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MODERN CLIMATE CHANGE

A Symptom of a Single-Species High-Energy Pulse

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Introduction

In 1912, Francis Molena contemplated the possibility of human activities causing climate change, and he concluded:

> It is largely the courageous, enterprising, and ingenious American whose brains are changing the world. Yet even the dull foreigner, who burrows in the earth by the faint gleam of his miner's lamp, not only supports his family and helps to feed the consuming furnaces of modern industry, but by his toil in the dirt and darkness adds to the carbon dioxide in the earth's atmosphere so that men in generations to come shall enjoy milder breezes and live under sunnier skies.
>
> *Molena, 1912*

Today, more than a century later, atmospheric CO_2 is much higher than Molena expected, and instead of enjoying the "milder breezes," fear of stronger storms is increasing, while the "sunnier skies" are associated with more frequent deadly heat waves and prolonged droughts. During the last century and particularly the last several decades, climate has been changing at a much higher rate than before 1900 throughout the Holocene, the last geological epoch that started approximately 12,000 years ago (e.g., Gaffney & Steffen, 2017). Evidence documenting modern climate change is abundant (e.g., Pachauri et al., 2014; IPCC, 2018) and the observed changes in the chemistry of the climate system can be linked to human activities. However, recent impacts of modern society on the planetary system go far beyond changing the climate. The rapid modern climate change is part of a larger syndrome of accelerated modern global change and can only be characterized and understood as part of this syndrome.

The planetary system can be viewed as a life-support system for a very large number of fine-tuned subsystems of species interacting with each other within this system and slowly changing it. The concept of a planetary life-support system of systems has been utilized recently in scientific assessments of the interaction of humanity with the planet (e.g., Young & Steffen, 2009; Pearce, 2010) and in communications of the anthropogenic degradation of the system to the public and world leaders (e.g., Wallström et al., 2004; Barnosky et al., 2014).

The concept of the Earth's life-support system was used by Griggs et al. (2013) to operationalize the principle of sustainable development by defining sustainable development as "a development that meets the needs of the present while safe-guarding the Earth's life-support system on which the welfare of current and future generations depends." Communities of human and non-human animals embedded in the planetary system interact with this life-support system through flows of matter and energy (Figure 1.1). In many aspects, the Earth's life-support system is similar to the organism of an animal, in which many fine-tuned processes generate flows that keep the organism in homeostasis. Like the planetary system, the animal organism provides a life-support system for many other organisms that are crucial for the generation of the flows that maintain homeostasis. Central to the

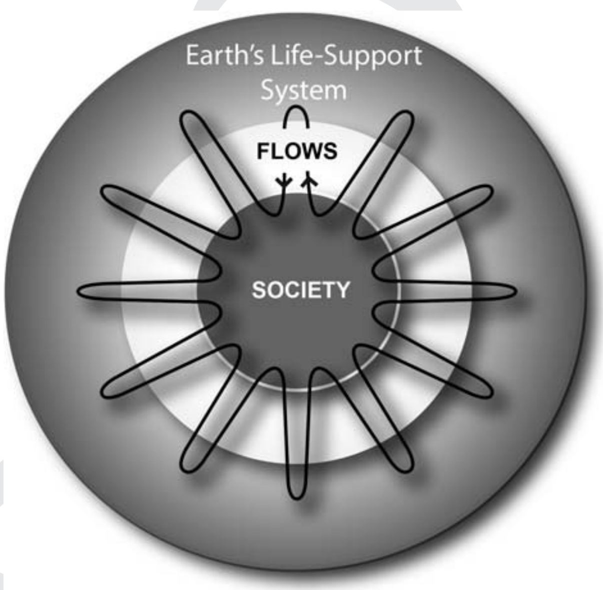

FIGURE 1.1 Earth's life-support system and humanity. Human and non-human communities embedded in the Earth's life-support system interact with it through flows of energy and matter. Unlike other animals, the flows between the life-support system and human communities are regulated by ethics, social norms, and the mainstream economic model.

Source: Modified from Plag & Jules-Plag (2017).

understanding of the physiological functioning of a body system is the integrated nature of chemistry and physics, coordinated homeostatic control mechanisms, and continuous communication between cells (Widmaier et al., 2016). Central to the understanding of the functioning of the Earth's life-support system is the integrated nature of chemistry and physics and the coordinated functioning of homeostatic control mechanisms provided by the continuous interaction of the "web of life" (Capra, 1996) embedded in, and integral to, the planetary life-support system.

Life has impacted the physiology of the planetary system from the start by creating and changing flows. To some extent, life determined many chemical and physical system variables throughout time and impacted climate. The flows manipulated by life kept the system in homeostasis and provided long stable states for life to evolve and occupy large regions of the planetary surface layers. Changes in the flows were slow and allowed species to adapt to equally slow changes in the mean state of the system, as well as most of the fluctuations around the mean.

In the case of human communities, the flows between the Earth's life-support system and society are regulated not only by human needs but also by ethics, social norms, and economic rules and practices. The modern growth-dependent economy has facilitated growth by increasing most of the flows by several orders of magnitude, and these rapid changes in the planetary physiology have resulted in major changes in the biological, chemical, and physical conditions in the Earth's life-support system. Among them is modern climate change.

Fever in a homeothermic species is a symptom of a malfunctioning of that system and often part of a syndrome of changes in the organism resulting from disruptions in the physiology of the organism. These disruptions can result, for example, from a breakdown of homeostatic control mechanisms, alterations of flows, or the attack of viruses or bacteria. The effectiveness of an external cure depends upon an accurate diagnosis of the disruption.

Similarly, a rapid increase in the global ocean and air temperature, which is indicating a rapid increase in the energy stored in the coupled atmosphere-ocean system, is a result of a disruption in the planetary physiology. The symptom of global warming indicates that the homeothermic processes in the Earth's life-support system no longer are functioning to keep the system in homeostasis. Consequently, only by considering the full planetary physiology can the symptoms of global warming and modern climate change be fully understood and traced back to the underlying cause, the "sickness."

An alien outside observer would not characterize the syndrome as anthropogenic but rather aim to see it as a distortion in the planetary life-support system that could have come from any individual or group of species. Having access to the very large database humans have compiled in the last few centuries, the alien observer would see the obvious: The distorting modern global change is the result of a single species that in a very short time of less than 200 years released a very large pulse of energy into the environment by tapping into energy resources stored in the planetary system over hundreds of millions of years. This species is using this energy pulse to re-engineer the planetary physiology by changing its chemical and physical state and modifying crucial flows by several orders of magnitude. To capture the main aspects of this distortion, the alien might denote it as a "single-species high-energy pulse" syndrome. The species causing the pulse acts as a virus in the Earth's life-support system, a virus that found the means to change almost all flows to sustain its population growth at an unprecedented rate, invasively occupy all regions of the planet's surface, and eliminate many other potentially competing species. By doing so, it destabilized the homeostatic mechanisms and initiated a rapid transition of the planetary system towards a new and currently unknown homeostasis.

Scientific evidence pointing to an ecological breakdown has become ubiquitous, and concerned scientists have issued warnings to humanity (Union of Concerned Scientists, 1992; Ripple et al., 2017). Major newspapers, including *The Guardian* and the *New York Times*, have picked up the alarming scientific findings concerning soil depletion, deforestation, and the collapse of fish stocks and insect populations. There is a growing consensus that these crises are driven by an economic model focused on unlimited growth of production and consumption, which is fundamentally reorganizing the flows in the Earth's life-support system.

Modern climate change is extensively documented in scientific literature and assessment reports at national, regional, and intergovernmental levels, and there is little benefit in adding another summary here. However, considering modern climate change as a symptom of the larger single-species high-energy pulse syndrome is a novel contribution. Looking at the Earth's life-support system from a medical point of view to assess its health, these five questions seem crucial:

- What is the baseline for a healthy planetary life-support system and what are the normal ranges of essential variables of this system?
- What characterizes the syndrome of the single-species high-energy pulse that the system is showing recently?
- What is the diagnosis of the underlying cause of this syndrome?
- What foresight can be developed with respect to the full spectrum of possible futures of the system and what are the likelihoods of these futures to realize?
- Is there a therapy to address the cause of the syndrome?

Understanding the extent of modern global change requires a baseline against which the changes can be characterized.

The remainder of this chapter is organized as follows: In the second section, selected aspects of the planetary baseline for a stable life-support system will be considered, including the background ranges of climate variability and change. In the third section, the full extent of the syndrome of modern global change is assessed against this baseline. The context of Earth's life-support system allows for a diagnosis of the main cause of this syndrome and this is discussed in the fourth section. Foresight about the full spectrum of possible futures of the planetary life-support system and humanity embedded in it is needed to inform our actions, and this foresight can be developed by considering several scenarios of human interactions with the planetary system, as discussed in the fifth section. The sixth section considers a therapy that directly results from the diagnosis of the cause of modern global change. Finally, concluding remarks are based on the working hypothesis that the future does not exist and has to be created. Since humanity has engaged in re-engineering and operating the planetary system, humanity also has responsibility to create a future that is consistent with the ethics it promotes.

Baseline and Normal Ranges

Climate Basics

The Earth's climate is the result of three main factors: the incoming solar radiation (solar irradiance), which determines the energy input to the Earth system; the albedo of the Earth's surface, which determines the radiation reflected at the Earth's surface; and the amount of so-called greenhouse gases in the atmosphere, which determines how much of the long-wavelength radiation is captured by the atmosphere. If any of these three factors change, climate will change. However, the spatial and temporal patterns of climate change can be complex and difficult to attribute to specific changes in any of the three forcing factors. The amount of heat stored or released in response to changes in the three forcing factors depends on the heat capacity of the main components, including the atmosphere, ocean, cryosphere, and solid land surface. Changes in the overall heat stored in the different components of the climate system have an impact on the dynamics within the climate system, in particular, the ocean and atmospheric circulation and the flows in the associated water cycle.

Climate can change on a wide range of spatial and temporal scales, and the changes in climate variables such as surface air temperature, air pressure, wind fields, air and soil moisture, precipitation, and evapotranspiration, among others, can differ along these scales. For example, the changes in five-year averaged air temperature between 1900 and 2010 vary spatially between -2°C and +4°C, with the increases in the Arctic on average being much larger than in other geographical regions. Over time, global mean air temperature has varied over a total range of about 5°C over the last 800,000 years (e.g., Hansen et al., 2008), but changes on century time scales have been very small (normally much less than 0.5°C).

Solar irradiance exhibits small fluctuations over time. Most remarkable for human time scales is the solar sunspot cycle of approximately 11 years. The corresponding climate variations are minuscule, and the processes that cause the variations are still being researched (Rind et al., 2008).

The Earth's albedo, i.e., the ratio of reflected to incoming radiation, depends on the Earth's surface properties. Ice and snow-covered areas reflect most of the solar radiations, while open water and land areas reflect much less. Urban areas also have a lower albedo than, for example, grasslands and forests.

Without an atmosphere, the mean global temperature on the Earth's surface would be close to -18°C, and this temperature would only depend on the incoming solar radiation. With the atmosphere present, the global mean surface temperature is today close to 16°C, and this much higher temperature is mainly the result of the greenhouse gases in the atmosphere. The greenhouse gases most abundant in the atmosphere include H_2O, CO_2, CH_4, and N_2O, while other gases such as fluorinated gases have high greenhouse potential but are less abundant in the atmosphere. If the atmospheric concentrations of greenhouse gases increase, then the surface air temperature also increases (Arrhenius, 1896).

However, due to the presence of the ocean, the full effect of a change in greenhouse gases can take a long time to develop. Water has a specific heat capacity more than 3,000 times that of air, and the slow heating of the ocean thus delays the atmosphere in reaching the equilibrium temperature consistent with a given level of atmospheric greenhouse gases. Thus, the climate system reacts to changes in greenhouse gases not like a greenhouse but rather like a pool house, in which the swimming pool provides a large thermal mass that delays changes in the air temperature.

The warming ocean also contributes to changes in the climate dynamics. A warmer ocean evaporates more water, and the amount of water vapor that can be stored in air increases strongly with the air temperature. For example, at 40°C, air can hold almost 5.5 times the water it can hold at 10°C. Thus, warmer air can store much more water before condensation and precipitation happen, which results in longer intervals without precipitation followed by more extreme precipitation events. The water vapor represents latent heat, that is, energy that becomes available again when the water vapor condensates. This energy is available to drive storms. The warmer the air, the more latent heat it can hold and make available for storms once condensation is triggered.

Thus climate change is the result of changes in flows: the flow of solar energy into the atmosphere-oceans system and storage of heat mainly in the ocean; the flow of water in the ocean currents that distributes energy throughout the ocean; the flow of energy in the form of latent heat carried by water vapor from the oceans to the atmosphere; the transformation of latent heat into kinetic energy when the water vapor condensates; the flow of air in storms that can bring devastation to human and non-human communities; and the flow of water in the global water cycle that can cause floods and droughts.

Normal Ranges

The Earth's life-support system is a dynamic system and changes are continuously taking place at a wide range of spatial and temporal scales. However, there are many biological, chemical, and physical feedback processes and loops that create prolonged periods of homeostatic stability, in which the system exhibits relatively small variations around a surprisingly stable mean state. For the last 1 million years, the climate system has fluctuated between cold glacial periods (ice ages) and warm inter-glacial periods, with the transition from warm to cold periods often taking much longer than the reverse transition. Data gathered from many natural recorders of climate variability, e.g., tree rings, ice cores, fossil pollen, ocean sediments, coral, and historical data, has been used to reconstruct many variables of the climate system and the overall planetary system. This so-called paleo-data can be used to establish a baseline indicating the range in which these variables have fluctuated during the last approximately 1 million years. This baseline provides a basis for the assessment of the syndrome of modern global change.

An essential variable associated with the planetary energy state is the Earth's energy imbalance. This is the difference between incoming solar energy and outgoing energy. Among others, the imbalance results from solar energy being used to produce biomaterial that partly is being deposited in subsurface reservoirs as fossil fuels. The energy used by non-human species, including plants, to generate and modify flows is at a very low level compared with the incoming solar energy. As a result, averaged over the last 200 million years, the imbalance was roughly on the order of 10^{-10}; that is, on the order of 10 megawatts of the incoming roughly 98,000 terawatts of solar energy were not returned to space. On shorter time scales, the energy imbalance varied between much larger positive and negative values particularly during the cooling or warming of ocean waters and the aggregation and melting of large ice sheets.

An essential variable indicating the stability of the biological system is the rate at which species go extinct. Although it is difficult to estimate background rates for extinction (Pimm et al., 2014; Ceballos et al., 2015), it appears that outside the five known periods of mass extinction (e.g., Bond & Grasby, 2017; Starr, 2018) the extinction rates are very low. For mammals, a recent study estimates the background rate to be two extinctions per 10,000 species per 100 years (Ceballos et al., 2015, and the references therein). However, during the transitions between the glacial and inter-glacial periods in the last 1 million years, extinction rates appear to have been higher. For example, terrestrial ecosystems experienced major transformations during the most recent warming and associated climate change after the last ice age, and many plant species became extinct (Nolan et al., 2018).

For the climate system, a number of physical and chemical variables are essential (Bojinski et al., 2014). Table 1.1 gives the ranges for a few essential climate variables for the last 800,000 years and for the Holocene. The total ranges for the

TABLE 1.1 "Normal range" of selected essential climate variables.

Variable	*Long-term range*	*Holocene*	*Current*	*Projected 2100*
CO_2	170–300 ppm	270–285 ppm	405 ppm	500–900 ppm
CH_4	320–800 ppb	550–800 ppb	1848 ppb	2000–2500 ppb
Greenhouse gas forcing	-4.0–0.0 W/m^2	-0.3–0.0 W/m^2	1.0 W/m^2	3.5–5.0 W/m^2
Albedo forcing	-4.0–0.0 W/m^2	-0.2–0.0 W/m^2	0.3 W/m^2	1.5–2.5 W/m^2
Global mean surface temperature	-4.0–1.0°C	0.0–1.0°C	1.0°C	2–6°C
Global mean sea level	-130–5 m	-3–0.0 m*	0.3 m	1–5 m

*This is for the last 7,000 years during the time sea level was exceptionally stable.
The normal ranges for the selected variables are determined based on data provided by Hansen et al. (2008) for the last 800,000 years. The long-term range is for the last 800,000 years prior to industrialization. The range for the Holocene is for the last 12,000 years before industrialization. Current values are for 2017. The projected ranges are those published based on model studies.

greenhouse gases CO_2 and CH_4 are 130 ppm and 480 ppb, respectively, translating into a total range of the greenhouse gas forcing of 4 W/m^2, which is similar to the total range of albedo forcing. Using the ranges in Table 1.1, 1 ppm change in atmospheric CO_2 corresponds to a change of 1 m in global mean sea level, and 25 ppm corresponds to 1°C in global mean air temperature.

During the Holocene, the range for the greenhouse gases was only a fraction of the range during the last 800,000. Likewise, global mean temperature variations were limited to a range of 1°C. During the first part of the Holocene, sea level continued to rise nearly 50 m until an equilibrium between the air temperature and land-based ice masses was reached about 7,000 years ago. Since then, the range of global sea level change was only on the order of a few meters.

The extreme stability of climate during the Holocene provided a safe operating space for humanity (Rockström et al., 2009), in which modern society could emerge. When climate became stable at the beginning of the Holocene, the transition to agriculture was possible. When sea level became stable, permanent settlements became feasible in river deltas, which provided valuable ecosystem services and logistical advantages, and cities could develop.

The Holocene can be characterized by planetary boundaries for essential variables. Rockström et al. (2009) identified boundaries for nine variables: biogeochemical flows (in particular nitrogen and phosphorus cycles), global freshwater, change in land use, biodiversity loss (extinction rate), atmospheric aerosol loading, chemical pollution (and new constituents), climate change, ocean acidification, and stratospheric ozone depletion. They found that several of these boundaries have been crossed recently due to human activities, and this is pushing the Earth's life-support system out of the safe operating space.

The Single-Species High-Energy Pulse Syndrome

Climate Symptoms

The observational evidence of a global temperature rise of close to 1°C since 1880 is overwhelming (Pachauri et al., 2014; IPCC, 2018) and indisputable. There are large spatial and temporal variations in the increase. For example, a rapid warming took place in the Arctic, where the land surface temperature increased by 3.5°C since 1900 (Morrison, 2017).

The most fundamental variable reflecting the extent of global warming is the Earth's energy imbalance. In recent decades, this imbalance has increased by many orders of magnitude (Hansen et al., 2011; Trenberth et al., 2014; von Schuckmann et al., 2016; Cheng et al., 2019). During the first decade of the 21st century the imbalance was estimated at 250–500 terawatts (Trenberth et al., 2014). Most of this energy is being stored in the ocean (> 90%) and only 1% is stored in the atmosphere and causing the increase in global air temperature (Laffoley & Baxter, 2016, and the reference therein). The remaining fractions go into melting of ice and the warming of the land surface. The energy currently stored in the planetary climate system is 14 to 28 times the total energy used by humanity. Thus, the anthropogenic re-engineering of the planetary system has an amplified impact on the energy imbalance of the planet, which is now on the order of 1 million to 10 million times larger than the long-term pre-human background rate (see p. 000). The energy stored leads to significant changes in land and sea-ice cover, snow cover, and increased desertification, which all impact the albedo of Earth's surface. However, the full impact of the additional heat on global mean air temperature is not yet being felt because of the large time-lag caused by the thermal mass of the ocean.

The many symptoms and full scale of modern climate change are described in a number of assessments at subnational (e.g., Bedsworth et al., 2018), national (e.g., Wuebbles et al., 2017), and international levels (e.g., Pachauri et al., 2014; IPCC, 2018). Atmospheric CO_2 has reached permanent levels of 405 ppm, i.e., more than 100 ppm above the baseline range. Given that during the last 800,000 years 25 ppm of CO_2 corresponded to 1°C in global mean air temperature, the current increase of only about 1°C above the pre-industrial temperature is most likely not reflecting the equilibrium temperature corresponding to a 100 ppm increase in CO_2. Moreover, several feedback loops seem to have been triggered, with the melting of permafrost having a high potential of contributing additional greenhouse gas emissions (e.g., Drake et al., 2015; Kohnert et al., 2017).

A few additional examples are considered here to illustrate the range of symptoms. On a regional scale, air temperatures have been found to increase faster during periods of droughts than on average: for example, in the southern and northeastern United States, concurrent occurrences of droughts and heat waves have caused compounding ecosystem and societal stresses (Chiang et al., 2018). For warmer air, much more water vapor is needed to reach the condensation

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point (p. 000), and when this point is reached, the resulting precipitation is much larger. Therefore, a warmer world will likely have many more extreme precipitation events. This is already visible in the amount of record flooding taking place in recent years in many regions (e.g., EASAC, 2013, 2018). The warming ocean and atmosphere appear to have increased the size and maximum precipitation of the 2018 Hurricane Florence compared with a similar hurricane under pre-warming conditions (Reed et al., 2018).

Many of the recent changes appear to have taken place earlier than predicted a few years ago. For example, the reduction in summer sea ice in the Arctic is taking place much faster than predicted, most likely due to underestimation of the increased summer solar heat absorption by the ice-free surface waters (Timmermans et al., 2018), which in turn accelerates the disappearance of sea ice in the region beyond the summer season. Importantly, a potential slow-down of the northward flow of warm surface waters and the matching southward flow of cooler waters at greater depths would have severe impacts for the climate on the Northern hemisphere, and it was not expected in the 21st century (National Research Council, 2013). However, there is now evidence that it has started to slow down (Bryden et al., 2005) and is slower than at any time in the last 1,600 years (Caesar et al., 2018; Thornalley et al., 2018).

Other Symptoms and Impacts

Like many other animal species, *Homo sapiens* has changed the physiology of Earth's life-support system since humans started to build simple dwellings more than 500,000 years ago. With the transition to agriculture, they started to control the flow of water (Bishop et al., 2017) and changed other flows including soil erosion, nutrient flows, and flows of bacteria. Already several thousand years ago, the use of fire and other means to clear forested areas for agricultural use changed the flow of carbon and started to increase atmospheric CO_2 with a likely impact on the long-term climate trend throughout the Holocene (Ruddiman, 2005).

In more recent times, the re-engineering of the land surface created many new flows and modified or interrupted existing flows. Destruction and degradation of ecosystems are the primary causes of extinction and the increasingly rapid declines in global biodiversity (Pereira et al., 2010). The fragmentation of habitats into smaller, isolated ecosystems separated by a matrix of built environment and human-transformed land cover leads to a greater exposure to anthropogenic flows along fragment edges, and this in turn initiates long-term changes in the structure and function of the remaining fragments (Haddad et al., 2015). Globally, 70% of the remaining forests are within 1 km of edges due to fragmentation, and this reduces biodiversity and impairs key ecosystem functions by decreasing biomass and altering flows in nutrient cycles (Haddad et al., 2015).

New boundaries in the aquatic system with steep gradients introduced by canals, dammed reservoirs, irrigation ditches, and pollution are changing species diversity, microbial communities, and nutrient levels in aquatic zones across the planet resulting in significant detrimental impacts on aquatic ecosystems (Bianchi & Morrison, 2018). The accelerated flows of nutrients into the ocean have created large dead zones and contribute to declining oxygen in the global ocean and coastal waters (Breitburg et al., 2018). Global ocean warming has a severe impact on marine ecosystems and is one of the main causes of widespread coral bleaching (Hughes et al., 2018; Frade et al., 2018). Ocean acidification caused by increased absorption of atmospheric CO_2 in the ocean adds another major threat: a threshold in the total carbon load added to the ocean that would lead to the catastrophic elimination of all marine life could be reached as early as 2050 to 2150 (Rothman, 2017).

Modern global change caused by human activities has had a significant impact on the biomass distribution. Over the last 5,000 years human activities have reduced total global biomass by about 50% (Smil, 2011), and this decline through harvesting of the wild and habitat conversion continues. Between 1900 and 2000, the carbon stored in humans increased by more than 400%, while for wild terrestrial animals it was reduced by 50%. Humans also increased the biomass of domesticated animals by 350%, with cattle accounting for two-thirds of the total mass of these animals (Smil, 2011). Besides a major impact on wildlife, the increase in cattle also creates a major source of greenhouse gases in the form of CH_4.

Modern climate change is also impacting the frequency and magnitude of other natural hazards. For example, the increased melting of glaciers and ice sheets has increased the risk of landslides and tsunamis triggered by these landslides (e.g., Higman et al., 2018). During the deglaciation that ended the last ice age, several megatsunamis were caused by subaerial landslides of sediments deposited around the melting ice sheets (Harbitz et al., 2014). It can be expected that the possible melting of the Greenland and Antarctic ice sheets will also create large sediment deposits on the surrounding shelves that will increase the probability of large subaerial landslides and megatsunamis.

In summary, the large range of symptoms within the single-species high-energy pulse syndrome indicate that the Earth's life-support system is rapidly moving out of the safe operating space for humanity. At least three of the nine planetary boundaries of this space have been crossed (biogeochemical cycles, extinction rates, climate change; Rockström et al., 2009; Steffen et al., 2015).

Diagnosis

Breaking Scaling Laws: The Journey to the Single-Species High Energy Pulse

Distortions in the planetary physiology have been caused by many events in Earth's long history. For example, episodes of high volcanic activity have impacted the chemical composition of the atmosphere and ocean, and in extreme cases

TABLE 1.2 Century-scale changes in essential variables of the Earth's life-support system.

Variable	*Before 1900*	*1900–2000*	*Acceleration*
Energy usage	0.01 TW/century	16 TW	1600
CO_2	0.2 ppm/century	120 ppm	600
Population	16 million/century	5.5 billion	350
Gini coefficient	0.003/century	0.3	100
Global mean temperature	0.01°C/century	1°C	100
Global mean sea level	0.05 m/century*	0.2 m	4

*Value is for the last 7,000 years, when sea level was exceptionally stable.
Changes per century in the essential variables of the climate system and humanity were very small up to 1900. The combination of technological innovations and humanity's newly gained access to seemingly unlimited energy facilitated in the last century changes in the planetary system that were several orders of magnitude larger than on average throughout the Holocene. A few variables such as global mean sea level, which lag behind in time, do not show the full impact yet.

caused mass extinction (Bond & Grasby, 2017). However, the changes in flows introduced by humanity in the high-energy pulse are exceptional in terms of the rate of change. Between 1900 and 2000, many essential variables exhibited changes that are 100 to 2,000 times larger than on average throughout the Holocene (Table 1.2). In particular, the rapid increase in energy usage during the last 100 years allowed the production of large amounts of fertilizers as well as a large-scale transformation of land to agricultural land. This resulted in an apparent transient increase of the planetary carrying capacity and sustained an increase of the global human population 350 times faster than before. The rapid increases of atmospheric CO_2 and global mean temperature are side effects of this dominance of *Homo sapiens*.

The minimum energy needed by animals (including humans) to stay alive is the basal metabolic rate, which can be expressed in watts. This basal metabolic rate depends on the mass of the animal, and the rates for different species are connected through a simple scaling law, which states that the basal metabolic rate is a constant times the mass of the animal to the power of 3/4. The constant differs among the three groups of homeotherms, poikilotherms, and unicellular organisms (West et al., 1997, and the references therein).

Homo sapiens is in the group of homeotherms, and the scaling law results in a range for the basal metabolic rate of 50 to 100 watts, depending on age, gender, and mass. Because they use fire to process food, humans can extract the energy to sustain this rate from food far more efficiently than most other species and they could afford to develop larger, energy-demanding brains (Herculano-Houzel, 2017). At the same time, it freed time that previously had been used to find and metabolically process the food. This put *Homo sapiens* on a distinctly different evolutionary path (Table 1.3). The use of fire for clearing forest and other land covers

TABLE 1.3 Humanity and energy.

Time	*Event*	*Impact*	*Population*	*Energy usage (terawatts)*
1,000,000 BP	Use of fire to prepare food	Allowed development of larger, more complex brains	?	0
10,000 BP	Transition to agriculture	Increased food security, reduced time needed to find food	4 million	< 0.000001
1000			50 million	< 0.001
1750	Advent of capitalism (Adam Smith) and colonialism	Industrialization and rapid acceleration of flows started; single-species dominance	650 million	0.1
1900		Threat of climate change and population growth identified	1.6 billion	0.5
1990	UNFCCC (1992) and 1st IPCC report (1994)	Climate change elevated to one of the main threats to humanity	5.3 billion	10.0
2000			6.0 billion	12.8
2010			6.9 billion	16.5
2100	Potential climate tragedy	Potential social collapse	1–14 billion	> 100?

The single-species high-energy pulse has its origin in humans learning to utilize fire to process food, which provided a basis for increasing the brain-body ratio. Later fire was used to clear spaces for agriculture. The focus on accumulation of human wealth in Europe, the disregard of Earth's life-support system, and the discounting of the future led to an unparalleled single-species dominance and rapid degradation of the life-support system for all.

for agriculture and pastures further eased food supply and freed time for other activities. The larger brain could be used to develop technologies to utilize more energy to transform the environment, triggering the development that eventually led to the single-species high-energy pulse; modern climate change is one of the most visible and severe symptoms of this syndrome.

Unlike other animals, today's *Homo sapiens* uses a large amount of energy to modify the planetary system and create conditions that are favorable and convenient for humans. Adding the energy used per capita to the basal metabolic rate, the resulting extended metabolic rate is much larger than what the scaling law indicates. In 2010, the global average energy used per capita was approximately 2,750 watts, resulting in an extended metabolic rate of 2,800 watts. Using the scaling law for homeotherms, an animal with a basal metabolic rate of 2,800 watts would have a mass of roughly 9,000 kg, which is equivalent to the mass of two large elephants. Based on the scaling law, humanity's energy usage is equivalent to what roughly 14 billion elephants would need. Thus, by breaking the scaling law, *Homo sapiens* became a planetary dominant force overloading the carrying capacity of Earth's life-support system.

Role of the Mainstream Economic Model

The current global mainstream economic model is based on a number of assumptions about the Earth's life-support system and humanity's relation to it, how economy works, and what the goal of economy is. The core purpose of today's economic model can be traced back to Adam Smith, who focused economy on the creation of human wealth (built capital, Smith, 1776). In the 18th century, the global population was less than 700 million and access to energy and technology was limited. Humanity was managing less than 1% of the Earth's surface. Built capital was the limiting factor, while natural capital was seemingly infinite. Consequently, it made sense to think of economy only in terms of marketed goods and services and to define the goal as increasing production and consumption without worrying much about impacts on the planetary life-support system.

The mainstream economic model does not consider the health of the planetary life-support system and the state of this system is not accounted for in any economic measure. While this approach allowed human economy to develop rapidly and facilitate an unparalleled growth of the global population, it required the acceleration of flows in the planetary physiology. As a result, the per capita use of materials, including metals, minerals, fossil fuels, and biomass, increased rapidly, particularly since 1950, and reached in 2008 on average 10 tons per person, i.e., 27 kg each day, or a global total of 68 gigatons of materials (Assadourian, 2013).

Economic growth has been directly linked to rapidly increasing energy use and greenhouse gas emissions. Global CO_2 emissions from fossil fuel combustion, cement production, and other industrial processes account for about 70% of total global greenhouse gas emissions (UNEP, 2017). Other emissions result from land use, land-use change, and forestry. Emissions are still increasing, although the rate of increases has been slowing down recently (UNEP, 2017). However, it is not clear whether this slowdown will continue as a result of a decoupling of CO_2 emissions and economic growth or reverse if economic growth is accelerating.

The apparent success of the current economic model in reducing poverty and increasing human welfare is based on a consumption of planetary non-renewable resources (Assadourian, 2013) and a rapid degradation of the planetary life-support system, including modern climate change. It is increasingly clear that the mainstream economic model is at the core of the current unsustainability. Only a reconceptualizing of the economic model can therefore provide a path to more sustainability (Costanza et al., 2013).

Foresight

Embedded in the Earth's life-support system, *Homo sapiens* today can be characterized as a virus in this system. The attempt to provide a prognosis of how this virus will impact the system's health is hampered by the unpredictability of the virus's actions. However, the spectrum of possible futures can be explored to inform foresight. In particular, models can be used to explore the range of possible futures of the climate system for a large set of scenarios for human-caused emissions of greenhouse gases. Unfortunately, the predictive capabilities of the models are limited because of epistemic uncertainties; that is, knowledge gaps. The importance of the knowledge gaps is emphasized by the many impacts of human activities on the planetary system that have not been predicted or even anticipated before they were discovered. For example, the large dead zones in the ocean caused by overloads of nutrients from agriculture, the rapid reduction in the area of sea ice in the Arctic, the increase in extinction rates, and the large change in the Earth's energy imbalance were either not predicted at all or underestimated by model prediction. However, the understanding of basic relationships often is sufficient to develop foresight in the sense of what are possible futures without predicting which future actually is going to realize. This foresight then allows a risk assessment that can inform decisions. In particular, complex systems stressed beyond their homeostatic limits will rather abruptly transition into new states that cannot be predicted. Mounting evidence suggests that in the case of the Earth's life-support system (including the climate system), the new states may well be inimical to humankind (e.g., Barnosky et al., 2012; Steffen et al., 2018). Therefore, a rudimentary cost-benefit analysis argues strongly for caution and strong actions to mitigate global warming and species extinction.

Climate Change Scenarios

A key challenge for the prognosis is the limited knowledge of climate sensitivity. Climate sensitivity is the increase in the global mean equilibrium temperature as a result of an increase in climate forcing. It is independent of the nature of the change in the forcing and gives the increase in temperature for a unit change in forcing. In connection with increases in atmospheric CO_2 it is often given as the temperature increase for a doubling of atmospheric CO_2. The range of climate sensitivity is between 1.5 and 4.5°C and the most likely value is between 2.5 and 3.0°C (Pachauri et al., 2014, and the references therein).

The large range in climate sensitivity introduces a significant uncertainty in models used to compute trajectories of possible future climates. Another uncertainty is in the future anthropogenic emissions of greenhouse gases. To address this uncertainty, ensemble studies utilizing a large number of Earth system climate models in combination with a large set of emission scenarios have been carried out (e.g., Pachauri et al., 2014). The results indicate a wide range of temperature

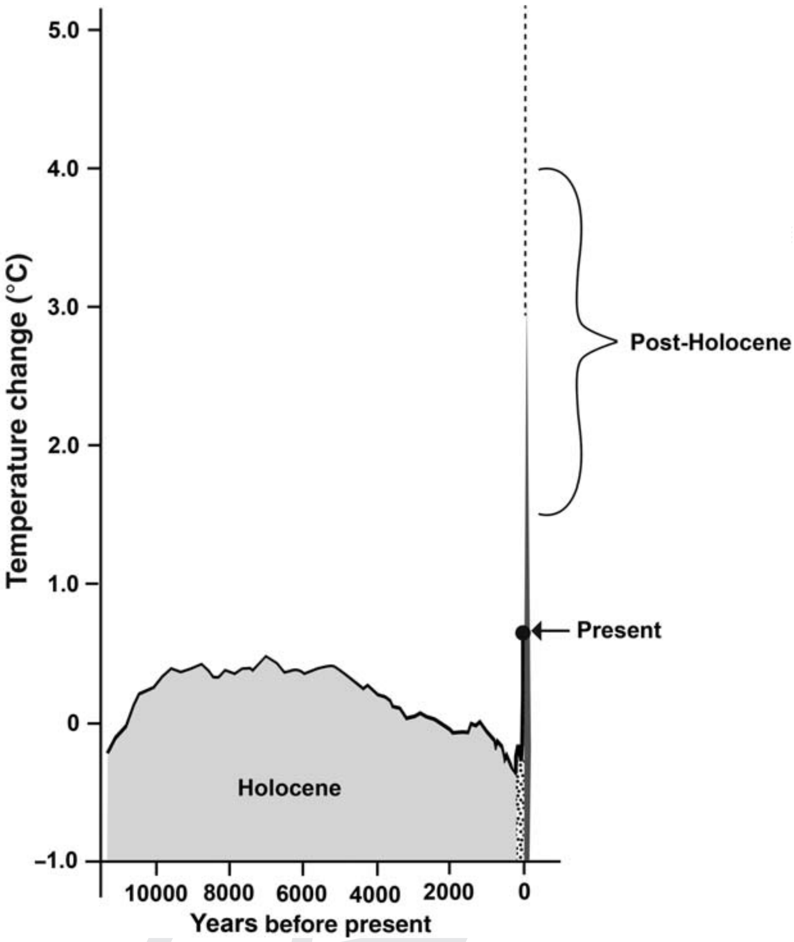

FIGURE 1.2 Possible temperature changes in the 21st century compared with Holocene temperature variations. The total range of global mean temperature variation during the Holocene up to 1900 was on the order of 1°C. The likely change of 2°C or more by 2100 would cause a rapid transition into a post-Holocene unknown to humanity. The dotted area indicates the time from 1880 to 2000.

Source: The temperature curve for the Holocene is based on Figure 1b in Marcott et al. (2013).

increases by 2100 with large regional variability. However, the likely increase will put the Earth's life-support system in a state unknown to humanity (see Figure 1.2 and Pachauri et al., 2014; IPCC, 2018).

The changes in the dynamics of the climate system triggered by the higher energy level have the potential to lead to changes in the regional distribution of floods and droughts. Model studies (e.g., Paltan et al., 2018) and recent observed changes (e.g., Wang et al., 2018) demonstrate the potential for large changes in regional patterns of precipitation, which can lead to extreme floods in areas that have not experienced such floods before, and to extreme droughts where droughts have been virtually unknown before. It appears likely that the magnified shift in temperatures will bring more concurrent temperature and drought extremes in the future, exacerbating individual impacts from heat waves and droughts (Chiang et al., 2018).

A global existential threat not addressed by the scenario studies mentioned above is associated with the passing of possible climate tipping points, which, if these points exist, could lead to a very different climate state. Steffen et al. (2018) point out that climate does not change linearly but rather in steps, which potentially could be large and catapult the Earth system into a hothouse state very detrimental to the human population. As a result, the single-species high-energy pulse comes with the potential to push the climate system over a tipping point separating the current climate from a hothouse state.

Impacts on Humanity

Climate change impacts on humans are not equally distributed across the planet, and it is very likely that the impacts will increase inequality. For example, the impacts of heat waves on workers are expected to be much larger in the developing world than in the developed world (Burke et al., 2015). There is also injustice in the sense that many of the countries that have least contributed to the cause of modern global and climate change will likely be burdened with the most severe consequences, while at the same time having the least resources to cope with them.

"Climate change is fundamentally redrawing the map of where people can live" (Solheim & Swing, 2018). Mass migration is already posing a global-scale problem and this challenge is very likely going to increase rapidly. Migration will also result from a potentially significant reduction in global carrying capacity, which could cause large-scale famine (Spratt & Dunlop, 2018).

A major economic risk is associated with sea-level rise. In many areas, population has moved into the coastal zone, and most of the megacities are located in coastal areas with little topography. Even a modest increase in sea level could result by 2100 in annual flood costs on the order of tens of trillion US dollars (Jevrejeva et al., 2018). However, an economic crisis of unparalleled scale could emerge much earlier if risk perception concerning sea-level rise changes and the currently high value of coastal real estate property evaporates.

Increased storminess can amplify the extensive disturbances that storms cause to marine ecosystems and habitats that support productive fisheries (Sainsbury et al., 2018). The impact of changing storms on fisheries will vary spatially due to spatial variations in projected changes in storm risk, changes in target fish species, the resilience of infrastructure and the extent of natural and man-made storm defenses. It is expected that the impacts will be larger for small-scale fisheries (Sainsbury et al., 2018). Considering that 3.1 billion people get close to 20% of their animal protein from fish, and fish are relied on for vital micronutrients, a negative impact of changes in storminess on fisheries can have a significant impact on food security.

The expected increase in atmospheric CO_2 is predicted to have an impact on the nutritional value of major food sources. Many food crops grown under atmospheres with CO_2 contents of 550 ppm have significantly reduced protein, iron, and zinc contents compared with current conditions (Smith & Myers, 2018). The likely increase in atmospheric CO_2 over the next decades could lead to an additional more than 100 million people being protein deficient, and many more impacted by a significant reduction of dietary iron, particularly in high risk regions such as South and Southeast Asia, Africa, and the Middle East (Smith & Myers, 2018).

The most devastating impact of modern climate change on humanity could result from a significant reduction of the Earth's carrying capacity. Lovelock (2009) estimated that by 2050 the global carrying capacity may be down to 1 billion humans. The fossil fuel-based industrial agriculture created a transient increase in carrying capacity in terms of food and allowed in the last century the addition of 5.5 billion individuals to the already existing population of 1.5 billion humans. It must be doubted that this increase in carrying capacity can be maintained indefinitely. In fact, it is not clear that the carrying capacity was actually increased, since it resulted from a large-scale use of non-renewable resources (including land and soil) and caused widespread soil degradation. Providing water and food to sustain the growing population is increasingly challenging (de Marsily & Abarca-del Rio, 2016). Moreover, the rapidly growing population is exceeding the carrying capacity in almost all other aspects including land-use (Barnosky et al., 2012), mineral resources (Assadourian, 2013), and harvesting the biosphere (Smil, 2011).

From an analytical outside look at an ecosystem typically applied by ecologists, it is easily recognized if a population exceeds the carrying capacity of this system. However, from a more experimental inside look strictly limited to the human population, it might appear that humans have not exceeded the carrying capacity because there are still enough individuals to produce offspring and increase the population size. Importantly, the point where the carrying capacity is exceeded is long before the impacts are felt and a complete collapse of the population is unavoidable (Figure 1.3). A transient increase in carrying capacity may delay the collapse, but it also increases the overshoot and the size of the subsequent catastrophic population collapse significantly. For humanity, the point of crossing the unmodified planetary carrying capacity appears to be some time before industrial agriculture facilitated a large transient increase. Modern global and climate change may make it increasingly difficult to sustain this transient increase in the carrying capacity to further delay the collapse.

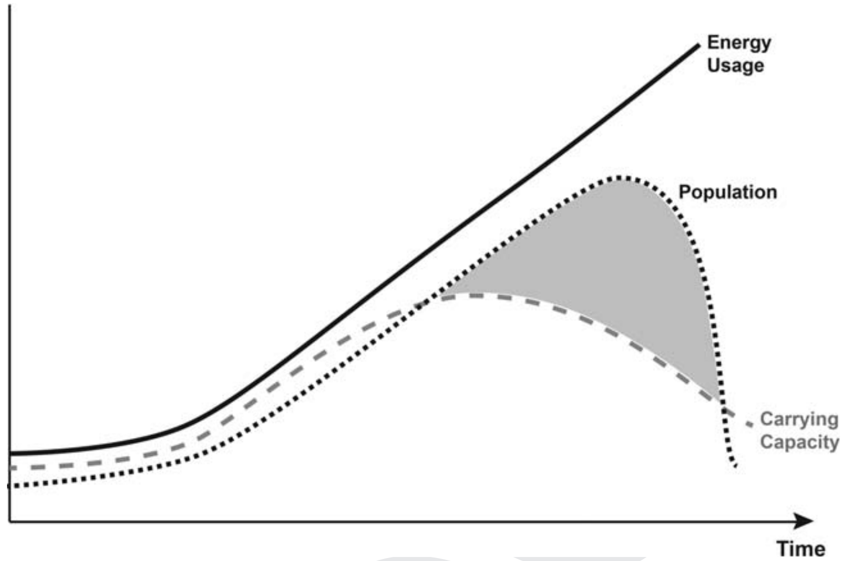

FIGURE 1.3 Impact of a transient increase in Earth's carrying capacity on population. Humanity has used its easy access to seemingly unlimited energy to facilitate a transient increase in Earth's carrying capacity, which sustained a rapid population growth most likely beyond the carrying capacity (gray area). The likely reduction of the carrying capacity will increase the overshoot and the severity of the population collapse.

Impacts on the Earth's Life-Support System

Ecosystems react to climate change by altering structure, behavior, and movements. For example, poleward extension of the tropics is a likely consequence of a warming climate (Staten et al., 2018). The extent of anthropogenic land use changes combined with climate change has the potential to initiate a state shift of the global biosphere (Barnosky et al., 2012). When species cannot tolerate climate change *in situ*, or migrate and colonize suitable habitat elsewhere quickly enough, they become extinct (Nogués-Bravo et al., 2018). The ability of species to adapt depends on the speed of changes. The option of migration also depends on the availability of suitable migration paths and locations. Anthropogenic climate disruption is predicted to soon compete with habitat destruction as the most important driver of contemporary extinctions (Nogués-Bravo et al., 2018). Without substantial mitigation efforts, terrestrial ecosystems are at risk of major transformation in composition and structure. Records of terrestrial vegetation since the last glacial period indicate that terrestrial ecosystems are highly sensitive to temperature change (Nolan et al., 2018). Considering that the projected temperature changes are much faster than those during the warming after the last ice age, it is highly likely that modern climate change puts terrestrial ecosystems worldwide at risk of major transformation, impacting biodiversity and disrupting ecosystem services (Nolan et al., 2018).

The anticipated changes in many aspects of climate could also lead to possible formation of novel climates with conditions that have no current or past analog (Williams & Jackson, 2007). This prospect, which entails that existing habitats would disappear and new reconfigured ones would arise, puts limits on the capability to describe the transitions the Earth's life-support system might be heading to and to develop foresight covering all possible futures (Kittel, 2013). Scenario-based studies consistently indicate that biodiversity will continue to decline throughout the 21st century, but the range of projected changes is still very broad because of major policy opportunities for interventions and large uncertainties in projections (Pereira et al., 2010).

Therapy

Addressing the Climate Symptom

Reduction of greenhouse gas emissions is widely considered to be the most important step for mitigating climate change, and a wide range of countries and organizations are focusing on a decarbonization of human systems. The commitments made as part of the Paris Agreement indicate the growing understanding of the importance of this action. Adopted in 2015, the Paris Agreement set the specific goal of keeping global warming well below 2°C above pre-industrial levels, and of pursuing efforts to limit the warming to 1.5°C. However, the most recent report published by the Intergovernmental Panel on Climate Change (IPCC, 2018) concludes that:

> Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (high confidence). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (medium confidence).

Considering the urgency of the required transitions in the next ten years, it is highly unlikely that humanity will be willing and able to thoroughly reorganize basically everything.

A number of geoengineering approaches have been proposed to reduce the incoming solar radiation reaching the Earth's surface, to accelerate CO_2 absorption in major sinks, to extract CO_2 from the atmosphere, or to increase ice accumulation in the Arctic to limit sea level rise, among others. Most of these proposals have potentially severe side effects and could easily lead to failure with severe consequences afterwards (e.g., Cotton-Barratt et al., 2016). A recent proposal to cover a very large part of the Sahara desert with solar panels both to utilize the electrical power generated and to change the surface albedo to increase rainfall and thus reverse the expansion of the desert caused by climate change (Li et al., 2018) is among the more realistic proposals. A promising removal strategy would utilize biogeochemical improvement of soils by adding crushed, fast-reacting silicate rocks to croplands (Beerling et al., 2018). This approach could lead to improved crop production, increased protection from pests and diseases, and restoration of soil fertility and structure. However, none of the climate geoengineering proposals appears to have the potential to sufficiently reduce emissions (Lawrence et al., 2018).

A major transition of building material from concrete and steel to wood also provides an opportunity to reduce carbon emission. A significant transition to a meat-reduced diet on global scale could further reduce greenhouse gas emissions in the form of CO_2 and CH_4. However, Rieder (2016) concludes that reducing procreation would be the single most efficient step to reduce greenhouse gas emissions.

Aiming for Sustainability

The global community is pursuing a quest for sustainable development, which in 2015 resulted in the agreement on seventeen Sustainable Development Goals in the 2030 Agenda for Sustainable Development (United Nations, 2015). Only one of these goals focuses on mitigation of climate change and adaptation to an emerging new climate, while several others are related to climate change drivers. Likewise, very few of the goals aim at reducing the flows in the Earth's life-support system. In the process leading to the Agenda, several proposals were made for goals that acknowledged the importance of safeguarding the Earth's life-support system and keeping it within the boundaries of the safe operating space (e.g., Griggs et al., 2013), but these proposals were not agreeable to the intergovernmental United Nations.

A number of fundamental transformations have been identified that would facilitate progress towards the Sustainable Development Goals (e.g., Utting, 2016; TWI2050 – The World in 2050, 2018). However, all of these transformations are anthropocentric and lack a deep understanding of humanity as an integral part of the Earth's life-support system together with all other species. While these transformations might slow down the rapid degradation of the health of the planetary life-support system and to some extent slow down climate change, they are by far not sufficient to reverse the degradation and improve the system's health.

Importantly, none of these transformations addresses the fact that the current economic model discounts the future and is focused on immediate needs and benefits. The growth-dependent mainstream economic model is a major obstacle for progress towards more sustainability and mitigating global and climate change. Climate change policies often are focused on increasing energy efficiency. However, efforts to decouple economic growth from impacts on the life-support system by increasing efficiency as part of a "green economy" are likely to fail due to the Jevons paradox (e.g., Jevons, 1866; Freire-González & Puig-Ventosa, 2015). This is a rebound effect in which the reduction of costs in energy (or resource) services actually leads to higher consumption as a result of increased efficiency. Model-based studies show that the rebound effect leads to an increase of resource usage far beyond the Earth's carrying capacity (Font Vivanco et al., 2016). Consequently, within an economic system that favors and demands growth, the cataclysmic energy pulse created by *Homo sapiens* can hardly be ended or reduced by an increase of efficiency, and the world as a whole is not on a track towards "greener growth" or a "green economy" (Giljum et al., 2014).

Ending the Energy Pulse

The most promising avenue to thoroughly limiting the impact of the single-species high-energy pulse on the Earth's life-support system is implicit in the definition of sustainable development as provided by Griggs et al. (2013). Recognizing the role of the mainstream economic model in the regulation of flows between human communities and the Earth's life-support system, the purpose of economy needs to be extended from the creation of human wealth to the safeguarding of the Earth's life-support system (Plag & Jules-Plag, 2017). With this extension, economic activities would inherently aim to meet the needs of human communities while at the same time limit the flows between these communities and the planetary life-support system and ensure that the flows are not degenerating the health of this system. Applying ethical principles to assess the morality of human interactions with the life-support system, as done, for example, by Rieder (2016), would provide additional justifications for this fundamental change in the purpose and goals of economy. This would transform the anthropogenic virus into the healer of the life-support system. By elevating the safeguarding of the planetary life-support system to being the purpose of economy, it seems possible for humanity to change its function from a potentially catastrophic virus in the Earth's life-support system to the "healer" of this system. In fact, without this transformation of the purpose of economy, it appears likely that a major state shift of the planetary life-support system will lead to a socio-economic collapse with a deconstruction of the current governance structures that ensure some level of civilization (Bendell, 2018).

Concluding Remarks

The extraordinary brains of *Homo sapiens* have enabled this species to outcompete all other mammals and to re-engineer the planetary life-support system to an extent very few other species were able to achieve in Earth's history. And those other highly successful species often modified the system to an extent that made it no longer suited for their own survival, particularly after thresholds were crossed. On the other hand, species that have low metabolic rates and are least impactful on their environment seem to have persisted over much longer times. The basal metabolic rate "could therefore represent an important metric for predicting future extinction patterns, with changes in global climate potentially affecting the lifespan of individuals, ultimately leading to the extinction of the species they are contained within" (Strotz et al., 2018). This raises the question of whether the principles of evolution actually limit the chances of a single exceptionally successful species to take control of the Earth's life-support system without pushing the system outside the safe operating space for this species. The extraordinary success of *Homo sapiens* in developing and maintaining a virtual metabolic rate far above the rate within the scaling law for mammals created a cataclysmic energy pulse that modified the Earth's life-support system fundamentally. The planetary system is being pushed into a new high-energy climate state, a hothouse state (Steffen et al., 2018), unsuitable for most mammals to survive. This success may be the basis for the demise of this—and many other—species.

As hard as it may be to accept this, modern climate change could turn out to be a process that ends the current high-energy pulse and the global dominance of a single species, thus restoring some inter-species equity and justice in the Earth's life-support system. Garnett (2018) asks whether the modern human impact on all aspects of the Earth's life-support system is leading to a total systemic failure of this system and suggests that humanity currently lacks "the tools and analytical capacity to understand the significance of these changes and therefore" cannot answer this question. This incapacity of fully assessing the human impact on the Earth's life-support system should lead humanity to a very careful progress and should put focus on "less being better," instead of trying to facilitate more economic growth and to sustain a rapidly increasing global population. Reducing the global population through a change in the morality of procreation, as concluded by Rieder (2016), would be at the core of mitigating modern global and climate change and safeguarding the Earth's life-support system.

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