Review

Society & Science: Doomsday Criticality for the Global Society

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Abstract:
The paper discusses global population changes from the beginning of the Anthropocene onset till 2024, based on the 'tools' and model concepts of Soft Matter dynamics. The 'bottom-up' approach, focused on the population data themselves and the distortion-sensitive validation of portrayal via a given scaling relation, is applied. Two exponential Super-Malthusian dependences are considered, namely (i) the empowered exponential one, and (ii) containing the time-dependent relaxation time. The latter follows the dominant linear pattern in the Industrial Revolution times, leading to 'constrained and frustrated' – type critical scaling for the global population growth. Finally, the evolution of the relative growth rate versus the population itself is considered. The link to the empowered exponential behavior is indicated.

This contribution presents a new cognitive path for studying global population growth, exploring the Soft Matter dynamics approach. It offers a reliable fundamental base of derived scaling equations, including the meaning of relevant parameters. Studies revealed the non-monotonic nature of global population growth, where temporal local events can significantly influence leading trends. For Industrial Revolutions, the essential meaning of technological innovation in feedback alliance with socio-economic innovatively re-shaping surrounding is noted.

Keywords: Global Population; Scaling Equations, Modelling, Soft Matter, Dynamics, Universalistic Features.

1. Soft Matter and Global Population as the Socio-Economic Counterpart

In 1991, Pierre G. de Gennes constituted the Soft Matter category in the Nobel Prize lecture (1991) entitled 'Soft Matter' (de Gennes, 1991; de Gennes and Badoz, 1996). There is no general definition of Soft Matter, but it is related to microscopically distinct systems showing common, universalistic features, namely: (i) dominance of mesoscale assemblies, (ii) extreme sensitivity to perturbations, (iii) spontaneous mesoscale self-assembling and self-organization, (iv) unique phase transitions, (v) common scaling functional patterns despite essential microscopic differences.

The canonic Soft Matter includes: liquid crystals, colloids, micellar systems, critical liquids, polymers, supercooled liquids, nanocolloids, vesicles based fluids, bio-systems, micellar systems … and also some semi-solids such as plastic crystals, … (de Gennes and Badoz, 1996; Brochard-Wyart, 2019; Roland et al., 2008; Drozd-Rzoska, et al., 2008; Rzoska, et al., 2001; Drozd-Rzoska, et al., 2013).

De Gennes' pointed out a large set of systems, earlier considered mostly in frames of material engineering, that can linked in this category due to universalistic features for 'isomorphic' physical properties. In subsequent decades, the concept of Soft Matter expanded. Currently, foods are considered the Complex Soft Matter (Mezzenga, et al., 2005). Living Soft Matter is focused on biosystems from DNA to bacteria and viruses, …, including their assemblies (Sinha, 2024). Quantum Soft Matter has become a special category (Thedford, et al., 2022). Focused liquid crystals and their nanocolloids studies revealed fascinating parallels to the elementary particles world: bosons, fermions, or Higgs fields (Jelen, et al., 2024). The concept of 'Soft cosmology' has emerged to interpret some exceptional properties in Universe sectors (Saridakis, 2021).

Soft Matter concept opened up extraordinary possibilities for experimental modeling of the mentioned systems on the Laboratory Table, with the support of materials engineering and monitoring by various physical methods. The Soft Matter cognitive advances yielded analytical tools and universal modeling concepts that could be implemented in various specific systems.

Global Population is composed of humans with an inherent tendency to interact, self-assemble, and spontaneously create ordered local structures - from families, tribes, and cities to countries/states & empires. It is related to the rising range of 'interactions' related to developing management. Notable is the extreme sensitivity to endogenic and exogenic perturbations, often leading to qualitative transformations of societies (‚phase' transitions?). Hence, the question arises (Sojecka and Drozd-Rzoska, 2024, 2025): Isn't the Global Population a unique Socio-Economic Soft Matter system?

2. Global population scaling: selected reference models

An adequate and fundamentally justified description of global population changes, using model-validated scaling relations, is essential for the insight into past and future-focused reliable predictions. It can deliver cardinal data supporting effective socio-economic planning and global governance.

The 'classic' reference for Population Growth is the Malthus equation (Malthus, 1798; Weil and Wilde, 2010):

$$P(t) = P_0 exp(rt) \quad \Rightarrow \quad lnP(t) = lnP_0 + rt \quad \Rightarrow \quad \frac{dP(t)}{dt} = rP(t) \qquad (1)$$

where time t refers to the onset time t_0, coupled with the prefactor N_0, and $r = const$ is the Malthus rate coefficient.

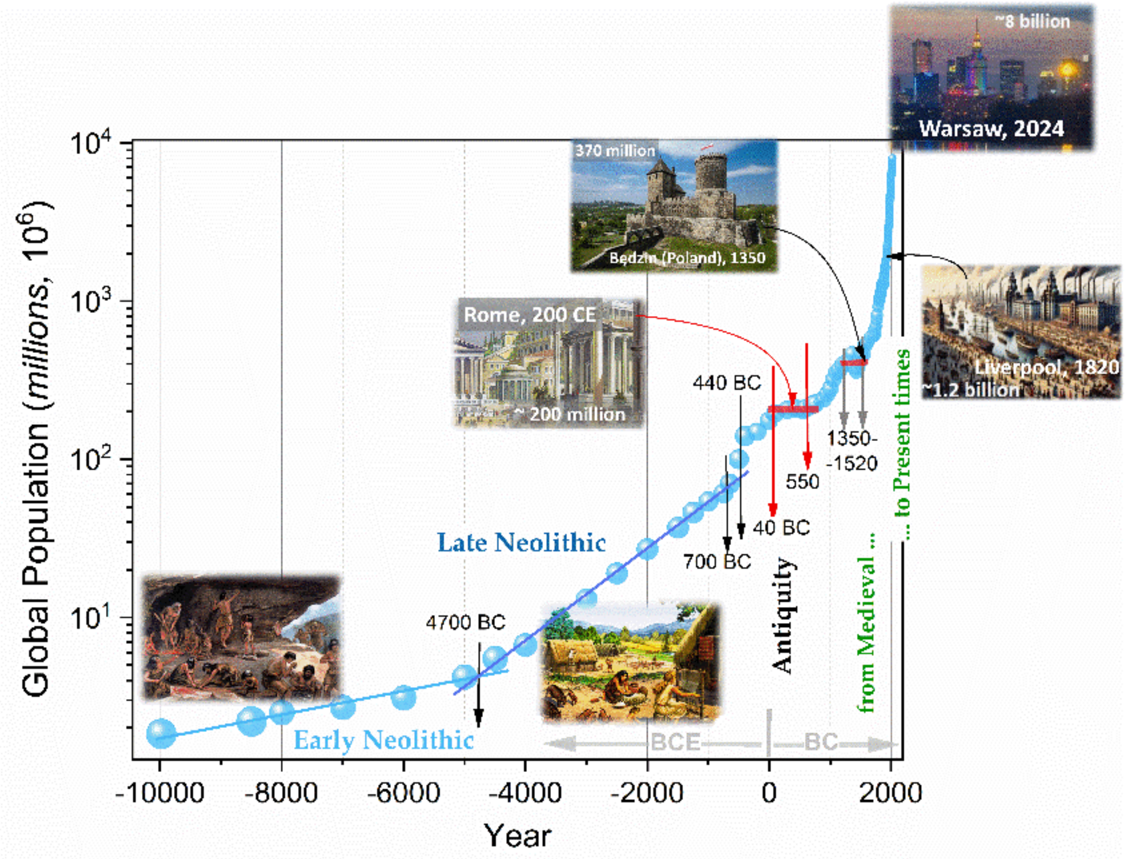

Figure 1. Global population changes from the Holocene (Anthropocene) onset till nowadays, based on data introduced in (Sojecka and Rzoska, 2024). Linear dependence is related to the basic Malthus behavior and red-horizontal lines to ~constant population in the given time domain. Subsequent historical epochs are indicated by characterizing them with pictures, which include messages regarding global population values.

The right part of Eq. (1), shows the basic assumption, namely that the population rise in the subsequent time domain is proportional to the current population, following the constant rate coefficient r. It directly leads to the exponential equation, shown in the left part of Eq. (1). For the Malthus model, one should expect linear population changes when using the semi-log plot, as shown in the middle part of Eq. (1).

Figure 1 presents global population changes from the Anthropocene onset (10 000 BCE) till nowadays, using the new data set introduced in (Sojecka and Drozd-Rzoska, 2024 and 2025). It is based on collecting global population data from a few sources and their subsequent numerical filtering to obtain an analytic set for which data-related derivative analysis is possible. The global population followed the linear behavior, in the semi-log scale, described by Malthus' Eq. (1) for ~9 millennia, - related to Neolithic times, splitting into domains: Early & Late'. The crossover can be linked to climate changes. From the end of the Bronze Era, via Antiquity, Medieval, …. till nowadays - the increasingly nonlinear behavior appears in **Figure 1**. For such pattern, beyond the basic Malthus model (Eq. (1)), the name Super-Malthus (S-M) behavior was proposed (Sojecka and Drozd-Rzoska, 2024 and 2025). The significant feature of the discussed S-M equations was the relaxation time τ introduced instead of the Malthus rate coefficient, namely $\tau = 1/r$. It allows a simple estimation of 50% change from the given $P(t)$ value: $t_{50\%} = \tau \ln 2$.

In the first half of the 19th century, Verhulst proposed the model extending the Malthus approach by including the factor directly addressing required resources, such as food. It is explicitly visible for the model-related differential equation (Verhulst, 1847; Vandamme and Rocha, 2022):

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

where s is the Verhulst parameter describing available resources in the given systems. The carrying capacity coefficient $K = 1/s$ was introduced by Pearl (Pearl, 1927; Volterra, 1928).

Eq. (2) shows that the carrying capacity coefficient K can be interpreted as the maximal population that can be hypothetically maintained in the given system with a given amount of resources. The right-hand part of Eq. (2) shows that for $K \gg P(t)$ it reduces to the basic Maltus Eq. (1).

For $sP \to r$, increasing distortion from the unlimited Malthus-type rise appears. Finally at $sP = r$, related to $\mathrm{d}P(t)/\mathrm{d}t = 0$, the population rise terminal is reached.

For the Verhulst equation, one can consider the following scenarios occurying after the first Malthusian growth stage (Sojecka and Drozd-Rzoska, 2025):

(i) For infinite resources, only permanent Malthiusian-type population growth occurs.

(ii) A constant amount of renewable resources ($s(t) = s = \mathrm{const}$) is available. It remains constant despite the population rise. The condition $\mathrm{d}P(t)/\mathrm{d}t = 0$ means the transition to a plateau where $P(t) = \mathrm{const}$.

(iii) A constant amount of non-renewable resources is available. It irreversibly decreases with the population rise. The rise terminal is related to $\mathrm{d}P(t = t_{max})/\mathrm{d}t = 0$, and for $t > t_{max}$ the population declines.

(iv) The population is 'specifically sustainable', i.e., it limits demands for 'resources' by restricting needs. Consequently, the amount of resources 'relatively increases', postponing the terminal condition $\mathrm{d}P(t = t_{max})/\mathrm{d}t = 0$.

A model manifestation of the option (iv) can be the evolutionary size reduction of animals on isolated islands. For the human population, it can be associated with lesser demands for food, raw materials, and limited harmful environmental impacts, which correlates with general requiremen0st of the Sustainable Society.

The integration of the differential Eq. (2) leads to the basic Verhulst scaling equation (Verhults, 1847; Sojecka and Drozd-Rzoska, 2025):

$$P(t) = \frac{K}{1+CK\exp(-rt)} = \frac{1}{1/K + C\exp(-rt)} \quad \Rightarrow \quad (K \to \infty) \quad \Rightarrow \quad P(t) = P_0 \exp(rt) \tag{3}$$

where $C = P_0 - (1/K)$. The right-hand part indicates the simplification to the Malthus Eq. (1). Malthus and Verhulst scaling equations remain a significant reference for population studies. Nevertheless, the 'empirical' pattern of global population growth does not correlate with the abovementioned characterization. However, they are an essential and proven tool in microbiology, general biology, epidemiology and medicine (Vandamme, 2021).

There are currently many model concepts for describing global population changes (Umpleby, 1990). For the authors, worth noting is the 'hyperbolic. Doomsday' equation (von Foerster, et al., 1960):

$$'P(t) = \frac{1.79\times 10^{11}}{(2026.87-t)^{\gamma=0.99}} \quad \propto \quad \frac{1}{D-t} \tag{4}$$

where $D = 2026.87$ was linked to Friday, 13 November 2026, Doomsday.

It was validated via the log-log scale plot analysis for 28 global population data ranging from ~500 CE till 1958. The title of von Foerster et al., (1960) report recalling 'Doomsday', and the suggestion of the 'human extinction' before 2026, led to decades of commentary and remarks in the general mass media, but also criticism from population change researchers, who mainly criticized the lack of model justification (Umpleby, 1990; Yakovenko, 2025). However, an excellent descriptive agreement, with the surprising simplicity of Eq. (4), remained a surprising fact.

From the 1970s, more historical estimates of global population data became available, and depending on the data set tested and the time period selected, the power exponent $\sim 0.7 < \gamma < 1$ was reported for Eq. (4) (Taagapera, 1979).

In the last decade, Taagapera and Nemčok developed a scaling function that avoids the 'Doomsday' singularity and can be reduced to the von Foerster scaling functional form. They suggest 'stationary, terminal phases' as the generic feature of global population development: 1st at Roman Empire times, & 2nd in the last decades. They were scaled as follows (Taagapera, 2014; Taagapera and Nemčok, 2024):

$$P(t) = \frac{A}{[ln(B+E)]^M} \quad , \qquad E = \exp[(D-t)/\tau] \qquad (5)$$

associated with $D = 100 \text{ CE}$ for the 1st (Prehistoric- Roman Empire) period and $D = 1980$ for the second (early Medieval – Nowadays).

Equation (5) offers an excellent reproduction of the global population changes. However, it contains 5 parameters for each mentioned period and requires nonlinear fitting. Notable, that the experience gained in Soft Matter systems for similar patterns of data change led to the general indication that optimal scaling equations should rely on no more than 3-4 parameters.

A significant shortcoming of the analysis trend initiated by the work of (von Foerster et al., 1960) seems to be the lack of fundamental justification for such a unique characterization. Nevertheless, the unique descriptive efficiency seems to remain the fact (Drozd-Rzoska et al., 2023).

3. Localized & Soft Matter view on Global Population Growth

The standard analytic method for testing population changes relies on fitting data via a given scaling equation in an *ad hoc* selected time domain, often using nonlinear routines.

This report presents a novel bottom-up approach to Global Population dynamics. It does not focus on fitting via a given scaling equation in an arbitrary time domain but on population data itself. It is related to the following basic issues (Sojecka and Drozd-Rzoska, 2024, 2025):

1. For the optimal description of *P(t)* changes, and reliable forecasts, it is necessary to analyze trends over a sufficiently long period.
2. The crucial problem for global population growth data constitutes multiple estimates of population data, particularly when shifting to the past. The authors reduced this problem by implementing numerical filtering to a large data set collected from different sources.
3. The latter led to the unique set of 198 global population data from 10 000 BC - 2024, with an analytic pattern. i.e., the derivative analysis is possible.
4. The linearized & derivative-based analysis, recalling 3-parameters model – equations, has been carried out for the' new generation' data set.
5. The latter yielded distortions-sensitive insights into local distortions, revealing time domains where a given scaling equation can be used. It also derived optimal values of relevant parameters - consequntly the nonlinear fitting routine was avoided.
6. The Soft Matter base of model scaling relations offers a fundamental reference meaning of relevant parameters.

In refs. (Sojecka, Drozd-Rzoska; 2024, 2025) two Super-Malthus (S-M) equations have been developed and implemented to discuss Global Population Growth. The first one is the 'empowered' S-M1 equation:

$$P(t) = P_0 \exp\left(\frac{t}{\tau}\right)^{\beta} \quad \Rightarrow \ln P(t) = \ln P_o + \frac{t^{\beta}}{\tau^{\beta}} \qquad (6)$$

where P_0 is the prefactor related $t = 0$, in the given report related to the mentioned Anthropocene onset; parameters τ, $\beta = const$.

The right-hand part shows that the simple semi-log plot analysis, successful for the basic Malthus Eq. (1), does not yield relevant parameters due to the essential non-linearity, related to the exponent β . Nevertheless, one can consider the derivative of the right-hand part of Eq. (6) and, subsequently implement the log-log scale analysis:

$$\log_{10}\left[\frac{\mathrm{d}\ln P(t)}{\mathrm{d}t}\right] = \log_{10} G_P = \log_{10}\left(\frac{\beta}{\tau^{\beta}}\right) + (\beta - 1)\log_{10} t = A + B \times x \qquad (7)$$

where $x = \log_{10} t$.

The plot of transformed $P(t)$ data via Eq. (7), namely $y = \log_{10} G_P = \log_{10}[\mathrm{d}\ln P(t)/\mathrm{d}t]$ vs. $x = \log_{10} t$, validates domains of S-M1 description via the linear behavior, for which the linear regression yields optimal values of relevant parameters, namely τ and β.

Eq. (6) simplifies to the basic Malthus Eq. (1) for the power exponent $\beta = 1$. Recalling consideration related to Soft Matter, it can be related to systems with a single, dominant relaxation process. A continuous distribution of multiple relaxation times is related to $\beta \neq 1$. It can be associated with the feedback process amplification for $\beta > 1$ and the system 'internal energy' dissipation for $\beta < 1$ (Sojecka and Drozd-Rzoska, 2024).

The second Super-Malthus relation (S-M2) is associated with the following dependence (Sojecka and Drozd-Rzoska, 2024):

$$P(t) = P_0 \exp\left(\frac{t}{\tau(t)}\right) \quad \Rightarrow \quad \tau(t) = t \times \ln[P_0/P(t)] \quad . \tag{8}$$

In the above relation, the concept of the local and time-dependent relaxation time and then growth rate $r(t) = 1/\tau(t)$, has been introduced. It simplifies to the basic Malthus Eq. (1) for $\tau(t) = \tau = 1/r = \text{const}$ in the given time domain.

The direct analysis of $P(t)$ data via S-M2 relation (left-hand part of Eq.(8)) might seem to be impossible because of the *apriori* unknown $\tau(t)$ functional form. Nevertheless, one can determine $\tau(t)$ temporal changes, as shown in the right-hand part of Eq. (8). The result of such analysis is shown in **Figure 2**.

The plot reveals that the relaxation time $\tau(t)$ and growth rate $r(t)$ are constant for the extreme period reaching ~700 years, from the mid-Medieval Age till the Enlightenment epoch onset, as shown by horizontal dashed lines. It means that in this extreme time domain, the global population growth dominantly followed the simple Arrhenius pattern (Eq. (1)), with a huge distortion matched with the Black Death pandemic times. From the beginning of the 18th century till nowadays, a new general pattern is visble:

$$\tau(t) = -a + bt \quad \Rightarrow \quad r(t) = 1/(-a + bt) \tag{9}$$

where constant parameters $a, b > 0$.

Substititutrig above to Eq. (8) one obtains the exponential relation with internal critical-like singular change (Sojecka and Drozd-Rzoska; 2024):

$$P(t) = P_0 \exp\left(\frac{t}{\tau(t)}\right) = P_0 \exp\left(\frac{t}{-a+bt}\right) = P_0 \exp\left(\frac{ct}{T_C - t}\right) = 610 \times \exp\left(\frac{1.62t}{2216-t}\right) \tag{10}$$

where P_0 is related to the Industrial Revolutions times onset at $t = 1710$, detected in **Figure 2**.

Notable is the link to the reference hyperbolic/Doomsday Eq.(4) (Von Foerster et al., 1960). Namely, when applying the Taylor series expansion for Eq. (10) one obtains (Sojecka and Drozd-Rzoska, 2024) the following relation:

$$P(t) = P_0 \exp\left(\frac{ct}{T_C - t}\right) = P_0\left(1 + \frac{ct}{T_C - t} + \cdots\right) \propto \frac{1}{D-t} \tag{11}$$

Equations (9), (10), and **Figure 2** indicate the singularity at the year $T_C \approx 2216$, whereas for von Foerster et al. (1960) Eq. (4) the 'Doomsday year' appeared $D \approx 2026$. Eq. (11) shows that this difference can result from neglecting higher-order terms in Eq. (4).

The model scaling Eq. (10) parallels relations characterizing dynamics in constrained and frustrated critical systems, with inherent spontaneously appearing multi-element critical fluctuations. Hence, for Eq. (10) and von Foerster (1960) Eq. (4), the name 'critical' instead of 'hyperbolic' seems to be more appropriate.

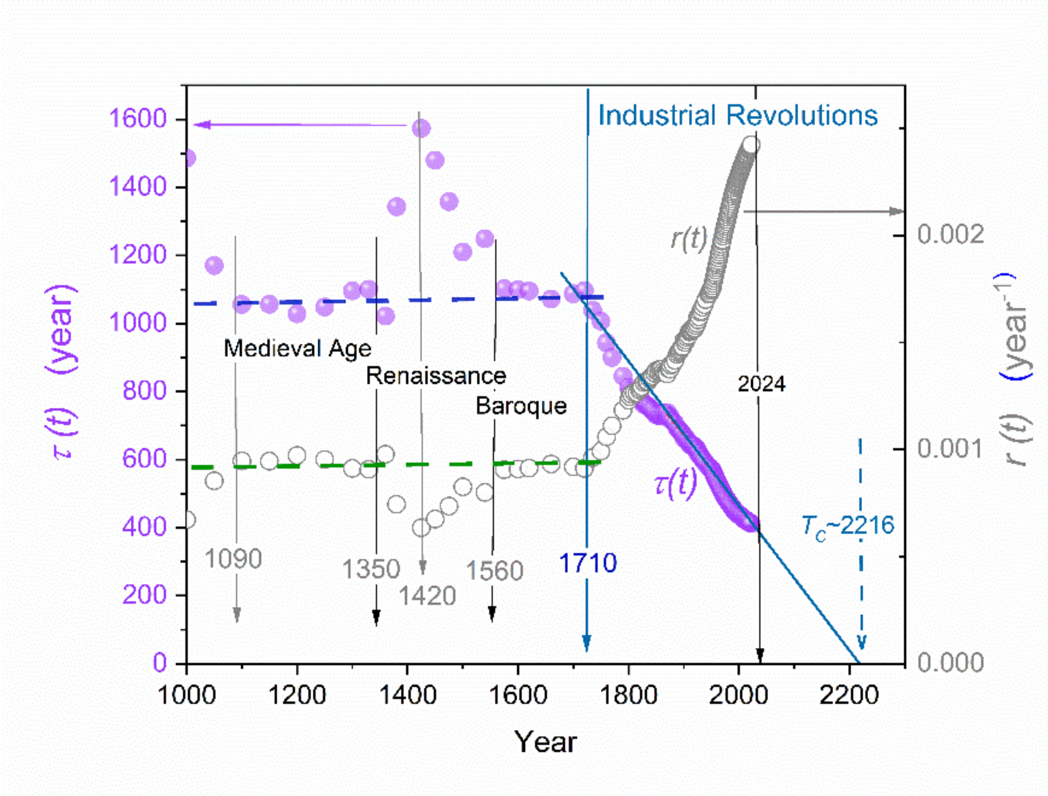

Figure 2. Temperature changes of the population growth rate $r(t)$ coefficient and the relaxation time $\tau(t) = 1/r(t)$. Related historical epochs and dates are noted. Horizontal dashed lines are related to the basic Malthus behavior (Eq. (1)), with $r = const$ and $\tau = const$.

The above reasoning considered the time-related growth of the global population. However, one can consider the relative population growth (RGR) vs. the population rise itself. In ref. (Lehman et al., 2021) considered the application of Verhulst Eq. (3) via the application of Pearl (1920) and Volterra (1927) concept of using a set of (r, s) parameters in subsequent time domains, and then a set of Verhulst equations for which next steps transformations $(r_i, s_i) \to (r_{i+1}, s_{i+1})$ occurred, before reaching the 'saturation phase' for the previous one. Lehman et al. (2021) explained these steps by overcoming subsequent bio- and eco-barriers during the global population development since the Anthropocene onset. In ref. (Lehman, et al., 2021), particular attention was drawn to the population relative growth rate (RGR) $G_P(\Delta t_i, \Delta P_i)$. Lehman, et al. (2021) considered changes in this parameter via the discrete analysis of population changes ΔP_i in subsequent time domains Δt_i. The resulted plot $G_P(\Delta t_i, \Delta P_i)$ vs. P_i revealed two linear dependences with crossover ~1965, namely:

$$G_P(t, P) = a + bP(t) \quad , \tag{12}$$

where $a, b = const$ and the slope parameter $b > 0$ for periods $10\,000\ BCE < t < 1965$ and $1965 < t < 2010$. The crossover is associated with population $P \approx 3.2$ billion.

In ref. (Lehman et al., 2021) such behavior was discussed as the argument supporting the portrayal of the global population changes via Verhulst model (Eqs. (2) and (3)), with multi-parameter crossover introduced by Pearl (1927) and Volterra (1928).

Very recently Sojecka and Drozd-Rzoska (2025) introduced the analytic $G_P(P, t)$ factor, instead of the discrete form earlier used. It is based on the new analytic set of global population data mentioned above (Sojecka and Drozd-Rzoska, 2024), namely:

$$G_P(t_i, P_i) = \frac{1}{P_i(t_i)} \frac{\Delta P_i(t_i)}{\Delta t_i} \Rightarrow G_P(t, P) = \frac{1}{P(t)} \frac{\mathrm{d}P(t)}{\mathrm{d}t} = \frac{\mathrm{d}P(t)/P(t)}{\mathrm{d}t} = \frac{\mathrm{d}lnP(t)}{\mathrm{d}t} \quad . \tag{13}$$

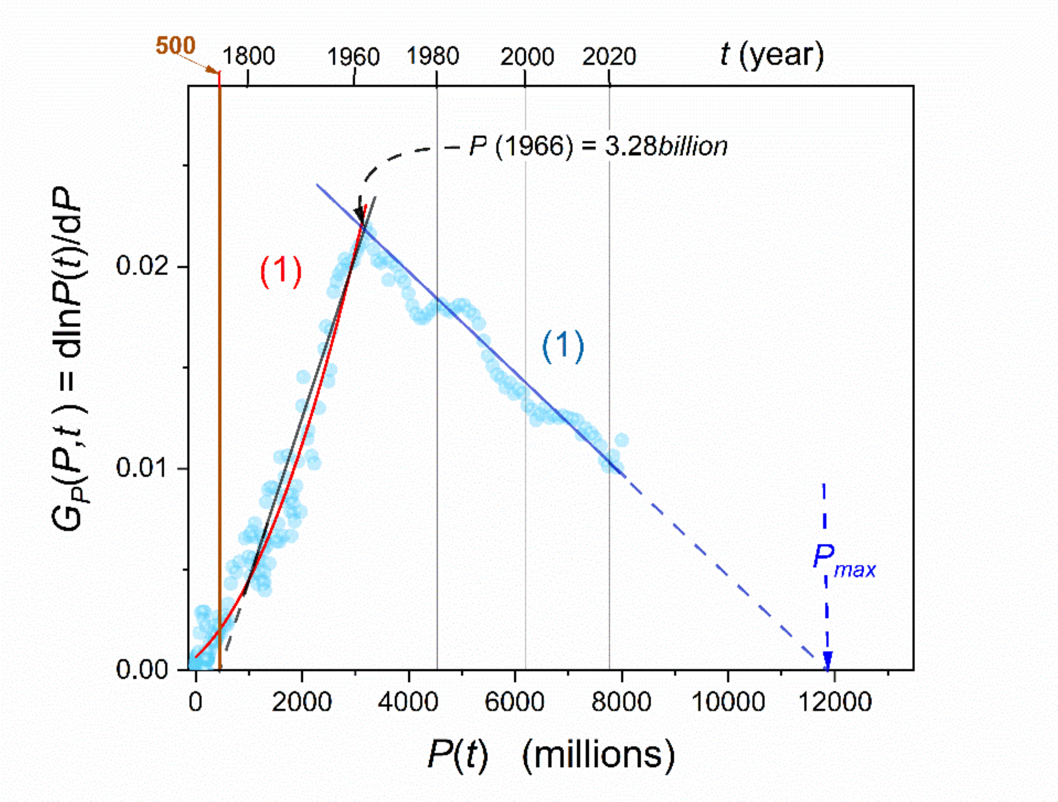

Figure 3. The global population-related changes of relative growth rate (RGR) coefficient since the Anthropocene onset till nowadays expressed vs. the global population values itself. The upper scale presents the coupled time scale. The brown vertical line indicates the Roman Empire terminal, which is also considered the early Medieval Age onset. Two domains (1) and (2), and the crossover between them are indicated. For domain (1), extended down to 10 000 the complete portrayal is nonlinear: in the plot via the second-order polynomial. Prepared using data shown in **Figure 1** and ref. (Sojecka and Drozd-Rzoska, 2025). The linear description of the $G_P(P)$ seems to be limited to ~2 centuries in domain (1).

Figure 3 shows the results of such analysis. It reasonably agrees with a similar plot presented in ref. (Lehman, et al., 2021) where the discrete definition $G_P(P_i, t_i)$ was used. The agreement includes two linear domains appearing for the eye-view test in **Figure 3**, as in ref. (Lehman et al.,2021). However, following Eq.(2), parameters describing the linear behavior via Eq. (12) should explicitly determine key parameters for the Verhults Eq. (3), namely: $r = a$ and $s = b$. It means that following the above reasoning, related to **Figure 3** and Eq. (12), only two sets of parameters $(r_1 = a_1, s_1 = b_1)$ and $(r_s = a_2, s_2 = b_2)$ for domains (1) and (2) in **Figure 3** are allowed. It does not agree with the multi-parameter concept by Pearl (1927) and Volterra (1928). Also notable that the substitution of (r_1, s_1)) and (r_2, s_2) parameters to the Verhulst model Eq. (3) does not describe global population data $P(t)$ in the subsequent two domains.

The above can question the ability of the Verhulst model for scaling global population growth.

The behavior presented in **Figure 3** based on the mentioned new generation data offers a higher resolution than earlier tests. It can indicate that the linear domain of $G_P(P)$ changes are relatively limited (black line in **Figure 3**). For the period reaching 10 000 BCE, the nonlinear evolution (2nd order polynomial) seems to offer better portrayal (red curve in **Figure 3**). Worth stressing problem of data presented in Figure 3 is the 'compression;' and superimposition for a colossal time domain covering 10 millennia, till ca. 500CE.

Figure 4. shows RGR evolution, presenting data from **Figure 3** in the log-log scale, two overcome the 'compression problem' mentioned above.

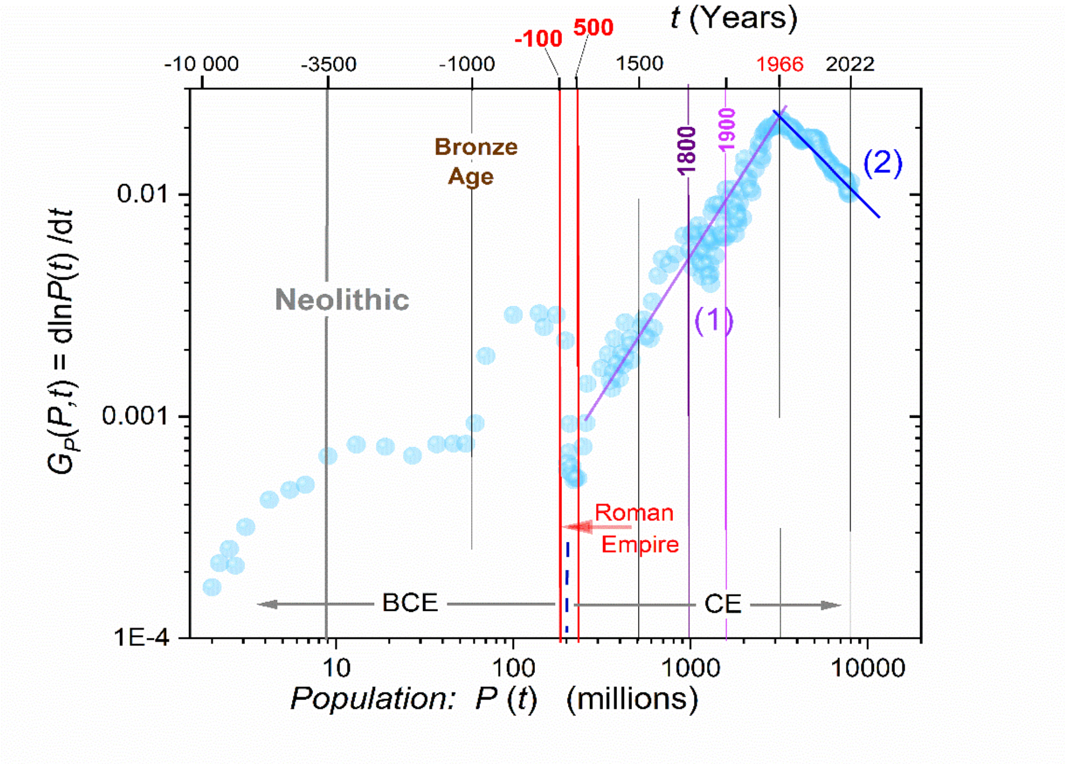

Figure 4. Relative Growth Rate (RGR) parameter changes vs. global population, for basic data from **Figure 3** presented in the log-log scale. The upper scale presents the coupled time scale. Some characteristic epochs are indicated.

The emergence of the 'complex structure' for Antiquity and Pre-Antiquity times and the grand RGR collapse for the Roman Empire times is notable. The linear portrayal of domains (1) and (2) is notably better for the log-log plot in **Figure 4** than for the reference 'direct' presentation in **Figure 3**. The extension of the fair linear behavior from the Roman Empire collapse to the crossover at ~1966 is notable.

Taking into account the definition of the 'analytic' RGR parameter (Eq. (13)) and log-log scale in **Figure 4,** one obtains the direct link to Eq. (7) associated with the empowered super Malthus S-M1 Eq. (6). Following the latter, the crossover year $t_{cross} \approx 1966$, related to the global population $P \approx 3.26$billion, can be associated with the power exponent crossover in S-M1 Eq. (6): $\beta > 1 \Rightarrow \beta < 1$.

Following general features of the empowered Super-Malthus S-M1 equation, it can suggest the transition from a world where feedback interactions between different globally relevant factors amplified the 'Global Human Energy (GHE)' to a world where this energy is dissipated. It can mean that starting from the year ~1966, the global population began to spontaneously perceive the impact of grand constraints related to reaching real planetary borders – spatial and ecological.

4. Conclusions

This report presents a resume and new conclusions related to the recent works of the authors (Sojecka and Drozd-Rzoska, 2024 and 2025) and the report by Lehman et al., (2021). Complex Soft Matter Science methodology and tools not previously used in global population research have allowed a new discussion related to a new model scaling equation associated with fundamentally defined relevant parameters. The distortions-sensitive analysis showed significant local-temporal variability of global population changes. This casts doubt on attempts to study global population change based on the assumption of the possibility of monotonic description over long time intervals. The temporal variability and locality of global population growth are related to specific exogenous and endogenous disturbances, indicating that attempts to estimate future trends for the more distant future may be unreliable.

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