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Active Human 'Soft Matter': The Critical Insight into 'Doomsday' Growth of Global Population

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Datum in ura: 1.7.2025, ob 14h
Lokacija: MST - na **daljavo**

Projekt sofinancirata Republika Slovenija, Ministrstvo za visoko šolstvo, znanost in inovacije, in Evropska unija – NextGenerationEU. Projekt se izvaja skladno z načrtom v okviru razvojnega področja Pametna, trajnostna in vključujoča rast, komponente Krepitev kompetenc, zlasti digitalnih in tistih, ki jih zahtevajo novi poklici in zeleni prehod (C3 K5), za ukrep investicija F. Izvajanje pilotnih projektov, katerih rezultati bodo podlaga za pripravo izhodišč za reformo visokega šolstva za zelen in odporen prehod v družbo 5.0: projekt Pilotni projekti za prenovo visokega šolstva za zelen in odporen prehod.

Introduction

In 1991, Pierre G. de Gennes presented the Nobel Prize Lecture entilted: „SOFT MATTER"

It introduced the novel category of systems, linking:
liquid crystals, polymers, blends, gels, foams, supercooled glass-formers, colloids, critical liquids …

Picture: J. Goodby & P. G. de Gennes:
' Soft Matter - Smectic Zoo '

SOFT MATTER systems exhibit common features:

1. Dominance of Mesoscale Species leading to ‚universal' scaling patterns of ‚isomorphic' physical properties
2. Ability to self-assembling
3. Extreme Sensitivity to Exo- & Endogenic Impacts, linked to weak interactions between mesoscales species

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https://assets.science.nasa.gov/dynamicimage

In subsequent years the concept of Soft Matter category entered other branches of Soft Matter Science, For instance, see the reports given below:

- ✓ R.P Thedford, F. Yu, W.R. Tait, K. Shastri, F. Monicone, U. Wiesner, *The promise of **Soft Matter enabled Quantum Materials;*** Advanced Materials **2023**, 5, 220398
- ✓ F. Serra, U. Tkalec, T. Lopez-Leon (editors), ***Topological Soft Matter;*** Frontiers in Physics **2020** (Special Issues)
- ✓ E.N. Saridakis, ***Do we need Soft Cosmology***. Physics Letters B **2021**, 822, 136649
- ✓ R. Mezzenga, P. Schurtenberger, A. Burbridge, ***Foods as Soft Matter***. Nature Materials **2005**, 4, 729

Hence: Quantum Soft Matter, Topological Soft Matter, Food Soft Matter, Cosmological Soft Matter

… another Soft Matter category is emerging … ‚Inteligence' Active Human Soft Matter

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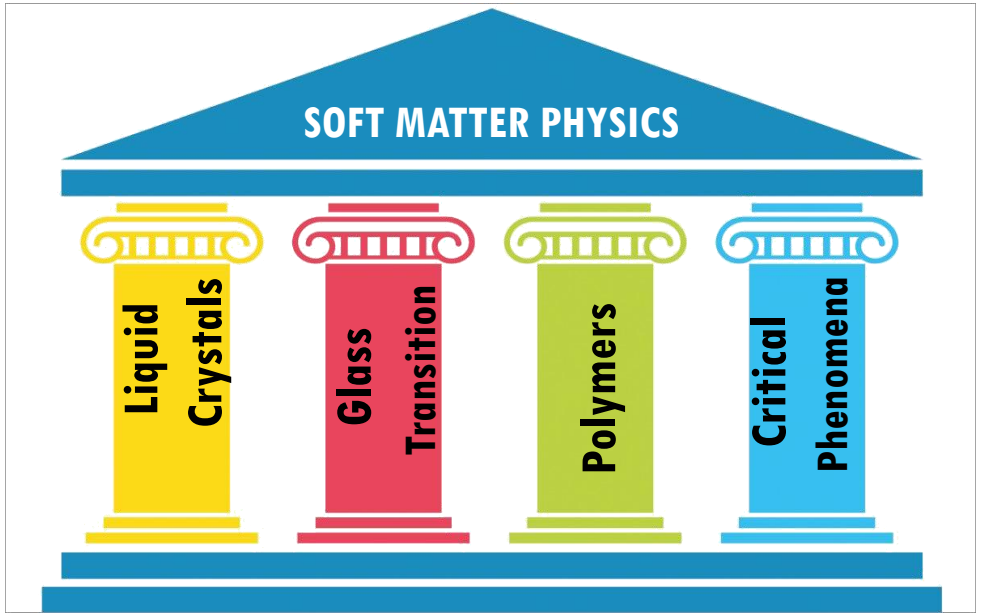
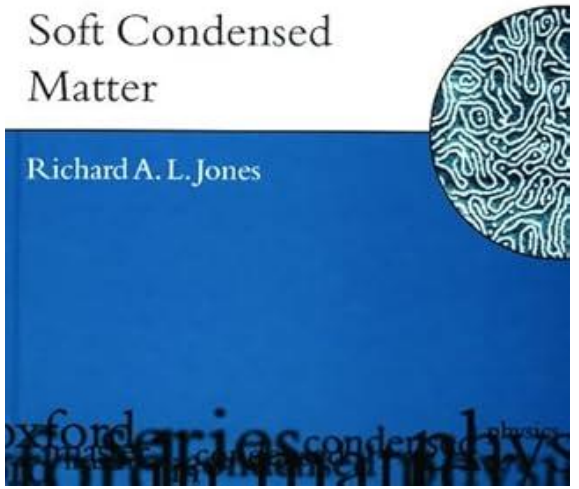
Soft Matter & Active Soft Matter

ACTIVE MATTER is defined as a system composed of large numbers of active „agents", each of which consumes Energy in order to move or to exert mechanical forces.

ACTIVE MATTER exhibit spontaneous motions and form spatiotemporal structures, far from equilibrium.

A significant sub-domain constitutes Biological Active (Soft) Matter, including LIVING MATTER.





Recalling the classic monograph by R.A.L. Jones.
there are the following conceptual Soft Matter ‚cognitive pillars' – significant for scaling equations

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Explaining the title: # Intelligent Active Human Soft Matter'

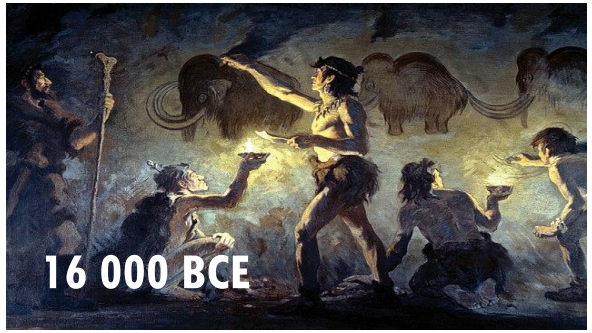
There are exceptional features of Humans considered as 'Intelligent Active Soft Matter':

- An extraordinary range of adaptation to a 'system' despite environmental changes, food resources, threats, etc..
- Creation of 'innovations', their memorization, improvement, and transfer to the next generations, supporting adaptation to the system, and even shaping it
- The ability to create 'structures' for defensive purposes, food resources, or a defensive/aggressive super-predator
- Multidimensional interactions – 'biological', 'ecological' with the environment, but also social. Significant is the rapid development of language, or the development of seemingly 'impractical' actions, indirectly strengthening communities (rituals, religion, art, etc.).

Grand ‚Fire' Innovation

The last Ice Age

Cave Paintings



The Ice Age end

Stonehenge, *England* (temple?)

Neolithic

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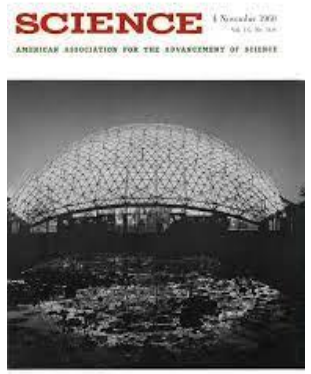


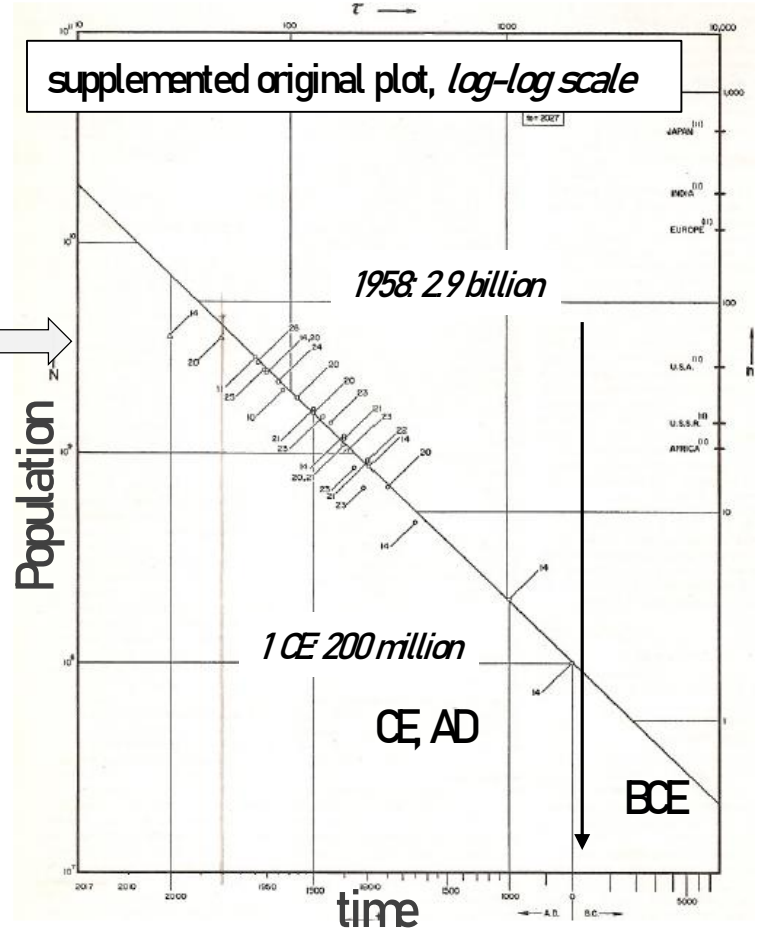
H. von Foerster, P.M. Mora, L.W. Amiota, ***Doomsday: Friday, 13 November, A.D. 2026.*** *At this date human population will approach infinity if it grows as it has grown in the last two millennia.* Science **1960**, 132, 1291.

It shows the following simple scaling of the Global Population data from 400 BCE to 1958, using 28 available population data:

$$P(t) \approx \frac{A}{(D-t)^M} \Rightarrow \log P(t) = \log A - M \times \log(D-t)$$

where P(t) means Global Population, and $M = 1$

It is named '**Hyperbolic Equation**', '**Doomsday Equation**', since when approaching the year 2026 the Global Extinction should occur



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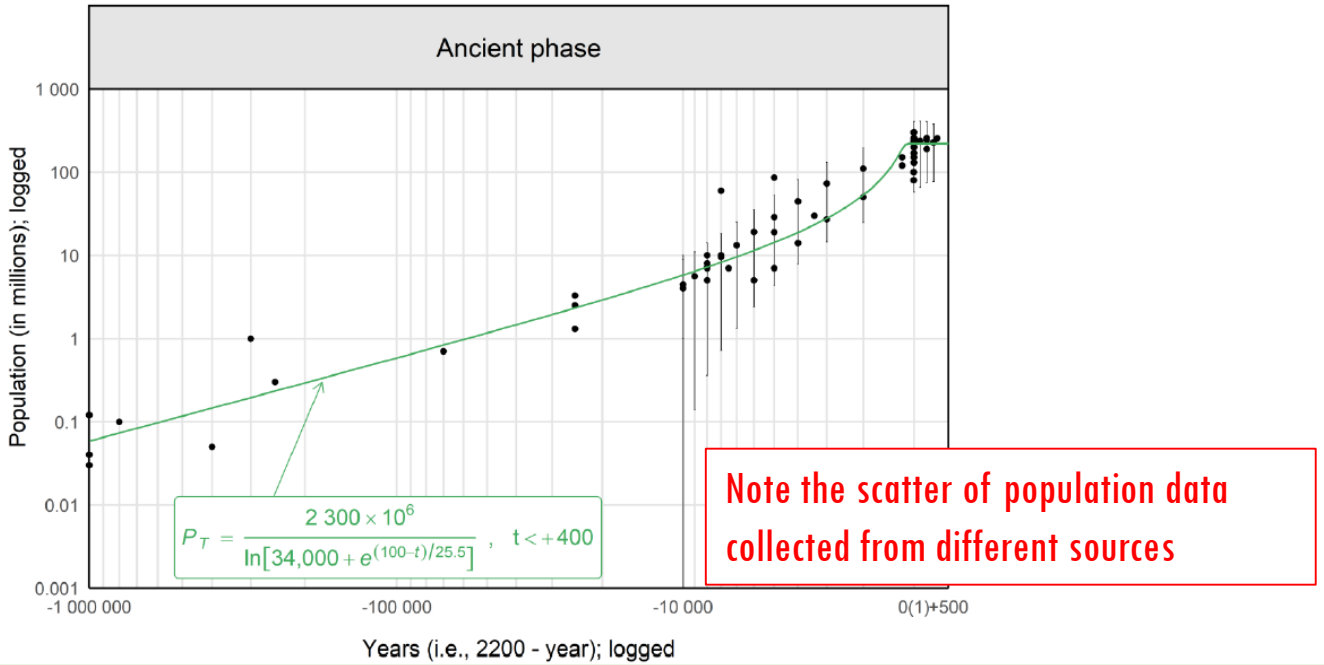
'Doomsday' challenge

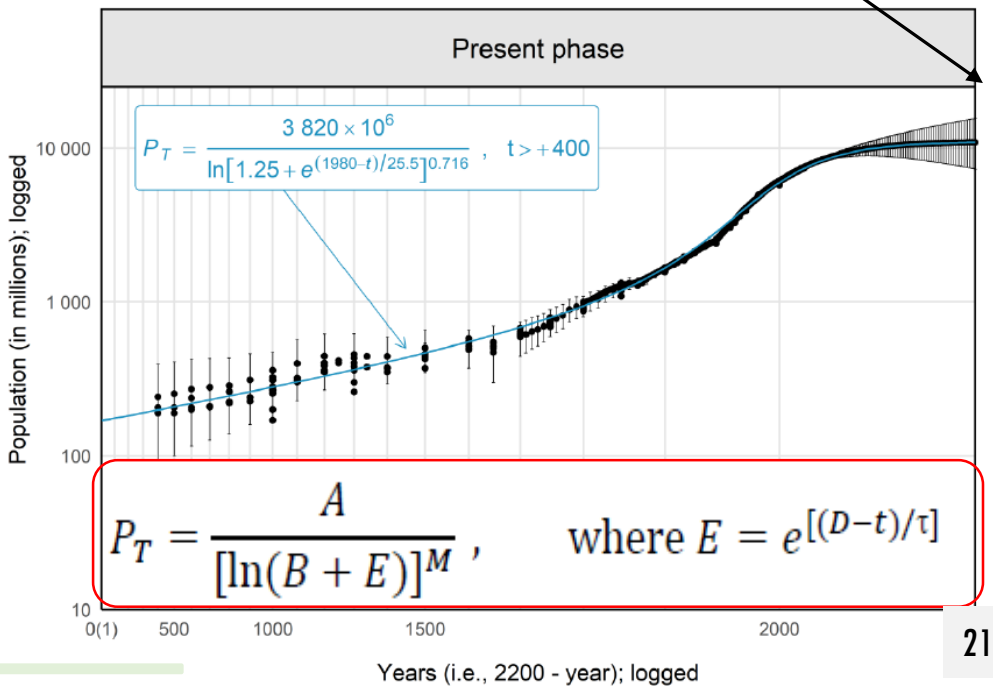
In the last decade **Taagapera and Nemčok,** developed a scaling function that avoids the ‚Doomsday' singularity but can be reduced to von Foerster scaling. They suggest 2 'stationary, terminal phases' as the generic feature of global population development:

1st for Roman Empire times, & 2nd for the last decades.

Problem: **2 equations, with 6 adjustable parameters each**. Consequently, arbitrariness for 2100 year forecast appear. The base of two stationary phases (Roman Emire nad the last decades) is not convincingly explained.



Note the scatter of population data collected from different sources



2100

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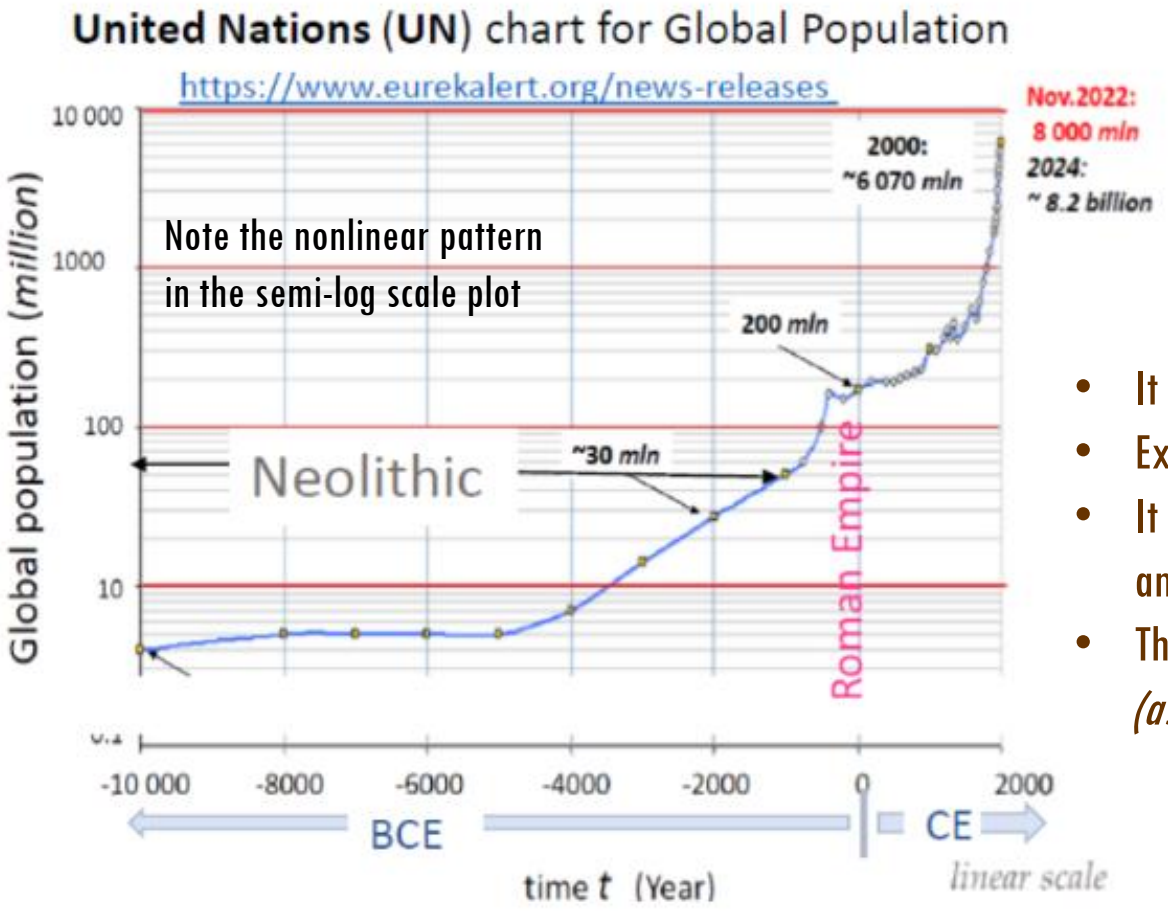
R. Taagepera, M. Nemčok, *The Anthropocene Review* **2024**, 11, 163.

Global Population as the Planetary Model System



Global Population Growth since the Holocene / Anthropocene (10,000 BCE) onset. UN official data

Global Population can be considered a model-system in the extreme (12 000 years) Anthropocene period:

- It is a ‚closed', **Planetary System**
- External impacts are minimal
- It is governed and driven only by internal features and dynamics
- There is no external populations impacts *(assuming UFO, Aliens, etc. do not exist)*

Significant is the lack of other human groups' impact, and disturb the growth - it is a ‚standard' for local communities, cities, states, and even continents

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BASIC MODELS FOR GLOBAL POPULATION SCALING AND FUTURE TRENDS FORECASTING

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The 18th century was Isaac Newton's (1642-1727) era of inspirational dominance. He showed that even seemingly separate phenomena can be related to a common explanation, and described by the same (universal) scaling relations. To facilitate the analyses, he introduced differential calculus.

This was the Scientific Method's 'grand proof in practice'.

This inspiration was declared by Robert Malthus (**1798**), who introduced the first model & scaling relation for human population changes:

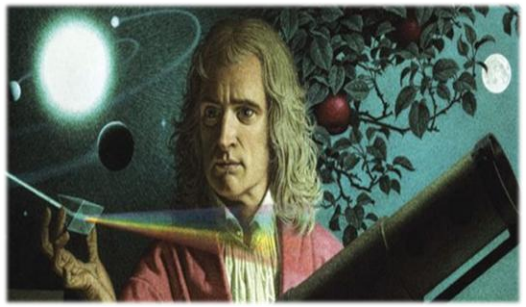
$$P(t) = P_0 exp(rt) \Rightarrow lnP(t) = lnP_0 + rt \Rightarrow \frac{dlnP(t)}{dt} = r = const$$

where time t refers to the onset time t_0, coupled to the prefactor P_0, and $r = const$ is the Malthus rate coefficient.

It is the geometric growth, with the growth directly proportional to the current population size, with the rate described by the coefficient r, characteristic for the given population, namely:

$$\frac{\mathrm{dlnP(t)}}{\mathrm{dt}} = \frac{\mathrm{dP(t)/P(t)}}{\mathrm{dt}} = r = const \quad \text{or} \quad \frac{\mathrm{dP(t)}}{\mathrm{dt}} = r \times \mathrm{P(t)}$$

- Malthus, T. *An Essay on the Principle of Population* (first published in 1798); in Stimson, S.C. *Rethinking the Western Tradition*; de Gruyter: Amsterdam, 2013.
- Kaack, L. H, Katul, G. G. (2013). *Fifty Years to Prove Malthus Right*. PNAS: USA, 110 (2013) 4161.



Isaak Newton
(1642-1727)

Thomas Malthus
(1766-1834)

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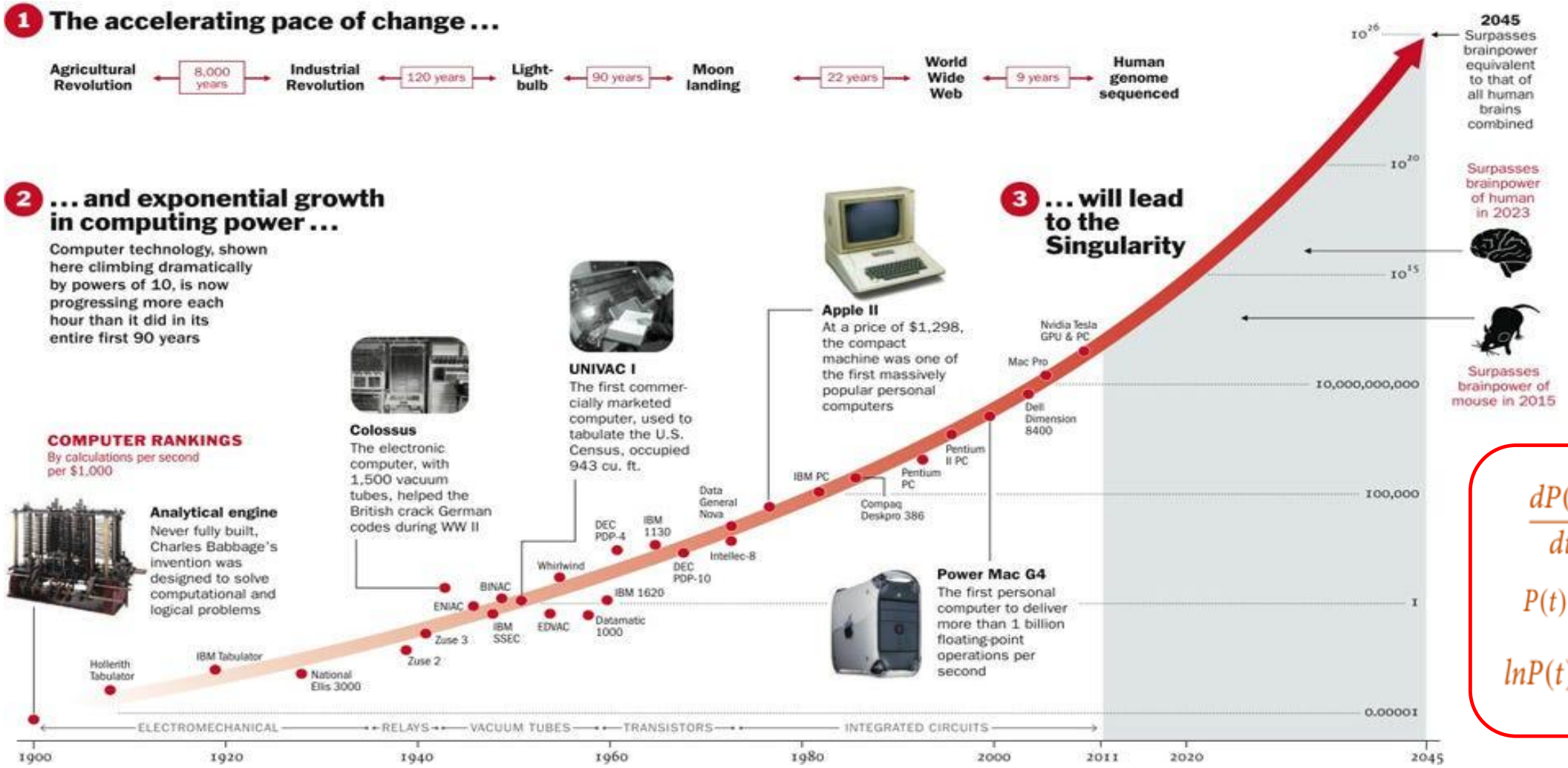

$$\frac{dP(t)}{dt} = rP(t)$$

$$P(t) = P_0 exp(rt)$$

$$lnP(t) = lnP_0 + rt$$

Malthus's model is effective for various processes related to population changes in physics, chemistry, biology, innovations numer, computing power and other ... However, by the 20th century, long-term Global Population data were already available, showing the inadequacy of its portrayal. But, the discussion demographic significance of the Malthus model has remained.

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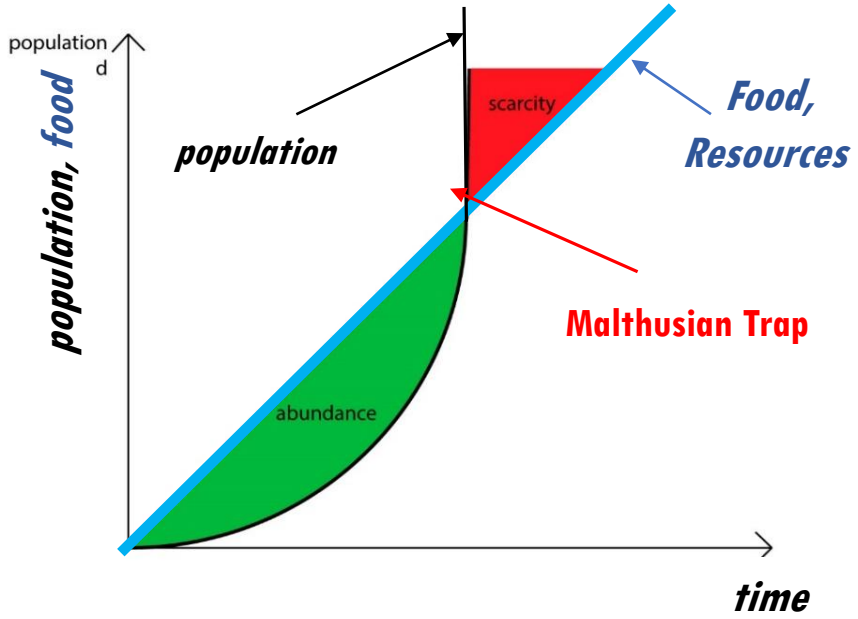
Kaack, L. H, Katul, G. G. (2013). *Fifty Years to Prove Malthus Right*. PNAS: USA, 110 (2013) 4161.

Malthusian Trap

Malthus (1798) supplemented the model for the human population growth by the heuristic assumption for the much weaker growth of necessary resources (**F**ood). Note – there are two separate equations:

Food, linear growth: $F(t) = a + bt$

Population, ‚geometric' growth: $P(t) = P_0 exp(rt)$



Malthus concluded '*The population increases in geometrical ratio and the subsistence rises only linearly, which finally leads to times of vice and misery*'.

This the Malthusian Trap (Catastrophe)
when the quantity of food becomes increasingly insufficient for the growing population.

Malthus advised population constraints or an extra rise in **s**ubsistence (food) to escape the Trap disaster. Unfortunately, the primitive escape concept, such as robbery or conquest of other countries, has often been implemented by rulers or politicians to ‚solve the problem'

Jacques Callot (1592-1635): *The Miseries of War*

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Verhulst equation: population and food in one scaling equation

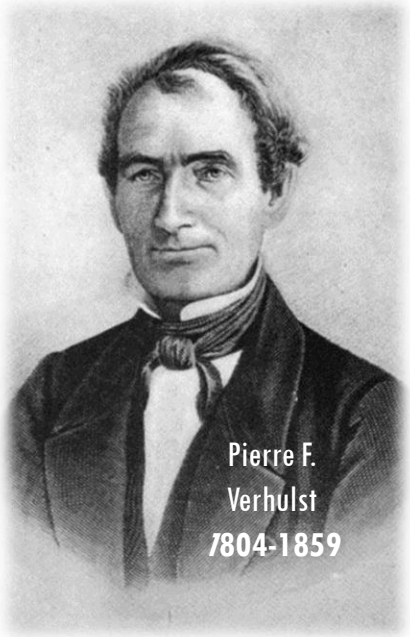
Malthus considered Population and resources (food) via two separate equations.
In **1837**, Verhulst included (*food, resources, subsistence s*) factor into the basic scaling equation:

$$\frac{dP(t)}{dt} = rP - sP^2 = P(r - sP)$$

The integration yields:

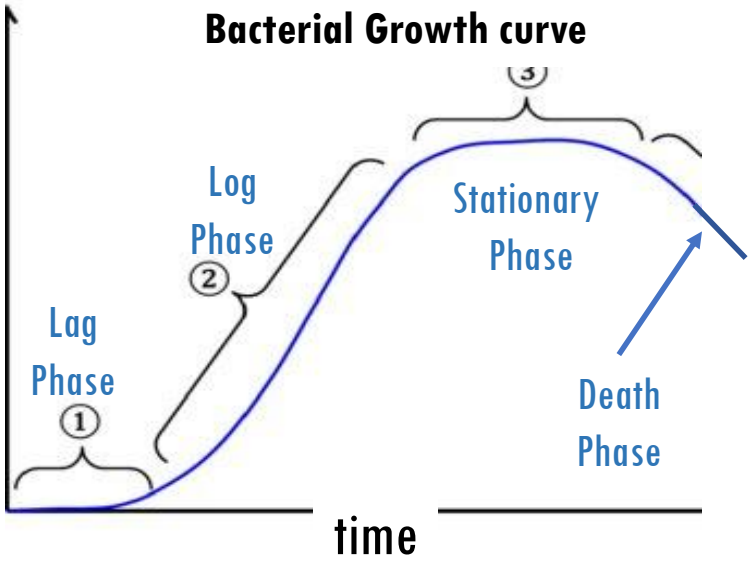
$$P(t) = \frac{1}{s/r + Cexp(-rt)} \Rightarrow (s \to 0) \Rightarrow P(t) = P_0 exp(rt)$$

$$'Verhulst' \Rightarrow\Rightarrow\Rightarrow 'Malthus'$$



The Malthus equation can address only the rise ('log') phase. Verhulst's model indicates that the Global Population can enter the stationary phase and also the Death Phase, when the , ***s***ubsistence (food) factor ***s*** decreases.

However, the only certainty, so far, is the ability of Verhulst's relation to describe the growth of a bacterial population confined in a container and isolated from its surroundings, with a given amount of food.



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Verhulst-type modeling discussion

Essentially, Verhulst considered so-called bimodal behavior, where, after a Malthus-like rise, the transition to the stationary phase occurs. The plot illustrates changes in the yeast population over time in an isolated container.

They are portrayed via:

i. *Malthus* ' unlimited' rise, associated with 'no-constraints' for resources, i.e., $s = 0$. **TWO** adjustable parameters (P_0, r)

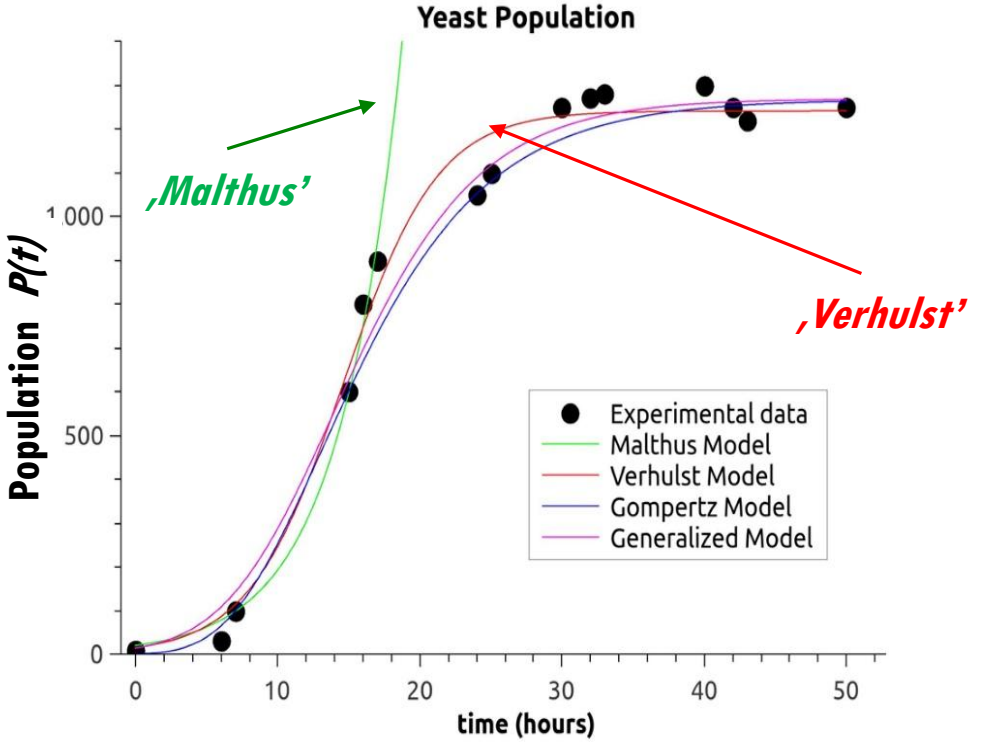
i. ***Verhulst*** model: **THREE** adjustable parameters

ii. *'Gompertz model'* extension of the Verhulst model, introduced by Jeffries et al (1982), who implemented the Gompertz function (1825) instead of the simple Malthus exponential rise: **FOUR** adjustable parameters

iii. *Generalized*/Unified *Gompertz's* approaches (since 1992), which consider the inteplay between the growth rate and resources metric: **FIVE or SIX** 'adjustable parameters

Models (iii) and (iv) are particularly often used in biology.

For review of the Gompertz function related concept see:



Problems in available reports:

The focus on ,visual' fitting results. Poor reference to the real fitting error, boosting due to the rising number of fitted parameters.

[K.M.C Tjørve, E. Tjørve, PLoS ONE **2016**, 12, e0178691]

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Verhulst model: Pearl & Reed multi-equation approach

In 1920, Pearl and Reed suggested that human population growth may follow **a sequence of Verhulst scaling equations coupled with a sequence of s_i ‚resources-related' parameters**, leading to next-step crossover well before the previous one's stationary phase is approached. It leads to successive Verhulst-type steps without any distinctive manifestation of the Verhulst plateau. Significant Pearl's contribution was the **Carrying Capacity *K*** concept, today the basic ‚ecological' metric of a system:

$$\frac{dP(t)}{dt} = rP - sP^2 = rP(1-(s/r)P) = rP\left(1-\frac{P}{K}\right) \quad , \quad \text{where } K = r/s$$

Note: when the amount of resources increases Carrying Capacity K also increases

Recently, Sojecka & Drozd-Rzoska reformulate the above relations in term of the per capita relative growth rate (RGR) G_P, and the apparent (changeable) growth rate coefficient $r' = r(P)$:

$$G_P = \frac{1}{P(t)}\frac{dP(t)}{dt} = r - sP = r \times \left(\frac{K-P(t)}{K}\right) = r'(P)$$

It also shows that the carrying capacity K can be considered the maximal population allowed in the given system. Note the apparent growth rate $r'(r,t) = r(1-P(t)/K)$: $P(t)$ first follows the Malthus where $r' \approx r$; next $r'(r,t)$ decreases, and , finally $r'(r,t) \to 0$ and $P(t) \to K$ for the stationary phase.

Following above the carrying capacity K is the maximal population allowed in the given

Pearl R, Reed L. *On the rate of growth of the population of the United States since 1790* PNAS USA **1920**, 6, 275.

Sojecka, A.A.; Drozd-Rzoska, *A. Verhulst-type equation and the universal pattern for global population growth.* PLoS ONE **2025**, 20, e0323165.

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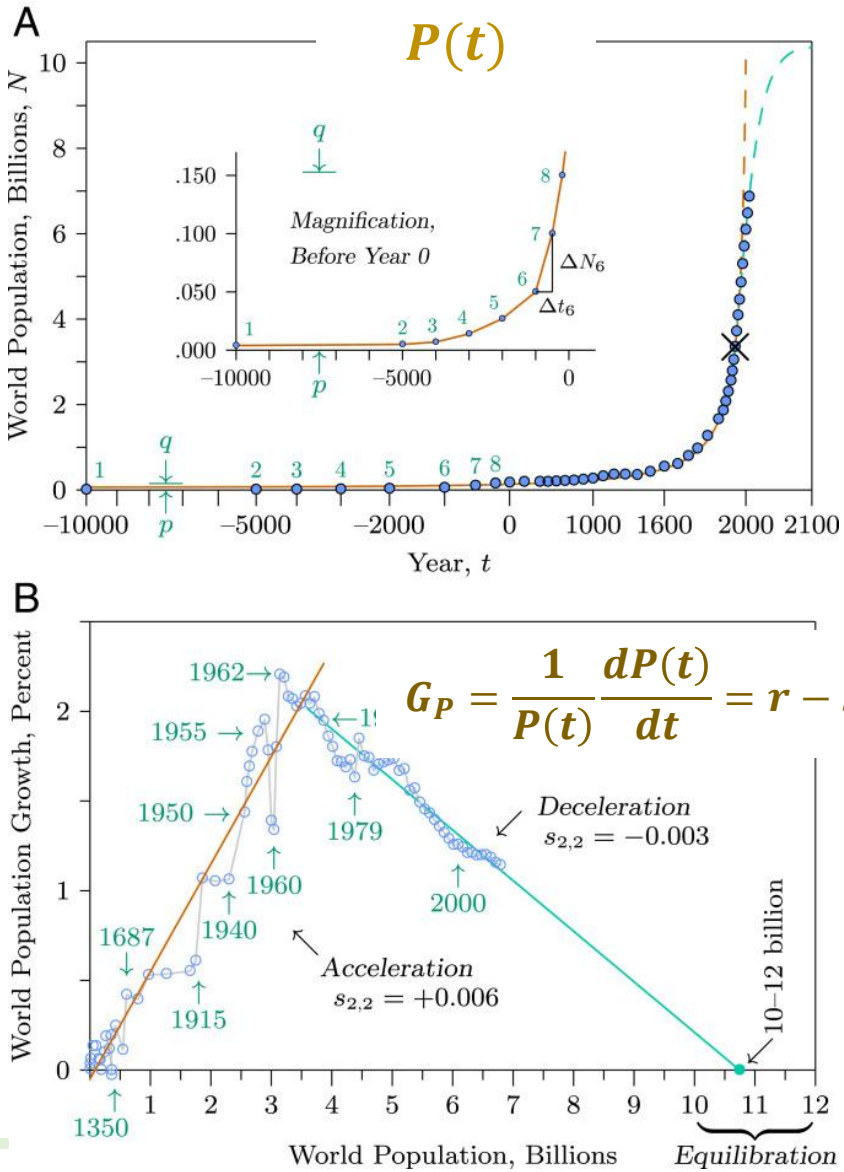
Lehman et al. (2021): Pearl multi-Verhulst equations concept implemented for the Global Population

In 2021, Lehman et al. developed these concepts by considering global population growth in terms of three successive bio-ecological levels:

(1) interactions with predators, **(2)** interactions with prey, **(3)** intraspecific interactions.

At each level population change are governed by ecological coefficients $(r_i; si)$, $i = 1; 2; 3$, which leads to population evolution levels:

(i) a primordial phase: pre-human ancestors interacted with their environment as animals do
(ii) a mastery of tools, fire, and specialization
(iii) an agricultural phase
(iv) a present controlled-fertility phase



Lehman, C.; Loberg, S.; Wilson, M.; Girham, E. *Ecology of the Anthropocene signals hope for consciously managing the planetary ecosystem*.

PNAS USA **2021**, 118, e2024150118.

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Lehman et al. (2021) continued

A_ The upper plot shows the obtained 'smooth' portrayal of the global population

B_ The lower plot is for **Relative Growth Rate (RGR)** $G_P(P)$,

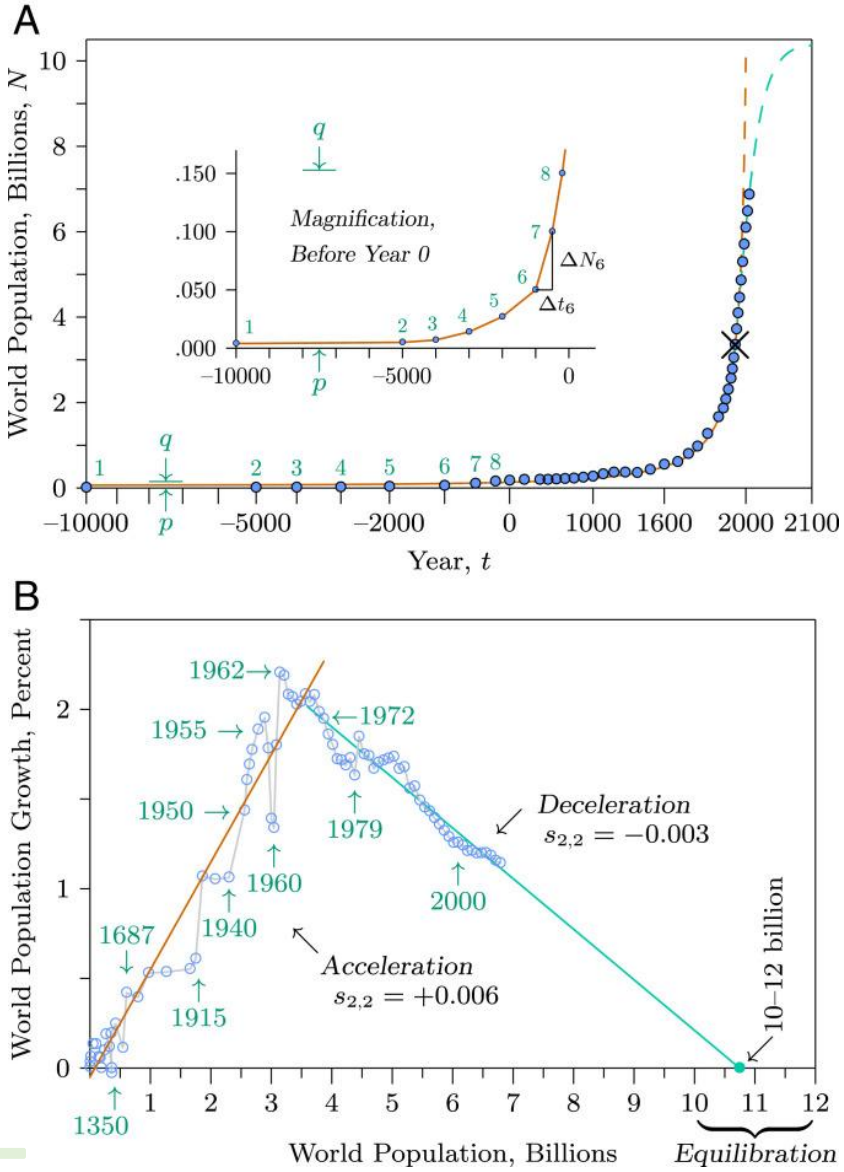
which follows the linear behaviour, recalling the Verhulst model differential equation:

$$G_P(P) = (1/P)\, dP/dt = r + sP$$

For the Lehman et al. plot the 'discrete' calculation of RGR were made:

$$G_P(P) = (1/P_i)\, \Delta P_i/\Delta t_i,$$

using 96 population data since the Anthropocene onset.



Lehman, C.; Loberg, S.; Wilson, M.; Girham, E. *Ecology of the Anthropocene signals hope for consciously managing the planetary ecosystem*. PNAS USA **2021**, 118, e2024150118.

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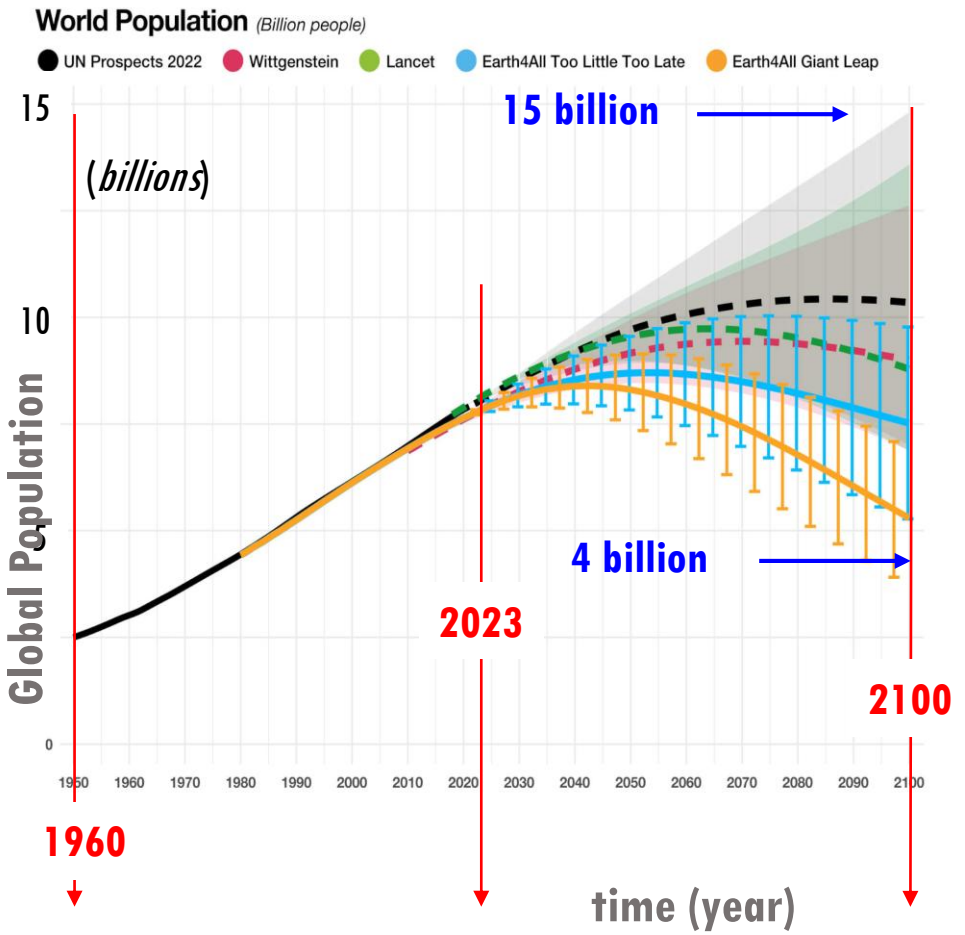
Global Population Cognitive Paths

1___The above brief resume presents the **1st path of Global Population growth studies**, related to creating a cognitively convincing model scaling equation, which subsequently is used for portraying the population data in an (arbitrarily) selected time period.

2___The **2nd cognitive path** aims to define the Global Population via impacts of geographical regions, social groups, education, multiple social interactions - especially the role of women, migration , education, birth/death ratio, age structure, economic development... Such a multitude odata is analyzed statistically via models developed in management, econometrics, bio-evolution, or socio-economic sciences .



Path 2 problems:

(i) necessary precise data are available only after 1950,

(ii) 'weights' of different factors' impacts are required, often based on the subjective expert opinions.

Consequence: forecasts from 4 to 15 bilion – for the year 2100

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The NEW cognitive path for the global population description

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The 3rd Path for the Global Population Growth

The focus on population data, *instead of the direct fitting via a scaling equation*

1. The focus on the empirical data itself, which: (i) are collected from different sources, which gives them a large scatter – a big problem so far, (ii) the data are then subjected to numerical filtering (using Savitzky-Golay principle) – until an 'analytical' set is obtained, which can be directly differentiated
2. The focus on scaling equations with no more than 3 adjustable parameters, & used in testing dynamics of Soft Matter systems (and not for Global Population studies, so far)
3. Instead of direct fitting, the adequacy of a given scaling relation for describing a given set of 'empirical' data is tested, using the **distortion-sensitive & derivative-based analysis**
4. The above analysis shows the time domains of given relation validity and determines optimal values of parameters, and subsequently inserted into he scaling relations for portraying *P(t)* data

1. Sojecka, A.A.; Drozd-Rzoska, *A. Verhulst-type equation and the universal pattern for global population growth*. PLoS ONE **2025**, 20, e0323165.
2. Sojecka, A.A.; Drozd-Rzoska, *Global population:from Super-Malthus behaviour to Doomsday criticality*. Scientific Reports **2024**, 14, 9853.
3. Sojecka, A.A.; Drozd-Rzoska, *Society & Science: Criticality for the global society*. Proc. Socrat. Lect. **2025**, 12(II).155.
4. Sojecka, A.A.; Drozd-Rzoska, *The story about one island and four cities: the socio-economoc soft matter model – based report*. Proc. Socrat. Lect. **2023**, 8,131.
5. Sojecka, A.A.; Drozd-Rzoska, Rzoska, S.J. *Global population growth, carrying capacity, and high-quality foods in the Industrial Revolutions epoch*. Sustainability **2025**, available at: DOI:10.20944/preprints202505.0583.v1.

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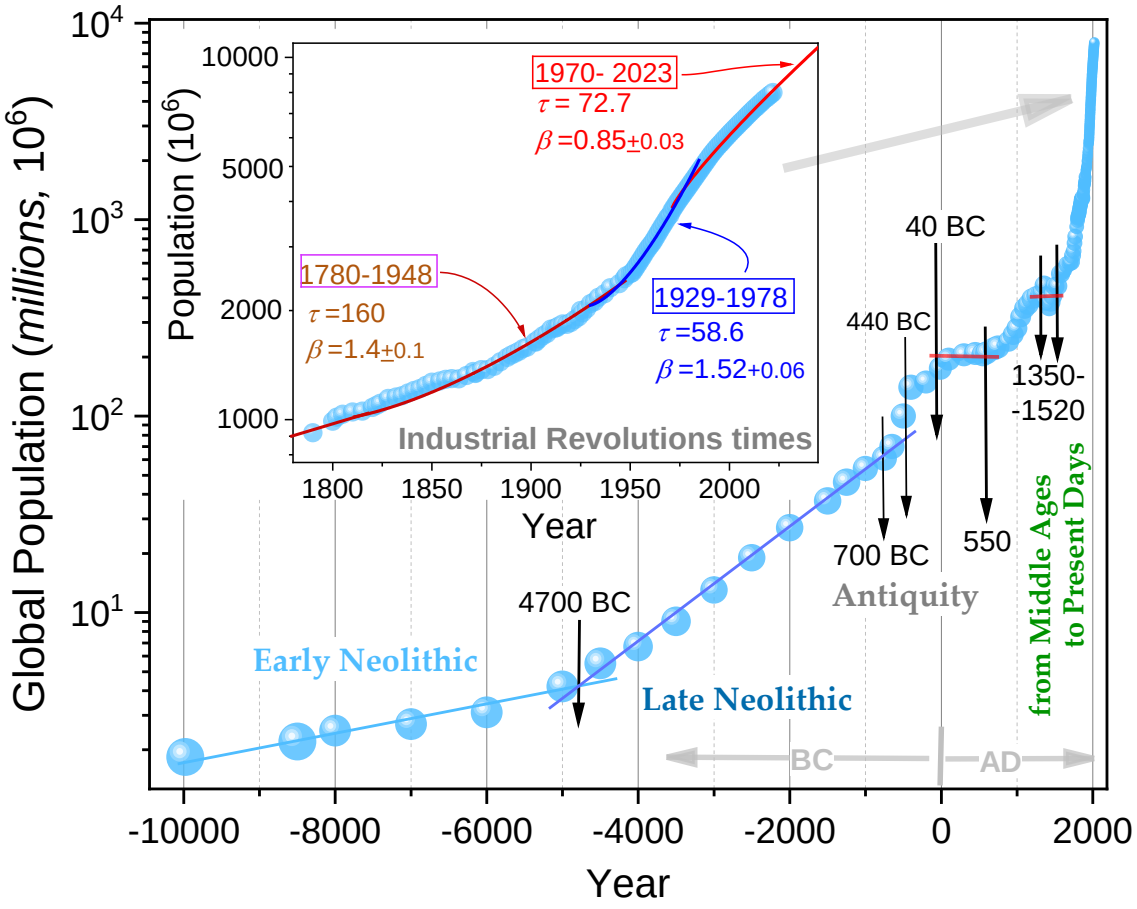
New Global Population data: 198 values in the 'analytic' set-up



- Global population data since 10,000 BCE till 2023, obtained via the new protocol, and employing numerical filtering.
- The size of points reflects the rising uncertainty when shifting toward prehistoric times.
- The red horizontal lines indicate the Roman Empire & Black Death times impacts.
- The inset is for Industrial Revolution times, with portrayals via the empowered exponential function (see below).
- **The linear changes in the semi-log scale indicate the simple Malthusian behavior:**

  it obeyed for 9,000 years (!)

Subsequent historical epochs are indicated,

red horizontal lines indicate near-constant Global Population times:
Roman Empire & Black Death pandemia

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A. A. Sojecka, A. Drozd-Rzoska, Scientific Reports **2024**, 9, 6816.

Returning to the Unusual von Foerster Doomsday equation

As mentioned before, in 1960, von Foerster et al. showed graphically a simple pattern for Global Population changes:

$$P(t) = \frac{1.79 \times 10^{11}}{(2026.87 - t)^{M=0.99}} \propto \frac{1}{D - t}$$

where the ‚Dooms Day' $D = 2026.87$ was linked to: Friday, 13 November 2026

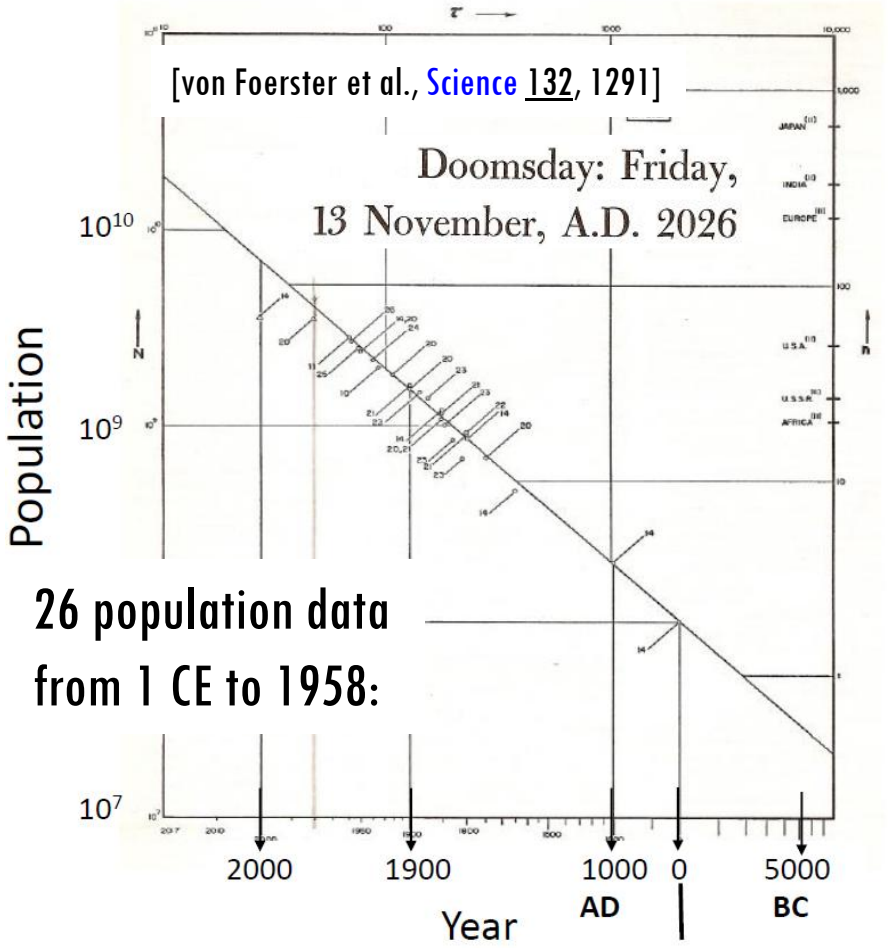
It means: infinite population in 2026, & the Global Extinction (!)

It was *named* ***Doomsday or Hyperbolic equation***. However:

Following its form one can also consider the name: ‚***Critical equation***'

The catastrophic vision led to the enormous mass media interest, and massive criticisms.
However, numerous critics could not explain the fair portrayal.

Nevertheless, in subsequent years, more estimates for 'historical' Global Population data corrected the exponent: $1 > M > 0.7$



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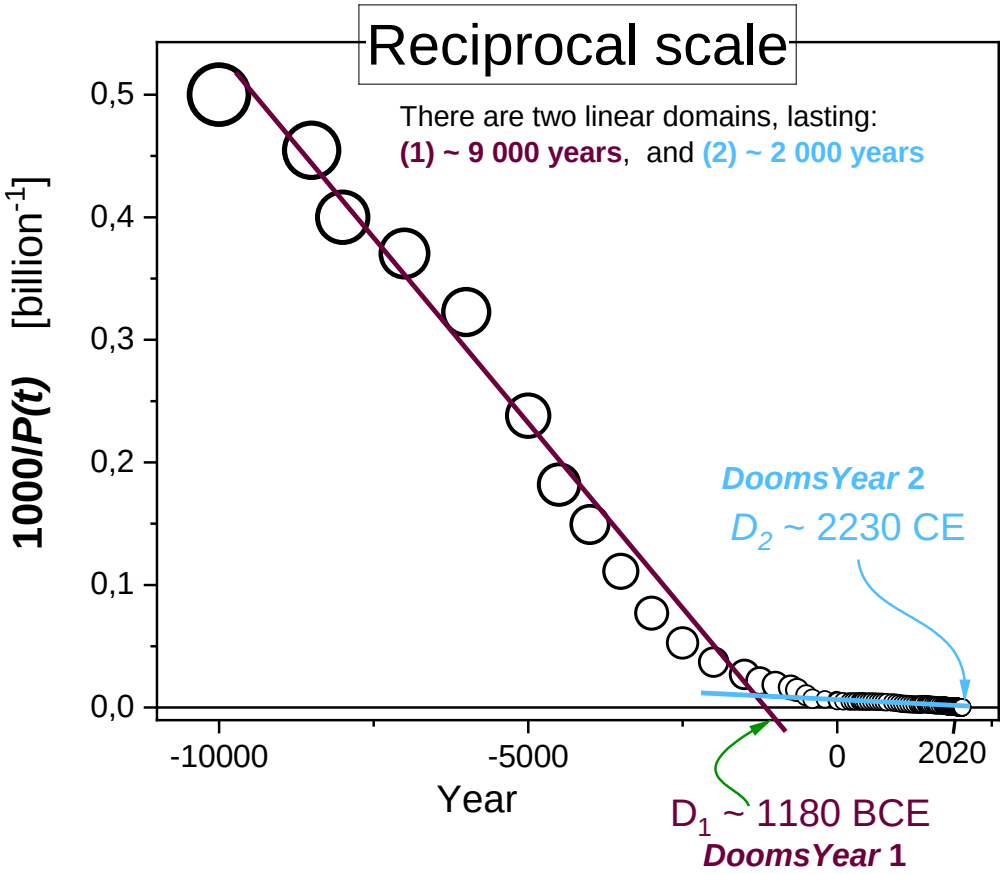
(1) Simply - but non-conclusive - Doomsday equation test

$$P(t) = \frac{A}{t-D} \quad \Rightarrow \quad \frac{1}{P(t)} = A^{-1}t - A^{-1}t_C = at - b \quad \Rightarrow\Rightarrow$$

the reciprocal of P(t) should yield a linear dependence

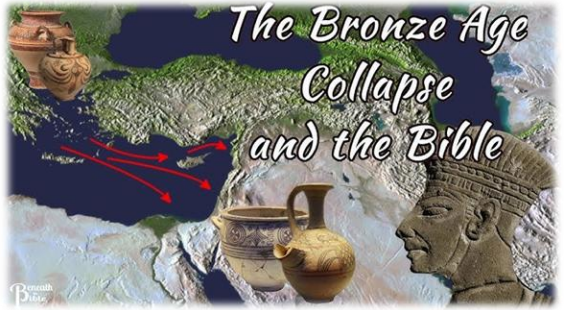


The reciprocal plot seems to indicate that a Hyperbolic-Doomsday function seems to offer the following portrayals

- from 10 000 BCE to ~ 1180 BCE – It lasted ca. 9 000 years in Anthropocene (BCE times)
- from ~100 BCE to 2024, i.e., it lasted ca. ~ 2000 years

(!) The DoomsYear $D_1 = 1180\ BCE$ correlates witt the BRONZE AGE civilizations END:

Is it an Accidental Coincidence?



But this is only an 'apparent' picture (!!)

Emerging due to specifc features of the ‚reciprocal scale'. It can ‚mask' natural features of data, well visible for basic *P(t)* global population data.

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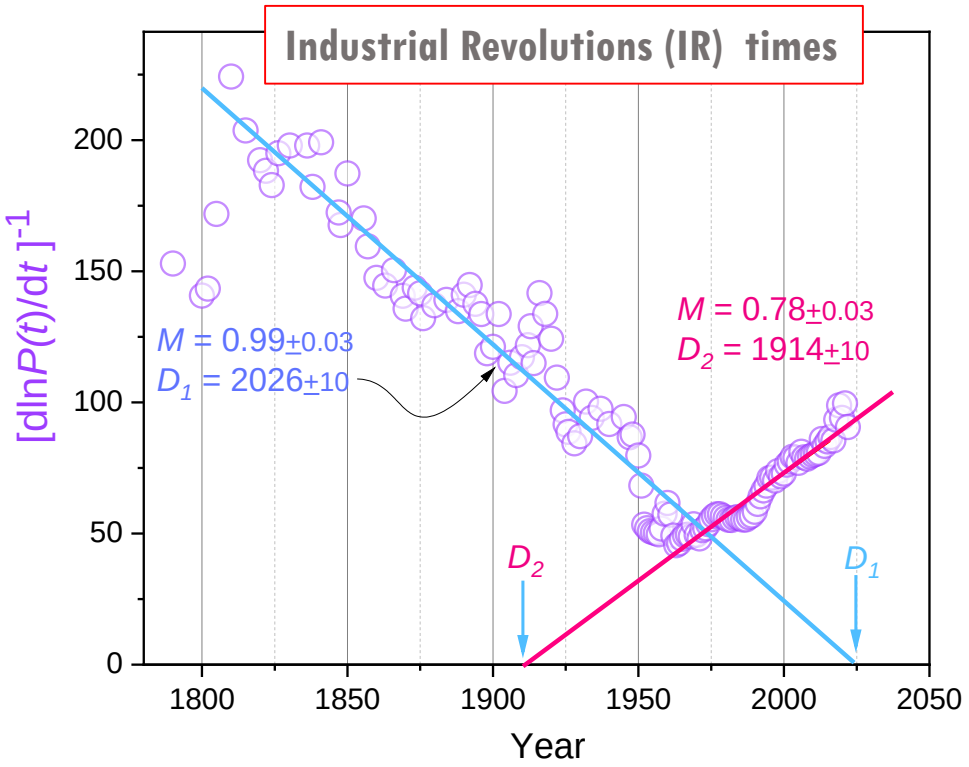
(2) New solution for the ‚critical' ‚(‚Doomsday') dynamics description

The ‚innovative' distortions sensitive analysis, able to detect local temporal distortions, for the quasi-hyperbolic (critical-like) population growth portrayal has been proposed. It is based on the following transformation of P(t) data:



$$A(2026-t)^{-1} \overset{?}{\Rightarrow} 1970 \Rightarrow A'(t-1914)^{0.78}$$

$$'critical' \quad 1970 \Rightarrow inverse\ critical$$

$$P(t) = \frac{A}{(D-t)^M} \Rightarrow lnP(t) = lnA - ln(D-t)^{-M}$$

$$lnP(t) = lnA + Mln(D-t)$$

$$\frac{dlnP(t)}{dt} = \frac{M}{D-t} \Rightarrow \left(\frac{dlnP(t)}{dt}\right)^{-1} = -Mt + MD = -Mt + m'$$

where M, m' = const and the ‚Doomsday' $D = t_c$

- The distortions-sensitive analysis validated the explicitely hyperbolic (critical-type) behavior (with the exponent M = 1), but only from between years 1800 – 1970.
- Later, the new ‚inversed quasi-hyperbolic' or rather **‚Inverse Critical'** trend appears

The plot SUGGESTS THE RISE OF THE GLOBAL POPULATION UP TO

~ 15.166 billions at 2100

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Empowered Super-Malthus (SM1) equation

Let's consider the Super-Malthus SM1 scaling expressed via the empowered exponential function, surprisingly not used in Globa'l Population studies, so far. Note the links to the per capita Global Relative Rate (RGR, G_p) and Weibull's hazard function:

$$P(t) = P_0 exp\left[\pm\left(\frac{t}{\tau}\right)\right]^{\beta} \Rightarrow lnP(t) = lnp_0 \pm \frac{t^{\beta}}{\tau^{\beta}} \Rightarrow \frac{dlnP(t)}{dt} = \frac{dP(t)/P(t)}{dt} = \frac{\beta}{\tau^{\beta}} t^{\beta-1} = h(t)$$

The basic Malthus equation is for exponent $\beta = 1,\ \text{and}\ r = 1/\tau = const.$ The above equation contains the relaxation time τ - not used in *Global Population* studies. Before. The Super Malthus description concept has been introduced in the reference given below.

τ allows to estimate the time for 50% population rise: $t_{50\%} = \tau \times ln2.$

Notable is the link to the statistical Weibull distribution, essential for complex dynamics

Significant is the hazard function *h(t)* telling how likely something is to fail given that it has survived so far.

It correlates with RGR function G_p - if population changes are described by SM1 function.

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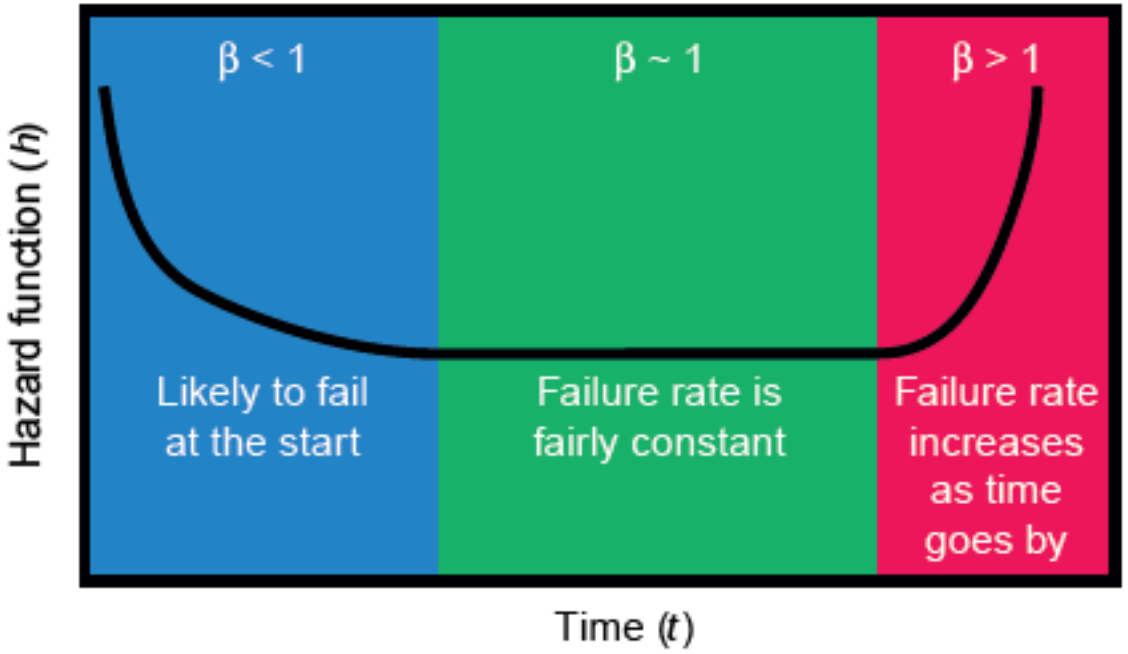
A.A. Sojecka, A. Drozd-Rzoska. Scientific Reports 9, 6816 (2024).

Distortions-sensitive test of SM1 relation via RGR or hazard factor analysis

The plot $logG_P(t)$ vs. t shows linear domains where the empowered SM1 equation can implemented:

$$y(t) = log_{10}\left[\frac{dlnP(t)}{dt}\right] = log_{10}G_P(t) = log_{10}\left(\frac{\beta}{\tau^{\beta}}\right) + (\beta - 1)log_{10}t = A + B \times x$$

The above equation is the distortion-sensitive test of the validity of the population portrayal via SM1



For plots recalling this equation, linear behaviour indicates domains where SM1 portrayal can be applied, and determines values of leading parameters: relaxation time τ. (parameter A) and the power exponent ($B = 1 - \beta$).

For the SM1 Super-Malthus function, the relative growth rate (RGR, G_p) coincides with the hazard function h(t) in the Weibull distribution. Hence, the above equation is also for the log scale presentation of the hazard function.

For SM1, the exponent ($\beta < 1$ or $\beta > 1$) indicates chances to fail/win in global-scale actions, as shown in the picture.

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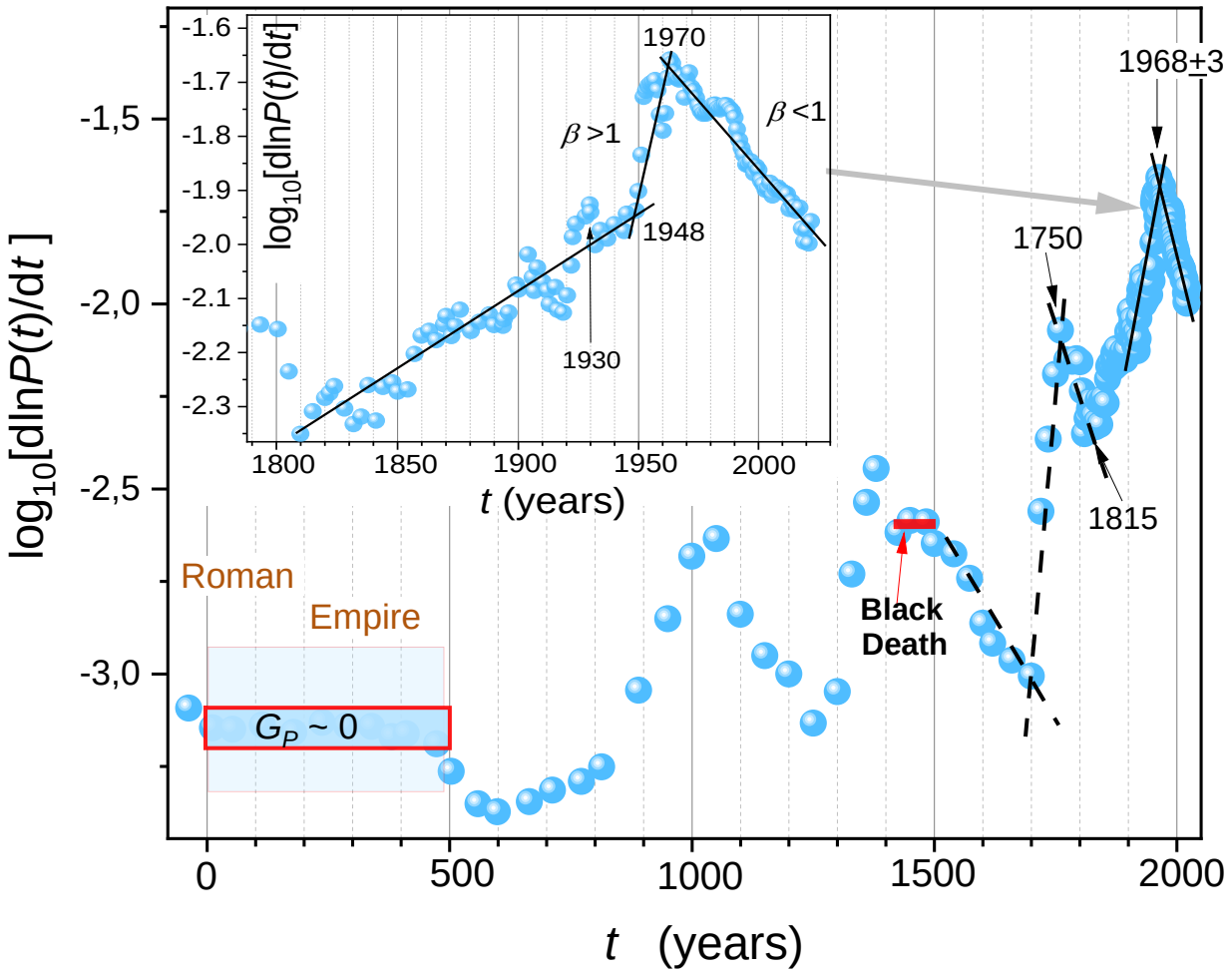
1. A. A. Sojecka, A. Drozd-Rzoska. Scientific Reports 9, 6816 (2024).
2. H. Rinne, *The Weibull Distribution: A Handbook*. Boca Raton, CRC,2009

SM1 RGR - hazard factor change in the last two millenia



The Soft Matter interpretation:

- For the Kohlrausch-Williams-Watts (KWW) model the exponent $\beta = 1$ is for systems governed by a single relaxation time & $\beta \neq 1$ is for a set of relaxation times.
- KWW) model for $\beta < 1$ suggest energy loss and $\beta > 1$ energy gaining in a system
- One can recall the nucleation theory by Avrami yields which the relation $\beta = D + 1$, where D is for dominant (local) assemblings dimensionality.

Note: the uniqueness of Roman Empire and Black Death times ($G_P \approx 0$) and periodic crossovers $\beta > 1 \Rightarrow \beta < 1$:
Such behavior appears periodically since 500 CE till 2024.

Should we expect the next one ?

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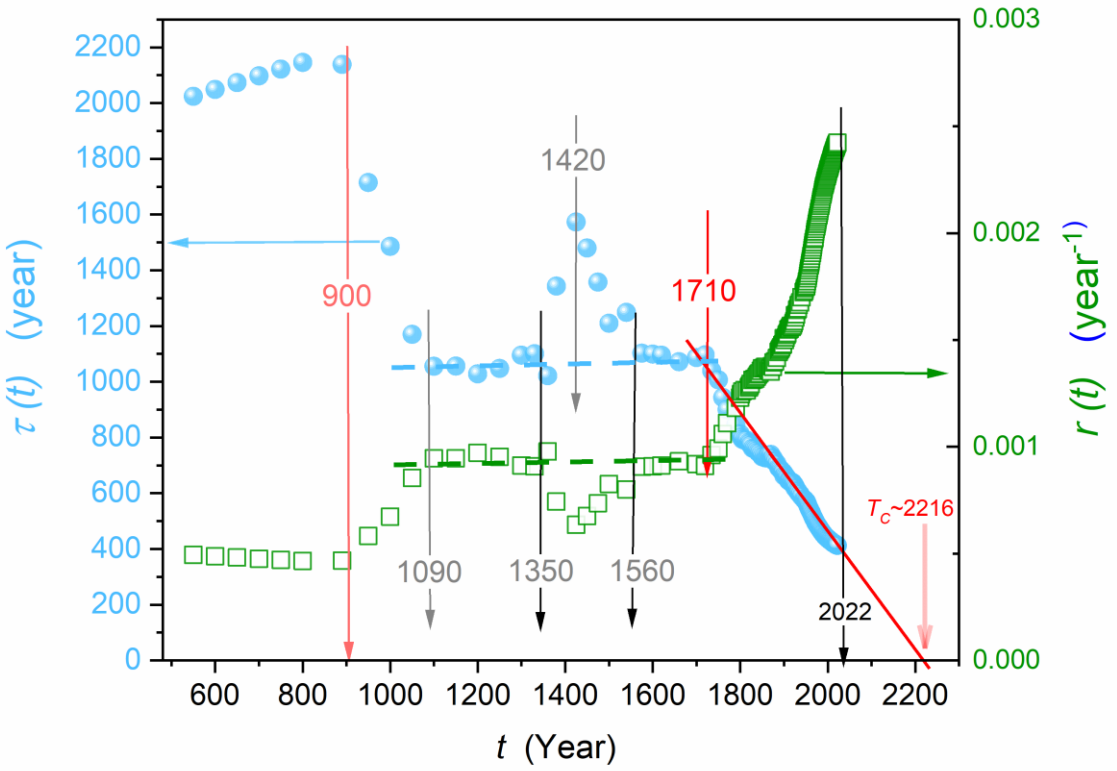
SM2 Super-Malthus equation

Another Super-Malthus scaling (SM2) can be related to the time-dependent relaxation time:

$$P(t) = P_0 exp\left(\frac{t}{\tau(t)}\right) = P_0 exp(r(t) \times t) \Rightarrow r(T) = 1/\tau(T) = (1/t) ln(P(t)/P_0)$$

It is not possible to fit (immediately) empirical data with the SM2 relation, because we do not know *a priori* the form of t(t) changes - but we can easily calculate changes in t(t), as shown above.



The Figure presents the evolution of the relaxation time $\tau(t)$ and the apparent growth rate $r(t) = 1/\tau(t)$ after the Roman Empire fall, i.e., since the Medieval epoch onset.

The plot shows:

- the prevalence for using τ over r coefficient
- Poor population situation in Roman Empire times
- the simple Malthus pattern from ~1000 BC till 1710 (Industrial Revolutions (IR) onset), with the Black Death pandemic times distortion
- for the still-lasting IR period, the relaxation time: $\tau(t) = a - bt$

New Dooms-year for $t \rightarrow D \approx 2216\ (year)$

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1. A. Sojecka, A. Drozd-Rzoska. Scientific Reports 2024, 9, 6816
2. A.A. Sojecka,; A. Drozd-Rzoska, PLoS ONE **2025**, 20, e0323165.

SM2 relation and the constrained criticality

Introducing the last equation $\tau(t) = a - bt$ to the last Super-Malthus SM2 dependence, one obtains:

$$P(t) = P_0 exp\left(\frac{t}{\tau(t)}\right) = P_0 exp\left(\frac{t}{a - bt}\right) = P_0 exp\left(\frac{t/b}{a/b - t}\right) = P_0 exp\left(\frac{b\prime \times t}{T_c - t}\right)$$

$$P(t) = P_0 exp\left(\frac{b\prime \times t}{T_c - t}\right) = 610 \times exp\left(\frac{1.62t}{2216 - t}\right)$$

Note the link to the von Foerster hyperbolic , Doomsday equation, when applying the Taylor expansion:

$$P(t) = P_0 exp\left(\frac{b\prime \times t}{T_c - t}\right) \Rightarrow P(t) = P_0\left(1 + \frac{b\prime \times t}{T_C - t} + \ldots\right) \propto \frac{B}{D - t}$$

$T_C = 2216$, but $D = 2026$ – these values are different, because in von Foerster 'hyperbolic' equation higher order terms are neglected

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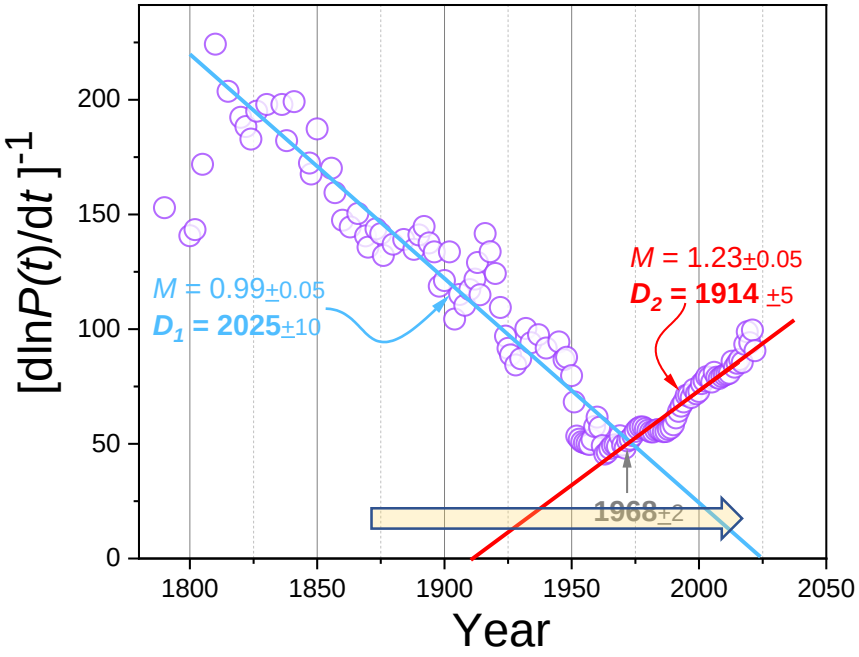
1. A Sojecka, A Drozd-Rzoska. Scientific Reports 2024, 9, 6816
2. AA Sojecka,; A Drozd-Rzoska, PLoS ONE 2025, 20, e0323165.

SM2 relation and the constrained criticality

Does the above analysis that the Population Doomsday will occur ???

NO – it does not happen.

- The new 'exponential' 'Doom' relation has a form characteristic of dynamics in critical systems under constraints, including 'frustration', i.e., internal constraints (local disturbances).
- Such a form of dynamics within the Griffiths model for constrained criticality in slightly disordered systems, originally developed for quantum systems, and later generalized for any complex system.
- One should expect 'tunneling' *(shown by the ‚thick', yellow arrow in the plot)* before reaching the 'Doomsday constrained singularity' (~2026) to the 'tail' of the earlier. ‚hidden' criticality. It means: the transition to a gradual slowing of the population growth.



For the Griffiths phases, see:

M.A. Amaral, A.M. de Oliveira, *Criticality and Griffiths phase in random games with quenched disorder*. Phys. Rev. E **2021**, 104, 064102.

A. A. Sojecka, A. Drozd-Rzoska. Scientific Reports 2024, 9, 6816.

A. A. Sojecka,; A. Drozd-Rzoska, PLoS ONE 2025, 20, e0323165.

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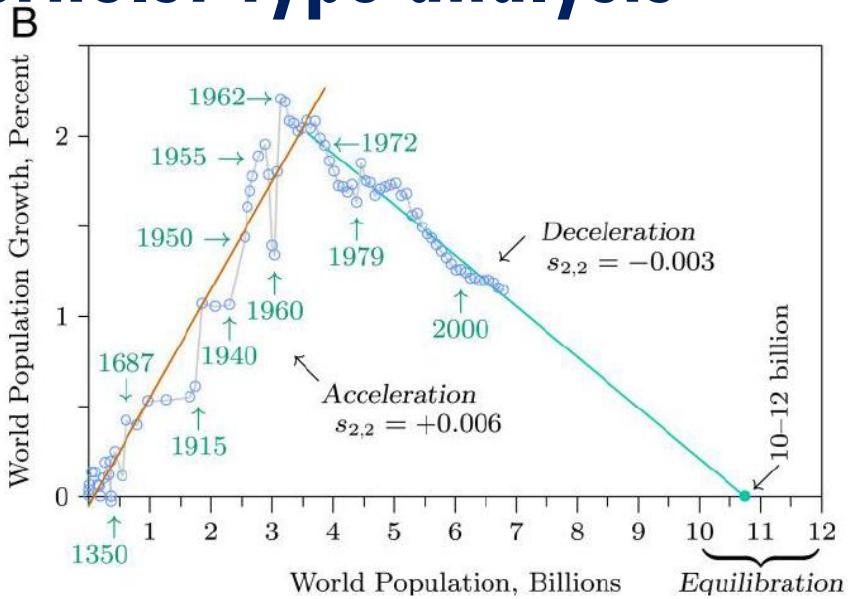
Singularities emerging from the extended Verhulst-type analysis

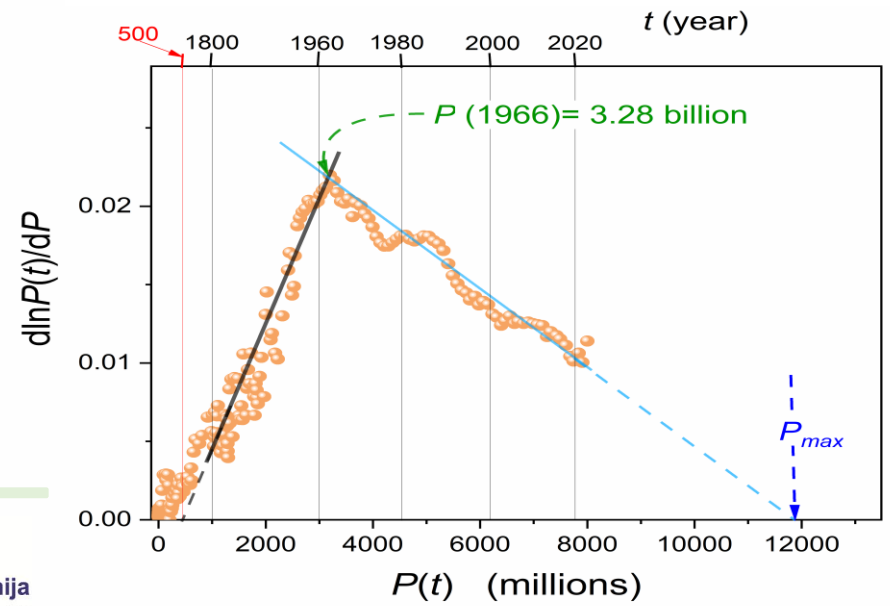
Lehman et al. (2021) showed the significance of the per capita relative growth rate (RGR), indicating its linear behaviour
$(P) = (1/P)(dP/dt) = r + sP$, where r is the Malthus growth rate and r is the s the parameter describing resources, originally food.

Lehman et al. used 96 population data, since 10 000 BCE till 2017, and applied the 'discrete' calculation of $G_P(P_i) = (1/P_i)(P_i/t_i)$

Note the (apparent!) agreement between plots.

The qualitatively new 'analytic' set of Global Population data made it possible the 'not-by-hand' derivative analysis, namely: $G_P(P) = (1/P)(dlnP/dt)$, using 198 population data) (Sojecka & Drozd-Rzoska, 2025)





- Lehman, C.; Loberg, S.; Wilson, M.; Girham, E. *Ecology of the Anthropocene signals hope for consciously managing the planetary ecosystem.* PNAS USA **2021**, 118, e2024150118
- Sojecka, A.A.; Drozd-Rzoska, *A. Verhulst-type equation and the universal pattern for global population growth.* PLoS ONE **2025**, 20, e0323165.

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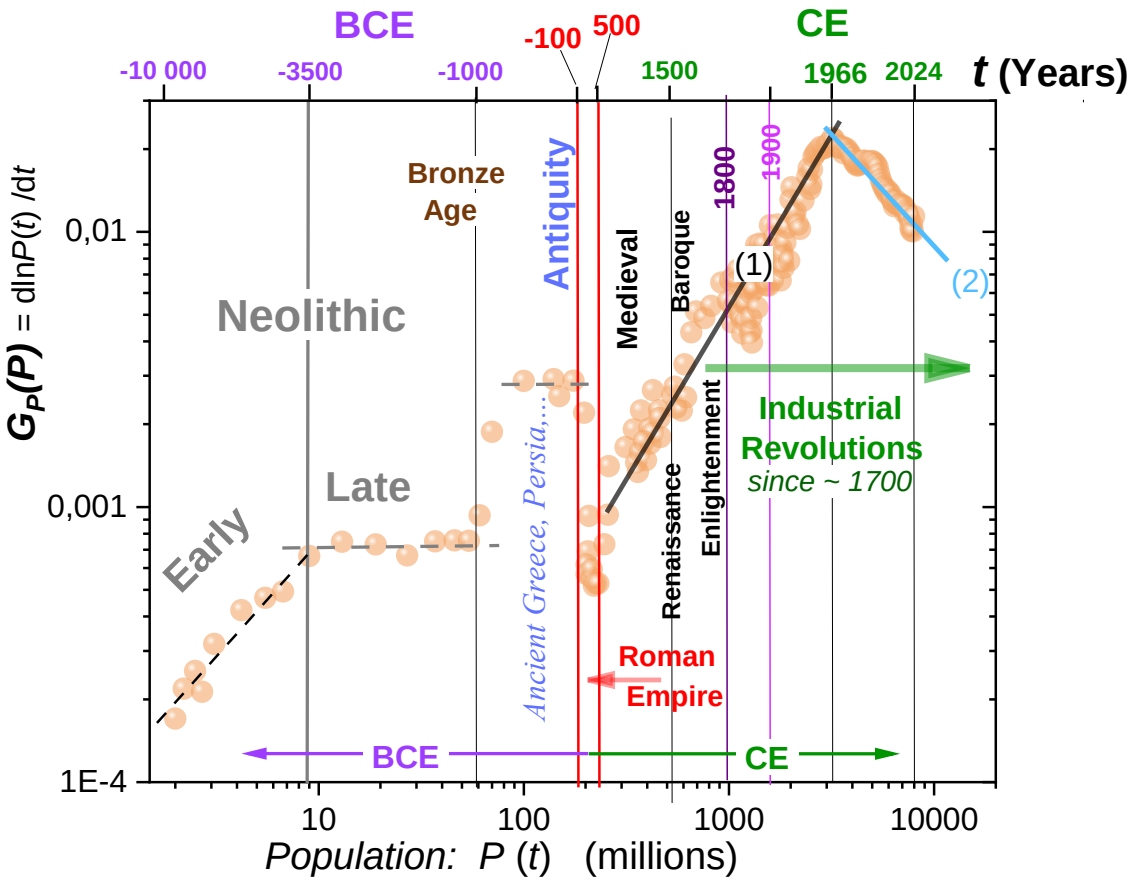
Slowing down Global Population Growth

The Log-plot reveals essential disturbances from the ‚simple' Verhulst model behavior:



$$G_P(P) = \frac{dP(t)/P(t)}{dt} = \frac{dlnP(t)}{dt} = r \pm sP$$

The , apparent linear' behavior since the *Roman Empire* collapse is related to:

$$\boldsymbol{G_P(P) = \frac{dlnP(dt)}{dt} = r \times \exp(bP)}$$

It means that the global population maximum, shown in the previous slide, <u>does not appear</u>.

A permanent population rise, slowing down, should be expected in the future.

The 'Verhulst' reference can be retrieved using the Taylor expansion:

$$G_P(P) \approx r \times (1 + bP + bP^2/2) + \cdots) \approx r + (ab)P + \cdots$$

The plot reveals an extraordinary relationship between subsequent historical epochs and global population changes.

Note , the destructive impact' of the Roman Empire (40-70 million) on the Global Population. Over the Imperial 5 centuries, Global Population remained constant: ~ 200 million.

It ceased to rise (!)

.A. A. Sojecka,; A. Drozd-Rzoska, PLoS ONE **2025**, <u>20</u>, e0323165.

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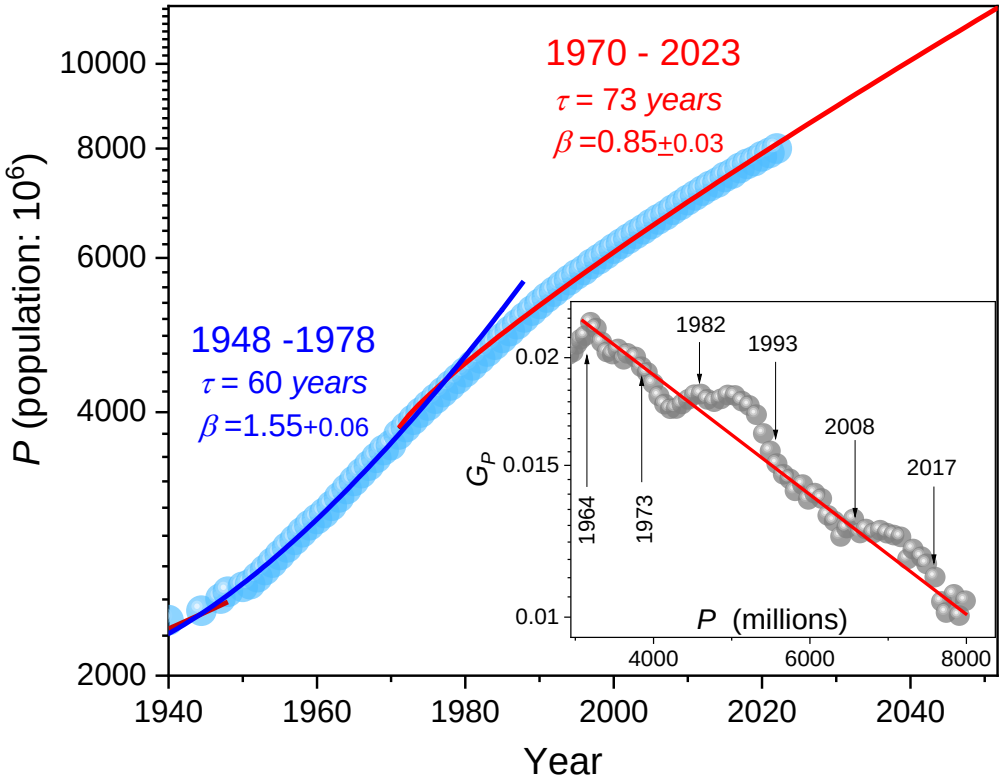

Slowing down Global Population Growth

Following the above, the Figure shows the gradual slowing of global population growth using the SM1 equation over the last few decades. The inset is for the related RGR parameter changes.

Such estimation yields:

- 8.9 billion in 2030
- 11.3 billion in 2050
- 14.9 billion in 2100

- One can consider that in Roman Empire times, the crucial 'energy resource' was slaves. Did the abuse and shortage of 'supplies' lead to a global population anomaly and the Empire's collapse?
- Today, we are again facing an Energy crisis, accompanied by an ecological one. But now, Science, if it gains the support of politicians and societies, can help overcome the challenge.
  - Note: different representations: (i) reciprocal, (ii) 'critical', (iii) SM1, (*iv*) SM2 supported by the derivative-based analysis can yield insights into different aspects of the population changes

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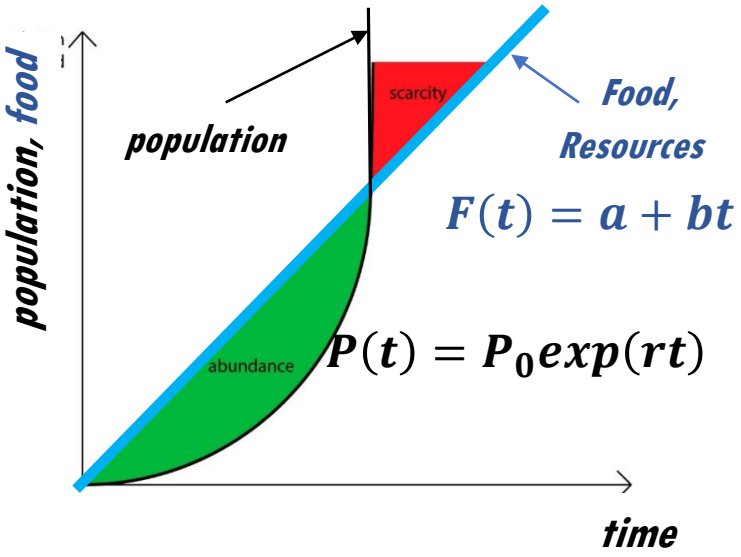

Population & Resources

Malthus considered the linear rise of food, motivated by the enormous poverty & overpopulation in Industrial Revolution centers and the commonn conviction:

more food = more arable areas

https://library.norwood.vic.edu.au

Verhulst introduced the 'resources, food' parameter directly into the model scaling equation. A significant extension was done by Pearl, who introduced the **Carying Capacity** concept, expressed via the factor K:

$$\frac{dP(t)}{dt} = rP - sP^2 \qquad \frac{dP(t)}{dt} = rP\left(1 - \frac{1}{K}P\right) \qquad \frac{1}{P}\frac{dP(t)}{dt} = r - \frac{r}{K}P$$

Nowadays, in the times of '**Circular Economy**' and '**Sustainable Soci**ety', the concept of '**Carrying Capacity**' has become one of the most important 'universal' metrics for assessing sustainable development within environmental constraints and related threats: Global Warming, pollution, shortages of raw materials and food, water shortages…

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Pearl R, Reed L. *On the rate of growth of the population of the United States since 1790 and its mathematical representation*. PNAS USA. **1920**, 6, 275-88.

Population & Carrying Capacity

Unfortunately, so far, discussions are descriptive-heuristic in nature, and there is a lack of convincing functional analysis that could lead to reliable estimates and trend predictions, as well as reliable quantitative indicators of carrying capacity.

The estimates of carrying capacity changes are not only tricky but also ambiguous due to numerous impact factors, ranging from environmental and geographical factors to socio-economic factors. The situation becomes even more ambiguous as we go back in time.
Cohen (1995) suggested that the pattern of the carrying capacity may be contained in the empirically available Global Population changes, and the Verhulst-Pearl model is of particular inspiration here.

$$\frac{dK(t)}{dt} = c(t)\frac{dP(t)}{dt} = \left(\frac{L}{P(t)}\right)\frac{dP(t)}{dt}$$

where the coefficient 'c' is the basic Condorcet metric; $L' = La$, $b = const.$

Cohen named it *"the 'Condorcet equation', following the name of Nicolas Condorcet, an 18th century philosopher, mathematician, and diplomat who pointed out common coherence/links of seemingly separate issues.*

Pearl R. *The growth of populations.* Quarter. Rev. Biol. **1927**, 2, 532–548

Cohen, J.E. *Population growth and Earth's human carrying capacity.* Science **1995**, 269, 341–346.

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Population & Carrying Capacity

In the Condorcet equation, starting from $c = 1$, the parameter decreases in each subsequent time t, i.e., $c < 1$. Finally, it reaches $c = 0$, yielding the Verhulst model's stationary state. For $c < 0$ carrying capacity, food resources, and consequently population diminishes. When $c > 1$, each additional person in the population introduces additional values to the system carrying capacity above their own needs, thus yielding conditions to accelerate population growth, even a boost to infinity.

Following, the analysis showing the significance of the per capita relative growth rate (RGR) *$G_P(P,t)$ and including* its functional parametrization presented above, one obtains :

$$\frac{dK(t)}{dt} = c(t)\frac{dP(t)}{dt} = \left(\frac{L}{P(t)}\right)\frac{dP(t)}{dt} \Rightarrow \frac{dK(t)}{dt} = L\frac{dlnP(t)}{dt} = LG_P(P,t) = L'exp(bP)$$

One can further reformulate the basic Cohen's Condorcet implementation via RGR factor for the empowered exponential SM1 equation for *P(t)* changes:

$$P(t) = P_0 exp\left(\frac{t}{\tau}\right)^{\beta} \Rightarrow \frac{dK(t)}{dt} = L\frac{dP(t)/P(t)}{dt} = L\frac{dlnP(t)}{dt} = LG_P(t) = \frac{L}{\beta\tau}\left(\frac{t}{\tau}\right)^{\beta-1}$$

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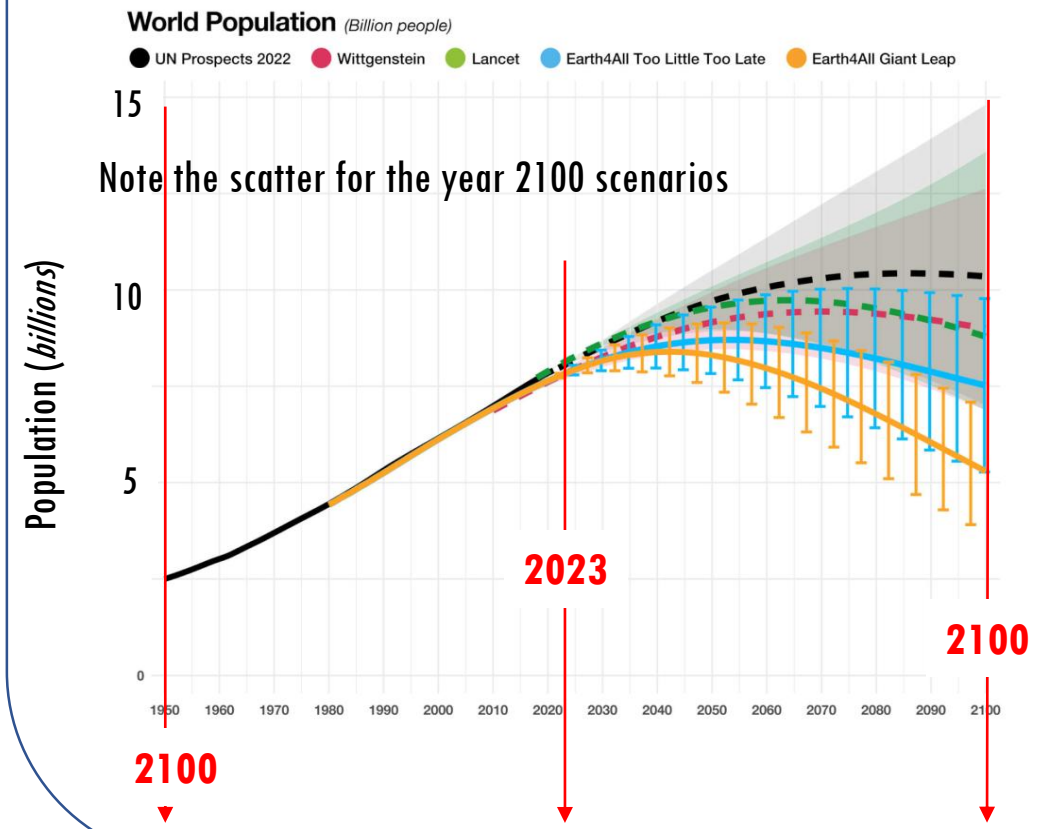
- Sojecka, A.A.; Drozd-Rzoska, *A.* PLoS ONE **2025**, 20, e0323165.
- Sojecka, A.A.; Drozd-Rzoska, Rzoska, S.J. Sustainability **2025**, DOI:10.20944/preprints202505.0583.v1.

PREDICT THE FUTURE

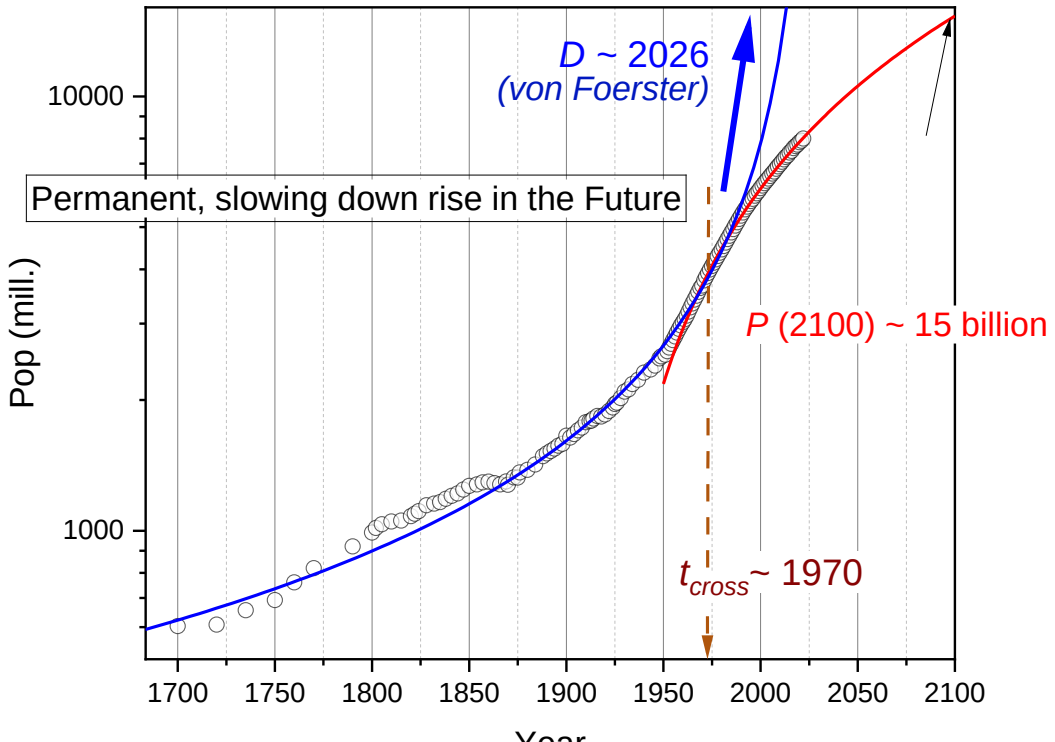
No Doomsday !

Current ‚official' UN & World Bank predictions of the Global Population Growth

They assumed the ‚smooth' portrayal, from (at least) 1950 till today



This work: the qualitative trend-change associated with crossover from the *‚ordinary criticality'* to *‚frustrated criticality'*



$$A(2025 - t)^{-1} \Rightarrow 1970 \Rightarrow A'(t - 1914)^{1.16}$$

No maximum !, Slowing down rise !

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The global population exhibits the essential feature of the model system: the isolation from disturbing external impacts.

The exception is global climate change, affecting everyone and everything on Earth.
Currently, such a significant problem is global warming.
Moreover, many ‚internal' actions and disturbances are ‚averaged' or cancelled for a global scale, thus simplifying modeling.

Global → *but what about* → Local ?

The question arises whether population changes evoke analogies to the dynamics of collective phenomena within *Soft Matter Science* may appear ???

also for human 'clusters' on a smaller scale than the global scale, where apparent interactions with the surroundings seem to be obligatory.

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What about local populations ???

RAPA NUI

Rapa Nui is a small island in the Pacific, inhabited by two groups of Polynesian sailors around the year 400. Subsequently, despite being totally isolated, they developed an incredible culture. Its footprint constitutes ~ 1000 Moai statues. The largest of them is 27 meters high and weighs 270 tons. At the end of the 17th century, the island's population reached 10,000.

A small population on a geographically isolated island: 3,500 km from South America and 6,000 km from Hawaii, limited only to the island's internal resources.

Perfect model-system for the population evolution ?

In 1722 admiral Jacob Roggeeven (the Netherlans), discovered the Island for Europeans and named it Easter Island. He noted ~ 2,000 - 3,000 inhabitants. In 1774 captain James Cook (UK) during the great expedition aboard Endevour noted maximum of 200 natives, vegetating in dugouts.

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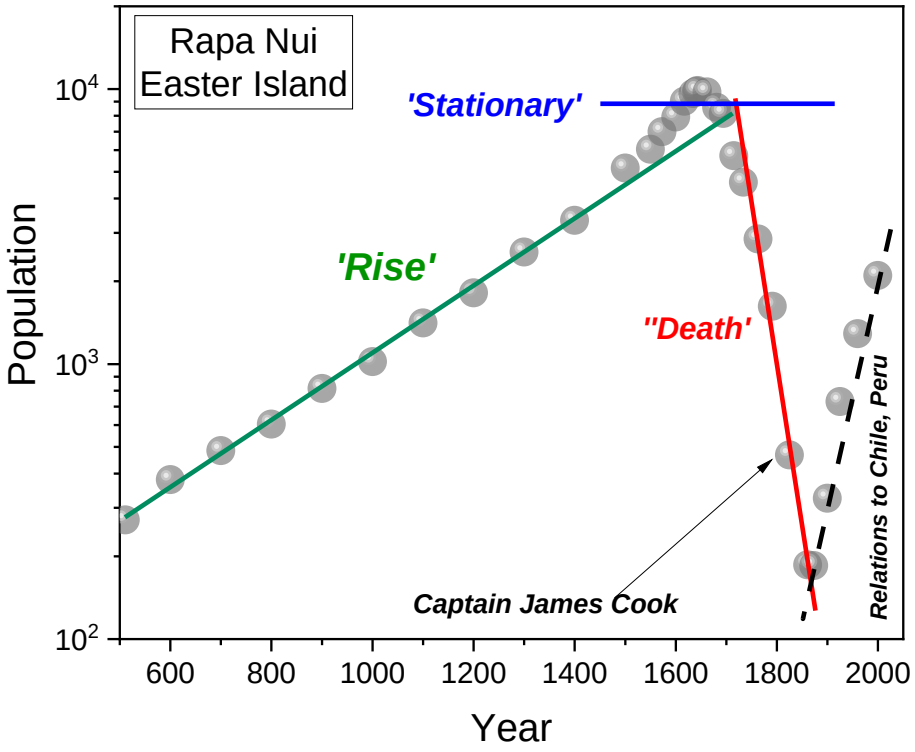
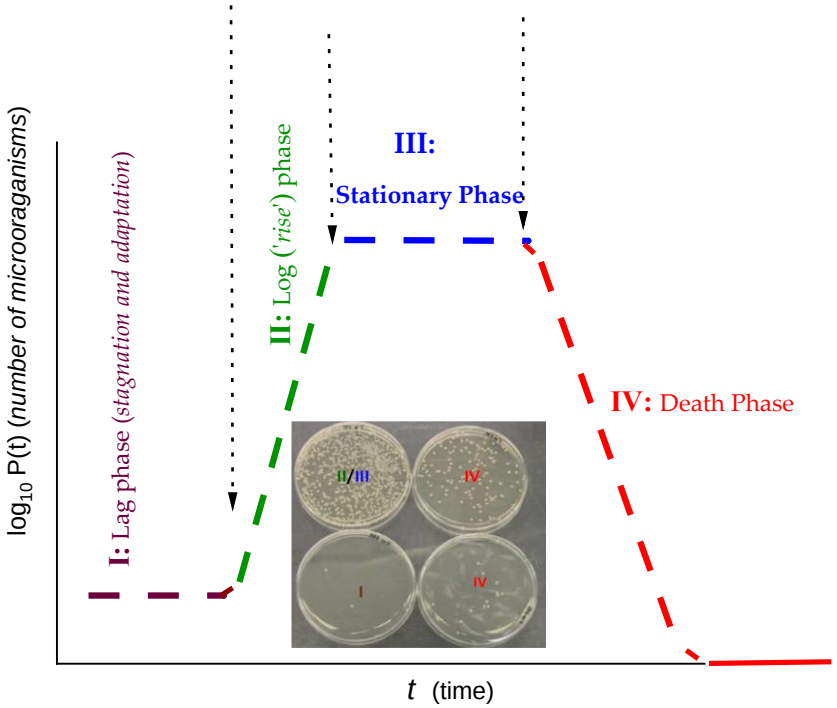
RAPA NUI

The Rapa Nui/Easter Island, the population developed in a way parallel to the dynamics of an ‚active' Soft Matter living system: a colony of bacteria



Changes of Easter Island (Rapa Nui) population since the hypothetical settlement till nowadays. The Decay can be associated with the lack of resources and related wars.



The evolution of microorganisms population in a closed container with a defined (limited) amount of food.

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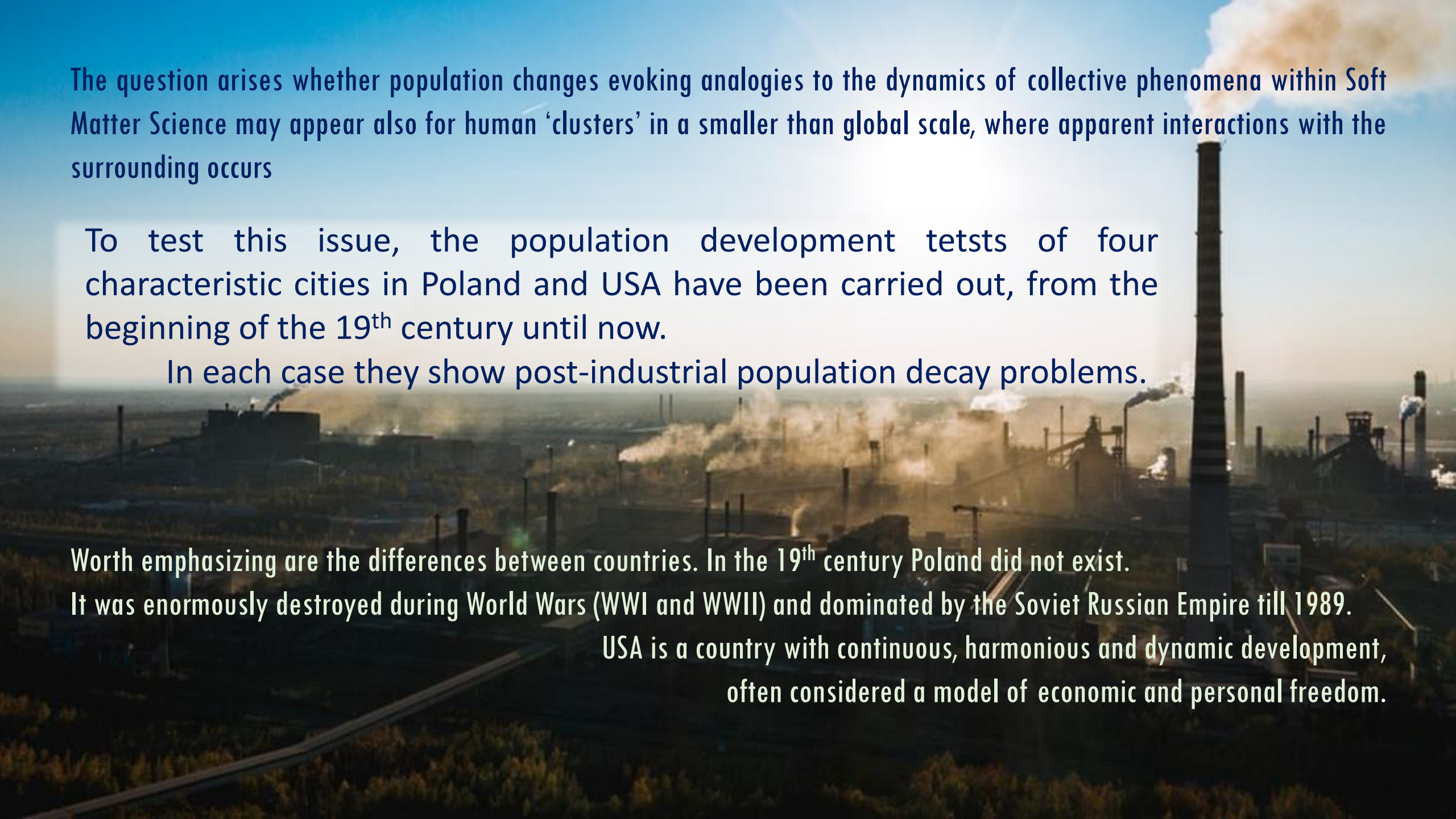

The question arises whether population changes evoking analogies to the dynamics of collective phenomena within Soft Matter Science may appear also for human ‘clusters’ in a smaller than global scale, where apparent interactions with the surrounding occurs

To test this issue, the population development tetsts of four characteristic cities in Poland and USA have been carried out, from the beginning of the 19th century until now.

In each case they show post-industrial population decay problems.

Worth emphasizing are the differences between countries. In the 19th century Poland did not exist.
It was enormously destroyed during World Wars (WWI and WWII) and dominated by the Soviet Russian Empire till 1989.

USA is a country with continuous, harmonious and dynamic development,
often considered a model of economic and personal freedom.

What about local populations???

USA

Cleveland, OH.

It is the largest city and a major port on the coast of Lake Erie. The role of a great transport intermediary seems to be the driving force for strong development. It includes industries in Cleveland that benefit from access to raw materials and transportation. It is also a considerable financial, commercial, and scientific measure. For decades, its population has been in decline.

➢ **Detroit (MI)**

Had experienced rapid growth since 1830 when it became an important port on the Great Lakes following the advent of steamboats. Already in 1903, companies associated with such car' brands as Buick, Cadillac, Ford, and Packard appeared. Since 1908, Henry Ford has been the world's largest car manufacturer for decades. The collapse of the automotive production in Detroit and city mismanagement resulted in the depopulation and bankruptcy in 2014.

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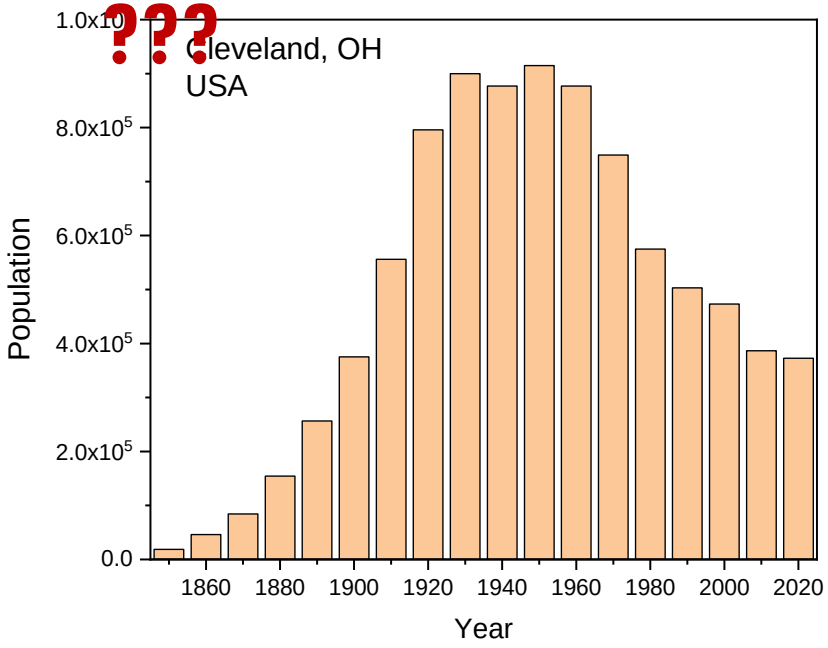
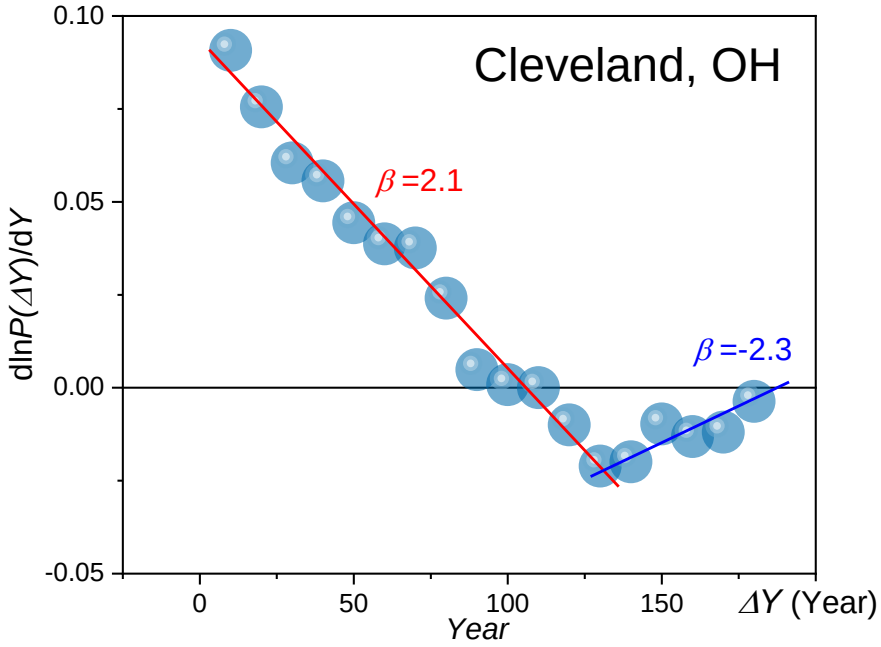
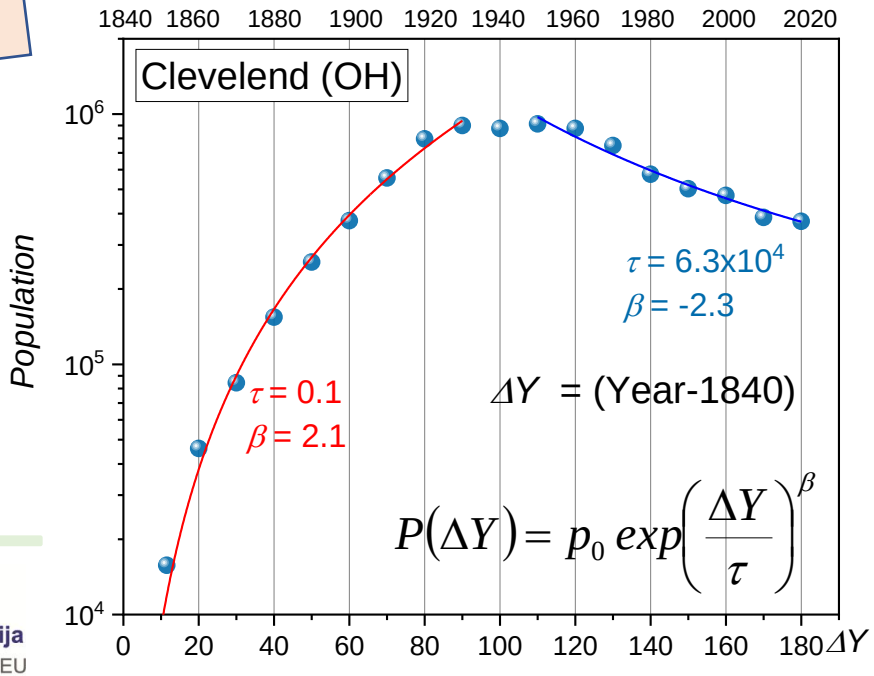
What about local populations ???



- The classic population bar-plot,
- the derivative analysis of these data by Eq. (2)
- the resulted powered exponential portrayal (Eq. (1)





Cleveland (OH) population changes show strong increase and subsequently a significant decrease in the population, with a short intermediate period.
The ‚complex' portrayal by Eq. (1), with the exponent β different from **1**.
It can indicate an underlying multi-process dynamics.

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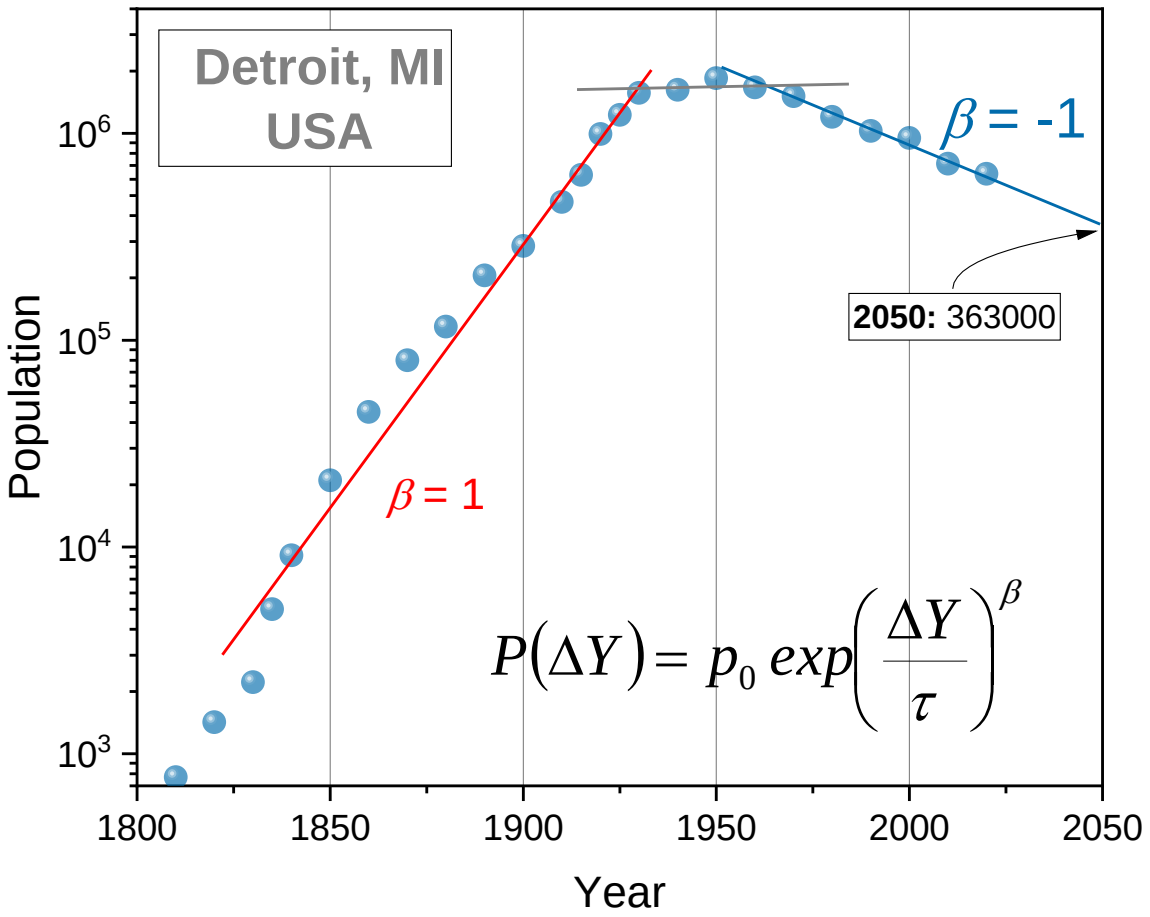
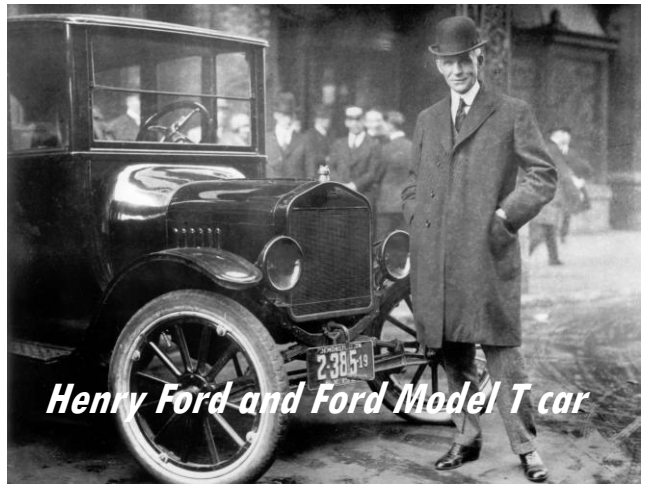
What about local populations ???



For analyzing population evolution in **Detroit**, a satisfactory semi-log plot reveals a single relaxation 'channel' or Malthus-type pattern.

Note:

For Detroit, the decline in population occurs despite the strong, continuous rise in the US population.



$$P(t) = p_0 exp\left[\pm\frac{\Delta t}{\tau(t)}^{\beta}\right] \rightarrow \beta = 1 \rightarrow \quad lnP(\Delta t) = \quad lnp_0 + \frac{1}{\tau}\Delta t$$

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What about local populations ???

POLAND

➢ Bytom

Is one of the oldest cities in Silesia, with a history dating back to the Middle Ages. The boosted development began in the 19th century, thanks to the exploitation of vast, high-quality coal deposits. Until 1945, Bytom belonged to Germany (the kingdom of Prussia, the Empire of Germany, the Weimar Republic, and the Third Reich). Later, Bytom found itself in Poland (PRL), and coal mining continued to grow It was the most important export commodity from the 'communist' state. After its collapse, coal production in Bytom declined until it became practically extinct at present.

➢ Łódź

City was founded as an economic enclave on the western border of the Russian Empire - in the Pri-Vistula Krai (as the Russians called Poland) ruled by the Tsar. The rapid development from the mid-19th century was a result of the growth of large weaving mills and the textile industry; Łódź was thus dubbed the *Polish Manchester*. Unlimited access to the large Russian market was essential for łódź development. After 1918, Łódź belonged to Poland, and industrialists had to search for new markets. From 1946, another stage in the development of Łódź in 'communist' Poland began. Again, the primary recipient was Russia (Soviet Russia), although the 'forced' profitability may be a matter of debate. After the fall of communism, the great mills collapsed due to the flood of cheap textiles from Asia.

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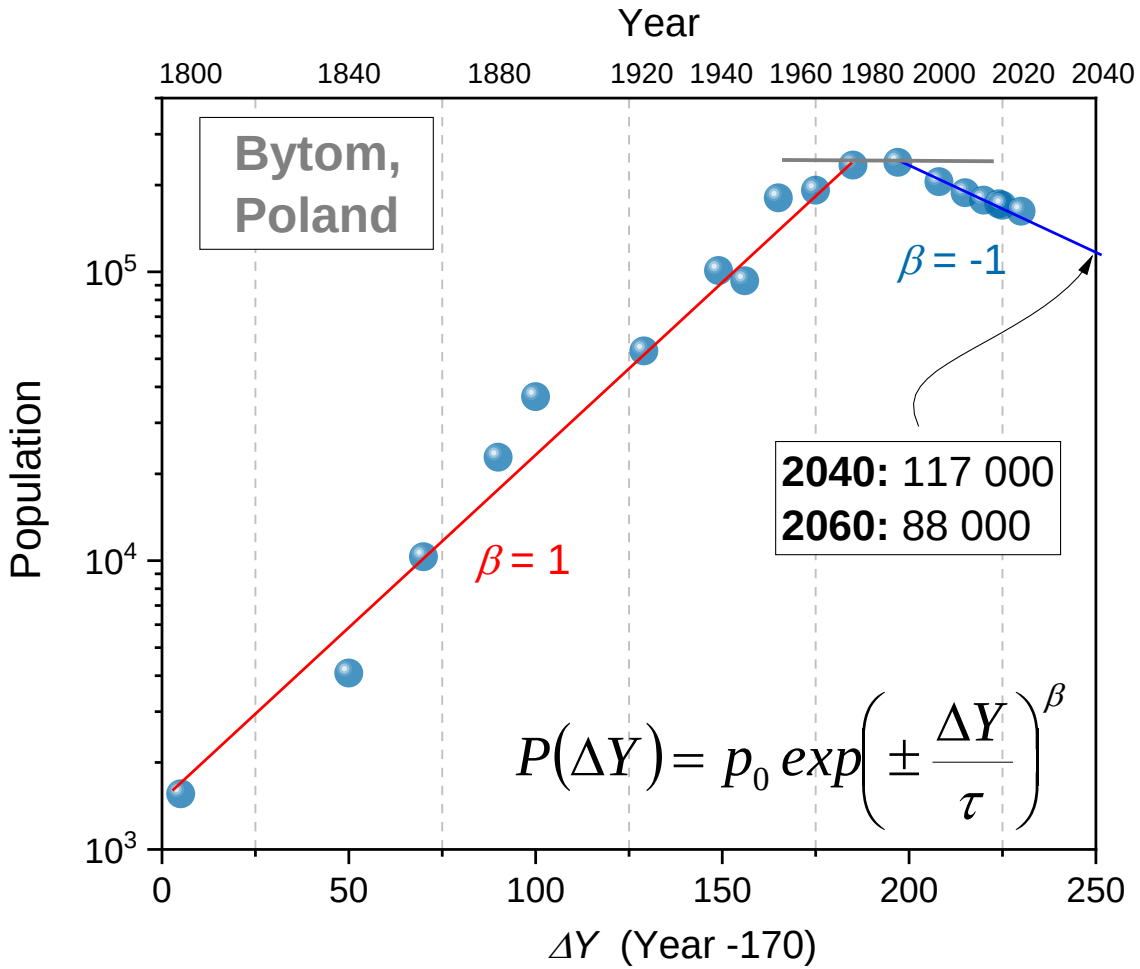
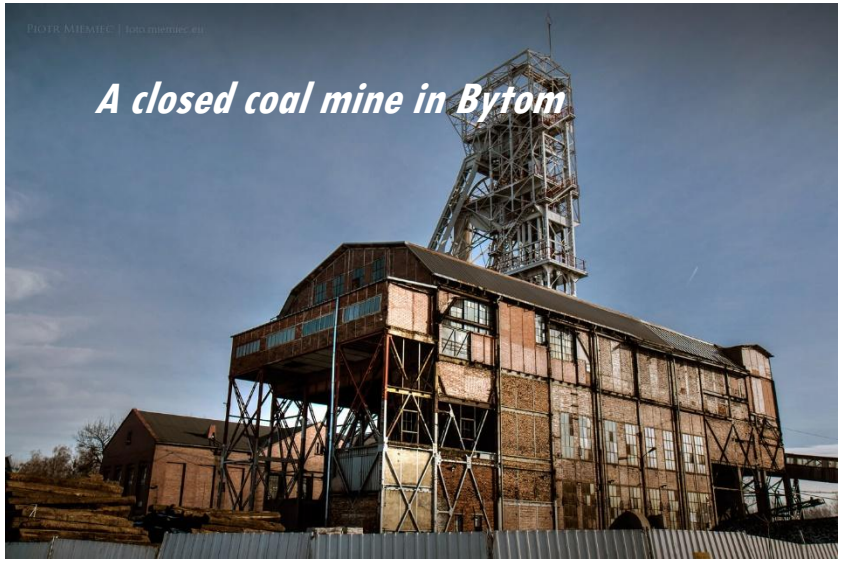


What about local populations ???

For analyzing the population evolution in **Bytom (Silesia, Poland),** a satisfactory description is offered by the semi-log plot, showing a single relaxation 'channel' or the Malthus-type pattern.



$$P(t) = p_0 exp\left[\pm \frac{\Delta t}{\tau(t)}^{\beta}\right] \rightarrow \beta = 1 \rightarrow \quad lnP(\Delta t) = \quad lnp_0 + \frac{1}{\tau}\Delta t$$

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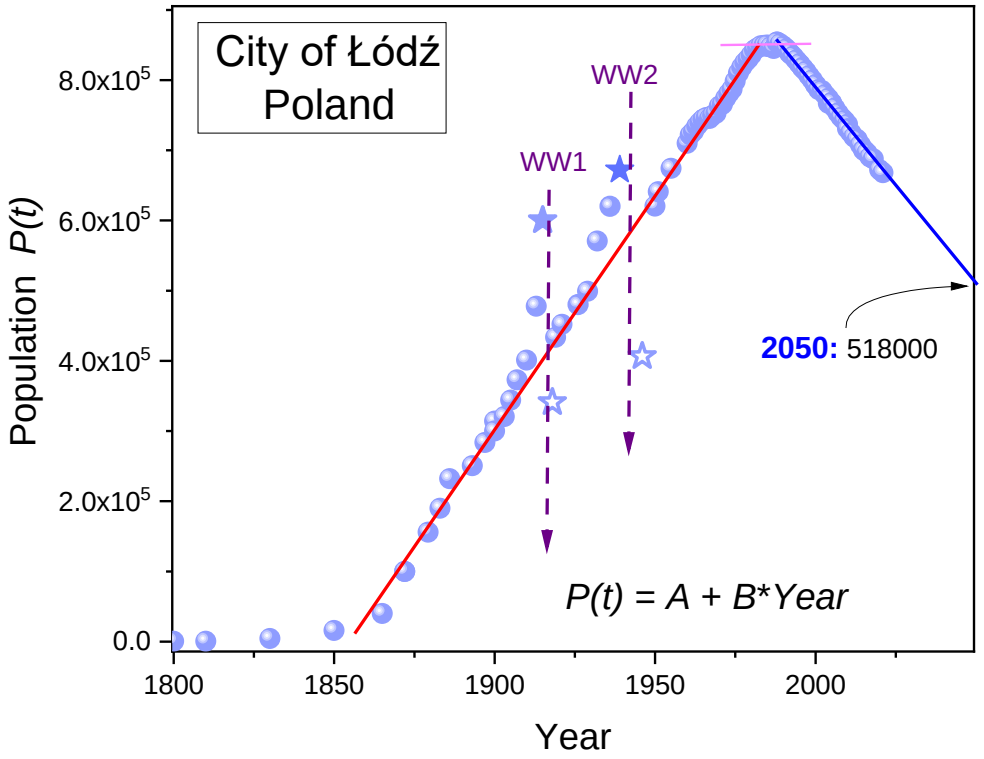

What about local populations ???

For analyzing the population evolution in **Łódź (Poland),** a pretty good portrayal offers linear changes.

Does it mean the ‚Łódź' is the unique ‚non-exponential' dynamics example?!

Not necessarily,....

Huge textile ‚factory' turned into a shopping and cultural center

Developing Eq. (1) in Taylor series approximation, one obtains:

$$P(t) = p_0 exp\left[\pm \frac{\Delta t}{\tau(t)}^{\beta=1}\right] \Rightarrow P(t) = p_0\left[1 \pm \frac{1}{\tau}\Delta t \pm \frac{1}{2\tau}\Delta t^2 \pm \frac{1}{3\tau}\Delta t^3 \pm \cdots\right]$$

If the impact of higher-order (power) terms can be neglected:

$$P(t) \approx p_0\left[1 \pm \frac{1}{\tau}\Delta t\right]$$

one obtains the linear relation, in agreement with the plot above.

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Conclusions for Post-Industrial Cities

Bytom and Detroit experienced growth and population increases in a Malthusian model with exponential (single-process, $b = 1$) growth from the 19th century onwards. In Detroit, the same trend continued before and after ~ 1900, when it shifted to the automotive industry.

In **Bytom**, the same Malthusian trend existed for almost 200 years, despite changes in nationality, administrative and political systems, and even an extensive population exchange in 1946/7.

In both cases, the leading industries shaped the development. They belong to leading and innovative (as far as the given times), and also very profitable branches. It also had a significant impact on wages and salaries, as well as the social conditions of workers.

The disappearance of dominant industries (such as cars and mining) and the lack of new 'attractors' led to a Malthusian population decline.

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Conclusions for Post-Industrial Cities

Cleveland, as a city, was established as a hub for goods exchange due to its strategic location, which also stimulated a diverse range of industries that benefited from the availability of various goods and the harbor.
Subsequently, **Cleveland** emerged as a financial and information exchange center. Thus, for **Cleveland**, the development motivator was multidimensional, which correlates with the Super-Malthusian (power exponent *b* different from 1).

As U.S. freight and passenger transportation shifted to rail, truck, and air , in the 1950s, **Cleveland's** major development and population growth motivator/attractor began to decline. Interestingly, this follows the parallel pattern observed for the rise stage.

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Conclusions for Post-Industrial Cities

Łódź experienced rapid development at the beginning of the 19th century and continued it for 200 years, following a surprisingly simple linear population growth pattern, which can be obtained from implementing the Taylor series expansion into a polynomial and omitting all power terms except the linear term. However, the power terms Dt_2, Dt_3, ... indicate specific feedback loops that increase the city's population, which can be associated with the city's growing attractiveness.

In **Łódź**, the feedback factor seems to be absent, and there is only a simple accumulation from year to year. In Łódź, the domination of one industry was probably even more significant than in Bytom or Detroit. However, the industry was not as leading and innovative as in these cities.

It appears that in **Łódź**, salaries and social attractiveness have never reached the relative levels of Detroit or Bytom. It can be linked to the fact that women were the primary workforce. The population decline, correlated with the collapse of the textile industry in Łódź, is also perfectly linear.

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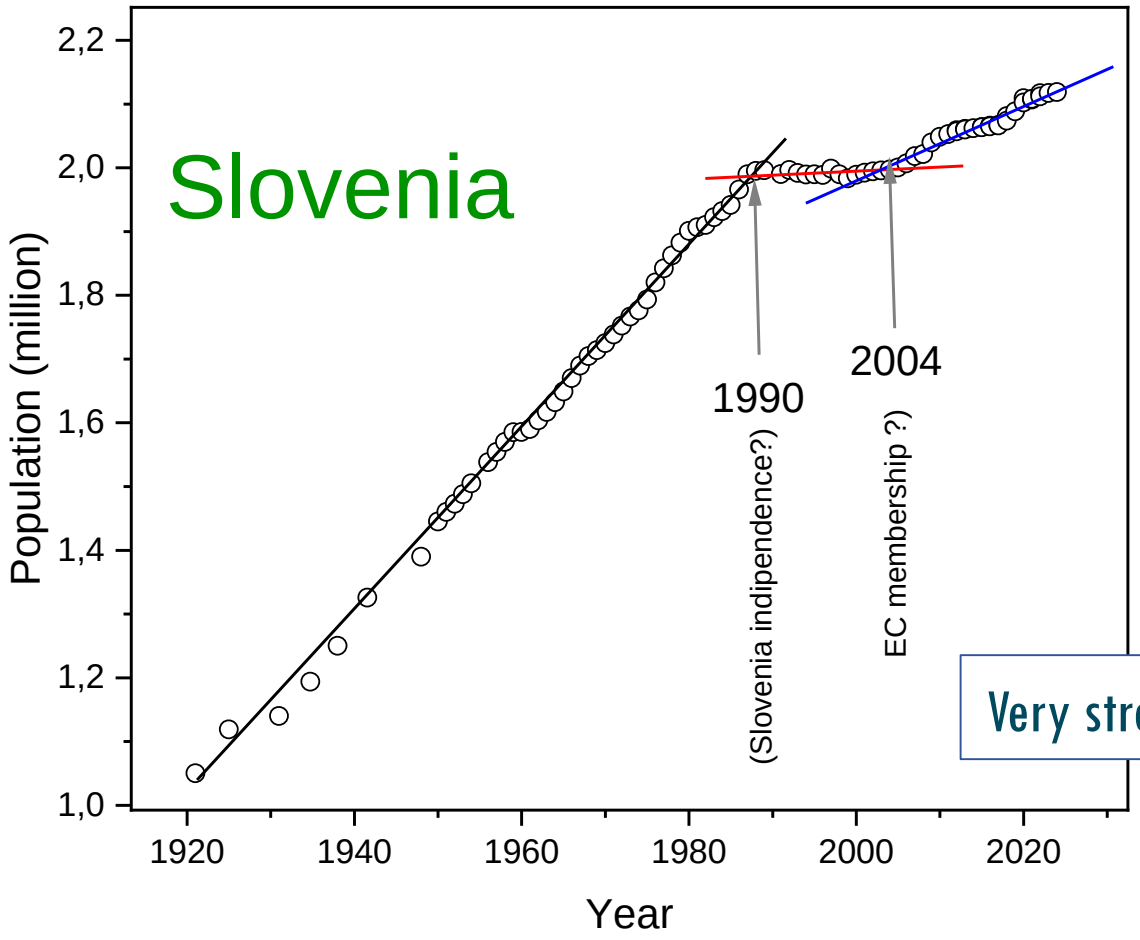
What about Slovenia ?



The unusual determinism of linear population changes – following the same pattern – from 1920 to ~1990 marked the end of Yugoslavia and the emergence of independent Slovenia.

This may be associated with an impact of the ‚natural' population rise and immigration (?).

In the years 1990–2004, 'population stagnation' appeared, which may be related to significant emigration. After the accession to the European Union (2004), the population is growing again, although its functional nature will be possible to estimate in several decades.

Very strong links to political changes and ‚out of model' linear behavior

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Summary - from the of Soft Matter science point of view

Some aspects of the development of post-industrial cities can be considered within the Socio-Economic Soft Matter modeling.

In such an approach, population changes are governed' not only by its internal dynamics, as in the case of bacteria in a container or Rapa Nui island population, but also by an 'attractor' in a given city. It attracts people from outside the city, but its weakening and new attractors outside decrease the population.

The environment of some cities can also be considered in terms of an averaged factor - in Soft Matter Science such situation is known as the 'mean field' approximation theory. It reduces the effective description of interactions with surrounding to a single parametric number. In such a picture, some cities may be surrounded by a kind of 'amorphous' socio-economic 'field' which makes them similar to a specific isolated model island.

Notable is the long–time-range determinism in the population development and decay, occurring despite essential changes regarding historical events, economy, and even population changes (!)

Picture: J. Goodby & P. G. de Gennes: *'Soft Matter - Smectic Zoo'*

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Summary - from the of Soft Matter science point of view

The question of the 3rd-path of Verthulst model implementation mentioned above remains.

This problem is related to progressive and self-adaptive changes in the population itself, further renormalizing the system's carrying capacity towards new, lesser needs of the population.
It can be called a 'spontaneous self-adaptation of complex 'active-matter population'recalling the language of complex systems physics. It seems to coincide with the sustainable civilization trend, which is dominant nowadays.

Picture: J. Goodby & P. G. de Gennes: *'Soft Matter - Smectic Zoo'*

The significance of the new path implemented enable:

(i) the application of numerical filtering, which enables the effective use of population data from various sources,

(ii) the application of distortion-sensitive and derivative-based transformation of P(t) data, enabling the model-free preliminary insight; it is also the case of per capita global population rate coefficient.

(iii) the implementation for arbitrary time-evolving data, from biology and medicine to economic issues. The particular efficiency of such a bottom-up approach matched with the distortions-sensitive analysis can appear when local distortions, also aperiodic, distort or even hide the leading trend.

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10 000 years

1000 years

120 years

The End ?

Active Human Soft Matter: The Critical Insight into Doomsday Growth of Global population

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