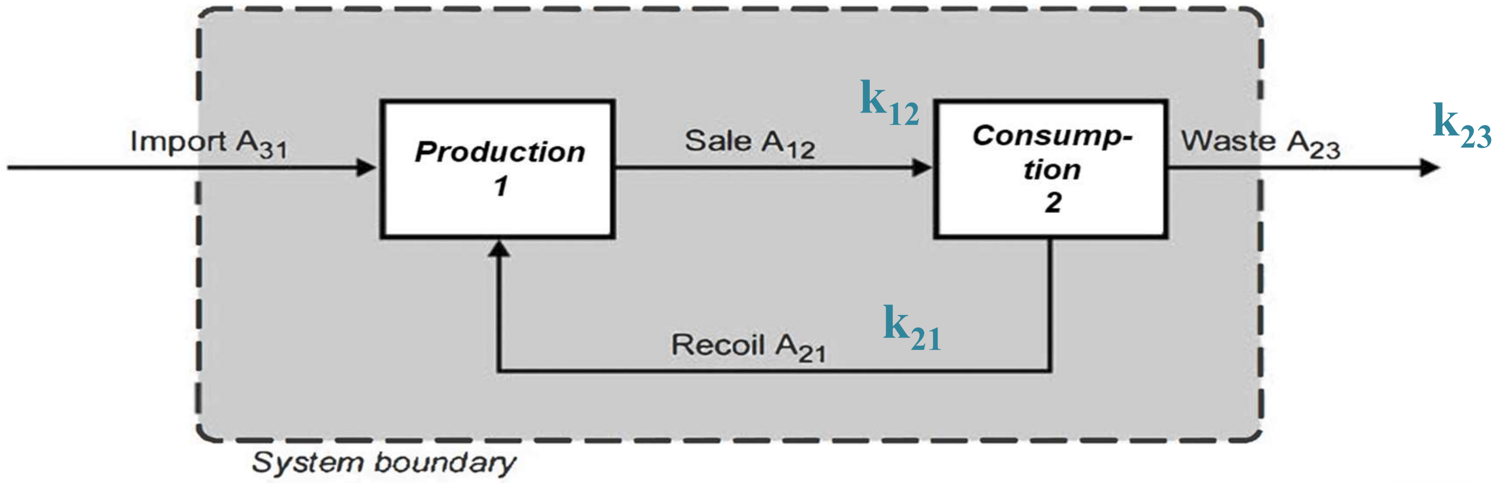
$$A_{23} = k_{23}A_{12}$$

Solving for each Flow A

$$k_{i,j} = \frac{A_{i,j}}{\sum_n A_{n,i}}$$

- Laboratory on Human-Environment Relations in Urban Systems

6 parameter equations



$$M^{(1)} = 0$$

$$M^{(2)} = 0$$

$$A_{31} = \text{given input}$$

$$k_{21} = \text{given input}$$

$$A_{12} = \frac{A_{31}}{1-k_{21}}$$

$$A_{21} = \frac{k_{21}\,A_{31}}{1-k_{21}}$$

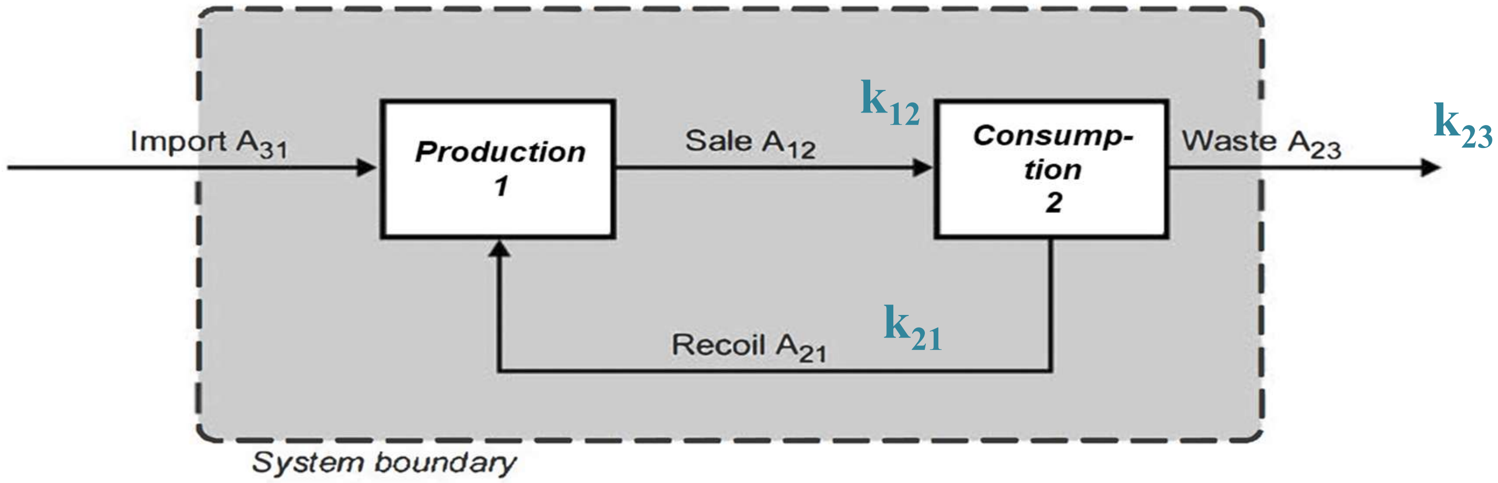
$$A_{23} = A_{31}$$

$$k_{i,j} = \frac{A_{i,j}}{\sum_n A_{n,i}}$$

$$k_{i,j} + k_{i,l} = 1$$

Laboratory on Human-Environment Relations in Urban Systems

6 parameter equations



$$M^{(1)} = 0$$

$$M^{(2)} = 0$$

$$A_{31} = \text{given input}$$

$$k_{21} = \text{given input}$$

$$A_{12} = \frac{A_{31}}{1 - k_{21}}$$

$$A_{21} = \frac{k_{21} A_{31}}{1 - k_{21}}$$

$$A_{23} = A_{31}$$

Import

$$A_{31} = 19 \text{ kg}$$

Recycling rate

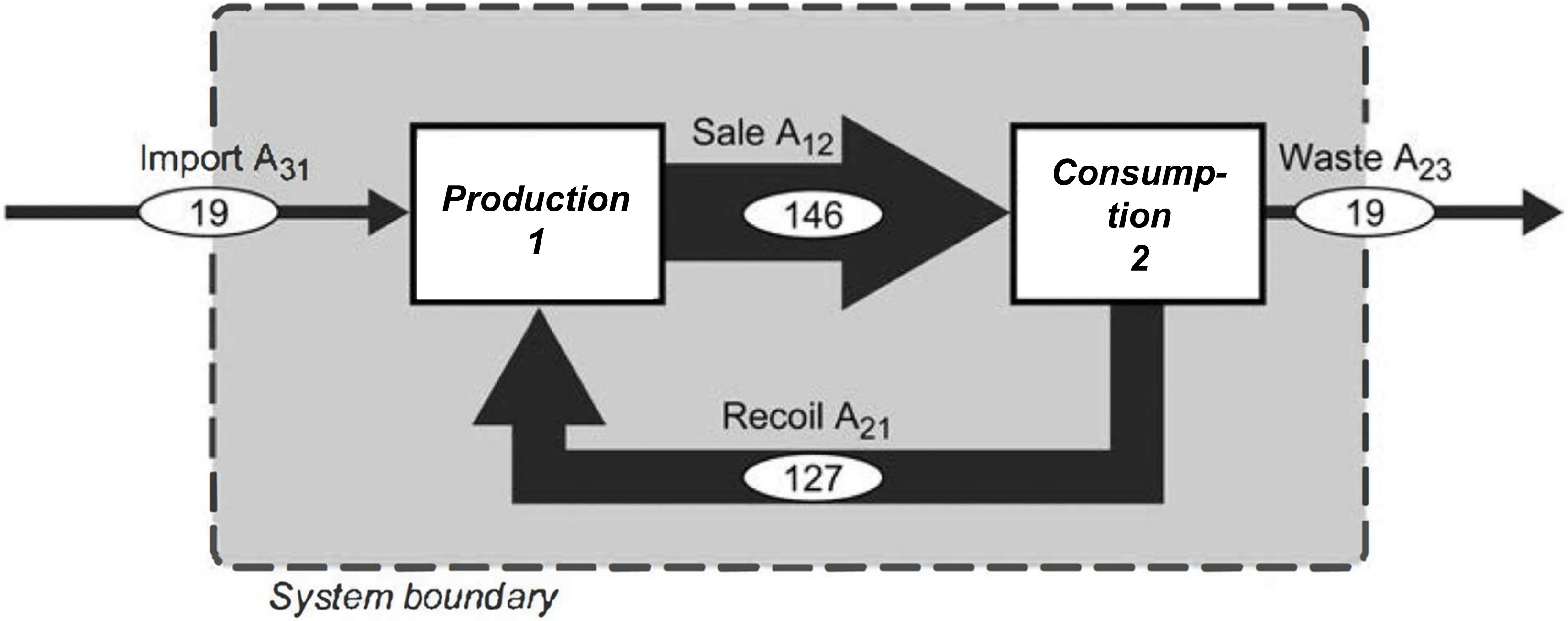
$$k_{21} = 0.87$$

Binder, Félix Martín del Campo

Results

Binder, Félix Martín del Campo

kg/c,yr



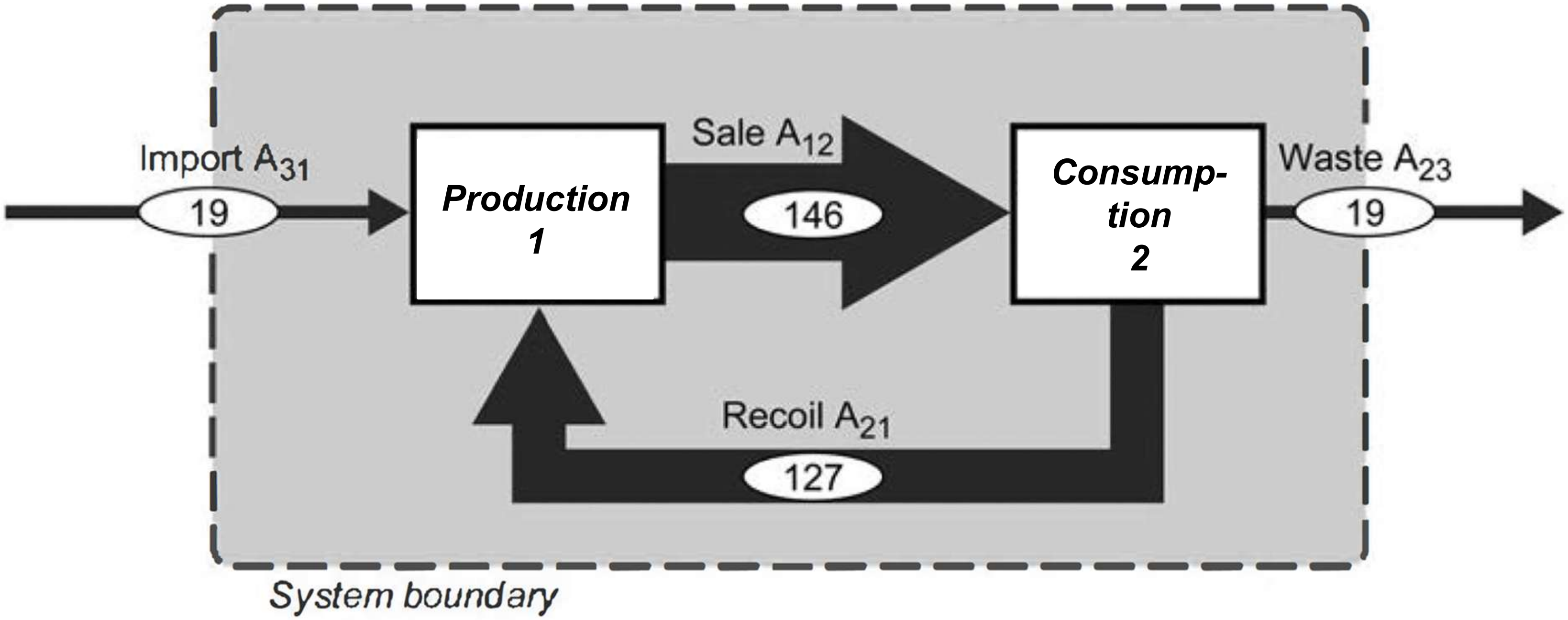
Baccini & Brunner, 2012

Results

What if recycling rate increases by 10%

assuming that glass imports and exports stay constant?

kg/c,yr



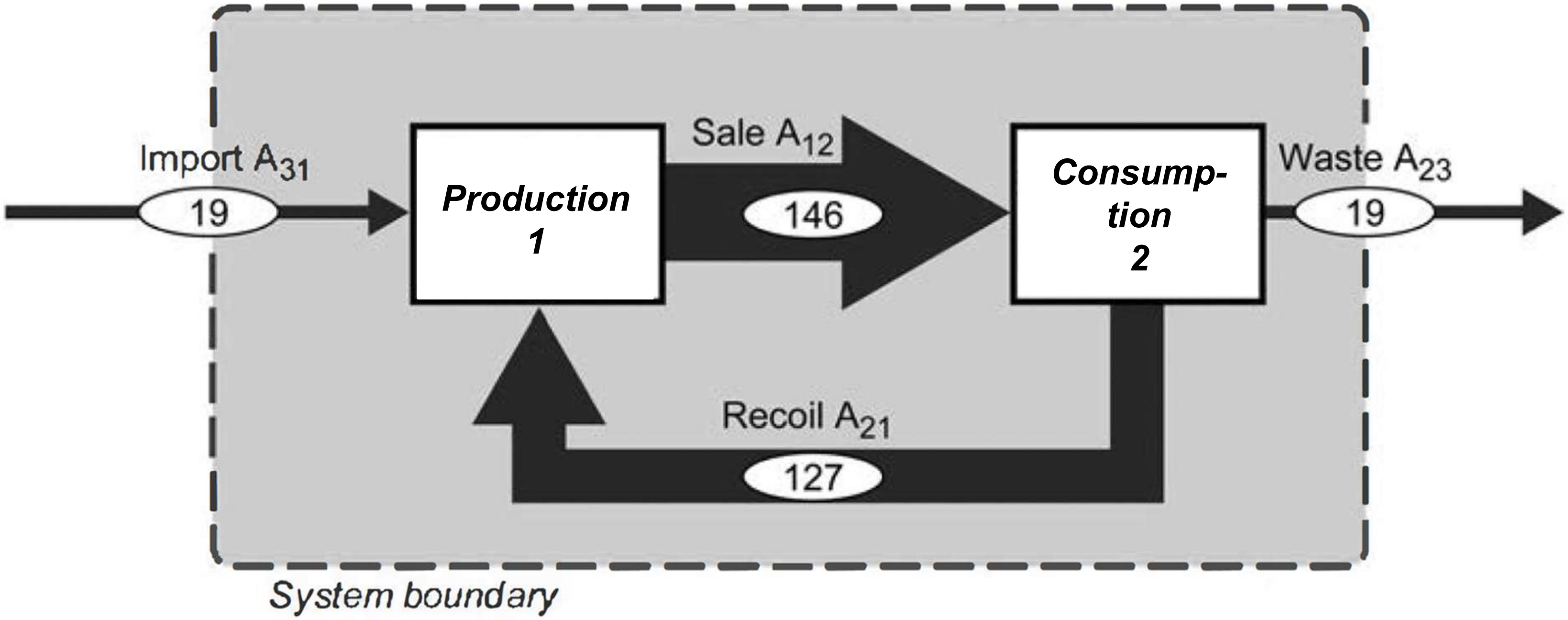
Baccini & Brunner, 2012

Results

What if recycling rate increases by 10%

assuming that glass bottle sales stay constant?

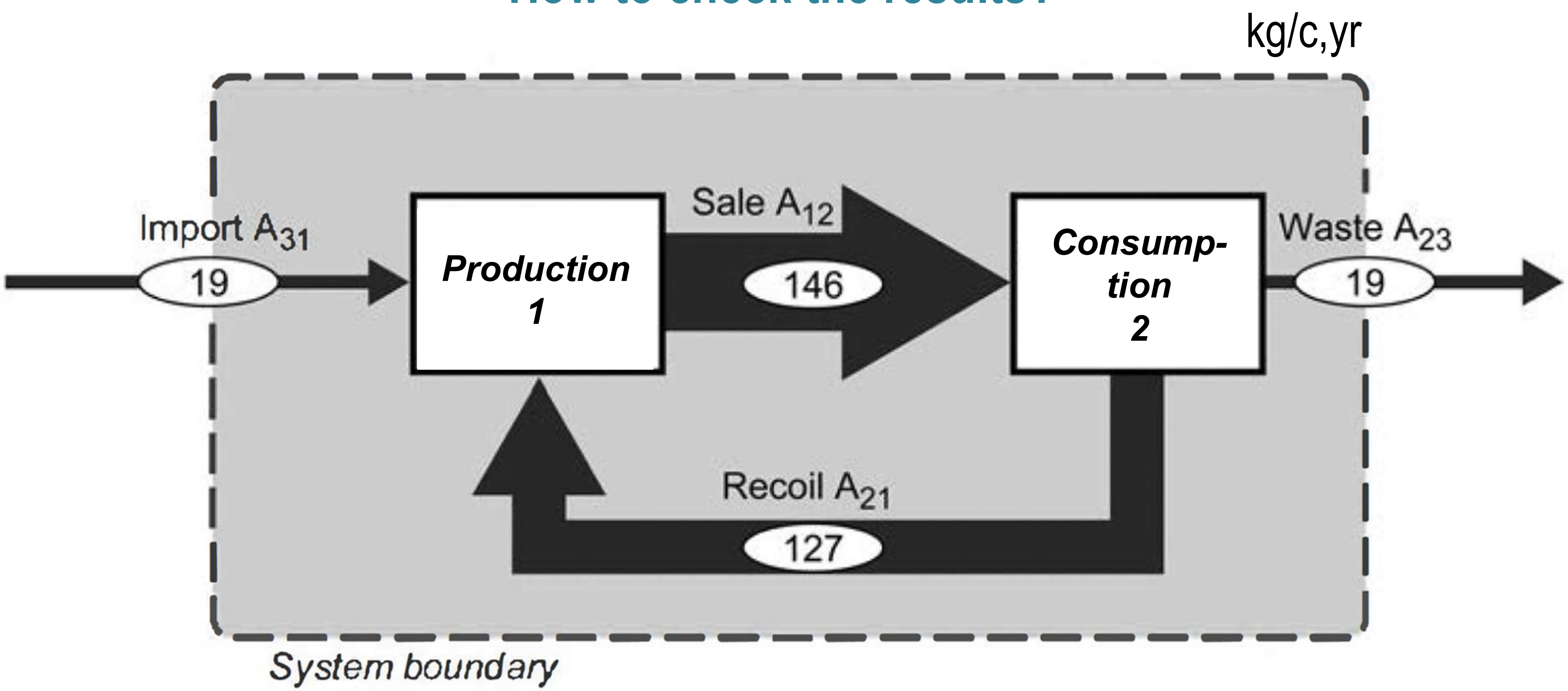
kg/c,yr



Baccini & Brunner, 2012

Results

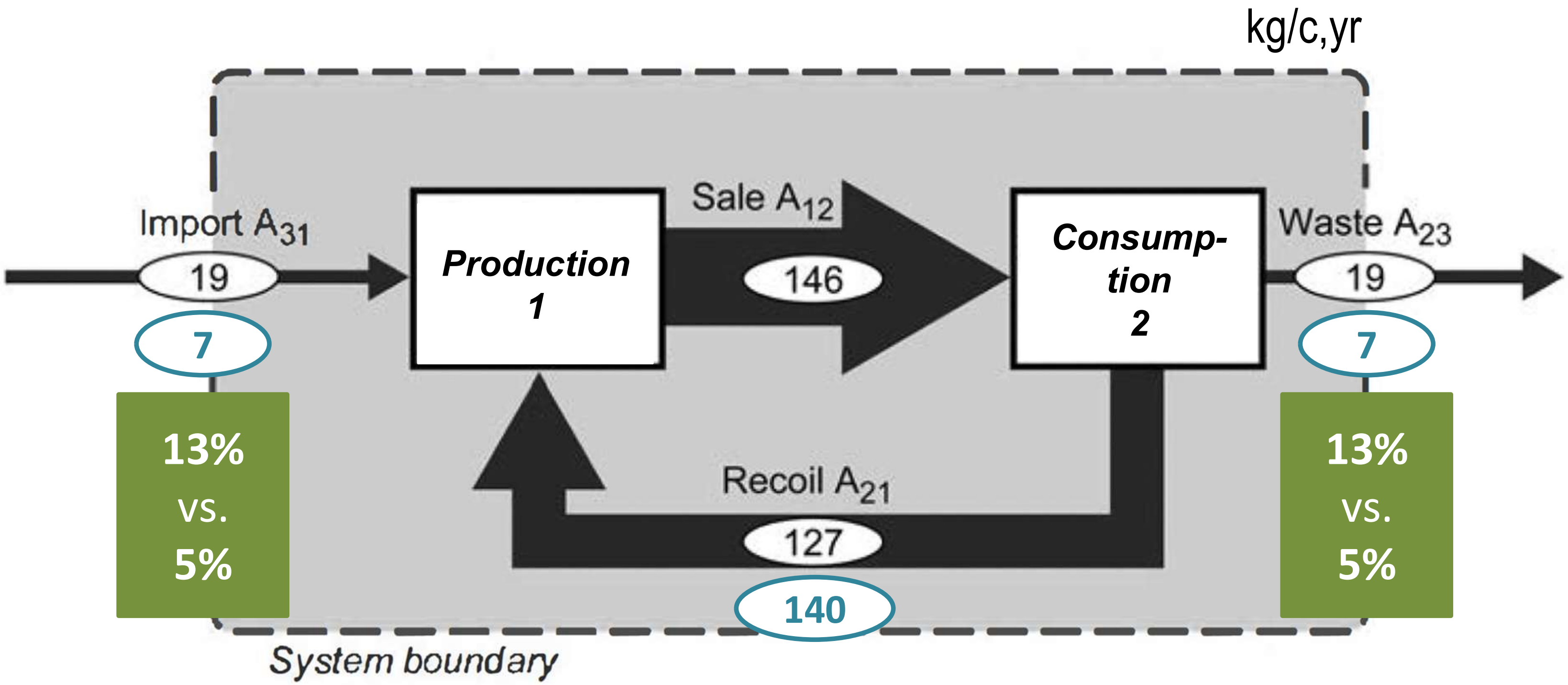
How to check the results?



Indicators

Binder, Félix Martín del Campo

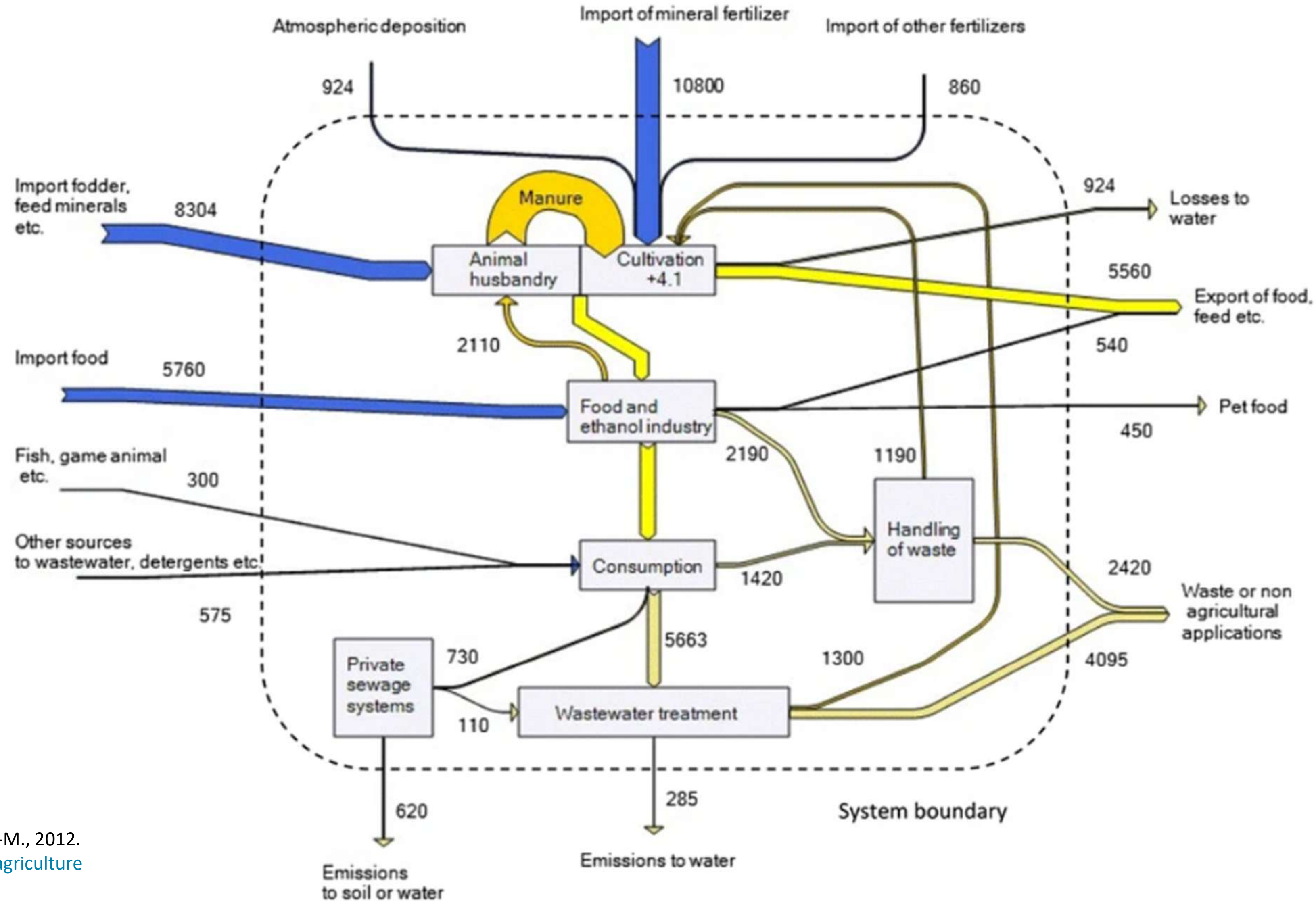
How would you define indicators?



a. Import rate (sale/import)

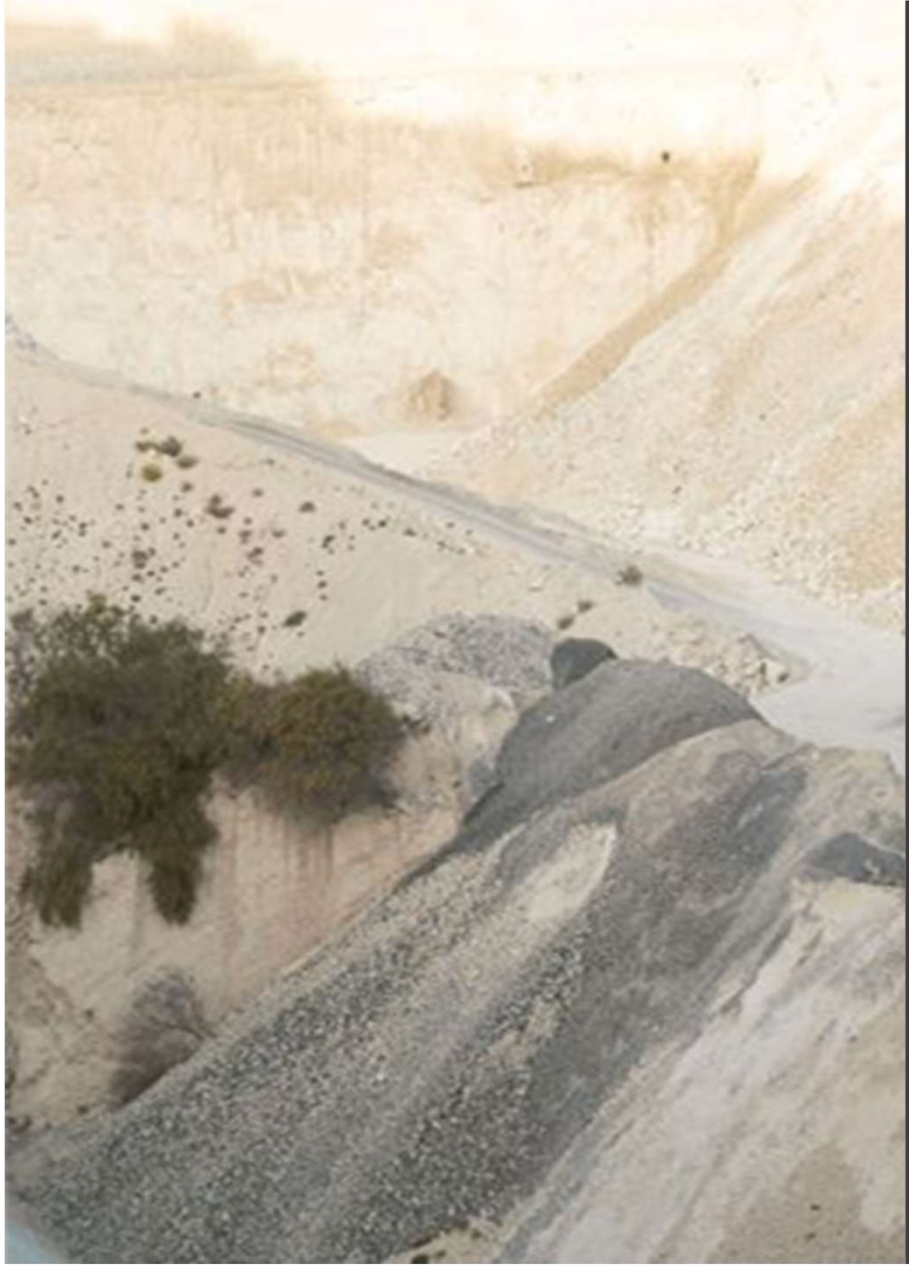
Baccini & Brunner, 2012

From: Phosphorus Flows to and from Swedish Agriculture and Food Chain



Linderholm, K., Mattsson, J., Tillman, A.-M., 2012. Phosphorus flows to and fromSwedish agriculture and food chain. AMBIO 41, 883–893.

EPFL



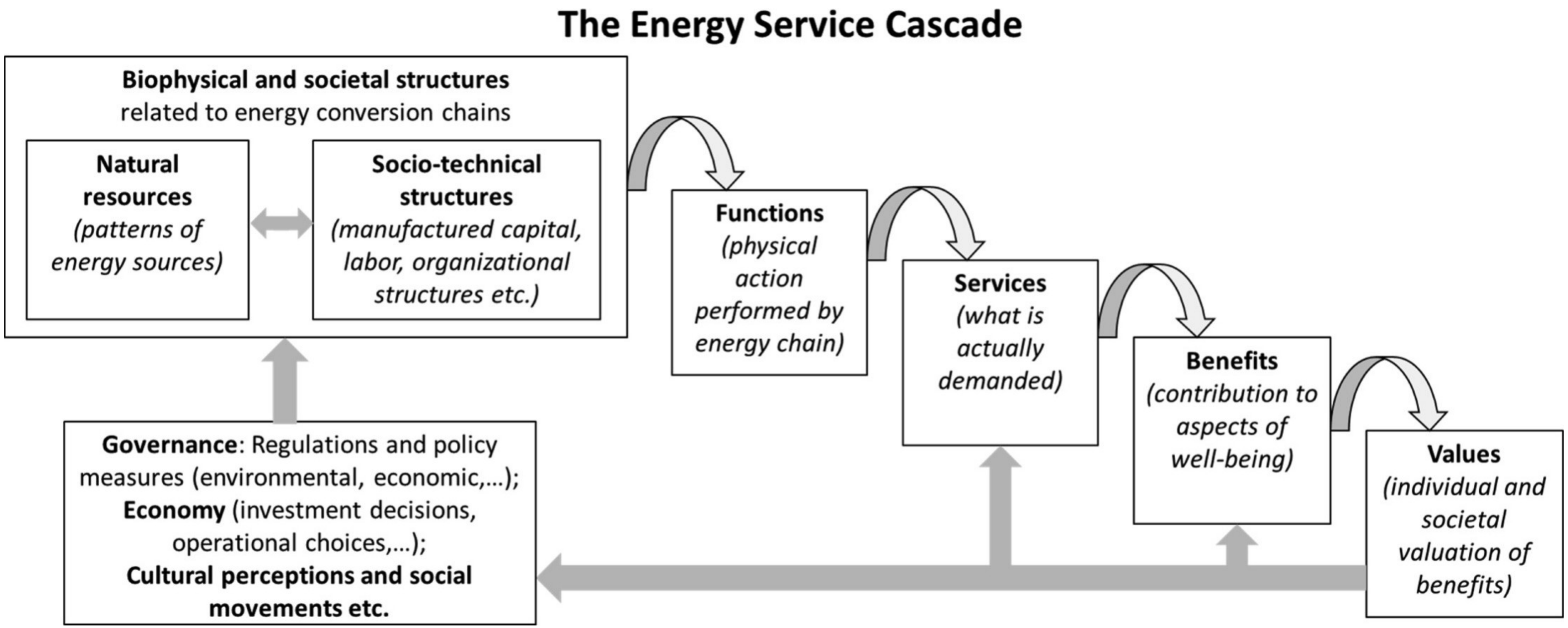
MFA and services

Using services instead of stocks to fulfill the needs

Definitions and relevance

• Laboratory on Human-Environment Relations in Urban Systems

The Energy Service Cascade



Source: Kalt et al. 2019

The “cascade” approach

A “cascade” approach: used to understand the **multi-step process** through which **benefits** and finally their **values** are **derived** from **biophysical structures and processes**, which in turn **influences** the **functioning** of (eco)systems and their **services**

Source: Kalt et al. 2019

Some definitions

Structure:
- Infrastructure (stock) for providing a service (mobility, heating, etc.)

Function:
- Capacities that human find useful (accelerating vehicle, food kept cool in a fridge) – but independent from human beneficiary

Service:
- What humans actually demand – a "service" is only a "service" if a human beneficiary can be identified

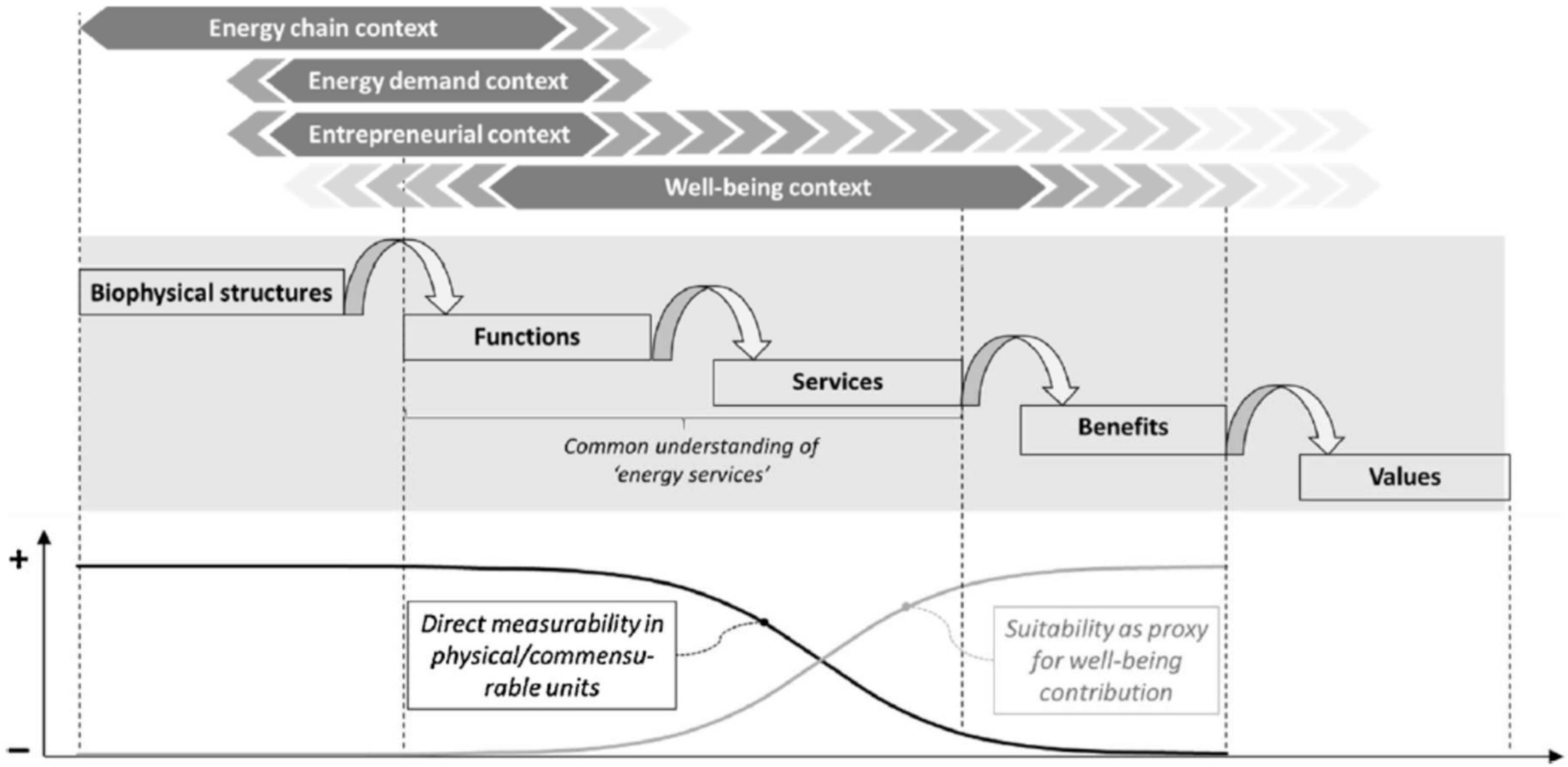
Benefits:
- Contribution to human wellbeing – benefits are outcomes of services

Examples

Electricity system (infrastructure) allows a space to be *illuminated* (service) which in turn enables the inhabitants to be to *enjoy forms of entertainment, or participate in social life* (benefits)

How much “service” I need to perceive “well-being” (how much benefit do I need?) is individually determined.

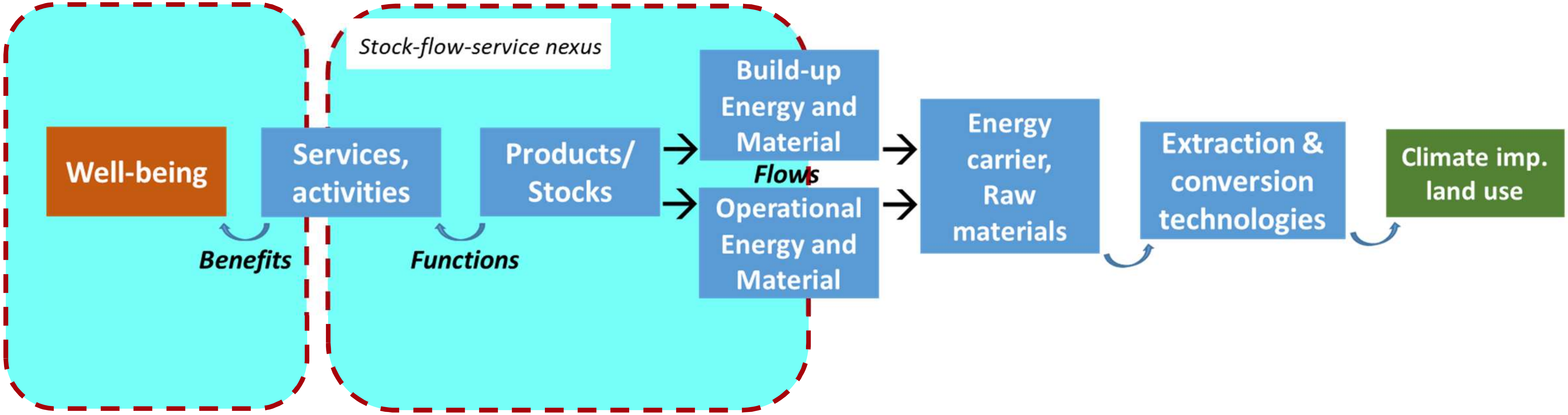
Ex: the energy – service cascade



Kalt et al., 2019

Energy & material service cascade - urban scale

Binder, Félix Martín del Campo



Pauliuk, Binder, Hecher, in prep.

The Stock-Flows-Service Nexus: The challenge

Binder, Félix Martín del Campo

- **Reducing** resource **use** by determining **alternative** options for **service** provisioning
  - Clarity about services
  - Identify and measure the links between flows and stocks

- Questions:
  - **How** to determine alternatives?
  - What possible **alternatives** exist?
  - What could be **potential obstacles** for **implementing** these alternatives?

EPFL

Question related to your project

Binder, Félix Martín del Campo

How can we provide the same well-being while reducing resource use?

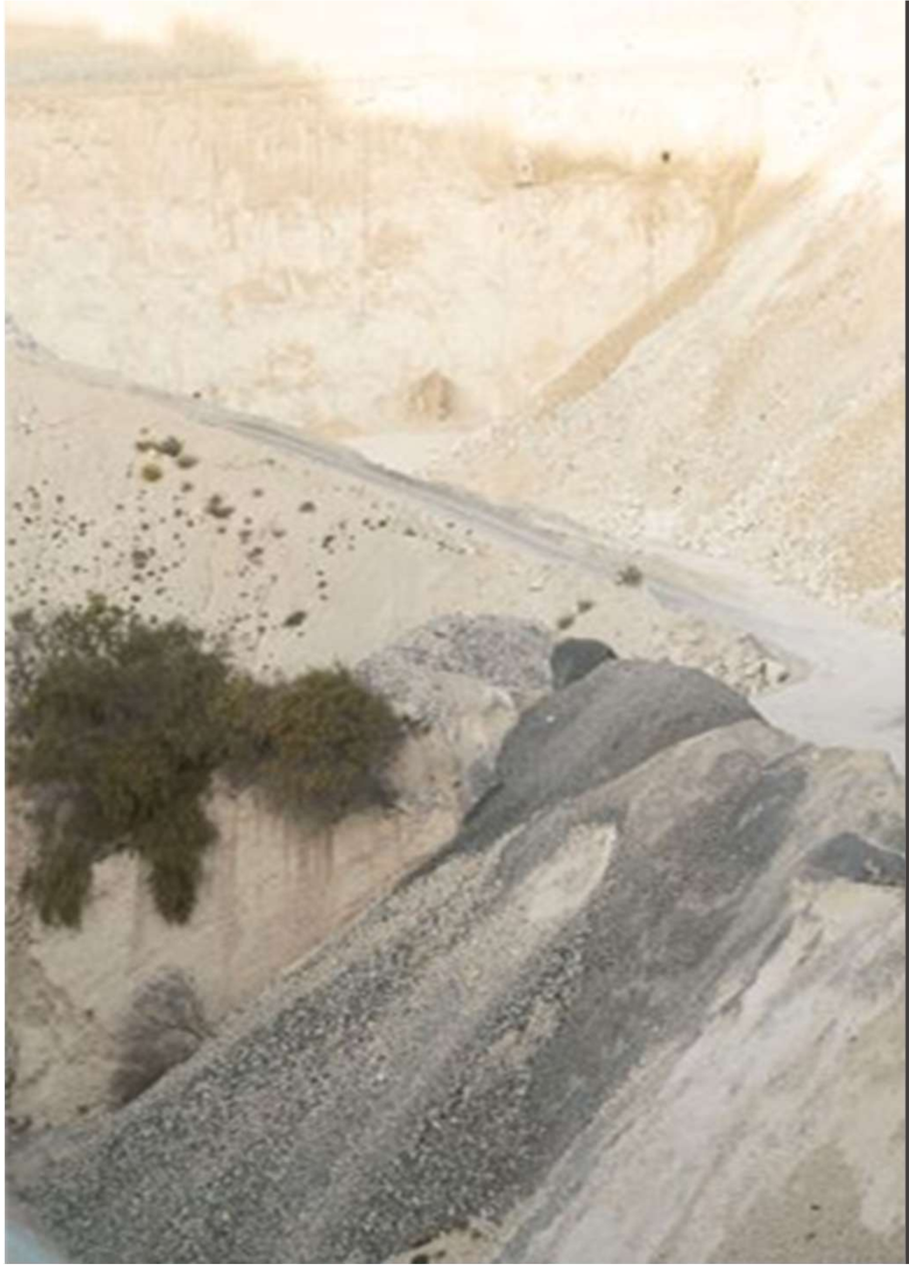
→ **Rethinking our way of how we use and provide services**

Ex.

- I need a car
- I need to get from A to B

→ **I need mobility but I do not need a good**

- I need to work (home office)



Thank you for your attention!

EPFL

Guest lecturer: Dynamic MFA Prof. Stefan Pauliuk

Binder, Félix Martín del Campo

- **Position and Role:**
  - Professor of Sustainable Energy and Material Flow Management at the University of Freiburg, Germany, heading the Industrial Ecology Freiburg research group since 2021.
- **Research Focus:**
  - Specializes in **industrial ecology** and **socio-metabolic research**, including global supply chains, sustainable material cycles, environmental footprints, and circular economy strategies.
- **Methodological Expertise:**
  - Advanced methods such as **Material Flow Analysis** (MFA), **Life Cycle Assessment** (LCA), and **Multiregional Input-Output Analysis** (MRIO).
- **Professional Contributions:**
  - Led projects on resource efficiency and circular economy, contributed to policy development, and authored influential studies on sustainable material management.
- **Teaching and Community Engagement:**
  - Teaches various MSc-level courses, offers an online course in Industrial Ecology, and actively engages in scientific committees and international collaborations.

Course evaluation

Indicative Student Feedback on Teaching

- This feedback system asks students to respond to a single question about the course (“*The running of the course enables my learning and an appropriate class climate*”)
- Opportunity for **students** to **provide comments**

- **Go to ISA and respond the Indicative Feedback**
- **Feedback is anonymous**

Final remarks

- MFA (flows and stocks) are beneficial to **understand** past **trajectories** and current and future **patterns** of society-nature **interactions**
- **Need** to distinguish flows and stocks **services!**

- Future research on this will likely be able to underpin strategies for:
  - **Decoupling** between societal well-being and resource demand
  - **Contingencies and lock-ins** resulting from past build-up of material stocks,
  - Possible **leverage points** to foster sustainability transformations