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INVITED PAPER

The Anthropocene: From Global Change to Planetary Stewardship

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Abstract Over the past century, the total material wealth of humanity has been enhanced. However, in the twenty-first century, we face scarcity in critical resources, the degradation of ecosystem services, and the erosion of the planet's capability to absorb our wastes. Equity issues remain stubbornly difficult to solve. This situation is novel in its speed, its global scale and its threat to the resilience of the Earth System. The advent of the Anthropence, the time interval in which human activities now rival global geophysical processes, suggests that we need to fundamentally alter our relationship with the planet we inhabit. Many approaches could be adopted, ranging from geoengineering solutions that purposefully manipulate parts of the Earth System to becoming active stewards of our own life support system. The Anthropocene is a reminder that the Holocene, during which complex human societies have developed, has been a stable, accommodating environment and is the only state of the Earth System that we know for sure can support contemporary society. The need to achieve effective planetary stewardship is urgent. As we go further into the Anthropocene, we risk driving the Earth System onto a trajectory toward more hostile states from which we cannot easily return.

Keywords Earth System · Anthropocence · Planetary stewardship · Ecosystem services · Resilience

PEOPLE AND THE PLANET: HUMANITY AT A CROSSROADS IN THE TWENTY-FIRST CENTURY

The twin challenges of "peak oil"—decreasing petroleum resources and increasing demand—and climate change are redefining the pathways of human development in the twenty-first century (Sorrell et al. 2009; ASPO 2010; Richardson et al. 2011). Less well known is the potential shortage of the mineral phosphorus and the increasing competition for land—sometimes referred to as the "land grab" in relation to Africa—as the new economic giants of Asia move to secure food resources in non-Asian territories. The pathways of development followed by today's wealthy countries after the Second World War—built on plentiful, cheap fossil fuel energy resources, an abundance of other material resources, and large expanses of productive land to be developed—cannot be followed by the 75–80% of the human population who are now at various stages of their trajectories out of poverty, and are beginning to compete with today's wealthy countries for increasingly scarce resources.

A large fraction of our population of nearly 7000 million people needs more access to food, water and energy to improve their material standard of living, and the prospect of an additional 2000 million by 2050 intensifies the need for basic resources. These challenges come at a time when the global environment shows clear signs of deterioration and, as a consequence, questions the continuing ability of the planet to provide the same accommodating environment that has facilitated human development over the past 10 000 years.

Climate change is a prominent sign of human-driven changes to the global environment. The evidence that the Earth is warming is unequivocal, and human emissions of greenhouse gases, most importantly carbon dioxide (CO_2), have been responsible for most of the warming since the middle of the twentieth century (IPCC 2007). The man-made greenhouse gases have already trapped enough infrared energy to warm the planet by more than 2°C (Ramanathan and Feng 2008). Although many uncertainties still surround the risks associated with climate change, impacts are already observable at today's mean global surface temperature rise of about 0.8°C since the mid-nineteenth century. These risks, such as those associated with sea-level rise, extreme events, and shifts in rainfall patterns, rise sharply as the temperature climbs toward 2°C above pre-industrial and quite possibly beyond (Richardson et al. 2011).

At least as disturbing as climate change, and far less well known and understood, is the erosion over the past two centuries of ecosystem services, those benefits derived from ecosystems that support and enhance human well-being. The Millennium Ecosystem Assessment (MA 2005) assessed 24 ecosystems services, from direct services such as food provision to more indirect services such as ecological control of pests and diseases, and found that 15 of them are being degraded or used unsustainably. Humanity now acquires more than the ongoing productivity of Earth's ecosystems can provide sustainably, and is thus living off the Earth's natural capital in addition to its productivity. This can lead to continued improvements to human well-being for some time, but cannot be sustained indefinitely.

The challenges of peak oil, peak phosphorus (where the demand for phosphorus may soon outstrip supply; Cordell et al. 2009; Sverdrup and Ragnarsdottir 2011) and climate change demonstrate the existence of limits to the rate or magnitude at which humanity can consume the planet's geophysical resources. Furthermore, climate change and the appearance of the ozone hole owing to man-made chemicals are strong evidence that humanity can overwhelm important chemical, physical, and biological processes that modulate the functioning of the Earth System. These unintended consequences on the global life support system that underpins the rapidly expanding human enterprise lie at the heart of the interconnected twenty-first century challenges.

The classification system developed to define ecosystem services (MA 2005) might be extended to include geophysical goods and services and expanded to the scale of the planet as a whole. These could be called Earth System goods and services. The classification, based on three of the four ecosystem services of the MA (2005), would include the following types.

Provisioning goods and services: Most commonly known as "resources", these include the well-known ecosystem services of food, fiber, and fresh water (natural resources), but would now also include fossil fuels, phosphorus, metals, and other materials derived from Earth's geological resources. Many, but far from all, of these types of goods and services have market prices, which can regulate supply and demand to some extent.

Supporting services: In the ecosystem framework, these include nutrient cycling, soil formation and primary production. All are necessary to support, for example, well-functioning agricultural systems. They are also sometimes called "environmental resources". Geophysical processes also provide supporting services that indirectly yield benefits for humanity. Examples include the long-term provision of fertile soils through glacial action, the upwelling branches of ocean circulation that bring nutrients from the deep ocean to support many of the marine ecosystems that provide protein-rich food, and the Himalayan glaciers that act as giant water storage facilities for the provision of water resources.

Regulating services: Two of the most well known of these are the ecological control of pests and diseases and regulation of the climate system through the uptake and storage of carbon by ecosystems. These regulating services, also sometimes considered environmental resources, help maintain an environment conducive for human life, rather than directly contributing to provisioning goods and services. Storage of carbon by ecosystems is a part of a larger, Earth System regulatory service that has a significant geophysical component—the dissolution of atmospheric CO_2 into the ocean. Other Earth System services include the set of chemical reactions in the stratosphere that continually form ozone, essential for filtering out biologically damaging ultraviolet radiation from the sun, and the role of the large polar ice sheets in regulating temperature. Regulating services are generally considered as "free services" provided by nature.

The accelerating pressures on all three types of Earth System goods and services that connect people and the planet are coming together in the first decades of the twenty-first century to generate a global sustainability crisis. The concept of social–ecological systems is proving to be a powerful concept to deal with sustainability challenges arising from the complex interaction of people and environment at local and regional scales. It has been little applied yet to the global scale (Folke et al. 2011). However, the concept of a planetary-scale social–ecological–geophysical system is rapidly becoming a reality. Or, more simply, the human enterprise is now a fully coupled, interacting component of the Earth System itself (Steffen et al. 2004).

A human-inclusive Earth System implies that global-scale social and economic processes are now becoming significant features in the functioning of the System, like atmospheric and oceanic circulation. Prominent social processes are the globalization of trade and finance and the rapid increase in communication, especially via the internet (Castells 2010). This level of social and economic connectivity is generating some instabilities in the human enterprise. The Global Financial Crisis is a good example, where an instability in one country—in the US sub-prime market—quickly propagated and amplified to drive a drop in US GDP of about 400 times the total value of the subprime market, and cascaded internationally to trigger a global recession, shrink the availability of credit, and increase the levels of poverty and unemployment in many countries around the world (Taylor 2009), with long-term effects for some but relatively rapid recovery for others.

When the hyper-connectivity of the human enterprise intersects with the pressures on Earth System goods and services, some concatenated global crises can propagate rapidly through the Earth System. The food price crisis of 2008 is a recent example. Global prices of staples such as rice and wheat rose sharply (wheat by 81% and rice by 255%) from 2004 to 2008, with most of the rise coming in the last 12 months (IRRI 2010), leading to food riots in some countries and affecting 100 million people worldwide. One analysis points to several interacting drivers as the cause—rising energy prices, pro-biofuel policies, and export restrictions by managers in middle- and low-income countries (Biggs et al. 2011), and speculative actions by strong players in the market may also have played a role. However, it now seems likely that energy price rises were the dominant global driver, overshadowing the other contributing factors. The connectivity provided by the Internet and mobile phones has also likely played a role in the unrest in North Africa in early 2011. Citizens there were able to see what others elsewhere in the world have while they face rising food prices, in part driven by a grain export ban in Russia in 2010 owing to a fire-related reduction in yields (Fraser and Rimas 2011).

As these twenty-first century problems become better understood, the focus turns toward finding solutions. One of the key developments in moving from problem definition to solution formulation is the concept of the Anthropocene (Crutzen 2002), which cuts through a mass of complexity and detail to place the evolution of the human enterprise in the context of a much longer Earth history. This analysis sharpens the focus on an overarching long-term goal for humanity—keeping the Earth's environment in a state conducive for further human development.

The Anthropocene implies that the human imprint on the global environment is now so large that the Earth has entered a new geological epoch; it is leaving the Holocene, the environment within which human societies themselves have developed. Humanity itself has become a global geophysical force, equal to some of the "great forces of Nature" in terms of Earth System functioning (Williams et al. 2011). The term is still informal, but is being analyzed by a working group of the International Commission on Stratigraphy as regards potential formalization (Zalasiewicz et al. 2012).

The concept of the Anthropocene focuses the twenty-first century challenges for humanity away from resource constraints and environmental impacts toward more fundamental questions. What are the implications of the Anthropocene for the future of humanity in the twenty-first century and beyond? Can we become active, effective stewards of the Earth System, our own life support system (Schellnhuber 1999)?

THE ANTHROPOCENE: FROM HUNTER-GATHERERS TO A GLOBAL GEOPHYSICAL FORCE

For well over 90% of its 160 000 year history, *Homo sapiens* have existed as hunter-gatherers only. During that time our ancestors had demonstrable impacts on their environment, even at scales approaching continental, through, for example, fire-stick farming and hunting of mega-fauna during the latest Pleistocene. However, these human impacts registered only slightly at the global scale, and the functioning of the Earth System continued more or less unchanged.

About 10 000 years ago, near the onset of the Holocene, agriculture was developed in four different parts of the world. This eventually led to a more sedentary lifestyle, the development of villages and cities, and the creation of complex civilizations that eventually spanned large regions. Land-clearing for agriculture affected large areas of the land surface but the rate of clearing was tightly constrained by the availability of energy; only human and animal power was available. These early agricultural activities may have had an appreciable effect on the functioning of the Earth System via an increase in atmospheric CO_2 concentration (Ruddiman 2003), but any increase was not enough to raise the CO_2 concentration beyond the envelope of natural variability (Steffen et al. 2007). The Earth System was still operating within the Holocene state, even with the influence of early agriculture.

Around 1800 AD, the industrial era began with greatly enhanced use of fossil fuels. Land-clearing occurred at a much greater rate, and land ecosystems were converted from mostly wild to mostly anthropogenic, passing the 50% mark early in the twentieth century (Ellis et al. 2010). The industrial fixation of nitrogen from the atmosphere, now possible with fossil fuels, produced large amounts of fertilizer, breaking a constraint on food production. Sanitation systems were improved, yielding great benefits for human health and improving urban environments, while passing the effluent to downstream ecosystems whose buffering capacities were able to purify the water until being overwhelmed in recent decades (Scheffer et al. 2001). Population grew more rapidly, with increases in life expectancy and well-being. Fossil fuel-based manufacturing systems enhanced the production of goods, and consumption began to grow with population. Unknown to human societies at the time (but see Arrhenius 1896), the rapid expansion of fossil fuel usage was slowly raising the CO_2 concentration in the atmosphere, and by the early twentieth century the CO_2 concentration was clearly above the upper limit of Holocene variability.

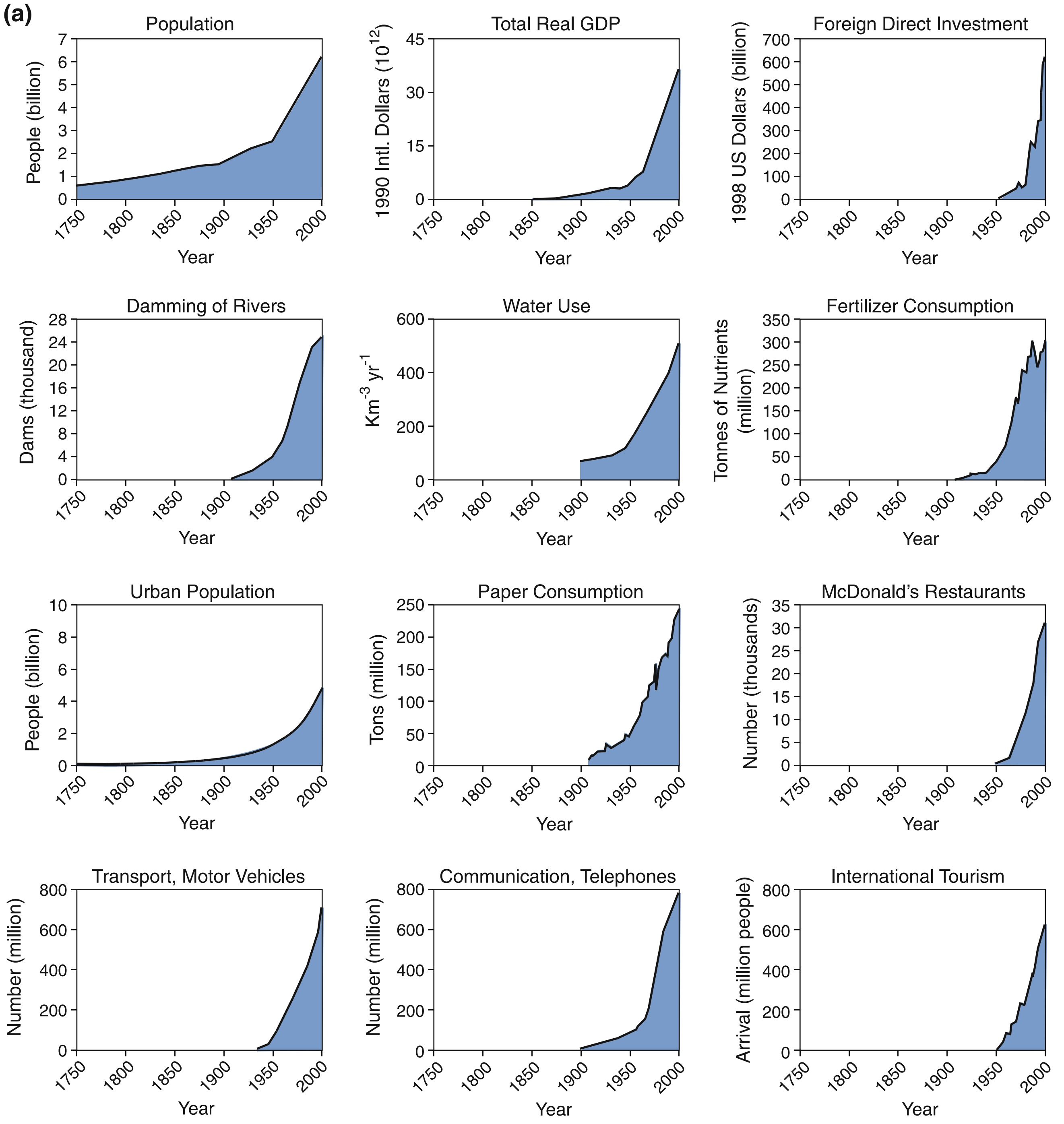


Fig. 1 **a** The increasing rates of change in human activity since the beginning of the Industrial Revolution to 2000. Significant increases in rates of change occur around the 1950s in each case and illustrate how the past 50 years have been a period of dramatic and unprecedented change in human history (Steffen et al. 2004, and references therein). In the following part figures, the parameters are disaggregated into OECD (wealthy) countries (*blue*) and non-OECD (developing) countries (*red*); **b** Population change from 1960 through 2009, in 1000 millions of people (World Bank 2010); **c** Increase in real GDP from 1969 through 2010, in trillions 2005 USD (USDA 2010); **d** Communication: increase in telephones (millions), both land-lines and mobile phones, from 1950 through 2009 (Canning 1998; Canning and Farahani 2007; ITU 2010)

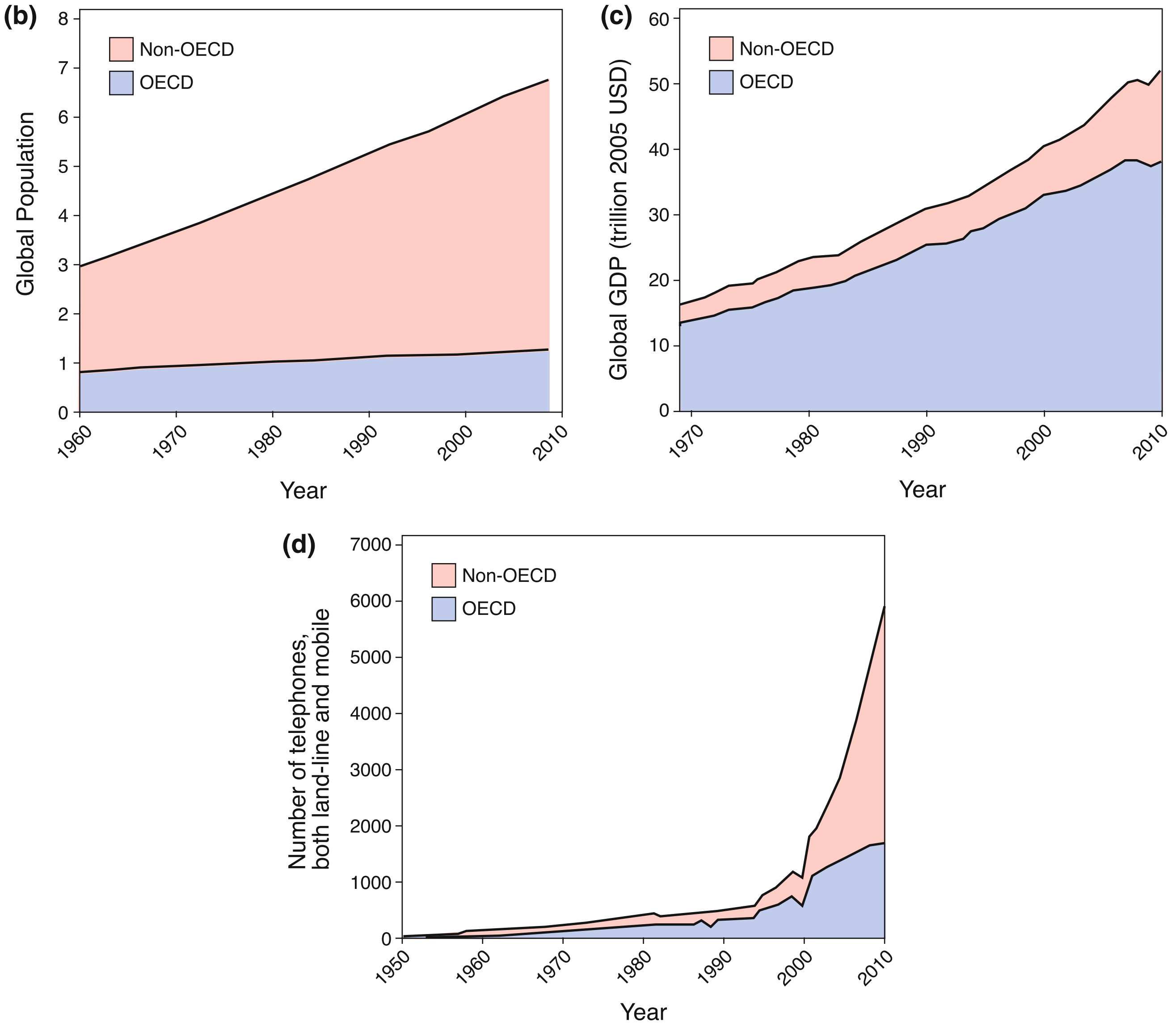


Fig. 1 continued

The remarkable discontinuity in the human enterprise about the middle of the twentieth century defines the beginning of second stage of the Anthropocene. The speeding up of just about everything after the Second World War—sometimes called the Great Acceleration (Hibbard et al. 2006)—is shown in Fig. 1a. Human population has tripled, but the global economy and material consumption have grown many times faster. The connectivity of humanity has grown at an astounding rate since 1950, as seen in foreign direct investment, international tourism and the numbers of motor vehicles and telephones.

A simple way to estimate the overall impact of the Great Acceleration on the global environment is via the IPAT identity, where the impact is the aggregate of changes in population, affluence (an indicator for consumption) and technology. The volume of the box in Fig. 2 depicts the overall impact (I) and the three axes represent the three drivers (P, A, T). The enormous increase in the volume of the box from 1950 to 2011 relative to the 1900–1950 period shows the Great Acceleration. Also evident is the change in the relative importance of the factors. From 1900 to 1950 population, consumption and technology had roughly equal effects, while from 1950 to the present increases in consumption and technology have become the dominant factors driving environmental impact.

Figure 3, using the same time period as Fig. 1a, shows the corresponding changes in the structure and functioning of the Earth System. Human causation of the trends is obvious, indeed, by definition, in four of the six lower panels—exploitation of fisheries, conversion of mangrove

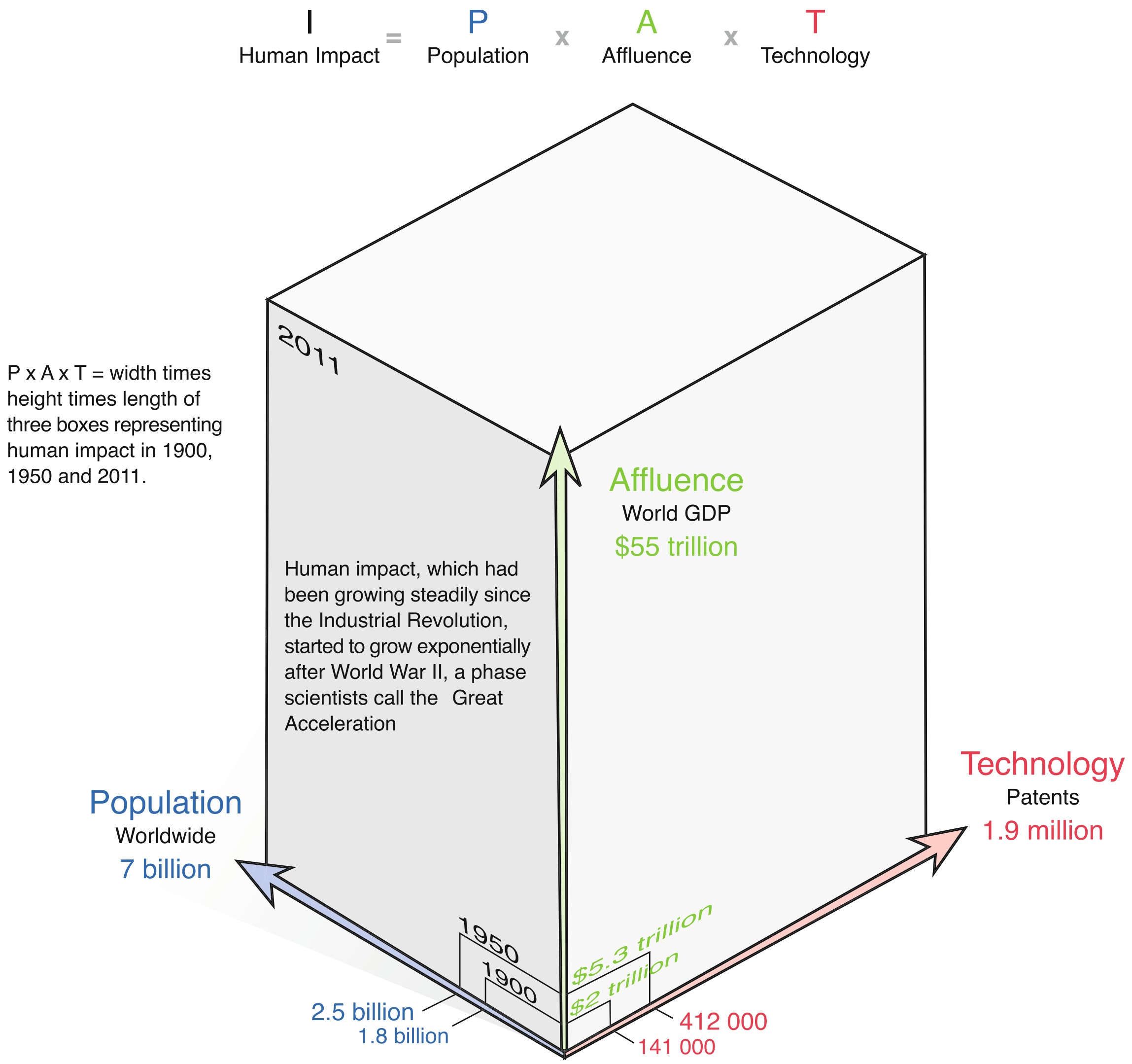


Fig. 2 I = PAT identity at the global scale from 1900 to the present. Note the difference in volume between the 1990–1950 period and the 1950–2011 period, which represents the Great Acceleration (Kolbert 2011)

forests to shrimp farms, tropical deforestation and increase in domesticated land. Of the other two, increasing nitrogen fluxes in the environment can be traced directly to human fixation of atmospheric nitrogen (Galloway and Cowling 2002), and the increasing loss of biodiversity (Barnosky et al. 2011) is undoubtedly caused by a number of human activities (MA 2005). Of the top six panels, increases in the three well-known greenhouse gases can be unequivocally linked to anthropogenic sources (IPCC 2007), and the role of human-made chemicals in the reduction of stratospheric ozone has been beyond doubt for some time (Crutzen 1995). There remains debate only on human causation of the rise in northern hemisphere temperature and the increase in large floods; according to the IPCC (2007), there is overwhelming evidence that the former is primarily due to human-driven increases in greenhouse gas levels.

As humans are terrestrial creatures, we focus strongly on changes in the planetary environment that occur on the land (e.g., degradation and deforestation) or the atmosphere (e.g., climate change) rather than the cryosphere or the ocean. However, in terms of planetary stewardship, the ocean is arguably more important than either land or atmosphere in the functioning of the Earth System; it modulates modes of climate variability, provides the moisture for most of rainfall over land that supports agriculture and cities, and stores much more carbon than the land and atmosphere combined.

The concept of Earth System goods and services is an effective framework to explore the important roles of the ocean. Provisioning services include food, medicinal products and fresh water via desalination. Supporting services include the absorption and recycling of human-generated waste products; much of the nitrogen and

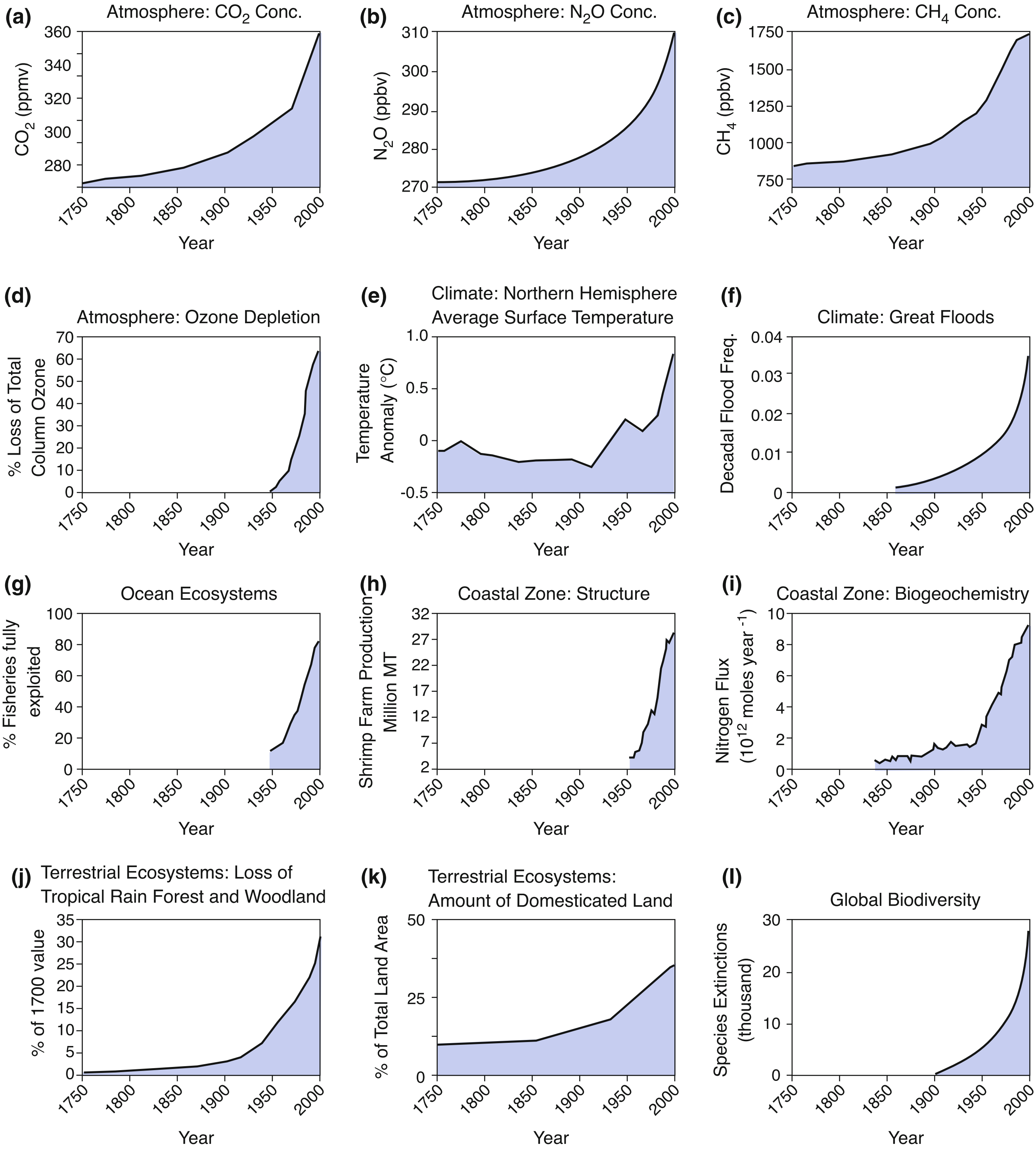


Fig. 3 Global-scale changes in the Earth System as a result of the dramatic increase in human activity: **a** atmospheric CO_2 concentration, **b** atmospheric N_2O concentration, **c** atmospheric CH_4 concentration, **d** percentage total column ozone loss over Antarctica, using the average annual total column ozone, 330, as a base, **e** northern hemisphere average surface temperature anomalies, **f** natural disasters after 1900 resulting in more than 10 people killed or more than 100 people affected, **g** percentage of global fisheries either fully exploited, overfished or collapsed, **h** annual shrimp production as a proxy for coastal zone alteration, **i** model-calculated partitioning of the human-induced nitrogen perturbation fluxes in the global coastal margin for the period since 1850, **j** loss of tropical rainforest and woodland, as estimated for tropical Africa, Latin America and South and Southeast Asia, **k** amount of land converted to pasture and cropland, and **l** mathematically calculated rate of extinction (Steffen et al. 2004, and references therein)

phosphorus waste from agricultural fertilizers and animal and human excrement ends, ultimately, in the coastal oceans, where they are metabolized. Regulating services include climate regulation via the uptake of atmospheric CO_2, but which also increases ocean acidity (Royal Society 2005), which in turn places stress on calcifying organisms such as corals and thus influences the provisioning service that coral reefs provide (Moberg and Folke 1999). More subtle is the role of the ocean circulation in establishing the global distribution patterns of heat and moisture and thus the patterns of water availability for human societies.

Returning to Fig. 1, some important changes have occurred in the characteristics of the human enterprise around the end of the twentieth century. Parts b, c, and d of the figure split the globally aggregated data for population, global GDP and the number of telephones into developed (OECD) and developing and transitional (non-OECD) countries for approximately the last 50 years. This disaggregation reveals two important features of the last decade. First, the post-2000 increase in growth rates of some non-OECD economies (e.g., China and India) is evident, but the OECD countries still accounted for about 75% of the world's economic activity. On the other hand, the non-OECD countries continue to dominate the trend in population growth. Comparing these two trends demonstrates that consumption in the OECD countries, rather than population growth in the rest of the world, has been the more important driver of change during the Great Acceleration, including the most recent decade, as shown also in Fig. 2.

The second feature is the encouraging "leapfrogging" of the non-OECD countries in some aspects of their development pathway, compared to the earlier development pathway of the OECD countries. For example, the increase in telephones over the past decade (Fig. 1d) has been dominated by the sharp rise in the number of phones in the developing world, with most of these being mobile phones rather than landlines (Canning and Farahani 2007; Canning 1998; ITU 2010). Much more challenging, however, is for the non-OECD countries to leapfrog the OECD fossil fuel intensive energy development pathways and thus decouple greenhouse gas emissions from strong economic growth.

Equity issues are also apparent in the changing pattern of CO_2 emissions (Raupach et al. 2007). While the wealthy countries of the OECD dominated emissions for much of the twentieth century, the share of emissions from developing countries rose rapidly to 40% of the annual total by 2004. By 2008 China had become the world's largest emitter of CO_2, with India becoming the third largest. However, the world's wealthy countries account for 80% of the cumulative emissions of CO_2 since 1751; cumulative emissions are important for climate given the long lifetime of CO_2 in the atmosphere. The world's poorest countries, with a combined population of about 800 million, have contributed less than 1% of the cumulative emissions.

One other twenty-first century feature of the Anthropocene, a great paradox, involves life itself. Humanity has now come very close to synthesizing life with the construction in 2010 of a genome from its chemical constituents, which was then implanted successfully into a bacterium where it replaced the original DNA (Gibson et al. 2010). This costly, labor-intensive and time-consuming exercise is in stark contrast to the continuing decline in the Earth's existing biological diversity. In a recent study, 31 indicators of biodiversity change show no reduction in the rate of biodiversity decline from 1970 to 2010; furthermore, the rate of human response to the biodiversity decline has itself slowed over the past decade (Butchart et al. 2010). Understanding the trajectory of the human enterprise from our long past as hunter-gathers to the Great Acceleration and into the twenty-first century provides an essential context for the transformation from resource exploitation toward stewardship of the Earth System. This has evolved from its early state, hostile to human existence, to the one we know today. We now take from it the goods and services that underpin our lives, at a scale and rate that is eroding its capacity to support us (Fig. 4—photo: Irrigated agriculture).

UNDERSTANDING PLANETARY DYNAMICS: EARTH AS OUR LIFE SUPPORT SYSTEM

Humans have been in existence for only a very small fraction of the Earth's history. The planet's evolution has produced environments far different from that we know today—at least two episodes of near-complete freezing; much warmer periods than the present; atmospheric change from a chemically reducing to an oxidizing atmosphere; constant rearrangement of land and ocean; and a biology that has evolved from primitive beginnings into a succession of spectacular and diverse life forms. Figure 5 shows the temperature variation during the most recent 70 million years, with increasing higher temporal resolution from panels a to d.

Two features shown in Fig. 5 are particularly important for this analysis. First, the Quaternary as a whole thus clearly shows a systematic increase in long-term climate variability (panel b). Model simulations hint that the late Quaternary may represent a short, transient phase of climate instability toward a new stable state of a permanently glaciated, low-CO_2 world—a potential future now derailed by the injection of large amounts of greenhouse gases into the atmosphere (Crowley and Hyde 2008). Regardless, the late Quaternary clearly represents a time when the Earth

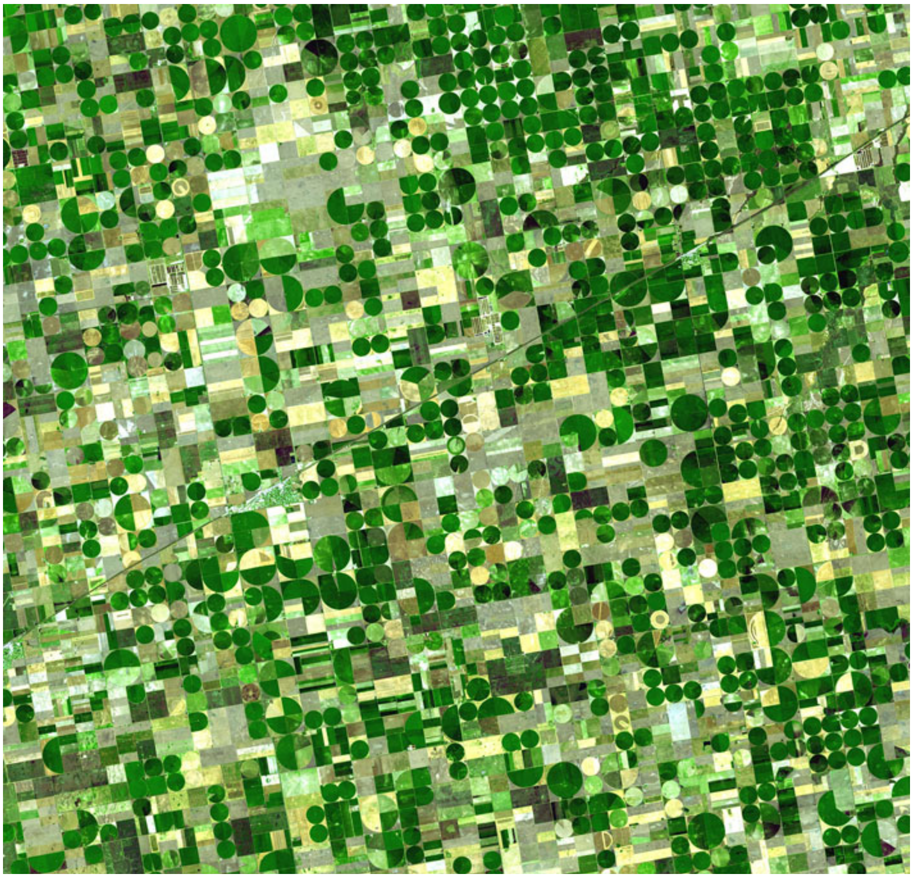


Fig. 4 The human domination of land systems in the Anthropocene. Irrigated landscape, USA (photo: Azote)

System is unusually sensitive to being switched between strongly contrasting states by modest forcing agents or internal feedbacks.

Second, the Holocene, by comparison with the late Pleistocene, has shown remarkable climate stability (panel c; Petit et al. 1999), with relatively minor changes of a millennial and smaller-scale periodicity, such as the ca., 1°C change from the Medieval Warm Period to the Little Ice Age, a mainly northern hemisphere phenomenon, but nothing remotely on the scale of a Dansgaard–Oeschger cycle (panel c). This stability has been maintained for longer than in the last three interglacials, and might naturally continue for at least 20 000 years, or perhaps even longer, based on orbital similarities with earlier 'long interglacials' (Berger and Loutre 2002).

The stable Holocene has proven to be a very accommodating global environment for the development of humanity; it has allowed agriculture, villages and larger settlements and more complex civilizations to develop and thrive. As we move into the Anthropocene, it is important to understand the envelope of natural variability that characterizes the Holocene as a baseline to interpret the global changes that are now under way.

Some features of the Holocene state are well defined by palaeo-evidence. For example, the parameters that characterize the climate, such as temperature and CO_2 concentration, can be obtained with good accuracy from ice cores. Biome distribution before agriculture can be inferred from pollen records. Wetness or dryness of climate can be estimated by techniques such as speleothem (stalactite) records. Other aspects of the Holocene environment, such as the behavior of the nitrogen cycle, the type and amount of atmospheric aerosols, and the changes in ocean circulation, are more difficult to discern. Together, the group of indicators that cover land, ocean, atmosphere and cryosphere and that consider physical, geological, chemical and biological processes define the environmental envelope of the Holocene. Thus, they characterize the only global environment that we are sure is "safe operating space" for the complex, extensive civilization that *Homo sapiens* has constructed.

Biodiversity is a particularly important indicator for the state of the global environment. Although little is known about the relationship between biodiversity and the functioning of the Earth System, there is considerable evidence that more diverse ecosystems are more resilient to variability and change and underpin the provision of a large number of ecosystem services (MA 2005). Biodiversity may thus be as important as a stable climate in sustaining the environmental envelope of the Holocene.

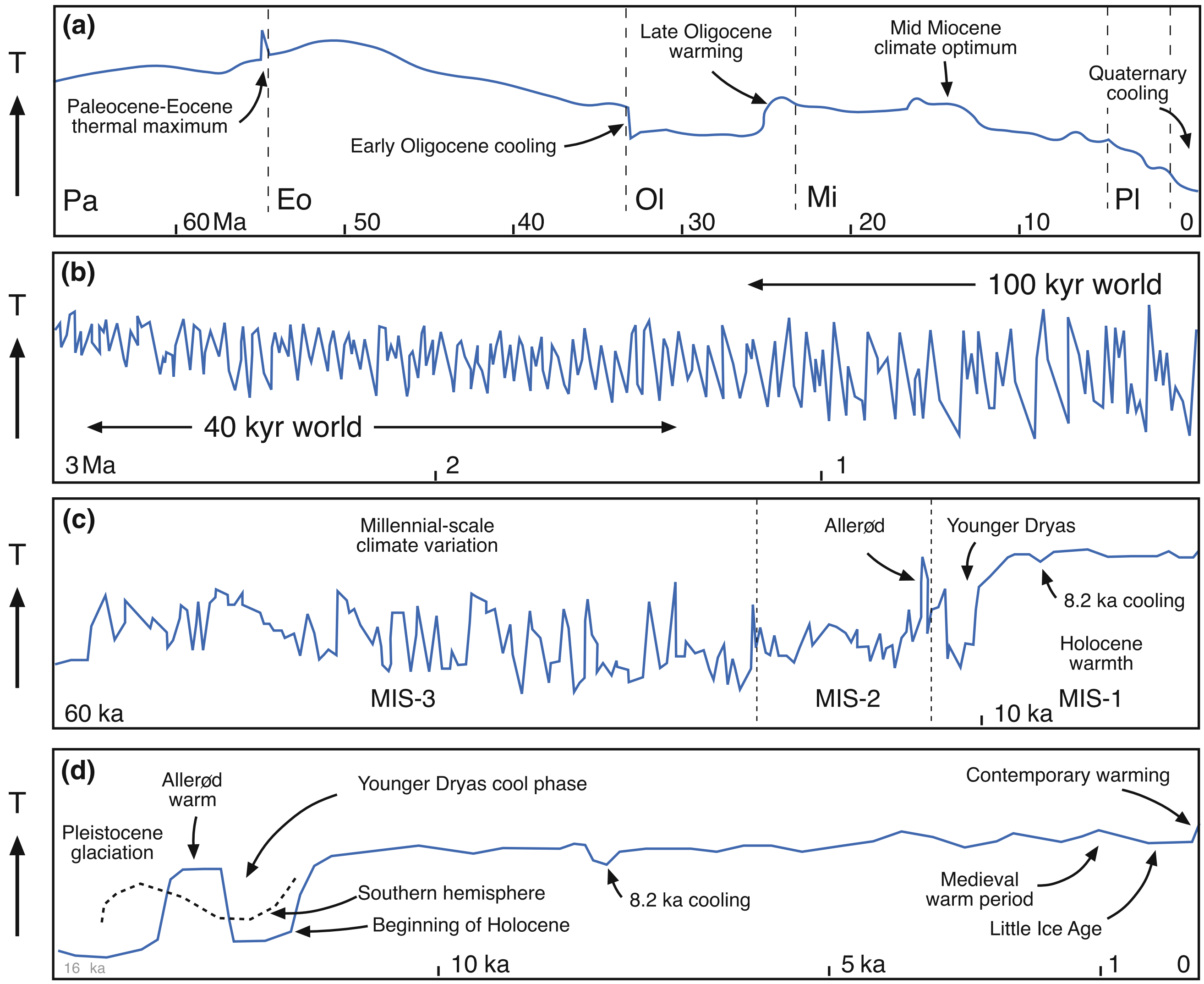


Fig. 5 Changes in global average surface temperature through Earth history, from ca., 70 million years ago to the present (adapted from Zalasiewicz and Williams 2009). **a** The most recent 70 million years, showing the long cooling trend to the present, coincident with decreasing atmospheric CO_2 concentration; the Antarctic ice sheets formed about 34 million years ago and the northern hemisphere ice sheets about 2.5 million years ago. **b** The most recent 3 million years, encompassing the Quaternary period. The late Quaternary, the time during which *Homo sapiens* evolved, is characterized by ca., 100 000-year rhythmic oscillations between long, variable cold periods and much shorter warm intervals. The oscillations are triggered by subtle changes in the Earth's orbit but the temperature changes are driven by the waxing and waning of ice sheets and changes in greenhouse gas concentrations. **c** The most recent 60 000 years of Earth history, showing the transition from the most recent ice age into the much more stable Holocene about 12 000 years ago. The most recent ice age, which humans experienced, was characterized by repeated, rapid, severe, and abrupt changes in northern hemisphere climate (Dansgaard–Oeschger events), with changes in oceanic circulation, periodic major ice sheet collapses, 5–10 m scale sea-level changes, and regional changes in aridity/humidity. **d** The most recent 16 000 years of Earth history, showing the Holocene and the transition into it from the most recent ice age

Widespread biodiversity loss could affect the regulating services of the Earth System, given the importance of biological processes and feedbacks. Past biodiversity change can place the current mass extinction event into a longer term, Earth System context. Based on the fossil record, none of the five past mass extinction events are direct analogues for modern biodiversity loss, but their study can improve understanding of the role of biodiversity in Earth System dynamics (Erwin 2008). For instance, the partial loss of terrestrial herbivorous megafauna by hunting around the Pleistocene/Holocene boundary has been linked with regional temperature changes driven by consequent changes to vegetation and albedo (Doughty et al. 2010).

Such knowledge can inform questions about what types and how much biodiversity must be preserved in what regions to sustain the resilience of the Earth System or large parts of it. These questions will become more prominent as we move from a focus on exploiting Earth System goods and services to becoming active stewards of our own planetary life support system.

THE TWENTY-FIRST CENTURY CHALLENGE: TOWARD PLANETARY STEWARDSHIP

The twenty-first century challenge is different from any other that humanity has faced. The planetary nature of the challenge is unique, and demands a global-scale solution that transcends national boundaries and cultural divides (Svedin 1998). The collision of the human enterprise with the rest of nature has occurred many times in the past at sub-global scales, leading to a new paradigm of integrated social-ecological systems (Folke et al. 2011). At the global scale, this paradigm challenges humanity to become active stewards of our own life support system (Kates et al. 2001; Young and Steffen 2009; Chapin et al. 2010). We are the first generation with the knowledge of how our activities influence the Earth System, and thus the first generation with the power and the responsibility to change our relationship with the planet.

The challenge for humanity is shown by a comparison of the Human Development Index (HDI), a measure of well-being, and the Ecological Footprint (Global Footprint Network 2011), an indicator of the human imprint on the global environment (Fig. 6). The world population-weighted average HDI rose to 0.68 in 2010 from 0.57 in 1990, continuing the upward trend from 1970, when it stood at 0.48 (UNDP 2010). The global ecological footprint has also been rising, leading to an overshoot of Earth's annual biocapacity in the mid-1970s, corresponding to 1.5 planets in 2007. The increase is mainly due to higher demand for CO_2 absorption generated primarily by fossil fuel energy usage (WWF 2010).

The bottom right shaded area of Fig. 6 represents the "sustainability quadrant", in which the HDI reaches an acceptably high value but the ecological footprint remains with the limits of one planet Earth (Global Footprint Network 2011). Currently, no country achieves these two levels simultaneously. However, a promising development, shown by the downwards-sloping trajectories of some countries, is that they have improved wellbeing while reducing both natural resource demand and pollution. At the aggregated global scale, however, the trends are clear. Population growth in combination with more intense resource use and growing pollution still sets the world as a whole on a pathway toward a growing total footprint (Global Footprint Network 2011).

In summary, human well-being has reached high levels in many countries while our planetary life support system is simultaneously being eroded. An analysis of this 'environmentalist's paradox', based on the assessment that 15 of 24 types of ecosystem services are in decline globally (MA 2005), concluded that provisioning services are currently more important than supporting and regulating services for human well-being, as measured by the rise in HDI over the 1970–2005 period (Raudsepp-Hearne et al. 2010). Thus,

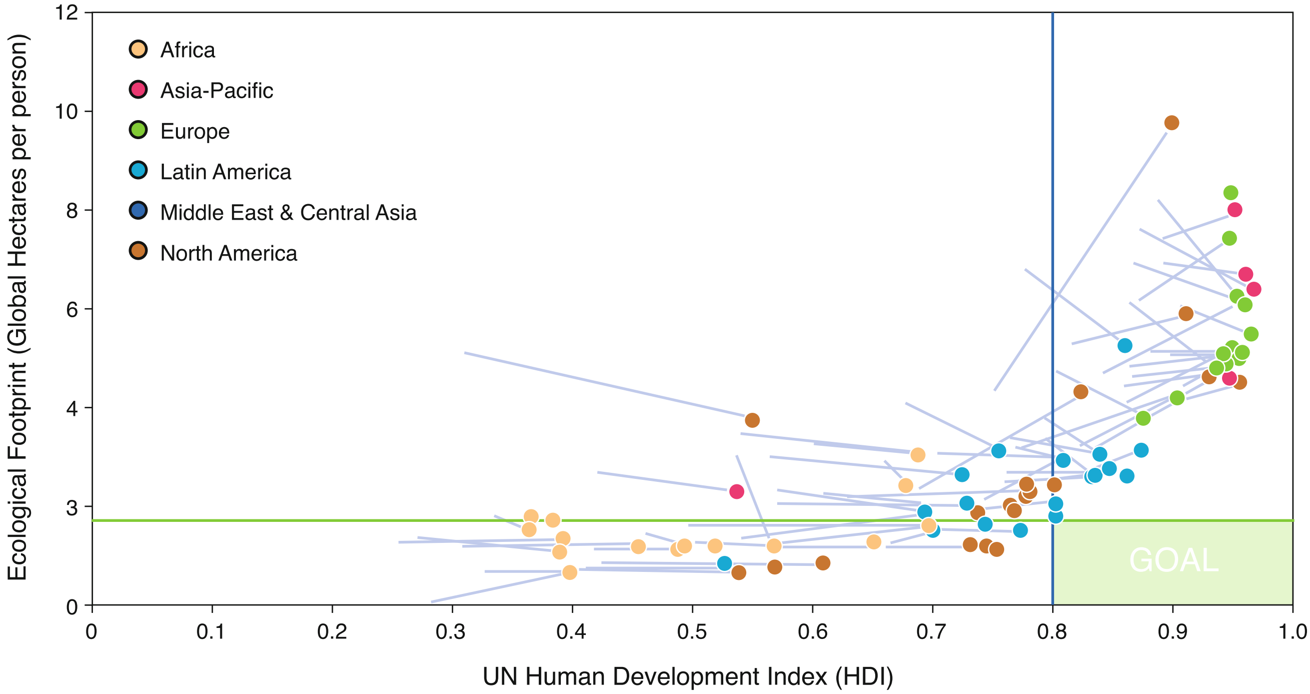


Fig. 6 National Human Development Index and Ecological Footprint trajectories, 1980–2007, compared with goal levels. (Global Footprint Network 2011) (see flash video at http://www.footprintnetwork.org/en/index.php/GFN/page/fighting_poverty_our_human_development_initiative/)

the benefits associated with food production (a provisioning service) currently outweigh the costs of declines in other services at the global scale.

Several questions have been raised about this conclusion. First, the HDI is too narrow, failing to incorporate cultural or psychological dimensions or security considerations and ignoring involuntary adaptation as a result of environmental deterioration and opportunity costs. Second, global aggregates mask the ways in which the distribution of wealth and the impacts of ecosystem service decline are skewed, between nations and within them, a factor that may have a strong bearing on well-being (Wilkinson and Pickett 2009). Finally, an alternative explanation is the existence of time lags between the decline in ecosystem services and their effect on human well-being, particularly time lags associated with geophysical processes, such as loss of ice in the large polar ice sheets and changes in ocean circulation that operate on timescales of decades, centuries and millennia (Fig. 7—photo: melting ice).

Fig. 7 The planetary boundary for climate change is designed to avoid significant loss of ice from the large polar ice sheets. Melting Greenland ice sheet (photo: Bent Christensen, Azote)

Additional insights into the twenty-first century challenge for humanity can be obtained from analyzing the interaction of human societies with their environment in the past, which highlight three types of societal responses to environmental pressures: collapse, migration, and creative invention through discovery (Costanza et al. 2007). Collapse, which refers to the uncontrolled decline of a society or civilization via a drop in population and reductions in production and consumption, leads to a sharp decline in human well-being. Many historical (pre-Anthropocene) societal collapses have occurred, and the causal mechanisms are generally complex and difficult to untangle, usually involving environmental, social, and political interactions (Costanza et al. 2007, and references therein).

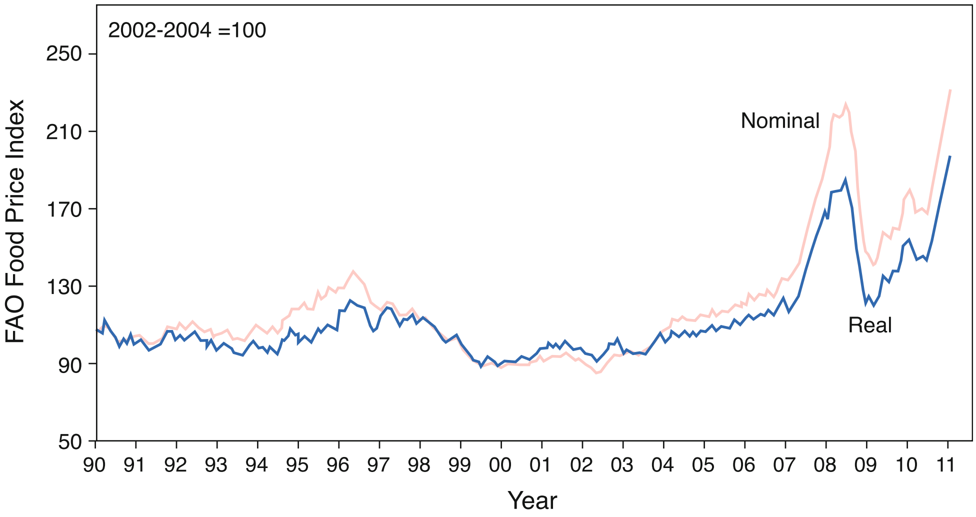
Some hypotheses regarding the causes of collapses in the past are particularly relevant to the Anthropocene. For example, increasing societal complexity in response to problems is an adaptive strategy at first, but as complexity increases, resilience is eroded and societies become more, rather than less, vulnerable to external shocks (Tainter 1998). Another hypothesis (Diamond 2005) proposes that societies collapse if core values become dysfunctional as the external world changes and they are unable to recognize emerging problems. Such societies are locked into obsolete values hindering, for example, the transition to new values supporting a reconnection to the biosphere (Folke et al. 2011). A core value of post-World War II contemporary society is ever-increasing material wealth generated by a growth-oriented economy based on neoliberal economic principles and assumptions (McNeill 2000; Hibbard et al. 2006), a value that has driven the Great Acceleration but that climate change and other global changes are calling into question.

How likely are environmental pressures to trigger collapse in the contemporary world? With a more interconnected world through trade, transportation and communication and with economic structures less reliant on local agricultural production, vulnerability profiles of societies have been fundamentally altered. The nature of human-environment interactions has also changed along several dimensions—scale, speed, and complexity—which contribute to the new forms of vulnerability.

The increasingly *global scale* of environmental degradation in the Anthropocene has led to some (partial) solutions (e.g., international treaties, international market mechanisms), but the distribution of environmental and economic impacts are highly uneven. Whether the local impact is sufficient to cause local collapse, and whether local collapse can propagate rapidly throughout the globalized human enterprise, as in the global financial crisis, are important questions. On the other hand, a well-connected human enterprise could lead to increased knowledge and techniques for local adaptation, averting or containing local collapse before it can spread. Another qualitatively new problem is the "democratic deficit" associated with international institutions, which are comprised of a collection of sovereign nation-states (Mason 2005; Bäckstrand et al. 2010). Human impacts on Earth System functioning cannot be resolved within individual jurisdictions alone; supranational cooperation is required.

Understanding the *speed* of environmental change is also important for distinguishing vulnerability to slow-onset versus quick-onset events. Many historical cases of collapse involved slow-onset or gradual change, where the rate of change was proportional to the pressure of the causal agent. Contemporary societies have a broad set of options to deal with such changes. While vulnerability to quick-onset events such as natural disasters has decreased in many respects (Parry et al. 2007), the frequency and intensity of extreme events are expected to increase with climate change (IPCC 2007; UNISDR 2009).

Fig. 8 FAO food price index, 1990–2010 (FAO 2011)



Concatenation of both slow- and quick-onset events, coupled with the increasing connectivity of the human enterprise, can lead to some unexpected global crises (Folke et al. 2011), such as the spikes in food prices (Fig. 8). The Earth System scale adds another twist to the concept of speed of change, as for the very large geophysical changes that have exceptionally long lag times but may then occur suddenly with potential devastating effects, as in the very abrupt warmings associated with the Pleistocene D/O events. Humanity, now largely in its post-agrarian phase of development, has no experience of dealing with such combinations of scale and speed of environmental change.

Finally, in addressing increasing *complexity*, Walker et al. (2009) argue that it is no longer useful to concentrate on environmental challenges and variables individually, but the challenge lies in the intertwining of multi-scale challenges across sectors (e.g., environment, demographics, pandemics, political unrest). An historical case occurred in fourteenth century Europe, when the Medieval Warm Period ended and was followed by colder and wetter growing seasons, a locust invasion, a millennial-scale flood and a pandemic (the Black Death) (Costanza et al. 2007). An oft-cited contemporary example is the food price crisis (Biggs et al. 2011). Climate change itself is an example of such a complex challenge. Multiple crises may coincide or trigger each other, and there is a need to move beyond narrow sectoral approaches toward more coherent and effective institutions that can deal with complex systems perspectives (UNISDR 2009; Walker et al. 2009).

The scale, speed and complexity of twenty-first century challenges suggest that responses based on marginal changes to the current trajectory of the human enterprise—“fiddling at the edges”—risk the collapse of large segments of the human population or of globalised contemporary society as whole. More transformational approaches may be required. Geo-engineering and reducing the human pressure on the Earth System at its source represent the end points of the spectrum in terms of philosophies, ethics, and strategies.

Geo-engineering—the deliberate manipulation or “engineering” of an Earth System process—is sometimes argued to be an appropriate response to challenges posed by the Anthropocene, most often as a response to climate change. Manipulation of two different types of Earth System process are most often proposed: (i) those processes ultimately controlling the amount of heat entering the Earth’s lower atmosphere (solar radiation management, SRM), and (ii) those affecting the amount of heat energy retained near the Earth’s surface, that is, control of greenhouse gas concentration through manipulation of the global carbon cycle.

Both SRM and manipulation of the carbon cycle constitute a form of “symptom treatment” rather than removal or reduction of the anthropogenic pressures leading to climate change. In particular, SRM targets only the temperature change by decreasing the heat input to the lower atmosphere through, for example, production of sulfate aerosols in the stratosphere (Crutzen 2006). This approach has no direct impact on atmospheric greenhouse gas concentrations, and other processes influenced by elevated concentrations of greenhouse gases, for example, ocean acidification (Royal Society 2005), would continue unchecked even if SRM managed to slow global temperature increases.

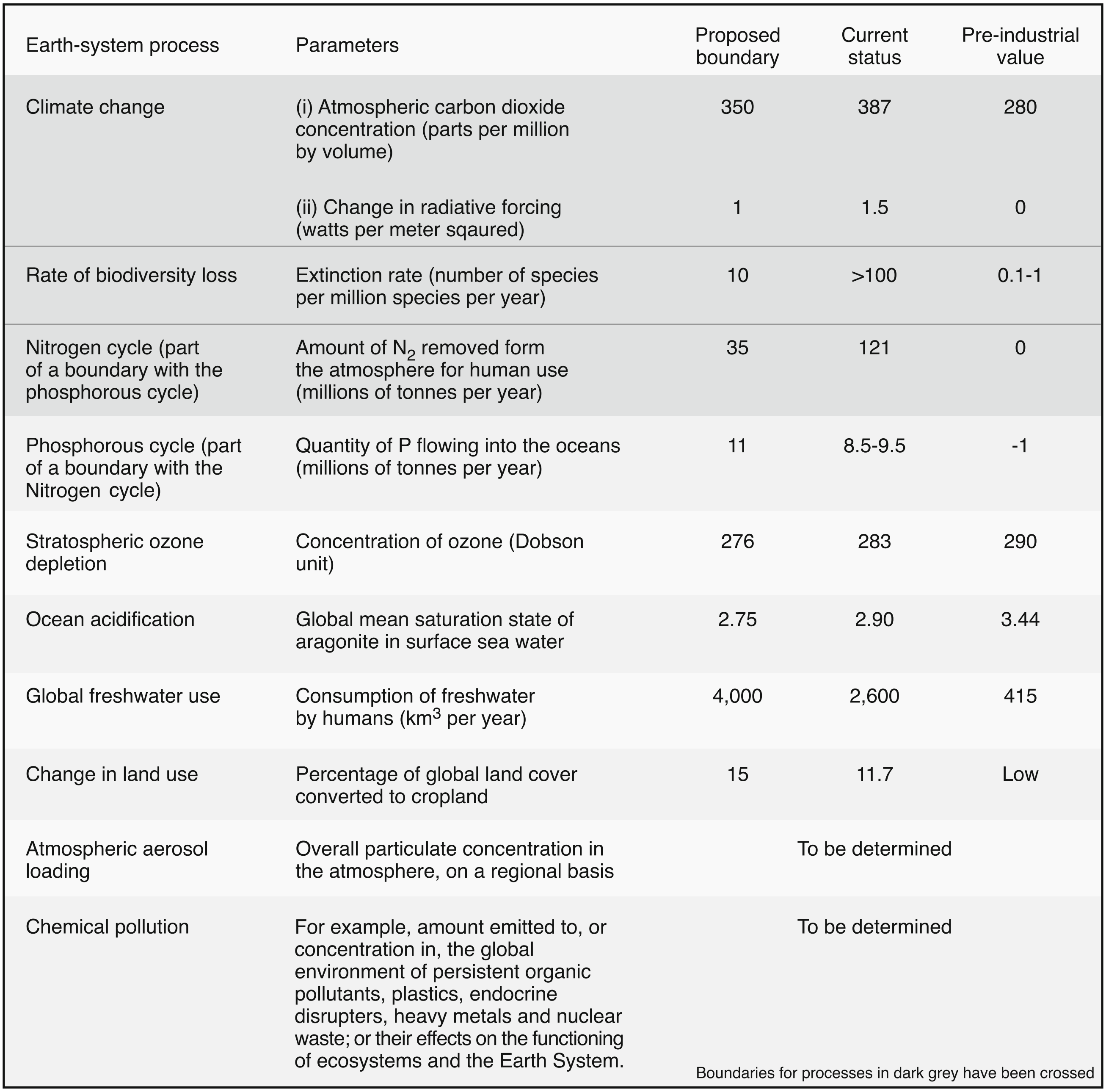
Approaches that manipulate the carbon cycle, such as carbon capture and storage, could slow the rate of increase of atmospheric greenhouse gas concentrations, or perhaps ultimately reduce the atmospheric concentration of CO_2. However, there are no proven mechanisms yet developed that would return the carbon removed from the atmosphere to a form as inert as the fossil fuels from which it was derived. Thus, although removed from the atmosphere, the carbon captured is stored biologically, in underground caverns or in the deep sea if the carbon capture is via chemical or mechanical means. Carbon stored in biological compartments is particularly vulnerable to return to the atmosphere with further climate change or with changes in human management.

In addition to CO_2, there are several other man-made greenhouse gases, which have contributed as much 45% to the total man-made greenhouse effect. The life times of several of these gases (methane, ozone, HFCs) are short (<15 years) compared with the century to millennium time scales of CO_2 and hence actions to reduce their concentrations, possible with existing technologies, will lead to quick reduction in the total warming effect (Ramanathan and Xu 2010).

Nevertheless, it may become necessary to supplement efforts to reduce human emissions of greenhouse gases with geo-engineering to prevent severe anthropogenic climate change. If this strategy is required, then SRM mechanisms would probably be the more effective as the Earth System would respond more quickly to these than to manipulation of the carbon cycle (Richardson et al. 2011). However, in contrast to emissions reduction, the problem with geo-engineering is “not how to get countries to do it, (but) the fundamental question of who should decide whether and how geo-engineering should be attempted – a problem of governance” (Barrett 2008). Many potential forms of geo-engineering would be relatively inexpensive, could be carried out unilaterally and could potentially alter climate and living conditions in neighboring countries. Thus, the potential geopolitical consequences of geo-engineering are enormous, and urgently require guiding principles for their application.

At the other end of the spectrum lie a number of alternative strategies to reduce or modify the human influence on the functioning of the Earth System at its source. The Planetary Boundaries (PB) approach (Rockström et al. 2009a, b) is a recent example that attempts to define a "safe operating space" for humanity by analyzing the intrinsic dynamics of the Earth System and identifying points or levels relating to critical global-scale processes beyond which humanity should not go. The fundamental principle underlying the PB approach is that a Holocene-like state (Fig. 5, panel c; Petit et al. 1999) of the Earth System is the only one that we can be sure provides an accommodating environment for the development of humanity.

Table 1 The planetary boundaries



Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per meter sqaured)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1-1
Nitrogen cycle (part of a boundary with the phosphorous cycle)	Amount of N_2 removed form the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorous cycle (part of a boundary with the Nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5-9.5	-1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined		
Chemical pollution	For example, amount emitted to, or concentration in, the global environment of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste; or their effects on the functioning of ecosystems and the Earth System.	To be determined		

Boundaries for processes in dark grey have been crossed

Those rows shaded in dark grey represent processes for which the proposed boundaries have already been transgressed (Rockström et al. 2009a, which also includes the individual references for the data presented in the table)

Nine planetary boundaries have been proposed (Table 1) which, if respected, would likely ensure that the Earth System remains in a Holocene-like state. Preliminary analyses (Rockström et al. 2009a, b) estimated quantitative boundaries for seven of the Earth System processes or elements—climate change, stratospheric ozone, ocean acidification, the nitrogen and phosphorus cycles, biodiversity loss, land-use change and freshwater use. For some of these it is a first attempt at quantifying boundaries of any kind, that is, quantifying the supply of some of the regulating and supporting Earth System services. There is insufficient knowledge to suggest quantitative boundaries for two of the processes—aerosol loading and chemical pollution. Rockström and colleagues estimate that three of the boundaries—those for climate change, the nitrogen cycle and biodiversity loss—have already been transgressed while we are approaching several others (Fig. 9).

Even if a scientific consensus around boundary definitions could be achieved, much more is required to achieve successful and effective global governance and stewardship (Richardson et al. 2011). Focusing on climate change, the outcomes of the COP15 meeting in Copenhagen in 2009 showed that (i) climate change has now been raised to an issue of high political priority internationally, and (ii) the road to achieving a legally binding international climate agreement, based on burden- or cost-sharing in the context of a global commons, is a long and complex one, with further steps beyond COP15 required to deliver such an agreement (Falkner et al. 2010; Richardson et al. 2011).

Recently, however, Ostrom (2010) has suggested that the traditional approach of collective action to climate change

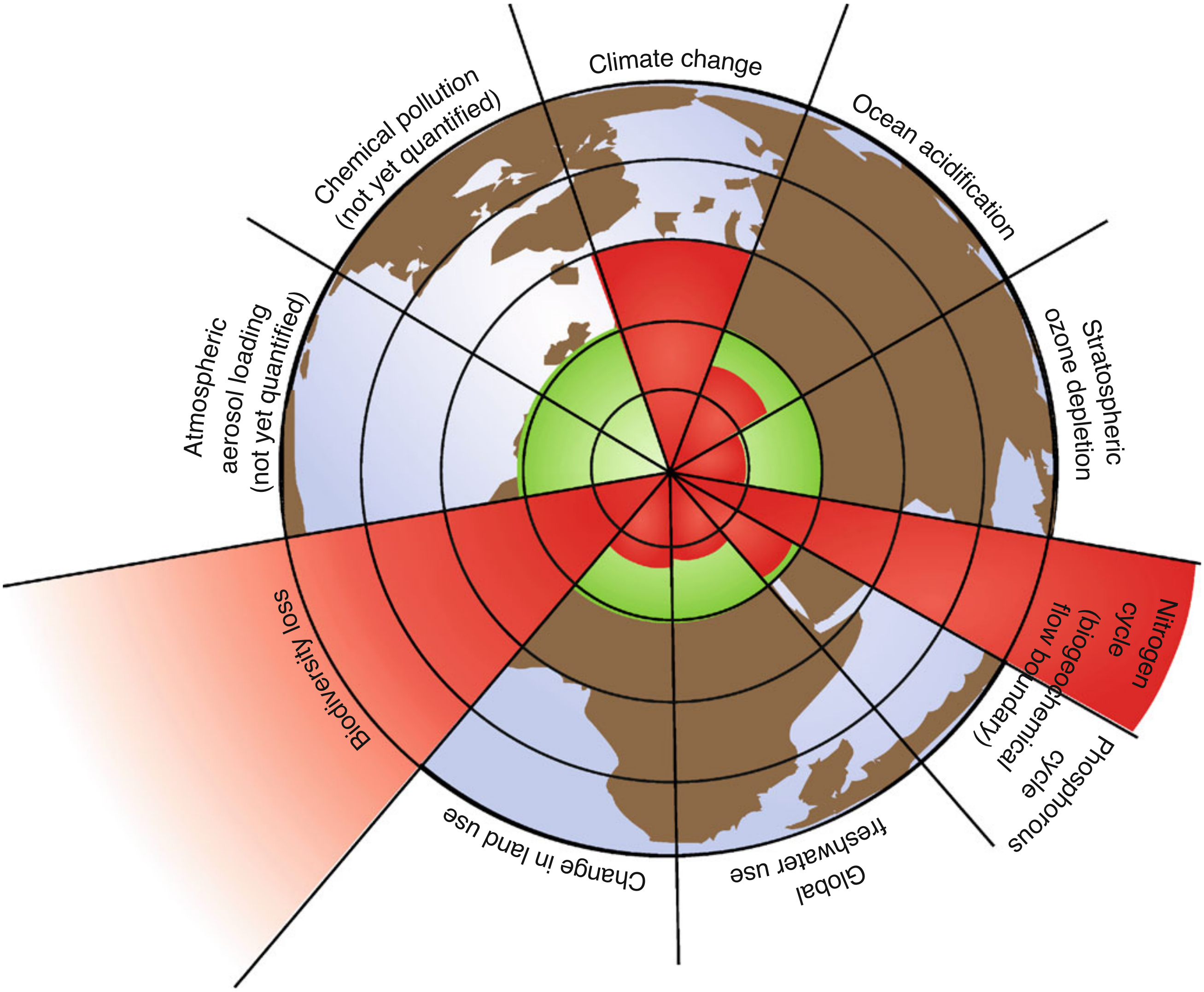


Fig. 9 The inner green shading represents the proposed safe operating space for nine planetary systems. The *red wedges* represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle) have already been exceeded (Rockström et al. 2009a)

based on one international treaty may be misconceived. Addressing climate change through emission reductions can, for example also bring benefits at local and regional scales, such as improved air quality in metropolitan areas. This is particularly so for the emission of the short-term climate warming gases (ozone, methane, HFCs). This approach suggests that global governance and planetary stewardship could also be built in a multi-level, cumulative way by identifying where, when and for whom there are—or could be as a result of policy—incentives to act, independently of the international level (Liljenström and Svedin 2005). The resulting governance system would be ‘polycentric’, also allowing for more experimentation and learning.

Discussions on climate change, global change and global sustainability implicitly assume that the current global environmental changes are perturbations of the stable Holocene state of the Earth System. The assumption is that effective governance will turn the trajectory of the human enterprise toward long-term sustainability and the Earth System back toward a Holocene-like state. However, the concept of the Anthropocene, coupled with complex systems thinking, questions that assumption. The Anthropocene is a dynamic state of the Earth System, characterized by global environmental changes already significant enough to distinguish it from the Holocene, but with a momentum that continues to move it away from the Holocene at a geologically rapid rate.

THE ANTHROPOCENE FROM A COMPLEX SYSTEMS PERSPECTIVE

Several pieces of evidence suggest that the Earth as a whole can be considered as a complex system, with the Holocene the most recent state of the system. This complex systems approach places the Anthropocene in a different perspective. Very long time-scales are associated with some features of the Anthropocene (Zalasiewicz et al. 2011). For example, millennial timescales are associated with significant changes in the large polar ice sheets and even longer timescales associated with recovery of mass extinctions of biological species. This suggests that the Anthropocene will not be a spike of a century or two’s duration but may be evident for a geologically significant period of time (Zalasiewicz et al. 2012). From a complex systems perspective (Scheffer 2009), this raises the possibility that the Anthropocene could become an alternative, more or less stable state of the Earth System.

The most striking feature of Earth System dynamics in the late Quaternary is the regular oscillation between two well-defined states: glacial phases and the shorter, intervening warm interglacials. This is characteristic behavior of a complex system that has two stable states, or basins of attraction, between which it oscillates, that is, a limit cycle (Scheffer 2009). Figure 10 shows a “stability landscape” in which a system (the ball) can move between two different states or basins of attraction (the valleys). A critical feature of a complex system is the existence of feedbacks that can move the system from an intermediate point toward either of the stable states. For the Earth System, the most important feedbacks that move the system toward either the glacial or the interglacial state are (i) the release or uptake of greenhouse gases as the surface warms (net release) or cools (net uptake), and (ii) the change in reflectively as the ice sheets grow (increased reflectivity, cooling) or retreat (decreased reflectivity, warming). The interglacial state is much shorter than the glacial one, hinting that it is inherently less stable as regards duration, that is, it is a weaker basin of attraction or a shallower valley in Fig. 10.

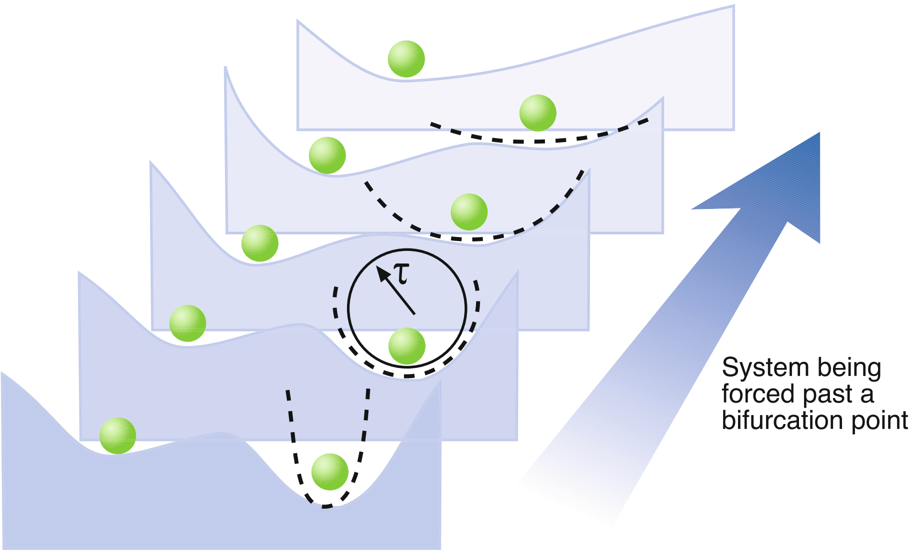


Fig. 10 A stability landscape with two stable states. The valleys, or basins of attraction, in the landscape represent the stable states at several different conditions, while the hilltops represent unstable conditions as the system transitions from one state to another. If the size of the basin of attraction is small, resilience is small, and even a moderate perturbation may bring the system into the alternative basin of attraction (Scheffer 2009)

Is the human perturbation to Earth System dynamics, which is pushing the system *away* from the glacial-interglacial limit cycle, strong and persistent enough to tip the system out of the Holocene stability domain and into an alternative, geologically long-lived, generally warmer state of the Earth System?

The degree of resilience, or the depth of the basin of attraction, of the Holocene state is at issue (cf. Fig. 10; Folke et al. 2010). The Holocene is already of significantly longer duration than the three previous interglacials, and, without human perturbation, may continue for many thousands of years. This suggests that the Holocene is inherently more stable than the three earlier interglacials. The tight regulation of global mean temperature through the Holocene and the strength of the land and ocean carbon sinks in absorbing over half of the human emissions of CO_2 (Le Quéré et al. 2009; Raupach and Canadell 2010) is consistent with this suggestion, although the possible weakening of the ocean carbon sink over the last few decades (Le Quéré et al. 2009) may challenge it.

Carbon cycle feedbacks highlight the role of the biosphere in contributing to the resilience of the Holocene. The role of biology in promoting homeostasis in the Earth System, that is, contributing to a strong basin of attraction around a state conducive to life, has been highlighted by James Lovelock (Lovelock 1979, 1988). An analysis of the functioning of the Earth System in the Anthropocene (Steffen et al. 2004) has confirmed the importance of biological processes, but has also shown that biological feedback processes can contribute to the destabilization of states in large subsystems of the Earth, for example, the rapid shifts in vegetation in the Sahel-Sahara region of Africa (Claussen et al. 1999; deMenocal et al. 2000). Little is known, however, about the ways in which major features of Earth System structure and functioning—ocean circulation, atmospheric chemistry, ecosystem physiology, the hydrological cycle, and biodiversity—interact to contribute to the resilience and stability of the Holocene state, or of the degree to which human pressures—deforestation, acidification of ecosystems, loss of biodiversity—are eroding this resilience.

The tipping elements analysis of Lenton et al. (2008) describes many examples of complex system behavior—bifurcation points, threshold-abrupt change, bi-stability domains—in important sub-systems of the Earth System. Considering the Earth as a single system, these sub-systems could be classified into (i) those that affect the two main feedback mechanisms that drive the Earth System between glacial and interglacial states (e.g., melting of permafrost; loss of Greenland ice sheet); (ii) those that may change the resilience of the Holocene state (e.g., loss of Amazon rainforest), and (iii) those that would affect humans but not the basin of attraction, or the overall stability, of the Holocene (e.g., the bistability of the Indian monsoon). Two of the tipping elements that already show signs of instability—the Greenland ice sheet and the Amazon rainforest—represent important sub-systems that, if tipped, would move the Earth System toward a warmer state, that is, away from the Holocene basin of attraction.

Evidence of complex system behavior is common in the past record of Earth System dynamics. For example, the 100 000-year cycles between glacial and interglacial states, which are linked to rather weak orbital forcing with minor changes in solar insolation, may be an example of phase locking—the observed cycles are tuned to the time it takes for the large polar ice sheets to grow and decay (Scheffer 2009). Model studies suggest that the glacial-interglacial limit cycle is not particularly stable; the late Quaternary may be a geologically short phase of climate instability that was headed toward a new stable state of a permanently glaciated, low-CO_2 world if we had not injected large amounts of greenhouse gases into the atmosphere (Crowley and Hyde 2008). Thus, the late Quaternary, including the Holocene, may represent a time when the Earth System is unusually sensitive to being switched between strongly contrasting states by modest forcing agents or internal feedbacks.

What are the implications of this complex systems perspective for the future of humanity? Will our attempts to achieve effective planetary stewardship slow and then halt the current trajectory further into the Anthropocene, eventually steering the Earth System back toward Holocene-like conditions and, in so doing, move contemporary civilization toward a new state of sustainability? Or is it already too late to return to a world of the Holocene that may be already lost? Is the Anthropocene, a one-way trip for humanity to an uncertain future in a new, much warmer—and very different—stable state of the Earth System? While these questions demand a greatly enhanced research effort, they reinforce the urgency for effective Earth System stewardship to maintain a global environment within which humanity can continue to develop in a humane and respectful fashion.

CONCLUSION—KEY MESSAGES

The challenges of the twenty-first century—resource constraints, financial instability, inequalities within and between countries, environmental degradation—are a clear signal that “business-as-usual” cannot continue. We are passing into a new phase of human experience and entering a new world that will be qualitatively and quantitatively different from the one we have known.

The Anthropocene provides an independent measure of the scale and tempo of human-caused change—

biodiversity loss, changes to the chemistry of atmosphere and ocean, urbanization, globalization—and places them in the deep time context of Earth history. The emerging Anthropocene world is warmer with a diminished ice cover, more sea and less land, changed precipitation patterns, a strongly modified and impoverished biosphere and human-dominated landscapes.

We are the first generation with widespread knowledge of how our activities influence the Earth System, and thus the first generation with the power and the responsibility to change our relationship with the planet. Responsible stewardship entails emulating nature in terms of resource use and waste transformation and recycling, and the transformation of agricultural, energy and transport systems.

Effective planetary stewardship can be built around scientifically developed boundaries for critical Earth System processes that must be observed for the Earth System to remain within a Holocene-like state. An effective architecture of a governance system for planetary stewardship is likely to be polycentric and multi-level rather than centralized and hierarchical.

Effective planetary stewardship must be achieved quickly, as the momentum of the Anthropocene threatens to tip the complex Earth System out of the cyclic glacial-interglacial pattern during which *Homo sapiens* has evolved and developed. Without such stewardship, the Anthropocene threatens to become for humanity a one-way trip to an uncertain future in a new, but very different, state of the Earth System.

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