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The Great Deceleration in human activities and impacts

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Abstract. Economic growth is inadvertently connected with human impacts on the environment. The currently accepted interpretation is that the intensity of human activities and impacts accelerated dramatically in the 1950s or more broadly in the second half of the 21st century. These claims are not based or a rigorous analysis of data but on impressions. The important question for human future is whether these claims are true. Distributions describing time dependence of human activities and impacts have now been mathematically analysed. Conclusions can be summarised as follows. (1) The intensity of human activities and impacts decelerated in the 1950s or more broadly in the second half of the 21st century. (2) Distributions describing time dependence of human activities and impacts cannot be used to determine the beginning of the Anthropocene because there are no suitableintensification landmarks. (3) Mathematical analysis suggests a new interpretation of the concept of the Anthropocene. Human activities and impacts did not emerge with high intensity at any specific time. They evolved gradually over a long time.
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1. Introduction

Human activities and impacts on the environment are now so strong (Steffen *et al.,* 2004; Nielsen, 2006) that they have been proposed to represent a new stage in human history and maybe even a new geological epoch (Crutzen & Stoermer, 2000). The aim of the work described here is to present results of mathematical analysis of human activities and impacts, referred to collectively as anthropogenic signatures. This analysis will be supported by data compiled by Ludwig (2014). They represent the updated data used first by Steffen *et al.,* (2004). The work reported here was motivated by the following considerations.

(1) *Never analysed.* Data used originally by Steffen *et al.,* (2004), updated by Ludwig (2014) and used again by Steffen *et al.*, (2015), play important role in discussions of the Anthropocene but they were never mathematically analysed. All conclusions and explanations are based on impressions, but impressions can be misleading. “From these considerations then it is clear that the earth does not move, and that it does not lie elsewhere than at the centre” declared Aristotle in 350 BC (Aristotle, 2012, p.14). However, what was so obviously and undeniably clear for Aristotle is now so obviously and undeniably incorrect.

(2) *New geological epoch.* Human activities and impacts, so well-illustrated by these data, are claimed to be now so strong that they are supposed to be pushing the Earth System from the Holocene to the Anthropocene (Lenton*et al.,* 2008; Steffen *et al.,* 2016). It is, therefore, essential to understand their intensity.

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(3) *Acceleration.* It is claimed that human activities and impactsaccelerated rapidly from around 1950 (Steffen *et al.,* 2004, 2011, 2015; Steffen in ABC, 2016). This acceleration was supposed to have been so prominent that it was described as a skyrocket acceleration (Steffen in ABC, 2016). It is also claimed that there was a smaller earlier acceleration described as "take-off points sometime in the twentieth century" (Steffen *et al.,* 2004, p.131). The claim of prominent accelerations and of the earlier take-off points is based entirely on a subjective and visual examination of data. The sharp increase in the 1950s in the slopes of the curves, first claimed by Steffen *et al.,* (2004) and later repeated in other publications, was never convincingly demonstrated.

(4) *Beginning.* This claimed, but not proven, acceleration from around 1950 is proposed to mark the beginning of the Anthropocene (Steffen *et al.,* 2015; Zalasiewicz*et al.,* 2012). The characteristic and fundamental feature of the Anthropocene is the apparently recent intensification in anthropogenic impacts and activities. If the intensification occurred suddenly, then the beginning of the Anthropocene can be determined. However, the intensification might have developed gradually. In such a case, the beginning of the Anthropocene cannot be determined, or at least it cannot be assigned to any recent time. Furthermore, if the beginning of the Anthropocene cannot be positively identified in recent time, this concept would have to be revised.

Some distributions describing the increasing intensity of anthropogenic signatures start in around 1950 or even later. However, this feature was causing no problem for Steffen *et al.,* (2004), who claimed a clear acceleration around the 1950s, in each presented case, even though there were no data before 1950. This feature was also causing no problem to Steffen *at al.,* (2015) who used precisely the same set of data (Ludwig, 2014) to repeat the claim of the common accelerations and even to suggest that these unproven accelerationscould be used to mark the beginning of the Anthropocene. Precisely the same data are also used or referred to regularly by members of the Anthropocene Working Group to claim accelerations in the 1950s.

Data compiled by Ludwig do not represent precisely the same set as published earlier by Steffen *et al.,* (2004) in the form of diagrams only. For instance, McDonald restaurants are not included in the new compilation and it would be for Ludwig to explain why the set she has presented is not exactly the same as the set published originally by Steffen *et al.,* (2004). However, her compilation represents virtually the same setsof data as used by Steffen *et al.,* (2004) but now extended to later years. Her compilation wasaccepted by Steffen, *et al.,* (2015) as a better representation of the original set, illustrating precisely the same processes as before and leading to precisely the same conclusions.

Out of all the data describing anthropogenic signatures, growth of population and economic growth have a special place, not only because they are described by an exceptionally wide range of data (for the growth of human population down to around 2,000,000 years ago and for the economic growth down to AD 1) but also because of their special role in the concept of the Anthropocene.

The primary driving force of anthropogenic signatures is the growth of human population. As observed by Waters *et al.,* (2016, p.aad2622-2) the "increase in the consumption of natural resources is closely linked with the growth of the human population." Correlations might not be linear but it is hardly surprising that with the gradually increasing population human activities and impacts have been also increasing.

While the primary driving force of anthropogenic activities and impacts appears to be the growth of population, their combined intensity is reflected in the economic growth, which is closely linked with such anthropogenic signatures as the production and consumption of energy, consumption of fertilizers, pollution of the atmosphere, land and water, water consumption, land degradation, loss of tropical forests, consumption of marine resources, ocean acidification, stratospheric ozone depletion, increased transportation, increased consumption of renewable and non-renewable resources, interference with nitrogen and phosphorus cycles, and more. Maybe all anthropogenic impacts and activities are embodied in the economic growth but if not all, then many of them are. Economic growth appears to reflect the combined intensity of anthropogenic impacts and activities. It is hard, maybe even impossible, to decouple economic growth from environmental impacts. Recent study of this issue resulted in the following conclusion: "It is therefore misleading to develop growth-oriented policy around the expectation that decoupling is possible" (Ward *et al.,* 2016, p. e0164733-10).

Thus, by studying economic growth, one can already get an overall information about anthropogenic activities and impacts. In particular, one can already get information about the beginning of the Anthropocene and whether there was a sudden surge in anthropogenic impacts and activities in recent years. Time-depended distributions of economic growth and of the growth of population are a rich source of information about the mechanism of the Anthropocene.

These two processes have been studied earlier (Nielsen, 2016a, 2016b, 2016c, 2016d, 2017a, 2017b) using extensive sets of data of Biraben, 1980; Birdsell, 1972; Clark, 1968; Cook, 1960; Deevey, 1960; Durand, 1974; Gallant, 1990; Hassan, 2002; Haub, 1995; Livi-Bacci, 1997; Maddison, 2010; McEvedy & Jones, 1978; Taeuber & Taeuber, 1949; Thomlinson, 1975; Trager, 1994, United Nations, 1973, 1999, 2013; US Census Bureau, 2017. Some historical data were also conveniently compiled by Manning (2008) and by US Census Bureau (2017).

Analysis of the remaining anthropogenic signatures is based on data published by the International Geosphere-Biosphere Programme (Ludwig, 2014). References to the respective individual sets of data are listed in this compilation. I have also included data for the carbon dioxide emissions from fossil fuels (EPI, 2013) to study correlation between these emissions and the atmospheric concentration of carbon dioxide.

2. Rudiments of the mathematical analysis

One of the simplest distributions related to anthropogenic signatures is hyperbolic growth. It describes, for instance, the historical growth of population and the historical economic growth (Nielsen, 2016a, 2016b, 2017a). Hyperbolic distributions are described by the following simple equation:

$$S(t) = \frac{1}{a - kt} \quad . \tag{1}$$

where $S(t)$ is the size of the growing entity, a and k are positive constants and t is the time. It is just the reciprocal of a linear function.

For a good quality data over a sufficiently large range, hyperbolic growth can be uniquely identified by the decreasing straight line representing its reciprocal values (Nielsen, 2017b):

$$\frac{1}{S(t)} = a - kt \quad , \tag{2}$$

Hyperbolic distributions escape to infinity at a fixed time when $t = a / k$, i.e. when their reciprocal values are zero.

Extended or higher-order hyperbolic growth can be described by the reciprocal of higher order polynomials.

$$S(t) = \left[\sum_{i=0}^{n>1} a_i t^i \right]^{-1} . \tag{3}$$

If restriction for n is removed, the eqn (3) includes also the first-order hyperbolic distribution described by the eqn (1).

Exponential growth is described by the following equation:

$$S(t) = ce^{rt} \tag{4}$$

where c is the normalisation constant related to the constant of integration and r is the growth rate.

For a good quality data over a sufficiently large range, exponential growth can be uniquely identified by a straight line in the semilogarithmic display because

$$\ln S(t) = \ln c + rt . \tag{5}$$

Extended or higher-order exponential growth is described by the following equation:

$$S(t) = \exp\left[\sum_{i=0}^{n>1} a_i t^i \right] . \tag{6}$$

The normalisation constant is given by a_0 .

Growth rate R is defined as

$$R = \frac{1}{S(t)} \frac{dS(t)}{dt} . \tag{7}$$

For a discrete set of values, it is calculated using the following formula:

$$R_{i+1} = \frac{1}{S_i} \frac{S_{i+1} - S_i}{t_{i+1} - t_i} . \tag{8}$$

Growth rate plays essential role in the mathematical analysis of data (Nielsen, 2017b).

Growth rate can be represented as a function of time or as a function of the size of the growing entity. If it is represented as a function of time, then there is a general solution to the relevant differential equations, which can be used to calculate mathematical distribution describing growth.

If

$$\frac{1}{S(t)} \frac{dS(t)}{dt} = f(t) , \tag{9}$$

then

$$S(t) = \exp \int f(t) dt . \tag{10}$$

If growth rate is represented as

$$f(t) = a + bt\,, \tag{11}$$

then

$$S(t) = \exp(at + 0.5bt^2 + C)\,, \tag{12}$$

where C is a constant of integration, which is determined by comparing calculated curve with data.

This expression can be presented as

$$S(t) = \exp(a_0 + a_1 t + a_2 t^2)\,. \tag{13}$$

It is a second-order exponential distribution. If $a_1 > 0$ and $a_2 > 0$, then the distribution described by eqn (13) will continue to increase indefinitely with time. In this case, the second-order exponential distribution is continually accelerating. If $a_1 > 0$ and $a_2 < 0$, then the distribution described by eqn (13) will be gradually decelerating, will reach a maximum and will start to decrease. If $a_1 < 0$ and $a_2 > 0$, then the distribution described by eqn (13) will be decreasing, will reach a minimum and will be then accelerating and increasing indefinitely with time. If $a_1 < 0$ and $a_2 < 0$, then the distribution described by eqn (13) will be continually decreasing.

Parameters a_1 and a_2 determine the shape of the distribution, while parameter a_0 is just the normalization constant, which has to be determined by comparing the calculated distribution with data.

If growth rate decreases exponentially with time, i.e. if

$$\frac{1}{S(t)}\frac{dS(t)}{dt} = ae^{bt}\,, \tag{14}$$

then (Nielsen, 2017b)

$$S(t) = C\exp\left[\frac{a}{b}e^{bt}\right]. \tag{15}$$

It is a pseudo-logistic growth because, with the increasing time, the size the growing entity increases asymptotically to the constant value C. This is one of the two types of trajectories, which describe the current growth of the world population (Nielsen, 2017b).

If growth rate depends linearly on the *size* of the growing entity, i.e. if

$$\frac{1}{S}\frac{dS}{dt} = a_0 + a_1 S\,, \tag{16}$$

and if $a_0 \neq 0$, then (Nielsen, 2017b)

$$S(t) = \left[Ce^{-a_0 t} - \frac{a_1}{a_0} \right]^{-1}, \tag{17}$$

where

$$C = \left[\frac{1}{S_0} + \frac{a_1}{a_0} \right] e^{a_0 t_0}. \tag{18}$$

If $a_0 > 0$ and $a_1 < 0$, i.e. if growth rate is decreasing linearly with the size of the growing entity, then eqn (17) describes logistic growth.

If $a_1 > 0$, then eqn (17) describes a pseudo-hyperbolic growth, which escapes to infinity at a fixed time.

If $a_0 = 0$, then eqn (16) is

$$\frac{1}{S}\frac{dS}{dt} = a_1 S \tag{19}$$

It describes the first-order hyperbolic growth and has to be solved separately. Its solution is by substitution $Z = S^{-1}$. If eqn (19) is expressed as

$$\frac{1}{S}\frac{dS}{dt} = kS, \tag{20}$$

then its solution is given by eqn (1).

If k is not constant but is assumed to depend on time, i.e. if k is replaced by $k(t)$, then eqn (20) is

$$\frac{1}{S}\frac{dS}{dt} = k(t)S, \tag{21}$$

and its solution is

$$S(t) = -\left[\int k(t) \right]^{-1}. \tag{22}$$

If $k(t)$ is represented by a polynomial, then the eqn (22) can be expressed as eqn (3).

I shall always use the simplest mathematical descriptions of growth trajectories, as described in Table 1.

Table 1. *The simplest mathematical descriptions of growth rates and the corresponding simplest growth trajectories used in the analysis of anthropogenic signatures*

Growth Rate	*Growth*	*Growth Trajectory*
$R(t)=r$	Exponential	$S(t)=ce^{rt}$
$R(t)=a_1+a_2t$	Second-order exponential	$S(t)=\exp(a_0+a_1t+a_2t^2)$
$R(S)=kS$	Hyperbolic	$S(t)=(a-kt)^{-1}$
$R(S)=a_0+a_1S$ $a_0\neq 0$, $a_1>0$	Pseudo-hyperbolic	$S(t)=\left[Ce^{-a_0t}-\frac{a_1}{a_0}\right]^{-1}$
$R(S)=a_0+a_1S$ $a_0>0$, $a_1<0$	Logistic	$S(t)=\left[Ce^{-a_0t}-\frac{a_1}{a_0}\right]^{-1}$
$R(t)=ae^{bt}$	Pseudo-logistic	$S(t)=C\exp\left[\frac{a}{b}e^{bt}\right]$

Mathematical formulae listed in Table 1 are derived by using the simplest representations of growth rates, which are in general linear. However, I have also included an exponential representation, which is also relatively simple and applies, for instance, to the recent growth of the world population (Nielsen, 2017b).

When interpreting results of mathematical analysis, it is essential to understand that decelerated trajectories should not be interpreted as decreasing trajectories. A decelerated trajectory could be still increasing and even accelerating. If a decelerated trajectory is increasing and decelerating, it is potentially sustainable but if it is accelerating it is not sustainable.

The decelerated trajectory should not be seen as a solution to the associated problems. A good example is the current growth of population. It is well-known that the growth of population is now slowing down. The trajectory has been decelerated and is decelerating but the predicted maximum of human population of 12 billion or 15.6 billion (Nielsen, 2017b) might be too high to be sustainable.

Decelerated and slower trajectories might be offering a better opportunity for solving problems but they do not give a guarantee that solutions will be found. Solutions might be achievable but not necessarily easy. Even decelerated trajectories can lead to serious developments and even to crisis as surely as the earlier accelerating trajectories.

Hyperbolic and pseudo-hyperbolic growth represent accelerating trajectories. They both escape to infinity at a fixed time. Such a growth is obviously impossible after a certain time and it will be either suddenly terminated or changed to a new trajectory. However, exponential growth is also increasing and accelerating and it is also unsustainable. Exponential growth has to be also terminated after a certain time, even though it does not increase to infinity at a fixed time.

Logistic and pseudo-logistic growth represent decelerating trajectories. They approach an asymptotic maximum and under suitable conditions they can be sustainable. However, they can be still unsustainable if the asymptotic maximum is too high.

Second-order exponential growth could be either accelerating or decelerating. Conditions have been described earlier but in practice if $a_2>0$, then the growth is accelerating and is unsustainable. If $a_2<0$ then the growth is decelerating and potentially sustainable.

The term *potentially sustainable* describes mathematical property. It describes growth, which has a potential of reaching a localised or asymptotic maximum, in contrast with other types of growth, which increase indefinitely over unrestricted range of time, such as exponential growth, or to infinity at a fixed time, such as hyperbolic growth.

A potentially sustainable growth is not necessarily sustainable. Mathematically possible maximum might never be reached. Alternatively, if a localised maximum can be reached, mathematical prediction is that the growth trajectory should start to decrease, but such a declining trajectory could be representing an unsustainable process. A good example is the marine fish capture (Figure 28), which reached a predicted maximum in 1997 and started to follow the mathematically predicted decline. The declining fish capture describes an unsustainable process. However, decreasing population could be interpreted as representing a sustainable process, but only over a certain time.

The fundamental requirement for the potentially sustainable process to be sustainable is that the predicted maximum should be sufficiently low to be sustainable. Furthermore, if the predicted localised maximum is reached, then depending on the type of the process, the predicted decline should be, if possible, closely regulated. A fast decline, or even any decline, might be undesirable.

3. Results of mathematical analysis

Results of mathematical analysis of anthropogenic signatures are shown in Figures 1-32 in the Appendix. Five of these signatures contain natural components. They are: atmospheric concentration of carbon dioxide, atmospheric concentration of nitrous oxide, atmospheric concentration of methane, hydrogen ion concentration is sea water and temperature anomaly. The remaining 19 signatures are of purely anthropogenic origin. Short description of the results of mathematical analysis is presented below.

1. *Growth of human population:*
    - Figures 1, 3 and 4.
    - Data are from AD 1.
    - Initially, hyperbolic growth (accelerating).
    - 1950 – minor but temporary boosting.
    - 1963 – deceleration and diversion to a slower and decelerating trajectory.
    - No major acceleration in the 1950s or after 1950 claimed by Steffen *et al.,* (2004, 2011, 2015) and Steffen (in ABC, 2016) but major deceleration around the same time.
    - No earlier take-off point "sometime in the twentieth century" claimed by Steffen *et al.,* (2004, p. 131).
    - No abrupt acceleration around the time of the Industrial Revolution claimed by Steffen *et al.,* (2011).
    - No distinctive landmarks that could be used to mark the beginning of the Anthropocene.
    - For the beginning of anthropogenic activities and impacts, which have led to their recent strong intensity, the phenomenon described as the Anthropocene, one has to look before the time of the Industrial Revolution, even before AD 1 and most likely to the early beginning of genus *Homo* around 2.5 million years ago (Nielsen, 2017a). It was a gradual evolution.
    - The recent fast growth of population is the natural continuation of the historical hyperbolic growth (see Figure 3). There was no sudden transition from slow to fast growth.
2. *Gross Domestic Product (GDP):*
    - Figures 2 and 5.
    - Data are from AD 1.
    - Initially, hyperbolic growth (accelerating).
    - 1950 – deceleration and diversion to a slower trajectory.
    - The new trajectory was initially decelerating but is now approaching asymptotically an accelerating exponential growth.
    - No acceleration in the 1950s but deceleration around the same time.
    - No earlier take-off point.
    - No abrupt acceleration around the time of the Industrial Revolution.

- No clear feature, which could be used to determine the recent beginning of the Anthropocene.
- For the beginning of anthropogenic activities and impacts, which have led to their recent strong intensity, one has to look well before the time of the Industrial Revolution.
- The recent fast economic growth is the natural continuation of the historical hyperbolic growth (see Figure 5). There was no sudden transition from the slow to fast growth.

3. *Income per capita (GDP/cap):*
    - Figures 6 and 7.
    - Data are from AD 1.
    - Initially, linearly-modulated hyperbolic growth (accelerating).
    - 1950 – deceleration and diversion to a slower trajectory
    - No acceleration in the 1950s but deceleration in 1950.
    - No earlier take-off point.
4. *Foreign direct investment:*
    - Data from 1970.
    - Figures 8 and 9.
    - Initially, second-order exponential growth (accelerating).
    - 2000 – deceleration and diversion to a slower pattern of growth.
    - No abrupt acceleration within this range of time.
5. *Urban population:*
    - Data from 1750.
    - Figures 10 and 11.
    - Initially, pseudo-hyperbolic growth (accelerating)
    - 1960 – deceleration and diversion to a slower and decelerating second-order exponential trajectory.
    - No acceleration in the 1950s but deceleration around the same time.
    - No earlier take-off point.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
6. *Consumption of primary energy:*
    - Data from 1750.
    - Figure 12.
    - Initially, growth hyperbolic (accelerating).
    - 1945 – deceleration and diversion to a slower and decelerating second-order exponential trajectory.
    - No acceleration in the 1950s but deceleration around the same time.
    - No earlier take-off point.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
7. *Consumption of fertilizers:*
    - Data from 1900.
    - Figure 13.
    - Initially, second-order exponential growth (accelerating).
    - 1973 – deceleration and diversion to a slower trajectory.
    - 1988 – growth reached unexpected maximum and started to decrease.
    - 1993 – growth diverted to an even slower and continually decelerating second-order exponential trajectory.
    - No acceleration in the 1950s but deceleration around the same time.
    - No earlier take-off point.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
8. *Large dams:*
    - Data from 1750.
    - Figures 15 and 16.

- Initially, growth was increasing monotonically along a second-order exponential trajectory (accelerating).
- 1965 – deceleration and diversion to a decelerating logistic trajectory.
- No acceleration in the 1950s but deceleration around the same time.
- No earlier take-off point.
- No clear feature, which could be used to determine the recent beginning of the Anthropocene.

9. *Water consumption:*
    - Data from 1901.
    - Figure 17.
    - Initially, hyperbolic growth (accelerating).
    - 1979 – deceleration and diversion to a slowly accelerating exponential growth.
    - No acceleration in the 1950s but deceleration around the same time.
    - No earlier take-off point.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
10. *Paper production:*
    - Data from 1961.
    - Figure 18.
    - Decelerating trajectory.
    - Relatively short time range but no acceleration within this range.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
11. *Transportation:*
    - Data from 1963.
    - Figure 19.
    - Decelerating trajectory.
    - Relatively short time range but no sudden acceleration within this range.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
12. *Telecommunication:*
    - Data from 1960.
    - Figure 20.
    - 2000 – deceleration and diversion to a decelerating trajectory.
    - Relatively short time range but no sudden acceleration within this range.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
13. *International tourism:*
    - Data from 1950.
    - Figure 21.
    - Decelerating trajectory
    - Relatively short time range but no sudden acceleration within this range.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
14. *Atmospheric concentration of carbon dioxide:*
    - Data from 1750.
    - Figure 22.
    - Anthropogenic and natural contributions.
    - 1750-1965 – second-order exponential growth (accelerating).
    - 1965 – acceleration and diversion to a more rapidly accelerating second-order exponential growth. This feature cannot be used to mark the beginning of the Anthropocene because it contains both natural and anthropogenic components.
15. *Carbon dioxide emissions from burning fossil fuels:*
    - Data from 1751.
    - Figure 23.
    - Decelerating trajectory. No acceleration in the 1950s.

- No earlier take-off point.
- No clear feature, which could be used to determine the recent beginning of the Anthropocene.

16. *Atmospheric concentration of nitrous oxide (N_2O):*
    - Data from 1750.
    - Figure 24.
    - Anthropogenic and natural components.
    - 1750-1850 – a decreasing, second-order exponential distribution (decelerating).
    - 1850 – growth accelerated and diverted to a continually accelerating pseudo-hyperbolic trajectory.
    - No abrupt acceleration in the 1950s but only around 1850. However, this acceleration cannot be used to mark the beginning of the Anthropocene because concentration of nitrous oxide contains natural components.
17. *Atmospheric concentration of methane (CH_4):*
    - Data from 1750.
    - Figure 25.
    - Anthropogenic and natural contributions.
    - Initially, pseudo-hyperbolic growth until 1990 (accelerating).
    - 1980 – deceleration and diversion to a slower and decelerating second-order exponential trajectory.
    - 2006 – predicted maximum.
    - No acceleration in the 1950s.
    - No earlier take-off point.
    - Currently, possible acceleration.
18. *Loss of the stratospheric ozone:*
    - Data from 1956.
    - Figure 26.
    - Initially, loss of stratospheric ozone was increasing exponentially, accelerating at the rate of 6.45% per year and doubling every 11 years.
    - 1992 – deceleration.
    - Future trajectory is hard to predict because of the combination of the poor-quality data and their short range.
    - Relatively short time range but no abrupt acceleration within this range.
19. *Ocean acidification:*
    - Data from 1850.
    - Figure 27.
    - Anthropogenic and natural contributions.
    - 1850-1965 – slowly-increasing hyperbolic trajectory (accelerating)
    - From 1965 – a faster-increasing hyperbolic trajectory (accelerating)
    - Clear sudden acceleration around 1965, which cannot be used in support of the sudden increase in the intensity of anthropogenic impacts because of the combination of natural and anthropogenic contributions to ocean acidification.
    - No earlier take-off point.
20. *Marine fish capture:*
    - Data from 1950.
    - Figure 28.
    - Decelerating trajectory.
    - 1997 – predicted maximum followed by decline.
    - Relatively short time range but no abrupt acceleration within this range.
21. *Shrimp production:*
    - Data from 1950.
    - Figure 29.
    - 1950-1990 – accelerating trajectory.
    - 1990 – deceleration and diversion to a slower exponential trajectory.
    - Relatively short time range but no abrupt acceleration within this time.
22. *Loss of tropical forests:*

- Data from 1750.
- Figure 30.
- 1750-1960 – exponential trajectory (accelerating).
- 1960 – deceleration and diversion to a much slower exponential trajectory.
- No acceleration in the 1950s but deceleration around the same time.
- No earlier take-off point.
- No clear feature, which could be used to determine the recent beginning of the Anthropocene.

23. *Agricultural land area:*
    - Data from 1750.
    - Figure 31.
    - 1750-1960 – accelerating trajectory.
    - 1960 – deceleration and diversion to a decelerating, second-order trajectory.
    - No acceleration in the 1950s but deceleration around the same time.
    - No earlier take-off point.
    - No clear feature, which could be used to determine the recent beginning of the Anthropocene.
24. *Temperature anomaly:*
    - Data from 1850.
    - Figure 32.
    - Contains natural and anthropogenic components
    - Strongly irregular
    - 1850-1909 – decreasing
    - 1909-1944 – increasing
    - 1944-1974 – decreasing
    - 1974-2007 – increasing
    - 2007-2013 – levelling off
    - Future temperature anomaly unpredictable.

4. Discussion

A striking and unexpected result of the mathematical analysis presented here and summarised in Table 2, is the common and systematic deceleration in the intensity of purely anthropogenic signatures in the second half of the 20th century, commencing from around 1950. Trajectories, which were previously accelerating, began to be diverted to slower patterns of growth. This striking phenomenon could be described as the Great Deceleration.

Mathematical analysis demonstrates consistently thatthere were no sharp accelerations claimed by Steffen *et al.,*(2004, 2011, 2015) and by Steffen (in ABC, 2016) around 1950. Using precisely the same set of anthropogenic signatures as published by Ludwig (2014), Steffen *at al.,* (2015) repeated their earlier claim of the "post-1950 acceleration in the Earth System" (Steffen *et al.,* 2015, p.81). It is remarkable that the same data show systematic decelerations at the precisely the same time when the dramatic accelerations (Steffen *et al.,* 2004, 2011, 2015) or skyrocket accelerations (Steffen in ABC, 2016) were supposed to have happened.

These diametrically different conclusions can be easily explained. Certain empirical distributions can be strongly misleading and even the most respectable scholars can make a mistake with their interpretations. The best way to interpret correctly empirical distributions is to analyse them mathematically.

Table 2.[a] *The Great Deceleration. Data demonstrate systematic decelerations in the intensity of anthropogenic signature and the absence of the earlier take-off points.*

Signature	*Data From*	*Initial*	*Recent*	*Boost*	*Decel.*	*Figures*	*Sharp Accel.*	*Take-off*
Population	AD 1	A	D	1950[b]	1963	1, 3, 4	X	X
GDP	AD 1	A	A[c]		1950	2, 5	X	X
GDP/cap	AD 1	A	A[c]		1950	6, 7	X	X
FDI	1970	A	U		2000	8, 9	(X)	ND
Urban Pop.	1750	A	D		1960	10, 11	X	X
Energy	1750	A	D		1945	12	X	X
Fertilizers	1900	A	D		1973	13, 14	X	X
Large Dams	1750	A	D		1965	15, 16	X	X
Water	1901	A	A[c,d]		1979	17	X	X
Paper	1961	D	D		1961	18	(X)	ND
Transportation	1963	D	D		1963	19	(X)	ND
Telecom.	1960	A	D	1991[b]	2000	20	(X)	ND
Tourism	1950	D	D		1950	21	(X)	ND
CO_2 from Fuels	1751	D	D		1770[g]	23	X	X
Ozone	1956	A	D		1992	26	(X)	ND
Marine Fish	1950	D	D		1950	28	(X)	ND
Shrimp Prod.	1950	A	A[c,e]		1989	29	(X)	ND
Tropical Forests	1750	A	A[c,f]		1960	30	X	X
Arable Land	1750	A	D	1850[h]	1960	31	X	X

Data From – data discussed in this publication; Initial – initial growth trajectory; Recent – recent growth trajectory; Boost – insignificant boosting; Decel. – strong deceleration; Sharp Accel. – acceleration in the 1950s claimed by Steffen *et al.,* (2004, 2011, 2015) and by Steffen (in ABC, 2016); Take-off claimed by Steffen *et al.,* (2004); GDP – Gross Domestic Product; FDI – Foreign Direct Investment; A – accelerating growth; D – decelerating growth; U – decelerated and strongly unstable growth; X – no sudden acceleration in the 1950s, claimed by Steffen *et al.,* (2004, 2011, 2015) and by Steffen (in ABC, 2016); no earlier take-off point claimed by Steffen *et al.,* (2004); (X) – no data before 1950 but no "post-1950 acceleration" claimed by Steffen *et al.,* (2015, p.81) within the range of available data; ND – no earlier data to claim (Steffen *et al.,* 2004) or to check the existence of the claimed take-off points "sometime in the twentieth century (Steffen *et al.,* 2004, p.131). [a]) – only anthropogenic signatures are listed. [b]) – minor and temporary boosting followed by a strong deceleration. [c]) – significantly slower than the initial trajectory. [d]) – slow acceleration at the rate of only 1% per year. [e]) – fast acceleration at the rate of 8.8% per year. [f]) – slow acceleration at the rate of only 0.8% per year. [g]) – emissions were constant between 1751 and 1770; [h]) –insignificant boosting of exponential growth from 0.5% to 0.8% per year followed from 1960 by strong deceleration.

It appears that Steffen knew all the time that there were no accelerations in human activities and impacts at any specific time. When informed about my intention to analyse data mathematically his response was: "My recollection was that only the population graph showed an acceleration in the mathematical sense" (Steffen, 2017). However, even population graph did not show a prominent acceleration at any specific time but only minor boosting in 1950 followed by deceleration from around 1963 (see Figure 4). This minor boosting cannot be used to mark the beginning of the Anthropocene because it was not only insignificant but also it quickly faded away and was replaced by a continuing deceleration in the growth of human population.

If there was no acceleration at any specific time, then there was obviously no transition from a slow to fast growth at any specific time. However, if there was no such transition, then it is also obvious that there is nothing in this set of anthropogenic signatures that can be used to mark the time of the transition from less intensive to more intensive human activities and impacts, and consequently nothing to determine the beginning of the Anthropocene. The sooner this simple conclusion could be accepted, the sooner progress could be made in a better understanding of the Anthropocene.

The word "acceleration" is so well known that there is no ambiguity about its meaning. It is the increase in the speed or rate that something happens. Every acceleration in empirical distributions is in the mathematical sense. To claim that it is not, would be unconvincing.

Acceleration can be monotonically continuing or sudden. There could be trajectories accelerating all the time and hyperbolic trajectories describing the historical growth of population or historical economic growth are good examples of such continually accelerating trajectories. For them, acceleration is directly proportional to the size of the growing entity. The better-known exponential growth is also continually accelerating.

For such trajectories, acceleration is occurring monotonically all the time and it is impossible to find or to claim any specific time along these trajectories to mark a clear change in the acceleration because there is no such sudden change.

Sudden acceleration is distinctly different. It marks a clear event in time when there is a change in the pattern of growth. Every time acceleration or increase is claimed at a certain specific time, it is always a sudden acceleration and it is also acceleration in the mathematical sense.

Thus, for instance, if acceleration is claimed to have occurred in the 1950s or at the time of the Industrial Revolution, it is acceleration in the mathematical sense. If a take-off is claimed sometime during the second half of the twentieth century (Steffen *et al.,* 2004), it is also acceleration in the mathematical sense. There is no other interpretation.

Sudden acceleration does not have to be followed by a continuing acceleration. It can be even followed by a continuing deceleration. However, every time an intensification of growth is claimed as having occurred at a certain specific time or within a relatively short range of time, it is acceleration in the mathematical sense and there is no way around it.

In the original publication of Steffen *et al.,* (2004), it is claimed that there was a sudden acceleration in anthropogenic activities and impacts. "*Sharp* changes in the *slopes of the curves* occur around the *1950sin each case* and illustrate how the past 50 years have been a period of *dramatic and unprecedented change* in human history" (Steffen *et al.,* 2004, p.132; italics added).

These sharp changes around the 1950s are defined explicitly as sharp accelerations on page 131 of the same book. The described accelerations are explicitly used in the mathematical sense not only because they describe increase at a certain specific time but also because they refer to a mathematical property, to sharp changes in the slopes of the curves. Many examples of the claimed accelerations in the 1950s or after 1950, in explicitly mathematical sense, can be found in the published literature. The fundamental point is that there were no such accelerations.

Results of mathematical analysis presented here do not debate the elusive and confusing concept of the Great Acceleration (Hibbard, *et al.,* 2007). Sometimes this concept is interpreted as acceleration but sometimes it is not. Even though Steffen at al. (2004) claimed accelerations around 1950, now Steffen claims that the Great Acceleration is not acceleration (Steffen, 2018). However, acceleration around 1950 for the Great Acceleration is routinely claimed.

The concept of the Great Acceleration, confusing as it may be, has no impact whatever on the conclusions based on the results of the presented here mathematical analysis that at the precisely the same time or within precisely the same range of time, when accelerations (in the mathematical sense) in the intensity of anthropogenic signatures are repeatedly claimed in the published literature, there were in fact decelerations, the phenomenon described here as the Great Deceleration (in the mathematical sense, and in the commonly understood sense).

The claim of the "increasing rates of change in human activity since the beginning of the Industrial Revolution" (Steffen *et al.,* 2011, p.851) describes also acceleration in the mathematical sense, because it was supposed to have been an increase at a certain specific range of time. This claim is now also contradicted by the mathematical analysis of data.

Industrial Revolution did not occur precisely in a certain year but over a number of years, between about 1760 and 1840 (Floud & McCloskey, 1994). In order to see a possible intensification in the empirical distributions describing human activities and impacts, it is necessary to have data going well before 1760. The majority of indicators used by Steffen *et al.,* (2004, 2011, 2015) do not extend that far in time to support their claim of the intensification caused by the Industrial Revolution. The exceptions are only data describing the growth of human population and economic growth. Analysis of these data demonstrates conclusively that Industrial Revolution had no impact on shaping growth trajectories (see Figures 3-5). The growth was monotonic without any form of disturbance, any form of acceleration, around the time of the Industrial Revolution.

There is also nothing in the data used by Steffen *et al.,* (2004, 2011, 2015) to support the claim that "Many human activities reached take-off points sometime in the twentieth century" (Steffen *et al.,* 2004, p.131). This claim is not based on a rigorous analysis of data but on impressions prompted perhaps by a desire to see such intensifications.

Intensive human activities and impacts are real. For the first time in human history, humans have profound global impacts on the environment. For the first time, humans are shaping their own future and, to a certain degree, even the future of our planet. However, there is no clear evidence that these profound global activities and impacts commenced around the time of the Industrial Revolution or in the 1950s or around any other recent specific time.

5. Further research

Evidence supporting the concept of the Great Deceleration is overwhelmingly strong. All purely anthropogenic distributions were either diverted to decelerating trajectories or they were already decelerating over the entire range of the available data. In this last group, global paper production wasdecelerating from 1961, global transportation from 1963, international tourism from 1950, global emissions of carbon dioxide from burning fossil fuels from 1770 and global marine fish capture from 1950. It would be interesting to extend this study to other data.

When looking for other examples of anthropogenic activities and impacts it is essential to understand that fast-increasing trajectories should not be automatically interpreted as accelerating trajectories. Such interpretation is, perhaps unintentionally, suggested by the unfortunate term of the "Great Acceleration" (Hibbard, *et al.,* 2007) and only through a private correspondence one can discover that the Great Acceleration is not an acceleration. However, published literature suggests that it is.

Accelerating trajectories are characterised by a positive constant or increasing growth rate. Decelerating trajectories are characterised by a decreasing growth rate. If the growth rate is positive and decreasing, then the corresponding growth trajectory will be decelerating but it will be still increasing. Depending on the value of the growth rate, it can be also increasing fast.

Mathematical analysis is essential to see whether a given trajectory is accelerating or decelerating, particularly if data are over a relatively short range of time. Furthermore, for a small range of data, it might be impossible to decide whether an accelerating trajectory is a result of an earlier deceleration. Table 2 lists a few examples of such accelerating trajectories, which resulted from an earlier deceleration. Economic growth is one of them. It was originally accelerating along a fast-increasing hyperbolic trajectory. It was deceleratingfrom around 1950 and now is accelerating again but along a significantly slower trajectory than before 1950 (Nielsen, 2015). This new accelerating trajectory is less critical than the earlier hyperbolic trajectory and it is easier to divert it to a decelerating trajectory.

Decelerating trajectories do not give a guarantee of a sustainable future but only increase its chance. On the other hand, accelerating trajectories, if continued, lead to unsustainable future. Trends can also change their characteristic features.

For instance, from around 1963, growth rate of the world population was steadily decreasing. Growth started to decelerate but the size of the world population continues to increase, and even to increase fast.Furthermore, this decelerating trajectory does not guarantee that the growth of population is going to be sustainable. The optimistically predicted maximum is around 12 billion (United Nations 2015, Nielsen, 2017b). However, a more likely outcome is an asymptotic maximum of 15.6 billion (Nielsen, 2017b). Will any of these predicted maxima be sustainable? However, growth rate is now decreasing so slowly that it might become constant. If it is going to remain constant, growth of the world population will be accelerating along an exponential trajectory and will be unsustainable, unless in due time it is going to change again to a suitably fast decelerating trajectory.

Growth rate for the growth of population in China was decreasing. Growth trajectory was decelerating but it was still increasing. However, from around 2008, growth rate started to hover around a constant value (World Bank, 2017). If this pattern is going to continue, growth of population in China will continue to be accelerating along an exponential trajectory and the growth of population will be unsustainable.

World economic growth has now settled around an accelerating exponential trajectory. Such a growth, if continued, is unsustainable. However, the currently constant growth rate might, in due time, start to decrease when, for instance, economic stress is going to reach a high level. If this is going to happen, the current accelerating trajectory will be changed to a decelerating trajectory with a prospect, but not with a guarantee, of a sustainable future.

Another issue, which could be further investigated, apart from studying other anthropogenic signatures, is to try to explain the mechanism of the Great Deceleration. There could be various contributing factors such as improved environmental management, limits of the Earth System and cross interaction between various anthropogenic activities and impacts. Each anthropogenic signature is also probably characterised by a different mechanism of growth. The distinction should be also made between potentially harmful and potentially beneficial human activities such as the increasing use of alternative sources of energy or the increasing use of electronic media, which gradually replaces paper production. All such studies could help to asses a chance of a sustainable future.

Self-regulation is not necessarily imposed by an improvement in human interaction with Nature or by the limits and boundaries of the Earth System. Even with unlimited resources, there could be still a limit to growth. For instance, world economic growth was increasing along a hyperbolic trajectory but from 1950 it started to be diverted to a slower trajectory. This deceleration did not happen because all nations in the world agreed amiably and unanimously to stop following the fast-accelerating hyperbolic trajectory and to slow down their economic activities. There was no such mutual agreement. This deceleration was also not imposed by the critical boundaries of the Earth System because economic growth continues to increase and even to accelerate. The deceleration occurred spontaneously probably because it was simply impossible to cope with such a fast-hyperbolic growth. Economic growth started to follow a decelerating trajectory but gradually its growth rate approached asymptotically a smaller constant value, which describes exponential growth (Nielsen, 2015). It is a slower growth than the previous hyperbolic growth but accelerating. It is also an unsustainable growth and it will have to be terminated either by a diversion to a slower trajectory or by a collapse. Maybe this termination will be dictated by ecological limits but maybe not. When, in due time, exponential growth is going to lead to a high-intensity production and consumption, it will be no longer supported. There is a limit to how much can be produced and consumed over a certain time and this limit does not necessarily depends on the availability of natural resources or on a decision of some kind of an international economic tribunal. However, with limitations of natural resources, limit to growth can be reached earlier. Self-regulation might be helpful but controlled regulation is likely to produce better results.

A puzzling feature revealed by the current analysis is the sudden acceleration in the atmospheric carbon dioxide concentration around 1965, which coincides with ocean acidification but is not correlated with the carbon dioxide emissions from burning fossil fuels. Reasons for this sudden acceleration are unclear.

Without a successful control of anthropogenic activities, the concept of the Anthropocene might fade into insignificance in the future. The Earth will survive without humans and so will also many life forms. They will probably even thrive without humans. However, if humans are still going to be around, they will probably worry only about how to survive rather than about debating the beginning of the Anthropocene and proving that it is a new geological epoch.

6. Conclusions

Accelerations of the anthropogenic signatures in the 1950s, claimed by Steffen *et al.,* (2004, 2011, 2015) and by Steffen (in ABC, 2016), never happened. There were also no "take-off points sometime in the twentieth century" claimed by Steffen *et al.,*(2004, p.131) and no acceleration at the time of the Industrial Revolution claimed by Steffen *et al.,* (2011). There is nothing in the studied here anthropogenic signatures that can be used to determine the beginning of the Anthropocene. It is also interesting that at the precisely the same time when the massive and dramatic acceleration is repeatedly claimed, i.e. in the 1950s, there was in fact massive deceleration in the intensity of human activities and impacts described here as the Great Deceleration. The Great Acceleration cannot be used to mark the beginning of the Anthropocene because the beginning of the Anthropocene is supposed to be characterised by a transition from weak to strong anthropogenic activities and impacts, not from strong to weak.

Results of mathematical analysis presented here suggest a new interpretation of the Anthropocene. It is not a phenomenon that emerged at a certain recent time but a phenomenon that have been evolving over a long time until gradually and monotonically reached its strong intensity in recent years. Human activities and impacts were increasing in concert with the growth of human population and they are reflected in the economic growth. In order to understand the evolution of these activities and impacts, and consequently, in order to understand the Anthropocene, it is essential to understand the growth of human population and the economic growth in the past 2,000,000 years (Nielsen, 2017a). This issue will be discussed in a forthcoming publication.

Acknowledgements

I want to thank Cornelia Ludwig for making her compilation of data available on the website of the International Geosphere-Biosphere Programme. Without them, my analysis would have been much more difficult.

I also want to thank Will Steffen and his colleagues, for preparing their impressive and important set of diagrams and for publishing them in 2004. Without these diagrams there would probably be no compilation of data illustrating anthropogenic signatures and no discovery of the Great Deceleration.

I want to thank Paul Crutzen for checking and endorsing results of this study. I am grateful to Matt Edgeworth for his most helpful constructive criticism. Using his suggestions, I was able to reduce the potential misinterpretations of my discussion and to improve significantly the presentation of results of my study. Correspondence with Will Steffen and his feedback was also most helpful.

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Appendix

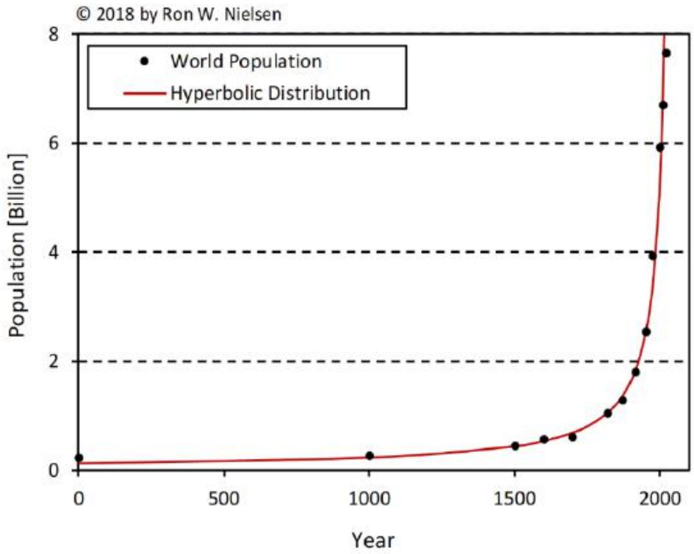

Figure 1. *Growth of human population. Data describing growth of the world population (Maddison, 2010) follow closely monotonically increasing hyperbolic distribution defined by parameters* $a = 8.724 \times 10^{0}$ *and* $k = 4.267 \times 10^{-3}$ *. Growth of population was not exponential, as expected by Malthus (1798) but hyperbolic. There was no abrupt acceleration in the 1950s or around any recent time, no sudden intensification, which could be used to determine the beginning of the Anthropocene. There was also no earlier take-off point.*

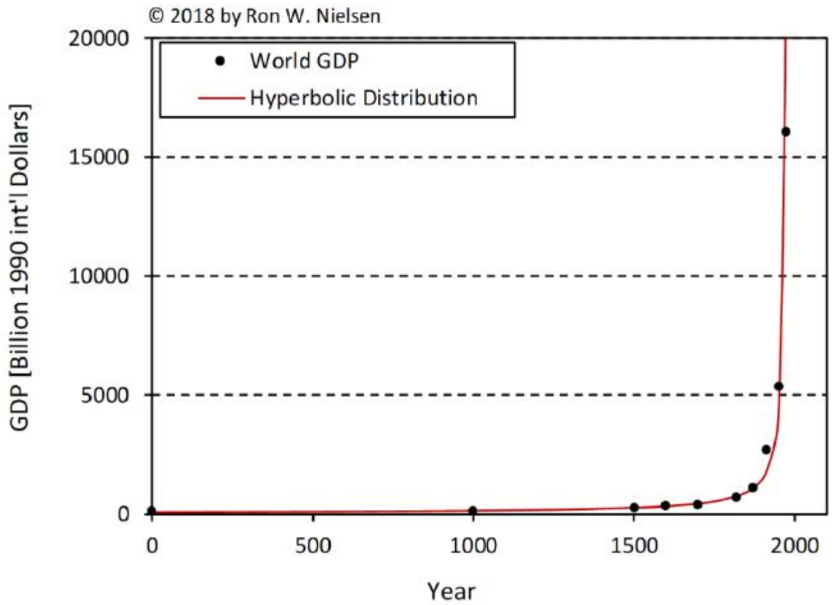

Figure 2. *Economic growth. Data describing growth of the world Gross Domestic Product (GDP) (Maddison, 2010), expressed in billions of 1990 international Geary-Khamis dollars, are compared with the monotonically increasing hyperbolic distribution (* $a = 1.716 \times 10^{-2}$ *and* $k = 8.671 \times 10^{-6}$ *). There was no abrupt acceleration in the 1950s and no earlier take-off point.*

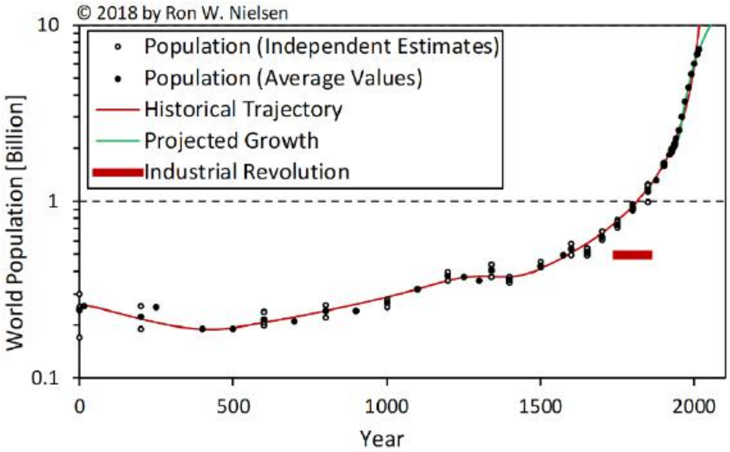

Figure 3. *Growth of the world population (Nielsen, 2016b, 2017a) during the AD time. Data from a complete set are used (see text). Calculated trajectory accounts for the major transition between two hyperbolic trajectories (425 BC – AD 510) and for a minor disturbance of the hyperbolic growth, which occurred between AD 1195 and AD 1470. Parameters describing these calculations are listed in the earlier publications (Nielsen, 2016b, 2017a). Industrial Revolution had no impact on the growth trajectory. The rate of growth did not begin to rise above the previous level around the time of the Industrial Revolution, as claimed by Steffen et al., (2011). There was no abrupt acceleration in the 1950s claimed by Steffen et al. (2004,2011, 2015) and by Steffen (in ABC, 2016) or around any recent time, no sudden intensification, which could be used to determine the beginning of the Anthropocene. There was also no earlier take-off "sometimes in the twentieth century" (Steffen et al., 2004, p. 131). The perceived sudden increase seen in Figure 1 is just the natural continuation of the monotonically increasing hyperbolic growth.*

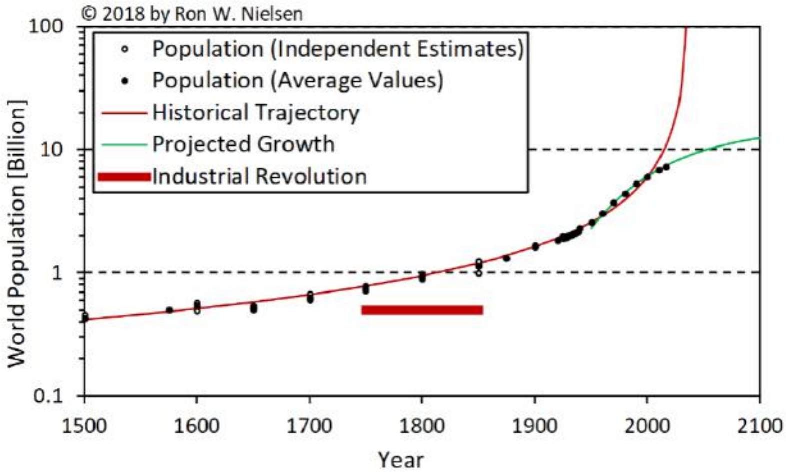

Figure 4. *Magnified section of the growth of population presented in Figure 3. Now it can be seen more clearly that what might have appeared as a sudden population explosion in Figure 1, is just the natural continuation of the monotonic growth. From 1500 to 1950 – monotonically increasing hyperbolic growth. Around 1950 – minor boosting. Around 1963 – deceleration. Industrial Revolution had no impact on the growth trajectory. The rate of growth did not begin to rise above the previous level around the time of the Industrial Revolution, as claimed by Steffen et al. (2011). There was no major sudden acceleration claimed in the 1950s (Steffen et al., 2004, 2011, 2011; Steffen in ABC, 2016) but only a minor and temporary boosting. There is nothing in the data that can be used to mark the beginning of the Anthropocene.*

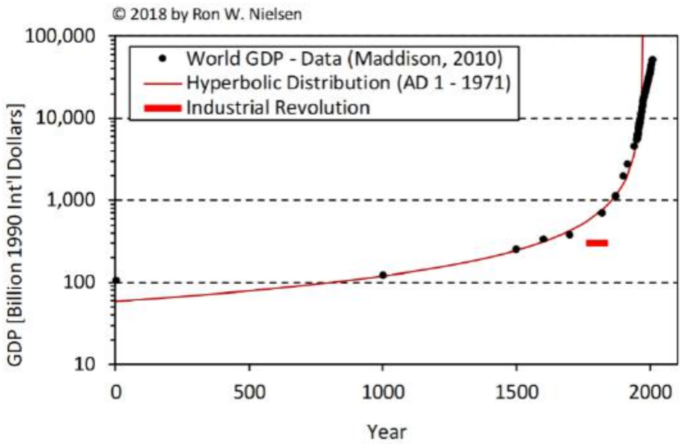

Figure 5. *Data for the world Gross Domestic Product (GDP) between AD 1 and 2008 (Maddison, 2010), expressed in billions of 1990 international Geary-Khamis dollars, are compared with the monotonically increasing hyperbolic distribution. Between AD 1000 and 1950 – monotonically increasing hyperbolic growth. Around 1950 – deceleration and diversion to a slower trajectory. Industrial Revolution had no impact on shaping economic growth trajectory, even in Western Europe and even in the United Kingdom (Nielsen, 2016a, 2016d). The rate of growth did not begin to rise above the previous level around the time of the Industrial Revolution, as claimed by Steffen et al. (2011). There was no sudden acceleration around 1950 or around any other time, no sudden intensification, which could be used to determine the beginning of the Anthropocene. On the contrary, from 1950 economic growth started to follow a slower trajectory. There was also no earlier take-off point.*

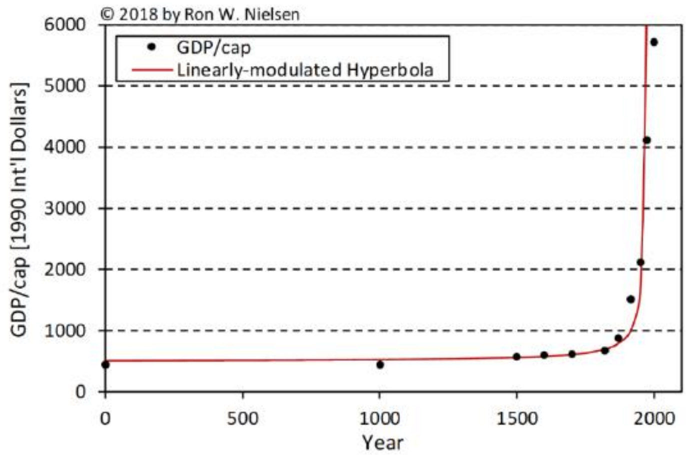

Figure 6. *Distribution describing income per capita (GDP/cap) obtained by dividing distributions shown in Figures 1 and 2. The best fit to the data is represented by a monotonically increasing linearly-modulated hyperbolic distribution (Nielsen, 2017c). This distribution is even more deceptive than hyperbolic distribution shown in Figures 1 and 2. Income per capita was approximately constant in the past but most recently it was fast increasing. However, there was no sudden transition from the slow to fast growth. The perceived sudden increase is an illusion created by the strongly deceptive hyperbolic-like distribution. Growth was increasing monotonically all the time. There is no mathematically determinable beginning of the fast increase, no sudden change in the slope of the curve describing the growth of income per capita.*

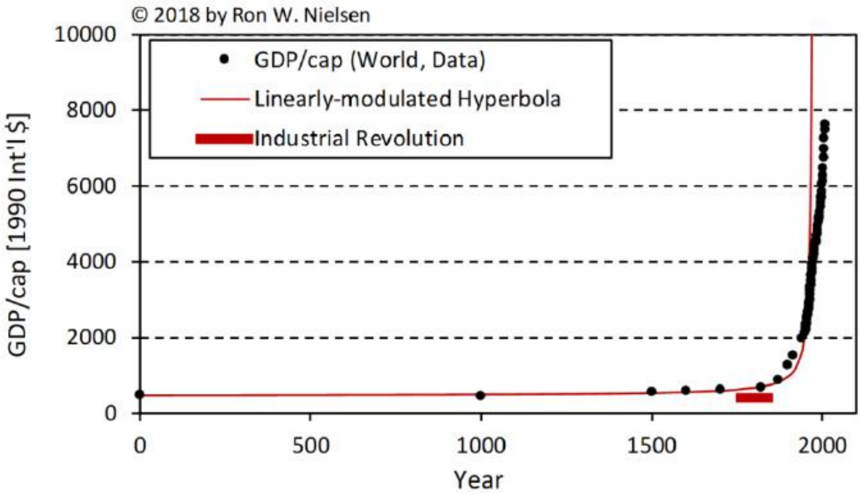

Figure 7. *Extended data describing growth of income per capita (GDP/cap) (Maddison, 2010) are compared with the linearly-modulated hyperbolic distribution (Nielsen, 2017c). From AD 1 to 1950 – monotonically increasing linearly modulated hyperbolic growth. Around 1950 – deceleration and diversion to a slower trajectory. Growth was not accelerated around 1950.*

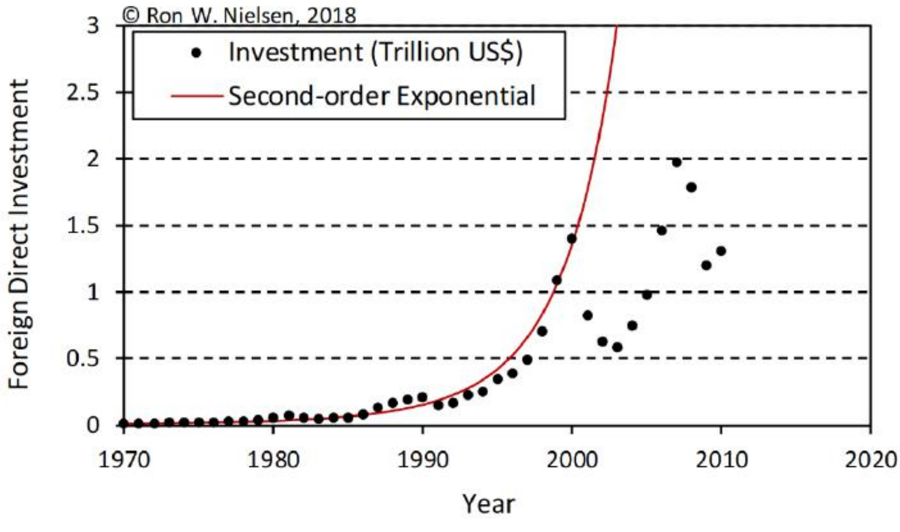

Figure 8. *Global foreign direct investment (FDI) in trillions of the current US$. 1970-2000 – second-order exponential growth (* $a_0 = 1.380\times10^4$ *,* $a_1 = -1.405\times10^1$ *and* $a_2 = 3.575\times10^{-3}$ *). 2000 – deceleration. There was no acceleration in the 1950s.*

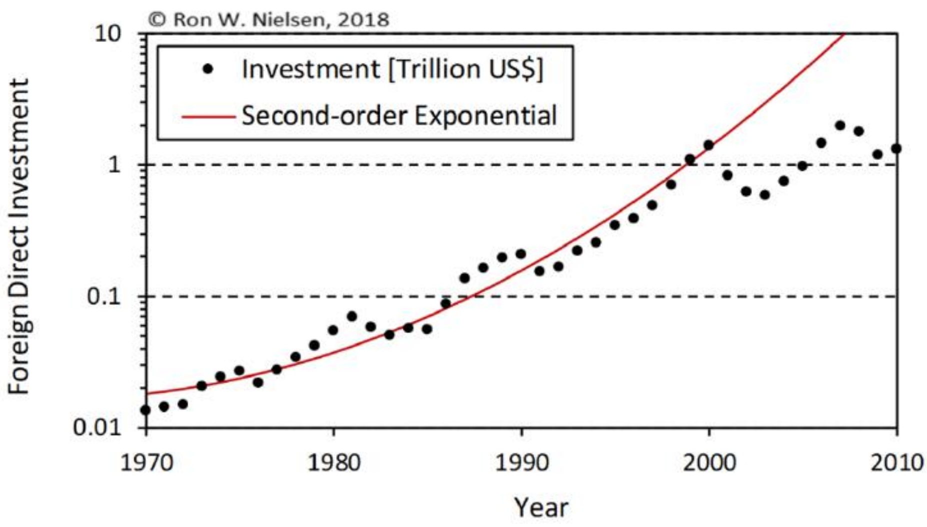

Figure 9. *Global foreign direct investment displayed using semilogarithmic scales of reference, showing more clearly that growth was oscillating around a monotonically increasing trajectory and that from around 2000 it started to follow a generally slower pattern of growth.*

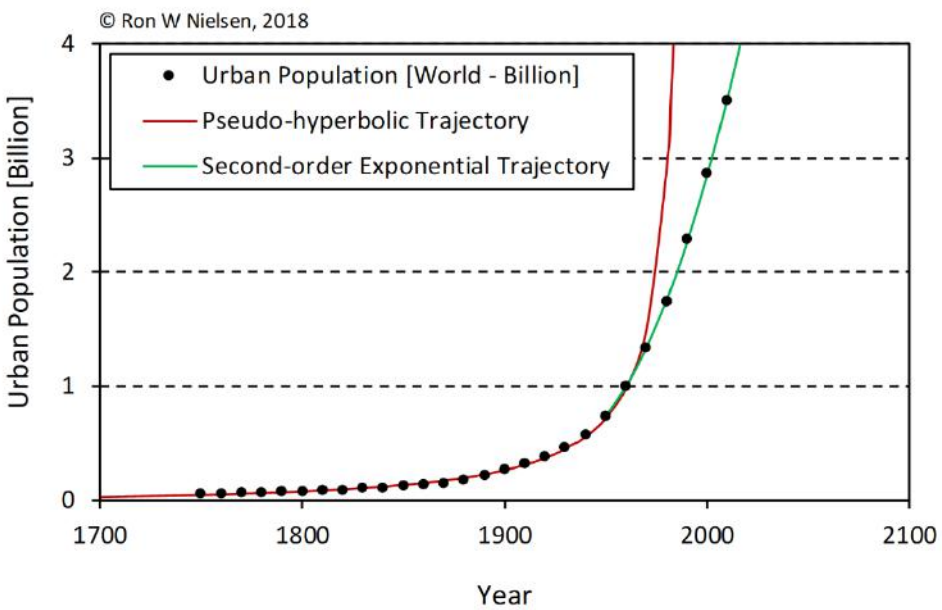

Figure 10. *Growth of urban population. 1750-1960 – pseudo-hyperbolic trajectory described by parameters* $C = 1.536\times10^{7}$, $a_1 = 7.658\times10^{-3}$ *and* $a_2 = 2.798\times10^{-2}$. *Around 1960 – deceleration and diversion to a slower, second-order exponential trajectory described by parameters* $a_0 = -4.345\times10^{2}$ $a_1 = 4.133\times10^{-1}$ *and* $a_2 = -9.776\times10^{-5}$ *There was no sudden acceleration in the 1950s but deceleration. There was also no earlier take-off point.*

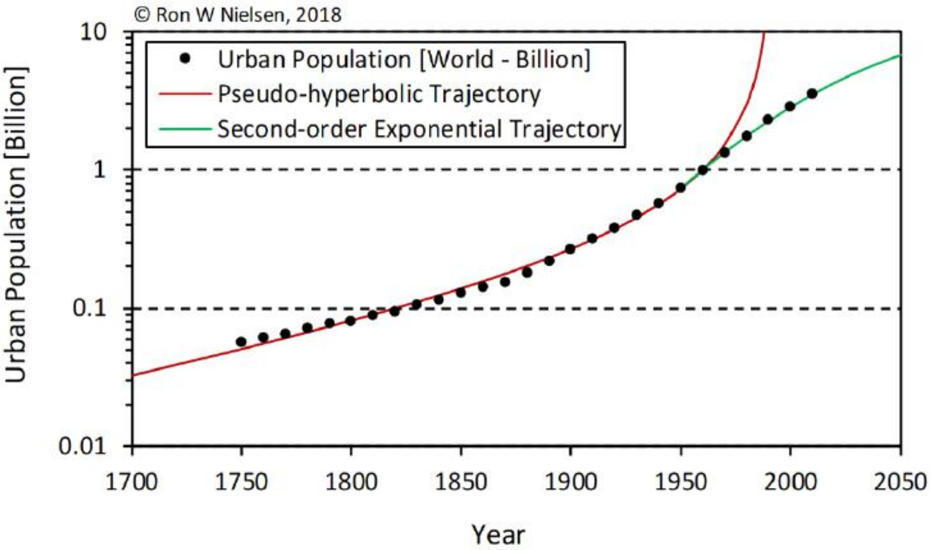

Figure 11. *Semilogarithmic display of the growth of global urban population showing even more clearly the monotonic growth until 1960 and deceleration around that year.*

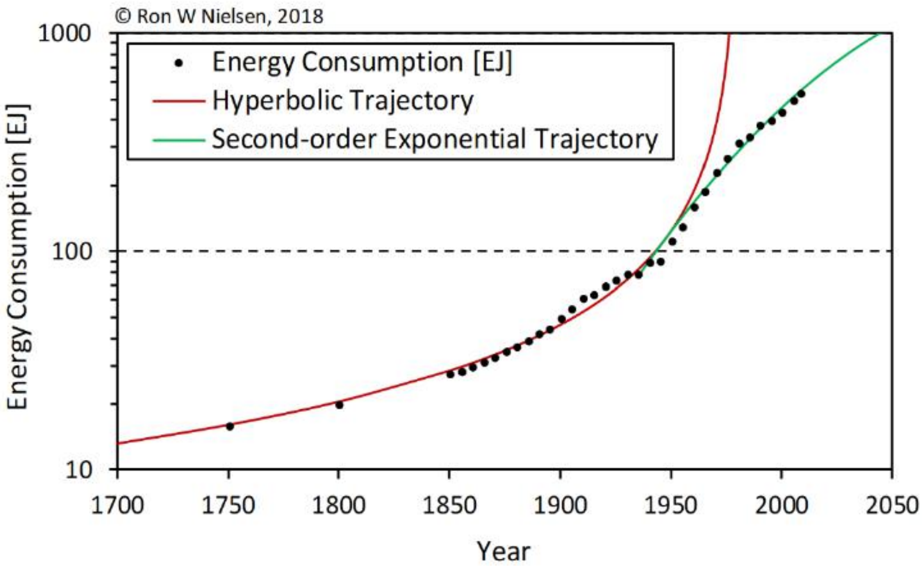

Figure 12. *Global consumption of primary energy in exajoules [EJ]. 1750-1950 – hyperbolic growth(* $a = 5.356 \times 10^{-1}$ *and* $k = 2.705 \times 10^{-4}$ *). 1945 – deceleration and diversion to a slower, second-order exponential trajectory (* $a_0 = -3.955 \times 10^{2}$ *,* $a_1 = 3.799 \times 10^{-1}$ *and* $a_2 = -8.954 \times 10^{-5}$ *). There was no acceleration in the 1950s but deceleration in 1950. There was also no earlier take-off point.*

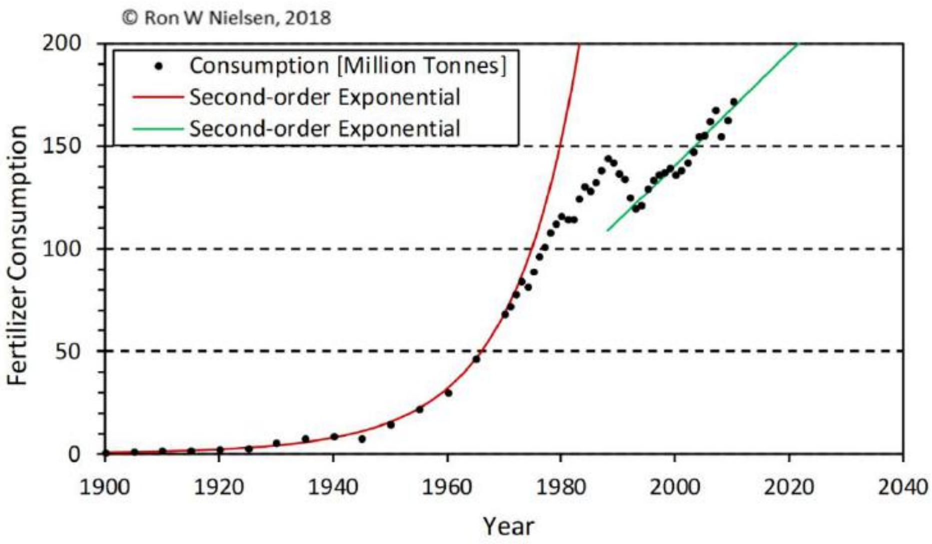

Figure 13. *Global consumption of fertilizers (in million tonnes). 1900-1973 - second-order exponential trajectory (* $a_0 = 7.788 \times 10^2$ *,* $a_1 = -8.646 \times 10^{-1}$ *and* $a_2 = 2.393 \times 10^{-4}$ *). 1973 – deceleration and diversion to a slower trajectory. 1988 – maximum. 1988-1993 – decreasing trajectory. 1993-2010 – even slower and decelerating second-order exponential trajectory (* $a_0 = -6.341 \times 10^2$ $a_1 = 6.195 \times 10^{-1}$ *and* $a_2 = -1.500 \times 10^{-4}$ *). There was no acceleration in the 1950s and no earlier take-off point.*

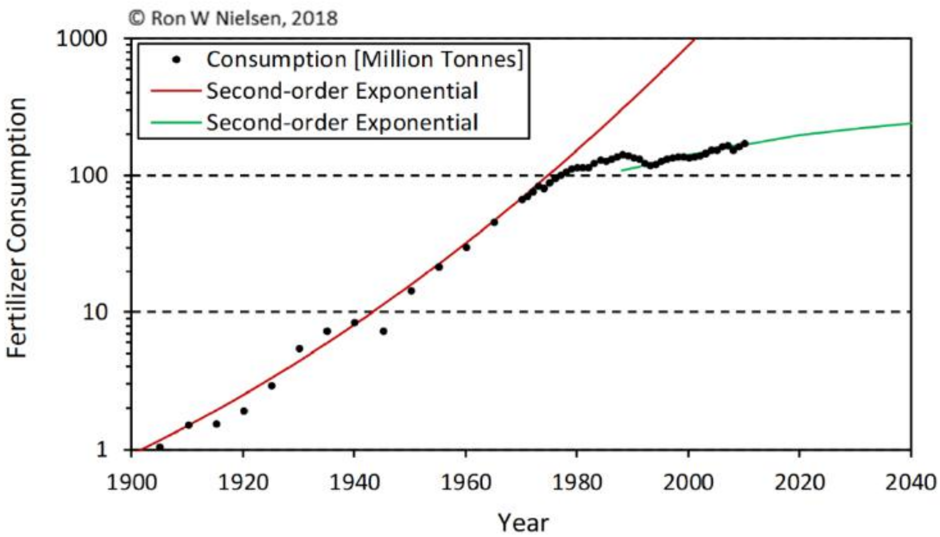

Figure 14. *Global consumption of fertilizers (in million tonnes) is shown here using semilogarithmic scales of reference. This diagram shows even better that there was no acceleration in the 1950s and no earlier take-off point.*

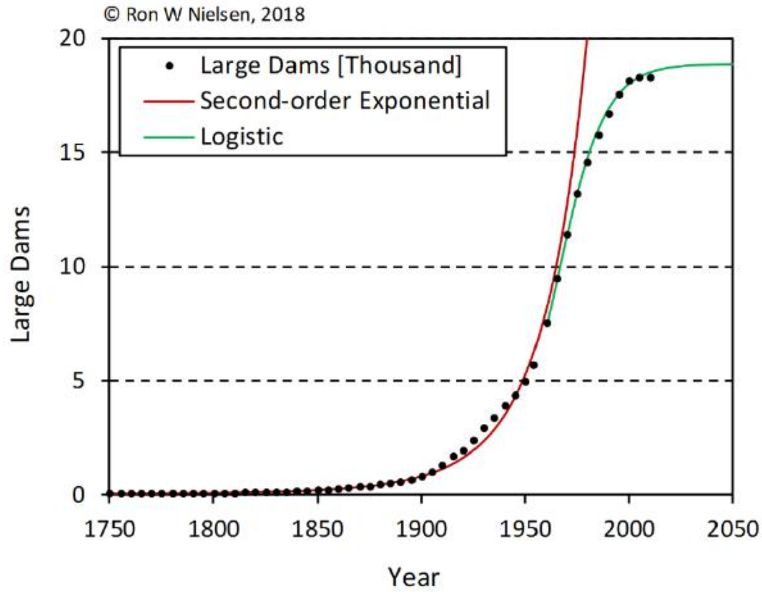

Figure 15. *Global number of existing large dams, in thousands. 1750-1965 – second-order exponential trajectory ($a_0 = 2.734\times10^{2}$, $a_1 = -3.208\times10^{-1}$ and $a_2 = 9.305\times10^{-5}$). 1965 – deceleration and diversion to a slower, logistic trajectory ($C = 7.642\times10^{72}$, $a_0 = 8.689\times10^{-2}$ and $a_1 = -4.599\times10^{-3}$). There was no acceleration in the 1950 but deceleration and there was no earlier take-off point.*

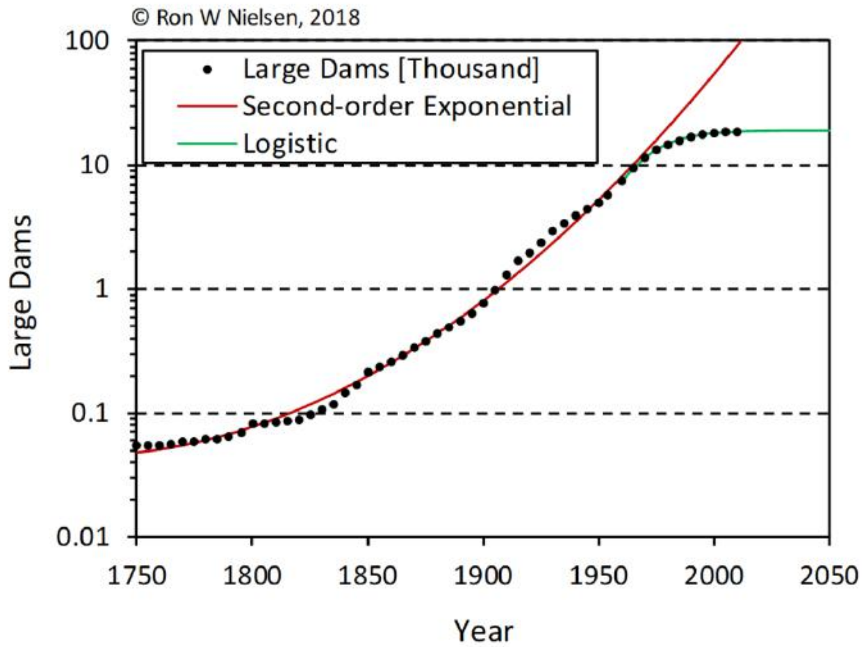

Figure 16. *Global number of existing large dams in thousands displayed here by using semilogarithmic scales of reference. This diagram shows even better that there was no acceleration in the 1950s, but deceleration, and no earlier take-off point.*

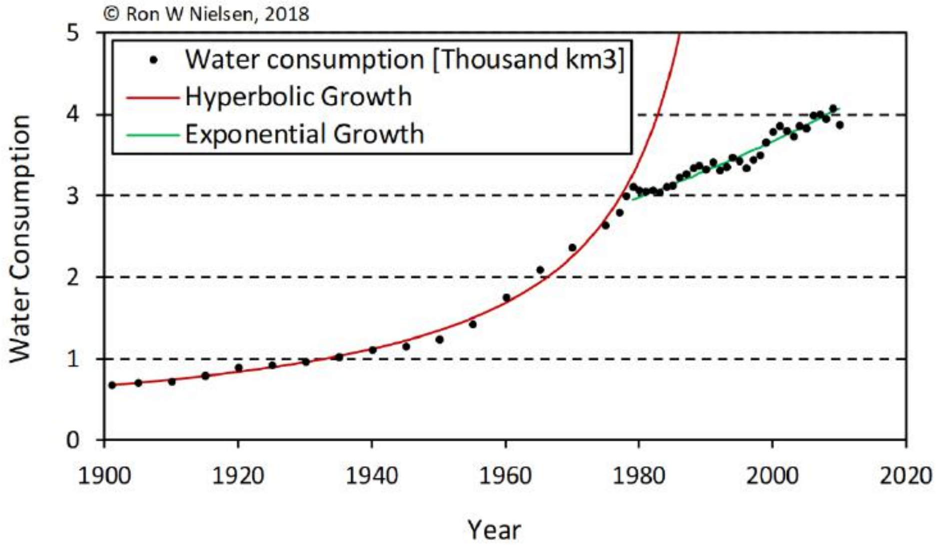

Figure 17. *Global consumption of water, in cubic kilometres. 1901-1979 – hyperbolic growth(* $a = 3.025 \times 10^{1}$ *and* $k = 1.513 \times 10^{-2}$ *). 1979 – deceleration and diversion to a slower, exponential trajectory (* $c = 3.310 \times 10^{-9}$ *,* $r = 1.041 \times 10^{-2}$ *). There was no acceleration in the 1950sand no earlier take-off point.*

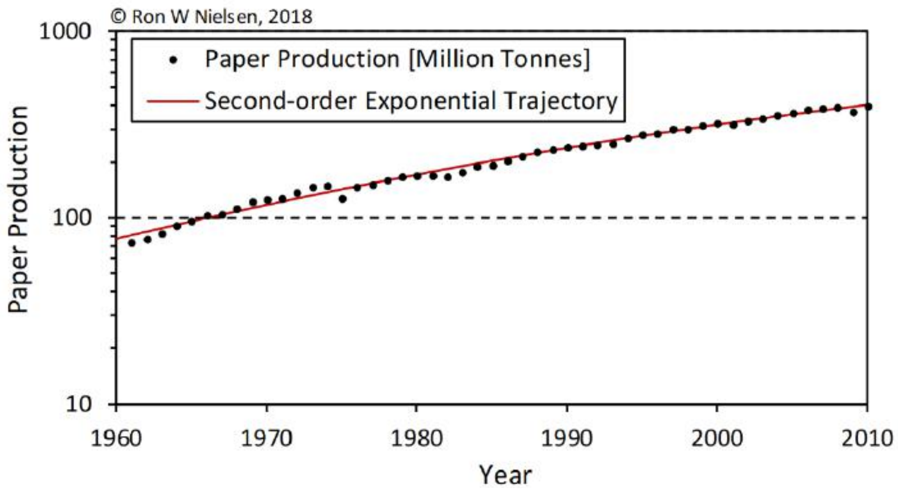

Figure 18. *Paper production. 1961-2010 – gradually decelerating, second-order, exponential trajectory (* $a_0 = -9.279 \times 10^{2}$ *,* $a_1 = 9.072 \times 10^{-1}$ *,* $a_2 = -2.202 \times 10^{-4}$ *). There was no sudden acceleration within this range of time.*

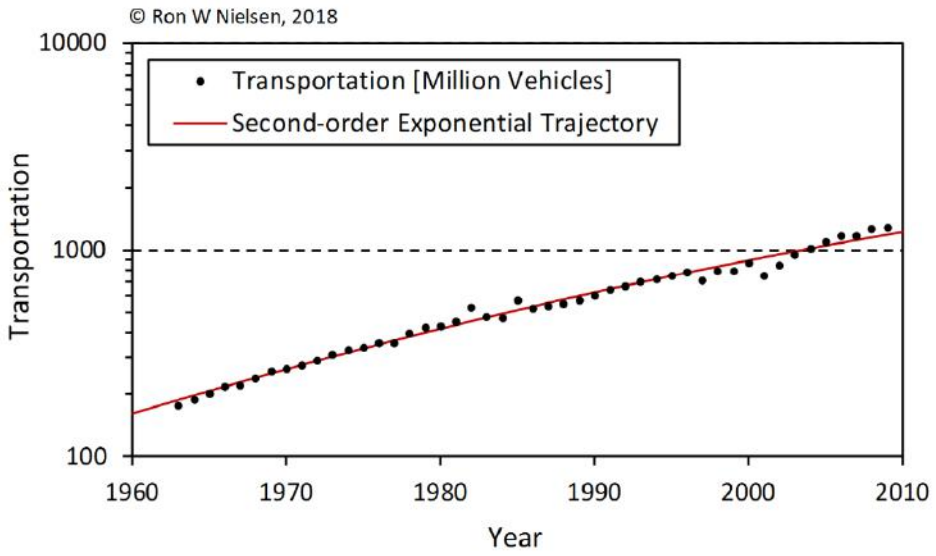

Figure 19. *Global transportation. 1963-2010 – gradually decelerating second-order exponential trajectory (* $a_0 = -9.279 \times 10^2$ *,* $a_1 = 9.072 \times 10^{-1}$ *and* $a_2 = -2.202 \times 10^{-4}$ *). There was no sudden acceleration within this range of time.*

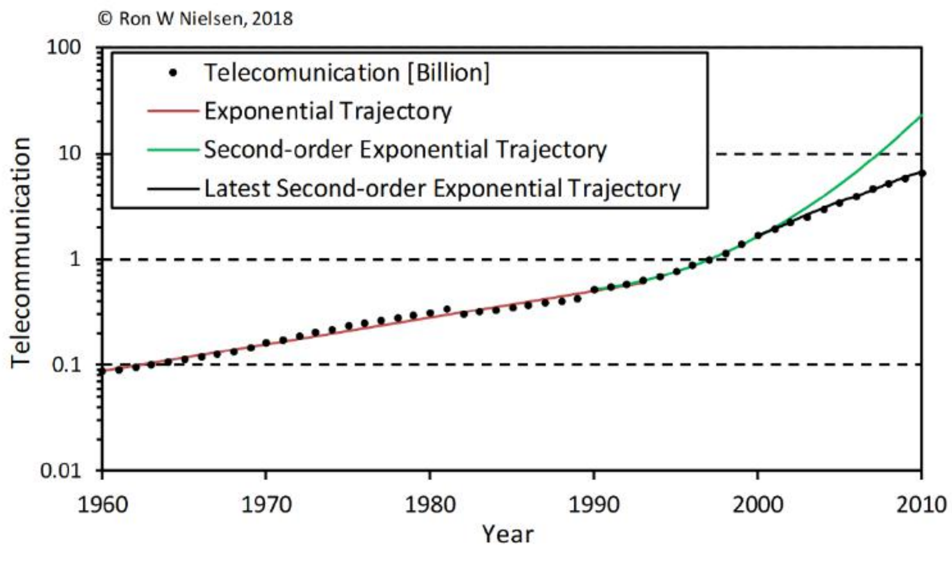

Figure 20. *Global telecommunication (billions of landlines and subscriptions). 1960-1991 – exponential growth (* $c = 3.944 \times 10^{-51}$ *,* $r = 5.798 \times 10^{-2}$ *). 1991-2000 – second-order, exponential trajectory (* $a_0 = 2.945 \times 10^4$ *,* $a_1 = -2.964 \times 10^1$ *and* $a_2 = 7.457 \times 10^{-3}$ *). 2000 – deceleration and diversion to a slower, second-order exponential trajectory described by parameters* $a_0 = -4.771 \times 10^3$ *,* $a_1 = 4.622 \times 10^0$ *and* $a_2 = -1.118 \times 10^{-3}$ *. There was no prominent sudden acceleration within this range of time but deceleration in 2000.*

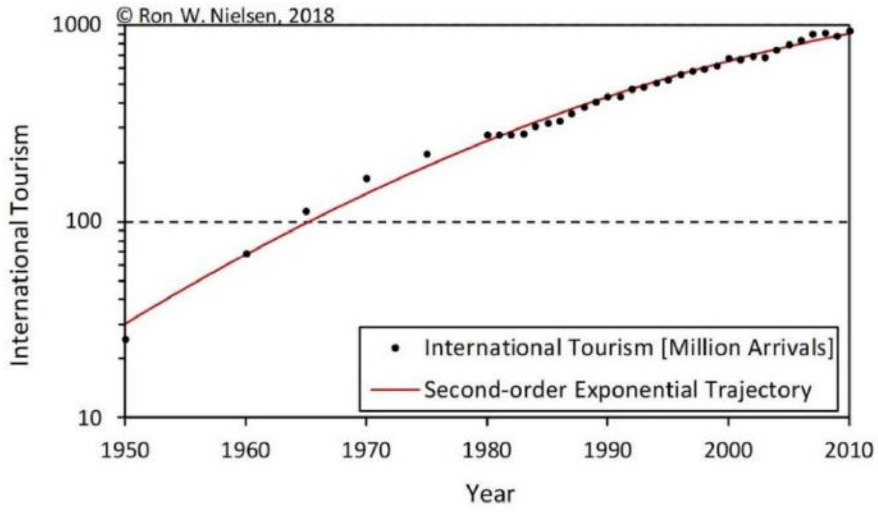

Figure 21. *Global international tourism. 1950-2010 – a decelerating, second-order exponential trajectory (* $a_0 = 2.060 \times 10^3$ *,* $a_1 = 2.030 \times 10^0$ *,* $a_2 = -4.982 \times 10^{-4}$ *). There was no sudden increase within this range of time.*

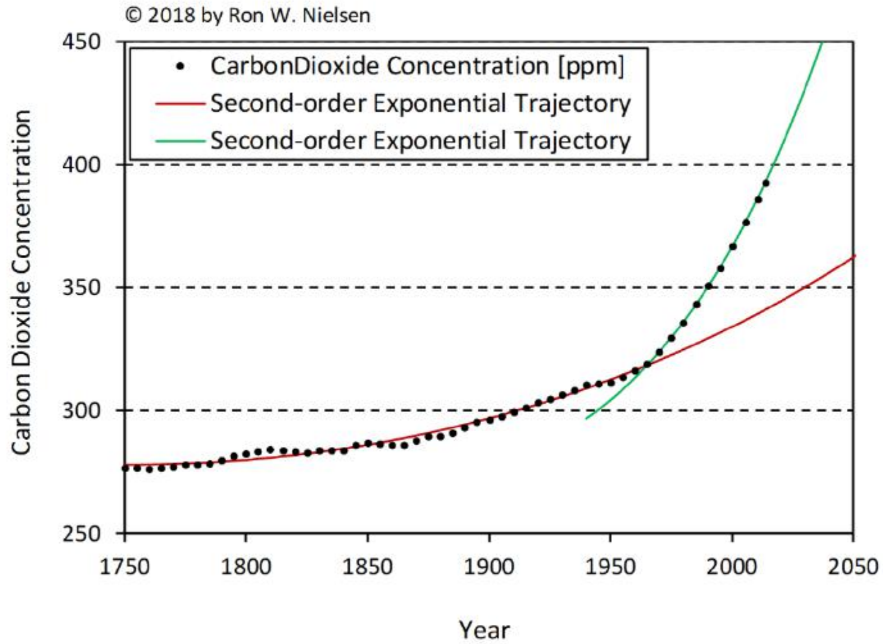

Figure 22. *Atmospheric concentration of carbon dioxide. 1750-1965 – second-order exponential trajectory (* $a_0 = 1.481 \times 10^1$ *,* $a_1 = -1.048 \times 10^{-2}$ *,* $a_2 = 2.991 \times 10^{-6}$ *). Around 1965 – acceleration and diversion to a faster second-order exponential trajectory described by parameters* $a_0 = 7.835 \times 10^1$ *,* $a_1 = -7.721 \times 10^{-2}$ *and* $a_2 = 2.049 \times 10^{-5}$ *. This is a good example of a signature, which shows sudden acceleration in the 1950s, the type of accelerations claimed by Steffen et al. (2004, 2011, 2015) and be Steffen (in ABC, 2016). Unfortunately, this example cannot be used in support of their claim of a sudden acceleration in anthropogenic signature because atmospheric concentration of carbon dioxide is made not only of anthropogenic but also of natural components.*

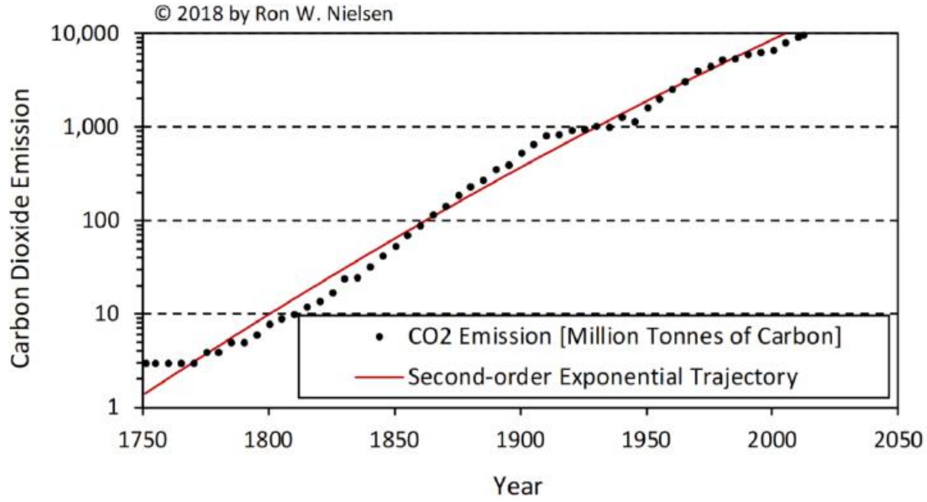

Figure 23. *Global emission of carbon dioxide from burning fossil fuels (EPI, 2013). 1770-2010 – growth oscillates around a gradually decelerating second-order exponential trajectory (* $a_0 = -1.432 \times 10^{2}$ *,* $a_1 = 1.230 \times 10^{-1}$ *,* $a_2 = -2.346 \times 10^{-5}$ *). This distribution shows that the sudden acceleration in the atmospheric carbon dioxide concentration around 1965 cannot be explained by the carbon dioxide emissions from burning fossil fuels.*

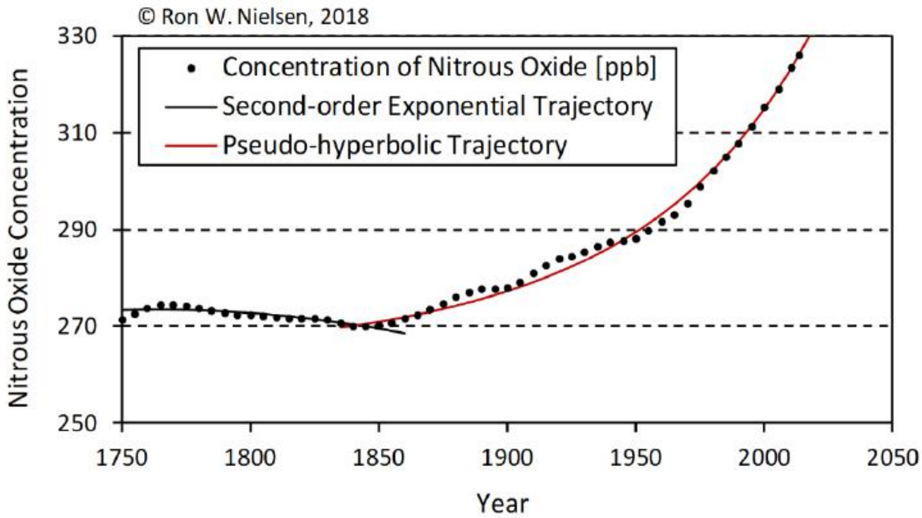

Figure 24. *Atmospheric concentration of nitrous oxide (N_2O), expressed in parts per billion [ppb]. 1750-1850 – second-order exponential trajectory (* $a_0 = -4.727 \times 10^{-1}$ *,* $a_1 = 6.898 \times 10^{-3}$ *,* $a_2 = -1.956 \times 10^{-6}$ *). 1850 – acceleration and diversion to a pseudo-hyperbolic trajectory (* $C = -2.406 \times 10^{-14}$ *,* $a_0 = -1.198 \times 10^{-2}$ *,* $a_1 = 4.546 \times 10^{-5}$ *). Nitrous oxide concentration is also made of natural and anthropogenic components.*

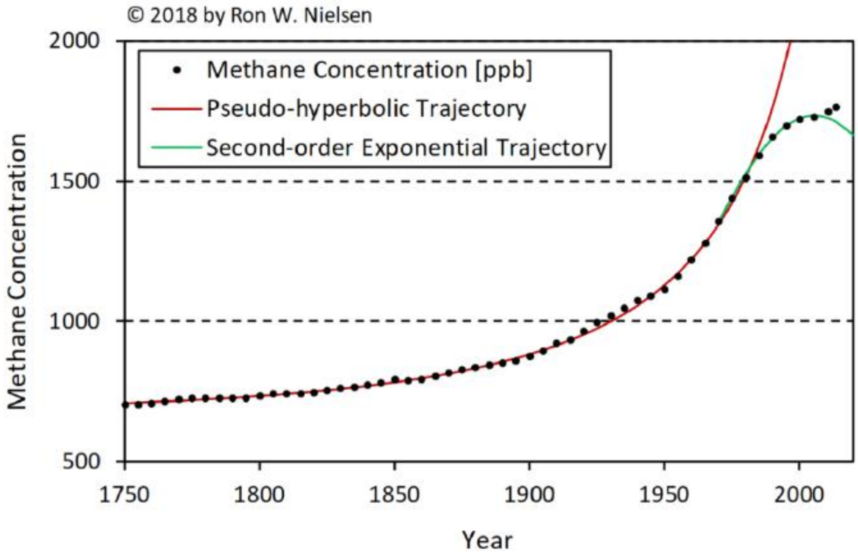

Figure 25. *Atmospheric concentration of methane (CH_4) in parts per billion [ppb]. 1750-1980 – pseudo-hyperbolic trajectory (*$C = -5.007 \times 10^{-13}$*,* $a_0 = -1.072 \times 10^{-2}$ *and* $a_1 = 1.587 \times 10^{-5}$ *). 1980 – deceleration and diversion to a slower, second-order exponential trajectory (*$a_0 = -7.863 \times 10^{2}$*,* $a_1 = 7.915 \times 10^{-1}$ *,* $a_2 = -1.973 \times 10^{-4}$ *). Around 2006 – predicted maximum. There is a sign of a renewed increase. Methane emissions are made of natural and anthropogenic components.*

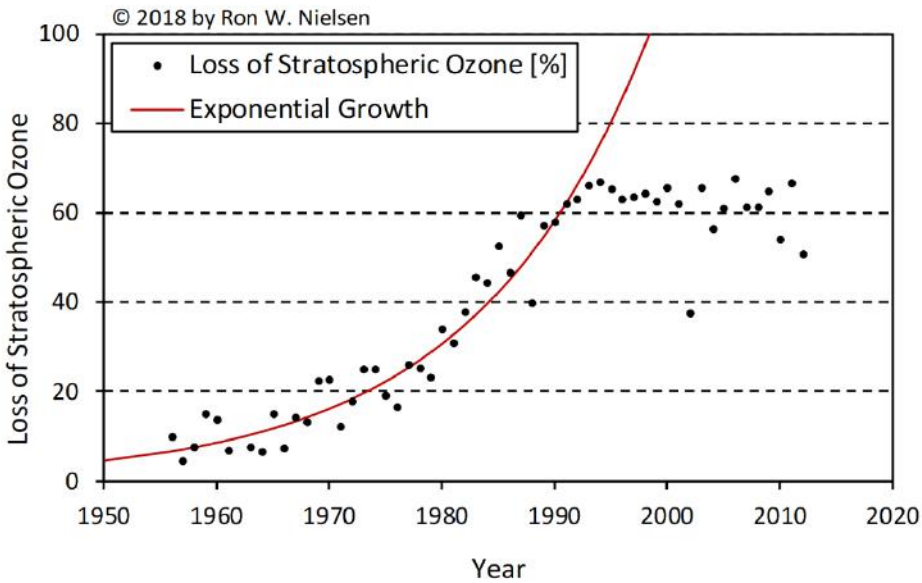

Figure 26. *Loss of stratospheric ozone. 1956-1992 – exponential increase described by parameters* $c = 1.139 \times 10^{-54}$ *and* $r = 6.446 \times 10^{-2}$ *). 1992 – deceleration and diversion to a slower and possibly decreasing trajectory.*

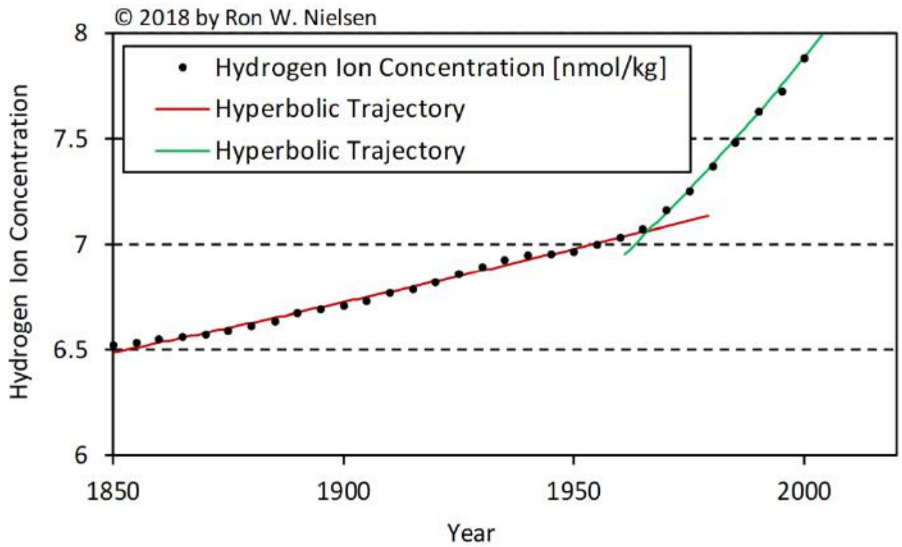

Figure 27. *Ocean acidification, described by the concentration of hydrogen ions (H^+) in nmol/kg. 1850-1965 – hyperbolic trajectory ($a = 3.553 \times 10^{-1}$ and $k = 1.087 \times 10^{-4}$). Around1965 – acceleration and diversion to a faster hyperbolic trajectory ($a = 9.975 \times 10^{-1}$, $k = 4.353 \times 10^{-4}$). Ocean acidification is made of natural and anthropogenic contributions.*

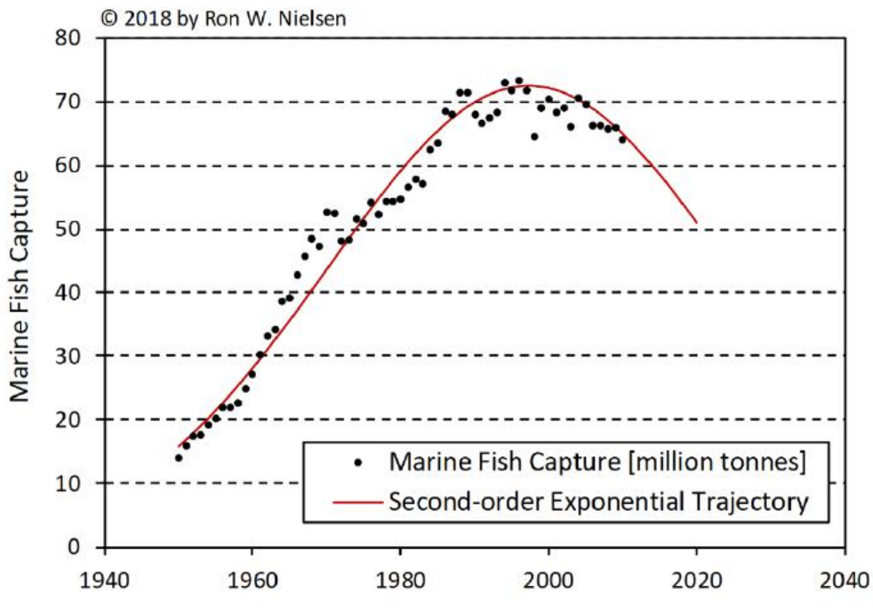

Figure 28. *Global marine fish capture (in million tonnes per year). 1950-2010 – second-order exponential trajectory ($a_0 = -2.714 \times 10^{3}$, $a_1 = 2.722 \times 10^{0}$, $a_2 = -6.814 \times 10^{-4}$). 1997 – predicted maximum and decline. There was no sudden acceleration within this range of time.*

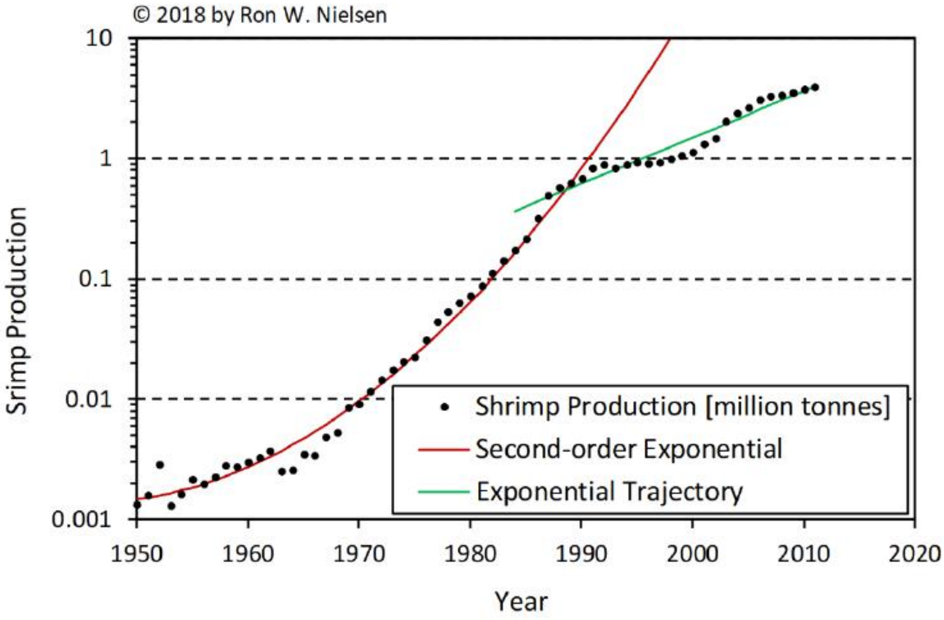

Figure 29. *Global shrimp production by aquaculture (in million tonnes). 1950-1989 – second-order exponential trajectory (* $a_0 = 1.220 \times 10^4$ *,* $a_1 = -1.255 \times 10^1$ *and* $a_2 = 3.226 \times 10^{-3}$ *). 1989 – deceleration and diversion to a slower, exponential trajectory (* $c = 5.718 \times 10^{-77}$ *,* $r = 8.798 \times 10^{-2}$ *). There was no sudden acceleration within this range of time but only sudden deceleration.*

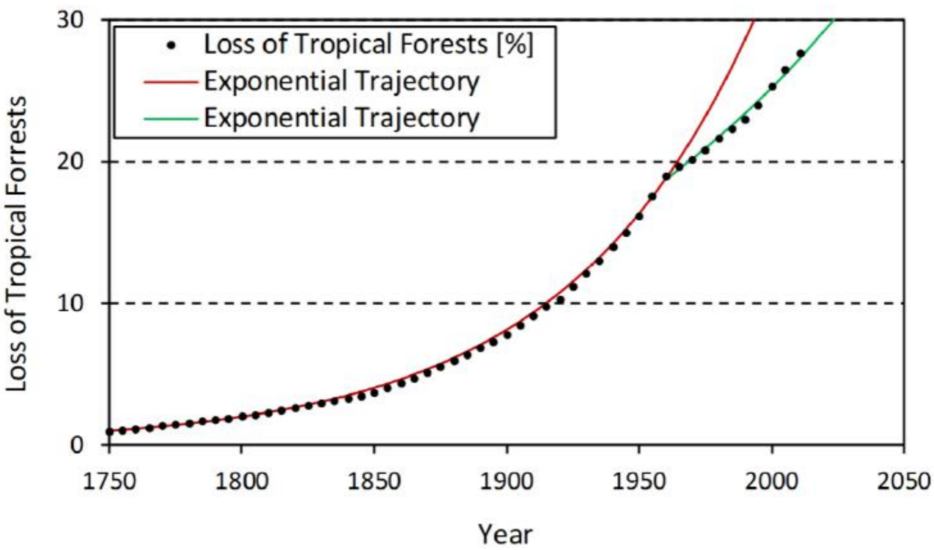

Figure 30. *Global loss of tropical forests (in percent of the forest area in 1700). 1750-1960 – exponential growth (* $c = 2.337 \times 10^{-11}$ *,* $r = 1.399 \times 10^{-2}$ *). 1960 – deceleration and diversion to a slower, exponential trajectory (* $c = 9.640 \times 10^{-6}$ *,* $r = 7.388 \times 10^{-3}$ *). There was no acceleration in the 1950sand no earlier take-off point.*

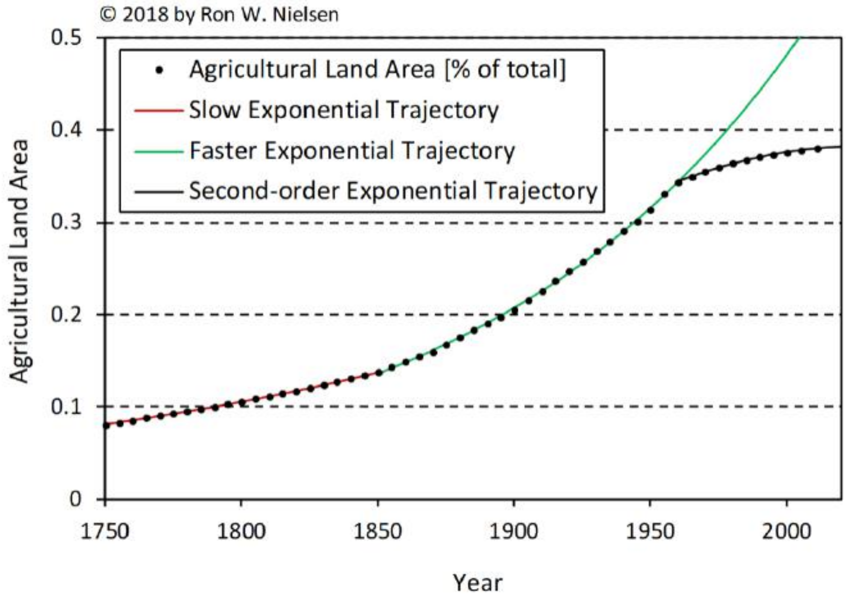

Figure 31. *Global agricultural land area (in per cent of the total land area). 1750-1850 – exponential trajectory (* $c = 7.357\times10^{-6}$ *,* $r = 5.315\times10^{-3}$ *). 1850-1960 – marginally faster exponential growth (* $c = 2.301\times10^{-8}$ *,* $r = 8.428\times10^{-3}$ *). 1960 – deceleration and diversion to a slower, second-order exponential trajectory (* $a_0 = -1.007\times10^{2}$ *,* $a_1 = 9.847\times10^{-2}$ *,* $a_2 = -2.431\times10^{-5}$ *). There was no prominent acceleration in the 1950s and no earlier take-off point.*

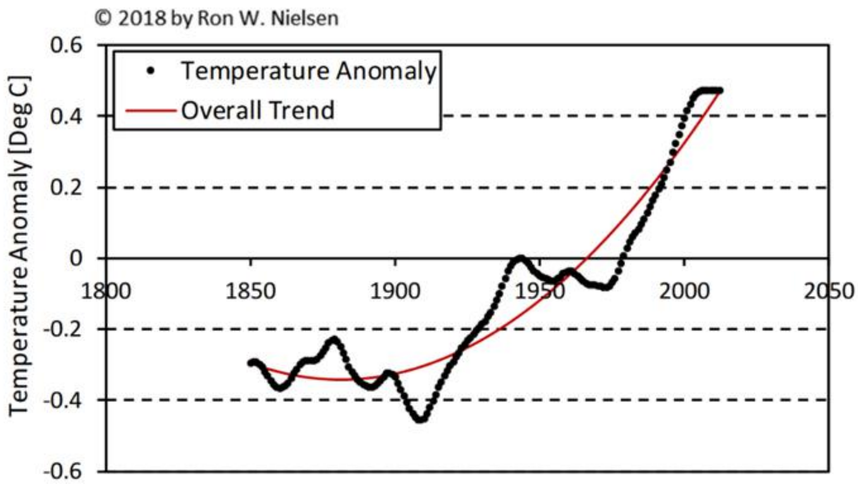

Figure 32. *Temperature anomaly in degrees of Celsius is strongly irregular and unpredictable. The overall trend was determined by the analysis of gradient. It is represented by the second order polynomial (* $a_0 = 1.676\times10^{2}$ *,* $a_1 = -1.786\times10^{-1}$ *,* $a_2 = 4.747\times10^{-5}$ *). This overall trend should not be used to calculate the future temperature anomaly.*

References

ABC, (2016). The Anthropocene: a new age of humans. [Retrieved from].
Aristotle, (2012). *On the Heavens.* New York: Start Publishing LLC.
Biraben, J-N. (1980). An Essay Concerning Mankind's Evolution. Population, Selected Papers, December.
Birdsell, J.B. (1972). *Human Evolution: An Introduction to the New Physical Anthropology.* Chicago: Rand Mc Nelly.
Clark, C. (1968). *Population Growth and Land Use.* New York, NY: St Martin's Press.
Cook, R.C. (1960). World Population Growth. *Law and Contemporary Problems,* 25(3), 379-388. doi. 10.2307/1190745
Crutzen, P.J.,& Stoermer, E.F. (2000). "The 'Anthropocene'". *Global Change Newsletter,* 41, 17-18
Deevey, E.S.Jr (1960). The human population. *Scientific American,*203(9), 195-204.
Durand, J.D. (1974). Historical Estimates of World Population: An Evaluation. *Analytical and Technical Reports,* Number 10. University of Pennsylvania, Population Center.
EPI (2013). Carbon Emissions. [Retrieved from].
Floud, D., & McCloskey, D.N. (1994). *The Economic History of Britain since 1700.* Cambridge, UK: Cambridge University Press.
Gallant, R.A. (1990). *The Peopling of Planet Earth: Human Growth through the Ages.* New York, NY: Macmillan Publishing Company.
Hassan, F.A. (2002). Population dynamics. *In* G. Barker (Ed), *Companion Encyclopedia of Archaeology.* (pp.672-713), London: Routledge.
Haub, C. (1995). How many people have ever lived on Earth? *Population Today,* February.
Hibbard, K.A., Crutzen, P.J., Lambin, E.F., Liverman, D., Mantua, N.J., McNeill, J.R., Messerli, B., &Steffen, W. (2007). Decadal interactions of humans and the environment. In: R. Costanza, L. Graumlich, &W. Steffen, (Eds). *Integrated History and Future of People on Earth, Dahlem Workshop Report,*96, 341-375.
Lenton, T.M., Held, H., Kiegler, E., Hall, J.W., Lucht, W., Rahmstorf, S.,&Schellnhuber H.J. (2008), Tipping elements in the Earth's climate system, *Proc. Natl. Acad. Sci. USA, 105,* 1786-1793. doi. 10.1073/pnas.0705414105
Livi-Bacci, M. (2007). *A Concise History of World Population* (2nd ed.). Malden, MA: Blackwell Publishers.
Ludwig, C, (2014). The Great Acceleration Data. [Retrieved from].
Maddison, A. (2010). Historical Statistics of the World Economy: 1-2008 AD. [Retrieved from].
Malthus, T. R. (1798). *An Essay on the Principle of Population.* London: J. Johnson.
Manning, S. (2008). *Year-by-Year World Population Estimates: 10,000 B.C. to 2007 A.D.* [Retrieved from]. and references therein.
McEvedy, C. & Jones, R. (1978). *Atlas of World Population History.* Harmondsworth, Middlesex, England: Penguin Books Ltd.
Nielsen, R. (2006). *The Green Handbook: Seven trends shaping the future of our planet.* New York: St. Martin's Press.
Nielsen, R. W. (2015). The Insecure Future of the World Economic Growth. *Journal of Economic and Social Thought,* 2(4), 242-255.
Nielsen, R. W. (2016a). Mathematical analysis of the historical economic growth with a search for takeoffs from stagnation to growth. *Journal of Economic Library,* 3(1), 1-23.
Nielsen, R. W. (2016b). Growth of the world population in the past 12,000 years and its link to the economic growth. *Journal of Economics Bibliography,* 3(1), 1-12.
Nielsen, R.W. (2016c). Mathematical analysis of the historical income per capita distributions. *Economic Review,* 3(2), 300-319.
Nielsen, R.W. (2016d). Industrial revolution did not boost the economic growth or the growth of population even in the United Kingdom. *Journal of Economic Bibliography,* 3(4), 434-446.
Nielsen, R.W. (2017a). Economic growth and the growth of human population in the past 2,000,000 years. *Journal of Economic Bibliography,* 4(2), 128-149.
Nielsen, R.W. (2017b). Application of differential equations in projecting growth trajectories. *Journal of Economic Bibliography,* 4(3), 203-221.
Nielsen, R.W. (2017c). Puzzling features of income per capita explained.*Journal of Economics Bibliography.*4(1), 10-24.
Steffen, W. (2017). Private communication.
Steffen, W. (2018). Private communication.
Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review,* 2(1) 81-98. doi. 10.1177/2053019614564785
Steffen, W., Grinevald, J., Crutzen, P., & McNeill, J. (2011). The Anthropocene: conceptual and historical perspectives. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,*369, 842–867.
Steffen, W., Leinfelder, R., Zalasiewicz. J., Waters, C.N., Williams, M., Summerhayes, C., … Schellnhuber, H.J. (2016). *Earth's Future, 4,* 324–345. doi. 10.1002/2016EF000379
Steffen, W, Sanderson. A., Tyson, P.D., Jager, J., Matson, P.A., Moore III, B., … Wasson, R.J. (2004). *Global Change and the Earth System: A Planet Under Pressure.* The IGBP Book Series. Berlin, Heidelberg, New York: Springer-Verlag.

Taeuber, C., & Taeuber, I.B. (1949). World population trends. *Journal of Farm Economics,* 31(1), 241.
Thomlinson, R. (1975). *Demographic Problems, Controversy Over Population Control* (2nd ed.). Encino, Ca.: Dickenson Pub.
Trager, J. (1994). *The People's Chronology: A Year-by-Year Record of Human Events from Prehistory to the Present.* New York, NY: Henry Holt and Company.
United Nations, (1973). The Determinants and Consequences of Population Trends, *Population Studies*, No. 50. p.10.
United Nations, (1999). The World at Six Billion, [Retrieved from].
United Nations, (2013). *World Population Prospects: The 2012 Revision*, DVD Edition. Washington DC: United Nations, Department of Economic and Social Affairs, Population Division,[Retrieved from].
United Nations, (2015). *World Population Prospects: The 2015 Revision*. New York: United Nations. [Retrieved from].
US Census Bureau, (2017). *International Data Base*. [Retrieved from].
Ward, J.D., Sutton, P.C., Werner, A.D., Costanza, R., Mohr, S.H., & Simmons, C.T. (2016). Is decoupling GDP growth from environmental impact possible?*PLoS ONE* 11(10), e0164733.doi.10.1371/journal.pone.0164733
Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Gałuszka, A., … Wolfe, A.P. (2016). The Anthropocene is functionally and stratigraphically distinct from the Holocene, *Science,* 351(6269), 137, aad2622-1-10. doi. 10.1126/science.aad262
World Bank, (2017). World Development Indicators. [Retrieved from].
Zalasiewicz, J, Crutzen, P.J., & Steffen, W. (2012). The Anthropocene. In: F.M. Gradstein,J. Ogg, M. Schmitz, & G.M. Ogg (Eds) *A Geological Time Scale 2012.* (pp.1033-1040), Amsterdam: Elsevier.