Summer school: Eco-ICT 2024

Large dynamic system: applications to Earth analysis or ICT

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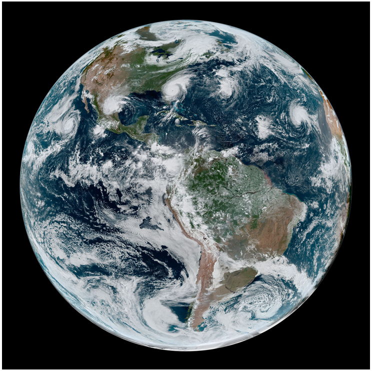
Outline

- Criteria for Earth-system
- Dynamic systems
  - Complex systems
  - Possible mathematical framework
  - Feedback loop and systemic charts
  - Examples from Environmental and Life Sciences
    - ↪ Finite Amplitude Impulse Response (FaIR) model
    - ↪ Carbon, Nitrogen, and Phosphorus cycles
    - ↪ World3 model
- Application to Energy production and ICT
  - Hydrogen-based energy system
  - Future wireless network
  - Smart farming

Section 1 : Earth system criteria

Introduction: Earth system ?



source: NASA

Interactions between

- Human societies
- Other life: animals, plants, ...
- Types of energies: external (sun), internal (wind, fossils, geothermal)
- Different areas of interaction: air, biosphere, hydrosphere, cryosphere, lithosphere

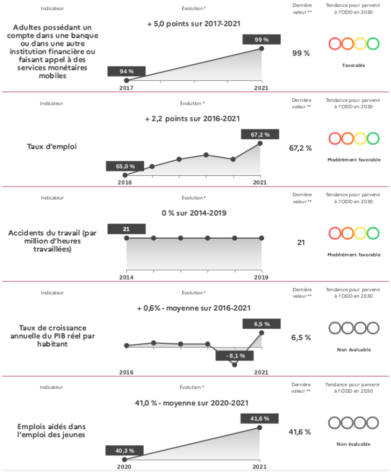
Criterion 1: "Human societies" approach

- Sustainable Development Goals (SDG) defined in 2015 by UN
- Non-mandatory goals for 2030: just a compass
- Each SDG is composed by some subcriteria
- *Global Sustainability Development Reports*

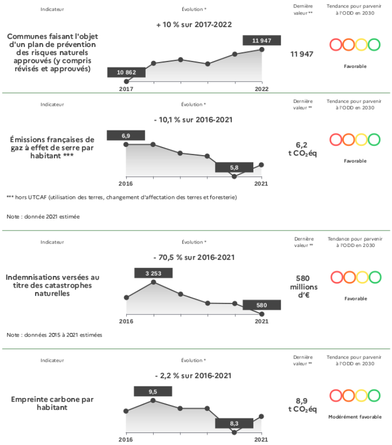
source: http://www.agenda-2030.fr

SDG08 (employment) and SDG (climate) for France

SDG08



SDG13



Criterion 2: "Biological planet" approach

Planetary limits defined in 2009 by *Stockholm Resilience Center*

- identify disturbing biological phenomena leading to non-controlled environmental changes
- but this disturbance comes from human activities

  Example: soil modification → biodiversity decrease

  ↪ decrease of eco-systemic duties (pollination)

  ↪ decrease of natural carbon storage ability

  ↪ increase of Greenhouse Gas (GHG)
- quantify the phenomena-limits (Example: percentage of soil modification)

We need to stay on the disk whose the border is the limits to guarantee safe life conditions for human beings: "safe space" for human life. Warning: these limits are not resource based limits.

source: J. Rockström et al., "A safe operating space for humanity", Nature, 2009

Nine planetary limits (1/2)

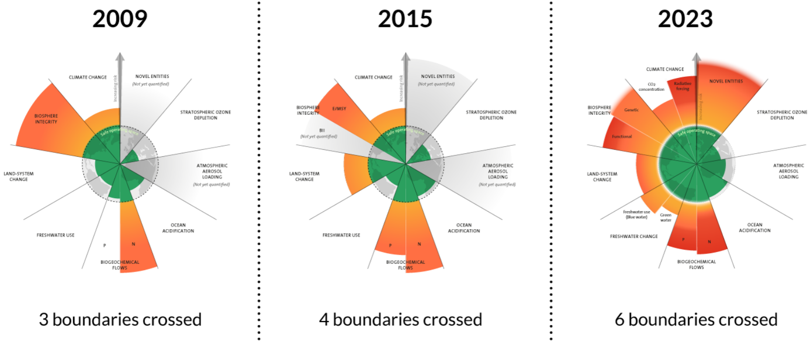
Phenomenon	2009/23	threshold	ante-1950
Climate warming			
CO_2 concentration in ppm	380/415	350	280
extra radiative radiation $W.m^{-2}$	1.5/2.9	1	0
Tipping point	Ice melting		
Biosphere/biodiversity			
species extinction in ppm/yr	100	*10*	1
human production monopolization %	30	*10*	2
Tipping point	One order of magnitude		
Biochemical cycles			
N: extra in Tg/yr^{-1}	190	60	0
P: discharge in Ocean in Tg/yr^{-1}	18	6	0
Tipping point	Anoxia		
Ozone layer			
O_3 in Dobson=$0.44mol/m^2$	283/285	275	275
Tipping point	UV protection		

Nine planetary limits (2/2)

Ocean acidification *concentration in $CaCO_2$ in %*	2.9/2.8	2.8	3.44
Tipping point	Exoskeleton forming		
Fresh water use *consumption in km^3/yr*	2600/4300	*4000*	415
Tipping point	Ecosystem needs		
Soil modification use *primary forest in field in %*	85/60	*75*	99
Tipping point	Carbon sinks		
Aerosols (dust) *interhemisphere optical depth*	? /0.076	*0.1*	0.03
Tipping point	Cloud forming / Rainfall		
Chemical pollution *non-secured new molecules*	?/$>$ 1	*0*	0
Tipping point	Health		

source: www.statistiques.developpement-durable.gouv.fr/edition-numerique/la-france-face-aux-neuf-limites-planetaires

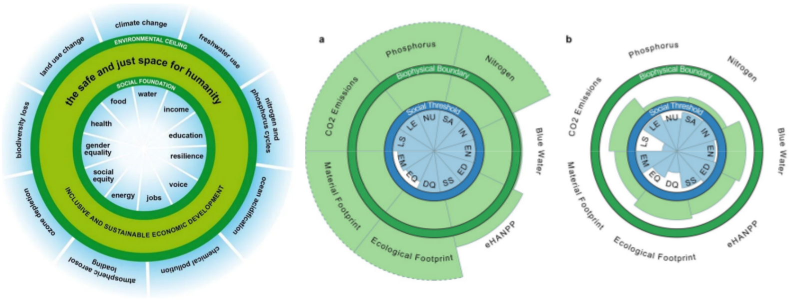
Planetary limits over time



- First complete evaluation in 2023
- Warning: static approach (inertia not taken into account)

source: K. Richardson et al., "Earth beyond six of nine planetary bounds", Science Advances, 2023

Criterion 3: "Socio-environmental" approach



- Doughnut theory
- Social floor (11 SDG) and environmental ceiling (9 SDG)

source: K. Raworth, "A safe and just space for humanity : can we live within the doughnut?", 2012 ; D. O'Neil, "A good life for all within planetary boundaries", Nature Sustainability, 2018

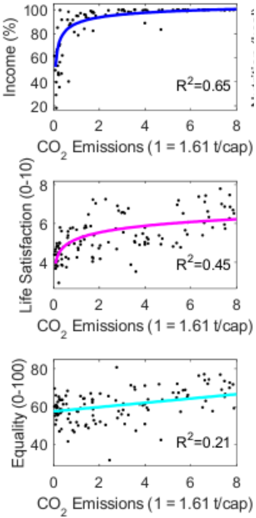
Metrics in different approaches are not independent !

Types of regression:

- $y = \alpha_1 + \beta_1 x$ (lin-lin)
- $y = \alpha_2 + \beta_2 \log(x)$ (lin-log)
- $\log(y) = \alpha_3 + \beta_3 \log(x)$ (log-log)

Quality of interpolation:

$$R^2 = 1 - \frac{\sum_{i\in\mathcal{I}}(y_i - \hat{y}_i)^2}{\sum_{i\in\mathcal{I}}(y_i - \overline{y})^2}$$



Multi-metrics optimization (1/2)

$$\min_{\mathbf{x}\in\mathcal{C}} f_i(\mathbf{x}), \ \forall i$$

It is not well-posed problem due to coupling in f_i

1. We only keep one metric i_0 (eg: CO_2 or GDP)

$$\min_{\mathbf{x}\in\mathcal{C}} f_{i_0}(\mathbf{x})$$

2. We aggregate the criteria (eg: inflation rate)

$$\min_{\mathbf{x}\in\mathcal{C}} \sum_i w_i f_i(\mathbf{x})$$

3. We bound the criteria (eg: Doughnut's theory)

$$\mathbf{x}\in\mathcal{C}, \quad \text{s.t.} \quad f_i(\mathbf{x}) \geq L_i, i \in \mathcal{I}_L \text{ and } f_i(\mathbf{x}) \leq M_i, i \in \mathcal{I}_M$$

$\hookrightarrow$ barrier function (eg: logarithm)

Multi-metrics optimization (2/2)

4. Pareto point : at this point, no uniform improvement possible

$$\mathcal{P} = \{\mathbf{x}' \in \mathcal{C} | \{\mathbf{x} \in \mathcal{C} | f_i(\mathbf{x}') > f_i(\mathbf{x}), \forall i\} = \emptyset\}$$

Toy example : function maximization

$f_1(x_1, x_2) = x_1 + x_2$ and $f_2(x_1, x_2) = \frac{x_1}{x_1 + x_2}$ with $(x_1, x_2) \in [0, 1]^2$

1. If $i_0 = 1$, $x_1^\star = 1$ and $x_2^\star = 1$
2. If $f = f_1 + 4f_2$, $x_1^\star = 1$ and $x_2^\star = 0$
3. If $f_1 \geq 0.5$, $f_2 \leq 0.25$, $x_1^\star = 0$ and $x_2^\star = 1$
4. Pareto: $x_1^\star = 1$ et $x_2^\star = 1$

Section 2 : Dynamic systems

Complex system

- Many inter-connected units
- no central decision point
- Complicated at each scale (macro/meso/micro)
- Often time-varying structure
- Often mis-defined functions
- Emerging properties (macro-level phenomenon not predictable at micro-level)

- Counter-example: the car (complicated but clear goal)
- Mathematical example: graphs
- Physical example: wind direction
- Example in that lecture: Earth system

Dynamic system

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t), \boldsymbol{\theta}_t, \mathbf{u}) \quad \text{or} \quad \mathbf{x}_{n+1} = f(\mathbf{x}_n, \boldsymbol{\theta}_n, \mathbf{u}_n)$$

with

- $\dot{\mathbf{x}}(t) = d\mathbf{x}/dt$
- $\mathbf{x}(t)$: state at time t (init. at $\mathbf{x}(0)$ or $\mathbf{x}_0$)
- $\boldsymbol{\theta}_t$: parameters
- $\mathbf{u}$: control

System characterization (through f)

By default, nonlinear system with feedback loop

- If f does not depend on $\mathbf{u}$:

	$\boldsymbol{\theta}_t$ ind. of t	$\boldsymbol{\theta}_t$ depends on t
f linear	lin and aut.	lin. and non-aut.
f nonlinear	non-lin. and aut.	non-lin. and non-aut.

- If f depends on $\mathbf{u}$: possible controllable system

Autonomous linear system

- 1-D system:

$$\dot{x} = \alpha x \Rightarrow x(t) = x(0)e^{\alpha t}$$

$\hookrightarrow$ Asymptotic behavior: $x(t) \to 0$ if $\alpha < 0$, $x(t) \to \infty$ if $\alpha > 0$

$\hookrightarrow$ This behavior independent of any initialization

- N-D system:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} \Rightarrow \mathbf{x}(t) = e^{\mathbf{A}t}\mathbf{x}(0)$$

with

$\hookrightarrow$ $e^{\mathbf{A}t} = \sum_{n\geq 0} \mathbf{A}^n / n!$

$\hookrightarrow$ behavior depends on the eigenvalues (if diagonalizable matrix)

Example: 2-D system (1/2)

- $\mathbf{A}$: 2×2 matrix of determinant δ and trace τ
- Assumptions: $\delta \neq 0$ (invertible), $\tau^2 - 4\delta \neq 0$ (diagonalizable)
- Distinct eigenvalues:

$$\{\lambda_1, \lambda_2\} = \frac{\tau \pm \sqrt{\tau^2 - 4\delta}}{2}$$

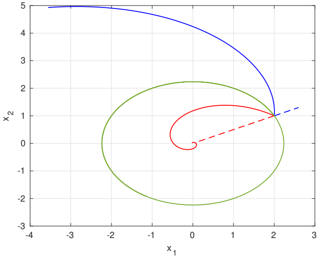
Which analysis?

- At equilibrium point: $\mathbf{x}_e$ t.q $\dot{\mathbf{x}} = 0 \Leftrightarrow f(\mathbf{x}_e) = 0$
  $\hookrightarrow$ here, unique point $\mathbf{x}_e = 0$
- Asymptotic behavior: when $t \to \infty$

Example: 2-D system (2/2)

Assumption: $\delta > 0$

- $\tau^2 - 4\delta > 0$:
  - $\tau < 0$: stable equilibrium
  - $\tau > 0$: unstable equilibrium
- $\tau^2 - 4\delta < 0$:
  - $\tau < 0$: stable focal point
  - $\tau > 0$: unstable focal point
- $\tau = 0$: circle



State equations

System state representation: state of system $\mathbf{x}$ is not always observable or with some noise

$$\begin{cases} \dot{\mathbf{x}} &= f(\mathbf{x}, \mathbf{u}) \\ \mathbf{y} &= h(\mathbf{x}, \mathbf{u}, \mathbf{w}) \end{cases} \overset{\text{if lin.}}{\Rightarrow} \begin{cases} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} + \mathbf{E}\mathbf{w} \end{cases}$$

with $\mathbf{w}$ a random vector

Example: $y_n = h_0 x_n + h_1 x_{n-1} + h_2 x_{n-2} + w_n$

We get $\mathbf{x}_n = [x_{n-1}, x_{n-2}]^{\mathrm{T}}$ and $u_n = x_n$ with

$$\mathbf{A} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \mathbf{C} = [h_1, h_2], \mathbf{D} = h_0, \mathbf{E} = 1$$

Controllability condition

A system is *controllable* if we can start from any state $\mathbf{x}_i$ in t_i and comes at any state $\mathbf{x}_f$ in t_f with a control $\mathbf{u}$ applied on $[t_i, t_f]$.
Warning: in discrete-time case, time of arrival t_f is just finite

Kalman criterion for linear system

Let $\mathbf{A}$ be a $m \times m$ matrix. The system is controllable iff

$$\text{rank}\left([\mathbf{B}, \mathbf{AB}, \cdots, \mathbf{A}^{m-1}\mathbf{B}]\right) = m$$

Remarks:

- Any linear system is not controllable
- In the "climate" case, control = public policies

Sketch of proof (discrete-time case)

Let

- $\mathbf{B}$ of size $m \times p$.
- then $\mathbf{Q} = [\mathbf{B}, \mathbf{AB}, \cdots, \mathbf{A}^{n-1}\mathbf{B}]$ of size $m \times np$

We get

$$
\begin{aligned}
\mathbf{x}_n &= \mathbf{A}^n \mathbf{x}_0 + \sum_{i=0}^{n-1} \mathbf{A}^{n-1-i}\mathbf{B}\mathbf{u}_i \\
&= \mathbf{A}^n \mathbf{x}_0 + \mathbf{Q}\underline{\mathbf{u}}
\end{aligned}
$$

If $\mathbf{Q}$ full rank (with $m \leq np$ and so rank $= m$), then $\mathbf{Q}$ right-invertible, and if goal is $x_n = x_n^\star$, then choose

$$
\underline{\mathbf{u}}^\star = \mathbf{Q}^{\#}(\mathbf{x}_n^\star - \mathbf{A}^n \mathbf{x}_0)
$$

Counter-example: non-controllability and non-reversibility

- Start from $\mathbf{x}_0$
- Arrival at $\mathbf{x}_n$ through control $\underline{\mathbf{u}}_n$

Question: can we go back to $\mathbf{x}_0$ of non-controllable system?

Let

$$\mathbf{A} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ and } \mathbf{x}_0 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Non-controllable system since $\mathbf{Q}_n = [\mathbf{B}, \cdots, \mathbf{B}] \Rightarrow \text{rank}(\mathbf{Q}_n) = 1$

$$\mathbf{x}_n = \mathbf{A}^n \mathbf{x}_0 + \mathbf{Q}_n \underline{\mathbf{u}}_n = \begin{bmatrix} \alpha := \sum_{i=0}^{n-1} \mathbf{u}_i(1) \\ 0 \end{bmatrix}, \text{ for } n \geq 1$$

$$\begin{aligned} \mathbf{x}_{n+N} &= \mathbf{A}^N \mathbf{x}_n + \sum_{i=n}^{n+N-1} \mathbf{A}^{n+N-1-i} \mathbf{B} \mathbf{u}_i \\ &= \begin{bmatrix} \alpha \\ 0 \end{bmatrix} + \begin{bmatrix} \beta := \sum_{i=n}^{n+N-1} \mathbf{u}_i(1) \\ 0 \end{bmatrix} = \begin{bmatrix} \gamma \\ 0 \end{bmatrix} \neq \mathbf{x}_0 \end{aligned}$$

and so **non-reversible** system!

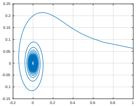
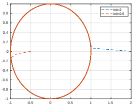
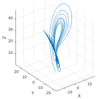
Attractors

Definition

Set $\mathcal{A}$ to which some trajectories $\mathbf{x}(t)$ converge.

- let $t \mapsto \phi_t(x)$ be a flow, ie, solution of dynamic system initialized at x
- $\phi_t(\mathcal{A}) = \mathcal{A}$
- it exist a set $\mathcal{B}$ different from $\mathcal{A}$ s.t. $\forall t > t_0$, then $\phi_t(\mathcal{B}) \in \mathcal{A}$

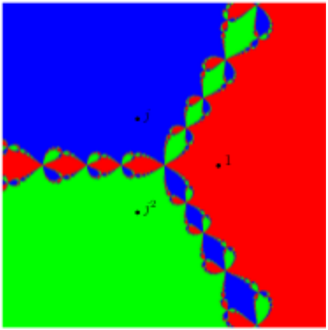
Different types

Pointwise	Periodic	Strange
		

Example of attractors

$$z_{n+1} = f(z_n) \text{ with } f(z) = \frac{2z}{3} + \frac{1}{3z^2}$$

The equilibria are: 1, j, and j^2



source: P. Collet, "Quelques notions et résultats sur les systèmes dynamiques", lecture of Ecole Polytechnique

Link with Environmental and Life Sciences

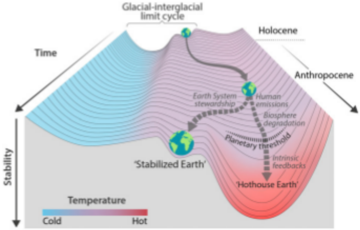
- f is not precisely known
- f is time-varying (some hyper-parameters may be non-constant)
- f may have different behaviors depending on the value of $\mathbf{x}$ (and so of $\mathbf{u}$)
- even the underlying states $\mathbf{x}$ are not precisely known
- even only partial observations $\mathbf{y}$ and can not be reproduced

Nevertheless, we know

- complex system: strange attractor or tipping points possible
- non-reversibility:
  - $\hookrightarrow$ a dead species does not come back
  - $\hookrightarrow$ some chemical reactions do not come back (photosynthesis stops at $47,5^{\circ}$C and does not operate anymore)

Tipping points

- $\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u})$ with $\mathbf{u}$ (CO_2)
  ↪ seen as a control or as a parameter
- attractors (their area) change with $\mathbf{u}$



- Different equilibrium points with attraction area
- Tipping point (No-return point) corresponds the attraction area's borders leading to a different behavioral regime

source: W. Steffen et al., "Trajectories of the Earth System in the Anthrophocene", Proceedings of the National Academy of Sciences, 2018

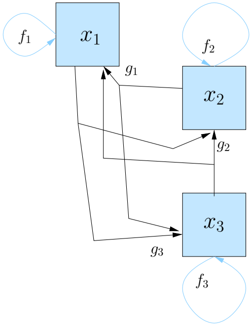
Feedback loop

If $\mathbf{x} = [x_1, \cdots, x_m]^T$, then, for $i = 1, \cdots, m$,

$$\dot{x}_i = f_i(x_i) + g_i(x_i, \mathbf{x}_{\bar{i}})$$

with g_i the feedback/coupling loop

Systemic chart:



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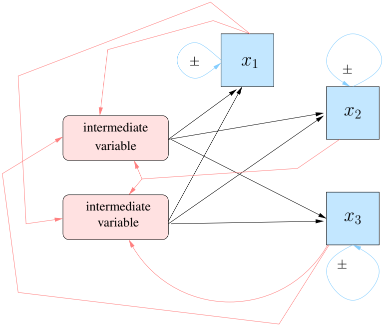
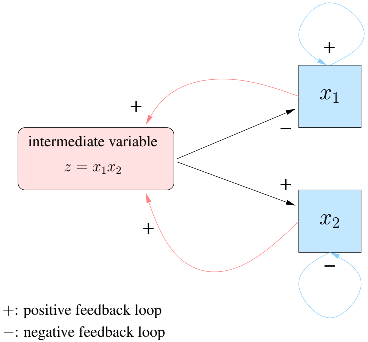


Example 1: Lotka-Volterra model [1926]

- x_1: population density of prey
- x_2: population density of predator

$$\begin{cases} \dot{x}_1 = x_1(\alpha - \beta x_2) \\ \dot{x}_2 = -x_2(\gamma - \delta x_1) \end{cases}$$



with

- α: growth rate for prey
- β: death rate for prey linked with predator's density
- γ: death rate for predator
- δ: growth rate for predator linked with prey's density

source: I. Akjouj, "Large random LV systems with vanishing species: a mathematical approach", 2023

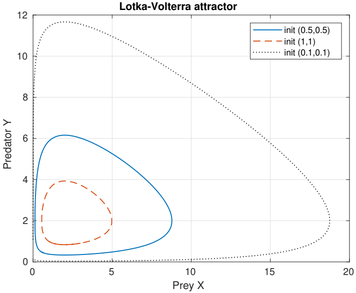
Analysis of Lotka-Volterra model

- **Equilibrium points:**

$$\mathbf{x}_e^{(0)} = (0,0) \text{ and } \mathbf{x}_e^{(1)} = \left(\frac{\gamma}{\delta}, \frac{\alpha}{\beta}\right)$$

- **Analysis of equilibrium points:** Jacobian matrix

$$\begin{bmatrix} \alpha & 0 \\ 0 & -\gamma \end{bmatrix} \text{ and } \begin{bmatrix} 0 & -\frac{\beta\gamma}{\delta} \\ \frac{\alpha\delta}{\beta} & 0 \end{bmatrix}$$



- ◦ $\mathbf{x}_e^{(0)}$ saddle point
- ◦ $\mathbf{x}_e^{(1)}$ ellipse (since eigenvalues are purely imaginary)

Example 2: IPCC/AR5 climate model [2014]

$$\begin{cases} \dot{\mathbf{c}} &= \mathbf{A}\mathbf{c} + \mathbf{b}u \\ \dot{\boldsymbol{\theta}} &= \mathbf{C}\boldsymbol{\theta} + \mathbf{d}f(\mathbf{c}) \\ y &= \mathbf{e}\boldsymbol{\theta} \end{cases}$$

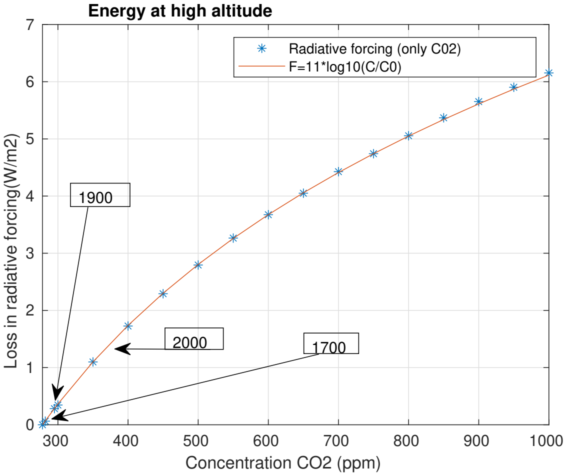
with

- y: global temperature gap
- $\mathbf{c}$: CO_2 concentration in several boxes (ocean, surface, air, etc)
- $\boldsymbol{\theta}$: temperature gap in each box
- u: CO_2 emission
- v: radiative forcing function $\rightarrow f(\mathbf{c}) = \mathbf{f}.\log\left(\frac{\mathbf{c}}{\mathbf{c}_{ref}}\right) + f_{noCo2}$
- $\mathbf{A}$ and $\mathbf{C}$ have negative diagonal terms

Geometric growth in CO_2 leads to arithmetic growth in temperature

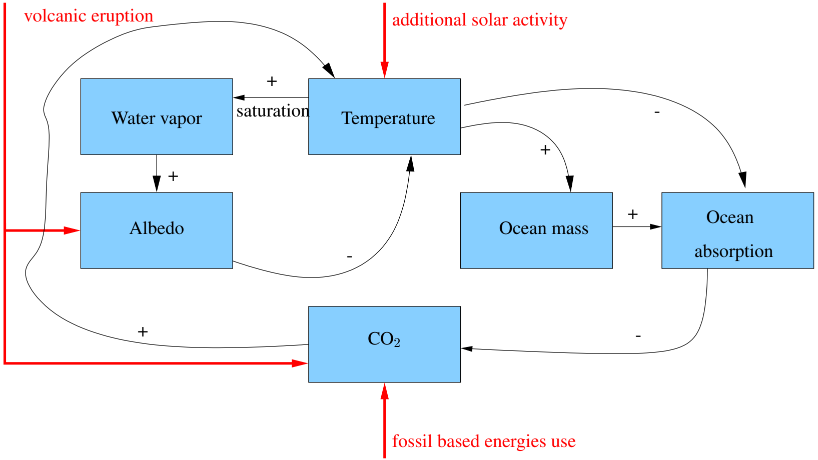
source: R. Millar et al., "A modified impulse response representation of the global near surface air temperature and atmospheric concentration response to CO_2 emissions", 2017 ; N. Leach et al., "FAIRv2.0.0: an impulse response model for climate uncertainty and future scenario exploration", 2021

Link between radiative forcing and CO_2 concentration

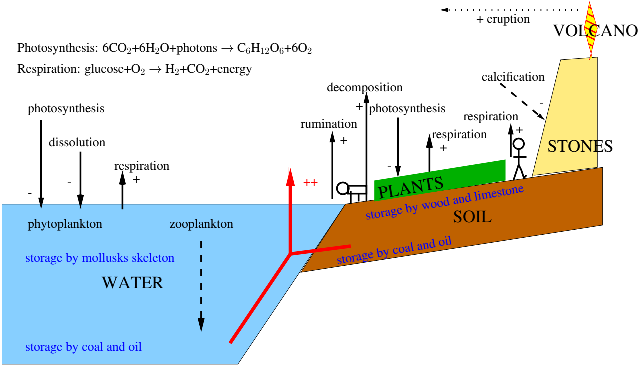


source: Model MODTRAN, https://climatemodels.uchicago.edu/modtran, University of Chicago

Some feedback loops (hidden in the model)



Example 3: Biogeochemical carbon cycle (C)

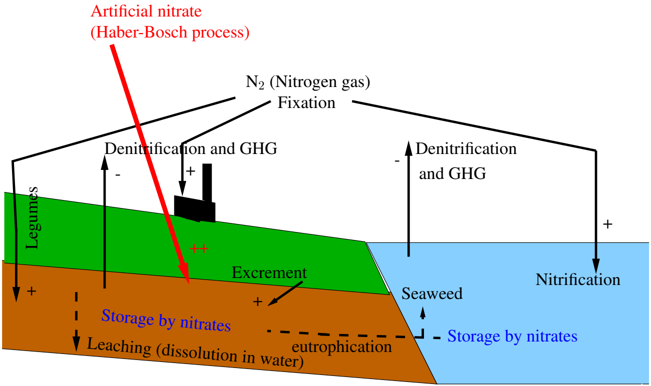


CO_2 concentration change:

+ volcanism: -250Myr (end of Permian period) in Central Siberia
– erosion: -330Myr (beginning of Permian period) with Pangea
– vegetation emergence: -400Myr (end of Devonian period)
+ industrial revolution: 1850 (“beginning” of Anthropocene)

Example 4: Nitrogen cycle (N)

Nitrogen useful for ADN forming and Protein manufacturing



This cycle can be seen as a dynamic system with

- **x**: concentration of N-based molecules in different areas
- **u**: control by adding/removing nitrate via HB or excrement

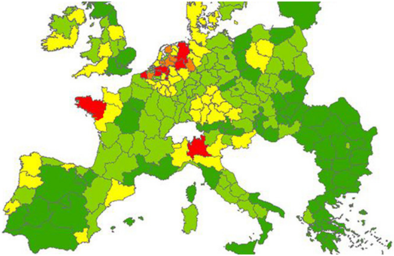
Political crisis and cycle disturbance

Dutch political crisis due to N cycle !

- Due to Natura2000 area (from EU law)
  - each State has to do some analysis about N
  - in France, biodiversity state ; in Netherlands, aggregated concentration analysis

Concern: values are higher than target threshold. Why ?

- Second world exporter of agricultural products
- 12M porks (13M in France)



Political crisis and cycle disturbance (cont'd)

Due to complain (at Dutch State Council in 2019),

- goal for a rejection reduction of 50% by 2030
- stronger reduction around Natura2000 area
- any increase has to be compensated for an equivalent decrease

New policy in 2022:

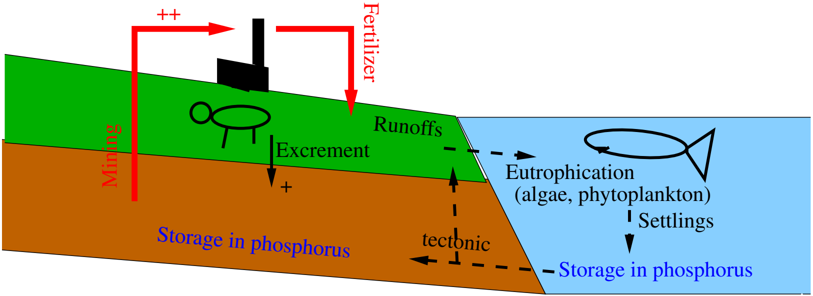
- Any new construction is stopped
- New speed limit: 130 $\rightarrow$ 100 km/h (gain of 75000 flats)
- Stop (20%) or decrease of size or organic conversion (30%) for farms (budget of 25G€)

Impact on Dutch political life:

- Creation of new political party: BBB (*BoerBurgerBeweging*)
- Resignation of Prime Minister M. Rutte (right) in June 2023
- Victory of G. Wilders' party (ultra-right) in November 2023

Example 5: Phosphorus cycle (P)

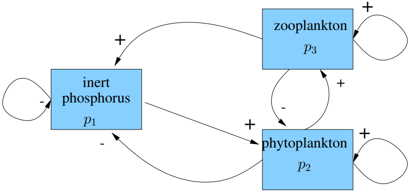
Phosphorus useful for ADN forming and bones



Dynamic system model in water

- p_1: inert phosphorus
- p_2: phytoplankton (like predator)
- p_3: zooplankton (like prey)

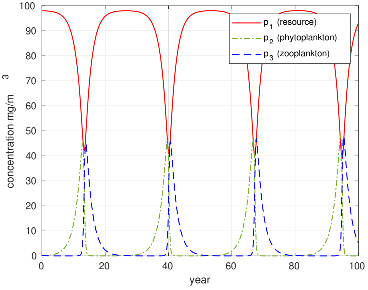
$$\begin{cases} \dot{p}_1 & = & k_3 p_3 - k_2 \frac{p_1}{k+p_1} p_2 \\ \dot{p}_2 & = & k_2 \frac{p_1}{k+p_1} p_2 - k_1 p_2 p_3 \\ \dot{p}_3 & = & k_1 p_2 p_3 - k_3 p_3 \end{cases}$$



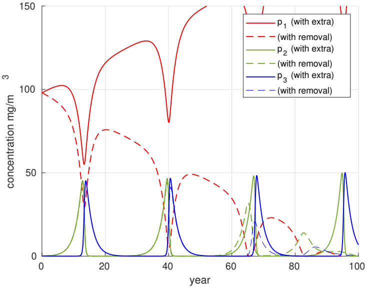
- $\frac{p_1}{k+p_1}$ corresponds to Michaelis-Menten principle (linear then saturation)
- If human control (fertilization), then $k_3 p_3 - k_2 \frac{p_1}{k+p_1} p_2 + u$

Numerical results

Without forcing:



With forcing:



when

- $p_1(0) = 98,\ p_2(0) = p_3(0) = 0.1$
- $u = 2$ or -1 mg/(m^3.j)

Example 6: Global Earth system model

Around '70, new ideas: Earth is a global system with interactions

- Gaia hypothesis [Lovelock1970] with Daisyworld model
  - "each Earth element plays a (small) role for saving the global life" (complex system definition)
  - Human beings are just an element
  - Crucial issue: No compatible with Darwinian theory
  - "new way for seeing the link of beings and Earth" [Latour]

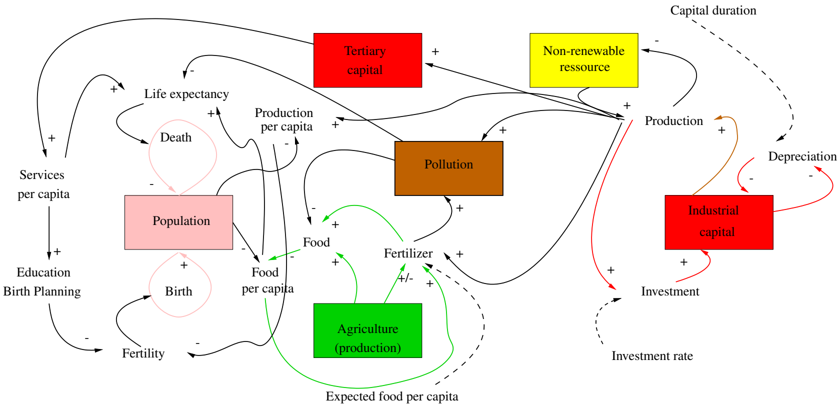
In parallel, biological-economical-sociological point of view

- Gosplan in Soviet Union
  - Economy/Industry/Ressources model with 14,440 parameters
- Club of Rome report (so-called "Meadows" report) [1972]
  - Forrester then Meadows *et al.* built World3 model
- Climate change impact on Economy: DICE model [1992]

source: D. Meadows et al., "Limits to Growth", 1972 ; E. Egnell et al., "URSS: entreprise et Etat", 1974

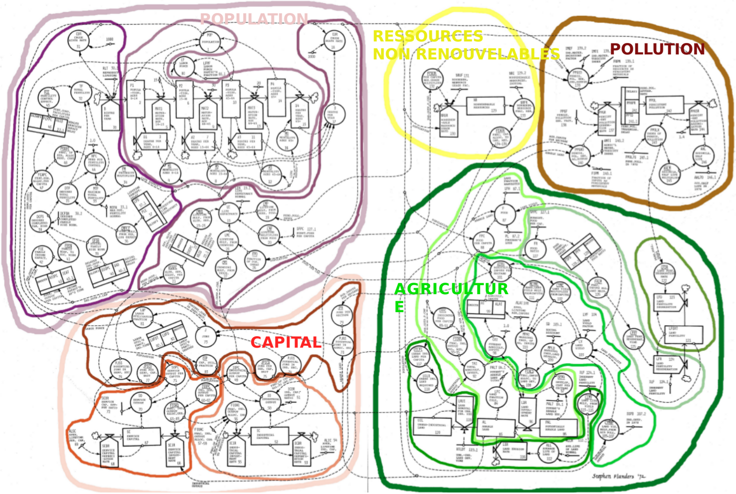
World 3: relationship between main boxes

Five main boxes/states: agriculture, capital (industrial/tertiary), pollution, population, non-renewable resource



World 3: final model

Last World3 has 315 intermediate variables (but still 5 states)



source: M. Jochaud du Plessix, "Analyse du modèle World3", 2019

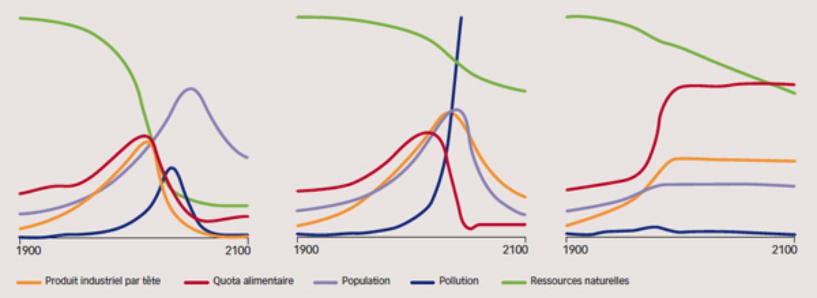
World 3: box/state "Pollution"

- x: persistent pollution
- controls from other boxes
  - u_1 (population),
  - u_2 (resource per capita),
  - u_3 (arable land),
  - u_4 (fertilizer per hectare)

$$\dot{x} = \left(2.10^{-2} u_1 u_2 + 10^{-4} u_3 u_4\right) - \frac{x}{2.1 f(x/x_0)}$$

with x_0 a common benchmark and f a lookup table related to non pollution absorption

World 3: some storys



- Left: same growth as in 1970
- Center: growth of non-renewable resource use
- Right: new public policy (fertility rate of 2, vanishing economical growth, technologies for pollution control)

source: F. Rechenmann, "Limites de la croissance", Interstices, 2014 (image: V. Landrin)

Section 3 : Applications to Energy production and ICT

Application 1: Hydrogen based energy system

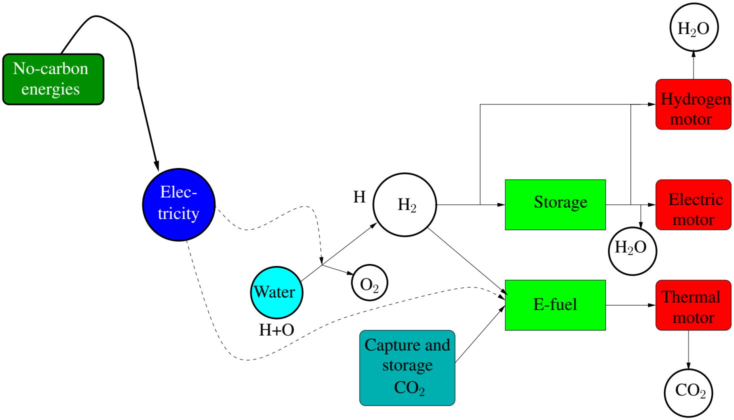
Possible solution as an energy vector for

- storage (irregular production) instead of dams or batteries
- embodied/mobile system
  - compressed air at 700 bars: 40kWh/kg .... 1,25MWh/m^3
  - fluid at 20°K: 40kWh/kg .... 2,36MWh/m^3
  - Reminder (kerosene): 12kWh/kg .... 10MWh/m^3

Taxonomy of production

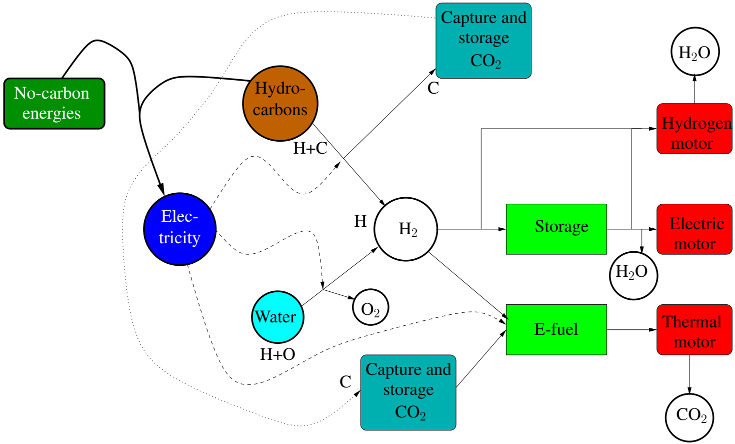
	Processing	Matter	Energy
Black Brown	Gazeification	Coal and Water	Fossil
Grey	Steam forming	Methane and Water	Fossil
Yellow Green	Electrolysis	Water	Nuclear Renewable

Systemic chart for Hydrogen use



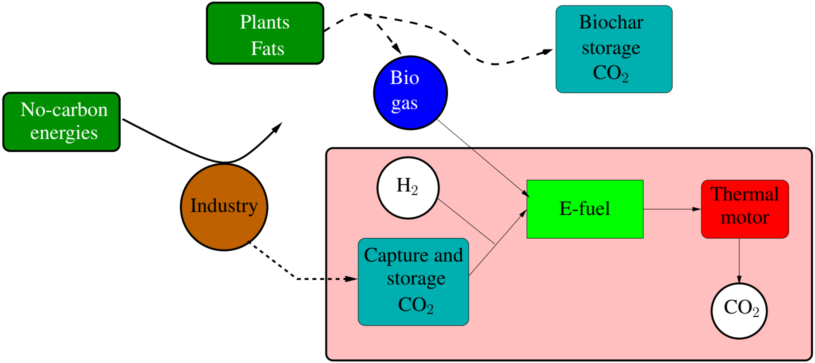
Zero CO_2 net emission

Systemic chart for Hydrogen use



CO_2 emission level depends on the path in the graph

Systemic chart for E-fuel (related to Hydrogen)



- *Sustainable Aviation Fuel (SAF), E-fuel*
- Be careful on double counting (Industry or Motor)
- Be careful on incompatibility of solution

Application 2: Future wireless network

A new generation each 10 years

- 2G: first digital generation: design for voice
- 3G: data (mobile Internet on the street: what an idea?)
- 4G: high data rate (touch screen saves the idea)
- 5G:
  - Very high data rate (eMMB) : cellular network
  - Low Latency and high reliability (URLLC) : automation
  - Massive connectivity (mMTC) : Internet of Things (IoT)
- 6G: under progress $\rightarrow$ Ultra high data rate, $\cdots$

Solutions "for" or "by" these networks

- Solution 1: *GreenIT*

$$\textbf{Energy efficiency} = \frac{\textbf{performance metric}}{\textbf{consumed energy}}$$

  - Relative goal (less GHG per unit)
  - Rebound effect (number of units increases)
  - This technical answer may be not enough to fix the problem
- Solution 2: *IT for Green*
  - Deported goal (less GHG but elsewhere)
  - Enablement effect with deportation of energy efficiency
  - This technical answer may be not enough to fix the problem
- Solution 3: Sufficiency
  - Consumed energy/power is pre-fixed
  - Avoid rebound effect, ensure enablement effect
  - but use limits to be defined. By whom?

Efficiency = Optimization ; Sufficiency = Way of Life

Is it efficient?

Very high data rate: massive MIMO, larger bandwidth

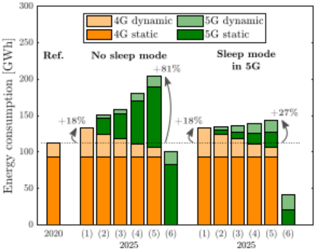
$$E_{\mathrm{tx,file}} = \frac{L P_{\mathrm{tx}}}{n_{\mathrm{tx}} B \log_2 \left(1 + \gamma \frac{P_{\mathrm{tx}}}{n_{\mathrm{tx}} B N_0}\right)}$$

- Efficiency
  - in transmit energy E_{tx}: yes
  - in consumed energy per device: ?
  - in consumed energy for manufacturing: ? (#depreciation year)
- Sufficiency: no

- Other ideas for 6G but only in efficiency or decarbonization
  - Harvested (solar/wind) energy
  - Distributed storage to limit core network access
  - but no manufacturing cost or variable device cost

Example 1: macroscopic analysis

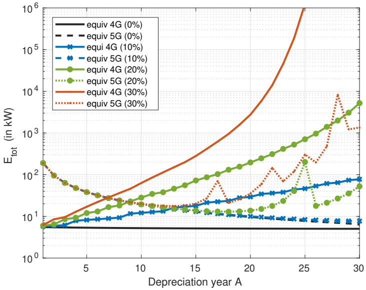
- 4G model: $P = P_0 + \alpha R$
- 5G model: $P_{5g} = \beta P(B_{5g}/B)^{0.95}(S_{5g}/S)^{0.1}$ with S flows
- Traffic (sleeping mode)



source : L. Golard et al., "Evaluation and projection of 4G and 5G RAN energy footprints : the case of Belgium for 2022-2025," Annals of Telecoms, 2024

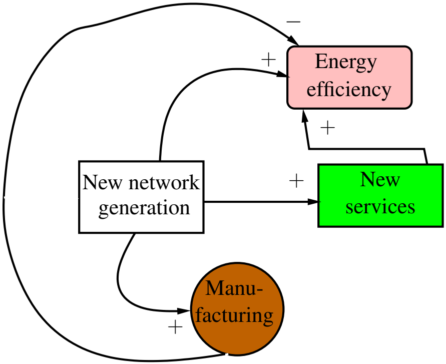
Example 2: microscopic analysis

- 4G model: 4 antennas, already 10 depreciation years
- 5G model: 100 antennas
- Manufacturing taken into account (especially antennas cost)

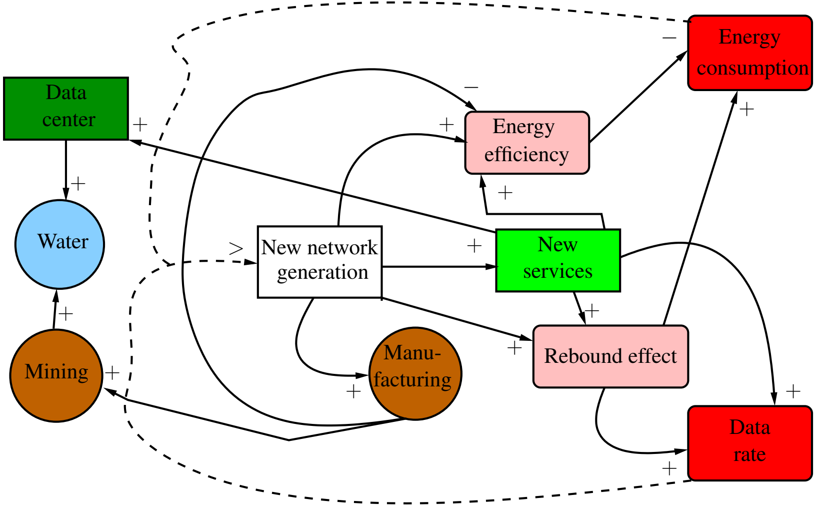


source : P. Ciblat, "A propos du MIMO massif dans un contexte de sobriété numérique," Gretsi, 2022

Systemic chart

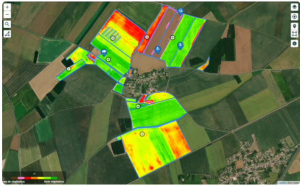


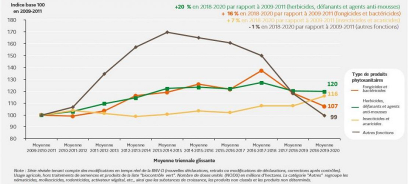
Systemic chart



Application 3: Smart farming

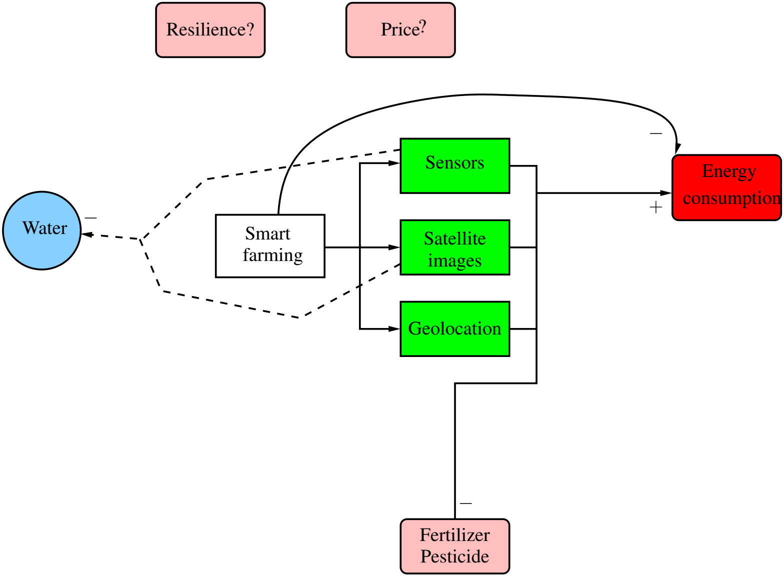
- Sensing, monitoring (communication & control)
  - ↪ geolocation, satellite image, local sensors, data network, computation for decision-making → large techno-structure
- Goals
  - ↪ First, increase of yields
  - ↪ Second, fertilizer/water decrease <u>but</u> failure of Ecophyto plan



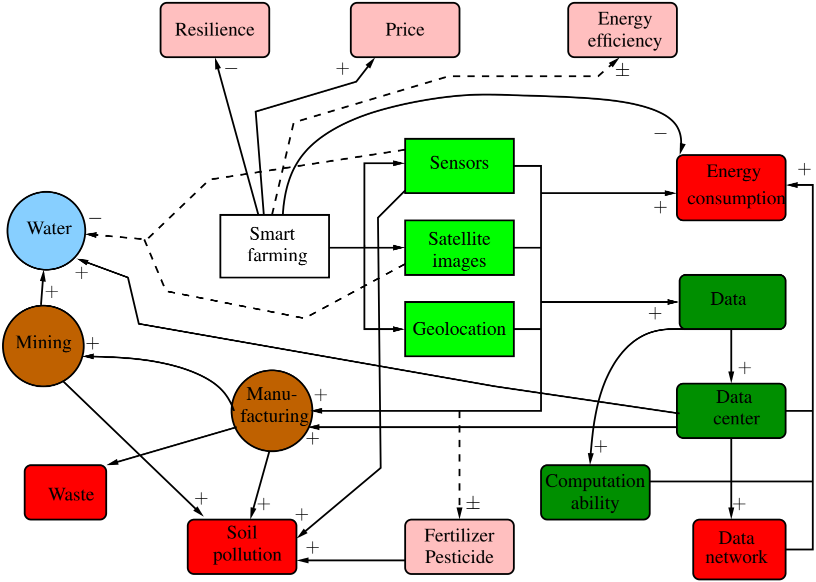


source: https://blog.spotifarm.fr ; http://www.ofb.gouv.fr ; J. Oui, "Produire une faute -conforme-. Outils numériques et normes environnementales en agriculture", Sociologies Pratiques, 2024

Systemic chart



Systemic chart



Conclusion

Sustainable system (SDG): an old story ...

- *"satisfy the needs for the current generation without preventing the next generation to satisfy their needs"*, G. Brundtland (Norwegian Prime minister) in 1988
- *"speed up the technical progress but without high natural resource consumption, without dangerous pollution, and without exhausting the soil"*, L. Brejnev (General Secretary of Communist Party of Soviet Union) in 1971

... <u>but</u> both types of Human societies fail on that point